Spintronics: Fundamentals and applications

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Spintronics, or spin electronics, involves the study of active control and manipulation of spin degrees of freedom in solid-state systems. This article reviews the current status of this subject, including both recent advances and well-established results. The primary focus is on the basic physical principles underlying the generation of carrier spin polarization, spin dynamics, and spin-polarized transport in semiconductors and metals. Spin transport differs from charge transport in that spin is a nonconserved quantity in solids due to spin-orbit and hyperfine coupling. The authors discuss in detail spin decoherence mechanisms in metals and semiconductors. Various theories of spin injection and spin-polarized transport are applied to hybrid structures relevant to spin-based devices and fundamental studies of materials properties. Experimental work is reviewed with the emphasis on projected applications, in which external electric and magnetic fields and illumination by light will be used to control spin and charge dynamics to create new functionalities not feasible or ineffective with conventional electronics.

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I. INTRODUCTION

A. Overview

Spintronics is a multidisciplinary field whose central theme is the active manipulation of spin degrees of free-

dom in solid-state systems.[1] In this article the term spin stands for either the spin of a single electron **s**, which can be detected by its magnetic moment $-g\mu_B\mathbf{s}$ (μ_B is the Bohr magneton and g is the electron g factor, in a solid generally different from the free-electron value of $g_0=2.0023$), or the average spin of an ensemble of electrons, manifested by magnetization. The control of spin is then a control of either the population and the phase of the spin of an ensemble of particles, or a coherent spin manipulation of a single or a few-spin system. The goal of spintronics is to understand the interaction between the particle spin and its solid-state environments and to make useful devices using the acquired knowledge. Fundamental studies of spintronics include investigations of spin transport in electronic materials, as well as of spin dynamics and spin relaxation. Typical questions that are posed are (a) what is an effective way to polarize a spin system? (b) how long is the system able to remember its spin orientation? and (c) how can spin be detected?

Generation of spin polarization usually means creating a nonequilibrium spin population. This can be achieved in several ways. While traditionally spin has been oriented using optical techniques in which circularly polarized photons transfer their angular momenta to electrons, for device applications electrical spin injection is more desirable. In electrical spin injection a magnetic electrode is connected to the sample. When the current drives spin-polarized electrons from the electrode to the sample, nonequilibrium spin accumulates there. The rate of spin accumulation depends on spin relaxation, the process of bringing the accumulated spin population back to equilibrium. There are several mechanisms of spin relaxation, most involving spin-orbit coupling to provide the spin-dependent potential, in combination with momentum scattering to provide a randomizing force. Typical time scales for spin relaxation in electronic systems are measured in nanoseconds, while the range is from picoseconds to microseconds. Spin detection, also part of a generic spintronic scheme, typically relies on sensing the changes in the signals caused by the presence of nonequilibrium spin in the system. The common goal in many spintronic devices is to maximize the spin detection sensitivity to the point that it detects not the spin itself, but changes in the spin states.

Let us illustrate the generic spintronic scheme on a prototypical device, the Datta-Das *spin field-effect transistor* (SFET; Datta and Das, 1990), depicted in Fig. 1. The scheme shows the structure of the usual FET, with a drain, a source, a narrow channel, and a gate for controlling the current. The gate either allows the current to flow (ON) or does not (OFF). The spin transistor is similar in that the result is also a control of the charge current through the narrow channel. The difference, however, is in the physical realization of the current control. In the Datta-Das SFET the source and the drain are ferromagnets acting as the injector and detector of the electron spin. The drain injects electrons with spins parallel to the transport direction. The electrons are transported ballistically through the channel. When they arrive at the drain, their spin is detected. In a simplified picture, the electron can enter the drain (ON) if its spin points in the same direction as the spin of the drain. Otherwise it is scattered away (OFF). The role of the gate is to generate an effective magnetic field (in the direction of $\mathbf{\Omega}$ in Fig. 1), arising from the spin-orbit coupling in the substrate material, from the confinement geometry of the transport channel, and the electrostatic potential of the gate. This effective magnetic field causes the electron spins to precess. By modifying the voltage, one can cause the precession to lead to either parallel or antiparallel (or anything between) electron spin at the drain, effectively controlling the current.

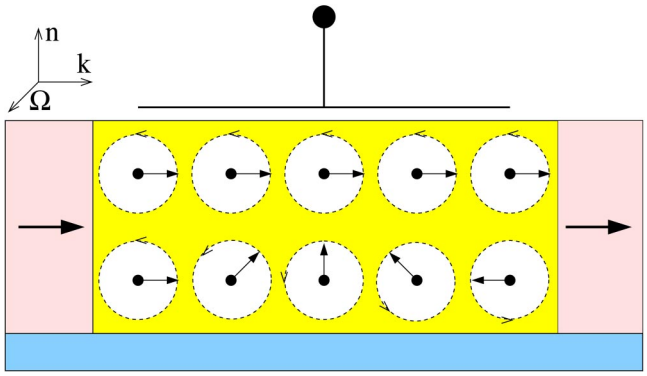

FIG. 1. (Color in online edition) Scheme of the Datta-Das spin field-effect transistor (SFET). The source (spin injector) and the drain (spin detector) are ferromagnetic metals or semiconductors, with parallel magnetic moments. The injected spin-polarized electrons with wave vector **k** move ballistically along a quasi-one-dimensional channel formed by, for example, an InGaAs/InAlAs heterojunction in a plane normal to **n**. Electron spins precess about the precession vector $\mathbf{\Omega}$, which arises from spin-orbit coupling and which is defined by the structure and the materials properties of the channel. The magnitude of $\mathbf{\Omega}$ is tunable by the gate voltage V_G at the top of the channel. The current is large if the electron spin at the drain points in the initial direction (top row)—for example, if the precession period is much larger than the time of flight—and small if the direction is reversed (bottom).

Even though the name *spintronics* is rather novel,[2] contemporary research in spintronics relies closely on a long tradition of results obtained in diverse areas of physics (for example, magnetism, semiconductor physics, superconductivity, optics, and mesoscopic physics) and establishes new connections between its different subfields (Rashba, 2002c; Žutić, 2002a). We review here both well-established results and the physical principles

[1]While there are proposals for spintronic devices based on deoxyribonucleic acid (DNA) molecules (Zwolak and Di Ventra, 2002), the whole device, which includes electrodes, voltage/current source, etc., is still a solid-state system.

[2]The term was coined by S. A. Wolf in 1996, as a name for a DARPA initiative for novel magnetic materials and devices.

relevant to present and future applications. Our strategy is to give a comprehensive view of what has been accomplished, focusing in detail on a few selected topics that we believe are representative for the broader subject within which they appear. For example, while discussing the generation of spin polarization, we survey many experimental and theoretical studies of both optical orientation and electrical spin injection and present a detailed and self-contained formalism of electrical spin injection. Similarly, when we discuss spin relaxation, we give a catalog of important work, while studying spin relaxation in the cases of Al and GaAs as representative of the whole field. Finally, in the section on spin devices we give detailed physical principles of several selected devices, such as, for example, the above-mentioned Datta-Das SFET.

There have been many other reviews written on spintronics, most focusing on a particular aspect of the field. We divide them here, for an easier orientation, into two groups, those that cover the emerging applications[3] and those covering already well-established schemes and materials.[4] The latter group, often described as *magnetoelectronics* typically covers paramagnetic and ferromagnetic metals and insulators, which utilize magnetoresistive effects, realized, for example, as magnetic read heads in computer hard drives, nonvolatile magnetic random access memory (MRAM), and circuit isolators (Wang *et al.*, 2002). These more established aspects of spintronics have also been addressed in several books[5] and will be discussed in another review[6] complementary to ours.

Spintronics also benefits from a large class of emerging materials, such as ferromagnetic semiconductors (Ohno, 1998; Pearton *et al.*, 2003), organic semiconductors (Dediu *et al.*, 2002), organic ferromagnets (Pejaković *et al.*, 2002; Epstein, 2003), high-temperature superconductors (Goldman *et al.*, 1999), and carbon nanotubes (Tsukagoshi *et al.*, 1999; Zhao *et al.*, 2002), which can bring novel functionalities to the traditional devices. There is a continuing need for fundamental studies before the potential of spintronic applications can be fully realized.

After an overview, Sec. I covers some basic historical and background material, part of which has already been extensively covered in the context of magnetoelectronics and will not be discussed further in this review. Techniques for generating spin polarization, focusing on optical spin orientation and electrical spin injection, are described in Sec. II. The underlying mechanisms responsible for the loss of spin orientation and coherence, which impose fundamental limits on the length and time scales in spintronic devices, are addressed in Sec. III. Spintronic applications and devices, with the emphasis on those based on semiconductors, are discussed in Sec. IV. The review concludes with a look at future prospects in Sec. V.

B. History and background

1. Spin-polarized transport and magnetoresistive effects

In a pioneering work, Mott (1936a, 1936b) provided a basis for our understanding of spin-polarized transport. Mott sought an explanation for an unusual behavior of resistance in ferromagnetic metals. He realized that at sufficiently low temperatures, where magnon scattering becomes vanishingly small, electrons of majority and minority spin, with magnetic moment parallel and antiparallel to the magnetization of a ferromagnet, respectively, do not mix in the scattering processes. The conductivity can then be expressed as the sum of two independent and unequal parts for two different spin projections—the current in ferromagnets is spin polarized. This is also known as the two-current model and has been extended by Campbell *et al.* (1967) and Fert and Campbell (1968). It continues, in its modifications, to provide an explanation for various magnetoresistive phenomena (Valet and Fert, 1993).

Tunneling measurements played a key role in early experimental work on spin-polarized transport. Studying N/F/N junctions, where N was a nonmagnetic[7] metal and F was an Eu-based ferromagnetic semiconductor (Kasuya and Yanase, 1968; Nagaev, 1983), revealed that I-V curves could be modified by an applied magnetic field (Esaki *et al.*, 1967) and now show potential for developing a solid-state spin filter. When unpolarized current is passed across a ferromagnetic semiconductor, the current becomes spin-polarized (Moodera *et al.*, 1988; Hao *et al.*, 1990).

A series of experiments (Tedrow and Meservey, 1971b, 1973, 1994) in ferromagnet/insulator/superconductor (F/I/S) junctions has unambiguously proved that the tunneling current remains spin polarized even outside of the ferromagnetic region.[8] The Zeeman-

[3]Reviews on emerging applications include those of Das Sarma *et al.* (2000a, 2000b, 2000c, 2001); Wolf and Treger (2000); Das Sarma (2001); Wolf *et al.* (2001); Oestreich *et al.* (2002); Rashba (2002c); Žutić (2002a, 2002b).

[4]Established schemes and materials are reviewed by Tedrow and Meservey (1994); Prinz (1995, 1998); Gijs and Bauer (1997); Gregg *et al.* (1997); Ansermet (1998); Bass and Pratt, Jr. (1999); Daughton *et al.* (1999); Stiles (2004).

[5]See, for example, the books of Hartman (2000); Ziese and Thornton (2001); Hirota *et al.* (2002); Levy and Mertig (2002); Maekawa *et al.* (2002); Parkin (2002); Shinjo (2002); and Chtchelkanova *et al.* (2003).

[6]In preparation by S. S. P. Parkin for Reviews of Modern Physics.

[7]Unless explicitly specified, we shall use the terms "nonmagnetic" and "paramagnetic" interchangeably, i.e., assume that they both refer to a material with no long-range ferromagnetic order and with Zeeman-split carrier spin subbands in an applied magnetic field.

[8]It has been shown that electrons photoemitted from ferromagnetic gadolinium remain spin polarized (Busch *et al.*, 1969).

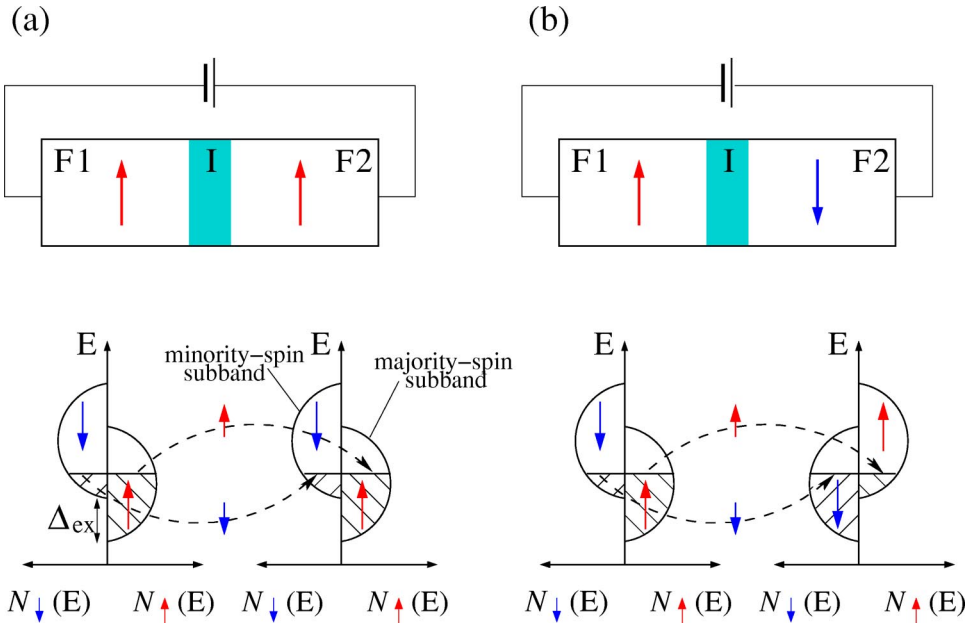

FIG. 2. (Color in online edition) Schematic illustration of electron tunneling in ferromagnet / insulator / ferromagnet (F/I/F) tunnel junctions: (a) Parallel and (b) antiparallel orientation of magnetizations with the corresponding spin-resolved density of the d states in ferromagnetic metals that have exchange spin splitting Δ_{ex}. Arrows in the two ferromagnetic regions are determined by the majority-spin subband. Dashed lines depict spin-conserved tunneling.

split quasiparticle density of states in a superconductor (Tedrow *et al.*, 1970; Fulde, 1973) was used as a detector of spin polarization of conduction electrons in various magnetic materials. Jullière (1975) measured tunneling conductance of F/I/F junctions, where I was an amorphous Ge. By adopting the Tedrow and Meservey (1971b, 1973) analysis of the tunneling conductance from F/I/S to the F/I/F junctions, Jullière (1975) formulated a model for a change of conductance between the parallel ($\uparrow\uparrow$) and antiparallel ($\uparrow\downarrow$) magnetization in the two ferromagnetic regions F1 and F2, as depicted in Fig. 2. The corresponding *tunneling magnetoresistance*[9] (TMR) in an F/I/F magnetic tunnel junction (MTJ) is defined as

$$\mathrm{TMR}=\frac{\Delta R}{R_{\uparrow\uparrow}}=\frac{R_{\uparrow\downarrow}-R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}=\frac{G_{\uparrow\uparrow}-G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}}, \tag{1}$$

where conductance G and resistance $R=1/G$ are labeled by the relative orientations of the magnetizations in F1 and F2 (it is possible to change the relative orientations, between $\uparrow\uparrow$ and $\uparrow\downarrow$, even at small applied magnetic fields $\sim$10 G). TMR is a particular manifestation of a magnetoresistance that yields a change of electrical resistance in the presence of an external magnetic field.[10] Historically, the anisotropic magnetoresistance in bulk ferromagnets such as Fe and Ni was discovered first, dating back to the experiments of Lord Kelvin (Thomson, 1857). Due to spin-orbit interaction, electrical resistivity changes with the relative direction of the charge current (for example, parallel or perpendicular) with respect to the direction of magnetization.

Within Jullière's model, which assumes constant tunneling matrix elements and that electrons tunnel without spin flip, Eq. (1) yields

$$\mathrm{TMR}=\frac{2P_1P_2}{1-P_1P_2}, \tag{2}$$

where the polarization $P_i=(\mathcal{N}_{Mi}-\mathcal{N}_{mi})/(\mathcal{N}_{Mi}+\mathcal{N}_{mi})$ is expressed in terms of the spin-resolved density of states $\mathcal{N}_{Mi}$ and $\mathcal{N}_{mi}$, for majority and minority spin in F_i, respectively. Conductance in Eq. (1) can then be expressed as (Maekawa and Gäfvert, 1982) $G_{\uparrow\uparrow}\sim\mathcal{N}_{M1}\mathcal{N}_{M2}+\mathcal{N}_{m1}\mathcal{N}_{m2}$ and $G_{\uparrow\downarrow}\sim\mathcal{N}_{M1}\mathcal{N}_{m2}+\mathcal{N}_{m1}\mathcal{N}_{M2}$ to give Eq. (2).[11] While the early results of Jullière (1975) were not confirmed, TMR at 4.2 K was observed using NiO as a tunnel barrier by Maekawa and Gäfvert (1982).

The prediction of Jullière's model illustrates *the spin-valve effect*: the resistance of a device can be changed by manipulating the relative orientation of the magnetizations $\mathbf{M}_1$ and $\mathbf{M}_2$, in F1 and F2, respectively. Such orientation can be preserved even in the absence of a power supply, and the spin-valve effect,[12] later discovered in multilayer structures displaying the *giant magnetoresistance*[13] (GMR) effect (Baibich *et al.*, 1988; Binasch *et al.*, 1989) can be used for nonvolatile memory applications (Hartman, 2000; Hirota *et al.*, 2002; Parkin,

[9]Starting with Jullière (1975) an equivalent expression $(G_{\uparrow\uparrow}-G_{\uparrow\downarrow})/G_{\uparrow\uparrow}$ has also been used by different authors and is often referred to as *junction magnetoresistance* (Moodera and Mathon, 1999).

[10]The concept of TMR was proposed independently by R. C. Barker in 1975 [see Meservey *et al.* (1983)] and by Slonczewski (1976), who envisioned its use for magnetic bubble memory (Parkin, 2002).

[11]In Sec. IV we address some limitations of the Jullière model and its potential ambiguities to identify precisely which spin polarization is actually measured.

[12]The term was coined by Dieny *et al.* (1991) in the context of GMR, by invoking an analogy with the physics of the TMR.

[13]The term "giant" reflected the magnitude of the effect (more than $\sim$10%), as compared to the better known anisotropic magnetoresistance ($\sim$1%).

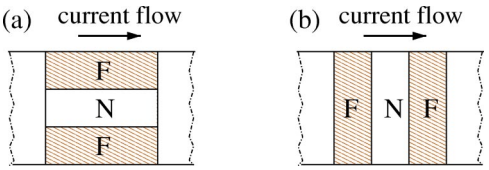

FIG. 3. (Color in online edition) Schematic illustration of (a) the current in plane (CIP), (b) the current perpendicular to the plane (CPP) giant magnetoresistance geometry.

2002). GMR structures are often classified according to whether the current flows parallel (CIP, current in plane) or perpendicular (CPP, current perpendicular to the plane) to the interfaces between the different layers, as depicted in Fig. 3. Most of the GMR applications use the CIP geometry, while the CPP version, first realized by Pratt *et al.* (1991), is easier to analyze theoretically (Gijs and Bauer, 1997; Levy and Mertig, 2002) and relates to the physics of the tunneling magnetoresistance effect (Mathon and Umerski, 1997). The size of magnetoresistance in the GMR structures can be expressed analogously to Eq. (1), where parallel and antiparallel orientations of the magnetizations in the two ferromagnetic regions are often denoted by "P" and "AP," respectively (instead of $\uparrow\uparrow$ and $\uparrow\downarrow$). Realization of a large room-temperature GMR (Parkin, Bhadra, and Roche, 1991; Parkin, Li, and Smith, 1991) enabled a quick transition from basic physics to commercial applications in magnetic recording (Parkin, Jiang, *et al.*, 2003).

One of the keys to the success of magnetoresistance-based applications is their ability to control[14] the relative orientation of $\mathbf{M}_1$ and $\mathbf{M}_2$. An interesting realization of such control was proposed independently by Berger (1996) and Slonczewski (1996). While in GMR or TMR structures the relative orientation of magnetizations will affect the flow of spin-polarized current, they predicted a reverse effect. The flow of spin-polarized current can transfer angular momentum from carriers to ferromagnet and alter the orientation of the corresponding magnetization, even in the absence of an applied magnetic field. This phenomenon, known as *spin-transfer torque*, has since been extensively studied both theoretically and experimentally (Bazaliy *et al.*, 1998; Tsoi *et al.*, 1998; Myers *et al.*, 1999; Sun, 2000; Waintal *et al.*, 2000; Stiles and Zangwill, 2002), and current-induced magnetization reversal has been demonstrated at room temperature (Katine *et al.*, 2000). It was also shown that the magnetic field generated by passing the current through a CPP giant magnetoresonance device could produce room-temperature magnetization reversal (Bussmann *et al.*, 1999). In the context of ferromagnetic semiconductors additional control of magnetization was demonstrated optically, by shining light (Koshihara *et al.*, 1997; Boukari *et al.*, 2002; Oiwa *et al.*, 2002) and electrically, by applying gate voltage (Ohno, Chiba, *et al.*, 2000; Boukari *et al.*, 2002; Park *et al.*, 2002) to perform switching between the ferromagnetic and paramagnetic states.

Jullière's model also justifies the continued quest for highly spin-polarized materials—they would provide large magnetoresistive effects, desirable for device applications. In an extreme case, spins would be completely polarized even in the absence of magnetic field. Numerical support for the existence of such materials—the so-called half-metallic ferromagnets[15]—was provided by de Groot, Janner, and Mueller (1983), and these materials were reviewed by Pickett and Moodera (2001). In addition to ferromagnets, such as CrO_2 (Soulen *et al.*, 1998; Parker *et al.*, 2002) and manganite perovskites (Park *et al.*, 1998a), there is evidence for high spin polarization in III-V ferromagnetic semiconductors like (Ga,Mn)As (Braden *et al.*, 2003; Panguluri, Nadgorny, *et al.*, 2003). The challenge remains to preserve such spin polarization above room temperature and in junctions with other materials, since the surface (interface) and bulk magnetic properties can be significantly different (Fisher, 1967; Mills, 1971; Falicov *et al.*, 1990).

While many existing spintronic applications (Hartman, 2000; Hirota *et al.*, 2002) are based on the GMR effects, the discovery of large room-temperature TMR (Miyazaki and Tezuka, 1995; Moodera *et al.*, 1995) has renewed interest in the study of magnetic tunnel junctions, which are now the basis for the several magnetic random-access memory prototypes[16] (Parkin, Roche, *et al.*, 1999; Tehrani *et al.*, 2000). Future generations of magnetic read heads are expected to use MTJ's instead of CIP giant magnetoresonance. To improve the switching performance of related devices it is important to reduce the junction resistance, which determines the RC time constant of the MTJ cell. Consequently, semiconductors, which would provide a lower tunneling barrier than the usually employed oxides, are being investigated both as the nonferromagnetic region in MTJ's and as the basis for an all-semiconductor junction that would demonstrate large TMR at low temperatures (Tanaka and Higo, 2001; Tanaka, 2002). Another desirable property of semiconductors has been demonstrated by the extraordinary large room-temperature magnetoresistance in hybrid structures with metals, reaching 750 000% at a magnetic field of 4 T (Solin *et al.*, 2000), which could lead to improved magnetic read heads (Solin *et al.*; 2002; Moussa *et al.*, 2003). Magnetoresistance effects of similar magnitude have also been found in hybrid metal/semiconductor granular films (Akinaga, 2002). Another approach to obtaining large room-temperature magnetoresistance ($>100\%$ at $B\sim 100$ G) is to fabricate ferromagnetic regions separated by a nanosize contact. For simplicity, such a structure could be thought of as the

[14]For example, with small magnetic field (Parkin, 2002) or at high switching speeds (Schumacher *et al.*, 2003a, 2003b).

[15]Near the Fermi level they behave as metals only for one spin, the density of states vanishes completely for the other spin.

[16]Realization of the early magnetic random-access memory proposals used the effect of anisotropic magnetoresistance (Pohn *et al.*, 1987, 1988).

limiting case of the CPP giant magnetoresonance scheme in Fig. 3(b). This behavior, also known as *ballistic magnetoresistance*, has already been studied in a large number of materials and geometries (Bruno, 1999; Garcia *et al.*, 1999; Tatara *et al.*, 1999; Imamura *et al.*, 2000; Versluijs *et al.*, 2001; Chung *et al.*, 2002).

2. Spin injection and optical orientation

Many materials in their ferromagnetic state can have a substantial degree of *equilibrium* carrier spin polarization. However, as illustrated in Fig. 1, this alone is usually not sufficient for spintronic applications, which typically require current flow and/or manipulation of the *nonequilibrium* spin (polarization).[17] The importance of generating *nonequilibrium* spin is not limited to device applications; it can also be used as a sensitive spectroscopic tool to study a wide variety of fundamental properties ranging from spin-orbit and hyperfine interactions (Meier and Zakharchenya, 1984) to the pairing symmetry of high-temperature superconductors (Vas'ko *et al.*, 1997; Wei *et al.*, 1999; Tsuei and Kirtley, 2000; Ngai *et al.*, 2004) and the creation of spin-polarized beams to measure parity violation in high-energy physics (Pierce and Celotta, 1984).

Nonequilibrium spin is the result of some source of pumping arising from transport, optical, or resonance methods. Once the pumping is turned off the spin will return to its equilibrium value. While for most applications it is desirable to have long spin relaxation times, it has been demonstrated that short spin relaxation times are useful in the implementation of fast switching (Nishikawa *et al.*, 1995).

Electrical spin injection, an example of a transport method for generating nonequilibrium spin, has already been realized experimentally by Clark and Feher (1963), who drove a direct current through a sample of InSb in the presence of a constant applied magnetic field. The principle was based on the *Feher effect*,[18] in which the hyperfine coupling between the electron and nuclear spins, together with different temperatures representing electron velocity and electron spin populations, is responsible for the dynamical nuclear polarization (Slichter, 1989).[19] Motivated by the work of Clark and Feher (1963) and Tedrow and Meservey (1971b, 1973) and the principle of optical orientation (Meier and Zakharchenya, 1984), Aronov (1976a, 1976b), and Aronov and Pikus (1976) established several key concepts in electrical spin injection from ferromagnets into metals, semiconductors,[20] and superconductors. Aronov (1976b) predicted that, when a charge current flowed across the F/N junction (Fig. 4), spin-polarized carriers in a ferromagnet would contribute to the net current of magnetization entering the nonmagnetic region and would lead to nonequilibrium magnetization δM, depicted in Fig. 4(b), with the spatial extent given by the spin diffusion length (Aronov, 1976b; Aronov and Pikus, 1976).[21] Such a δM, which is also equivalent to a nonequilibrium spin accumulation, was first measured in metals by Johnson and Silsbee (1985, 1988d). In the steady state δM is re-

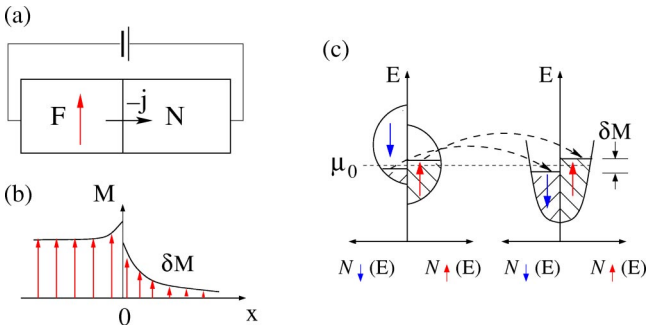

FIG. 4. (Color in online edition) Pedagogical illustration of the concept of electrical spin injection from a ferromagnet (F) into a normal metal (N). Electrons flow from F to N: (a) schematic device geometry; (b) magnetization M as a function of position—nonequilibrium magnetization δM (spin accumulation) is injected into a normal metal; (c) contribution of different spin-resolved densities of states to both charge and spin transport across the F/N interface. Unequal filled levels in the density of states depict spin-resolved electrochemical potentials different from the equilibrium value μ_0.

[17]Important exceptions are tunneling devices operating at low bias and near equilibrium spin. Equilibrium polarization and the current flow can be potentially realized, for example, in spin-triplet superconductors and thin-film ferromagnets (König *et al.*, 2001), accompanied by dissipationless spin currents. Using an analogy with the quantum Hall effect, it has been suggested that the spin-orbit interaction could lead to dissipationless spin currents in hole-doped semiconductors (Murakami *et al.*, 2003). Rashba (2003b) has pointed out that similar dissipationless spin currents in thermodynamic equilibrium, due to spin-orbit interaction, are not transport currents which could be employed for transporting spins and spin injection. It is also instructive to compare several earlier proposals that use spin-orbit coupling to generate spin currents, discussed in Sec. II.A.

[18]The importance and possible applications of the Feher effect (Feher, 1959) to polarize electrons was discussed by Das Sarma *et al.* (2000c) and Suhl (2002).

[19]Such an effect can be thought of as a generalization of the *Overhauser effect* (Overhauser, 1953b), in which the use of a resonant microwave excitation causes the spin relaxation of the nonequilibrium electron population through hyperfine coupling to lead to the spin polarization of nuclei. Feher (1959) suggested several other methods, instead of microwave excitation, that could produce a nonequilibrium electron population and yield a dynamical polarization of nuclei (see also Weger, 1963).

[20]In an earlier work, spin injection of minority carriers was proposed in a ferromagnet/insulator/p-type semiconductor structure. Measuring polarization of electroluminescence was suggested as a technique for detecting injection of polarized carriers in a semiconductor (Scifres *et al.*, 1973).

[21]Supporting the findings of Clark and Feher (1963), Aronov calculated that the electrical spin injection would polarize nuclei and lead to a measurable effect in the electron spin resonance. Several decades later related experiments on spin injection are also examining other implications of dynamical nuclear polarization (Johnson, 2000; Strand *et al.*, 2003).

alized as the balance between spins added by the magnetization current and spins removed by spin relaxation.[22]

Generation of nonequilibrium spin polarization and spin accumulation is also possible by optical methods known as *optical orientation* or *optical pumping*. In optical orientation, the angular momentum of absorbed circularly polarized light is transferred to the medium. Electron orbital momenta are directly oriented by light and through spin-orbit interaction electron spins become polarized. In Sec. II.B we focus on optical orientation in semiconductors, a well-established technique (Meier and Zakharchenya, 1984). In a pioneering work Lampel (1968) demonstrated that spins in silicon can be optically oriented (polarized). This technique is derived from the optical pumping proposed by Kastler (1950) in which optical irradiation changes the relative populations within the Zeeman and hyperfine levels of the ground states of atoms. While there are similarities with previous studies of free atoms (Cohen-Tannoudji and Kostler, 1966; Happer, 1972), optical orientation in semiconductors has important differences related to the strong coupling between the electron and nuclear spin and the macroscopic number of particles (Paget *et al.*, 1977; Meier and Zakharchenya, 1984; Hermann *et al.*, 1985). Polarized nuclei can exert large magnetic fields ($\sim$5 T) on electrons. In bulk III-V semiconductors, such as GaAs, optical orientation can lead to 50% polarization of electron density, which could be further enhanced in quantum structures of reduced dimensionality or by applying a strain. A simple reversal in the polarization of the illuminating light (from positive to negative helicity) also reverses the sign of the electron density polarization. Combining these properties of optical orientation with semiconductors tailored to have a negative electron affinity allows photoemission of spin-polarized electrons to be used as a powerful detection technique in high-energy physics and for investigating surface magnetism (Pierce and Celotta, 1984).

II. GENERATION OF SPIN POLARIZATION

A. Introduction

Transport, optical, and resonance methods (as well as their combination) have all been used to create nonequilibrium spin. After introducing the concept of spin polarization in solid-state systems we give a pedagogical picture of electrical spin injection and detection of polarized carriers. While electrical spin injection and optical orientation will be discussed in more detail later in this section, we also survey here several other techniques for polarizing carriers.

[22]The spin diffusion length is an important quantity for CPP giant magnetoresonance. The thickness of the N region in Fig. 3 should not exceed the spin diffusion length, otherwise the information on the orientation of the magnetization in F1 will not be transferred to the F2 region.

Spin polarization not only of electrons, but also of holes, nuclei, and excitations can be defined as

$$P_X = X_s / X, \tag{3}$$

the ratio of the difference $X_s = X_\lambda - X_{-\lambda}$, and the sum $X = X_\lambda + X_{-\lambda}$ of the spin-resolved λ components for a particular quantity X. To avoid ambiguity as to what precisely is meant by spin polarization, both the choice of the spin-resolved components and the relevant physical quantity X need to be specified. Conventionally, λ is taken to be $\uparrow$ or $+$ (numerical value $+1$) for spin up, and $\downarrow$ or $-$ (numerical value -1) for spin down, with respect to the chosen axis of quantization.[23] In ferromagnetic metals it is customary to refer to $\uparrow$ ($\downarrow$) as carriers with magnetic moment parallel (antiparallel) to the magnetization or, equivalently, as carriers with *majority* or *minority spin* (Tedrow and Meservey, 1973). In semiconductors the terms majority and minority usually refer to relative populations of the carriers while $\uparrow$ or $+$ and $\downarrow$ or $-$ correspond to the quantum numbers m_j with respect to the z axis taken along the direction of the light propagation or along the applied magnetic field (Meier and Zakharchenya, 1984; Jonker *et al.*, 2003). It is important to emphasize that both the magnitude and the sign of the spin polarization in Eq. (3) depend on the choice of X, relevant to the detection technique employed, say optical vs transport and bulk vs surface measurements (Mazin, 1999; Jonker *et al.*, 2003). Even in the same homogeneous material the measured P_X can vary for different X, and it is crucial to identify which physical quantity—charge current, carrier density, conductivity, or the density of states—is being measured experimentally.

The spin polarization of electrical current or carrier density, generated in a nonmagnetic region, is typically used to describe the efficiency of electrical spin injection. Silsbee (1980) suggested that the nonequilibrium density polarization in the N region, or equivalently the nonequilibrium magnetization, acts as the source of spin electromotive force (emf) and produces a measurable "spin-coupled" voltage $V_s \propto \delta M$. Using this concept, also referred to as *spin-charge coupling*, Silsbee (1980) proposed a detection technique consisting of two ferromagnets F1 and F2 (see Fig. 5) separated by a nonmagnetic region.[24] F1 serves as the spin injector (spin aligner) and F2 as the spin detector. This could be called the polarizer-analyzer method, the optical counterpart of the transmission of light through two optical linear polarizers. From Fig. 5 it follows that the reversal of the magnetization direction in one of the ferromagnets

[23]For example, along the spin angular momentum, applied magnetic field, magnetization, or direction of light propagation.

[24]A similar geometry was also proposed independently by de Groot, Janner, and Mueller (1983), where F1 and F2 were two half-metallic ferromagnets, with the goal of implementing spin-based devices to amplify and/or switch current.

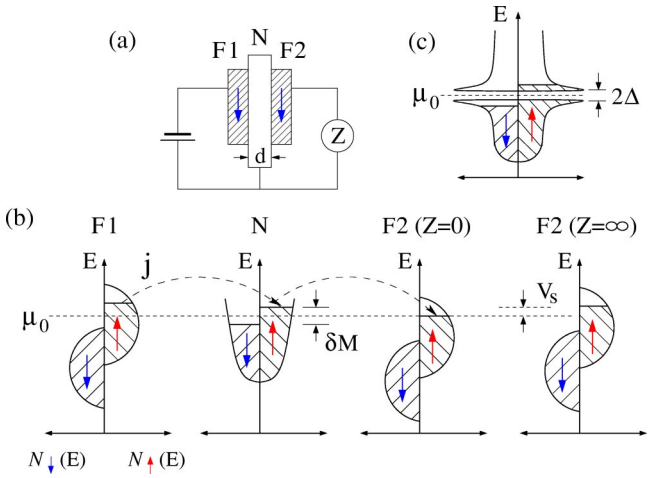

FIG. 5. (Color in online edition) Spin injection, spin accumulation, and spin detection: (a) two idealized completely polarized ferromagnets F1 and F2 (the spin-down density of states $\mathcal{N}_\downarrow$ is zero at the electrochemical potential energy $E=\mu_0$) with parallel magnetizations are separated by the nonmagnetic region N; (b) density-of-states diagrams for spin injection from F1 into N, accompanied by the spin accumulation-generation of nonequilibrium magnetization δM. At F2 in the limit of low impedance ($Z=0$) electrical spin is detected by measuring the spin-polarized current across the N/F2 interface. In the limit of high impedance ($Z=\infty$) spin is detected by measuring the voltage $V_s \sim \delta M$ developed across the N/F2 interface; (c) spin accumulation in a device in which a superconductor (with the superconducting gap Δ) is occupying the region between F1 and F2.

would lead either to $V_s \rightarrow -V_s$, in an open circuit (in the limit of large impedance Z), or to the reversal of charge current $j \rightarrow -j$, in a short circuit (at small Z), a consequence of Silsbee-Johnson spin-charge coupling (Silsbee, 1980; Johnson and Silsbee, 1987, 1988a). Correspondingly, as discussed in the following sections, spin injection could be detected through the spin accumulation signal as either a voltage or a resistance change when the magnetizations in F1 and F2 are changed from parallel to antiparallel alignment.

Since the experiments demonstrating the spin accumulation of conduction electrons in metals (Johnson and Silsbee, 1985), spin injection has been realized in a wide range of materials. While in Sec. II.C we focus on related theoretical work motivated by potential applications, experiments on spin injection have also stimulated proposals for examining the fundamental properties of electronic systems.[25]

The generation of nonequilibrium spin polarization has a long tradition in magnetic resonance methods (Abragam, 1961; Slichter, 1989). However, transport methods to generate carrier spin polarization are not limited to electrical spin injection. For example, they also include scattering of unpolarized electrons in the presence of spin-orbit coupling (Mott and Massey, 1965; Kessler, 1976) and in materials that lack inversion symmetry (Levitov *et al.*, 1984), adiabatic (Mucciolo *et al.*, 2002; Sharma and Chamon, 2003; Watson *et al.*, 2003) and nonadiabatic quantum spin pumping (Zheng *et al.*, 2003; for an instructive description of parametric pumping see Brouwer, 1998), and proximity effects (Ciuti *et al.*, 2002a).

It would be interesting to know what the limits are on the magnitude of various spin polarizations. Could we have a completely polarized current [$P_j \rightarrow \infty$; see Eq. (3)], with only a spin current ($j_\uparrow - j_\downarrow$) and no charge current ($j_\uparrow + j_\downarrow = 0$)? While it is tempting to recall the Stern-Gerlach experiment and try to set up magnetic drift through inhomogeneous magnets (Kessler, 1976), this would most likely work only as a transient effect (Fabian and Das Sarma, 2002). It was proposed by D'yakonov and Perel' (1971a, 1971c) that a transverse spin current (and transverse spin polarization in a closed sample) would form as a result of spin-orbit coupling-induced skew scattering in the presence of a longitudinal electric field. This interesting effect, also called the *spin Hall effect* (Hirsch, 1999; Zhang, 2000), has yet to be demonstrated. An alternative scheme for producing pure spin currents was proposed by Bhat and Sipe (2000), motivated by the experimental demonstration of phase-coherent control of charge currents (Atanasov *et al.*, 1996; Haché *et al.*, 1997) and carrier population (Fraser *et al.*, 1999). A quantum-mechanical interference between one- and two-photon absorptions of orthogonal linear polarizations creates an opposite ballistic flow of spin-up and spin-down electrons in a semiconductor. Only a spin current can flow without a charge current, as demonstrated by Stevens *et al.* (2003) and Hübner *et al.* (2003), who were able to achieve coherent control of the spin current direction and magnitude by the polarization and relative phase of two exciting laser light fields.

Charge current also can be driven by circularly polarized light (Ivchenko and Pikus, 1997). Using the principles of optical orientation (see Sec. I.B.2 and further discussion in Sec. II.B) in semiconductors of reduced dimensionality or lower symmetry, both the direction and the magnitude of a generated charge current can be controlled by circular polarization of the light. This is called the circular photovoltaic effect (Ganichev and Prettl, 2003), which can be viewed as a transfer of the angular momentum of photons to directed motion of electrons. This could also be called a spin corkscrew effect, since a nice mechanical analog is a corkscrew whose rotation generates linear directed motion. A related effect, in which spin photocurrent is driven, is called the spin-galvanic effect (Ganichev and Prettl, 2003). The current here is caused by the difference in spin-flip scattering rates for electrons with different spin states in some systems with broken inversion symmetry. A comprehensive survey of the related effects, from the circular photogalvanic effect (Asnin *et al.*, 1979) to recent demonstrations in semiconductor quantum wells

[25]For example, studies probing the spin-charge separation in the non-Fermi liquids have been proposed by Kivelson and Rokhsar (1990); Zhao and Hershfield (1995); Si (1997, 1998); Balents and Egger (2000, 2001). Spin and charge are carried by separate excitations and can lead to spatially separated spin and charge currents (Kivelson and Rokhsar, 1990).

(Ganichev *et al.*, 2001; Ganichev, Danilov, *et al.*, 2002; Ganichev, Ivchenko, *et al.*, 2002; Ganichev *et al.*, 2003), is given by Ganichev and Prettl (2003).

There is a wide range of recent theoretical proposals for devices that would give rise to a spin electromotive force (Žutić *et al.*, 2001a, 2001b; Brataas *et al.*, 2002; Governale *et al.*, 2003; Long *et al.*, 2003; Mal'shukov *et al.*, 2003; Ting and Cartoixà, 2003), often referred to as spin(-polarized) pumps, cells, or batteries. However, even when it is feasible to generate pure spin current, this does not directly imply that it would be dissipationless. In the context of superconductors, it has been shown that Joule heating can arise from pure spin current flowing through a Josephson junction (Takahashi *et al.*, 2001).

B. Optical spin orientation

In a semiconductor the photoexcited spin-polarized electrons and holes exist for a time τ before they recombine. If a fraction of the carriers' initial orientation survives longer than the recombination time, that is, if $\tau < \tau_s$,[26] where τ_s is the spin relaxation time (see Sec. III), the luminescence (recombination radiation) will be partially polarized. By measuring the circular polarization of the luminescence it is possible to study the spin dynamics of the nonequilibrium carriers in semiconductors (Oestreich *et al.*, 2002) and to extract such useful quantities as the spin orientation, the recombination time, or the spin relaxation time of the carriers (Parsons, 1969; Ekimov and Safarov, 1970; Garbuzov *et al.*, 1971; Meier and Zakharchenya, 1984).

We illustrate the basic principles of optical orientation by the example of GaAs, which is representative of a large class of III-V and II-VI zinc-blende semiconductors. The band structure is depicted in Fig. 6(a). The band gap is $E_g = 1.52$ eV at $T = 0$ K, while the spin split-off band is separated from the light and heavy hole bands by $\Delta_{so} = 0.34$ eV. We denote the Bloch states according to the total angular momentum J and its projection onto the positive z axis m_j: $|J, m_j\rangle$. Expressing the wave functions with the symmetry of s, p_x, p_y, and p_z orbitals as $|S\rangle$, $|X\rangle$, $|Y\rangle$, and $|Z\rangle$, respectively, the band wave functions can be written as listed in Table I (Pierce and Meier, 1976, with minor typos removed; see also Kittel, 1963).

To obtain the excitation (or recombination) probabilities, consider photons arriving in the z direction. Let $\sigma^{\pm}$ represent the helicity of the exciting light. When we represent the dipole operator corresponding to the $\sigma^{\pm}$ optical transitions as[27] $\propto (X \pm iY) \propto Y_1^{\pm 1}$, where Y_l^m is the spherical harmonic, it follows from Table I that

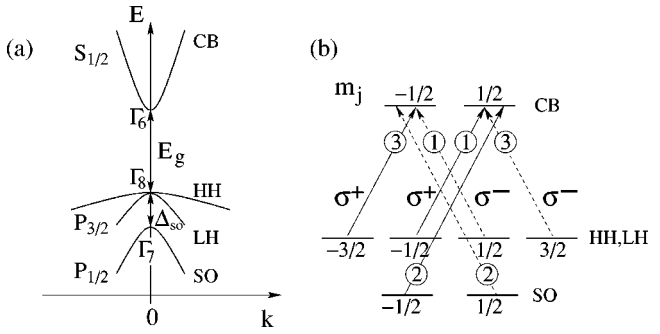

FIG. 6. Interband transitions in GaAs: (a) schematic band structure of GaAs near the center of the Brillouin zone (Γ point), where E_g is the band gap and Δ_{so} the spin-orbit splitting; CB, conduction band; HH, valence heavy hole; LH, light hole; SO, spin-orbit split-off subbands; $\Gamma_{6,7,8}$ are the corresponding symmetries at the $k = 0$ point, or, more precisely, the irreducible representations of the tetrahedron group T_d (Ivchenko and Pikus, 1997); (b) selection rules for interband transitions between the m_j sublevels for circularly polarized light σ^+ and σ^- (positive and negative helicity). The circled numbers denote the relative transition intensities that apply for both excitations (depicted by the arrows) and radiative recombinations.

$$\frac{|\langle 1/2,-1/2|Y_1^1|3/2,-3/2\rangle|^2}{|\langle 1/2,1/2|Y_1^1|3/2,-1/2\rangle|^2} = 3 \tag{4}$$

for the relative intensity of the σ^+ transition between the heavy ($|m_j = 3/2|$) and the light ($|m_j = 1/2|$) hole subbands and the conduction band. Other transitions are analogous. The relative transition rates are indicated in Fig. 6(b). The same selection rules apply to the optical orientation of shallow impurities (Parsons, 1969; Ekimov and Safarov, 1970).

The spin polarization of the excited electrons[28] depends on the photon energy $\hbar\omega$. For $\hbar\omega$ between E_g and $E_g + \Delta_{so}$, only the light and heavy hole subbands contribute. Denoting by n_+ and n_- the density of electrons polarized parallel ($m_j = 1/2$) and antiparallel ($m_j = -1/2$) to the direction of light propagation, we define the spin polarization as (see Sec. II.A)

$$P_n = (n_+ - n_-)/(n_+ + n_-). \tag{5}$$

For our example of the zinc-blende structure,

$$P_n = (1-3)/(3+1) = -1/2 \tag{6}$$

is the spin polarization at the moment of photoexcitation. The spin is oriented against the direction of light propagation, since there are more transitions from the heavy hole than from the light hole subbands. The circular polarization of the luminescence is defined as

[26] In Si this condition is not fulfilled. Instead of measuring the luminescence polarization, Lampel (1968) has used NMR to detect optical spin orientation.

[27] For an outgoing light in the $-z$ direction the helicities are reversed.

[28] Although holes are initially polarized too, they lose spin orientation very fast, on the time scale of the momentum relaxation time (see Sec. III.D.1). However, it was suggested that manipulating hole spin by short electric field pulses, between momentum scattering events, could be useful for ultrafast spintronic applications (Dargys, 2002).

TABLE I. Angular and spin part of the wave function at Γ.

Symmetry	$\|J,m_j\rangle$	Wave function
Γ_6	$\|1/2,1/2\rangle$	$\|S\uparrow\rangle$
	$\|1/2,-1/2\rangle$	$\|S\downarrow\rangle$
Γ_7	$\|1/2,1/2\rangle$	$\|-(1/3)^{1/2}[(X+iY)\downarrow-Z\uparrow]\rangle$
	$\|1/2,-1/2\rangle$	$\|(1/3)^{1/2}[(X-iY)\uparrow+Z\downarrow]\rangle$
Γ_8	$\|3/2,3/2\rangle$	$\|(1/2)^{1/2}(X+iY)\uparrow\rangle$
	$\|3/2,1/2\rangle$	$\|(1/6)^{1/2}[(X+iY)\downarrow+2Z\uparrow]\rangle$
	$\|3/2,-1/2\rangle$	$\|-(1/6)^{1/2}[(X-iY)\uparrow-2Z\downarrow]\rangle$
	$\|3/2,-3/2\rangle$	$\|(1/2)^{1/2}(X-iY)\downarrow\rangle$

$$P_{\text{circ}}=(I^+-I^-)/(I^++I^-), \tag{7}$$

where $I^{\pm}$ is the radiation intensity for the helicity $\sigma^{\pm}$. The polarization of the σ^+ photoluminescence is then

$$P_{\text{circ}}=\frac{(n_++3n_-)-(3n_++n_-)}{(n_++3n_-)+(3n_++n_-)}=-\frac{P_n}{2}=\frac{1}{4}. \tag{8}$$

If the excitation involves transitions from the spin split-off band, that is, if $\hbar\omega\gg E_g+\Delta_{so}$, the electrons will not be spin polarized ($P_n=P_{\text{circ}}=0$), underlining the vital role of spin-orbit coupling for spin orientation. On the other hand, Fig. 6 suggests that a removal of the heavy/light hole degeneracy can substantially increase P_n (D'yakonov and Perel', 1984), up to the limit of complete spin polarization. An increase in P_n and P_{circ} in GaAs strained due to a lattice mismatch with a substrate, or due to confinement in quantum well heterostructures, has indeed been demonstrated (Vasilev *et al.*, 1993; Oskotskij *et al.*, 1997), detecting P_n greater than 0.9.

While photoexcitation with circularly polarized light creates spin-polarized electrons, the nonequilibrium spin decays due to both carrier recombination and spin relaxation. The steady-state degree of spin polarization depends on the balance between the spin excitation and decay. Sometimes a distinction is made (Pierce and Meier, 1976; Meier and Zakharchenya, 1984) between the terms *optical spin orientation* and *optical spin pumping*. The former term is used in relation to the minority carriers (such as electrons in p-doped samples) and represents the orientation of the excited carriers. The latter term is reserved for the majority carriers (electrons in n-doped samples), representing spin polarization of the "ground" state. Both spin orientation and spin pumping were demonstrated in the early investigations on p-GaSb (Parsons, 1969) and p- and n-$Ga_{0.7}Al_{0.3}As$ (Ekimov and Safarov, 1970, 1971; Zakharchenya *et al.*, 1971). Unless specified otherwise, we shall use the term optical orientation to describe both spin orientation and spin pumping.

To derive the steady-state expressions for the spin polarization due to optical orientation, consider the simple model of carrier recombination and spin relaxation (see Sec. IV.A.4) in a homogeneously doped semiconductor. The balance between direct electron-hole recombination and optical pair creation can be written as

$$r(np-n_0p_0)=G, \tag{9}$$

where r measures the recombination rate, the electron and hole densities are n and p, with index zero denoting the equilibrium values, and G is the electron-hole photoexcitation rate. Similarly, the balance between spin relaxation and spin generation is expressed by

$$rsp+s/\tau_s=P_n(t=0)G, \tag{10}$$

where $s=n_+-n_-$ is the electron spin density and $P_n(t=0)$ is the spin polarization at the moment of photoexcitation, given by Eq. (5). Holes are assumed to lose their spin orientation very fast, so they are treated as unpolarized. The first term in Eq. (10) describes the disappearance of the spin density due to carrier recombination, while the second term describes the intrinsic spin relaxation. From Eqs. (9) and (10) we obtain the steady-state electron polarization as (Žutić *et al.*, 2001b)

$$P_n=P_n(t=0)\frac{1-n_0p_0/np}{1+1/\tau_srp}. \tag{11}$$

In a p-doped sample $p\approx p_0$, $n\gg n_0$, and Eq. (11) gives

$$P_n=P_n(t=0)/(1+\tau/\tau_s), \tag{12}$$

where $\tau=1/rp_0$ is the electron lifetime.[29] The steady-state polarization is independent of the illumination intensity, being reduced from the initial spin polarization $P_n(t=0)$.[30] The polarization of the photoluminescence is $P_{\text{circ}}=P_n(t=0)P_n$ (Parsons, 1969). Early measurements of $P_n=0.42\pm0.08$ in GaSb (Parsons, 1969) and $P_n=0.46\pm0.06$ in $Ga_{0.7}Al_{0.3}As$ (Ekimov and Safarov, 1970) showed an effective spin orientation close to the maximum value of $P_n(t=0)=1/2$ for a bulk unstrained zinc-blende structure, indicating that $\tau/\tau_s\ll1$.

For spin pumping in an n-doped sample, where $n\approx n_0$ and $p\gg p_0$, Eqs. (9) and (11) give (D'yakonov and Perel', 1971b)

$$P_n=P_n(t=0)/(1+n_0/G\tau_s). \tag{13}$$

In contrast to the previous case, the carrier (now hole) lifetime $\tau=1/rn_0$ has no effect on P_n. However, P_n depends on the photoexcitation intensity G, as expected for a pumping process. The effective carrier lifetime is $\tau_J=n_0/G$, where J represents the intensity of the illuminating light. If it is comparable to or shorter than τ_s, spin pumping is very effective. Spin pumping works because the photoexcited spin-polarized electrons do not need to recombine with holes. There are plenty of unpolarized electrons in the conduction band available for recombination. The spin is thus pumped in to the electron system.

[29]After the illumination is switched off, the electron spin density, or equivalently the nonequilibrium magnetization, will decrease exponentially with the inverse time constant $1/T_s=1/\tau+1/\tau_s$ (Parsons, 1969).

[30]The effect of a finite length for the light absorption on P_n is discussed by Pierce and Celotta (1984). The absorption length α^{-1} is typically a micron for GaAs. It varies with frequency roughly as $\alpha(\hbar\omega)\propto(\hbar\omega-E_g)^{1/2}$ (Pankove, 1971).

When magnetic field **B** is applied perpendicular to the axis of spin orientation (transverse magnetic field), it will induce spin precession with the Larmor frequency $\Omega_L = \mu_B g B/\hbar$, where μ_B is the Bohr magneton and g is the electron g factor.[31] The spin precession, together with the random character of carrier generation or diffusion, leads to the spin dephasing (see Sec. III.A.1). Consider spins excited by circularly polarized light (or by any means of spin injection) at a steady rate. In a steady state a balance between nonequilibrium spin generation and spin relaxation is maintained, resulting in a net magnetization. If a transverse magnetic field is applied, the decrease of the steady-state magnetization can have two sources: (a) spins which were excited at random time and (b) random diffusion of spins towards a detection region. Consequently, spins precess along the applied field acquiring random phases relative to those which were excited or have arrived at different times. As a result, the projection of the electron spin along the exciting beam will decrease with the increase of transverse magnetic field, leading to depolarization of the luminescence. This is also known as *the Hanle effect* (Hanle, 1924), in analogy to the depolarization of the resonance fluorescence of gases. The Hanle effect was first measured in semiconductors by Parsons (1969). The steady-state spin polarization of the precessing electron spin can be calculated by solving the Bloch-Torrey equations (Bloch, 1946; Torrey, 1956), Eqs. (52)–(54) describing the spin dynamics of diffusing carriers.

In p-doped semiconductors the Hanle curve shows a Lorentzian decrease of the polarization (Parsons, 1969), $P_n(B) = P_n(B=0)/(1+\Omega_L T_s)^2$, where $P_n(B=0)$ is the polarization at $B=0$ from Eq. (12) and T_s^{-1} is the effective spin lifetime given by $1/T_s = 1/\tau + 1/\tau_s$; see footnote 29. Measurements of the Hanle curve in GaAlAs were used by Garbuzov *et al.* (1971) to separately determine both τ and τ_s at various temperatures. The theory of the Hanle effect in n-doped semiconductors was developed by D'yakonov and Perel' (1976), who showed the non-Lorentzian decay of the luminescence for the regimes of both low ($\tau_J/\tau_s \gg 1$) and high ($\tau_J/\tau_s \ll 1$) intensity of the exciting light. At high fields $P_n(B) \propto 1/B^{1/2}$, consistent with the experiments of Vekua *et al.* (1976) in $Ga_{0.8}Al_{0.2}As$, showing a Hanle curve different from the usual $P_n(B) \propto 1/B^2$ Lorentzian behavior (D'yakonov and Perel', 1984a). Recent findings on the Hanle effect in nonuniformly doped GaAs and reanalysis of some earlier studies are given by Dzhioev *et al.* (2003).

C. Theories of spin injection

Reviews on spin injection have covered materials ranging from semiconductors to high-temperature superconductors and have addressed the implications for device operation as well as for fundamental studies in solid-state systems.[32] In addition to degenerate conductors, examined in these works, we also give results for nondegenerate semiconductors in which the violation of local charge neutrality, electric fields, and carrier band bending require solving the Poisson equation. The notation introduced here emphasizes the importance of different (and inequivalent) spin polarizations arising in spin injection.

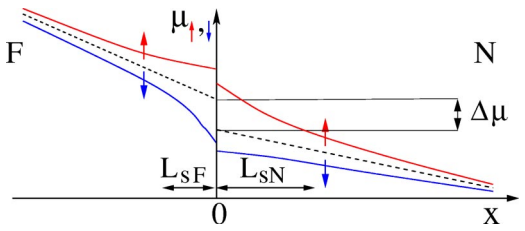

FIG. 7. (Color in online edition) Spatial variation of the electrochemical potentials near a spin-selective resistive interface at an F/N junction. At the interface $x=0$ both the spin-resolved electrochemical potentials (μ_λ, $\lambda=\uparrow,\downarrow$, denoted with solid lines) and the average electrochemical potential (μ_F, μ_N, dashed lines) are discontinuous. The spin diffusion lengths L_{sF} and L_{sN} characterize the decay of $\mu_s=\mu_\uparrow-\mu_\downarrow$ (or equivalently the decay of spin accumulation and the nonequilibrium magnetization) away from the interface and into the bulk F and N regions, respectively.

1. F/N junction

A theory of spin injection across a ferromagnet/normal metal (F/N) interface was first offered by Aronov (1976b). Early work also included spin injection into a semiconductor (Sm; Aronov and Pikus, 1976; Masterov and Makovskii, 1979) and a superconductor (S; Aronov 1976a). Spin injection in F/N junctions was subsequently studied in detail by Johnson and Silsbee (1987, 1988a),[33] van Son *et al.* (1987), Valet and Fert (1993), Hershfield and Zhao (1997), and others. Here we follow the approach of Rashba (2000, 2002b) and consider a steady-state[34] flow of electrons along the x direction in a three-dimensional (3D) geometry consisting of a metallic ferromagnet (region $x<0$) and a paramagnetic metal or a degenerate semiconductor (region $x>0$).

The two regions, F and N, form a contact at $x=0$, as depicted in Fig. 7. The relative magnitudes of three char-

[31] In our convention the g factor of free electrons is positive, $g_0 = 2.0023$ (Kittel, 1996).

[32] See, for example, Osofsky (2000); Goldman *et al.* (1999, 2001); Johnson (2001, 2002a); Maekawa *et al.* (2001); Jedema, Nijboer, *et al.* (2002); Schmidt and Molenkamp (2002); Tang *et al.* (2002); and Wei (2002).

[33] Johnson and Silsbee base their approach on irreversible thermodynamics and consider also the effects of a temperature gradient on spin-polarized transport, omitted in this section.

[34] Even some dc spin injection experiments are actually performed at low (audio-frequency) bias. Generalization to ac spin injection, with a harmonic time dependence, was studied by Rashba (2002a).

acteristic resistances per unit area[35] determine the degree of current polarization injected into a nonmagnetic material. These are the contact resistance r_c and the two characteristic resistances r_N and r_F, each given by the ratio of the spin diffusion length and the effective bulk conductivity in the corresponding region. Two limiting cases correspond to the transparent limit, where $r_c \to 0$, and the low-transmission limit, where $r_c \gg r_N, r_F$.

Spin-resolved quantities are labeled by $\lambda = 1$ or $\uparrow$ for spin up, $\lambda = -1$ or $\downarrow$ for spin down along the chosen quantization axis. For a free electron, spin angular momentum and magnetic moment are in opposite directions, and what precisely is denoted by "spin up" varies in the literature (Jonker *et al.*, 2003). Conventionally, in metallic systems (Tedrow and Meservey, 1973; Gijs and Bauer, 1997), spin up refers to carriers with majority spin. This means that the spin (angular momentum) of such carriers is antiparallel to the magnetization. Spin-resolved charge current (density) in a diffusive regime can be expressed as

$$j_\lambda = \sigma_\lambda \nabla \mu_\lambda , \tag{14}$$

where σ_λ is conductivity and the electrochemical potential is

$$\mu_\lambda = (q D_\lambda / \sigma_\lambda)\, \delta n_\lambda - \phi, \tag{15}$$

with q proton charge, D_λ diffusion coefficient, $\delta n_\lambda = n_\lambda - n_{\lambda 0}$ the change of electron density from the equilibrium value for spin λ, and ϕ the electric potential.[36]

In the steady state the continuity equation is

$$\nabla j_\lambda = \lambda q \left[\frac{\delta n_\lambda}{\tau_{\lambda -\lambda}} - \frac{\delta n_{-\lambda}}{\tau_{-\lambda\lambda}} \right], \tag{16}$$

and $\tau_{\lambda\lambda'}$ is the average time for flipping a λ spin to a λ' spin. For a degenerate conductor[37] the Einstein relation is

$$\sigma_\lambda = q^2 \mathcal{N}_\lambda D_\lambda , \tag{17}$$

where $\sigma = \sigma_\uparrow + \sigma_\downarrow$ and $\mathcal{N} = \mathcal{N}_\uparrow + \mathcal{N}_\downarrow$ is the density of states. Using a detailed balance $\mathcal{N}_\uparrow / \tau_{\uparrow\downarrow} = \mathcal{N}_\downarrow / \tau_{\downarrow\uparrow}$ (Hershfield and Zhao, 1997; Kravchenko, 2002) together with Eqs. (15) and (17), the continuity equation can be expressed as

$$\nabla j_\lambda = \lambda q^2 \frac{\mathcal{N}_\uparrow \mathcal{N}_\downarrow}{\mathcal{N}_\uparrow + \mathcal{N}_\downarrow} \frac{\mu_\lambda - \mu_{-\lambda}}{\tau_s}, \tag{18}$$

where $\tau_s = \tau_{\uparrow\downarrow}\tau_{\downarrow\uparrow} / (\tau_{\uparrow\downarrow} + \tau_{\downarrow\uparrow})$ is the spin relaxation time. Equation (18) implies the conservation of charge current $j = j_\uparrow + j_\downarrow = \text{const}$, while the spin counterpart, the difference of the spin-polarized currents $j_s = j_\uparrow - j_\downarrow$ is position dependent. Other "spin quantities," X_s, unless explicitly defined, are analogously expressed with the corresponding (spin) polarization given by $P_X = X_s / X$. For example, the current polarization[38] $P_j = j_s / j$, generally different from the density polarization $P_n = (n_\uparrow - n_\downarrow)/n$, is related to the conductivity polarization P_σ as

$$P_j = 2(\sigma_\uparrow \sigma_\downarrow / \sigma) \nabla \mu_s / j + P_\sigma , \tag{19}$$

where $\mu_s = \mu_\uparrow - \mu_\downarrow$. In terms of the average electrochemical potential $\mu = (\mu_\uparrow + \mu_\downarrow)/2$, P_σ further satisfies

$$\nabla \mu = -P_\sigma \nabla \mu_s / 2 + j/\sigma . \tag{20}$$

From Eqs. (15) and (18) it follows that μ_s satisfies the diffusion equation (van Son *et al.*, 1987; Valet and Fert, 1993; Hershfield and Zhao, 1997; Schmidt *et al.*, 2000)

$$\nabla^2 \mu_s = \mu_s / L_s^2 , \tag{21}$$

where the spin diffusion length is $L_s = (\bar{D}\tau_s)^{1/2}$ with the spin-averaged diffusion coefficient $\bar{D} = (\sigma_\downarrow D_\uparrow + \sigma_\uparrow D_\downarrow)/\sigma = \mathcal{N}(\mathcal{N}_\downarrow / D_\uparrow + \mathcal{N}_\uparrow / D_\downarrow)^{-1}$. Using Eq. (15) and the local charge quasineutrality $\delta n_\uparrow + \delta n_\downarrow = 0$ shows that μ_s is proportional to the nonequilibrium spin density $\delta s = \delta n_\uparrow - \delta n_\downarrow$ ($s = s_0 + \delta s = n_\uparrow - n_\downarrow$),

$$\mu_s = \frac{1}{2q} \frac{\mathcal{N}_\uparrow + \mathcal{N}_\downarrow}{\mathcal{N}_\uparrow \mathcal{N}_\downarrow} \delta s . \tag{22}$$

Correspondingly, μ_s is often referred to as the (nonequilibrium) *spin accumulation*[39] and is used to explain the GMR effect in CPP structures (Johnson, 1991; Valet and Fert, 1993; Gijs and Bauer, 1997; Hartman, 2000; Hirota *et al.*, 2002).

The preceding equations are simplified for the N region by noting that $\sigma_\lambda = \sigma/2$, $\sigma_s = 0$, and $D_\lambda = \bar{D}$. Quantities pertaining to a particular region are denoted by the index F or N.

Equation (21) has also been used to study the diffusive spin-polarized transport and spin accumulation in ferromagnet/superconductor structures (Jedema *et al.*, 1999). Some care is needed to establish the appropriate boundary conditions at the F/N interface. In the absence of spin-flip scattering[40] at the F/N interface (which can arise, for example, due to spin-orbit coupling or magnetic impurities), the spin current is continuous and thus $P_{jF}(0^-) = P_{jN}(0^+) \equiv P_j$ (omitting $x = 0^\pm$ for brevity, and superscripts $\pm$ in other quantities). These boundary conditions were used by Aronov (1976b; Aronov and Pikus,

[35]For this simple geometry various resistances have a common factor of the cross-sectional area, which can be factored out. This is no longer possible for a more complicated geometry (Takahashi and Maekawa, 2003).

[36]More generally, for a noncollinear magnetization, j_λ becomes a second-rank tensor (Johnson and Silsbee, 1988a; Margulis and Margulis, 1994; Stiles and Zangwill, 2002).

[37]In the nondegenerate case of Boltzmann statistics, the Einstein relation implies that the ratio of the diffusion coefficient and the mobility is $k_B T/q$.

[38]This is also referred to as a spin injection coefficient (Rashba, 2000, 2002b).

[39]Spin accumulation is also relevant to a number of physical phenomena outside the scope of this article, for example, to the tunneling rates in the quantum Hall regime (Chan *et al.*, 1999; MacDonald, 1999).

[40]The effects of nonconserving interfacial scattering on spin injection were considered by Valet and Fert (1993), Fert and Lee (1996), and Rashba (2002b).

1976) without relating P_j to the effect of the F/N contact or material parameters in the F region.

Unless the F/N contact is highly transparent, μ_λ is discontinuous across the interface (Johnson and Silsbee, 1988c; Valet and Fert, 1993; Hershfield and Zhao, 1997; Rashba, 2000), and the boundary condition is

$$j_\lambda(0)=\Sigma_\lambda[\mu_{\lambda N}(0)-\mu_{\lambda F}(0)], \tag{23}$$

where

$$\Sigma=\Sigma_\uparrow+\Sigma_\downarrow \tag{24}$$

is the contact conductivity. For a free-electron model $\Sigma_\uparrow\neq\Sigma_\downarrow$ can be simply inferred from the effect of the exchange energy, which would yield spin-dependent Fermi wave vectors and transmission coefficients. A microscopic determination of the corresponding contact resistance [see Eq. (27)] is complicated by the influence of disorder, surface roughness, and different scattering mechanisms and is usually obtained from model calculations (Schep *et al.*, 1997; Stiles and Penn, 2000). Continued work on the first-principles calculation of F/N interfaces (Stiles, 1996; Erwin *et al.*, 2002) is needed for a more detailed understanding of spin injection. From Eqs. (23) and (24) it follows that

$$\mu_{sN}(0)-\mu_{sF}(0)=2r_c(P_j-P_\Sigma)j, \tag{25}$$

$$\mu_N(0)-\mu_F(0)=r_c(1-P_\Sigma P_j)j, \tag{26}$$

where the effective contact resistance is

$$r_c=\Sigma/4\Sigma_\uparrow\Sigma_\downarrow. \tag{27}$$

The decay of μ_s, away from the interface, is characterized by the corresponding spin diffusion length

$$\mu_{sF}=\mu_{sF}(0)e^{x/L_{sF}},\quad \mu_{sN}=\mu_{sN}(0)e^{-x/L_{sN}}. \tag{28}$$

A nonzero value for $\mu_{sN}(0)$ implies the existence of nonequilibrium magnetization δM in the N region (for noninteracting electrons $q\mu_s=\mu_B\delta M/\chi$, where χ is the magnetic susceptibility). Such a δM, as a result of electrical spin injection, was proposed by Aronov and Pikus (1976) and first measured in metals by Johnson and Silsbee (1985).

By applying Eq. (19), separately, to the F and N regions, one can obtain the amplitude of spin accumulation in terms of the current and density-of-states spin polarization and the effective resistances r_F and r_N,

$$\mu_{sF}(0)=2r_F[P_j-P_{\sigma F}]j,\quad \mu_{sN}(0)=-2r_NP_jj, \tag{29}$$

where

$$r_N=L_{sN}/\sigma_N,\quad r_F=L_{sF}\sigma_F/(4\sigma_{\uparrow F}\sigma_{\downarrow F}). \tag{30}$$

From Eqs. (29) and (25) the current polarization can be obtained as

$$P_j=[r_cP_\Sigma+r_FP_{\sigma F}]/r_{FN}, \tag{31}$$

where $r_{FN}=r_F+r_c+r_N$ is the effective equilibrium resistance of the F/N junction. It is important to emphasize that a measured highly polarized current, representing an efficient spin injection, does not itself imply a large spin accumulation or a large density polarization, typically measured by optical techniques. In contrast to the derivation of P_j from Eq. (31), determining P_n requires using Poisson's equation or a condition of the local charge quasineutrality.[41]

It is useful to note[42] that Eq. (31), written as Eq. (18) in Rashba (2000), can be mapped to Eq. (A11) from Johnson and Silsbee (1987), where it was first derived.[43] An equivalent form for P_j in Eq. (31) was obtained by Hershfield and Zhao (1997) and for $r_c=0$ results from van Son *et al.* (1987) are recovered.

In contrast to normal metals (Johnson and Silsbee, 1985, 1988d) and superconductors, for which injection has been reported in both conventional (Johnson, 1994), and high-temperature superconductors (Hass *et al.*, 1994; Dong *et al.*, 1997; Vas'ko *et al.*, 1997; Yeh *et al.*, 1999), creating a substantial current polarization P_j by direct electrical spin injection from a metallic ferromagnet into a semiconductor proved to be more difficult (Hammar *et al.*, 1999; Monzon and Roukes, 1999; Filip *et al.*, 2000; Zhu *et al.*, 2001).

By examining Eq. (31) we can both infer some possible limitations and deduce several experimental strategies for effective spin injection into semiconductors. For a perfect Ohmic contact $r_c=0$, the typical resistance mismatch $r_F\ll r_N$ (where F is a metallic ferromagnet) implies inefficient spin injection with $P_j\approx r_F/r_N\ll 1$, referred to as the *conductivity mismatch* problem by Schmidt *et al.* (2000). Even in the absence of the resistive contacts, effective spin injection into a semiconductor can be achieved if the resistance mismatch is reduced by using for spin injectors either a magnetic semiconductor or a highly spin-polarized ferromagnet.[44]

While there was early experimental evidence (Alvarado and Renaud, 1992) that employing resistive (tunneling) contacts could lead to an efficient spin injection,[45] a systematic understanding was provided by Rashba (2000) and supported by subsequent experimental and theoretical studies (Fert and Jaffres, 2001; Smith and Silver, 2001; Rashba, 2002b; Johnson, 2003; Johnson and Byers, 2003; Takahashi and Maekawa, 2003). As can

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[41]Carrier density will also be influenced by the effect of screening, which changes with the dimensionality of the spin injection geometry (Korenblum and Rashba, 2002).

[42]E. I. Rashba (2002d).

[43]The substitutions are $P_j\to\eta^*$, $P_\sigma\to p$, $P_\Sigma\to\eta$, $r_c\to[G(\xi-\eta^2)]^{-1}$, $r_N\to\delta_n/\sigma_n\zeta_n$, $r_F\to\delta_f/\sigma_f(\zeta_f-p_f^2)$, $L_{sN,F}\to\delta_{n,F}$, and n, f label N and F regions, respectively. η, ζ_n, and ζ_f are of the order of unity. To ensure that resistances and the spin diffusion lengths in Johnson and Silsbee (1987) are positive, one must additionally have $(\xi-\eta^2)>0$ and $(\zeta_i-p_i^2)>0$, $i=n,f$ (for normal and ferromagnetic regions, respectively). In particular, assuming $\xi=\zeta_n=\zeta_f=1$, a detailed correspondence between Eq. (31) and Eq. (A11) in Johnson and Silsbee (1987) is recovered. For example, $r_c\to[G(\xi-\eta^2)]^{-1}$ yields Eq. (27), where $\Sigma\to G$.

[44]From Eq. (30) a half-metallic ferromagnet implies a large r_F.

[45]The influence of the resistive contacts on spin injection can also be inferred by explicitly considering resistive contacts (Johnson and Silsbee, 1987; Hershfield and Zhao, 1997).

be seen from Eq. (31), a spin-selective resistive contact $r_c \gg r_F, r_N$ (such as a tunnel or Schottky contact) would contribute to effective spin injection with $P_j \approx P_\Sigma$ being dominated by the effect r_c and not the ratio r_F/r_N.[46] This limit is also instructive to illustrate the principle of spin filtering (Esaki *et al.*, 1967; Moodera *et al.*, 1988; Hao *et al.*, 1990; Filip *et al.*, 2002). In a spin-discriminating transport process the resulting degree of spin polarization is changed. Consequently the effect of spin filtering, similar to spin injection, leads to the generation of (nonequilibrium) spin polarization.[47] For example, at low temperature EuS and EuSe, discussed in Sec. IV.C, can act as spin-selective barriers. In the extreme case, initially spin-unpolarized carriers (say, injected from a nonmagnetic material) via spin filtering could attain a complete polarization. For a strong spin-filtering contact $P_\Sigma > P_{\sigma F}$, the sign of the spin accumulation (nonequilibrium magnetization) is reversed in the F and N regions, near the interface [recall Eq. (25)], in contrast to the behavior sketched in Fig. 7, where $\mu_{sF,N} > 0$.

The spin injection process alters the potential drop across the F/N interface because differences of spin-dependent electrochemical potentials on either side of the interface generate an effective resistance δR. By integrating Eq. (20) for N and F regions separately, it follows that $Rj = \mu_N(0) - \mu_F(0) + P_{\sigma F}\mu_{sF}(0)/2$, where R is the junction resistance. Using Eqs. (26), (30), and (31) allows us to express $R = R_0 + \delta R$, where $R_0 = 1/\Sigma$ ($R_0 = r_c$ if $\Sigma_\uparrow = \Sigma_\downarrow$) is the equilibrium resistance, in the absence of spin injection, and

$$\delta R = [r_N(r_F P_{\sigma F}^2 + r_c P_\Sigma^2) + r_F r_c (P_{\sigma F} - P_\Sigma)^2]/r_{FN}, \tag{32}$$

where $\delta R > 0$ is the nonequilibrium resistance. Petukhov has shown (Jonker *et al.*, 2003a) that Eqs. (31) and (32) could be obtained by considering an equivalent circuit scheme with two resistors $\tilde{R}_\uparrow$, $\tilde{R}_\downarrow$ connected in parallel, where $\tilde{R}_\lambda = L_{sF}/\sigma_{\lambda F} + 1/\Sigma_\lambda + 2L_{sN}/\sigma_N$ and $\tilde{R}_\uparrow + \tilde{R}_\downarrow = 4r_{FN}$. For such a resistor scheme, by noting that $j_\uparrow \tilde{R}_\uparrow = j_\downarrow \tilde{R}_\downarrow$, Eq. (31) is obtained as $P_j = -P_{\tilde{R}} \equiv -(\tilde{R}_\uparrow - \tilde{R}_\downarrow)/(\tilde{R}_\uparrow + \tilde{R}_\downarrow)$. δR in Eq. (32) is then obtained as the difference between the total resistance of the nonequilibrium spin-accumulation region of the length $L_{sF} + L_{sN}$ [given by the equivalent resistance $\tilde{R}_\uparrow \tilde{R}_\downarrow/(\tilde{R}_\uparrow + \tilde{R}_\downarrow)$] and the equilibrium resistance for the same region, $L_{sF}/\sigma_F + L_{sN}/\sigma_N$.

The concept of the excess resistance δR can also be explained as a consequence of the Silsbee-Johnson spin-charge coupling (Silsbee, 1980; Johnson and Silsbee, 1985, 1987) and illustrated by considering the simplified schemes in Figs. 5 and 7. Accumulated spin near the F/N interface, together with a finite spin relaxation and a finite spin diffusion, impedes the flow of spins and acts as a "spin bottleneck" (Johnson, 1991). A rise of μ_{sN} must be accompanied by the rise of μ_{sF} [their precise alignment at the interface is given in Eq. (25)] or there will be a backflow of the nonequilibrium spin back into the F region. Because both spin and charge are carried by electrons in spin-charge coupling, the backflow of spin driven by diffusion creates an additional resistance for the charge flow across the F/N interface. Based on an analogy with the charge transport across a clean N/superconductor (S) interface (see Sec. IV.A.3), van Son *et al.* (1987) explained δR by invoking the consequences of current conversion from spin-polarized, far to the left of the F/N interface, to completely unpolarized, at far right in the N region.

The increase in the total resistance with spin injection can be most dramatic if the N region is taken to be a superconductor (S); see Fig. 5(c). Spin injection depletes the superconducting condensate and can result in switching to a normal state of much higher resistance (Dong *et al.*, 1997; Vas'ko *et al.*, 1997; Takahashi *et al.*, 1999; Wei *et al.*, 1999; Yeh *et al.*, 1999). A critical review of possible spurious effects in reported experiments (Gim *et al.*, 2001) has also stimulated the development of a novel detection technique which uses scanning tunneling spectroscopy combined with pulsed quasiparticle spin injection to minimize Joule heating (Ngai *et al.*, 2004; see Sec. IV.A.1). In the S region the quasiparticle energy is $E_k = (\xi_k^2 + \Delta^2)^{1/2}$, where ξ_k is the single-particle excitation energy corresponding to the wave vector $\mathbf{k}$ and Δ is the superconducting gap [see Fig. 5(c)]. Such a dispersion relation results in a smaller diffusion coefficient and a longer spin-flip time than in the N region, while their product, the spin diffusion length, remains the same (Yamashita *et al.*, 2002). Consequently, Eq. (21) also applies to the diffusive spin-polarized transport and spin accumulation in ferromagnet/superconductor structures (Jedema *et al.*, 1999; Yamashita *et al.*, 2002). Opening of a superconducting gap implies that a superconductor is a low carrier system for spin, which is carried by quasiparticles (Takahashi and Maekawa, 2003).

In the preceding analysis, appropriate for bulk, homogeneous, three-dimensional N and F regions and degenerate (semi)conductors, Poisson's equation was not invoked and the local charge neutrality $\delta n_\uparrow + \delta n_\downarrow$ was used only to derive Eq. (22).[48] Focusing on bulk samples in which both the size of the F and N regions and the corresponding spin diffusion lengths are much larger than the Debye screening length, one can find that the quasineutrality condition, combined with Eqs. (15) and (17), yields

[46] A similar result was stated previously by Johnson and Silsbee (1988a).

[47] While most of the schemes resemble a CPP geometry [Fig. 3(b)], there are also proposals for generating highly polarized currents in a CIP-like geometry [Fig. 3(a)] (Gurzhi *et al.*, 2001, 2003).

[48] For spin injection in nondegenerate semiconductors (with the carriers obeying the Boltzmann statistics) there can be large effects due to built-in fields and deviation from local charge neutrality, as discussed in Sec. II.C.3.

$$\phi = -\mu - P_{\mathcal{N}}\mu_s/2, \tag{33}$$

where the density-of-states spin polarization of $P_{\mathcal{N}}$ vanishes in the N region. At the contact $x=0$ there is a potential drop, even when $r_c=0$, which can be evaluated from Eqs. (26) and (33) as

$$\phi_N(0) - \phi_F(0) = -r_c[1 - P_\Sigma P_j]j + P_{\mathcal{N}F}(0)\mu_{sF}(0)/2. \tag{34}$$

The creation of nonequilibrium spin in the N region results in the spin emf in the F/N structure which can be used to detect electrical spin injection, as depicted in Fig. 5. Within a simplified semi-infinite geometry for the F and N regions, we consider an effect of spin pumping in the N region, realized either by electrical spin injection from another F region [as shown in Fig. 5(b)] or by optical pumping (see Sec. II.B). The resulting potential drop can be calculated by modifying μ_{sN} in Eq. (28),

$$\mu_{sN} = \mu_{sN}(\infty) + [\mu_{sN}(0) - \mu_{sN}(\infty)]e^{-x/L_{sN}}, \tag{35}$$

where $\mu_{sN}(\infty)$ represents the effect of homogeneous spin pumping in the N region. To calculate the open circuit voltage ($j=0$) the continuity of spin current at $x=0$ should be combined with the fact that $P_j j = j_s$. From Eq. (19) it follows that

$$j_s(0) = 2\frac{\sigma_\uparrow\sigma_\downarrow}{\sigma_F}\frac{\mu_{sF}(0)}{L_{sF}} = -\frac{1}{2}\sigma_N\frac{\mu_{sN}(0) - \mu_{sN}(\infty)}{L_{sN}}, \tag{36}$$

while the discontinuity of μ_s in Eq. (25) yields[49]

$$\mu_{sF}(0) = (r_F/r_{FN})\mu_{sN}(\infty), \quad j_s(0) = \mu_{sN}(\infty)/2r_{FN},$$

$$\mu_{sN}(0) = [(r_c + r_F)/r_{FN}]\mu_{sN}(\infty). \tag{37}$$

By substituting this solution into Eq. (34), we can evaluate the contact potential drop as

$$\phi_N(0) - \phi_F(0) = [r_F P_{\mathcal{N}F} + r_c P_\Sigma]\mu_{sN}(\infty)/2r_{FN}. \tag{38}$$

The total potential drop (recall $j=0$) at the F/N junction[50] is (Rashba, 2002b)

$$\Delta\phi_{FN} = \phi_N(\infty) - \phi_F(-\infty) = P_j\mu_{sN}(\infty)/2. \tag{39}$$

where P_j is given in Eq. (31). In the context of the spin-detection scheme from Fig. 5 and high impedance measurements at the N/F2 junction, the spin-coupled voltage V_s (Silsbee, 1980; Johnson and Silsbee, 1985) was also found to be proportional to current polarization and the spin accumulation ($\mu_s \propto \delta s \propto \delta M$; Johnson and Silsbee, 1988b).

2. F/N/F junction

The above analysis of the F/N bilayer can be readily extended to the geometry in which two infinite F regions are separated by an N region of thickness d. The quantities pertaining to the two ferromagnets are defined as in the case of an F/N junction and labeled by the superscripts L and R (left and right regions, respectively). It follows from Eq. (19), by assuming the continuity of the spin current at L, R, that the difference of the spin-resolved electrochemical potential, responsible for the spin accumulation, is

$$\mu_{sF}^L = 2r_F^L(P_j^L - P_{\sigma F}^L)je^{x/L_{sF}^L}, \quad x<0, \tag{40}$$

$$\mu_{sN} = 2r_N\{P_j^R\cosh(x/L_{sN}) - P_j^L\cosh[(d-x)/L_{sN}]\} \times j/\sinh(d/L_{sN}), \quad 0<x<d, \tag{41}$$

$$\mu_{sF}^R = -2r_F^R(P_j^R - P_{\sigma F}^R)je^{(d-x/L_{sF}^R)}, \quad x>d, \tag{42}$$

where the current spin polarization $P_j^{L,R}$ at the two contacts in the F/N/F geometry can be expressed (Rashba, 2002b) in terms of the P_j calculated for F/N junction with the infinite F and N regions in Eq. (19) and the appropriate effective resistances. By $P_{j\infty}^{L,R}$ we denote the P_j calculated in Eq. (31) for the left and right contact (with the appropriate parameters for the F/N/F junction) as if it were surrounded by the infinite F and N regions. Analogously to the F/N junction, the consequence of the spin injection is an increase in the resistance $R = R_0 + \delta R$, over the equilibrium value $R_0 = (\Sigma^L)^{-1} + (\Sigma^R)^{-1}$. The nonequilibrium resistance δR is also always positive for spin-conserving contacts (Rashba, 2000, 2002b), in agreement with experiments on all-semicondcutor trilayer structures (Schmidt *et al.*, 2001; see Sec. II.D.3).

Many applications based on magnetic multilayers rely on the spin-valve effect, in which the resistance changes due to the relative orientations of the magnetization in the two F regions. The geometry considered here is relevant for CPP giant magnetoresistance (Gijs and Bauer, 1997; Bass and Pratt, 1999; Parkin, 2002) and the all-metallic spin injection of Johnson and Silsbee (1985). In particular, the resistance change between antiparallel and parallel magnetization orientations in the two ferromagnets can be expressed using current polarization of an infinite F/N junction $P_{j\infty}^{L,R}$ (Rashba, 2002b):

$$\Delta R = R_{\uparrow\downarrow} - R_{\uparrow\uparrow} = 4P_{j\infty}^L P_{j\infty}^R\frac{r_{FN}^L r_{FN}^R r_N}{\mathcal{D}\sinh(d/L_{sN})}, \tag{43}$$

where $r_F^{L,R}$, $r_c^{L,R}$, and r_N are defined as in the case of an F/N junction and

$$\mathcal{D} = (r_F^L + r_c^L)(r_c^R + r_F^R) + r_N^2 + r_N(r_F^L + r_c^L + r_c^R + r_F^R)\coth(d/L_{sN}). \tag{44}$$

Up to a factor of 2, Eq. (43) has also been obtained by Hershfield and Zhao (1997) using Onsager relations. In the limit of a thin N region, $d/L_{sN}\to 0$, ΔR remains finite. In the opposite limit, for $d \gg L_{sN}$,

[49] A missprint in $\mu_{sF}(0)$ from Rashba (2002b) has been corrected.

[50] A similar potential drop was also calculated across a ferromagnetic domain wall (Dzero *et al.*, 2003).

$$\Delta R \sim P_{j\infty}^{L} P_{j\infty}^{R} \exp(-d/L_{sN}). \tag{45}$$

For a symmetric F/N/F junction, where $r_{c,F}^{L}=r_{c,F}^{R}$, it follows that

$$\Delta R = \frac{4r_N(r_c P_\Sigma + r_F P_{\sigma F})}{\mathcal{D}\sinh(d/L_{sN})}. \tag{46}$$

Considering the spin injection from F into a ballistic N region in the presence of diffusive interfacial scattering, where the phase coherence is lost and the Boltzmann equation can be applied, it is instructive to reconsider the effect of contact resistance (Kravchenko and Rashba, 2003). We introduce the *Sharvin resistance* R_{Sharvin} (Sharvin, 1965), arising in ballistic transport between two infinite regions connected by a contact (an orifice or a narrow and short constriction) of radius much smaller than the mean free path, $a \ll l$. In a 3D geometry the resistance is

$$R_{\mathrm{Sharvin}} = \frac{4\rho l}{3\pi a^2} = \left[\frac{e^2}{h}\frac{k^2 A}{2\pi}\right]^{-1}, \tag{47}$$

where $h/e^2 \approx 25.81\ \mathrm{k}\Omega$ is the quantum of resistance per spin, A is the contact area, and k is the Fermi wave vector. The opposite limit, of diffusive transport through the contact with $a \gg l$, corresponds to the *Maxwell or Drude resistance* $R_{\mathrm{Maxwell}}=\rho/2a$. The studies of intermediate cases provide an interpolation scheme between the R_{Maxwell} and R_{Sharvin} for various ratios of a/l (Wexler, 1966; Jansen *et al.*, 1980; de Jong, 1994; Nikolić and Allen, 1999). Following Kravchenko and Rashba (2003) the effective contact resistance $r_c = r_{c\uparrow} + r_{c\downarrow}$ (recall that it is defined per unit area) is obtained as

$$r_{c\lambda} = (4R_{\mathrm{Sharvin}}/A)(1 - t_\lambda^L - t_\lambda^R)/t_\lambda^L, \tag{48}$$

where $t_\alpha^{L,R}$ represent the transmission coefficients for electrons reaching the contact from the left and from the right and satisfy $t^L + t^R \leqslant 1$. For r_c which would exceed the resistance of the N and F bulk regions, the spin injection efficiency can attain $P_j \sim (r_{c\uparrow} - r_{c\downarrow})/r_c$ (Kravchenko and Rashba, 2003), showing, similarly to the diffusive regime, the importance of the resistive contacts to efficient spin injection. Connection with the results in the diffusive regime can be obtained (Kravchenko and Rashba, 2003) by identifying $r_{c\lambda} = 1/4\Sigma_\lambda$, where the contact conductivity Σ_λ was introduced in Eq. (24).

While most of the experimental results on spin injection are feasible in the diffusive regime, there are many theoretical studies treating the ballistic case and phase-coherent transport in both F/N and F/N/F junctions (Hu and Matsuyama, 2001; Hu, Nitta, *et al.*, 2001; Mireles and Kirczenow, 2001; Matsuyama *et al.*, 2002). Simple models in which the N region is a degenerate semiconductor often adopt an approach developed first for charge transport in junctions involving superconductors, discussed in Sec. IV.A.3. Considering spin-orbit coupling and the potential scattering at the F/N interface modeled by the δ function, Hu and Matsuyama (2001) have examined ballistic spin injection in the F/N junction. They show that even a spin-independent barrier can be used to enhance the spin injection and lead to an increase in the conductance polarization. First-principles calculations were also used for ballistic spin injection from a ferromagnetic metal into a semiconductor (Mavropoulos *et al.*, 2002; Wunnicke *et al.*, 2002; Zwierzycki *et al.*, 2003). In the limit of coherent (specular) scattering[51] and high interfacial quality it was shown that different band structure in the F and the N regions would contribute to a significant contact resistance and an efficient spin injection (Zwierzycki *et al.*, 2003).

3. Spin injection through the space-charge region

Interfaces making up a semiconductor often develop a space-charge region—a region of local macroscopic charges. Typical examples are the Schottky contact and the depletion layer in p-n junctions. While phenomenological models, such as the one introduced in Sec. II.C.1, capture a remarkable wealth of spin injection physics, they carry little information about spin-dependent processes right at the interfaces. Microscopic studies of spin-polarized transport and spin-resolved tunneling through space-charge regions are still limited in scope. The difficulty lies in the need to consider self-consistently simultaneous charge accumulation and electric-field generation (through Poisson's equation), both affecting transport. Non-self-consistent analyses of a Schottky-barrier spin injection were performed by Albrecht and Smith (2002, 2003) and Prins *et al.* (1995), while Osipov and Bratkovsky (2003) proposed an efficient spin injection method using a δ-doped Schottky contact.

Let us now consider spin injection through the depletion layer in magnetic p-n junctions (Fabian *et al.*, 2002a; Žutić *et al.*, 2002, 2003). The physics is based on drift and diffusion[52] limited by carrier recombination and spin relaxation, as described in more detail in Sec. IV.A.4. The transport equations are solved self-consistently with Poisson's equation, taking full account of electric field due to accumulated charges. Additional examples of magnetic p-n junctions are discussed in Sec. IV.D.

The system is depicted in Fig. 8. The p-n junction has a magnetic n region[53] with a net equilibrium electron spin P_{n0}^{R}, where R stands for the right (here n) region. Holes are assumed to be unpolarized. An important issue to be resolved is whether there will be spin accumu-

[51]The wave-vector component along the interface is conserved during scattering.

[52]Tunneling or field emission becomes important, for example, in thin Schottky barriers or in p-n junctions and heterostructures at large reverse biases (Kohda *et al.*, 2001; Johnston-Halperin *et al.*, 2002; Van Dorpe, Liu, *et al.*, 2003).

[53]Equilibrium magnetization can be a consequence of doping with magnetic impurities, yielding large carrier g factors, and applying magnetic field, or of using a ferromagnetic semiconductor (Ohno, 1998; Pearton *et al.*, 2003).

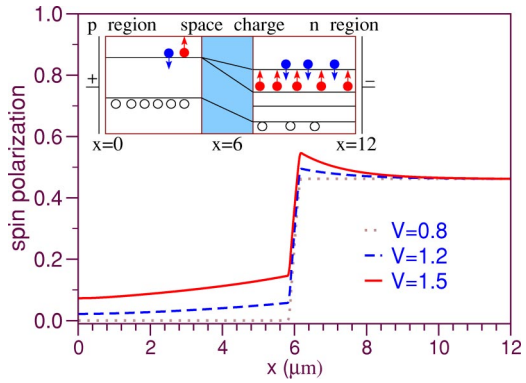

FIG. 8. (Color in online edition) Spin injection through the space-charge region of a magnetic p-n junction. The geometry is depicted in the inset, which shows a junction with a spin-split conduction band in the n region with spin-polarized electrons (solid circles) and unpolarized holes (empty circles). Under applied forward bias V the charge current flows to the right. The curves, labeled by V, show the electron density polarization profiles $P_n(x)$ for the depicted geometry and GaAs materials parameters. The equilibrium density polarization in the n region is about 0.5. At low bias (0.8 V) there is no spin injection. Spin injection, manifested by the increase of P_n in the p region, appears only at large biases (1.2 and 1.5 V), where it is driven by electric drift (Žutić *et al.*, 2002). Spin polarization of the current is discussed by Žutić *et al.* (2001a) and Fabian *et al.* (2002a). Adapted from Žutić *et al.*, 2002.

lation in the p region if a forward bias is applied to the junction. In other words, will spin be injected across the depletion layer? Naively the answer is yes, since spin is carried by electrons, but the result shown in Fig. 8 suggests a more complicated answer. At small biases there is no spin injection. This is the normal limit of diode operation, in which the injected carrier density through the depletion region is still smaller than the equilibrium carrier density. Only with bias increasing to the high-injection limit (typically above 1 V) is spin injected.

The explanation for the absence of spin injection at small biases and for nondegenerate doping levels (Boltzmann statistics is applicable) is as follows. On the n side there are more spin-up than spin-down electrons, $n_\uparrow > n_\downarrow$. If $2q\zeta$ is the spin splitting of the conduction band, $n_\uparrow(\zeta)/n_\uparrow(\zeta=0)=\exp(q\zeta/k_BT)$. Under a forward bias, electrons flow to the p region. The flow is limited by thermal activation over the barrier (given by the built-in electrostatic potential minus bias), which is, for the spin-up electrons, greater by $q\zeta$. For Boltzmann statistics, the rate of transmission of spin-up electrons over the barrier is $\sim\exp(-q\zeta/k_BT)$. Since current is proportional to both the carrier density and the transmission rate, the two exponential factors cancel out. Similarly for spin down. As a result, the spin-resolved current is unaffected by $2q\zeta$ and there is no spin current flowing through the depletion layer. There is no spin accumulation. Spin injection appears only at large biases, where it is driven by electric drift leading to nonequilibrium spin population already in the n region (Fabian *et al.*, 2002a; Žutić *et al.*, 2002). In addition to spin injection, spin extraction has also been predicted in magnetic p-n junctions with a magnetic p region (Žutić *et al.*, 2002). Under a large bias, spin is extracted (depleted) from the nonmagnetic n region.

Electric field in the bulk regions next to the space charge is important only at large biases. It affects not only spin density, but spin diffusion as well. That spin injection efficiency can increase in the presence of large electric fields due to an increase in the spin diffusion length (spin drag) was first shown by Aronov and Pikus (1976) and was later revisited by other authors.[54] To be important, the electric field needs to be very large,[55] more than 100 V/cm at room temperature. While such large fields are usually present inside the space-charge regions, they exist in the adjacent bulk regions only at the high injection limit and affect transport and spin injection. In addition to electric drift, magnetic drift, in magnetically inhomogeneous semiconductors, can also enhance spin injection (Fabian *et al.*, 2002a).

The following formula was obtained for spin injection at small biases (Fabian *et al.*, 2002a):

$$P_n^L=\frac{P_{n0}^L[1-(P_{n0}^R)^2]+\delta P_n^R(1-P_{n0}^L P_{n0}^R)}{1-(P_{n0}^R)^2+\delta P_n^R(P_{n0}^L-P_{n0}^R)}, \tag{49}$$

where L (left) and R (right) label the edges of the space-charge (depletion) region of a p-n junction. Correspondingly, δP_n^R represents the nonequilibrium electron polarization, evaluated at R, arising from a spin source. The case discussed in Fig. 8 is for $P_{n0}^L=\delta P_n^R=0$. Then $P_n^L=0$, in accord with the result of no spin injection. For a homogeneous equilibrium magnetization ($P_{n0}^L=P_{n0}^R$), $\delta P_n^L=\delta P_n^R$; the nonequilibrium spin polarization is the same across the depletion layer. Equation (49) demonstrates that only *nonequilibrium* spin, already present in the bulk region, can be transferred through the depletion layer at small biases (Žutić *et al.*, 2001b; Fabian *et al.*, 2002a). Spin injection of nonequilibrium spin is also very effective if it proceeds from the p region (Žutić *et al.*, 2001b), which is the case for a spin-polarized solar cell (Žutić *et al.*, 2001a). The resulting spin accumulation in the n region extends the spin diffusion range, leading to spin amplification—increase of the spin population away from the spin source. These results were also confirmed in the junctions with two differently doped n regions (Pershin and Privman, 2003a, 2003b). Note, however, that the term "spin polarization density" used in Pershin and Privman (2003a, 2003b) is actually the spin density $s=n_\uparrow-n_\downarrow$, not the spin polarization P_n.

[54]See, for example, Margulis and Margulis (1994); Flensberg *et al.* (2001); Žutić *et al.* (2001b); Fabian *et al.* (2002a); Yu and Flatté (2002a); Bratkovsky and Osipov (2003); Martin (2003); and Vignale and D'Amico (2003).

[55]The critical magnitude is obtained by dividing a typical energy, such as the thermal or Fermi energy, by q and by the spin diffusion length. At room temperature the thermal energy is 25 meV, while the spin diffusion length can be several microns.

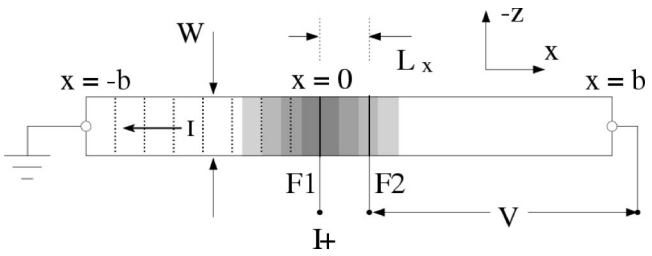

FIG. 9. Schematic top view of nonlocal, quasi-one-dimensional geometry used by Johnson and Silsbee (1985): F1 and F2, the two metallic ferromagnets having magnetizations in the x-z plane; dotted lines, equipotentials characterizing electrical current flow; gray shading, diffusing population of nonequilibrium spin-polarized electrons injected at $x=0$, with darker shades corresponding to higher density of polarized electrons. From Johnson, 2002a.

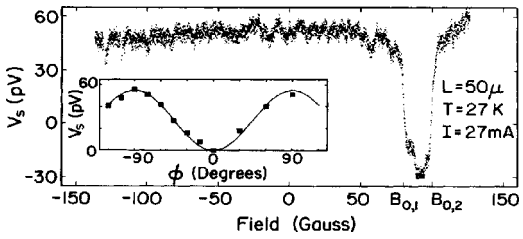

FIG. 10. Spin injection data from bulk Al wire sample. Negative magnetic field is applied parallel to the magnetization ($-z$ axis) in the two ferromagnetic regions. As the field is increased, at $B_{0,1}$ magnetization in one of the ferromagnetic regions is reversed, and at $B_{0,2}$ the magnetization in the other region is also reversed (both are along $+z$ axis). Inset: amplitude of the observed Hanle signal as a function of orientation angle ϕ of magnetic field. From Johnson and Silsbee, 1985.

Theoretical understanding of spin injection has focused largely on spin density while neglecting spin phase, which is important for some proposed spintronic applications. The problem of spin evolution in various transport modes (diffusion, tunneling, thermionic emission) remains to be investigated. Particularly relevant is the question of whether spin phase is conserved during spin injection. Malajovich *et al.* (2001) showed, by studying spin evolution in transport through a n-GaAs/n-ZnSe heterostructure, that the phase can indeed be preserved.

D. Experiments on spin injection

1. Johnson-Silsbee spin injection

The first spin polarization of electrons by electrical spin injection (Johnson and Silsbee, 1985) was demonstrated in a "bulk wire" of aluminum on which an array of thin film permalloy (Py) pads (with 70% nickel and 30% iron) was deposited spaced in multiples of 50 μm, center to center (Johnson and Silsbee, 1988d) to serve as spin injectors and detectors. In one detection scheme a single ferromagnetic pad was used as a spin injector while the distance to the spin detector was altered by selecting different Py pads to detect V_s and through the spatial decay of this spin-coupled voltage infer L_{sN}.[56] This procedure is illustrated in Fig. 9, where the separation between the spin injector and detector L_x is variable.

Johnson and Silsbee (1985) point out that in the depicted geometry there is no flow of the charge current for $x>0$ and that in the absence of nonequilibrium spins a voltage measurement between $x=L_x$ and $x=b$ gives zero. Injected spin-polarized electrons will diffuse symmetrically (at low current density the effect of electric fields can be neglected), and the measurement of voltage will give a spin-coupled signal V_s related to the relative orientation of magnetizations in F1 and F2.[57] The results, corresponding to the polarizer-analyzer detection and the geometry of Fig. 9, are given in Fig. 10. An in-plane field ($\mathbf{B}\|\hat{\mathbf{z}}$), of a magnitude several times larger than a typical field for magnetization reversal, $B_0 \approx 100$ G, is applied to define the direction of magnetization in the injector and detector. As the field sweep is performed, from negative to positive values, at B_{01} there is a reversal of magnetization in one of the ferromagnetic films accompanied by a sign change in the spin-coupled signal. As B_z is further increased, at approximately B_{02}, there is another reversal of magnetization, resulting in parallel orientation of F1 and F2 and a V_s of magnitude similar to that for the previous parallel orientation when $B_z<B_{01}$.

A more effective detection of the spin injection is realized through measurements of the Hanle effect, also discussed in Secs. II.B and III.A.2, and described by Bloch-Torrey equations [Bloch, 1946; Torrey, 1956; see Eqs. (52)–(54)]. The inset of Fig. 10 summarizes results from a series of Hanle experiments on a single sample. For the Hanle effect $\mathbf{B}$ must have a component perpendicular to the orientation axes of the injected spins. Only projection of $\mathbf{B}$ perpendicular to the spin axis applies a torque and dephases spins. The magnitude of $\mathbf{B}$, applied at an angle ϕ to the z axis in the y-z plane, is small enough that the magnetizations in ferromagnetic thin films remain in the x-z plane (see Fig. 9). If, at $\mathbf{B}=0$, injected nonequilibrium magnetization is $\delta M(0)\hat{z}$ then at finite field $\delta\mathbf{M}$ precesses about $\mathbf{B}$ with a cone of angle 2ϕ. After averaging over several cycles, only $\delta M(0)\cos\phi$, the component $\|\mathbf{B}$, will survive. The voltage detector[58] senses the remaining part of the magnetization projected on the axis of the detector $\delta M(0)\cos\phi\times\cos\phi$ (Johnson and Silsbee, 1988a). The

[56]The spin relaxation time in a ferromagnet is often assumed to be very short. Correspondingly, in the analysis of the experimental data, both the spin diffusion length and δM are taken to vanish in the F region (Silsbee, 1980; Johnson and Silsbee, 1985, 1988a, 1988d).

[57]This method for detecting the effects of spin injection is also referred to as a *potentiometric method*.

[58]Recall from the discussion leading to Eq. (39) that the spin-coupled signal is proportional to δM.

predicted angular dependence for the amplitude of the Hanle signal (proportional to the depolarization of δM in a finite field) $[\delta M(0) - \delta M(0)\cos^2\phi]$ is plotted in the inset together with the measured data.[59] Results confirm the first application of the Hanle effect to dc spin injection.

The Hanle effect was also studied theoretically by solving the Bloch-Torrey equations for an arbitrary orientation, characterized by the angle α, between the magnetization in F1 and F2 (Johnson and Silsbee, 1988a). From the Hanle curve $[V_s(B_\perp)]$ measured at $T=4.3$ (36.6) K, the parameters $L_s=450$ (180) μm and $P_\Sigma=0.06$ (0.08) were extracted.[60] This spin injection technique using the few-pV resolution of a superconducting quantum interference device (SQUID) and with an estimated $P_\Sigma \approx 0.07$ provided an accuracy able to detect $P_n \approx 5\times 10^{-12}$, causing speculation that a single-spin sensitivity might be possible in smaller samples (Johnson and Silsbee, 1985, 1988d). While in a good conductor, such as Al, the observed resistance change ΔR was small $(\sim n\Omega)$, the relative change at low temperatures and for $L_x \ll L_s$ was $\Delta R/R \approx 5\%$, where ΔR is defined as in Eq. (1), determined by the relative orientation of the magnetization in F1 and F2, and R is the Ohmic resistance (Johnson, 2002a). Analysis from Sec. II.C.2 shows that measurement of ΔR could be used to determine the product of injected current polarizations in the two F/N junctions.

The studies of spin injection were extended to the thin-film geometry, also known as the "bipolar spin switch" or "Johnson spin transistor" (Johnson, 1993a, 1993b) similar to the one depicted in Fig. 5(a). The measured spin-coupled signals[61] in Au films were larger than the values obtained in bulk Al wires (Johnson and Silsbee, 1985, 1988d). A similar trend, $V_s \sim 1/d$, potentially important for applications, was already anticipated by Silsbee (1980). The saturation of this increase can be inferred from Eqs. (43) and (44) for $d \ll L_{sN}$ and been discussed by Fert and Lee (1996) and Hershfield and Zhao (1997).

When polarizer-analyzer detection was used, one of the fitting parameters from the measured data P_Σ sometimes exceeded 1—which corresponds to complete interfacial polarization. The origin of this discrepancy remains to be fully resolved (Johnson, 1993b, 2002a; Fert and Lee, 1996; Hershfield and Zhao, 1997; Geux *et al.*, 2000). Results obtained from the Hanle effect, on similar samples, gave the expected $P_\Sigma < 1$ values (Johnson, 2002a).[62]

A modification of the bipolar spin-switch structure was used to demonstrate spin injection into a niobium film (Johnson, 1994), realizing the theoretical assertion of Aronov (1976a) that nonequilibrium spin could be injected into a superconductor. Two insulating Al_2O_3 films were inserted between F1 and F2 (both made of Py) and a Nb film [see Fig. 5(b)]. The measurements were performed near the superconducting transition temperature T_c with the data qualitatively similar, above and below T_c, to the spin-coupled voltage, as obtained in the magnetic-field sweep from Fig. 10. The results were interpreted as support for enhanced depletion of the superconducting condensate (and correspondingly the reduction of the critical current I_c) by spin-polarized quasiparticles, as compared to the usual spin-unpolarized quasiparticle injection. Related measurements were recently performed in a CPP geometry (Gu *et al.*, 2002), and the penetration depth of the quasiparticle in the Nb films was measured to be ~ 16 nm, as compared to 2 nm in Johnson (1994). The corresponding temperature dependence of CPP giant magnetoresistance is well explained by the theory of Yamashita, Imamura, *et al.* (2003) and the modification of Andreev reflection (see Sec. IV.A.3) by spin polarization.

The spin injection technique of Johnson and Silsbee was also applied to semiconductors. Initial experiments on using a metallic ferromagnet to inject spin into a two-dimensional electron gas (2DEG) showed only a very low $(\sim 1\%)$ efficiency (Hammar *et al.*, 1999) for which various explanations were offered (Hammar *et al.*, 2000; Monzon *et al.*, 2000; van Wees, 2000). However, stimulated by the proposal of Rashba (2000) to employ spin-selective diffusive contacts (Sec. II.C.1), the subsequent measurements have showed substantially more efficient spin injection into a 2DEG after an insulating layer was inserted (Hammar and Johnson, 2001, 2002). The geometry employed is depicted in Fig. 9. In interpreting the results, the spin-orbit coupling and the energy-independent density of states at the Fermi level were taken into account (Silsbee, 2001). This topic is reviewed by Tang *et al.* (2002).

2. Spin injection into metals

An important part of the operation of CPP giant magnetoresistance structures is the presence of nonequilib-

[59]The range of the angle ϕ, in the inset, is corrected from the one originally given in Fig. 3 of Johnson and Silsbee (1985).

[60]The fitting parameters are τ_s, P_Σ, and α (Johnson and Silsbee, 1988d), and since the diffusion coefficient is obtained from Einstein's relation L_s is known.

[61]$d \sim 100$ nm was much smaller than the separation between F1 and F2 in bulk Al wires (Johnson and Silsbee, 1985), and the amplitude of the Hanle effect was about 10^4 larger (Johnson, 2002a).

[62]Theoretical estimates for V_s from which $P_\Sigma > 1$ was inferred are modified when one considers the Coulomb interaction and proximity effects—near the N/F interface the spin splitting of the carrier bands in the N region will be finite even at equilibrium. Model calculations (Chui, 1995; Chui and Cullen, 1995), which treat the F/N/F junction as a whole, show that the magnetic susceptibility χ in N can be much smaller than the free-electron value and can increase the predicted $V_s \propto 1/\chi$. These corrections to the free-electron picture of an F/N/F junction are smaller for larger d, as in the bulk-wire geometry of Johnson and Silsbee (1985), where theoretical estimates of V_s did not lead to $P_\Sigma > 1$.

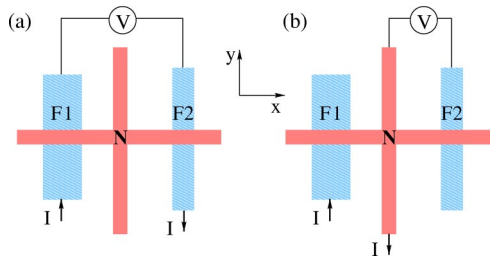

FIG. 11. (Color in online edition) Schematic representation of (a) local and (b) nonlocal geometry used to measure the effects of spin injection and spin accumulation.

rium spin polarization in nonmagnetic metallic regions. Studies of spin-injection parameters in such systems have been reviewed by Bass and Pratt (1999) and Gijs and Bauer (1997). However, until recently, except for the work of Johnson and Silsbee, there were few other experimental studies directly concerned with spin injection into metals. A series of experiments (Jedema *et al.*, 2001; Jedema, Costache, *et al.*, 2002; Jedema, Heersche, *et al.*, 2002a; Jedema, Nijboer, *et al.*, 2002) at both low (4.2 K) and room temperature, were performed using the van der Pauw geometry depicted in Fig. 11. In various structures (Jedema, 2002) the two ferromagnetic regions (made of Py, Co, or Ni) were chosen to be of different sizes to provide different coercive fields, allowing an independent reversal of magnetization in F1 and F2. The cross-shaped nonmagnetic region was made of Al or Cu (Jedema, 2002). Nonlocal measurements, similar to the approach shown in Figs. 5 and 9 (discussed by Johnson, 1993b; Johnson and Silsbee, 1988d), were shown to simplify the extraction of spurious effects (for example, anisotropic magnetoresistance and the Hall signal) from effects intrinsic to spin injection, as compared to the local or conventional spin-valve geometry.

In the first type of experiment the cross-shaped region was deposited directly over the F region (Fig. 11), and the spin-coupled resistance ΔR, defined analogously to Eq. (1), was measured as a function of an in-plane magnetic field. A theoretical analysis (Jedema *et al.*, 2001; Jedema, Nijboer, *et al.*, 2002) was performed assuming no interfacial resistance ($r_c=0$) and the continuity of the electrochemical potentials at the F/N interface (see Sec. II.C.1). For a spin injection from Py into Cu, the maximum current polarization obtained was $P_j \approx 0.02$ at 4.2 K. The results for ΔR (Jedema *et al.*, 2001) scaled to the size of the samples used by Johnson (1993a, 1993b) were interpreted to be three to four orders of magnitude smaller. As discussed in Secs. II.C.1 and II.C.2, the presence of interfacial spin-selective resistance can substantially change the spin injection efficiency and influence the resistance mismatch between the F and N regions [see Eq. (19)]. Estimates of how these considerations would affect the results of Jedema *et al.* (2001) were given by Jedema, Heersche, *et al.* (2002b) as well as by others (Johnson and Byers, 2003; Takashi and Maekawa, 2003), who analyzed the importance of multidimensional geometry. In addition to comparing characteristic values of the contact resistance obtained on different samples,[63] for a conclusive understanding it will be crucial to have *in situ* measurements.

In analyzing data for the van der Pauw cross, a two-dimensional geometry has an important effect—while the electric current is following the paths depicted in Fig. 11, the spin current, through the diffusion of nonequilibrium spin, would have similar flow in all four arms (Johnson, 2002a). This is different from the usual (quasi-)one-dimensional analysis in which spin and charge currents flow along the same paths. For a full understanding of the van der Pauw cross geometry, two-dimensional modeling might be necessary (Johnson and Byers, 2003; Takahashi and Maekawa, 2003).

In the second type of experiment, tunneling contacts were fabricated by inserting Al_2O_3 as an insulator into the regions where F1 and F2 overlapped with the cross. By applying a transverse field B_z (see Fig. 11) the precession of the injected nonequilibrium spin was controlled and the amplitude of the Hanle effect was measured (Jedema, Costache, *et al.*, 2002; Jedema, Heersche, *et al.*, 2002a) as outlined in Sec. II.D.1. From $Co/Al_2O_3/Al/Al_2O_3/Co$ structures $L_s \approx 0.5$ μm was extracted at room temperature. The analysis of the Hanle signal was performed by averaging contributions of different lifetimes (D'yakonov and Perel', 1984, p. 40). This proved to be equivalent to Johnson and Silsbee's (1988d) solution to the Bloch-Torrey equations.

3. All-semiconductor spin injection

If a magnetic semiconductor could be used as a robust spin injector (spin aligner) into a nonmagnetic semiconductor it would facilitate the integration of spintronics and semiconductor-based electronics. Comparable resistivities of magnetic and nonmagnetic semiconductors could provide efficient spin injection [see Eq. (31), with $r_F \approx r_N$] even without using resistive contacts. Ultimately, for a wide range of applications and for compatibility with complementary metal-oxide semiconductors (CMOS; Wong *et al.*, 1999), it would be desirable to be able to inject spin into silicon at room temperature.

Early studies (Osipov *et al.*, 1990, 1998; Viglin *et al.*, 1991, 1997), which have since largely been ignored, used a Cr- and Eu-based chalcogenide ferromagnetic semiconductor (FSm) (Nagaev, 1983) as the spin injector.[64] The experiments were motivated by the theoretical

[63]For example, the measured resistance of clean F/N contacts in CPP giant magnetoresistance (Bussmann *et al.*, 1998) was used to infer that there is also a large contact resistance in all-metal spin injection experiments (Johnson, 2002b).

[64]These materials, while more difficult to fabricate than the subsequent class of III-V ferromagnetic semiconductors, have the desirable properties of providing injection of spin-polarized electrons (with spin lifetimes typically much longer than for holes) and large spin splitting [$\sim$0.5 eV at 4.2 K for n-doped $HgCr_2Se_4$ (Nagaev, 1983)] with nearly complete spin polarization and a Curie temperature T_C of up to 130 K ($HgCr_2Se_4$) (Osipov *et al.*, 1998).

work of Aronov (1976a; Aronov and Pikus, 1976) predicting that the electron spin resonance signal, proportional to the steady-state magnetization, would be changed by spin injection. The measurements of Osipov *et al.* (1990) and Viglin *et al.* (1991) prompted a related prediction (Margulis and Margulis, 1994) that spin injection could be detected through changes in electric dipole spin resonance (EDSR). EDSR is the spin-flip resonance absorption for conduction electrons at Zeeman frequency, which is excited by the electric-field vector of an incident electromagnetic wave. The theory of EDSR, developed by Rashba and Sheka (1961), is extensively reviewed by Rashba and Sheka (1991).

Ferromagnetic semiconductor spin injectors formed p-n and n-n heterostructures with a nonmagnetic semiconductor InSb. The choice of InSb is very suitable, due to its large negative (~ -50) g factor (McCombe and Wagner, 1971), for detecting the effects of spin injection through electron spin resonance. The observed absorption and emission of microwave power (Osipov *et al.*, 1998) was tuned by an applied magnetic field (from 35 GHz at $\approx$400 G up to 1.4 THz at 20 kG) and only seen when electrons flowed from FSm into an Sm region. The injection to the lower Zeeman level increased the absorption of electron spin resonance, while injection to the higher Zeeman level, leading to population inversion, generated microwave emission.

The most recent experiments using semiconductor spin injectors can be grouped into two different classes. In one approach (II,Mn)VI paramagnetic semiconductors were employed as the spin aligners. These included CdMnTe (Oestreich *et al.*, 1999), BeMnZnSe (Fiederling *et al.*, 1999), and ZnMnSe (Jonker *et al.*, 2000). In the second approach ferromagnetic semiconductors like (Ga,Mn)As (Ohno, Young, *et al.*, 1999; Chun *et al.*, 2002; Mattana *et al.*, 2003) were used. Both approaches were also employed to inject spins into CdSe/ZnSe (Seufert *et al.*, 2004) and InAs (Chye *et al.*, 2002) quantum dots, respectively.

In (II,Mn)VI materials, at low Mn concentration and at low temperatures, there is a giant Zeeman splitting $\Delta E = g^* \mu_B H$ (Furdyna, 1988; Gaj, 1988) of the conduction band, in which g^* is the effective electron g factor. Such splitting arises due to sp-d exchange between the spins of conduction electrons and the $S=5/2$ spins of the localized Mn^{2+} ions. The g^* factor for $H \neq 0$ can exceed[65] 100 and is given by (Brandt and Moshchalkov, 1984; Furdyna, 1988)

$$g^* = g + \alpha M/(g_{Mn}\mu_B^2 H), \tag{50}$$

where g is the $H=0$ II-VI "band" value g, generally different from the free-electron value, magnetization $M \propto \langle S_z \rangle \propto B_s[(g_{Mn}\mu_B SH)/(k_B T)]$, B_s is the Brillouin function (Ashcroft and Mermin, 1976), and α is the exchange integral for s-like Γ_6 electrons (see Table I in Sec. II.B), given by (Furdyna, 1988)

$$\alpha \equiv \langle S|J_{sp-d}|S\rangle/V_0, \tag{51}$$

where J_{sp-d} is the electron-ion exchange coupling, and V_0 is the volume of an elementary cell. From Eqs. (50) and (51) it follows that $g^* = g^*(H)$ can even change its sign. Similar analysis also applies to g factors of holes, with the Zeeman splitting of a valence band being typically several times larger than that of a conduction band (Brandt and Moshchalkov, 1984).

(II,Mn)VI materials can be incorporated in high-quality heterostructures with different optically active III-V nonmagnetic semiconductors which, by providing circularly polarized luminescence, can also serve as spin detectors. In this case carriers are excited by electrical means and we speak of *electroluminescence* rather than photoluminescence. The selection rules for the recombination light are the same as discussed in Sec. II.B.

Figure 12 depicts a scheme for realization of all-semiconductor electrical spin injection and optical detection (Fiederling *et al.*, 1999; Jonker *et al.*, 2000). Displayed is a spin light-emitting diode (LED; Jonker *et al.*, 1999) in a Faraday geometry where both the applied B field and the direction of propagation of the emitted light lie along the growth direction. Similar to an ordinary LED (Sze, 1981), electrons and holes recombine in a quantum well or a p-n junction and produce electroluminescence. However, in a spin LED, as a consequence of radiative recombination of spin-polarized carriers, the emitted light is circularly polarized. In experiments of

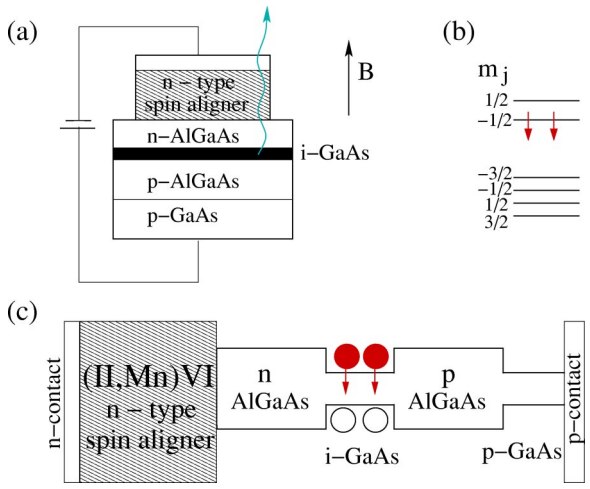

FIG. 12. (Color in online edition) Schematic device geometry and band diagram of a spin LED: (a) Recombination of spin-polarized electrons injected from the (II,Mn)VI spin aligner and unpolarized holes injected from the p-doped GaAs, in the intrinsic GaAs quantum well, producing circularly polarized light; (b) conduction and valence bands of a spin aligner in an external magnetic field; (c) sketch of the corresponding band edges and band offsets in the device geometry. In the quantum well, spin-down electrons and unpolarized holes are depicted by solid and empty circles, respectively. Adapted from Fiederling *et al.*, 1999.

[65]At low temperatures ($\sim$1 K) $Cd_{0.95}Mn_{0.05}Se$ has $|g^*|>500$ (Dietl, 1994), while in n-doped (In,Mn)As $|g^*|>100$ at 30 K (Zudov *et al.*, 2002). Such large g factors, in the presence of a highly inhomogeneous magnetic field could lead to the charge carrier localization (Berciu and Jankó, 2003).

Fiederling *et al.* (1999) and Jonker *et al.* (2000), at $B \approx 1$ T, $T \approx 4$ K, and forward bias, electrons entering from the n contact were almost completely polarized in the spin-down state as they left the spin aligner and were injected across the (II,Mn)VI/AlGaAs interface. The electrons further traveled (by drift and diffusion) to an intrinsic GaAs quantum well, where they recombined with the unpolarized holes, which were injected from the p-doped GaAs.[66]

The efficiency of electrical spin injection across the (II,Mn)VI/AlGaAs interface was studied (Fiederling *et al.*, 1999) using P_{circ} (defined in Sec. II.B) of electroluminescence, as a function of B and the thickenss of the magnetic spin aligner (0 nm, 3 nm, and 300 nm, respectively). P_{circ} increased with the thickness of the magnetic layer, suggesting the finite spin relaxation time needed for initially unpolarized electrons to relax into the lower (spin-down) Zeeman level. The results of Jonker *et al.* (2000) were similar to those of Fiederling *et al.* (1999) for the thickest magnetic region. The behavior of $P_{\mathrm{circ}}(B)$, up to the saturation value ($B \approx 3$ T), could be well explained by the magnetization described with the Brillouin function (Furdyna, 1988; Gaj, 1988), expected for the (II,Mn)VI semiconductors. In Fig. 12 the injected spin-down electrons are majority electrons with their magnetic moments parallel to the applied magnetic field. The principles of optical orientation discussed in Sec. II.B and the selection rules for GaAs sketched in Fig. 6 are used to infer P_n in a quantum well.

For quantum wells of approximately the same width (150 nm) the conversion of P_{circ} to P_n used by Fiederling *et al.* (1999) differed by a factor of 2 from that used by Jonker *et al.* (2000). Fiederling *et al.* (1999) assumed that confinement effects were negligible, leading to the selection rules for a bulk GaAs (recall $P_{\mathrm{circ}} = -P_n/2$, from Sec. II.B). The maximum $P_{\mathrm{circ}} \approx 43\%$ was interpreted as implying nearly 90% polarized injected electrons. Jonker *et al.* (2000) inferred $|P_n| \approx 50\%$, from $P_{\mathrm{circ}} = -P_n$ (Weisbuch and Vinter, 1991), as a consequence of quantum well confinement and lifting of the degeneracy between light and heavy hole states in the valence band ($\approx 5-6$ MeV); see Fig. 6. Both results clearly demonstrated a robust low-temperature spin injection using spin LED's. Subsequent studies (Park *et al.*, 2000; Jonker *et al.*, 2001; Stroud *et al.*, 2002) have supported the lifting of degeneracy between the light and heavy hole bands. The corresponding data are shown in Fig. 13. Similar values of P_{circ} were also measured in a resonant tunneling diode based on ZnMnSe (Gruber *et al.*, 2001; Waag *et al.*, 2001). Spin injection using the spin LED's, described above, is not limited to structures grown by molecular-beam epitaxy. It is also feasible using air-exposed interfaces (Park *et al.*, 2000) similar to the actual fabrication conditions employed in conventional electronics.

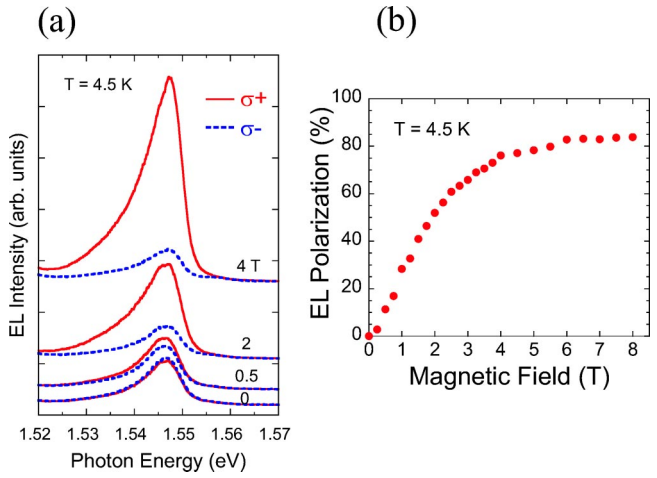

FIG. 13. (Color in online edition) Electroluminescence in a spin light-emitting diode (LED): (a) Electroluminescence (EL) spectra from a surface-emitting spin LED with a $Zn_{0.94}Mn_{0.06}Se$ contact for selected values of applied magnetic field, analyzed for $\sigma^{\pm}$ (positive and negative helicity); the magnetic field is applied along the surface normal (Faraday geometry) and the spectra are dominated by the heavy hole exciton; (b) magnetic field dependence of the EL circular polarization. Adapted from Jonker *et al.*, 2001.

The robustness of measured P_{circ} was studied by intentionally changing the density of linear defects, from stacking faults at the ZnMnSe/AlGaAs interface (Stroud *et al.*, 2002). An approximate linear decrease of P_{circ} with the density of stacking faults was shown to be consistent with the influence of spin-orbit interaction as modeled by Elliot-Yafet scattering (see Sec. III.B.1) at the interface. The nonspherically symmetric defect potential (entering the spin-orbit interaction) causes a highly anisotropic loss of spin polarization. At small angles to the axis of growth (see Fig. 12), the probability of the spin flip of an injected electron is very high, leading to a small spin polarization. These findings illustrate the importance of interface quality and the effect of defects on the spin injection efficiency, an issue not limited to semiconductor heterostructures. Related information is currently being sought by spatial imaging of the spin polarization in spin LED's (Thurber *et al.*, 2002; Thurber and Smith, 2003) using magnetic resonance force microscopy (Sidles *et al.*, 1995).

(III,Mn)V ferromagnetic semiconductors are also used to inject spin in spin-LED structures as depicted in Fig. 12. Spin injection can be achieved even with no external field, and the reports of high T_C in some compounds suggest that all-semiconductor spin LED's could operate at room temperature. The drawback, however, is that the most (III,Mn)V's have spin-polarized holes (rather than electrons) as the main carriers which, due to spin-orbit coupling, lose their polarization very quickly after being injected into a nonmagnetic semiconductor. Consequently, results of the spin injection show

[66]The spatial separation and spin relaxation between the injection and detection points (in a quantum well) make a fully quantitative analysis of the injected polarization more difficult. It would be valuable to perform realistic calculations of a spin-polarized transport and spin injection which would treat the whole spin LED as a single entity.

only a small degree of hole polarization.

In the experiment of Ohno, Young, *et al.* (1999), an intrinsic GaAs spacer of thickness d was introduced between the spin aligner (Ga,Mn)As and the (In,Ga)As quantum well. The electroluminescence in a quantum well was measured perpendicular to the growth direction [the easy magnetization axis of (Ga,Mn)As and the applied magnetic field were both perpendicular to the growth direction]. The corresponding relation between the P_{circ} and hole density polarization P_p is not straightforward; the analysis was performed only on the electroluminescence [for possible difficulties see Fiederling *et al.* (2003)]. A small measured signal ($P_{\mathrm{circ}}\sim 1\%$ at 5 K), consistent with the expectation for holes as the injected spin-polarized carriers, was also obtained in an additional experiment (Young *et al.*, 2002). P_{circ} was approximately independent of the GaAs thickness ($d=20-420$ nm), a behavior that remains to be understood considering that the hole spins should relax fast (Hilton and Tang, 2002) as they are transfered across the nonmagnetic semiconductor.[67] In contrast, for a repeated experiment (Young *et al.*, 2002) using a Faraday geometry (as in Fig. 12), with both measured electroluminescence and B along the growth direction, the same change of thickness P_{circ} was reduced from 7% to 0.5%. A highly efficient spin injection of $P_n\approx 80\%$ in GaAs has been realized using (Ga,Mn)As as a spin injector in a Zener diode structure (Van Dorpe, Liu, *et al.*, 2003). The detection employed the technique of an oblique Hanle effect, discussed in the next section.

All-electrical spin injection studies of trilayer structures (II,Mn)VI/II-VI/(II,Mn)VI have displayed up to 25% magnetoresistance at $B\approx 5$ T and $T=4$ K (Schmidt *et al.*, 2001). A strong suppression of this signal at applied bias of ~ 10 mV was attributed to the nonlinear regime of spin injection, in which the effects of band bending and charge accumulation at the (II,Mn)VI/II-VI interface were important (Schmidt *et al.*, 2002). It would be instructive to analyze these measurements by adopting the approach discussed in the context of magnetic p-n junctions (Secs. II.C.3 and IV.D), which self-consistently incorporates the effects of band bending and deviation from local charge neutrality.

4. Metallic ferromagnet/semiconductor junctions

A large family of metallic ferromagnets, some of them highly spin polarized, offer the possibility of spin injection at room temperature, even in the absence of applied magnetic field. Spin injection into (110) GaAs at room temperature has already been demonstrated using vacuum tunneling from a polycrystalline Ni STM tip and optical detection via circularly polarized luminescence (Alvarado and Renaud, 1992; Alvarado, 1995). It was shown that the minority spin electrons (spin $\downarrow$ in the context of metals; see Sec. II.A) in Ni produced the dominant contribution to the tunneling current, and the resulting polarization was inferred to be $P_n=(-31\pm 5.6)\%$ (Alvarado and Renaud, 1992). Even though the spin injection in future spintronic devices will likely be implemented by some means other than vacuum tunneling, this result supports the importance of the tunneling contact for efficient spin injection, as discussed in Sec. II.C.1. Similar studies of spatially resolved spin injection, sensitive to the topography of the GaAs surface, have employed a single-crystal Ni (100) tip (LaBella *et al.*, 2001). At 100 K nearly fully spin-polarized injection of electrons was reported. However, further analyses of the measurements of P_{circ} have substantially reduced these estimates to $\approx 25\%$ (Egelhoff *et al.*, 2002; LaBella *et al.*, 2002).

Direct spin injection from a ferromagnet into a 2D electron gas,[68] motivated by the proposal of Datta and Das (1990), initially showed only small effects (Gardelis *et al.*, 1999; Hammar *et al.*, 1999; Lee *et al.*, 1999), with $\Delta R/R\sim 1\%$, or effects within the noise (Filip *et al.*, 2000). Such inefficiency could be attributed to the resistance mismatch in the F and N regions, discussed in Secs. II.C.1 and II.C.2. The possibility of spurious effects arising from the Hall and anisotropic magnetoresistance signals in similar structures was suggested earlier (Monzon *et al.*, 1997) as well as after the initial experiments (Monzon *et al.*, 2000; van Wees, 2000; Tang *et al.*, 2002). Control measurements have been performed to address these issues (Hammar *et al.*, 2000; Hammar and Johnson, 2000). This debate about the presence/absence of spin injection effects via Ohmic contacts stimulated further studies, but the experimental focus has since shifted to other approaches.

Spin injection via Schottky contacts at room temperature was demonstrated in a Fe/GaAs junction by Zhu *et al.* (2001), who reported detection of $P_{\mathrm{circ}}\approx 2\%$ using spin LED structures and optical detection as described in Sec. II.D.3. These studies were extended (Ramsteiner *et al.*, 2002) by using molecular-beam epitaxy to grow MnAs, a ferromagnetic metal, on top of the GaAs to provide high-quality interfaces (Tanaka, 2002). There was no preferential behavior for spin injection using different azimuthal orientations of the epitaxial MnAs layer, which could have been expected from the symmetry between the conduction-band wave functions in MnAs and GaAs. The tunneling properties of a Schottky barrier were discussed by Meservey *et al.* (1982); Gibson and Meservey (1985); Prins *et al.* (1995); and Kreuzer *et al.* (2002). The measured I-V curves display a complicated behavior (Hirohata *et al.*, 2001; Isaković *et al.*, 2001) which can be significantly affected by the interface (midgap) states at the Schottky barrier (Jonker *et al.*, 1997). A theoretical explanation for this behavior is still lacking.

[67] A possible exception is the quantum well, in which the effects of quantum confinement and quenching spin-orbit coupling lead to longer τ_s.

[68] For a comprehensive review of the 2D electron gas, see Ando *et al.* (1982).

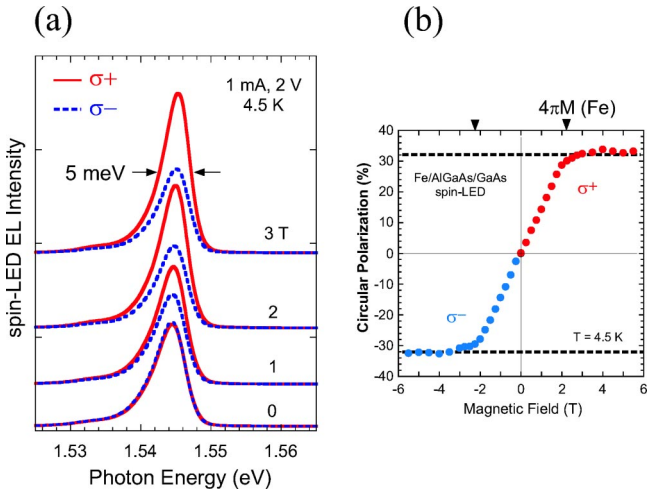

FIG. 14. (Color in online edition) Electroluminescence (EL) and polarization due to spin injection from Fe Schottky contact: (a) EL spectra from a surface-emitting spin LED with an Fe/AlGaAs Schottky tunnel contact for selected values of applied magnetic field, analyzed for $\sigma^{\pm}$ circular polarization. The large difference in intensity between these components indicates successful spin injection from the Fe into the GaAs quantum well and reveals an electron spin polarization in the quantum well of 32%. The magnetic field is applied along the surface normal (Faraday geometry). The spectra are dominated by the heavy hole exciton. Typical operating parameters are 1 mA and 2 V. (b) Magnetic-field dependence of the EL circular polarization of the heavy hole exciton. The polarization tracks the hard axis magnetization of the Fe contact and saturates at an applied magnetic-field value $4\pi M = 2.2$ T, at which the Fe magnetization is entirely along the surface normal. From Hanbicki *et al.*, 2003.

As discussed in Sec. II.C.1, tunnel contacts formed between a metallic ferromagnet and a semiconductor can provide effective spin injections. Optical detection in spin LED structures, as discussed in Sec. II.D.3, was used to show carrier polarization of $P_n \approx 30\%$ using Fe as a spin injector (Hanbicki *et al.*, 2003). Experimental results are given in Fig. 14. Some care has to be taken in defining the efficiency of the spin injection, normalized to the polarization of a ferromagnet, as used in related previous experiments (Hanbicki and Jonker, 2002; Hanbicki *et al.*, 2002; Jansen, 2002). Furthermore, there are often different conventions for defining the sign of P_n (Hanbicki *et al.*, 2003), used in the context of semiconductors and ferromagnetic metals, as discussed in Sec. II.A. Jiang *et al.* (2004) have demonstrated that MgO can be a suitable choice of an insulator for highly efficient spin injection into GaAs. Spin LED with GaAs/AlGaAs quantum well was used to detect $P_n \approx 50\%$ at 100 K injected from CoFe/MgO (100) tunnel injector. While quantum well emission efficiency limits detection at higher temperatures (>100 K), the same tunnel injector should also be suitable for efficient spin injection even at room temperature.

An oblique Hanle effect (D'yakonov *et al.*, 1974; see also Secs. II.B and II.D.1) was used (Motsnyi *et al.*, 2002, 2003; Van Dorpe, Motsnyi, *et al.*, 2003) to detect spin injection, giving up to $P_n \approx 16\%$, at room temperature. The geometry used is similar to that sketched in Fig. 12(a), with an insulating layer (AlO_x) separating the ferromagnetic spin injector and the (Al,Ga)As/GaAs spin LED. The magnetization easy axis lies in the plane of the ferromagnet. An oblique magnetic field is applied to give a net out-of-plane component of injected spin which could contribute to the emission of circularly polarized light. This approach allows one to apply a magnetic field several times smaller than would be needed to pull the magnetization out of plane [for Fe it is ≈ 2 T (Hanbicki *et al.*, 2002)] and to measure polarized luminescence in a Faraday geometry. Furthermore, using standard measurements of the Hanle curve, one can extract separately the spin lifetime and carrier recombination time.

Hot-electron spin injection above the Schottky barrier is another method for using a high polarization of metallic ferromagnets to create a nonequilibrium spin in a semiconductor even at room temperatures. Typically such injection is performed in three-terminal, transistor-like devices, as discussed in Sec. IV.E.3.

Direct electrical spin injection has also been demonstrated in organic semiconductors (Dediu *et al.*, 2002). Magnetoresistance measurements were performed in an F/N/F junction, where F is $La_{0.7}Sr_{0.3}MnO_3$ (LSMO), a colossal magnetoresistive manganite, and N is sexithienyl (T_6), a π-conjugated rigid-rod oligomer organic semiconductor. The decrease of magnetoresistance with increasing thickness of the N region was used to infer $L_{sN} \sim 100$ nm at room temperature. The resulting spin diffusion length is a combination of low mobility, $\sim 10^{-4}$ cm^2 V^{-1} s^{-1} (about $\sim 10^7$ times smaller than for the bulk GaAs), and long spin relaxation times, $\sim \mu$s,[69] as compared to the usual III-V inorganic semiconductors. Motivated by these findings Xiong *et al.* (2004) have replaced one of the LSMO electrodes by Co. Different coercive fields in the two ferromagnetic electrodes allowed them to measure a spin-valve effect with $\Delta R/R \sim 40\%$ at 11 K. Related theoretical studies of the ferromagnetic metal/conjugated polymer interfaces were reported by Xie *et al.* (2003).

III. SPIN RELAXATION AND SPIN DEPHASING

A. Introduction

Spin relaxation and spin dephasing are processes that lead to spin equilibration and are thus of great importance for spintronics. The fact that nonequilibrium electronic spin in metals and semiconductors lives relatively long (typically a nanosecond), allowing for spin-encoded information to travel macroscopic distances, is what makes spintronics a viable option for technology. After introducing the concepts of spin relaxation and spin

[69]This is also a typical value for other organic semiconductors (Krinichnyi, 2000), a consequence of weak spin-orbit coupling (Davis and Bussmann, 2003).

dephasing times T_1 and T_2, respectively, which are commonly called τ_s throughout this paper, we discuss four major physical mechanisms responsible for spin equilibration in *nonmagnetic* electronic systems: Elliott-Yafet, Dyakonov-Perel', Bir-Aronov-Pikus, and hyperfine-interaction processes. We then survey recent works on electronic spin relaxation in nonmagnetic metals and semiconductors, using the important examples of Al and GaAs for illustration.

1. T_1 and T_2

Spin relaxation and spin dephasing of a spin ensemble are traditionally defined within the framework of the Bloch-Torrey equations (Bloch, 1946; Torrey, 1956) for magnetization dynamics. For mobile electrons, *spin relaxation time* T_1 (often called longitudinal or spin-lattice time) and *spin dephasing time* T_2 (also called transverse or decoherence time) are defined via the equations for the spin precession, decay, and diffusion of electronic magnetization $\mathbf{M}$ in an applied magnetic field $\mathbf{B}(t) = B_0\hat{\mathbf{z}} + \mathbf{B}_1(t)$, with a static longitudinal component B_0 (conventionally in the $\hat{z}$ direction) and, frequently, a transverse oscillating part $\mathbf{B}_1$ perpendicular to $\hat{\mathbf{z}}$ (Torrey, 1956; Kaplan, 1959):

$$\frac{\partial M_x}{\partial t} = \gamma(\mathbf{M}\times\mathbf{B})_x - \frac{M_x}{T_2} + D\nabla^2 M_x, \tag{52}$$

$$\frac{\partial M_y}{\partial t} = \gamma(\mathbf{M}\times\mathbf{B})_y - \frac{M_y}{T_2} + D\nabla^2 M_y, \tag{53}$$

$$\frac{\partial M_z}{\partial t} = \gamma(\mathbf{M}\times\mathbf{B})_z - \frac{M_z - M_z^0}{T_1} + D\nabla^2 M_z. \tag{54}$$

Here $\gamma = \mu_B g/\hbar$ is the electron gyromagnetic ratio (μ_B is the Bohr magneton and g is the electronic g factor), D is the diffusion coefficient (for simplicity we assume an isotropic or a cubic solid with scalar D), and $M_z^0 = \chi B_0$ is the thermal equilibrium magnetization with χ denoting the system's static susceptibility. The Bloch equations are phenomenological, describing quantitatively very well the dynamics of mobile electron spins (more properly, magnetization) in experiments such as conduction-electron spin resonance and optical orientation. Although relaxation and decoherence processes in a many-spin system are generally too complex to be fully described by only two parameters, T_1 and T_2 are nevertheless an extremely robust and convenient measure for quantifying such processes in many cases of interest. To obtain microscopic expressions for spin relaxation and dephasing times, one starts with a microscopic description of the spin system (typically using the density-matrix approach), derives the magnetization dynamics, and compares it with the Bloch equations to extract T_1 and T_2.

Time T_1 is the time it takes for the longitudinal magnetization to reach equilibrium. Equivalently, it is the time of thermal equilibration of the spin population with the lattice. In T_1 processes an energy has to be taken from the spin system, usually by phonons, to the lattice. Time T_2 is classically the time it takes for an ensemble of transverse electron spins, initially precessing in phase about the longitudinal field, to lose their phase due to spatial and temporal fluctuations of the precessing frequencies. For an ensemble of mobile electrons the measured T_1 and T_2 come about by averaging spin over the thermal distribution of electron momenta. Electrons in different momentum states have not only different spin-flip characteristics, but also slightly different g factors and thus different precession frequencies. This is analogous to precession frequency fluctuations of localized spins due to inhomogeneities in the static field B_0. However, since momentum scattering (analogous to intersite hopping or exchange interaction of localized spins) typically proceeds much faster than spin-flip scattering, the g-factor-induced broadening is inhibited by *motional narrowing*[70] and need not be generally considered as contributing to T_2 [see, however, Dupree and Holland (1967)]. Indeed, motional narrowing of the g-factor fluctuations, δg, gives a contribution to $1/T_2$ of the order of $\Delta\omega^2\tau_p$, where the B_0-dependent precession frequency spread is $\Delta\omega = (\delta g/g)\gamma B_0$ and τ_p is the momentum scattering time. For B_0 fields of the order of 1 T, scattering times of 1 ps, and δg as large as 0.01, the "*inhomogeneous broadening*" is a microsecond, which is much more than the observed values for T_2. Spatial inhomogeneities of B_0, like those coming from hyperfine fields, are inhibited by motional narrowing, too, due to the itinerant nature of electrons. For localized electrons (e.g., for donor states in semiconductors), spatial inhomogeneities play an important role and are often observed to affect T_2. To describe such reversible phase losses, which can potentially be eliminated by spin-echo experiments, sometimes the symbol T_2^* (Hu, de Sousa, and Das Sarma, 2001) is used to describe spin dephasing of ensemble spins, while the symbol T_2 is reserved for irreversible loss of the ensemble spin phase. In general, $T_2^* \leqslant T_2$, although for conduction electrons to a very good approximation $T_2^* = T_2$.

In isotropic and cubic solids $T_1 = T_2$ if $\gamma B_0 \ll 1/\tau_c$, where τ_c is the so-called *correlation* or *interaction time*: $1/\tau_c$ is the rate of change of the effective dephasing magnetic field (see footnote 70). Phase losses occur during time intervals of τ_c. As shown below, in electronic systems τ_c is given either by τ_p or by the time of the interaction of electrons with phonons and holes. Those times

[70] Motional (dynamical) narrowing is an inhibition of phase change by random fluctuations (Slichter, 1989). Consider a spin rotating with frequency ω_0. The spin phase changes by $\Delta\phi = \omega_0 t$ over time t. If the spin is subject to a random force that makes spin precession equally likely clockwise and anticlockwise, the average spin phase does not change, but the root-mean-square phase change increases with time as $(\langle\Delta^2\phi\rangle)^{1/2} \approx (\omega_0\tau_c)(t/\tau_c)^{1/2}$, where τ_c is the correlation time of the random force, or the average time of spin precession in one direction. This is valid for rapid fluctuations, $\omega_0\tau_c \ll 1$. The phase relaxation time t_ϕ is defined as the time over which the phase fluctuations reach unity: $1/t_\phi = \omega_0^2\tau_c$.

are typically smaller than a picosecond, so $T_1 = T_2$ is fulfilled for magnetic fields up to several tesla. The equality between the relaxation and dephasing times was noticed first in the context of NMR (Bloch, 1946; Wangsness and Bloch, 1953) and later extended to electronic spin systems (Pines and Slichter, 1955; Andreev and Gerasimenko, 1958). A qualitative reason for $T_1 = T_2$ is that if the phase acquires a random contribution during a short time interval τ_c, the energy uncertainty of the spin levels determining the longitudinal spin is greater than the Zeeman splitting $\hbar\gamma B_0$ of the levels. The splitting then does not play a role in dephasing, and the dephasing field will act equally on the longitudinal and transverse spins. In classical terms, spin that is oriented along the direction of the magnetic field can precess a full period about the perpendicular fluctuating field, feeling the same dephasing fields as transverse components. As the external field increases, the precession angle of the longitudinal component is reduced, inhibiting dephasing.

The equality of the two times is very convenient for comparing experiment and theory, since measurements usually yield T_2, while theoretically it is often more convenient to calculate T_1. In many cases a single symbol τ_s is used for spin relaxation and dephasing (and called indiscriminately either of these terms), if it does not matter what experimental situation is involved, or if one is working at small magnetic fields.[71] Throughout this paper we adopt this notation to avoid unnecessary confusion.

If the system is anisotropic, the equality $T_1 = T_2$ no longer holds, even in the case of full motional narrowing of the spin-spin interactions and g-factor broadening. Using simple qualitative analysis Yafet (1963) showed that, while there is no general relation between the two times, the inequality $T_2 \leqslant 2T_1$ holds, and that T_2 changes with the direction by at most a factor of 2. In the motionally narrowed case this difference between T_1 and T_2 can be considered as arising from the tensorial nature of the spin relaxation rate. Specific examples of this will be discussed in studying spin relaxation in two-dimensional semiconductor heterostructures (Sec. III.B.2).

Finally, we discuss the connection between τ_s and the single-spin *decoherence time*[72] τ_{sc}, which is the single-spin correlation time. Time τ_{sc} becomes important for applications in spin-based quantum computing (Loss and DiVincenzo, 1998; Hu and Das Sarma, 2000), where spin coherence needs to last for at least $10^4 - 10^6$ gate operations for the computation to be fault tolerant (Preskill, 1998). The relative magnitudes of τ_s and τ_{sc} depend on many factors. Often $\tau_{sc} < \tau_s$, as is the case for a direct exchange interaction causing single-spin decoherence, while contributing to ensemble dephasing only as a dynamical averaging factor (the exchange interaction preserves total spin). An analogy with momentum scattering may be helpful. Electron-electron collisions lead to individual momentum equilibration while conserving the total momentum and hence do not contribute to charge current (unless umklapp processes are taken into account). A momentum scattering time obtained from conductivity (analogous to τ_s) would thus be very different from a single-state momentum time (analogous to τ_{sc}). It is not clear at present how much τ_s and τ_{sc} differ for different materials under different conditions, although it is often, with little justification, assumed that they are similar. As Dzhioev, Korenev, Zakharchenya, *et al.* (2002) recently suggested, τ_{sc} can be smaller than τ_s by several orders of magnitude in n-GaAs at low doping densities where electrons are localized in donor states, see also Sec. III.D.3.a. We note that it is τ_s that is relevant for spintronics (spin transport) applications, while τ_{sc} is relevant for solid-state quantum computing. Much remains to be learned about τ_{sc}.

2. Experimental probes

Experiments detecting spin relaxation and decoherence of conduction electrons can be grouped into two broad categories: (a) those measuring spectral characteristics of magnetization depolarization and (b) those measuring time or space correlations of magnetization.

Experiments of type (a) are exemplified by conduction-electron spin resonance (CESR) and optical orientation in combination with the Hanle effect. CESR was the first technique used to detect the spin of conduction electrons in metals (Griswold *et al.*, 1952; Feher and Kip, 1955) and donor states in semiconductors like Si (Feher and Gere, 1959). In GaAs, spin resonance techniques are aided by other measurements, e.g., optical detection (Weisbuch and Hermann, 1977), photoconductivity (Stein *et al.*, 1983), or magnetoresistance (Dobers *et al.*, 1988). The technique measures signatures of resonant absorption of microwaves by a Zeeman-split spin system of conduction electrons. Typically changes in surface impedance and in the transmission coefficient of the sample are observed. By comparing the absorption resonance curve with theory (Dyson, 1955; Kaplan, 1959) one can obtain both the carrier g factor and T_2.

Optical spin orientation (Meier and Zakharchenya, 1984) is a method of exciting spin-polarized carriers (electrons and holes) in direct-gap semiconductors like GaAs by absorption of circularly polarized light (see Sec. II.B). The injected spin polarization can be detected by observing circularly polarized luminescence resulting from recombination of the spin-polarized electrons and holes. Since in a steady state the excited spin polarization depends not only on τ_s but also on the carrier recombination time, the Hanle effect, polarization of luminescence by a transverse magnetic field (see Sec. II.D.1), is employed to deduce τ_s unambiguously.

[71]Sometimes one finds a spin relaxation time $2\tau_s$. While this is correct for just one spin state, conventionally by spin relaxation we mean magnetization relaxation, in which each spin flip adds to the equilibration of both spin-up and spin-down states, doubling the rate for magnetization relaxation.

[72]To distinguish ensemble and individual spin dephasing, we use the term decoherence in relation to single, or a few, spins.

The Hanle effect has also been a great tool for investigating T_2 in metals, in connection with electrical spin injection. The advantage of optical orientation over CESR is that, if carrier lifetime is known, zero-field (or zero-g-factor material) data can be measured. In addition, smaller τ_s values can be detected.

Type (b) experiments measure magnetization in a time or space domain. The most important examples are the Johnson-Silsbee spin injection experiment, time-resolved (pump-probe) photoluminescence (in which the probe is used on the same principle as optical orientation), and time-resolved Faraday and (magneto-optic) Kerr rotation. The last two methods can follow coherent (in the ensemble sense) dynamics of electron spin precession.

Spin injection experiments (Johnson and Silsbee, 1985) detect the amount of nonequilibrium magnetization by observing charge response (see Sec. II.D.1). In the Johnson-Silsbee scheme, electrons are first injected by electrical spin injection from a ferromagnetic electrode into a metal or semiconductor. As the spin diffuses throughout the sample, another ferromagnetic electrode detects the amount of spin as a position-dependent quantity. The detection is by means of spin-charge coupling, whereby an emf appears across the paramagnet/ferromagnet interface in proportion to the nonequilibrium magnetization (Silsbee, 1980). By fitting the spatial dependence of magnetization to the exponential decay formula, one can extract the spin diffusion length L_s and thus the spin relaxation time $T_1 = L_s^2/D$. The Hanle effect, too, can be used in combination with Johnson-Silsbee spin injection, yielding directly $T_1 = T_2$, which agrees with T_1 determined from the measurement of L_s. A precursor to the Hanle effect in spin injection was transmission-electron spin resonance (TESR), in which nonequilibrium electron spin excited in the skin layer of a metallic sample is transported to the other side, emitting microwave radiation. In very clean samples and at low temperatures, electrons ballistically propagating through the sample experience Larmor precession, resulting in Larmor waves, seen as an oscillation of the transmitted radiation amplitude with changing static magnetic field (Janossy, 1980).

Time-resolved photoluminescence detects, after creation of spin-polarized carriers, circular polarization of the recombination light. This technique was used, for example, to detect a 500-ps spin coherence time T_2 of free excitons in a GaAs quantum well (Heberle *et al.*, 1994). The *Faraday* and (magneto-optic) *Kerr effects* are the rotation of the polarization plane of a linearly polarized light, transmitted through (Faraday) or reflected by (Kerr) a magnetized sample. The Kerr effect is more useful for thicker and nontransparent samples or for thin films fabricated on thick substrates. The angle of rotation is proportional to the amount of magnetization in the direction of the incident light. Pump experiments, using a circularly polarized laser pulse, and probe experiments employing magneto-optic effects can now follow, with 100-fs resolution, the evolution of magnetization as it dephases in a transverse magnetic field. Using lasers for spin excitation has the great advantage of not only detecting, but also manipulating spin dephasing, as shown using Faraday rotation on bulk GaAs and GaAs/ZnSe heterostructures (Awschalom and Kikkawa, 1999; Kikkawa *et al.*, 2001). The Kerr effect was used, for example, to investigate the spin dynamics of bulk CdTe (Kimel *et al.*, 2000), and Faraday rotation was used to study spin coherence in nanocrystals of CdSe (Gupta *et al.*, 2002) and coherent control of spin dynamics of excitons in GaAs quantum wells (Heberle *et al.*, 1996).

B. Mechanisms of spin relaxation

Four mechanisms for spin relaxation of conduction electrons have been found relevant for metals and semiconductors: the Elliott-Yafet, D'yakonov-Perel', Bir-Aronov-Pikus, and hyperfine-interaction mechanisms.[73] In the Elliott-Yafet mechanism electron spins relax because the electron wave functions normally associated with a given spin have an admixture of the opposite-spin states, due to spin-orbit coupling induced by ions. The D'yakonov-Perel' mechanism explains spin dephasing in solids without a center of symmetry. Spin dephasing occurs because electrons feel an effective magnetic field, resulting from the lack of inversion symmetry and from the spin-orbit interaction, which changes in random directions every time the electron scatters to a different momentum state. The Bir-Aronov-Pikus mechanism is important for p-doped semiconductors, in which the electron-hole exchange interaction gives rise to fluctuating local magnetic fields flipping electron spins. Finally, in semiconductor heterostructures (quantum wells and quantum dots) based on semiconductors with a nuclear magnetic moment, it is the hyperfine interaction of the electron spins and nuclear moments which dominates spin dephasing of localized or confined electron spins. An informal review of spin relaxation of conduction electrons can be found in Fabian and Das Sarma (1999c).

1. Elliott-Yafet mechanism

Elliott (1954) was the first to realize that conduction-electron spins can relax via ordinary momentum scattering (such as by phonons or impurities) if the lattice ions induce spin-orbit coupling in the electron wave function. In the presence of the spin-orbit interaction

$$V_{so} = \frac{\hbar}{4m^2c^2} \nabla V_{sc} \times \hat{\mathbf{p}} \cdot \hat{\boldsymbol{\sigma}}, \tag{55}$$

where m is the free-electron mass, V_{sc} is the scalar (spin-independent) periodic lattice potential, $\hat{\mathbf{p}} \equiv -i\hbar\nabla$ is the linear momentum operator, and $\hat{\boldsymbol{\sigma}}$ are the Pauli matrices, single-electron (Bloch) wave functions in a solid are no longer the eigenstates of $\hat{\sigma}_z$, but rather a

[73] We do not consider magnetic scattering, that is, scattering due to an exchange interaction between conduction electrons and magnetic impurities.

mixture of the Pauli spin-up $|\uparrow\rangle$ and spin-down $|\downarrow\rangle$ states. If the solid possesses a center of symmetry, the case of elemental metals which Elliott considered, the Bloch states of "spin-up" and "spin-down" electrons with the lattice momentum $\mathbf{k}$ and band index n can be written as (Elliott, 1954)

$$\Psi_{\mathbf{k}n\uparrow}(\mathbf{r})=[a_{\mathbf{k}n}(\mathbf{r})|\uparrow\rangle+b_{\mathbf{k}n}(\mathbf{r})|\downarrow\rangle]e^{i\mathbf{k}\cdot\mathbf{r}}, \tag{56}$$

$$\Psi_{\mathbf{k}n\downarrow}(\mathbf{r})=[a^{*}_{-\mathbf{k}n}(\mathbf{r})|\downarrow\rangle-b^{*}_{-\mathbf{k}n}(\mathbf{r})|\uparrow\rangle]e^{i\mathbf{k}\cdot\mathbf{r}}, \tag{57}$$

where we write the explicit dependence of the complex lattice-periodic coefficients a and b on the radius vector $\mathbf{r}$. The two Bloch states are degenerate: they are connected by spatial inversion and time reversal (Elliott, 1954). That it makes sense to call $\Psi_{\mathbf{k}n\uparrow}$ and $\Psi_{\mathbf{k}n\downarrow}$, respectively, spin-up and spin-down states follows from the fact that in most cases the typical values of $|a|$ are close to unity, while $|b|\ll 1$.

Indeed, consider a band structure in the absence of spin-orbit coupling. Turning V_{so} on couples electron states of opposite Pauli spins which are of the same $\mathbf{k}$ (because V_{so} has the period of the lattice), but different n. Because the spin-orbit interaction is normally much smaller than the distance between the bands, perturbation theory gives

$$|b|\approx\lambda_{so}/\Delta E\ll 1, \tag{58}$$

where ΔE is the energy distance between the band state in question and the state (of the same momentum) in the nearest band, and λ_{so} is the amplitude of the matrix element of V_{so} between the two states. The spin-orbit coupling alone does not lead to spin relaxation. However, in combination with momentum scattering, the spin-up [Eq. (56)] and spin-down [Eq. (57)] states can couple and lead to spin relaxation.

Momentum scattering is typically caused by impurities (at low T) and phonons (at high T). There is another important spin-flip scattering mechanism that involves phonons. A periodic, lattice-ion-induced spin-orbit interaction is modified by phonons and can directly couple the (Pauli) spin-up and spin-down states. Such processes were first considered for a jellium model by Overhauser (1953a; see also Grimaldi and Fulde, 1997) and for band-structure systems by Yafet (1963). They must be combined with the Elliott processes discussed above to form a consistent picture of phonon-induced spin relaxation, especially at low temperatures (Yafet, 1963), where the two processes have similar magnitudes. At larger T, phonon-modified V_{so} is not important for polyvalent metals, whose spin relaxation is dominated by spin hot spots—states with anomalously large $|b|$—as shown by the explicit calculation of Fabian and Das Sarma (1999b). Spin hot spots are discussed in more detail in Sec. III.C.

We now give a recipe, useful for elemental metals and semiconductors, for calculating phonon-induced $1/\tau_s$ from the known band and phonon structure. The corresponding theory was systematically developed by Yafet (1963). The spin relaxation rate due to phonon scattering according to the Elliott-Yafet mechanism can be expressed through the spin-flip Eliashberg function $\alpha_S^2F(\Omega)$ as (Fabian and Das Sarma, 1999b)

$$1/\tau_s=8\pi T\int_0^{\infty}d\Omega\,\alpha_s^2F(\Omega)\partial N(\Omega)/\partial T, \tag{59}$$

where $N(\Omega)=[\exp(\hbar\Omega/k_BT)-1]^{-1}$ is the phonon distribution function. The spin-flip Eliashberg function gives the contribution of the phonons with frequency Ω to the spin-flip electron-phonon interaction,

$$\alpha_s^2F(\Omega)=\frac{g_S}{2M\Omega}\sum_{\nu}\langle\langle g^{\nu}_{\mathbf{k}n\uparrow,\mathbf{k}'n'\downarrow}\delta(\omega_{\mathbf{q}\nu}-\Omega)\rangle_{\mathbf{k}n}\rangle_{\mathbf{k}'n'}. \tag{60}$$

Here g_S is the number of electron states per spin and atom at the Fermi level, M is the ion mass, $\omega_{\mathbf{q}\nu}$ is the frequency of phonons with momentum $\mathbf{q}=\mathbf{k}-\mathbf{k}'$ and branch index ν, and the spin-flip matrix element is

$$g^{\nu}_{\mathbf{k}n\uparrow,\mathbf{k}'n'\downarrow}\equiv|\mathbf{u}_{\mathbf{q}\nu}\cdot(\Psi_{\mathbf{k}n\uparrow},\nabla V\Psi_{\mathbf{k}'n'\downarrow})|^2, \tag{61}$$

where $\mathbf{u}_{\mathbf{q}\nu}$ is the polarization of the phonon with momentum $\mathbf{q}$ and in branch ν. The brackets $\langle\cdots\rangle_{\mathbf{k}n}$ in Eq. (60) denote Fermi-surface averaging. The Bloch wave functions for this calculation are chosen to satisfy $(\Psi_{\mathbf{k}n\uparrow},\hat{\sigma}_z\Psi_{\mathbf{k}n\uparrow})=-(\Psi_{\mathbf{k}n\downarrow},\hat{\sigma}_z\Psi_{\mathbf{k}n\downarrow})$. The periodic lattice-ion interaction V contains both scalar and spin-orbit parts: $V=V_{sc}+V_{so}$.

There are two important relations giving an order-of-magnitude estimate of τ_s, as well as its temperature dependence: the Elliott and the Yafet relations. The *Elliott relation* relates τ_s to the shift Δg of the electronic g factor from the free-electron value of $g_0=2.0023$ (Elliott, 1954):

$$1/\tau_s\approx(\Delta g)^2/\tau_p, \tag{62}$$

where τ_p is the momentum relaxation time. This relation follows from the fact that for a momentum scattering interaction V_i the spin-flip scattering probability in the Born approximation is proportional to $|(\Psi_{\mathbf{k}n\uparrow},V_i\Psi_{\mathbf{k}'n'\downarrow})|^2\approx|b|^2\times|(\Psi_{\mathbf{k}n\uparrow},V_i\Psi_{\mathbf{k}'n'\uparrow})|^2$. Realizing that the spin-conserving scattering probability gives the momentum relaxation rate, after a Fermi-surface averaging we get the estimate

$$1/\tau_s\approx\langle b^2\rangle/\tau_p. \tag{63}$$

On the other hand, Δg is determined by the expectation value of $\hat{l}_z$, the z component of the orbital momentum in a Bloch state. Without the spin-orbit interaction this expectation value is zero. Considering the spin-orbit interaction to be a small parameter, we find by perturbation theory $\Delta g\approx|b|$, which combines with Eq. (63) to give the Elliott relation (62). An empirical test of the Elliott relation for simple metals in which spin relaxation is due to thermal phonons (Beuneu and Monod, 1978) gives the revised estimate

$$1/\tau_s\approx 10\times(\Delta g)^2/\tau_p. \tag{64}$$

The Elliott relation is only a very rough estimate of τ_s. The experimentally relevant ratio τ_p/τ_s depends on the scattering mechanism. The ratio is different for scat-

tering off impurities, boundaries, or phonons, although one would expect it to be within an order of magnitude. For example, scattering by heavy impurities induces an additional spin relaxation channel where spin flip is due to the spin-orbit interaction induced by the impurities. Equation (63) then does not hold. Scattering by phonons is too complex to be simply equated with the ratio τ_p/τ_s for impurity or boundary scattering. However, the ratio is comparable for scattering by light impurities and by boundaries. The ratio τ_p/τ_s for impurity and phonon scattering in Al and Cu is compared by Jedema *et al.* (2003).

The *Yafet relation* is only qualitative, connecting the temperature dependence of $1/T_1$ with that of the resistivity ρ:

$$1/T_1(T) \sim \langle b^2 \rangle \rho(T), \tag{65}$$

as follows directly from Eq. (63) after realizing that $1/\tau_p(T) \sim \rho(T)$. By careful symmetry considerations Yafet (1963) proved that $1/T_1 \sim T^5$ at low temperatures, similarly to the Bloch-Grüneisen law for resistivity, justifying Eq. (65) over a large temperature range. Yafet's T^5 law stems from the nontrivial fact that for spin-flip electron-phonon scattering $g^{\nu}_{\mathbf{k}n\uparrow,\mathbf{k}'n\downarrow} \sim (\mathbf{k}-\mathbf{k}')^4$ as $\mathbf{k} \rightarrow \mathbf{k}'$ (Yafet, 1963), while only a quadratic dependence holds for spin-conserving scattering. This corresponds to the long-wavelength behavior $\alpha_S^2 F(\Omega) \sim \Omega^4$ of the spin-flip Eliashberg function. The Yafet relation was tested experimentally by Monod and Beuneu (1979). This work led to a deeper understanding of the spin relaxation processes in polyvalent metals (Silsbee and Beuneu, 1983; Fabian and Das Sarma, 1998).

Realistic calculations of the Elliott-Yafet τ_s in semiconductors can be performed analytically using approximations of the band and phonon structures, as most important states are usually around high-symmetry points. Here we give a formula for the spin relaxation of conduction electrons with energy $E_{\mathbf{k}}$ in the frequently studied case of III-V semiconductors (Chazalviel, 1975; Pikus and Titkov, 1984):

$$\frac{1}{\tau_s(E_{\mathbf{k}})} = A\left(\frac{\Delta_{so}}{E_g+\Delta_{so}}\right)^2 \left(\frac{E_{\mathbf{k}}}{E_g}\right)^2 \frac{1}{\tau_p(E_{\mathbf{k}})}, \tag{66}$$

where $\tau_p(E_{\mathbf{k}})$ is the momentum scattering time at energy $E_{\mathbf{k}}$, E_g is the energy gap, and Δ_{so} is the spin-orbit splitting of the valence band (see Fig. 6). The numerical factor A, which is of order 1, depends on the dominant scattering mechanism (charge or neutral impurity, phonon, electron-hole). Analytic formulas for the Elliott-Yafet mechanism due to electron-electron scattering are given by Boguslawski (1980).

Equation (66) shows that the Elliott-Yafet mechanism is important for small-gap semiconductors with large spin-orbit splitting (the prototypical example is InSb). For degenerate electron densities the spin relaxation time is given by Eq. (66) with $E_{\mathbf{k}} = E_F$, while for nondegenerate densities the thermal averaging leads to a substitution of thermal energy $k_B T$ for $E_{\mathbf{k}}$ and thermal-averaged momentum relaxation time for τ_p. To estimate τ_s from Eq. (66) one needs to know τ_p. It often suffices to know the doping or temperature dependence of τ_p to decide on the relevance of the Elliott-Yafet mechanism (Pikus and Titkov, 1984).

The temperature dependence of $1/\tau_s$ for metals and degenerate semiconductors follows the dependence of $1/\tau_p$. In metals this means a constant at low T and a linear increase at large T. For nondegenerate semiconductors, $1/\tau_s(T) \sim T^2/\tau_p(T)$. In the important case of scattering by charged impurities ($\tau_p \sim T^{3/2}$) $1/\tau_s \sim T^{1/2}$. The magnetic-field dependence of the Elliott-Yafet spin relaxation has not been systematically investigated. At low temperatures, where cyclotron effects become important, one needs to average over cyclotron trajectories on the Fermi surface to obtain $1/\tau_s$. We expect that such averaging leads, in general, to an increase in $1/T_1$, especially in systems where spin hot spots are important (see Sec. III.C).

2. D'yakonov-Perel' mechanism

An efficient mechanism of spin relaxation due to spin-orbit coupling in systems lacking inversion symmetry was found by D'yakonov and Perel' (1971e). Without inversion symmetry the momentum states of the spin-up and spin-down electrons are not degenerate: $E_{\mathbf{k}\uparrow} \neq E_{\mathbf{k}\downarrow}$. Kramer's theorem still dictates that $E_{\mathbf{k}\uparrow} = E_{-\mathbf{k}\downarrow}$. Most prominent examples of materials without inversion symmetry come from groups III-V (such as GaAs) and II-VI (ZnSe) semiconductors, where inversion symmetry is broken by the presence of two distinct atoms in the Bravais lattice. Elemental semiconductors like Si possess inversion symmetry in the bulk, so the D'yakonov-Perel' mechanism does not apply to them. In heterostructures the symmetry is broken by the presence of asymmetric confining potentials.

Spin splittings induced by inversion asymmetry can be described by introducing an intrinsic $\mathbf{k}$-dependent magnetic field $\mathbf{B}_i(\mathbf{k})$ around which electron spins precess with Larmor frequency $\mathbf{\Omega}(\mathbf{k}) = (e/m)\mathbf{B}_i(\mathbf{k})$. The intrinsic field derives from the spin-orbit coupling in the band structure. The corresponding Hamiltonian term describing the precession of electrons in the conduction band is

$$H(\mathbf{k}) = \frac{1}{2}\hbar\sigma \cdot \mathbf{\Omega}(\mathbf{k}), \tag{67}$$

where σ are the Pauli matrices. Momentum-dependent spin precession described by H, together with momentum scattering characterized by momentum relaxation time τ_p,[74] leads to spin dephasing. While the microscopic expression for $\mathbf{\Omega}(\mathbf{k})$ needs to be obtained from the band structure, treating the effects of inversion asymmetry by introducing intrinsic precession helps to give a qualitative understanding of spin dephasing. It is

[74] In the qualitative reasonings below we use τ_p instead of the effective correlation time $\tilde{\tau}$ for Ω during momentum scattering, $\tilde{\tau}$ is defined later, in Eq. (69).

important to note, however, that the analogy with real Larmor precession is not complete. An applied magnetic field induces a macroscopic spin polarization and magnetization, while H of Eq. (67) produces an equal number of spin-up and spin-down states.

Two limiting cases can be considered: (i) $\tau_p\Omega_{av}\gtrsim 1$ and (ii) $\tau_p\Omega_{av}\lesssim 1$, where Ω_{av} is an average magnitude of the intrinsic Larmor frequency $\Omega(\mathbf{k})$ over the actual momentum distribution. Case (i) corresponds to the situation in which individual electron spins precess a full cycle before being scattered to another momentum state. The total spin in this regime initially dephases reversibly due to the anisotropy in $\mathbf{\Omega}(\mathbf{k})$. The spin dephasing rate,[75] which depends on the distribution of values of $\mathbf{\Omega}(\mathbf{k})$, is in general proportional to the width $\Delta\Omega$ of the distribution: $1/\tau_s\approx\Delta\Omega$. The spin is irreversibly lost after time τ_p, when randomizing scattering takes place.

Case (ii) is what is usually meant by the D'yakonov-Perel' mechanism. This regime can be viewed from the point of view of individual electrons as a spin precession about fluctuating magnetic fields, whose magnitude and direction change randomly with the average time step of τ_p. The electron spin rotates about the intrinsic field at an angle $\delta\phi=\Omega_{av}\tau_p$, before experiencing another field and starting to rotate with a different speed and in a different direction. As a result, the spin phase follows a random walk: after time t, which amounts to t/τ_p steps of the random walk, the phase progresses by $\phi(t)\approx\delta\phi\sqrt{t/\tau_p}$. Defining τ_s as the time at which $\phi(t)=1$, the usual motional narrowing result is obtained: $1/\tau_s=\Omega_{av}^2\tau_p$ (see footnote 70). The faster the momentum relaxation, the slower the spin dephasing. The difference between cases (i) and (ii) is that in case (i) the electron spins form an ensemble that directly samples the distribution of $\Omega(\mathbf{k})$, while in case (ii) it is the distribution of the *sums* of the intrinsic Larmor frequencies (the total phase of a spin after many steps consists of a sum of randomly selected frequencies multiplied by τ_p), which, according to the central-limit theorem, has a significantly reduced variance. Both limits (i) and (ii) and the transition between them have been experimentally demonstrated in n-GaAs/AlGaAs quantum wells by observing temporal spin oscillations over a large range of temperatures (and thus τ_p) (Brand *et al.*, 2002).

A more rigorous expression for τ_s in regime (ii) has been obtained by solving the kinetic rate equation for a spin-dependent density matrix (D'yakonov and Perel', 1971d, 1971e). If the band structure is isotropic and scattering is both elastic and isotropic, evolution of the z component of spin $\mathbf{s}$ is (Pikus and Titkov, 1984)

$$\dot{s}_z=-\tilde{\tau}_l[s_z\overline{(\Omega^2-\Omega_z^2)}-s_x\overline{\Omega_x\Omega_z}-s_y\overline{\Omega_y\Omega_z}], \tag{68}$$

where the bar denotes averaging over directions of $\mathbf{k}$. Analogous expressions for $\dot{s}_x$ and $\dot{s}_y$ can be written by index permutation. The effective momentum scattering time is introduced as

$$1/\tilde{\tau}_l=\int_{-1}^{1}W(\theta)[1-P_l(\cos\theta)]d\cos\theta, \tag{69}$$

where $W(\theta)$ is the rate of momentum scattering through angle θ at energy $E_{\mathbf{k}}$, and P_l is the Legendre polynomial whose order l is the power of $\mathbf{k}$ in $\Omega(\mathbf{k})$. [It is assumed that $\Omega(\mathbf{k})\sim k^l$ in Eq. (68).] In two dimensions $P_l(\cos\theta)$ is replaced by $\cos(l\theta)$ in Eq. (69) for the lth polar harmonic of $\mathbf{\Omega}(\mathbf{k})$ (Pikus and Pikus, 1995). Since it is useful to express the results in terms of the known momentum relaxation times[76] $\tau_p=\tilde{\tau}_1$, one defines[77] $\gamma_l=\tau_p/\tilde{\tau}_l$ to measure the effectiveness of momentum scattering in randomizing Larmor frequencies; $\tilde{\tau}_l$ accounts for the relative angle between $\mathbf{\Omega}$ before and after scattering. Generally $\gamma_l>1$ for $l>1$, that is, momentum scattering is more effective in randomizing spins than in randomizing momentum.

Comparing with the Bloch-Torrey equations (52)–(54), for $\mathbf{B}=\mathbf{0}$ and no spin diffusion, we see that spin decay is described by the tensor $1/\tau_{s,ij}$ (here i and j are the Cartesian coordinates) whose diagonal $1/\tau_{s,ii}$ and off-diagonal $1/\tau_{s,ij}$, for $i\neq j$, terms are

$$1/\tau_{s,ii}=\gamma_l^{-1}\tau_p(\overline{\Omega^2}-\overline{\Omega_i^2}),\quad 1/\tau_{s,ij}=-\gamma_l^{-1}\tau_p\overline{\Omega_i\Omega_j}. \tag{70}$$

In general, spin dephasing depends on the spin direction and on the dephasing rates of the perpendicular spin components. Equations (70) are valid for small magnetic fields, satisfying $\Omega_0\tau_p\ll 1$, where Ω_0 is the Larmor frequency of the external field.

The most important difference between the Elliott-Yafet and the D'yakonov-Perel' mechanisms is their opposite dependence on τ_p. While increased scattering intensity makes the Elliott-Yafet mechanism more effective, it decreases the effectiveness of the D'yakonov-Perel' processes. In a sense the two mechanisms are similar to collision broadening and motional narrowing in NMR (Slichter, 1989). Indeed, in the Elliott-Yafet process the precession frequency is conserved between collisions and the loss of phase occurs only in the short time *during* collision. The more collisions there are, the greater is the loss of phase memory, in analogy with collision broadening of spectral lines. On the other hand, in D'yakonov-Perel' spin dephasing, spin phases are randomized *between* collisions, since electrons precess with different frequencies depending on their momenta. Spin-independent collisions with impurities or phonons do not lead to phase randomization during the collision itself, but help to establish the random-walk-like evolution of the phase, leading to motional narrowing. While these two mechanisms coexist in

[75]The reversible decay need not be exponential.

[76]In fact, normal (not umklapp) electron-electron collisions should also be included in the effective spin randomization time $\tilde{\tau}$, though they do not contribute to the momentum relaxation time which appears in the measured mobility (Glazov and Ivchenko, 2002, 2003).

[77]Pikus and Titkov (1984) initially define γ_l as here, but later evaluate it, inconsistently, as the inverse $\gamma_l\to\gamma_l^{-1}$.

systems lacking inversion symmetry, their relative strength depends on many factors. Perhaps the most robust trend is that the D'yakonov-Perel' mechanism becomes more important with increasing band gap and increasing temperature.

In the rest of the section we apply Eq. (70) to the study of spin dephasing in bulk and two-dimensional III-V semiconductor heterostructures.

a. Bulk III-V semiconductors

In bulk III-V semiconductors the intrinsic Larmor-frequency vector of Eq. (67) due to the lack of inversion symmetry is (D'yakonov and Perel', 1971d)

$$\mathbf{\Omega}(\mathbf{k}) = \alpha\hbar^2(2m_c^3E_g)^{-1/2}\kappa, \tag{71}$$

where

$$\kappa = [k_x(k_y^2-k_z^2), k_y(k_z^2-k_x^2), k_z(k_x^2-k_y^2)]. \tag{72}$$

Here k_i are the lattice wave-vector components along the crystal principal axes. The material-specific parameters are the band gap E_g and the conduction electron mass m_c; α is a dimensionless parameter specifying the strength of the spin-orbit interaction. The spin splitting described by Eq. (71) is proportional to the cube of the lattice momentum, as was first found by Dresselhaus (1955). For GaAs $\alpha \approx 0.07$ (Marushchak *et al.*, 1984). Spin splitting of conduction electrons and heavy and light holes in GaAs quantum wells, due to bulk inversion asymmetry, was calculated by Rashba and Sherman (1988).

Substituting Eq. (71) for $\mathbf{\Omega}$ in Eq. (70), and using $\overline{\kappa_i\kappa_j} = (4/105)k^6\delta_{ij}$, we obtain the expected result that the off-diagonal elements of $1/\tau_{s,ij}$ vanish for cubic systems and the diagonal elements are all equal to (Pikus and Titkov, 1984)

$$1/\tau_s(E_\mathbf{k}) = \frac{32}{105}\gamma_3^{-1}\tau_p(E_\mathbf{k})\alpha^2\frac{E_\mathbf{k}^3}{\hbar^2E_g}. \tag{73}$$

The above expression describes D'yakonov-Perel' spin dephasing of degenerate ($E_\mathbf{k}=E_F$) or hot[78] electrons in bulk III-V semiconductors. For impurity scattering $\gamma_3 \approx 6$, for acoustic phonons $\gamma_3 \approx 1$, while for optical polar phonons $\gamma_3 \approx 41/6$. The temperature dependence of $1/\tau_s$ comes from the temperature dependence of τ_p. For the important case of charged impurity scattering ($\tau_p \sim T^{3/2}$), $1/\tau_s \sim T^{3/2}$.

Compared to the Elliott-Yafet expression, Eq. (66), the D'yakonov-Perel' spin dephasing increases much faster with increasing electron energy and is expected to be dominant at large donor doping levels and at high temperatures. The Elliott-Yafet mechanism can be dominant in small-band-gap and large-spin-orbit-splitting materials. The two mechanisms can also be easily distinguished by their opposite dependence on momentum relaxation. Contrary to the EY mechanism, greater impurity density will decrease the importance of the D'yakonov-Perel' processes. The most frequently used ways to distinguish between various methods of spin relaxation are comparing the electron density (through the variation of the Fermi energy) and the temperature dependences of $1/\tau_s$ with the theoretical estimates. Since the prefactors may vary with different scattering mechanisms, it is best to deduce $\tau_p(E_\mathbf{k})$ and $\tau_p(T)$ from mobility measurements and use Eqs. (66) and (73), or the equations given below for $1/\tau_s(T)$.

Another interesting distinction between the two mechanisms is revealed by the dependence of their spin diffusion lengths $L_s = \sqrt{D\tau_s}$ on momentum scattering. Since $D \sim \tau_p$, for Elliott-Yafet $L_s \sim \tau_p$, while for D'yakonov-Perel' L_s does not depend on the momentum scattering time and for a degenerate electron system should be a constant independent of T, of the order of v_F/Ω_{av}. We do not know of an experimental verification of this distinction.

If the electrons obey nondegenerate statistics, which is the usual case of p-doped materials, thermal averaging over the Boltzmann distribution gives (Pikus and Titkov, 1984).

$$1/\tau_s = Q\tau_m\alpha^2\frac{(k_BT)^3}{\hbar^2E_g}, \tag{74}$$

where $\tau_m = \langle\tau_p(E_\mathbf{k})E_\mathbf{k}\rangle/\langle E_\mathbf{k}\rangle$. The coefficient Q, which is of order 1, is

$$Q = \frac{16}{35}\gamma_3^{-1}\left(\nu+\frac{7}{2}\right)\left(\nu+\frac{5}{2}\right), \tag{75}$$

where the power law $\tau_p \sim E_\mathbf{k}^\nu$ is assumed for momentum relaxation time. For scattering by ionized impurities $Q \approx 1.5$, while scattering by polar optical or piezoelectric phonons gives $Q \approx 0.8$, and scattering by acoustic phonons (deformation potential) $Q \approx 2.7$ (Pikus and Titkov, 1984). The temperature behavior of D'yakonov-Perel' spin dephasing in nondegenerate samples is $1/\tau_s \sim T^3\tau_m(T)$. For scattering by charged impurities $1/\tau_s \sim T^{9/2}$.

Application of longitudinal (to the initial spin direction) magnetic field suppresses the D'yakonov-Perel' mechanism (Pikus and Titkov, 1984) for two reasons: (i) The B field suppresses precession along the transverse intrinsic fluctuating fields when $\Omega_L\tau_p > 1$, where Ω_L is the Larmor precession due to B. (ii) $\Omega_\mathbf{k}$ is orbitally averaged, which has a similar effect to averaging by random scattering, when $\Omega_c\tau_p > 1$, where Ω_c is the cyclotron frequency. Since for conduction electrons $m_c \ll m_e$, it follows that $\Omega_c \gg \Omega_L$, the orbital motion induced by B is the cause for suppression of spin relaxation in semiconductors.

[78]This is strictly true only if the spin relaxation of the hot electrons is faster than energy relaxation by optical-phonon emission, which is rarely the case. One has to consider either the spin relaxation at different energy levels during the cascade process of optical-phonon emission or, if the optical-phonon emission is particularly fast, spin relaxation only during the final stages of energy relaxation by acoustic-phonon emission (see Pikus and Titkov 1984).

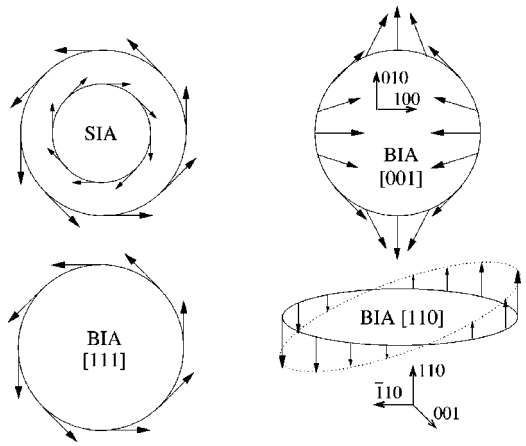

FIG. 15. Vector fields $\mathbf{\Omega}(\mathbf{k})\sim\kappa(\mathbf{k})$ on the Fermi surface (here a circle) for the structure inversion asymmetry (SIA) and bulk inversion asymmetry (BIA). Since $\mathbf{\Omega}(\mathbf{k})$ is also the spin quantization axis, the vector pattern is also the pattern of the spin on the Fermi surface. As the opposite spins have different energies, the Fermi circle becomes two concentric circles with opposite spins. This is shown here only for the SIA case, but the analogy extends to all examples. The field for BIA [110] lies perpendicular to the plane, with the magnitude varying along the Fermi surface. All other cases have constant fields lying in the plane.

b. Two-dimensional III-V semiconductor systems

In two-dimensional III-V semiconductor systems (quantum wells and heterostructures) there are two distinct Hamiltonian terms that contribute to D'yakonov-Perel' spin dephasing: the *bulk inversion asymmetry term* H_{BIA} and the *structure inversion asymmetry term* H_{SIA}, which appears only in asymmetric systems. Both H_{BIA} and H_{SIA} lead to spin splitting of the conduction band linear in $\mathbf{k}$. The two terms, however, predict a different dependence of τ_s on the quantum-well orientation relative to the principal axes. Figure 15 shows the vector field patterns of the intrinsic magnetic fields for both bulk and spin inversion asymmetry.

The bulk inversion asymmetry term comes from the bulk Dresselhaus spin splitting, Eq. (71). Treating wave vectors $\mathbf{k}$ in Eq. (71) as operators $\hat{\mathbf{k}}=-i\nabla$, and evaluating $\mathbf{\Omega}$ as the expectation value in the confined states, leads to momentum quantization along the confinement unit vector $\mathbf{n}$ of the quantum well. In the following, $\mathbf{k}$ denotes the wave vector for a Bloch state propagating in the plane, and $k_n^2\equiv\langle(\hat{\mathbf{k}}\cdot\mathbf{n})^2\rangle$ denotes the expectation value of the square of the component of the wave-number operator normal to the plane in the lowest subband state. For a rectangular quantum well of width a, $k_n^2=(\pi/a)^2$. For a triangular well of confining potential eEz, $k_n^2\approx 0.7794(2m_eE/\hbar^2)^{2/3}$ [see, for example, de Sousa and Das Sarma (2003c)]. Quantum averaging of κ can be done using the formula

$$\langle\hat{k}_i\hat{k}_j\hat{k}_l\rangle=k_n^2(k_in_jn_l+k_jn_ln_i+k_ln_in_j)+k_ik_jk_l. \quad (76)$$

This readily gives (D'yakonov and Kachorovskii, 1986)

$$\kappa_x=k_n^2[2n_x(n_yk_y-n_zk_z)+k_x(n_y^2-n_z^2)], \quad (77)$$

and similarly for κ_y and κ_z by index permutation. Terms cubic in k were omitted from the above equation, assuming that for narrow quantum wells $k^2\ll k_n^2$. The explicit knowledge of κ is useful in qualitative analysis of spin dephasing for particular orientations of quantum wells.

The spin dephasing tensor $1/\tau_{s,ij}$, defined in Eq. (70), is readily evaluated using Eqs. (71) and (77),[79]

$$1/\tau_{s,ij}=(\delta_{ij}\mathrm{Tr}\hat{\nu}-\nu_{ij})/\tau_s^0(E_{\mathbf{k}}), \quad (78)$$

where

$$\frac{1}{\tau_s^0(E_{\mathbf{k}})}=\frac{\alpha^2\hbar^2(k_n^2)^2}{2m_c^2E_g}E_{\mathbf{k}}\tau_p(E_{\mathbf{k}}). \quad (79)$$

The tensor $\hat{\nu}$ depends on the orientation of $\mathbf{n}$ with respect to the principal crystal axes (D'yakonov and Kachorovskii, 1986),[80]

$$\nu_{xx}=4n_x^2(n_y^2+n_z^2)-(n_y^2-n_z^2)^2(9n_x^2-1), \quad (80)$$

$$\nu_{xy}=n_xn_y[9(n_x^2-n_z^2)(n_y^2-n_z^2)-2(1-n_z^2)], \quad (81)$$

and analogously for other components.

We follow D'yakonov and Kachorovskii (1986) in discussing the three important cases of [001], [111], and [110] quantum wells. For [001],

$$\mathbf{\Omega}(\mathbf{k})\sim\kappa=k_n^2(-k_x,k_y,0). \quad (82)$$

While the magnitude of $\mathbf{\Omega}(\mathbf{k})$ is constant over the Fermi surface, the directions follow a "breathing" pattern as shown in Fig. 15. The spin relaxation times follow from Eq. (79): $1/\tau_{s,xx}=1/\tau_{s,yy}=1/2\tau_{zz}=1/\tau_s^0$. Defining $1/\tau_{s\parallel}$ and $1/\tau_{s,\perp}$ as spin dephasing rates of spins parallel and perpendicular to the plane, one obtains

$$1/\tau_{s,\parallel}=1/2\tau_{s,\perp}=1/\tau_s^0. \quad (83)$$

As expected for the case of the in-plane field, the lifetime of a spin parallel to the plane is twice that of the spin perpendicular to the plane.

For [111] quantum wells,

$$\mathbf{\Omega}(\mathbf{k})\sim\kappa=2/\sqrt{3}k_n^2(\mathbf{k}\times\mathbf{n}). \quad (84)$$

The intrinsic magnetic field lies in the plane, having a constant magnitude (refer to Fig. 15). Spin relaxation rates are now $1/\tau_{s,ii}=16/9\tau_s^0$ and $1/\tau_{s,i\neq j}=4/9\tau_s^0$. By diagonalizing $1/\tau_{ij}$ we obtain

$$1/\tau_{s\parallel}=1/2\tau_{s,\perp}=4/3\tau_s^0. \quad (85)$$

As for the [001] case, a perpendicular spin dephases twice as fast as a parallel one, since $\mathbf{\Omega}(\mathbf{k})$ lies in the plane.

The most interesting case is the [110] orientation for which $1/\tau_{s,xx}=1/\tau_{s,yy}=1/2\tau_{s,zz}=-1/\tau_{s,xy}=1/8\tau_s^0$. Other off-diagonal components vanish. Diagonalizing the tensor gives

[79] Averaging over the directions of $\mathbf{k}$ in a plane perpendicular to $\mathbf{n}$ can be performed by using $\overline{k_ik_j}=(k^2/2)(\delta_{ij}-n_in_j)$.

[80] A trivial typo in ν_{xx} is corrected.

$$1/\tau_{s,\parallel}=1/4\tau_s^0, \quad 1/\tau_{s,\perp}=0. \tag{86}$$

The perpendicular spin does not dephase. This is due to the fact that κ, unlike the previous cases, is always normal to the plane (see Fig. 15) and thus cannot affect the precession of the perpendicular spin. Indeed,

$$\mathbf{\Omega}(\mathbf{k})\sim\kappa=k_n^2(k_x/2)(-1,-1,0), \tag{87}$$

where it is used that $\mathbf{k}\cdot\mathbf{n}=0$. Spin dephasing in [110] quantum wells can still be due to the cubic terms in k left out of Eq. (77) or to other spin relaxation mechanisms. Note that the magnitude of $\mathbf{\Omega}(\mathbf{k})$ changes along the Fermi surface. Electrons moving along [001] experience little spin dephasing.

The structure inversion asymmetry term arises from the Bychkov-Rashba spin splitting (Rashba, 1960; Bychkov and Rashba, 1984a, 1984b) occurring in asymmetric quantum wells or in deformed bulk systems. The corresponding Hamiltonian is that of Eq. (67), with the precession vector

$$\mathbf{\Omega}(\mathbf{k})=2\alpha_{BR}(\mathbf{k}\times\mathbf{n}). \tag{88}$$

Here α_{BR} is a parameter depending on spin-orbit coupling and the asymmetry of the confining electrostatic potentials arising from the growth process of the heterostructure. The splitting can also arise in nominally symmetric heterostructures with fluctuations in doping density (Sherman, 2003a). The Bychkov-Rashba field always lies in the plane, having a constant magnitude. As for the bulk inversion asymmetry case, the structure inversion asymmetry leads to a splitting of the Fermi surface, according to the direction of the spin pattern—parallel or antiparallel to $\mathbf{\Omega}(\mathbf{k})$, as shown in Fig. 15. Perhaps the most appealing fact about structure inversion asymmetry is that α_{BR} can be tuned electrostatically, potentially providing an effective spin precession control without the need for magnetic fields (Levitov and Rashba, 2003; Rashba and Efros, 2003). This led to one of the pioneering spintronic proposals by Datta and Das (1990; see Sec. IV.E.1). Note that for the [111] orientation the bulk and structure inversion asymmetry terms have the same form.

Using the same procedure as for bulk inversion asymmetry, we describe the spin relaxation rate by Eq. (78) as

$$1/\tau_s^0=4\alpha_{BR}^2\frac{m_c}{\hbar^2}E_{\mathbf{k}}\tau_p \tag{89}$$

and

$$\nu_{ij}=1-n_in_j. \tag{90}$$

Since the intrinsic precession vector $\sim\mathbf{\Omega}(\mathbf{k})$ for the structure inversion asymmetry always lies in the plane, a perpendicular spin should dephase twice as fast as a spin in the plane. Indeed, by diagonalizing $1/\tau_{s,ij}$ one finds that

$$1/\tau_{s,\parallel}=1/2\tau_{s,\perp}=1/\tau_s^0 \tag{91}$$

holds for all quantum-well orientations $\mathbf{n}$. This interesting fact qualitatively distinguishes structure from bulk inversion asymmetry and can be used in assessing the relative importance of the Dresselhaus and Rashba spin splittings in III-V heterostructure systems. If bulk and structure inversion asymmetry are of similar importance, the interference terms from the cross product $\overline{\Omega_{\mathrm{BIA}}\Omega_{\mathrm{SIA}}}$ can lead to spin dephasing anisotropies within the plane, as was shown for [001] quantum wells by Averkiev and Golub (1999) and Kainz *et al.* (2003). This plane anisotropy can be easily seen by adding the corresponding vector fields in Fig. 15. Another interesting feature of bulk and structure inversion asymmetry fields is that injection of electrons along a quasi-one-dimensional channel can lead to large relaxation times for spins oriented along $\mathbf{\Omega}(\mathbf{k})$, where $\mathbf{k}$ is the wave vector for the states in the channel (Hammar and Johnson, 2002).

Model spin dephasing calculations based on structure inversion asymmetry were carried out by Pareek and Bruno (2002). Calculations of τ_s based on the D'yakonov-Perel' mechanism, with structural asymmetry due to doping fluctuations in the heterostructure interface, were performed by Sherman (2003a).

Research on spin inversion asymmetry is largely motivated by Datta-Das spin field-effect transistor proposal (see Secs. I.A and IV.E.1) in which α_{BR} is tailored by a gate. This tailoring, however, has been controversial and the microscopic origin of the Bychkov-Rashba Hamiltonian, and thus of the interpretation of experimental results on splitting in semiconductor heterostructures, has been debated. The Bychkov-Rashba Hamiltonian is often interpreted as arising from the electric field of the confining potential, assisted by external bias, which acts on a moving electron in a transverse direction. The relativistic transformation then gives rise to a magnetic field (spin-orbit coupling) acting on the electron spin. The parameter α_{BR} is then assumed to be directly proportional to the confining electric field. This is in general wrong, since the average electric force acting on a confined particle of uniform effective mass is zero.

The asymmetry that gives rise to structure inversion asymmetry is the asymmetry in the band structure (including spin-orbit coupling) parameters of a heterostructure, such as the effective mass, or the asymmetry in the penetration of the electron wave function into the barriers (de Andrada e Silva *et al.*, 1997). The difficulty in understanding the influence of the external gates is caused by the lack of the understanding of the influence of the gate field on the asymmetry of the well. For a clear qualitative explanation of the involved physics see Pfeffer and Zawadzki (1999) and Zawadzki and Pfeffer (2001). Band-structure $\mathbf{k}\cdot\mathbf{p}$ calculations of α_{BR} for quantum wells in GaAs/AlGaAs heterostructures can be found in Pfeffer and Zawadzki (1995), Pfeffer (1997), Wissinger *et al.* (1997), and Kainz *et al.* (2003); a calculation for InGaAs/InP quantum well is reported in Engels *et al.* (1997) and Schäpers *et al.* (1998), in InSb/InAlSb asymmetric quantum well it can be found in Pfeffer and Zawadzki (2003), and in *p*-InAs metal-oxide-semiconductor field-effect transistor channel in Lamari (2003). Adding to the controversy, Majewski and Vogl (2003) have recently calculated the structure inversion asymmetry by local density functional methods and

concluded that the induced spin splitting arises from microscopic electric fields in asymmetric atomic arrangements at the interfaces, so that a large Bychkov-Rashba term can be present in otherwise symmetric quantum wells with no common atom.

Interpretation of experimental data on structure inversion asymmetry is difficult, especially at determining the zero magnetic field spin splitting (usually seen in Shubnikov–de Haas oscillations), which is masked by Zeeman splitting at finite fields. In addition, the splittings are small, typically less than 1 meV. The Bychkov-Rashba parameter was measured in GaSb/InAs/GaSb quantum wells ($\alpha_{BR}\approx 0.9\times 10^{-11}$ eV m for a 75-Å-thick well) by Luo *et al.* (1990); in InAlAs/InGaAs/InAlAs quantum wells (20 nm), where also the gate voltage dependence is obtained: α_{BR} ranged from 10^{-11} eV m at the depleting gate voltage of -1 V, to 5×10^{-12} eV m at +1.5 V. Weak antilocalization studies of InAlAs/InGaAs/InAlAs quantum wells have recently been used to study electron density dependence of α_{BR} by Koga *et al.* (2002a). Gate dependence of α_{BR} was also measured in modulation-doped InP/InGaAs/InP quantum wells (Engels *et al.*, 1997; Schäpers *et al.*, 1998). The observed values are several 10^{-12} eV m. On the other hand, there are experimental reports that either fail to observe the expected spin splitting due to the Bychkov-Rashba field, or interpret the splitting differently [see, for example, Brosig *et al.* (1999) and Rowe *et al.* (2001)]. Furthermore, measurements of Heida *et al.* (1998) show a constant $\alpha_{BR}\approx 0.6\times 10^{-11}$ eV m, independent of gate voltage, in asymmetric AlSb/InAs/AlSb quantum wells, demonstrating that control of α_{BR} may be difficult. In order to unify the different views on what exactly the Bychkov-Rashba spin splitting means and how the spin splitting can be tuned with gate voltage, more experimental efforts need to be devoted to this interesting topic.

3. Bir-Aronov-Pikus mechanism

Spin relaxation of conduction electrons in p-doped semiconductors can also proceed through scattering, accompanied by spin exchange, by holes, as was first shown by Bir *et al.* (1975).

The exchange interaction between electrons and holes is governed by the Hamiltonian

$$H = A\,\mathbf{S}\cdot\mathbf{J}\,\delta(\mathbf{r}), \tag{92}$$

where A is proportional to the exchange integral between the conduction and valence states, $\mathbf{J}$ is the angular momentum operator for holes, $\mathbf{S}$ is the electron-spin operator, and $\mathbf{r}$ is the relative position of electrons and holes.

The spin-flip scattering probability depends on the state of the holes (degenerate or nondegenerate, bound on acceptors or free, fast or slow). We present below the most frequently used formulas when assessing the relevance of the Bir-Aronov-Pikus mechanism. The formulas are valid for the usual cases of heavy holes $m_v \gg m_c$. For electron-spin relaxation due to exchange with nondegenerate holes,

$$\frac{1}{\tau_s} = \frac{2}{\tau_0} N_a a_B^3 \frac{v_{\mathbf{k}}}{v_B}\left[\frac{p}{N_a}|\psi(0)|^4 + \frac{5}{3}\frac{N_a - p}{N_a}\right], \tag{93}$$

where a_B is the exciton Bohr radius $a_B = \hbar^2\epsilon/e^2 m_c$, p is the density of free holes, τ_0 is an exchange splitting parameter: $\hbar/\tau_0 = (3\pi/64)\Delta_{\rm ex}^2/E_B$ (with E_B denoting the Bohr exciton energy, $E_B = \hbar^2/2m_c a_B^2$ and $\Delta_{\rm ex}$ the exchange splitting of the excitonic ground state), and $v_B = \hbar/m_c a_B$; $|\psi(0)|^2$ is Sommerfeld's factor, which enhances the free hole contribution. For an unscreened Coulomb potential

$$|\psi(0)|^2 = \frac{2\pi}{\kappa}\left[1 - \exp\left(-\frac{2\pi}{\kappa}\right)\right]^{-1}, \tag{94}$$

where $\kappa = E_{\mathbf{k}}/E_B$. For a completely screened potential $|\psi(0)|^2 = 1$.

If holes are degenerate and the electrons' velocity $v_{\mathbf{k}}$ is greater than the Fermi velocity of the holes', then

$$\frac{1}{\tau_s} = \frac{3}{\tau_0} p a_B^3 \frac{v_{\mathbf{k}}}{v_B}\frac{k_B T}{E_{Fh}}, \tag{95}$$

where E_{Fh} is the hole Fermi energy. For degenerate holes $|\psi(0)|^2$ is of order 1. If electrons are thermalized, $v_{\mathbf{k}}$ needs to be replaced by the thermal velocity $v_e = (3k_B T/m_c)^{1/2}$.

The temperature dependence of τ_s is dominated by the temperature dependence of $|\psi(0)|^2$ as well as by p. The dependence on the acceptor density is essentially $1/\tau_s \sim N_a$ for nondegenerate/bound holes from Eq. (93) and $1/\tau_s \sim N_a^{1/3}$ for degenerate holes from Eq. (95). In between, $1/\tau_s$ is only weakly dependent on N_a. For GaAs $a_B \approx 114$ Å, $E_B \approx 4.9$ meV, $v_B \approx 1.7\times 10^7$ cm s^{-1}, $\tau_0 \approx 1\times 10^{-8}$ s, and $\Delta_{\rm ex} \approx 4.7\times 10^{-5}$ eV (Aronov *et al.*, 1983).

The Bir-Aronov-Pikus mechanism coexists with the Elliott-Yafet and D'yakonov-Perel' mechanisms in p-doped materials lacking inversion symmetry. The three mechanisms can be distinguished by their unique density and temperature dependences. A general trend is that the Bir-Aronov-Pikus dominates in heavily doped samples at small temperatures. At large temperatures, even for large acceptor densities, the D'yakonov-Perel' mechanism can become more important, due to its increased importance at large electron energies. Specific examples of the domain of importance for the three mechanisms are discussed in Sec. III.D.1. Model calculations of Bir-Aronov-Pikus processes for electrons in p-doped bulk and quantum wells were performed by Maialle (1996; Maialle and Degani, 1997).

Another potentially relevant mechanism for spin relaxation of donor-bound electrons in p-doped semiconductors is the exchange interaction with holes bound to acceptors (D'yakonov and Perel', 1973b). The exchange interaction provides an effective magnetic field for electron spins to precess, leading to inhomogeneous dephasing. Both electron hopping and hole spin flip motionally narrow the precession.

4. Hyperfine-interaction mechanism

The hyperfine interaction, which is the magnetic interaction between the magnetic moments of electrons and nuclei, provides an important mechanism (D'yakonov and Perel', 1973b) for ensemble spin dephasing and single-spin decoherence of localized electrons, such as those confined in quantum dots or bound on donors. The interaction is too weak to cause effective spin relaxation of free electrons in metals or in bulk semiconductors (Overhauser, 1953a), as it is strongly dynamically narrowed by the itinerant nature of electrons (see Sec. III.A.1). In addition to spin dephasing, the hyperfine interaction is relevant for spintronics as a means to couple, in a controlled way, electron and nuclear spins (D'yakonov and Perel', 1984).

Localized electrons are typically spread over many lattice sites (10^4–10^6), experiencing the combined magnetic moments of many nuclei. In GaAs all the lattice nuclei carry the magnetic moment of 3/2 spin, while in Si the most abundant isotope, ^{28}Si, carries no spin and the hyperfine interaction is due to ^{29}Si (natural abundance 4.67%) or the frequent donor ^{31}P, both of nuclear spin 1/2. As a result, an electron bound on a shallow donor in Si experiences only around 100 magnetic nuclei, and the effects of the hyperfine interaction are considerably smaller than in GaAs.

The effective Hamiltonian for the hyperfine interaction is the Fermi contact potential energy (Slichter, 1989),

$$H=\frac{8\pi}{3}\frac{\mu_0}{4\pi}g_0\mu_B\sum_i \hbar\gamma_{n,i}\mathbf{S}\cdot\mathbf{I}_i\delta(\mathbf{r}-\mathbf{R}_i), \tag{96}$$

where μ_0 is the vacuum permeability, $g_0=2.0023$ is the free-electron g factor, μ_B is the Bohr magneton, i is the label for nuclei at positions $\mathbf{R}_i$, $\mathbf{S}$ and $\mathbf{I}_i$ are, respectively, electron and nuclear spin operators expressed in the units of $\hbar$, and $\gamma_{n,i}$ is the nuclear gyromagnetic ratio. We stress that it is the free electron g factor g_0 and not the effective g that appears in the hyperfine interaction, Eq. (96), as shown by Yafet (1961) [see also Paget *et al.* (1977)]. It follows that the spin of an electron in an orbital state $\psi(\mathbf{r})$ experiences magnetic field

$$\mathbf{B}_n=\frac{2\mu_0}{3}\frac{g_0}{g}\sum_i \hbar\gamma_{n,i}\mathbf{I}_i|\psi(\mathbf{R}_i)|^2, \tag{97}$$

where g is the effective g factor of the electron. The electron Zeeman splitting due to the average B_n corresponds to a field of ~1 T or thermal energy of 1 K, for a complete nuclear polarization (Paget *et al.*, 1977).

There are three important regimes in which the hyperfine interaction leads to spin dephasing of localized electrons:

(i) In the limit of small orbital and spin correlation between separated electron states and nuclear spin states, spatial variations in $\mathbf{B}_n$ lead to inhomogeneous dephasing of the spin ensemble, with the rate proportional to the rms of B_n, given by the corresponding thermal or nonequilibrium distribution of the nuclear spins. Such inhomogeneous dephasing is seen by electron-spin-resonance (ESR) experiments on donor states both in Si (Feher and Gere, 1959) and in GaAs (Seck *et al.*, 1997). This effect can be removed by spin-echo experiments (in Si donor states performed, for example, by Gordon and Browers, 1958). The spread in the Larmor precession period due to the variance in B_n in GaAs is estimated to be around 1 ns (Dzhioev, Korenev, Merkulov, *et al.*, 2002; Merkulov *et al.*, 2002).

(ii) Temporal fluctuations in B_n, which can occur due to nuclear dipole-dipole interactions, lead to irreversible spin dephasing and decoherence of electron spins. Such processes are sometimes referred to as *spectral diffusion*, since the electron Zeeman levels split by B_n undergo random shifts (de Sousa and Das Sarma, 2003b). The typical time scale for the fluctuations in GaAs is given by the nuclear Larmor precession period in the field of neighboring nuclei and is of order 100 μs (Merkulov *et al.*, 2002). Nuclear moments also precess (and orient) in the magnetic fields of polarized electrons, an effect important in optical orientation (Meier and Zakharchenya, 1984), where the feedback from this precession can be directly observed through the modulated precession of electron spins. The time scale for the Larmor precession of nuclear spins in hyperfine fields is 1 μs in GaAs (Merkulov *et al.*, 2002), so this effect does not lead to motional narrowing of B_n; electron spins precess many times before the nuclear spin flips.

(iii) In the presence of strong orbital correlations (electron hopping or recombination with acceptor hole states) or spin correlations (direct exchange interaction) between neighboring electron states, spin precession due to B_n is motionally narrowed. While the direct spin exchange interaction does not cause ensemble spin relaxation (the total spin is preserved in spin flip-flops), it leads to individual spin decoherence, which can be much faster than what is inferred from T_2. This effect is much more pronounced in GaAs than in Si, since the donor states spread to greater distances, and thus even in the low-doping limits ($\approx 10^{14}$ cm^{-3} donors) the exchange interaction can be rather large, masking the effects of temporal fluctuations of B_n (see Sec. III.D.3). Many useful parameters for evaluating effective magnetic fields and precession frequencies due the hyperfine-interaction mechanism in GaAs are given by Paget *et al.* (1977).

Ensemble spin dephasing due to the hyperfine-interaction mechanism in an external magnetic field has been studied by D'yakonov and Perel' (1973b), who found suppression of $1/\tau_s$ if the external field is greater than B_n for regime (i), or a smaller Larmor precession period than the correlation time for random changes in B_n, in regime (iii), due to the external field.

Calculations of τ_s using the hyperfine-interaction mechanism were performed for shallow donor states in Si at low temperatures and magnetic fields (Saikin *et al.*, 2002), for electron spins in quantum dots (Merkulov *et al.*, 2002; Semenov and Kim, 2002), and even for the case of conduction electrons in semiconductors (revisited by Pershin and Privman, 2003c). Spin relaxation

processes due to phonon-assisted hyperfine interactions were investigated in GaAs quantum dots, but were found to be ineffective (Erlingsson *et al.*, 2001). Unfortunately, there are still too few experimental data to make conclusions about the merits of specific models of the hyperfine-interaction mechanism.

Spin decoherence times for single-electron spins were recently computed for case (ii) by Khaetskii *et al.* (2002, 2003), who studied spin coherence time τ_{sc} of a single electron spin in the regime in which the electron Larmor period due to B_n is much shorter than the correlation time of the nuclear magnetic field fluctuations. Realistic estimates of hyperfine-interaction spin dephasing in GaAs quantum dots were given by de Sousa and Das Sarma (2003a, 2003b), who offer reasons why mechanism (ii) should dominate spin decoherence in GaAs quantum dots of radius smaller than 100 nm. For instance, in a 50-nm-wide quantum dot, the estimated τ_{sc} is ≈ 50 μs, large enough for quantum computing applications (see Sec. IV.F). This claim is supported by the recent measurement of the spin dephasing time of about 60 ms of an isolated spin in a phosphorus donor in isotopically pure ^{28}Si, by spin echo measurements (Tyryshkin *et al.*, 2003).

C. Spin relaxation in metals

The spin relaxation time of conduction electrons in metals has been measured by both CESR and spin injection techniques. Typical values of τ_s were found to be 0.1 to 1 ns, but the range of observed values is large, from picoseconds to microseconds. To our knowledge the longest τ_s reported for a metal—a microsecond—was found in high-purity sodium below 10 K (Kolbe, 1971).

The majority of simple metals are believed to follow the Elliott-Yafet mechanism of spin relaxation, with the possible exception of Li (Damay and Sienko, 1976). This is supported by several facts:

(i) The Elliott-Yafet processes give the right order of magnitude for τ_s (Elliott, 1954; Yafet, 1963), while other known possible spin relaxation mechanisms lead to much greater τ_s than what is observed (Overhauser, 1953a).

(ii) The temperature dependence of τ_s is consistent with the Elliott-Yafet mechanism: $1/\tau_s$ is constant at low temperatures, indicating impurity spin-flip scattering, while at high temperatures $1/\tau_s$ grows linearly with increasing T, consistent with phonon-induced spin relaxation.

(iii) The Elliott relation, Eq. (62), has been tested for many important metals and found to be valid over many orders of magnitude of Δg (Beuneu and Monod, 1978; this reference contains a useful collection of data for Δg). For the majority of metals tested (alkali and noble), a best fit gives the quantitative formula, Eq. (64) (Beuneu and Monod, 1978).

(iv) The Yafet relation, Eq. (65), is satisfied for most metals with the known temperature dependence of τ_s (Monod and Beuneu, 1979; Fabian and Das Sarma, 1999c). The initially suggested deviation from the Yafet relation for several polyvalent metals (Al, Pd, Be, and Mg) was later resolved by spin-hot-spot theory (Silsbee and Beuneu, 1983; Fabain and Das Sarma, 1998, 1999c), to be described below. This work showed that the magnitudes of the spin-mixing probabilities b^2, taken from atomic physics to test Eq. (65), should not be used in the solid-state environment. Various band-structure anomalies (spin hot spots), such as crossing of the Brillouin-zone boundaries, accidental degeneracy points, or symmetry points on the Fermi surface, can increase the atomic-physics-derived b^2 by several orders of magnitude, strongly enhancing spin relaxation in polyvalent metals as compared to simple estimates (Fabian and Das Sarma, 1998, 1999a).

(v) A realistic, first-principles calculation for Al (Fabian and Das Sarma, 1999b; see Sec. III.C) using Eq. (59) shows excellent agreement with experiment.

CESR measurements of τ_s in various metals are numerous.[81] Various data on CESR τ_s are collected by Beuneu and Monod (1978; Monod and Beuneu, 1979).

The spin injection technique (see Sec. II) was also used to measure τ_s for various metals, including Al (Johnson and Silsbee, 1985; Jedema, Costache, *et al.*, 2002; Jedema, Heersche, *et al.*, 2002a; Jedema, Nijboer, *et al.*, 2003), Au (Elezzabi *et al.*, 1996), Cu (Jedema, Filip, and van Wees, 2001; Jedema, Nijboer, *et al.*, 2003), and Nb (Johnson, 1994). In addition to CESR and spin injection, information about spin-orbit scattering times τ_{so} (see below) in various (but mostly noble) metals at low temperatures has been also obtained from weak localization magnetoresistance measurements on thin films (Bergmann, 1982) and tunneling spectroscopy of metallic nanoparticles (Petta and Ralph, 2001). Surface-scattering spin relaxation times in normal metals and superconductors are collected by Meservey and Tedrow (1978). Interesting results were obtained by injecting spin into superconductors. Using $YBa_2Cu_3O_{7-\delta}$, for example, data were interpreted (Fi *et al.*, 2002) to infer that the in-plane spin relaxation time is unusually long,

[81] A list of selected metals includes Li (Feher and Kip, 1955; Orchard-Webb *et al.*, 1970; Damay and Sienko, 1976); Na (Feher and Kip, 1955; Vescial *et al.*, 1964; Kolbe, 1971); K (Walsh *et al.*, 1966a); Rb (Schultz and Shanabarger, 1966; Walsh *et al.*, 1966b); Cs (Schultz and Shanabarger, 1966; Walsh *et al.*, 1966b); Be (Cousins and Dupree, 1965; Orchard-Webb *et al.*, 1970); Mg (Bowring *et al.*, 1971); Cu (Schultz and Latham, 1965; Lubzens and Schultz, 1976a; Monod and Schultz, 1982); Au (Monod and Jánossy, 1977); Zn (Stesmans and Witters, 1981); Al (Lubzens and Schultz, 1976b); graphite (Wagoner, 1960; Matsubara *et al.*, 1991); Rb_3C_{60} (Jánossy *et al.*, 1993); MgB_2 (Simon *et al.*, 2001).

about 100 μs at low temperatures to 1 μs close to the superconducting transition temperature. For quasiparticles moving along the c axis, τ_s is more likely to be the usual spin-orbit-induced spin relaxation time, having values of 10–100 ps. The microscopic origin of quasiparticle spin relaxation in cuprate superconductors is not yet known.

There is one more important time scale, the spin-orbit scattering time τ_{so}, that is often invoked in mesoscopic transport as a characteristic of spin relaxation processes. We discuss it briefly in connection to τ_s. The spin-orbit scattering time is the scattering time of Bloch electrons by the spin-orbit potential induced by impurities. The spin-orbit part of the Fourier transform of the impurity potential can be written as $ic(\mathbf{k}-\mathbf{k}')(\mathbf{k}\times\mathbf{k}')\cdot\boldsymbol{\sigma}$, where $c(\mathbf{q})$ is proportional to the Fourier transform of the impurity potential. The spin-orbit scattering time then is (Werthamer, 1969)

$$1/\tau_{so}=\frac{2\pi}{\hbar}N_i\langle|c(\mathbf{k}-\mathbf{k}')|^2|\mathbf{k}\times\mathbf{k}'|\rangle^2\mathcal{N}(E_F), \tag{98}$$

where N_i is the impurity concentration, $\mathcal{N}(E_F)$ is the density of states per spin at the Fermi level, and the angle brackets denote Fermi-surface averaging. As a parameter τ_{so} also includes the spin-orbit coupling of the host lattice, in the sense of the Elliott-Yafet mechanism. Note, however, that $\tau_s\neq\tau_{so}$, even at low temperatures where the impurity scattering dominates spin relaxation, since the spin-orbit scattering includes both spin-flip and spin-conserving processes, which, for isotropic scattering rates are in the ratio 2:1. In addition, the spin relaxation rate is twice the spin-flip scattering rate, since each spin flip equilibrates both spins equally. For isotropic systems, $1/\tau_s\approx 4/(3\tau_{so})$. For a discussion of the effects of the D'yakonov-Perel' processes on weak localization see Knap *et al.* (1996).

We illustrate spin relaxation in metals by the case of Al, whose τ_s has been measured by CESR and spin injection and numerically calculated from first principles. The case is instructive since it demonstrates both the general principles of the Elliott-Yafet mechanism and the predicting power of realistic band-structure calculations of τ_s.

Spin relaxation in Al was originally observed in CESR experiments, in which τ_s was measured at low temperatures, from 1 to 100 K (Lubzens and Schultz, 1976b). The spin relaxation rate $1/\tau_s$ was found to be independent of temperature below 10–20 K; at higher temperatures $1/\tau_s$ increases linearly with increasing T. The same behavior was later observed in the original spin injection experiment (Johnson and Silsbee, 1985, 1988d). Recently, τ_s was measured by spin injection at room temperature (Jedema, Costache, *et al.*, 2002; Jedema, Heersche, *et al.*, 2002a; Jedema, Nijboer, *et al.*, 2003). Unlike the CESR and the original spin injection experiments, which were performed on bulk samples, the room-temperature measurement used thin Al films, observing strong spin relaxation due to surface scattering.

Spin relaxation in Al, as well as in other polyvalent metals, at first appeared anomalous (Monod and Beuneu, 1979), in that a simple application of the Yafet relation, Eq. (65), yielded estimates for $1/\tau_s$ two orders of magnitude smaller than the observed data. Consider Na as a reference. The atomic $\lambda_{so}/\Delta E$ [cf. Eq. (58)] for Na and Al are within about 10% of each other (Beuneu and Monod, 1978; Monod and Beuneu, 1979), yet the corresponding τ_s for Al is about two orders of magnitude smaller than that for Na (Feher and Kip, 1955; Vescial *et al.*, 1964). This anomaly extends to the g factors as well. For Na, $\Delta g_{\mathrm{Na}}\approx -8\times10^{-4}$ and for Al it is six times greater, $\Delta g_{\mathrm{Al}}\approx -5\times10^{-3}$, while one would expect them to differ also by about 10%. Note, however, that the Elliott relation, Eq. (62), is unaffected by this discrepancy, as it predicts that $\tau_s(\mathrm{Na})/\tau_s(\mathrm{Al})\approx 40$. It was later suggested (Silsbee and Beuneu, 1983) that this is due to accidental degeneracies in the two-band Fermi surface of Al.

A full theoretical description, supported by first-principles calculations, of spin relaxation in Al and other polyvalent metals led to the spin-hot-spots theory (Fabian and Das Sarma, 1998, 1999a, 1999b, 1999c). Spin hot spots are states on the Fermi surface that have anomalously large spin mixing probabilities $|b|^2\approx(\lambda_{so}/\Delta E)^2$, arising from small energy gaps ΔE. Quite generally, such states occur near Brillouin-zone boundaries and accidental degeneracy points, or at high-symmetry points. The condition for a spin hot spot is both a small band gap ΔE and nonvanishing λ_{so}.[82]

If an electron hops in or out of a spin hot spot, the chance of spin flip dramatically increases. Although the total area of spin hot spots on the Fermi surface is small, their contribution to $1/\tau_s$ is dominant, due to the large value of their $|b|^2$ in the Fermi-surface average $\langle|b|^2\rangle$, as was shown by analytical arguments (Fabian and Das Sarma, 1998, 1999a). A realistic numerical calculation (Fabian and Das Sarma, 1999b) for Al, also showed that both the accidental degeneracies considered by Silsbee and Beuneu (1983) and states close to the Brillouin-zone boundaries dominate spin relaxation.

A realistic calculation of τ_s in Al, based on pseudopotentials and a realistic phonon description, has been performed by Fabian and Das Sarma (1999b) and compared to the experimental data available for $T<100$ K (Johnson and Silsbee, 1985, 1988d). Figure 16 shows both the experiment and the theory. In the experimental data only the phonon contribution to $1/\tau_s$ is retained (Johnson and Silsbee, 1985); the constant background impurity scattering is removed. The figure shows a rapid decrease of τ_s with increasing T at low T, where the agreement between experiment and theory is very good. Above 200 K (the Debye temperature $T_D\approx 400$ K) the calculation predicts a linear dependence $\tau_s[\mathrm{ns}]\approx 24\times T^{-1}[\mathrm{K}^{-1}]$. In the phonon-dominated linear regime the Elliott-Yafet mechanism predicts that the ratio a^{ph}

[82]At some symmetry points $|b|$ may be very small. This occurs in the noble metals which have Fermi states at the Brillouin-zone boundaries, where ΔE is large, but the corresponding λ_{so} is very small due to symmetry.

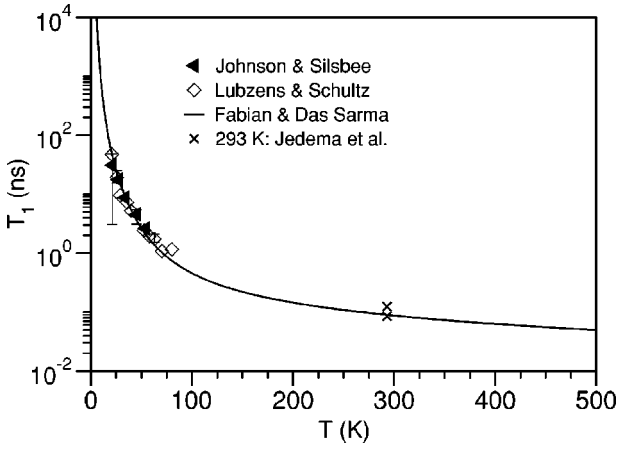

FIG. 16. Measured and calculated τ_s in Al. The low-T measurements are the conduction-electron spin resonance (Lubzens and Schultz, 1976b) and spin injection (Johnson and Silsbee, 1985). Only the phonon contribution is shown, as adapted from Johnson and Silsbee (1985). The solid line is the first-principles calculation, not a fit to the data (Fabian and Das Sarma, 1998). The data at $T=293$ K are results from room-temperature spin injection experiments of Jedema *et al.* (2002a, 2003). Adapted from Fabian and Das Sarma, 1999b.

$=\tau_p/\tau_s$ does not depend on T (see Sec. III.B.1). The calculated value is $a_{th}^{ph}=1.2\times10^{-4}$ (Fabian and Das Sarma, 1999b), showing that 10^4 phonon scatterings are needed to randomize electron spin.

An important step towards extending spin injection capabilities was undertaken recently by achieving spin injection into Cu and Al at room temperature (Jedema *et al.*, 2001; Jedema, Costache, *et al.*, 2002; Jedema, Heersche, *et al.*, 2002a; Jedema, Nijboer, *et al.*, 2003); the measured data are unique in providing reliable values for spin-diffusion lengths and spin-relaxation times in these two important metals at room temperature. The measured values for Al are somewhat sensitive to the experimental procedure and data analysis: $\tau_s=85$ ps (Jedema, Heersche, *et al.*, 2002a) and $\tau_s=124$ ps (Jedema, Nijboer, *et al.*, 2003), as compared to $\tau_s=90$ ps predicted by the theory at $T=293$ K. The room-temperature experimental data are included in Fig. 16 for comparison. They nicely confirm the theoretical prediction. Less sensitive to data analysis is the ratio a^{ph}, for which the experiments give 1.1×10^{-4} (Jedema, Heersche, *et al.*, 2002a) and 1.3×10^{-4} (Jedema, Nijboer, *et al.*, 2003), comparing favorably with the theoretical $a_{th}^{ph}=1.2\times10^{-4}$.

Spin relaxation in Al depends rather strongly on magnetic fields at low T. CESR measurements (Lubzens and Schultz, 1976a, 1976b) show that at temperatures below 100 K, $1/\tau_s$ increases linearly with increasing B. A specific sample (Lubzens and Schultz, 1976b) showed a decrease of τ_s from about 20 ns to 1 ns, upon increase in B from 0.05 to 1.4 T. It was proposed that the observed behavior was due to cyclotron motion through spin hot spots (Silsbee and Beuneu, 1983). The reasoning is as follows. Assume that there is considerable spread (anisotropy) $\delta g\approx\Delta g$ of the g factors over the Fermi surface. Such a situation is common in polyvalent metals, whose spin hot spots have anomalously large spin-orbit coupling. In a magnetic field the electron spins precess correspondingly, with rates varying by $\delta\Omega_L\approx(\delta g/g)\Omega_L$, where Ω_L is the Larmor frequency. Motional narrowing leads to $1/\tau_s\approx(\delta\Omega_L)^2\tau_c$, where τ_c is the correlation time for the random changes in g. At small magnetic fields $\tau_c=\tau_p$ and $1/\tau_s\sim B^2\tau_p$. Such a quadratic dependence of $1/\tau_s$ on B is a typical motional narrowing case and has been observed at low temperatures in Cu (Lubzens and Schultz, 1976b). As the field increases τ_c becomes the time of flight through spin hot spots, in which case $\tau_c\sim1/B$. As a result $1/\tau_s$ acquires a component linear in B, in accord with experiment.

In an effort to directly detect phonon-induced spin flips in Al, an interesting experiment was devised (Grimaldi and Fulde, 1996; Lang *et al.*, 1996) using the Zeeman splitting of the energy gap in Al superconducting tunnel junctions. Although the experiment failed, due to overwhelming spin-flip boundary scattering, it showed the direction for future research in studying spin-flip electron-phonon interactions.

D. Spin relaxation in semiconductors

Although sorting out different spin-relaxation mechanisms of conduction electrons in semiconductors is a difficult task, it has generally been observed that the Elliott-Yafet mechanism is relevant in small-gap and large-spin-orbit coupling semiconductors, while the D'yakonov-Perel' processes are responsible for spin dephasing in middle-gap materials and at high temperatures. In heavily p-doped samples the Bir-Aronov-Pikus mechanism dominates at lower temperatures, the D'yakonov-Perel' at higher. In low-doped systems the D'yakonov-Perel' dominates over the whole temperature range where electron states are extended. Spin relaxation of bound electrons proceeds through the hyperfine interaction. Finally, spin relaxation of holes is due to the Elliott-Yafet processes. In bulk III-V or II-VI materials, for holes $\tau_s\approx\tau_p$, since the valence spin and orbital states are completely mixed. However, in two-dimensional systems, where the heavy and light hole states are split, hole spin relaxation is much less effective.

1. Bulk semiconductors

There is a wealth of useful data on τ_s in semiconductors.[83]

[83]References for selected semiconductors include the following: p-GaAs (Fishman and Lampel, 1977; Seymour *et al.*, 1981; Aronov *et al.*, 1983; Marushchak *et al.*, 1984; Zerrouati *et al.*, 1988; Sanada *et al.*, 2002); n-GaAs (see III.D.3); p-$Al_xGa_{1-x}As$ (Garbuzov *et al.*, 1971; Clark *et al.*, 1975); p-GaSb (Safarov and Titkov, 1980; Sakharov *et al.*, 1981; Aronov *et al.*, 1983); n-GaSb (Kauschke *et al.*, 1987); n-InSb (Chazalviel, 1975); InAs (Boggess *et al.*, 2000); p-InP (Gorelenok *et al.*, 1986); n-InP (Kauschke *et al.*, 1987); n-GaN (Fanciulli *et al.*, 1993; Beschoten *et al.*, 2001).

A comprehensive theoretical investigation of spin dephasing in bulk semiconductors (both p and n types), applied to GaAs, GaSb, InAs, and InSb, has been carried out by Song and Kim (2002) by using the Elliott-Yafet, D'yakonov-Perel', and Bir-Aronov-Pikus mechanisms. The calculation uses analytical formulas like Eq. (66), while explicitly evaluating τ_p for different momentum scattering processes at different control parameters (temperature and density), but only for nondegenerate electron systems (Boltzmann statistics) and zero magnetic field. The main results are as follows: in n-type III-V semiconductors D'yakonov-Perel' dominates at $T \gtrsim 5$ K. At lower T the Elliott-Yafet mechanism becomes relevant. This crossover temperature appears to be quite insensitive to the electron density, being between 1 and 5 K in most investigated III-V semiconductors for donor densities greater than 10^{14} cm^{-3} (Song and Kim, 2002). For p-type materials the dominant mechanisms are D'yakonov-Perel' and Bir-Aronov-Pikus, with the crossover temperature sensitive to the acceptor density. For example, in p-GaAs at room temperature, the D'yakonov-Perel' mechanism dominates below 10^{18} cm^{-3}, while at large densities the Bir-Aronov-Pikus mechanism dominates. In small-gap InSb the D'yakonov-Perel' mechanism appears to be dominant for all acceptor densities at temperatures above 50 K. The strong disagreement with experiment found at low T (at 5 K, to be specific) points to our still limited theoretical understanding of spin relaxation in semiconductors. The discrepancy likely arises from neglect of hyperfine-interaction effects.

Spin-relaxation times as long as 300 ns were recently obtained in bulk, ≈100-nm-wide GaAs at 4.2 K, placed in the proximity of quantum wells (Dzhioev, Zakharchenya, *et al.*, 2001; Dzhioev, Korenev, Merkulov, *et al.*, 2002). The samples were low doped ($\approx 10^{14}$ cm^{-3} uncompensated donor density), so that optical orientation detected τ_s of electrons bound on donors. At such low donor concentrations the hyperfine-interaction mechanism is responsible for spin relaxation. The unusually large τ_s is attributed to the presence of additional conduction electrons in the structure, coming from the barriers separating the sample and the nearest quantum well. The hyperfine interaction is then motionally narrowed by the exchange interaction between the donor-bound and conduction electrons. Upon depletion of the conduction electrons from the sample by resonant excitations in the quantum well, τ_s decreased to 5 ns (Dzhioev, Korenev, Merkulov, *et al.*, 2002), implying that the effects of the static hyperfine fields on bound-electron spin precessions are not reduced by motional narrowing.

Spin relaxation of holes in bulk III-V materials is very fast due to complete mixing of orbital and spin degrees of freedom in the valence band. The Elliott-Yafet mechanism predicts that hole τ_s is similar to hole τ_p; this is a common assumption when considering hole contribution to spin-polarized transport. Hole spin lifetime in undoped GaAs has been measured by optical orientation and time-resolved spectroscopy (Hilton and Tang, 2002). The observed value at room temperature is $\tau_s \approx 110$ fs, consistent with the theoretical assumption.

Spin relaxation of conduction electrons in strained III-V crystals was studied experimentally and theoretically by D'yakonov *et al.* (1986). Spin relaxation under strain is enhanced and becomes anisotropic due to the strain-induced spin splitting of the conduction band, which is linear in k, similarly to the bulk inversion asymmetry in two-dimensional systems (see Sec. III.B.2). It was found that $1/\tau_s \sim \sigma^2$, where σ is the applied stress, and that τ_s is only weakly temperature dependent. Spin relaxation of photoholes in strain crystals has been studied by D'yakonov and Perel' (1973a), with the conclusion that the hole spin along the strain axis can relax (by the Elliott-Yafet processes) on time scales much longer than in unstrained samples, due to the lifting of heavy and light hole degeneracy.

Compared to III-V or II-VI, much less effort has been devoted to investigation of τ_s in bulk Si. The reason is that CESR is thus far the only technique capable of effective detection of spin relaxation in Si. Optical orientation is rather weak (Lampel, 1968) due to the indirect band-gap structure, while robust spin injection in Si is yet to be demonstrated. Spin relaxation in Si is slow due to the presence of inversion symmetry (the D'yakonov-Perel' mechanism is not applicable) and lack of a nuclear moment for the main Si isotope. Earlier experimental studies (Feher and Gere, 1959) were concerned with the hyperfine-interaction-dominated spin dephasing in donor states.

A comprehensive experimental study of low-doped Si (P donors were present at the levels $7.5\times10^{14} \leqslant N_d \leqslant 8\times10^{16}$ cm^{-3}), at temperatures $20 < T < 300$ K, was performed by Lepine (1970). Three distinct temperature regimes were observed:

(a) ($20 < T < 75$ K) Here τ_s decreases with increasing T. The hyperfine-interaction mechanism dominates: electrons are bound to the ground donor states, while thermal excitations to higher states and the exchange interaction with conduction electrons motionally narrows the hyperfine interaction.
(b) ($75 < T < 150$ K) In this temperature range τ_s continues to decrease with increasing T, the effect caused by the spin-orbit interaction in the first excited donor state being motionally narrowed by thermal motion.
(c) ($T > 150$ K) Here $1/\tau_s$ increases with T, in accord with the Elliott-Yafet mechanism. The observed room-temperature CESR linewidth is about 8 G, corresponding to the electron spin lifetime of 7 ns.

2. Low-dimensional semiconductor structures

The importance of low-dimensional semiconductor systems (quantum wells, wires, and dots) lies in their great flexibility in manipulating charge and, now, also spin properties of the electronic states. Studies of spin relaxation in those systems are driven not only by the need for fundamental understanding of spin relaxation

and decoherence, but also by the goal of finding ways to reduce or otherwise control spin relaxation and coherence in general. For a survey of spin relaxation properties of semiconductor quantum wells, see Sham (1993).

Spin relaxation in semiconductor heterostructures is caused by random magnetic fields originating either from the base material or from the heterostructure itself. All four mechanisms of spin relaxation can be important, depending on the material, doping, and geometry. The difference from the bulk is the localization of the wave function into two, one, or zero dimensions and the appearance of structure-induced random magnetic fields. Of all the mechanisms, the D'yakonov-Perel' and hyperfine interaction are believed to be most relevant.

The most studied systems are GaAs/AlGaAs quantum wells. The observed τ_s varies from nanoseconds to picoseconds, depending on the range of control parameters such as temperature, quantum-well width or confinement energy E_1, carrier concentration, mobility, magnetic field, or bias.[84]

Spin relaxation has also been investigated in In/GaAs (Paillard *et al.*, 2001; Cortez *et al.*, 2002), in an InAs/GaSb superlattice (Olesberg *et al.*, 2001), in InGaAs (Guettler *et al.*, 1998), in GaAsSb multiple quantum wells (Hall *et al.*, 1999). II-VI quantum wells, specifically ZnCdSe, were studied by Kikkawa *et al.* (1997), who found $\tau_s \approx 1$ ns, weakly dependent on both mobility and temperature, in the range $5 < T < 270$ K. Electron and hole spin dephasing have also been investigated in dilute magnetic semiconductor quantum wells doped with Mn ions (Crooker *et al.*, 1997; Camilleri *et al.*, 2001).

Reduction of spin relaxation by inhibiting the Bir-Aronov-Pikus electron-hole exchange interaction through spatially separating the two carriers has been demonstrated in δ-doped p-GaAs:Be/AlGaAs (Wagner *et al.*, 1993). The observed τ_s was ≈ 20 ns at $T < 10$ K, which is indeed unusually large. The exchange interaction was also studied at room temperature, observing an increase of τ_s with bias voltage which increases spatial separation between electrons and holes, reducing the Bir-Aronov-Pikus effects (Gotoh *et al.*, 2000). In the fractional quantum Hall effect regime it was demonstrated (Kuzma *et al.*, 1998) that nonequilibrium spin polarization in GaAs quantum wells can survive for tens of μs. Spin lifetime was also found to be enhanced in GaAs quantum wells strained by surface acoustic waves (Sogawa *et al.*, 2001). A theoretical study (Kiselev and Kim, 2000) proposed that spin dephasing in 2DEG can be significantly suppressed by constraining the system to finite stripes, several mean free paths wide.

Theoretical studies focusing on spin dephasing in III-V and II-VI systems include those of Wu and Metiu (2000); Lau *et al.* (2001); Wu (2001); Bronold *et al.* (2002); Lau and Flatté (2002); Wu and Kuwata-Gonokami (2002); Krishnamurthy *et al.* (2003); Puller *et al.* (2003). Spin relaxation due to D'yakonov-Perel' mechanism with bulk inversion asymmetry term in the important case of GaAs/AlGaAs rectangular quantum wells was investigated by Monte Carlo simulations (Bournel *et al.*, 2000) at room temperature, including interface roughness scattering. Nice agreement with experiment was found for $\tau_s(E_1)$, where E_1 is the confinement energy. Interface roughness becomes important at large values of E_1, where scattering increases τ_s (see also Sherman, 2003a).

Spin relaxation and spin coherence of spin-polarized photoexcited electrons and holes in symmetric p- and n-doped and undoped GaAs/AlGaAs quantum wells was investigated using rate equations (Uenoyama and Sham, 1990a, 1990b). It was shown that in these heterostructures hole spin relaxation proceeds slower than electron-hole recombination. Hole relaxation is found to occur mostly due to acoustic phonon emission. The ratio of the spin-conserving to spin-flip hole relaxation times was found to be 0.46, consistent with the fact that luminescence is polarized even in n-doped quantum wells at times greater than the momentum relaxation time. Similar observations hold for strained bulk GaAs, where hole spin relaxation is also reduced. Spin relaxation of holes in quantum wells was calculated (Ferreira and Bastard, 1991; Bastard and Ferreira, 1992) using the interaction with ionized impurities and s-d exchange in semimagnetic semiconductors. It was shown that size quantization significantly reduces spin relaxation of holes, due to the lifting of heavy and light hole degeneracy. The observed spin lifetimes for holes at low temperatures reached up to 1 ns, while at $T > 50$ K in the same samples τ_s got smaller than 5 ps (Baylac *et al.*, 1995).

Spin dynamics and spin relaxation of excitons in GaAs (Munoz *et al.*, 1995; Vina *et al.*, 2001) and ZnSe (Kalt *et al.*, 2000) were investigated experimentally and theoretically (Maialle *et al.*, 1993; Sham *et al.*, 1998). Coherent spin dynamics in magnetic semiconductors was considered by Linder and Sham (1998).

Spin relaxation in Si heterostructures has been investigated by electron spin resonance in modulation doped Si/SiGe quantum wells. Very-high-mobility (about 10^5 cm^2 V^{-1} s^{-1}) samples with $n \approx 3 \times 10^{11}$ cm^{-2} free electrons forming a 2D electron gas show, at $T = 4.2$ K, T_1 up to 30 μs (Graeff *et al.*, 1999; Sanderfeld *et al.*, 2000) and T_2 of the order of 100 ns (Graeff *et al.*, 1999), depending on the orientation of B with respect to the quantum-well growth direction. Spin relaxation was attributed to Bychkov-Rashba spin splitting in these asymmetric wells, estimating the corresponding $\hbar\alpha_{BR}$ in Eq. (88) to be around 1×10^{-14} eV m (Wilamowski and

[84]Here is a list of selected references with useful data on τ_s in GaAs/AlGaAs quantum wells: confinement energy dependence has been studied by Tackeuchi *et al.* (1996); Britton *et al.* (1998); Ohno, Terauchi, *et al.* (1999, 2000); Endo *et al.* (2000); Malinowski *et al.* (2000); temperature dependence is treated by Wagner *et al.* (1993); Ohno, Terauchi, *et al.* (1999, 2000); Malinowski *et al.* (2000); Adachi *et al.* (2001); carrier concentration dependence is studied by Sandhu *et al.* (2001); dependence on mobility is examined by Ohno, Terauchi, *et al.* (1999); and dependence on magnetic field is studied by Zhitomirskii *et al.* (1993).

Jantsch, 2002; Wilamowski *et al.*, 2002). Si/Ge heterostructures may have enhanced rates of spin relaxation due to the leakage of the electron wave function to Ge, which is heavier than Si and has greater spin-orbit interaction. Recent studies (Wilamowski and Jantsch, 2004) have confirmed the dominant role of the D'yakonov-Perel' spin relaxation mechanism, leading to microsecond spin relaxation times. The spin dephasing is argued to be strongly suppressed by cyclotron motion in high-mobility samples (see Sec. III.B.2.a for a brief discussion of the influence of magnetic field on τ_s). Spin-orbit coupling in symmetric Si/SiGe quantum wells has been studied theoretically by Sherman (2003b).

In quantum dots the relevant spin relaxation mechanism is still being debated, as the mechanisms (Elliott-Yafet and D'yakonov-Perel') effective for conduction electrons are ineffective for states localized in quantum dots (Khaetskii and Nazarov, 2000, 2001; Khaetskii, 2001). It is believed, however, that similar to electrons bound on donors, the dominant mechanism is a hyperfine-interaction process (Khaetskii *et al.*, 2002; Merkulov *et al.*, 2002; Semenov and Kim, 2002; de Sousa and Das Sarma, 2003a, 2003b). Unfortunately, experiments on CdSe quantum dots (of diameter 22–80 Å) show strong inhomogeneous dephasing ($\tau_s \approx 3$ ns at $B=0$, while $\tau_s \approx 100$ ps at 4 T) (Gupta *et al.*, 1999), masking the intrinsic spin dephasing processes. Recently a lower bound, limited by the signal-to-noise ratio, on T_1 of 50 μs has been measured at 20 mK in a one-electron quantum dot defined in a 2DEG GaAs/AlGaAs heterostructure by Hanson, Witkamp, *et al.* (2003). The magnetic field of 7.5 T was oriented parallel to the plane of the heterostructure. While the actual value of T_1 may be orders of magnitude larger, the observed bound suffices for performing elementary quantum gates (see Sec. IV.F).

3. Example: Spin relaxation in GaAs

We review recent experimental results on spin relaxation in bulk n-GaAs[85] and GaAs-based low-dimensional systems.

a. Bulk n-GaAs

The importance of GaAs for spintronics and quantum computing applications has been recently underlined by the discovery of rather long spin-relaxation times (of the order of 100 ns) in n-doped samples, as well as by the development of experimental techniques to manipulate spin precession in this semiconductor in a coherent manner (Awschalom, 2001; Oestreich *et al.*, 2002).

Both optical orientation and time-resolved Faraday rotation spectroscopy have been used to measure τ_s in bulk n-GaAs. In the earliest observations of optical spin orientation of electrons, in n-$Ga_{0.7}Al_{0.3}As$ with $N_d \approx 1\times10^{16}$ cm^{-3} at 4.2 K, it was found that $\tau_s \approx 1.2$ ns (Ekimov and Safarov, 1971). A much larger spin lifetime was found by optical orientation on n-GaAs (Dzhioev *et al.*, 1997), where for $N_d \approx 1\times10^{15}$ cm^{-3} the observed τ_s was ≈ 42 ns. Faraday rotation studies (Kikkawa and Awschalom, 1998; Awschalom, 2001) found even longer spin lifetimes. At the doping density $N_d = 1\times10^{16}$ cm^{-3} of Si donors and $T=5$ K, the observed τ_s was ≈ 130 ns at zero magnetic field. At greater and smaller doping densities, spin-relaxation time is significantly reduced: for both a nominally undoped sample and for $N_d = 1\times10^{18}$ cm^{-3}, $\tau_s \approx 0.2$ ns. A comprehensive theoretical investigation of τ_s in bulk n-GaAs is reported by Wu and Ning (2000) and Wu (2001), who solved numerically kinetic equations in the presence of magnetic field. Only the D'yakonov-Perel' mechanism was considered, acting with longitudinal phonon and impurity scattering.

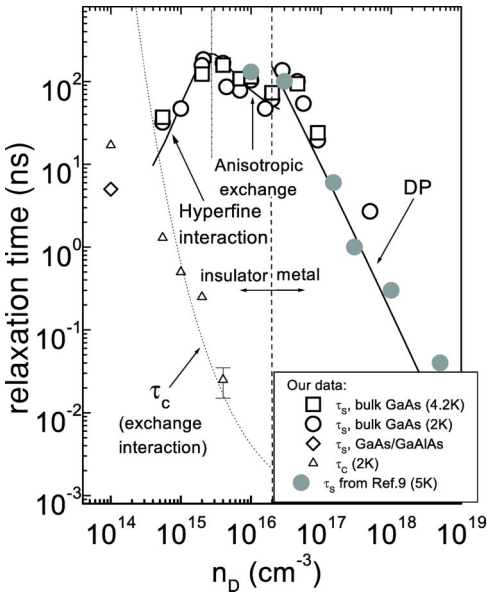

FIG. 17. (Color in online edition) Spin relaxation time in n-GaAs as a function of donor density N_d (labeled as n_D here) at low temperatures: empty symbols, the optical orientation data of Dzhioev, Kavokin, *et al.* (2002); solid circles, the time-resolved Faraday rotation data of Awschalom (2001) and Kikkawa and Awschalom (1998); open triangles, single-spin decoherence times $\tau_{sc} \approx \tau_c$ due to the exchange interaction between electron spins on neighboring donors; solid lines, parameter-free theoretical estimates with labels indicating the dominant spin relaxation mechanisms; dotted line, a fit to the experimental data on the exchange correlation time (triangles) τ_c, using a simple model of the exchange coupling between donor states; dashed vertical line, the metal-insulator transition at $N_{dc} = 2\times10^{16}$ cm^{-3}. From Dzhioev, Kavokin, *et al.*, 2002.

A recent comprehensive study of τ_s based on optical orientation revealed a nice, albeit complex, picture of spin relaxation in bulk n-GaAs over a large range of doping levels (Dzhioev, Korenev, Zakharchenya, *et al.*, 2002). Figure 17 summarizes these findings. The spin-relaxation time rises with increasing N_d at small doping levels, reaching its first maximum (180 ns) at around 3×10^{15} cm^{-3}; τ_s then decreases until $N_d = N_{dc} = 2\times10^{16}$ m^{-3}, where a sudden increase brings τ_s to an-

[85] p-GaAs is extensively discussed by Meier and Zakharchenya (1984).

other maximum, reaching ≈150 ns. At still higher doping levels τ_s decreases strongly with increasing doping.

The above picture is valid at $T \leqslant 5$ K, where isolated shallow donors are not normally ionized, and the sample is a Mott insulator at small dopings. Conductivity is due to hopping between donor states. Beyond the critical density $N_{dc} \approx 2\times10^{16}$ cm^{-3} (the dashed vertical line in Fig. 17) the donor states start to overlap and form an impurity conduction band—electronic states delocalize and the sample becomes metallic. Figure 17 shows that it is the rather narrow window around the metal-to-insulator transition where the largest τ_s are found.

At $N_d > N_{dc}$ the D'yakonov-Perel' mechanism dominates. Equation (73) for degenerate electrons explains the observed data rather well. Indeed, considering that $E_F \sim N_d^{2/3}$ and assuming the Brooks-Herring formula for the impurity scattering ($1/\tau_p \sim N_d/E_F^{3/2}$), one obtains $\tau_s \sim 1/N_d^2$, which is observed in Fig. 17. The Elliot-Yafet mechanism, Eq. (66), would give $\tau_s \sim N_d^{-4/3}$. The data on the insulating side are consistent with the hyperfine-interaction mechanism: the precession due to local random magnetic fields from the nuclear moments is motionally narrowed by the exchange interaction, which increases with increasing N_d (that is, with increasing overlap between donor states). The theoretical estimates (Dzhioev, Korenev, Zakharchenya, *et al.*, 2002) agree well with the data. The behavior of τ_s in the intermediate regime, 3×10^{15} cm$^{-3} < N_d < N_{dc}$, where τ_s decreases with increasing N_d, was proposed by Kavokin (2001) to be due to motional narrowing of the antisymmetric exchange interaction[86] between bound electrons, with the correlation time τ_c provided by the usual $\mathbf{S}_1 \cdot \mathbf{S}_2$, direct exchange. This new mechanism of spin relaxation, which should be generally present for bound electrons in systems lacking inversion symmetry (such as III-V and II-VI), although still being investigated (Kavokin, 2002b; Gorkov and Krotov, 2003), appears to give a satisfactory explanation for the experimental data.

In addition to the doping dependence of τ_s, both the temperature and the magnetic-field dependences of spin relaxation in bulk n-GaAs have been studied by Kikkawa and Awschalom (1998). Figure 18 shows $\tau_s(B)$ for samples with varying doping levels at $T = 5$ K. The spin-relaxation time increases with B in the metallic regime, a behavior qualitatively consistent with the predictions of the D'yakonov-Perel' mechanism. In contrast, τ_s in the insulating samples decreases with increasing B. Bound electrons are more susceptible to g-factor anisotropies (due to distribution of electron energies over donor states) and local magnetic-field variations (due to hyperfine interactions). These anisotropies are amplified by increasing B and motionally narrowed by the exchange interaction. It is thus likely that τ_s

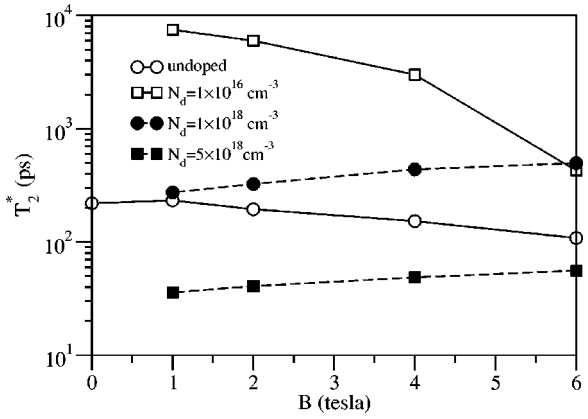

FIG. 18. Measured magnetic-field dependence of the spin dephasing time (here denoted as T_2^* to indicate the likely presence of inhomogeneous broadening; see Sec. III.A.1) for bulk n-GaAs at 5 K. Doping levels, varying from insulating ($N_d < N_{dc} = 2\times10^{16}$ cm^{-3}) to metallic ($N_d > N_{dc}$), are indicated. Adapted from Kikkawa and Awschalom, 1998.

$\sim B^{-2}\tau_c(B)$, where the exchange correlation time τ_c depends on B through magnetic orbital effects on the bound electron wave functions (magnetic confinement reduces the extent of the bound orbital, thus reducing the exchange integrals between neighboring donor states). However, no satisfactory quantitative explanation for $\tau_s(B)$ in insulating samples exists.

Figure 19 plots $\tau_s(T)$ for an insulating sample with $N_d = 1\times10^{16}$ cm^{-3} at $B = 0$ and $B = 4$ T. For the zero-field data the initial decrease of τ_s with B is very rapid, dropping from 130 ns at 5 K to less than 1 ns at 150 K. However, the sample held at $B = 4$ T shows at first a rapid increase with increasing T, and then a decrease at $T \approx 50$ K. The decrease of τ_s with increasing T above 50 K has been found to be consistent with the D'yakonov-Perel' mechanism (Kikkawa and Awschalom, 1998), taking $\tau_s \sim T^{-3}$ in Eq. (74), while extracting the tempera-

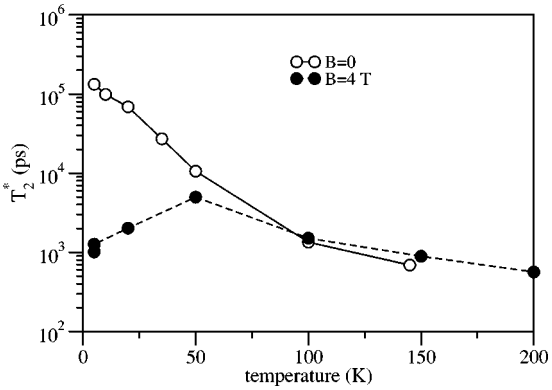

FIG. 19. Measured temperature dependence of the spin dephasing time for bulk n-GaAs doped with $N_d = 1\times10^{16}$ cm^{-3} Si donors, at $B = 0$ and $B = 4$ T. The sample is insulating at low T and nondegenerate at high T ($T \gtrsim 50$ K, assuming ≈4 MeV for the donor binding energy), where donors are ionized. Adapted from Kikkawa and Awschalom, 1998.

[86]The anisotropic exchange interaction of the Dzyaloshinskii-Moriya form, $\mathbf{S}_1 \times \mathbf{S}_2$ (Dzyaloshinskii, 1958; Moriya, 1960), appears as a result of spin-orbit coupling in semiconductors lacking inversion symmetry.

ture dependence of τ_p from the measurement of mobility. The D'yakonov-Perel' mechanism for conduction electrons was also observed in p-GaAs in the regime of nondegenerate hole densities $N_a \approx 10^{17}$ cm^{-3} at temperatures above 100 K (Aronov *et al.*, 1983), after the contribution from the Bir-Aronov-Pikus mechanism was subtracted using a theoretical prediction. From the observed mobility it was found that $\tau_p(T) \sim T^{-0.8}$, so that according to the D'yakonov-Perel' mechanism $\tau_s \sim T^{-2.2}$, which is indeed consistent with the experimental data. The origin of $\tau_s(T)$ below 50 K in Fig. 19 is less obvious. At low T, electrons are localized, so in order to explain the experimental data the theory should include ionization of donors. The increase with increasing T of τ_s at 4 T invokes a picture of motional narrowing in which the correlation time decreases with increasing T much faster than the dispersion of local Larmor frequencies. We do not know of a satisfactory quantitative explanation for these experimental results.[87] Similar behavior of $\tau_s(T)$ in insulating samples was found in GaN (Beschoten *et al.*, 2001).

The temperature dependence of τ_s for samples with $N_d \gg N_{dc}$ has been reported (Kikkawa and Awschalom, 1998) to be very weak, indicating, for these degenerate-electron densities, that $\tau_p(T)$ is only weakly dependent on T. What can be expected for τ_s at room temperature? The answer will certainly depend on N_d. Recent experiments on time-resolved Kerr rotation (Kimel *et al.*, 2001) suggest that $5\ \text{ps} < \tau_s < 10$ ps for undoped GaAs and $15\ \text{ps} < \tau_s < 35$ ps for a heavily doped n-GaAs with $N_d = 2 \times 10^{18}$ cm^{-3}.

For spintronic applications to make use of the large τ_s observed in bulk n-GaAs, one is limited to both very small temperatures and small doping levels. Although this may restrict the design of room-temperature spintronic devices, such a regime seems acceptable for spin-based quantum computing (see Sec. IV.F), where one is interested in the spin lifetime of single (or a few) electrons, bound to impurities or confined to quantum dots. How close is τ_s to the individual spin lifetime τ_{sc}? There is no clear answer yet. Ensemble spin dephasing seen for insulating GaAs samples appears to be due to motional narrowing of the hyperfine interaction. The randomizing processes are spin flips due to direct exchange, leading to the correlation time τ_c, which can be taken as a measure for the lifetime τ_{sc} of the individual spins. Extracting this lifetime from the experiment is not easy, but the obvious trend is the smaller the τ_c, the larger the τ_s. For a specific model of spin relaxation in bound electron states τ_c was extracted experimentally by Dzhioev, Korenev, Zakharchenya, *et al.* (2002) by detecting the changes in the spin polarization due to longitudinal magnetic fields. The result is shown in Fig. 17. The two times τ_c and τ_s differ by orders of magnitude. For the doping levels where τ_s is *greater* than 100 ns, τ_c is *smaller* than 0.1 ns. Unfortunately, the useful time for spin quantum computing would be extracted in the limit of very small dopings, where the data are still sparse. For an informal recent review of τ_s in n-GaAs, see Kavokin (2002a).

Closely related to spin relaxation is spin diffusion. Hägele *et al.* (1998) observed the transport of a spin population—longitudinal spin drift—in i-GaAs over a length scale greater than 4 μm in electric fields up to 6 kV/cm and at low temperatures. This was followed by a remarkable result of Kikkawa and Awschalom (1999), the observation of the drift of precessing electron spins—transverse spin drift—in GaAs with $N_d = 1 \times 10^{16}$ cm^{-3}, over 100 μm in moderate electric fields (tens of V/cm) at $T = 1.6$ K, setting the length scale for the spin dephasing. By directly analyzing the spreading and drifting of the electron spin packets in time, Kikkawa and Awschalom obtained the spin diffusion (responsible for spreading) and electronic diffusion (drift by electric field) coefficients. It was found that the former is about 20 times as large as the latter. These results are difficult to interpret, since the sample is just below the metal-to-insulator transition, where charge is transported via hopping, but they suggest that spin diffusion is strongly enhanced through the exchange interaction. Investigations of this type in even smaller doping limits may prove important for understanding single-spin coherence.

b. GaAs-based quantum wells

We discuss selected experimental results on spin relaxation in GaAs/Al$_x$Ga$_{1-x}$As quantum wells, presenting the temperature and confinement energy dependence of τ_s.

Figure 20 plots the temperature dependence of $1/\tau_s$ in the interval $90 < T < 300$ K for quantum wells of widths L ranging from 6 to 20 nm (Malinowski *et al.*, 2000). The wells, with $x = 0.35$ and orientation along [001], were grown on a single wafer to minimize sample-to-sample variations when comparing different wells. The reported interface roughness was less than the exciton Bohr radius of 13 nm. In these structures the excitonic effects

[87] There is a discrepancy in the data presented in Figs. 18 and 19. Take the $N_d = 1 \times 10^{16}$ cm^{-3} sample. While Fig. 18 reports $\tau_s \approx 3$ ns at 5 K and 4 T, τ_s is only about 1 ns in Fig. 19. The reason for this difference (Kikkawa, 2003) turns out to be electronically induced nuclear polarization (Kikkawa and Awschalom, 2000). At low temperatures and large magnetic fields, nuclear polarization develops via the Overhauser effect inhomogeneously throughout the electron spin excitation region. The inhomogeneous magnetic field due to polarized nuclei causes inhomogeneous broadening of the electronic τ_s. The measured spin dephasing time is indeed T_2^*, rather than the intrinsic T_2. Furthermore, since nuclear polarization typically takes minutes to develop, the measured T_2^* depends on the measurement "history." This is the reason why two different measurements, reported in Figs. 18 and 19, show different T_2^* under otherwise equivalent conditions. The nuclear polarization effect is also part of the reason why the $T_2(T)$ at 4 T sharply deviates from that at zero field at small T. The technique should give consistent results at small fields and large temperatures, as well as in heavily doped samples where the nuclear fields are motionally narrowed by the itinerant nature of electrons.

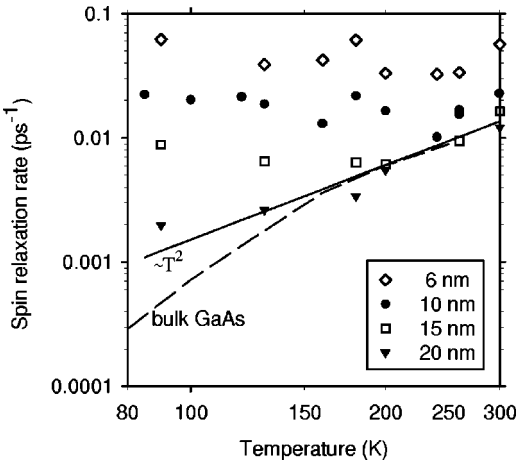

FIG. 20. Measured temperature dependence of the conduction-electron spin relaxation rate $1/\tau_s$ in GaAs/AlGaAs quantum wells of varying widths: dashed curve, data for a low-doped ($N_a=4\times10^{16}$ cm^{-3}) bulk p-GaAs (Meier and Zakharchenya, 1984); solid line, the $\tau_s\sim T^2$ dependence. From Malinowski *et al.*, 2000.

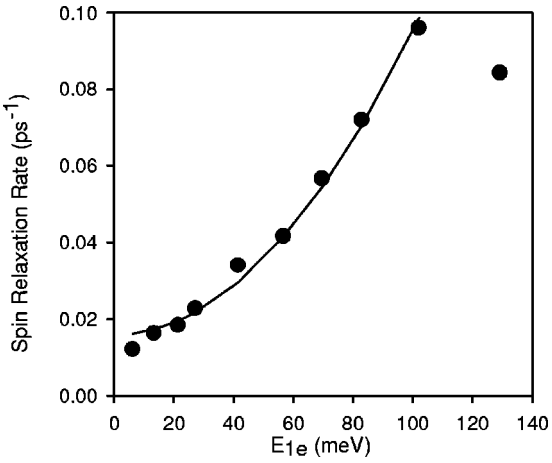

FIG. 21. Measured room-temperature dependence of $1/\tau_s$ on the confinement energy E_1 for GaAs/AlGaAs quantum wells. The solid line is a quadratic fit, showing behavior consistent with the D'yakonov-Peral' mechanism. From Malinowski *et al.*, 2000.

dominate at $T<50$ K (with the reported $\tau_s\approx50$ ps), while the exciton ionization is complete roughly at $T>90$ K, so the data presented are for free electrons. Spin relaxation was studied using pump-probe optical orientation spectroscopy with a 2-ps time resolution and the typical excitation intensity/pulse of 10^{10} cm^{-2}.

As Fig. 20 shows, τ_s depends rather weakly on T for the narrow wells with $L<10$ nm. For the well with $L=15$ nm, after being approximately constant (or somewhat decreasing) as T increases to about 200 K, τ_s increases with increasing T at greater temperatures. The increase is consistent with the $1/\tau_s\sim T^2$ behavior. The thickest well increases with the same power law, $1/\tau_s\sim T^2$, over the whole temperature range. In order to make a reliable comparison with theoretical predictions (the expected mechanism is that of D'yakonov-Perel' in two-dimensional systems), one needs to know the behavior of $\tau_p(T)$. The D'yakonov-Perel' mechanism predicts, for the nondegenerate-electron densities employed in the experiment, that $1/\tau_s\sim T^3\tau_p$ [see Eq. (74)] in the bulk and wide quantum dots, the condition being that thermal energy is greater than the subband separation), and $1/\tau_s\sim TE_1^2\tau_p$ from Eq. (79), for the bulk inversion asymmetry after thermal averaging ($E_{\mathbf{k}}\rightarrow k_BT$), when one realizes that confinement energy E_1 is $\sim\langle k_n^2\rangle$. When one assumes that momentum relaxation in these elevated temperatures is due to scattering by phonons, τ_p should be similar in bulk and low-dimensional structures. From the observed high-temperature bulk $\tau_s(T)$ (at low temperatures τ_s is affected by Bir-Aronov-Pikus processes) one can estimate $\tau_p\sim1/T$, which is consistent with the constant τ_s for the narrow wells, and with the quadratic dependence for the wide wells. At low T, in addition to the Bir-Aronov-Pikus mechanism, τ_s will deviate from that in the bulk due to impurity scattering. The Bir-Aronov-Pikus and Elliot-Yafet mechanisms were found not to be relevant to the observed data (Malinowski *et al.*, 2000).

Figure 21 shows the dependence of $1/\tau_s$ on the experimentally determined confinement energy E_1 for a variety of quantum wells on the same wafer (Malinowski *et al.*, 2000). The data are at room temperature. The spin-relaxation time varies from somewhat less than 100 ps for wide quantum wells, approximating the bulk data (cf. Kimel *et al.*, 2001, where 15 ps$<\tau_s<$35 ps was found for a heavily doped n-GaAs), to about 10 ps in most confined structures. The downturn for the highest-E_1 well (of width 3 nm) is most likely due to the increased importance of interface roughness at such small widths (Malinowski *et al.*, 2000). Confinement strongly enhances spin relaxation. This is consistent with the D'yakonov-Perel' mechanism for two-dimensional systems, in which spin precession about the intrinsic magnetic fields (here induced by bulk inversion asymmetry) increases as E_1^2 with increasing confinement. The observed data in Fig. 21 are consistent with the theoretical prediction.

Similarly to bulk GaAs, spin relaxation in GaAs quantum wells was found to be reduced at carrier concentrations close to the metal-to-insulator transition ($n\approx5\times10^{10}$ cm^{-2}; Sandhu *et al.*, 2001).

IV. SPINTRONIC DEVICES AND APPLICATIONS

In this section we focus primarily on the physical principles and materials issues for various device schemes, which, while not yet commercially viable, are likely to influence future spintronic research and possible applications.

A. Spin-polarized transport

1. F/I/S tunneling

Experiments reviewed by Tedrow and Meservey (1994) in ferromagnet/insulator/superconductor (F/I/S)

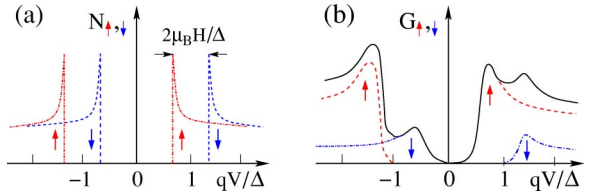

FIG. 22. (Color in online edition) Ferromagnet/insulator/superconductor tunneling in an applied magnetic filed: (a) Zeeman splitting of the BCS density of states as a function of applied bias; (b) normalized spin-resolved conductance (dashed lines) and the total conductance (solid line) at finite temperature.

junctions have established a sensitive technique for measuring the spin polarization P of magnetic thin films and at the same time, has demonstrated that the current will remain spin polarized after tunneling through an insulator. These experiments also stimulated more recent imaging techniques based on the spin-polarized scanning tunneling microscope (see Johnson and Clarke, 1990; Wiesendanger *et al.*, 1990; and a review, Wiesendanger, 1998) with the ultimate goal of imaging spin configurations down to the atomic level.

The degree of spin polarization is important for many applications such as determining the magnitude of tunneling magnetoresistance (TMR) in magnetic tunnel junctions (MTJ) [recall Eq. (2)]. Different probes for spin polarization generally can measure significantly different values even in experiments performed on the same homogeneous sample. In an actual MTJ, measured polarization is not an intrinsic property of the F region and could depend on interfacial properties and the choice of insulating barrier. Challenges in quantifying P, discussed here in the context of F/I/S tunneling, even when F is a simple ferromagnetic metal, should serve as a caution for studies of novel, more exotic, spintronic materials.

F/I/S tunneling conductance is shown in Fig. 22, where for simplicity we assume that the spin-orbit and spin-flip scattering (see Sec. III.C) can be neglected, a good approximation for Al_2O_3/Al (Tedrow and Meservey, 1971a, 1994) and a common choice for I/S regions. For each spin the normalized BCS density of states is $\tilde{\mathcal{N}}_S(E)=\mathrm{Re}(|E|/2\sqrt{E^2-\Delta^2})$, where E is the quasiparticle excitation energy and Δ the superconducting gap.[88] The BCS density of states is split in a magnetic field H, applied parallel to the interface, due to a shift in quasiparticle energy, $E\rightarrow E\pm\mu_B H$, for $\uparrow$ ($\downarrow$) spin parallel (antiparallel) to the field, where μ_B is the Bohr magneton. The tunneling conductance is normalized with respect to its normal-state value for an F/I/N junction, $G(V)\equiv(dI/dV)_S/(dI/dV)_N=G_\uparrow(V)+G_\downarrow(V)$, where V is the applied bias. This conductance can be expressed by generalizing analysis of Giaever and Megerle (1961) as

$$G(V)=\int_{-\infty}^{\infty}\frac{1+P}{2}\frac{\tilde{\mathcal{N}}_S(E+\mu H)\beta dE}{4\cosh^2[\beta(E+qV)/2]}+\int_{-\infty}^{\infty}\frac{1-P}{2}\frac{\tilde{\mathcal{N}}_S(E-\mu H)\beta dE}{4\cosh^2[\beta(E+qV)/2]}. \quad (99)$$

Here $\beta=1/k_BT$, k_B is the Boltzmann constant, T is the temperature, and q is the proton charge. The factors $(1\pm P)/2$ represent the difference in tunneling probability between $\uparrow$ and $\downarrow$ electrons. While a rigorous determination of P, in terms of materials parameters, would require a full calculation of spin-dependent tunneling, including the appropriate boundary conditions and a detailed understanding of the interface properties, it is customary to make some simplifications. Usually P can be identified as (Worledge and Geballe, 2000a; Maekawa *et al.*, 2002)

$$P\rightarrow P_G=(G_{N\uparrow}-G_{N\downarrow})/(G_{N\uparrow}+G_{N\downarrow}), \quad (100)$$

the spin polarization of the normal-state conductance (proportional to the weighted average of the density of states in F and S and the square of the tunneling matrix element), where $\uparrow$ is the electron spin with the magnetic moment parallel to the applied field (majority electrons in F). With the further simplifications of spin independence and a constant tunneling matrix element (Tedrow and Meservey, 1971b, 1994), Eq. (100) can be expressed as

$$P\rightarrow P_{\mathcal{N}}=(\mathcal{N}_{F\uparrow}-\mathcal{N}_{F\downarrow})/(\mathcal{N}_{F\uparrow}+\mathcal{N}_{F\downarrow}), \quad (101)$$

the spin polarization of the tunneling density of states in the F region at the Fermi level.

Spin polarization P of the F electrode can be deduced (Tedrow and Meservey, 1994) from the asymmetry of the conductance amplitudes at the four peaks in Fig. 22(b) [for $P=0$, $G(V)=G(-V)$]. In $CrO_2/I/S$ tunnel junctions, nearly complete spin polarization $P_G>0.9$ was measured (Parker *et al.*, 2002). Only two of the four peaks sketched in Fig. 22, have been observed, indicating no features due to the minority spin up to $H=2.5$ T. Parkin *et al.* (2004) have shown that by replacing aluminum oxide (a typical choice for an insulating region) with magnesium oxide, one can significantly increase the spin polarization in F/I/S junctions. Correspondingly, extraordinarily large values of TMR (>200% at room temperature) can be achieved even with conventional ferromagnetic (CoFe) electrodes.

The assumption of spin-conserving tunneling can be generalized (Tedrow and Meservey, 1994; Monsma and Parkin, 2000a, 2000b; Worledge and Geballe, 2000a) to extract P in the presence of spin-orbit and spin-flip scattering. Theoretical analyses (Maki, 1964; Bruno and Schwartz, 1973; Fulde, 1973) using many-body techniques show that the spin-orbit scattering would smear the Zeeman-split density of states, eventually merging the four peaks into two, while the magnetic impurities (Abrikosov and Gorkov, 1960) act as pair breakers and reduce the value of Δ. Neglecting the spin-orbit scatter-

[88]Here we focus on a conventional s-wave superconductor with no angular dependence in Δ.

ing was shown to lead to the extraction of higher P values (Tedrow and Meservey, 1994; Monsma and Parkin, 2000a).

With a few exceptions (Worledge and Geballe, 2000b), F/I/S conductance measurements (Tedrow and Meservey, 1994) have revealed positive P—the dominant contribution of majority spin electrons for different ferromagnetic films (for example, in Fe, Ni, Co, and Gd). However, electronic-structure calculations typically give $\mathcal{N}_{F\uparrow}<\mathcal{N}_{F\downarrow}$ and $P_{\mathcal{N}}<0$ for Ni and Co $\mathcal{N}_{F\uparrow}/\mathcal{N}_{F\downarrow}\sim 1/10$ (Butler *et al.*, 2001). Early theoretical work addressed this apparent difference,[89] and efforts to understand precisely what is being experimentally measured have continued.

Stearns (1977) suggested that only itinerant, freelike electrons will contribute to tunneling, while nearly localized electrons, with a large effective mass, contribute to the total density of states but not to $G(V)$ [see also Hertz and Aoi (1973) and, for spin-unpolarized tunneling, Gadzuk (1969)]. From the assumed parabolic dispersion of the spin subbands with fixed spin splitting, Stearns related the measured polarization to the magnetic moment, giving positive $P\rightarrow P_k=(k_{F\uparrow}-k_{F\downarrow})/(k_{F\uparrow}+k_{F\downarrow})$, the spin polarization of the projections of Fermi wave vectors perpendicular to the interface. Similar arguments, for inequivalent density-of-states contributions to $G(V)$, were generalized to more complex electronic structure. Mazin (1999) showed the importance of the tunneling matrix elements, which have different Fermi velocities for different bands (see also Yusof *et al.*, 1998, in the context of tunneling in a high-temperature superconductor). Consequently P_G could even have an opposite sign from $P_{\mathcal{N}}$—which, for example, would be measured by spin-resolved photoemission.

Good agreement between tunneling data and electronic structure calculations was illustrated by the example of Ni_xFe_{1-x} (Nadgorny *et al.*, 2000), showing, however, that P is not directly related to the magnetic moment (Meservey *et al.*, 1976). The difference between bulk and the surface densities of states of the ferromagnet (probed in tunneling measurements; Oleinik *et al.*, 2000), the choice of tunneling barrier (De Teresa *et al.*, 1999), and details of the interfacial properties, which can change over time (Monsma and Parkin, 2000b), have all been shown to affect the measured P directly.

The Tedrow-Meservey technique is also considered as a probe to detect spin injection in Si, where optical methods, due to the indirect gap, would be ineffective. F/I/S tunneling was also studied using amorphous Si (a-Si) and Ge (a-Ge) as a barrier. While with a-Si some spin polarization was detected (Meservey *et al.*, 1982), no spin-polarized tunneling was observed using an a-Ge barrier (Gibson and Meservey, 1985), in contrast to the first reports of tunneling magnetoresistance (Jullière, 1975).

[89]For a list of references see Tedrow and Meservey (1973, 1994).

Spin-dependent tunneling was also studied using a high-temperature superconducting electrode as a detector of spin polarization (Vas'ko *et al.*, 1998; Chen *et al.*, 2001). While this can significantly extend the temperature range in the tunneling experiments, a lack of understanding of high-temperature superconductors makes such structures more a test ground for fundamental physics than a quantitative tool for quantitatively determining P. There are also several important differences between studies using high-temperature and conventional low-temperature superconductors. The superconducting pairing symmetry no longer yields an isotropic energy gap, and even for the BCS-like picture the density of states should be accordingly modified. A sign change of the pair potential can result in $G(V=0)>0$ for $T\rightarrow 0$ even for a strong tunneling barrier and give rise to a zero-bias conductance peak (Hu, 1994; Tanaka and Kashiwaya, 1995; Wei *et al.*, 1998). This is explained by the two-particle process of Andreev reflection (discussed further in Sec. IV.A.3), which, in addition to the usual quasiparticle tunneling, contributes to the I-V characteristics of a F/I/S junction (Hu and Yan, 1999; Kashiwaya *et al.*, 1999; Zhu *et al.*, 1999; Žutić and Valls, 1999, 2000; a simpler N/I/S case is reviewed by Hu, 1998 and Kashiwaya and Tanaka, 2000). The suppression of a zero-bias conductance peak, measured by a scanning tunneling microscope, was recently used to detect spin injection into a high-temperature superconductor (Ngai *et al.*, 2004).

2. F/I/F tunneling

In the preface to a now classic reference on spin-unpolarized tunneling in solids, Duke (1969) concludes that (with only a few exceptions) the study of tunneling is an art and not a science. Perhaps this is also an apt description for the present state of experiment on spin-polarized tunneling between two ferromagnetic regions. Even for MTJ's with standard ferromagnetic metals, the bias and the temperature dependence of the TMR, as well as identification of the relevant spin polarization remain to be fully understood. In a brief review of current findings we intend to identify questions that could arise as new materials for MTJ's are being considered.

A resurgence in interest in the study of MTJ's, following a hiatus after the early work by Jullière (1975) and Maekawa and Gäfvert (1982), was spurred by the observation of large room-temperature TMR (Miyazaki and Tezuka, 1995; Moodera *et al.*, 1995). This discovery opened the possibility of using MTJ's for fundamental studies of surface magnetism and room-temperature spin polarization in various ferromagnetic electrodes as well as suggesting applications such as highly sensitive magnetic-field sensors, magnetic read heads, and nonvolatile magnetic memory applications.

It is instructive to notice the similarity between the schematic geometry and the direction of current flow in an MTJ and that in CPP giant magnetoresistance (recall Figs. 2 and 3), which only differ in the middle layer's being an insulator and a metal, respectively. By consid-

ering the limit of ballistic transport in CPP giant magnetoresistance[90] it is possible to give a unified picture of both TMR and CPP giant magnetoresonance by varying the strength of the hopping integrals (Mathon and Umerski, 1997) in a tight-binding representation.

Jullière (1975) modified Eq. (100) in the limit $V\to 0$, $T\to 0$, and applied it to study F/I/F tunneling. The two F regions are treated as uncoupled, with the spin-conserving tunneling across the barrier. This effectively leads to the two-current model proposed by Mott (1936a) and also applied to CPP giant magnetoresonance geometries (Valet and Fert, 1993; Gijs and Bauer, 1997). The values for P extracted from F/I/S measurements are in good agreement with the observed TMR values (typically positive, as expected from $P_{1,2}>0$). However, Jullière's formula[91] does not provide an explicit TMR dependence on bias and temperature.

Jullière's result can be obtained as a limiting case from a more general Kubo/Landauer approach (Mathon and Umerski, 1999), with the assumption that the component of the wave vector parallel to the interface $\mathbf{k}_\parallel$ is not conserved (incoherent tunneling). Such a loss of coherence is good approximation for simply capturing the effects of disorder for amorphous Al_2O_3, a common choice for the I region with metallic ferromagnets. Despite its simplicity, the Jullière model for the tunneling magnetoresistance has continued to be used for interpreting the spin polarization in various MTJ's. Recent examples include F regions made of manganite perovskites displaying colossal magnetoresistance (CMR; Bowen *et al.*, 2003), suggesting $P_{\mathcal{N}}>0.95$; magnetite (Fe_3O_4; Hu and Suzuki, 2002), with $P<0$ and TMR <0; III-V ferromagnetic semiconductors (Chun *et al.*, 2002); a nonmagnetic semiconductor used as a tunneling barrier (Kreuzer *et al.*, 2002); Co/carbon nanotube/Co MTJ (Tsukagoshi *et al.*, 1999); and resonant tunneling in F/I/N/F junctions (Yuasa *et al.*, 2002).

For novel materials, in which electronic structure calculations and an understanding of the interfacial properties are not available, Jullière's formula still provides useful insights. A quantitative understanding of MTJ's faces challenges similar to those discussed for F/I/S tunneling, including determining precisely which spin polarization is relevant and the related issue of reconciling the (typically positive) sign of the observed TMR with the electronic structure (Bratkovsky, 1997; MacLaren *et al.*, 1997; Mathon and Umerski, 1997; Tsymbal and Pettifor, 1997; Oleinik *et al.*, 2000; LeClair *et al.*, 2002).

In an approach complementary to Jullière's, Slonczewski (1989) considered F/I/F as a single quantum-mechanical system in a free-electron picture. When matching the two-component wave functions at interfaces, coherent tunneling was assumed, with conserved $\mathbf{k}_\parallel$, relevant to epitaxially grown MTJ's (Mathon and Umerski, 2001) and the I region was modeled by a square barrier.[92] The resulting TMR can be expressed as in Eq. (2) but with the redefined polarization

$$P\to P_k(\kappa^2-k_{F\uparrow}k_{F\downarrow})/(\kappa^2+k_{F\uparrow}k_{F\downarrow}), \tag{102}$$

where P_k, as defined by Stearns (1977), is also $P_{\mathcal{N}}$ (in a free-electron picture) and $i\kappa$ is the usual imaginary wave vector through a square barrier. Through the dependence of κ on V the resulting polarization in Slonczewski's model can change sign. A study of a similar geometry using a Boltzmann-like approach shows (Chui, 1997) that the spin splitting of electrochemical potentials persists in the F region all the way to the F/I interface, implying $\kappa_\uparrow\neq\kappa_\downarrow$ and an additional voltage dependence of the TMR. Variation of the density of states [inferred from the spin-resolved photoemission data (Park *et al.*, 1998a, 1998b)] within the range of applied bias in MTJ's of $Co/SrTiO_3/La_{0.7}Sr_{0.3}MnO_3$ (Co/STO/LSMO; De Teresa *et al.*, 1999), together with Jullière's model, was used to explain the large negative TMR (-50% at 5 K), which would even change sign for positive bias (raising the Co Fermi level above the corresponding one of LSMO). The bias dependence of the TMR was also attributed to the density of states by extending the model of a trapezoidal tunneling barrier (Brinkman *et al.*, 1970) to the spin-polarized case (Xiang *et al.*, 2002).

The decay of TMR with temperature can be attributed to several causes. Early theoretical work on N/I/N tunneling (Anderson, 1966; Appelbaum, 1966; for a detailed discussion and a review of related experimental results see Duke, 1969) showed that the presence of magnetic impurities in the tunneling barrier produces temperature-dependent conductance—referred to as zero-bias anomalies. These findings, which considered both spin-dependent and spin-flip scattering, were applied to fit the decay of the TMR with temperature (Inoue and Makeawa, 1999; Jansen and Moodera, 2000; Miyazaki, 2002). Hot electrons localized at F/I interfaces were predicted to create magnons, or collective spin excitations, near the F/I interfaces, and suppress the TMR (Zhang *et al.*, 1997). Magnons were observed (Tsui *et al.*, 1971) in an antiferromagnetic NiO barrier in single-crystal Ni/NiO/Pb tunnel junctions and were suggested (Moodera *et al.*, 1995) as the cause of decreasing TMR with T by spin-flip scattering. Using an s-d exchange (between itinerant s and nearly localized d electrons) Hamiltonian, it was shown (Zhang *et al.*, 1997) that, at $V\to 0$, $G(T)-G(0)$ is proportional to $T\ln T$, for both $\uparrow\uparrow$ and $\uparrow\downarrow$ orientations. A different temperature dependence of TMR was suggested by Moodera *et al.* (1998). It was related to the decrease of the surface magnetization (Pierce *et al.*, 1982; Pierce and Celotta, 1984)

[90]Related applications are usually in a diffusive regime.

[91]For its limitations and extensions see comprehensive reviews by Moodera and Mathon (1999) and Moodera *et al.* (1999).

[92]A formally analogous problem was considered by Griffin and Demers (1971) in an N/I/S system where the two-component wave functions represented electronlike and holelike quasiparticles rather then the two-spin projections; see Sec. IV.A.3.

$M(T)/M(0) \propto T^{-3/2}$. Such a temperature dependence (known as Bloch's law and reviewed by Krey, 2004), attributed to magnons, was also obtained for TMR (MacDonald *et al.*, 1998). An additional decrease of TMR with T was expected due to the spin-independent part of $G(T)$ (Shang *et al.*, 1998), seen also in N/I/N junctions.

Systematic studies of MTJ's containing a semiconductor (Sm) region (used as a tunneling barrier and/or an F electrode) have begun only recently.[93] To improve the performance of MTJ's it is desirable to reduce the junction resistance. A smaller RC constant would allow faster switching times in magnetic random-access memories (for a detailed discussion see De Boeck *et al.*, 2002). Correspondingly, using a semiconducting barrier could prove an alternative strategy for difficult fabrication of ultrathin (<1 nm) oxide barriers (Rippard *et al.*, 2002). Some F/Sm/F magnetic tunnel junctions have been grown epitaxially, and the amplitude of TMR can be studied as a function of the crystallographic orientation of a F/Sm interface. For an epitaxially grown Fe/ZnSe/Fe MTJ, electronic structure calculations have predicted (MacLaren *et al.*, 1999) large TMR (up to $\sim 1000\%$), increasing with ZnSe thickness. However, the observed TMR in Fe/ZnSe/$Fe_{0.85}Co_{0.15}$ was limited below 50 K, reaching 15% at 10 K for junctions of higher resistance and lower defect density[94] (Gustavsson *et al.*, 2001). Results on ZnS, another II-VI semiconductor, demonstrated a TMR of $\sim 5\%$ at room temperature (Guth *et al.*, 2001).

There is also a possibility of using all-semiconductor F/Sm/F single-crystalline MTJ's where F is a ferromagnetic semiconductor. These would simplify integration with the existing conventional semiconductor-based electronics and allow flexibility of various doping profiles and fabrication of quantum structures, as compared to the conventional all-metal MTJ's. Large TMR ($>70\%$ at 8 K), shown in Fig. 23, has been measured in an epitaxially grown (Ga,Mn)As/AlAs/(Ga,Mn)As junction (Tanaka and Higo, 2001). The results are consistent with $k_{\parallel}$ being conserved in the tunneling process (Mathon and Umerski, 1997), with the decrease of TMR with T expected from the spin-wave excitations (MacDonald *et al.*, 1998; Shang *et al.*, 1998), discussed above. Tunneling magnetoresistance is nonmonotonic with thickness in AlAs (with the peak at ~ 1.5 nm). For a given AlAs thickness, double MTJ's were also shown to give similar TMR values and were used to determine

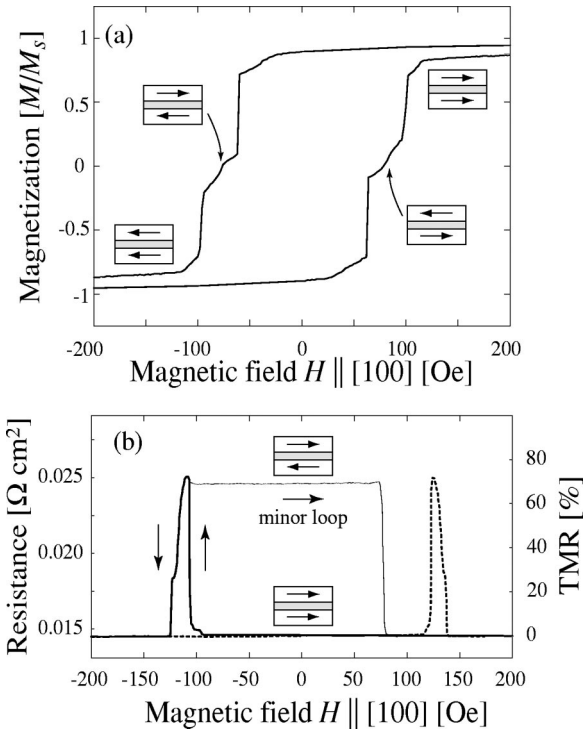

FIG. 23. All-semiconductor magnetic tunnel junction: (a) magnetization of $Ga_{1-x}Mn_xAs$ ($x=4.0\%$, 50 nm)/AlAs (3 nm)/$Ga_{1-x}Mn_xAs$ ($x=3.3\%$, 50 nm) trilayer measured by a SQUID at 8 K. The sample size is 3×3 mm^2. Magnetization shown is normalized with respect to the saturation value M_s. (b) TMR curves of a $Ga_{1-x}Mn_xAs$ ($x=4.0\%$, 50 nm)/AlAs (1.6 nm)/$Ga_{1-x}Mn_xAs$ ($x=3.3\%$, 50 nm) tunnel junction of 200 μm in diameter. Bold solid curve, sweep of the magnetic field from positive to negative; dashed curve, sweep from negative to positive; thin solid curve, a minor loop. From Tanaka and Higo, 2001.

electrically the spin injection in GaAs quantum wells (Mattana *et al.*, 2003). However, a room-temperature effect remains to be demonstrated as the available well-characterized ferromagnetic semiconductors do not have as high a ferromagnetic transition temperature.

A lower barrier in F/Sm/F MTJ's can have important implications in determining the actual values of TMR. The standard four-probe technique for measuring I and V has been known to give spurious values when the resistance of the F electrodes is non-negligible to the junction resistance. The tunneling current in that regime has been shown to be highly nonuniform[95] and the measured apparent resistance $R_m = V/I$ (different from the actual junction resistance R_J) can even attain negative values (Pederson and Vernon, 1967; Moodera *et al.*, 1996). The important implications for MTJ's are the possibility of large overestimates in the TMR amplitude (Moodera and Mathon, 1999) and a desirable hysteresis effect—at

[93]The early F/Ge/F results (Jullière, 1975) were not reproduced, and other metallic structures involving Si, Ge, GaAs, and GaN as a barrier have shown either no (Gibson and Meservey, 1985; Loraine *et al.*, 2000; Boeve *et al.*, 2001) or only a small (Meservey *et al.*, 1982; Jia *et al.*, 1996; Kreuzer *et al.*, 2002) spin-dependent signal.

[94]Interface defects could diminish measured TMR. We recall (see Sec. II.D.3) that at a ZnMnSe/AlGaAs interface they limit the spin injection efficiency (Stroud *et al.*, 2002) and from Eq. (32) infer a reduced spin-valve effect.

[95]Nonuniform tunneling current has been studied in nonmagnetic junctions (Pederson and Vernon, 1967), CPP multilayers (Lenczowski *et al.*, 1994), and conventional MTJ's (Moodera *et al.*, 1996; Rzchowski and Wu, 2000).

$H=0$ the two values of resistance can be used for various nonvolatile applications (Moodera *et al.*, 1996).

A detailed understanding of MTJ's will also require knowing the influence of the interface and surface roughness (Itoh *et al.*, 1999). Even in the spin-unpolarized case it is known that the full quantum-mechanical approach (Tešanović *et al.*, 1986) can lead to qualitatively different results from the usual quasiclassical picture and from averaging out the spatial information on the length scale of the inverse Fermi wave vector.

A comprehensive review of tunneling phenomena and magnetoresistance in granular materials, ferromagnetic single-electron transistors, and double tunnel junctions is given by Maekawa *et al.* (2002). A theoretical study of F/I/F junctions, in which the I region is a quantum dot, shows the importance of Coulomb interactions, which could lead to spin precession even in the absence of an applied magnetic field (König and Martinek, 2003).

3. Andreev reflection

Andreev reflection (Andreev, 1964) is a scattering process, at an interface with a superconductor, responsible for a conversion between a dissipative quasiparticle current and a dissipationless supercurrent [see also early work by de Gennes and Saint James (1963)]. For a spin-singlet superconductor an incident electron (hole) of spin λ is reflected as a hole (electron) belonging to the opposite spin subband $\bar{\lambda}$, back to the nonsuperconducting region, while a Cooper pair is transferred to the superconductor. This is a phase-coherent scattering process in which the reflected particle carries information about both the phase of the incident particle and the macroscopic phase of the superconductor.[96] Andreev reflection thus is responsible for a proximity effect where the phase correlations are introduced to a nonsuperconducting material (Demler *et al.*, 1997; Bergeret *et al.*, 2001; Halterman and Valls, 2002; Izyumov *et al.*, 2002; Fominov, 2003). The probability for Andreev reflection at low bias voltage ($qV \lesssim \Delta$), which is related to the square of the normal-state transmission, could be ignored for low-transparency junctions with conventional superconductors, as discussed in Sec. IV.A.1. In contrast, for high-transparency junctions (see the discussion of Sharvin conductance in Sec. II.C.2), single-particle tunneling vanishes [recall Eq. (100)] at low bias and $T=0$ and Andreev reflection is the dominant process. A convenient description is provided by the Bogoliubov–de Gennes equations (de Gennes, 1989),

$$\begin{bmatrix} H_\lambda & \Delta \\ \Delta^* & -H_{\bar{\lambda}}^* \end{bmatrix} \begin{bmatrix} u_\lambda \\ v_{\bar{\lambda}} \end{bmatrix} = E \begin{bmatrix} u_\lambda \\ v_{\bar{\lambda}} \end{bmatrix}, \tag{103}$$

and by matching the wave functions at the boundaries (interfaces) between different regions. Here H_λ is the single-particle Hamiltonian for spin $\lambda=\uparrow,\downarrow$, and $\bar{\lambda}$ denotes a spin opposite to λ (de Jong and Beenakker, 1995; Žutić and Valls, 2000). Δ is the pair potential (de Gennes, 1989), E the excitation energy, and u_λ, $v_{\bar{\lambda}}$ are the electronlike quasiparticle and holelike quasiparticle amplitudes, respectively.[97] Griffin and Demers (1971) have solved the Bogoliubov–de Gennes equations with square or δ-function barriers of varying strength at an N/S interface. They obtained a result that interpolates between the clean and the tunneling limits. Blonder *et al.* (1982) used a similar approach, known as the Blonder-Tinkham-Klapwijk method, in which the two limits correspond to $Z\to 0$ and $Z\to\infty$, respectively, and Z is the strength of the δ-function barrier. The transparency of this approach[98] makes it suitable for the study of ballistic spin-polarized transport and spin injection even in the absence of a superconducting region (Heersche *et al.*, 2001; Hu and Matsuyama, 2001; Hu, Nitta, *et al.*, 2001; Matsuyama *et al.*, 2002).

It is instructive to note a similarity between the two-component transport in N/S junctions (for electronlike and holelike quasiparticles) and F/N junctions (for spin $\uparrow$, $\downarrow$), which both lead to current conversion, accompanied by additional boundary resistance (Blonder *et al.*, 1982; van Son *et al.*, 1987). In the N/S junction Andreev reflection is responsible for the conversion between the normal and the supercurrent, characterized by the superconducting coherence length, while in the F/N case a conversion between spin-polarized and unpolarized current is characterized by the spin diffusion length.

For spin-polarized carriers, with different populations in two spin subbands, only a fraction of the incident electrons from a majority subband will have a minority subband partner in order to be Andreev reflected. This can be simply quantified at zero bias and $Z=0$, in terms of the total number of scattering channels (for each $k_\parallel$) $N_\lambda = k_{F\lambda}^2 A/4\pi$ at the Fermi level. Here A is the point-contact area, and $k_{F\lambda}$ is the spin-resolved Fermi wave vector. A spherical Fermi surface in the F and S regions, with no (spin-averaged) Fermi velocity mismatch, is assumed. When S is in the normal state, the zero-temperature Sharvin conductance is

$$G_{FN} = \frac{e^2}{h}(N_\uparrow + N_\downarrow), \tag{104}$$

equivalent to R_{Sharvin}^{-1}, from Eq. (47). In the superconducting state all of the $N_\downarrow$ and only $(N_\downarrow/N_\uparrow)N_\uparrow$ scattering channels contribute to Andreev reflection across the F/S interface and transfer charge $2e$, yielding (de Jong and Beenakker, 1995)

[96] For instructive reviews see Lambert and Raimondi (1998); Pannetier and Courtois (2000).

[97] Equation (103) can be simply modified to include the spin flip and spin-dependent interfacial scattering (Žutić and Das Sarma, 1999).

[98] A good agreement (Yan *et al.*, 2000) was obtained with the more rigorous nonequilibrium Keldysh technique (Keldysh, 1964; Rammer and Smith, 1986). For an illustration of how such a technique can be used to study spin-polarized transport in a wide range of heterojunctions see Mélin and Feinberg (2002); Zeng *et al.* (2003).

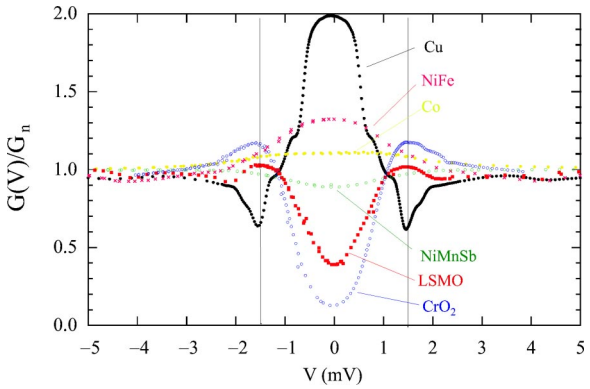

FIG. 24. (Color in online edition) The differential conductance for several spin-polarized materials, showing the suppression of Andreev reflection with increasing P_G. The vertical lines denote the bulk superconducting gap for Nb: $\Delta(T=0)=1.5$ meV. Note that NiMnSb, one of the Heusler alloys originally proposed as half-metallic ferromagnets (de Groot, Mueller, *et al.*, 1983), shows only partial spin polarization. From Soulen *et al.*, 1998.

$$G_{FS}=\frac{e^2}{h}\left(2N_{\downarrow}+\frac{2N_{\downarrow}}{N_{\uparrow}}N_{\uparrow}\right)=4\frac{e^2}{h}N_{\downarrow}. \tag{105}$$

The suppression of the normalized zero-bias conductance at $V=0$ and $Z=0$ (de Jong and Beenakker, 1995),

$$G_{FS}/G_{FN}=2(1-P_G), \tag{106}$$

with the increase in the spin polarization $P_G\rightarrow(N_{\uparrow}-N_{\downarrow})/(N_{\uparrow}+N_{\downarrow})$, was used as a sensitive transport technique to detect spin polarization in a point contact (Soulen *et al.*, 1998). Data are given in Fig. 24. A similar study, using a thin-film nanocontact geometry (Upadhyay *et al.*, 1998), emphasized the importance of fitting the conductance data over a wide range of applied bias, not only at $V=0$, in order to extract the spin polarization of the F region more precisely.

The advantage of such techniques is the detection of polarization in a much wider range of materials than those which can be grown for detection in F/I/S or F/I/F tunnel junctions. A large number of experimental results using spin-polarized Andreev reflection has since been reported (Bourgeois *et al.*, 2001; Ji *et al.*, 2001; Nadgorny *et al.*, 2001; Parker *et al.*, 2002; Panguluri, Tsoi, *et al.*, 2003), including the first direct measurements (Braden *et al.*, 2003; Panguluri, Nadgorny, *et al.*, 2003; Panguluri *et al.*, 2004) of the spin polarization in (Ga,Mn)As and (In,Mn)Sb.[99] However, for a quantitative interpretation of the measured polarization, important additional factors (similar to the limitations discussed for the application of Jullière's formula in Sec. IV.A.2) need to be incorporated in the picture provided by Eq. (106). For example, the Fermi surface may not be spherical [see the discussion of Mazin (1999), specifying what type of spin polarization is experimentally measured and also that of Xia *et al.* (2002)]. The roughness or the size of the F/S interface may lead to a diffusive component of the transport (Fal'ko *et al.*, 1999; Jedema *et al.*, 1999; Mazin *et al.*, 2001). As a caution concerning the possible difficulties in analyzing experimental data, we mention some subtleties that arise even for the simple model of a spherical Fermi surface used to describe both F and S regions. Unlike charge transport in N/S junctions (Blonder and Tinkham, 1983) in a Griffin-Demers-Blonder-Tinkham-Klapwijk approach, Fermi velocity mismatch between the F and the S regions does not simply increase the value of effective Z. Specifically, at $Z=V=0$ and normal incidence it is possible to have perfect transparency, even when all the Fermi velocities differ, satisfying $(v_{F\uparrow}v_{F\downarrow})^{1/2}=v_S$, where v_S is the Fermi velocity in a superconductor (Žutić and Das Sarma, 1999; Žutić and Valls, 1999, 2000). In other words, unlike in Eq. (106), the spin polarization (nonvanishing exchange energy) can *increase* the subband conductance, for fixed Fermi velocity mismatch. Conversely, at a fixed exchange energy, an increase in Fermi velocity mismatch could increase the subgap conductance.[100] In a typical interpretation of a measured conductance, complications can then arise in trying to disentangle the influence of parameters Z, P_G, and Fermi velocity mismatch from the nature of the point contacts (Kikuchi *et al.*, 2002) and the role of inelastic scattering (Auth *et al.*, 2003). Detection of P in a high-temperature superconductor is even possible with a large barrier or a vacuum between the F and S regions, as proposed by Wang and Hu (2002) using resonant Andreev reflection and a d-wave superconductor.[101]

Large magnetoresistive effects are predicted for crossed Andreev reflection (Deutscher and Feinberg, 2000) when the two F regions, separated within the distance of the superconducting coherence length,[102] are on the same side of the S region. Such structures have also been theoretically studied to understand the implications of nonlocal correlations (Apinyan and Mélin, 2002; Mélin and Feinberg, 2002).

4. Spin-polarized drift and diffusion

Traditional semiconductor devices such as field-effect transistors, bipolar diodes and transistors, or semicon-

[99]Similar measurements were also suggested by Žutić and Das Sarma (1999) to yield information about the FSm/S interface. A more complete analysis should also quantify the effects of spin-orbit coupling.

[100]Similar results were also obtained when F and S region were separated with a quantum dot (Zhu *et al.*, 2002; Feng and Xiong, 2003; Zeng *et al.*, 2003) and even in a 1D tight-binding model with no spin polarization (Affleck *et al.*, 2000).

[101]Interference effects between quasielectron and quasihole scattering trajectories that feel pair potentials of different sign lead to a large conductance near zero bias, even at large interfacial barrier (referred to as a zero-bias conductance peak in Sec. IV.A.1).

[102]Recent theoretical findings suggest that the separation should not exceed the Fermi wavelength (Yamashita, Takahashi, and Maekawa, 2003).

ductor solar cells rely in great part on carriers (electrons and holes) whose motion can be described as drift and diffusion, limited by carrier recombination. In inhomogeneous devices where charge buildup is the rule, the recombination-limited drift diffusion is supplied by Maxwell's equations, to be solved in a self-consistent manner. Many proposed spintronic devices as well as experimental settings for spin injection (Sec. II) can be described by both carrier and spin drift and diffusion, limited by carrier recombination and spin relaxation (Fabian *et al.*, 2002a; Žutić *et al.*, 2002). In addition, if spin precession is important for device operation, spin dynamics need to be explicitly incorporated into the transport equations (Qi and Zhang, 2003). Drift of the spin-polarized carriers can be due not only to the electric field, but also to magnetic fields. We illustrate spin-polarized drift and diffusion on the transport model of spin-polarized bipolar transport, where bipolar refers to the presence of electrons and holes, not spin up and down. A spin-polarized unipolar transport can be obtained as a limiting case by setting the electron-hole recombination rate to zero and considering only one type of carrier (either electrons or holes).

Consider electrons and holes whose density is commonly denoted here as c (for carriers), moving in the electrostatic potential ϕ which comprises both the external bias V and the internal built-in fields due to charge inhomogeneities. Let the equilibrium spin splitting of the carrier band be $2q\zeta_c$. The spin λ resolved carrier charge-current density is (Žutić *et al.*, 2002)

$$\mathbf{j}_{c\lambda} = -q\mu_{c\lambda}c_\lambda\nabla\phi \pm qD_{c\lambda}\nabla c_\lambda - q\lambda\mu_{c\lambda}c_\lambda\nabla\zeta_c, \quad (107)$$

where μ and D stand for mobility and diffusion coefficients, the upper sign is for electrons, and the lower sign is for holes. The first term on the right-hand side describes drift caused by the total electric field, the second term represents diffusion, while the last term stands for magnetic drift—carrier drift in inhomogeneously split bands.[103] More transparent are the equations for the total charge, $j=j_\uparrow+j_\downarrow$, and spin, $j_s=j_\uparrow-j_\downarrow$, current densities:

$$\mathbf{j}_c = -\sigma_c\nabla\phi - \sigma_{sc}\nabla\zeta_c \pm qD_c\nabla c \pm qD_{sc}\nabla s_c, \quad (108)$$

$$\mathbf{j}_{sc} = -\sigma_{sc}\nabla\phi - \sigma_c\nabla\zeta_c \pm qD_{sc}\nabla c \pm qD_c\nabla s_c, \quad (109)$$

where the carrier density $c=c_\uparrow+c_\downarrow$ and spin $s_c=c_\uparrow-c_\downarrow$, and we introduced the carrier charge and spin conductivities $\sigma_c=q(\mu_c c+\mu_{sc}s_c)$ and $\sigma_{sc}=q(\mu_{sc}c+\mu_c s_c)$, where $\mu_c=(\mu_{c\uparrow}+\mu_{c\downarrow})/2$ and $\mu_{cs}=(\mu_{c\uparrow}-\mu_{c\downarrow})/2$ are charge and spin mobilities, and similarly for the diffusion coefficients. Equation (108) describes the spin-charge coupling in bipolar transport in inhomogeneous magnetic semiconductors. Spatial variations in spin density can cause charge currents. Similarly, it follows from Eq. (109) that spatial variations in carrier densities can lead to spin currents.

Steady-state carrier recombination and spin relaxation processes are described by the continuity equations for the spin-resolved carrier densities:

$$\nabla\cdot\frac{\mathbf{j}_{c\lambda}}{q} = \pm w_{c\lambda}(c_\lambda\overline{c} - c_{\lambda 0}\overline{c_0}) \pm \frac{c_\lambda - c_{-\lambda} - \lambda\tilde{s}_c}{2\tau_{sc}}. \quad (110)$$

Here w is the spin-dependent recombination rate, the bar denotes a complementary carrier ($\overline{n}=p$, for example), τ_{sc} is the spin relaxation time of the carrier c (not to be confused with the single spin decoherence time discussed in Sec. III.A.1), and $\tilde{s}_c=P_{c0}c$ is the nonequilibrium spin density, which appears after realizing that spin relaxation equilibrates spin while preserving carrier density. Finally, the set of equations is completed with Poisson's equation,

$$\varepsilon\Delta\phi = -\rho, \quad (111)$$

connecting the electric field and charge $\rho=q(p-n+N_d-N_a)$, where N_d and N_a are the donor and acceptor densities, respectively, and ε is the dielectric constant.

In many important cases Eqs. (107), (110), and (111) need to be solved self-consistently, which usually requires numerical techniques (Žutić *et al.*, 2002). In some cases it is possible to extract the relevant physics in limiting cases analytically, usually neglecting electric field or magnetic drift. In unipolar spin-polarized transport one does not need to consider carrier recombination. It also often suffices to study pure spin diffusion, if the built-in electric fields are small. Unipolar spin-polarized transport in inhomogeneous systems in the presence of electric fields was analyzed by Fabian *et al.* (2002a); Yu and Flatte (2002a, 2002b); Martin (2003); Pershin and Privman (2003a). Spin-polarized drift and diffusion in model GaAs quantum wires was studied by Sogawa *et al.* (2000), while ramifications of magnetic drift for unipolar transport were studied by Fabian *et al.* (2002a) and Martin (2003). Bipolar transport in the presence of electrical drift and/or diffusion has been studied by Flatté and Byers (2000); Beck *et al.* (2002); Fabian *et al.* (2002a); Žutić *et al.* (2002). Transient dynamics of spin drift and diffusion was considered by Fabian and Das Sarma (2002). Recently an interesting study (Saikin *et al.*, 2003) was reported on a Monte Carlo simulation of quantum-mechanical spin dynamics limited by spin relaxation, in which quasiclassical orbital transport was carried out for the in-plane transport in III-V heterostructures where spin precession is due to bulk and structure inversion asymmetry (see Sec. III.B.2).

B. Materials considerations

Nominally highly spin-polarized materials, as discussed in the previous sections, could provide both effective spin injection into nonmagnetic materials and large magnetoresistance effects, important for nonvolatile applications. Examples include half-metallic oxides such as CrO_2, Fe_3O_4, CMR materials, and double per-

[103] Equation (107) can be viewed as the generalization of the Silsbee-Johnson spin-charge coupling (Johnson and Silsbee, 1987; Wegrowe, 2000; Heide, 2001) to bipolar transport and to systems with spatially inhomogenous charge density.

ovskites (Kobayashi *et al.*, 1998; for reviews of half-metallic materials see Pickett and Moodera, 2001; Fang *et al.*, 2002). Ferromagnetic semiconductors (Nagaev, 1983), known since $CrBr_3$ (Tsubokawa, 1960), have been demonstrated to be highly spin polarized. However, more recent interest in ferromagnetic semiconductors was spurred by the fabrication of (III,Mn)V compounds.[104] After the initial discovery of (In,Mn)As (Munekata *et al.*, 1989, 1991; Ohno *et al.*, 1992), most of the research has focused on (Ga,Mn)As (Ohno *et al.*, 1996; Hayashi *et al.*, 1997; Van Esch *et al.*, 1997). In contrast to (In,Mn)As and (Ga,Mn)As with high carrier density ($\sim 10^{20}$ cm^{-3}), a much lower carrier density in (Zn,Cr)Te (Saito *et al.*, 2002), a II-VI ferromagnetic semiconductor with Curie temperature T_C near room temperature (Saito *et al.*, 2003), suggests that transport properties can be effectively controlled by carrier doping. Most of the currently studied ferromagnetic semiconductors are p-doped with holes as spin-polarized carriers, which typically leads to lower mobilities and shorter spin relaxation times than in n-doped materials. It is possible to use selective doping to substantially increase T_c, as compared to the uniformly doped bulk ferromagnetic semiconductors (Nazmul *et al.*, 2003).

Early work on (Ga,Mn)As (De Boeck *et al.*, 1996) showed the low solubility of Mn and the formation of magnetic nanoclusters characteristic of many subsequent compounds and different magnetic impurities. The presence of such nanoclusters often complicates accurate determination of T_C as well as of whether the compound is actually in a single phase. Consequently, the reported room-temperature ferromagnetism in an increasing number of compounds (reviewed by Pearton *et al.*, 2003) is not universally accepted. Conclusive evidence for intrinsic ferromagnetism in semiconductors is highly nontrivial. For example, early work reporting ferromagnetism even at nearly 900 K in La-doped $CaBa_6$ (Young *et al.*, 1999; Ott *et al.*, 2000; Tromp *et al.*, 2001), was later revisited suggesting extrinsic effect (Bennett *et al.*, 2003). It remains to be understood what the limitations are for using extrinsic ferromagnets and, for example, whether they can be effective spin injectors.

A high T_C and almost complete spin polarization in bulk samples are alone not sufficient for successful applications. Spintronic devices typically rely on inhomogeneous doping, structures of reduced dimensionality, and/or structures containing different materials. Interfacial properties, as discussed in the previous sections, can significantly influence the magnitude of magnetoresistive effects[105] and the efficiency of spin injection. Doping

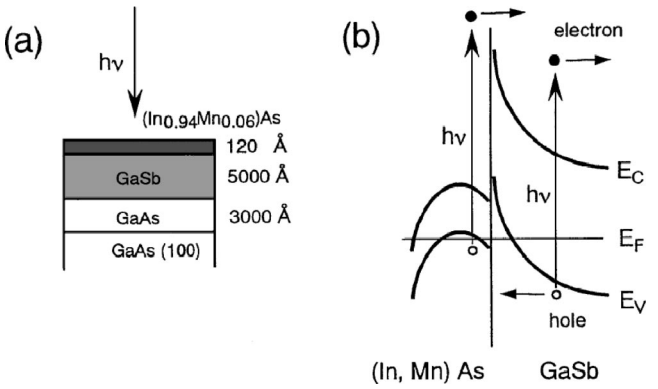

FIG. 25. Photoinduced ferromagnetism in a (In,Mn)As/GaSb heterostructure: (a) light-irradiated sample displaying photoinduced ferromagnetism—direction of light irradiation is shown by an arrow; (b) band-edge profile of (In,Mn)As/GaSb heterostructure. E_c, conduction band; E_v, valence band; E_F, Fermi level. From Koshihara *et al.*, 1997.

properties and the possibility of fabricating a wide range of structures allow spintronic applications beyond magnetoresistance effects, for example, spin transistors, spin lasers, and spin-based quantum computers (Sec. IV.F). Materials properties of hybrid F/Sm heterostructures, relevant to device applications, were reviewed by Samarth *et al.* (2003).

Experiments in which ferromagnetism is induced optically (Koshihara *et al.*, 1997; Oiwa *et al.*, 2002; Wang *et al.*, 2003) and electrically (Ohno, Chiba, *et al.*, 2000; Park *et al.*, 2002) provide a method for distinguishing carrier-induced ferromagnetism, based on the exchange interaction between the carrier and the magnetic impurity spins, from ferromagnetism that originates from magnetic nanoclusters. Such experiments also suggest possible nonvolatile multifunctional devices with tunable, optical, electrical, and magnetic properties. Comprehensive surveys of magneto-optical materials and applications, not limited to semiconductors, are given by Zvezdin and Kotov (1997) and Sugamo and Kojima (2000).

Photoinduced ferromagnetism was demonstrated by Koshihara *et al.* (1997) in p-(In,Mn)As/GaSb heterostructure, shown in Figs. 25 and 26. Unpolarized light penetrates through a thin (In,Mn)As layer and is absorbed in a GaSb layer. A large band bending across the heterostructures separates, by a built-in field, electrons and holes. The excess holes generated in the GaSb layer are effectively transferred to the p-doped (In,Mn)As layer, where they enhance the ferromagnetic spin exchange among Mn ions, resulting in a paramagnetic-ferromagnetic transition.

The increase in magnetization, measured by a SQUID, is shown in Fig. 26(a), and in Fig. 26(b) the corresponding Hall resistivity

$$\rho_{\mathrm{Hall}} = R_0 B + R_S M, \tag{112}$$

is shown, where the R_0 is the ordinary and R_S the anomalous Hall coefficient, respectively. Typical for (III,Mn)V compounds, ρ_{Hall} is dominated by the anomalous contribution, $\rho_{\mathrm{Hall}} \propto M$.

[104]Ferromagnetic order with Mn doping was obtained previously, for example, in (Sn,Mn)Te (Escorne *et al.*, 1974), (Ge,Mn)Te (Cochrane *et al.*, 1974), and (Pb,Sn,Mn)Te (Story *et al.*, 1986).

[105]In magnetic multilayers GMR is typically dominated by interfacial scattering (Parkin, 1993), while in MTJ's it is the surface rather than the bulk electronic structure which influences the relevant spin polarization.

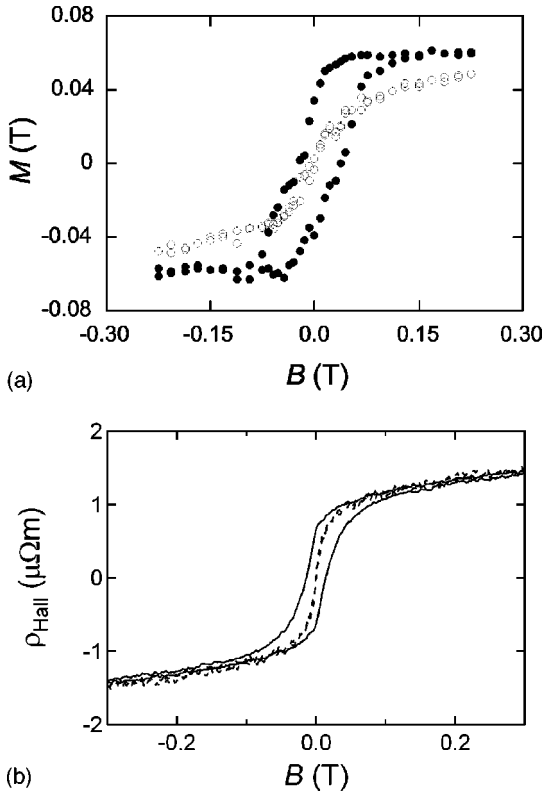

FIG. 26. Magnetization curves for (In,Mn)As/GaSb at 5 K observed before (open circles) and after (solid circles) light irradiation. Solid line show a theoretical curve. (b) Hall resistivity at 5 K before (dashed lines) and after (solid lines) light irradiation. From Koshihara *et al.*, 1997.

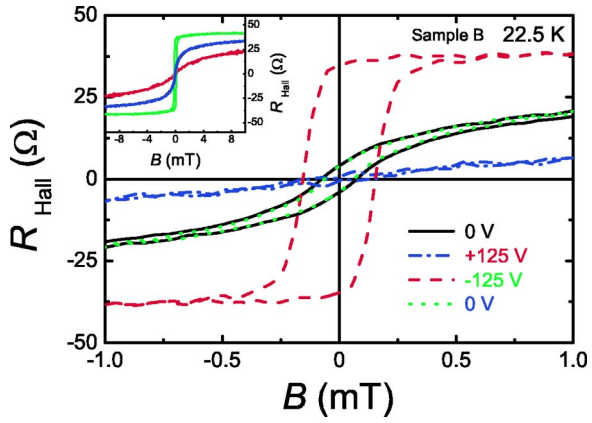

FIG. 27. (Color in online edition) Electric-field control of ferromagnetism. R_{Hall} vs field curves under three different gate biases. Application of $V_G=0$, $+125$, and -125 V results in a qualitatively different field dependence of R_{Hall} measured at 22.5 K (sample B): almost horizontal dash-dotted line, paramagnetic response when holes are partially depleted from the channel ($V_G=+125$ V); dashed lines, clear hysteresis at low fields (<0.7 mT) as holes are accumulated in the channel ($V_G=-125$ V); solid line, R_{Hall} curve measured at $V_G=0$ V before application of ± 125 V; dotted line, R_{Hall} curve after application of ± 125 V. Inset, the same curves shown at higher magnetic fields. From Ohno, Chiba, *et al.*, 2000.

A different type of photoinduced magnetization was measured in ferromagnetic (Ga,Mn)As.[106] In a Faraday geometry (Sec. II.D.3), by changing the polarization of a circularly polarized light, one can modulate the Hall resistance and thus the induced magnetization by up to 15% of the saturation value (Oiwa *et al.*, 2002). Additional experiments on photoinduced magnetization rotation (Munekata *et al.*, 2003; Oiwa *et al.*, 2003) suggest that the main contribution of carrier spin to such rotation is realized by generating an effective magnetic field through the p-d exchange interaction, rather than by spin-transfer torque, as discussed in Secs. I.B.1 and V (Moriya *et al.*, 2003). In GaAs-Fe composite films an observation of room-temperature photoenhanced magnetization was used to demonstrate that a magnetic force can be changed by light illumination (Shinshi *et al.*, 2003).

Electrically induced ferromagnetism was realized by applying gate voltage V_G to change the hole concentration in $d=5$ nm thick (In,Mn)As used as a magnetic channel in a metal-insulator semiconductor FET structure. Below a metal gate and an insulator the (In,Mn)As channel was grown on top of a InAs/(Al,Ga)Sb/AlSb and GaAs substrate. In Fig. 27, the corresponding data for $R_{\mathrm{Hall}}=\rho_{\mathrm{Hall}}/d\propto M$ [recall Eq. (112)] show that the ferromagnetism can be switched on and off, as an electric analog of the manipulation of M from Fig. 26. Subsequent work by Park *et al.* (2002) showed that in MnGe ferromagnetism can be manipulated at higher temperature and at significantly lower gate voltage (at ~ 50 K and ~ 1 V). The combination of light and electric-field control of ferromagnetism was used in modulation-doped p-type (Cd,Mn)Te quantum wells (Boukari *et al.*, 2002). It was demonstrated that illumination by light in p-i-n diodes would enhance the spontaneous magnetization, while illumination in p-i-p structures would destroy ferromagnetism.

In semiconductors g factors, which determine the spin splitting of carrier bands (and consequently influence the spin dynamics and spin resonance), can be very different from the free-electron value. With strong spin-orbit coupling in narrow-band III-V's they are ≈ -50 for InSb and ≈ -15 for InAs, while, as discussed in Sec. II.D.3, doping with magnetic impurities can give even $|g^*|\sim 500$. Manipulation of the g factor in a GaAs/AlGaAs quantum well in Fig. 28, relies on the results for a bulk $Al_xGa_{1-x}As$; the variation of Al concentration changes the g factor (Chadi *et al.*, 1976; Weisbuch and Herman, 1977) to $g=-0.44$ for $x=0$ and $g=0.40$ for $x=0.3$. Related experiments on modulation-doped $GaAs/Al_{0.3}Ga_{0.7}As$ have shown that by applying V_G one can shift the electron wave function in the quantum well and produce $\sim 1\%$ change in the g factor (Jiang and Yablonovitch, 2001). Subsequently, in an optimized $Al_xGa_{1-x}As$ quantum well, where x varied gradually

[106]Previous studies in paramagnetic (II,Mn)VI materials have shown that nonequilibrium spin-polarized carriers can change the orientation of magnetic spins in (Hg,Mn)Te (Krenn *et al.*, 1989, 1985) and in (Cd,Mn)Te (Awschalom *et al.*, 1987).

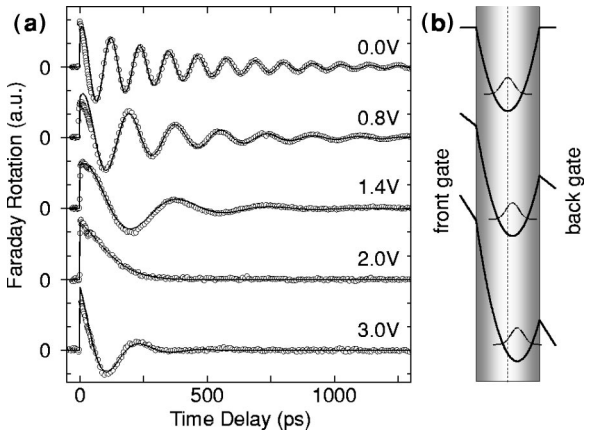

FIG. 28. Voltage-controlled spin precession: (a) time-resolved Kerr rotation measurements of electron spin precession in a quantum well at different gate voltages V_G with Al concentration of 7% at 5 K and $B=6$ T; (b) displacement of the electron wave function towards the back gate into regions with more Al concentration as a positive voltage V_G is applied between back and front gate; leading to an increase of g. At $V_G=2$ V, no precession is observed, corresponding to $g=0$. From Salis, Koto, *et al.*, 2001.

across the structure, much larger changes were measured—when V_G is changed, the electron wave function efficiently samples different regions with different g factors (Salis, Kato, *et al.*, 2001). Figure 28(a) gives the time-resolved Kerr rotation data (the technique is discussed in Sec. III), which can be described as $\propto\exp(-\Delta t/T_2^*)\cos(\Omega\Delta t)$, where Δt is the delay time between the circularly polarized pump and linearly polarized probe pulses, T_2^* is the transverse electron spin lifetime with inhomogeneous broadening, and the angular precession frequency $\Omega=\mu_B g B/\hbar$ can be used to determine the g factor. It is also possible to manipulate g factors dynamically using time-dependent V_G (Kato *et al.*, 2003). The anisotropy of g factor (g tensor) allows voltage control of both the magnitude and the direction of the spin precession vector $\mathbf{\Omega}$.

C. Spin filters

Solid-state spin filtering (recall the similarity with spin injection from Sec. II.C.1) was first realized in N/F/N tunneling. It was shown by Esaki *et al.* (1976) that magnetic tunneling through (ferro)magnetic semiconductor Eu chalcogenides (von Molnár and Methfess, 1967; Kasuya and Yanase, 1968; Nagaev, 1983), such as EuSe[107] and EuS,[108] could be modified by an applied magnetic field. The change in I-V curves in the N/F/N structure, where N is a normal metal and F is a ferromagnet, was explained by the influence of the magnetic field on the height of the barrier formed at the N/F interface (for EuSe, the barrier height was lowered by 25% at 2 T). The large spin splitting of the Eu chalcogenides was subsequently employed in the absence of applied field with EuS (Moodera *et al.*, 1988), and nearly 100% spin polarization was reached at $B=1.2$ T with EuSe (Moodera *et al.*, 1993). These spin-filtering properties of the Eu chalcogenides, used together with one-electron quantum dots, were proposed as the basis for a method to convert single spin into single charge measurements[109] and provide an important ingredient in realizing a quantum computer (DiVincenzo, 1999); see Sec. IV.F.

Zeeman splitting in semiconductor heterostructures and superlattices (enhanced by large g factors; Egues, 1998; Guo *et al.*, 2001), in quantum dots (Recher *et al.*, 2000; Deshmukh and Ralph, 2002; Borda *et al.*, 2003), and nanocrystals (Efros *et al.*, 2001) provide effective spin filtering and spin-polarized currents. Predicted quantum size effects and resonance tunneling (Duke, 1969, p. 79) also have their spin-dependent counterparts. The structures studied are typically double-barrier resonant tunneling diodes (for an early spin-unpolarized study see Tsu and Esaki, 1973), either with Zeeman splitting or using ferromagnetic materials, in which spin filtering can be tuned by an applied bias.[110]

Several other realizations of spin filtering have been investigated, relying on spin-orbit coupling[111] or hot-electron transport across ferromagnetic regions,[112] discussed in more detail in Sec. IV.E.3. A choice of particular atomically ordered F/Sm interfaces was suggested to give a strong spin-filtering effect (Kirczenow, 2001), limited by the spin-orbit coupling and interfacial spin-flip scattering.

Mesoscopic spin filters have also been suggested (Frustaglia *et al.*, 2001; Joshi *et al.*, 2001; Avodin *et al.*, 2003; Ionicioiu and D'Amico, 2003), and we discuss here a particular realization. In an applied magnetic field two quantum point contacts, an emitter, and a collector fabricated on top of a high-mobility 2DEG in GaAs/AlGaAs, can act as spin polarizer and analyzer (Potok *et al.*, 2002).[113] In a ballistic regime and at $T=70$ mK (mean free path$\approx$45 μm$\gg$sample size$\approx$1.5 μm) magnetic focusing[114] with $B_\perp$ results in base-collector volt-

[107]At zero magnetic field EuSe is an antiferromagnet, and at moderate fields it becomes a ferromagnet with $T_C\approx 5$ K.

[108]At zero magnetic field, exchange splitting of a conduction band in bulk EuS is $\approx$0.36 eV (Hao *et al.*, 1990).

[109]This method could be realized using single-electron transistors or quantum point contacts

[110]See, for example, Aleiner and Lyanda-Geller (1991); Brehmer *et al.* (1995); Mendez *et al.* (1998); Ohno (1998); Petukhov (1998); Petukhov *et al.* (2002); Giazotto *et al.* (2003); Slobodskyy *et al.* (2003); Vurgaftman and Meyer (2003).

[111]These include the works of Voskoboynikov *et al.* (1998, 1999); de Andrada e Silva and La Rocca (1999); Kiselev and Kim (2001); Governale *et al.* (2002); Koga *et al.* (2002b); Ting and Cartoxià (2002); Perel' *et al.* (2003).

[112]See Monsma *et al.* (1995); Filipe *et al.* (1998); Oberli *et al.* (1998); Upadhyay *et al.* (1999); Rippard and Buhrman (2000); Cacho *et al.* (2002); van Dijken *et al.* (2002b).

[113]QPC was also used to locally create and probe nonequilibrium nuclear spin in GaAs/AlGaAs heterostructures in the quantum Hall regime (Wald *et al.*, 1994).

[114]Suggested by Sharvin (1965) as a technique to study Fermi surfaces; see also van Houten *et al.* (1989).

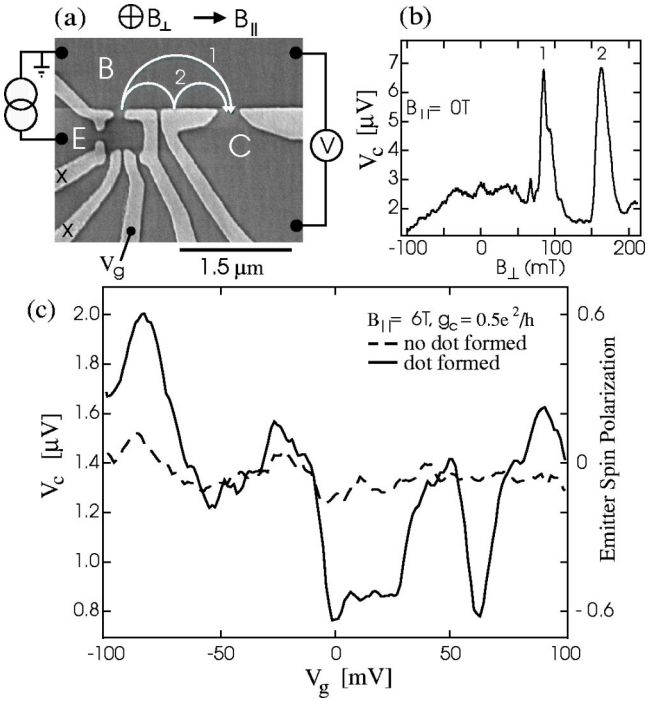

FIG. 29. (Color in online edition) Mesoscopic spin filter: (a) micrograph and circuit showing the polarizer-analyzer configuration used in the experiment of Folk *et al.* (2003). The emitter E can be formed into either a quantum dot or a quantum point contact. The collector C is a single point contact. Electrons are focused from E to C through the base region B, using a small perpendicular magnetic field. Gates marked with "×" are left undepleted when E is operated as a quantum point contact; (b) base-collector voltage (V_C) showing two focusing peaks; (c) focusing peak height at $B_\parallel = 6$ T with spin-selective collector conductance ($g_C = 0.5e^2/h$), comparing E as a quantum point contact at $2e^2/h$ (dashed curve) and E as a quantum dot with both leads at $2e^2/h$ (solid curve). Adapted from Folk *et al.*, 2003.

age peaks, when the separation of the two quantum point contacts is an even multiple of the cyclotron radius $m^* v_F/eB_\perp$, where m^* is the effective mass, and v_F the Fermi velocity. These results are illustrated in Figs. 29(a) and (b) on a slightly modified structure (Folk *et al.*, 2003) where, by applying a gate voltage, one can cause the emitter to form either a quantum dot or a quantum point contact. Effective spin filtering, due to the large in-plane field $B_\parallel$, can be tuned by the gate voltage, which changes the conductance of the quantum point contact. The resulting effect of spin filtering modifies the collector voltage V_C (Potok *et al.*, 2002),

$$V_C = \alpha(h/2e^2) I_E (1 + P_{I_E} P_{T_C}), \tag{113}$$

where $0 < \alpha < 1$ parametrizes the imperfections in focusing, P_{I_E} and P_{T_C} are the spin polarization [recall Eq. (3)] of the emitter current I_E, and the collector transmission coefficient T_C is related to the collector conductance by $g_C = (2e^2/h) T_C$. In Eq. (113) we note a recurring form for a spin-valve effect. The measured signal involves the product of two different spin polarizations, for example, similar to TMR in Eq. (2) or to spin-charge coupling due to nonequilibrium spin [recall Eqs. (43) and (114)]. Another mesoscopic spin filter with few-electron quantum dot (GaAs/AlGaAs-based) was used to demonstrate a nearly complete spin polarization which could be reversed by adjusting gate voltages (Hanson, Vandersypen, *et al.*, 2003).

D. Spin diodes

Spin diodes are inhomogeneous two-terminal devices whose electronic or optical properties depend on the spin polarization of the carriers. Such devices were envisaged long before the emergence of spintronics. Solomon (1976), for example, proposed and demonstrated a silicon p-n junction whose current was modified by changing the spin polarization of the recombination centers. In a magnetic field both the mobile carriers and the recombination centers have an equilibrium spin polarization due to the Zeeman splitting. The current in a p-n junction depends on the recombination rate, which, in turn, depends on the relative orientation of the spin of the carriers and the centers (Lepine, 1972). The trick to modifying the current is to decrease (even saturate) the spin polarization of either the electrons or the centers by electron spin resonance. Indeed, Solomon (1976) found a variation of $\approx 0.01\%$ of the saturation current at small biases where recombination in the space-charge region dominates. Similar experiments could be used to detect nonequilibrium spin due to (potential) spin injection in Si, where optical methods are ineffective, but also in other semiconductors where electrical detection would be desirable.[115]

Several spin diodes have recently been proposed or demonstrated with the goal of either maximizing the sensitivity of the I-V characteristics to spin and magnetic field, or facilitating spin injection and its detection through semiconductor interfaces comprising a magnetic semiconductor as the injector. Magnetic tunneling diodes have been used for spin injection from a ferromagnetic to a nonmagnetic semiconductor, in p-GaMnAs/n-GaAs p-n junctions (Kohda *et al.*, 2001; Johnston-Halperin *et al.*, 2002; Van Dorpe, Liu, *et al.*, 2003). As discussed in Sec. II.D.3, p-n heterostructures have combined Cr- or Eu-based ferromagnetic semiconductors and InSb (Viglin *et al.*, 1997; Osipov *et al.*, 1998). Spin light-emitting diodes (recall Figs. 12 and 13) were employed for injecting and detecting spins in semiconductors, while resonant tunneling diodes have been

[115]Spin diodes can also probe fundamental properties of electronic systems. The diode demonstrated by Kane *et al.* (1992) is based on a junction between two coplanar AlGaAs/GaAs 2DEG's, one with $\nu < 1$ and the other with $\nu > 1$, where ν is the Landau-level filling; that is, the two regions have opposite spins at the Fermi level. The current crossing such a junction, which has a diode property due to the existence of a built-in field in the contact, is accompanied by a spin flip. Interestingly, the current is also time dependent, due to the current-induced dynamic nuclear polarization.

demonstrated as effective spin injectors (Sec. II.D.3) and spin filters (Sec. IV.C). A magnetic unipolar diode has been proposed by Flatté and Vignale (2001) to simulate the working of ordinary diodes, but with homogeneous monopolar doping (either donors or acceptors, not both). The role of inhomogeneous doping in the p-n junction is played by the inhomogeneous spin splitting of the carrier band, with the spin-up and spin-down carriers playing roles similar to those of the electrons and holes in bipolar diodes. Si-based p-i-n diode sandwiched between two ferromagnetic metals was suggested to allow controlling the device performance by an externally applied magnetic field (Dugaev *et al.*, 2003). Finally, Žutić *et al.* (2002) have proposed the magnetic bipolar diode described below.

The magnetic bipolar diode[116] (MBD) is a p-n junction diode with one or both regions magnetic (Fabian *et al.*, 2002a; Žutić *et al.*, 2002). The MBD is the prototypical device of bipolar spintronics, a subfield of spintronics in which both electrons and holes take part in carrier transport, while either electrons or holes (or both) are spin polarized (see Sec. IV.A.4). Examples of nonmagnetic bipolar spintronic devices are the spin-polarized p-n junction (Žutić *et al.*, 2001b) and the spin solar cell (Žutić *et al.*, 2001a). These devices offer opportunities for effective spin injection, spin amplification (see Sec. II.C.3), or spin capacity—the effect of changing, by voltage, nonequilibrium spin density (Žutić *et al.*, 2001b). The advantages of magnetic bipolar spintronic devices (Fabian *et al.*, 2002a, 2002b; Žutić *et al.*, 2002, 2003) lie in the combination of equilibrium magnetism and nonequilibrium spin and effective methods to manipulate a minority carrier population. The most useful effects of the spin-charge coupling in MBD's are the spin-voltaic and the giant-magnetoresistive effects, which are enhanced over those of metallic systems by the exponential dependence of the current on bias voltage.

A scheme of an MBD is shown in Fig. 30 (also see Fig. 8). The p region is magnetic, by which we mean that it has a spin-split conduction band with the spin splitting (Zeeman or exchange) $2q\zeta \sim k_B T$. Zeeman splitting can be significantly enhanced by the large g^* factors of magnetically doped (Sec. II.C.3) or narrow-band-gap semiconductors (Sec. IV.B). Using an MBD with a ferromagnetic semiconductor slightly above its T_C is also expected to give large g^* factors. The n region is nonmagnetic, but electrons can be spin polarized by a spin source (circularly polarized light or magnetic electrode). The interplay between the equilibrium spin of polarization $P_{n0}=\tanh(q\zeta/k_B T)$ in the p region, and the nonequilibrium spin source of polarization δP_n in the n region, at the edge of the depletion layer, determines the

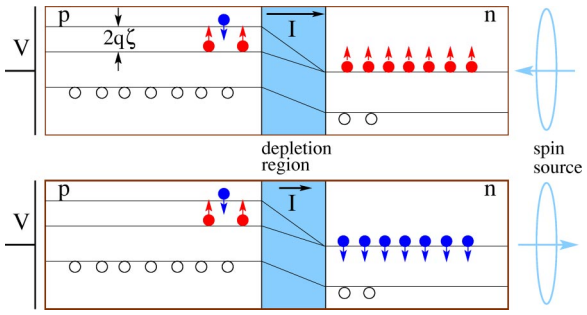

FIG. 30. (Color in online edition) Scheme of a magnetic bipolar diode. The p region (left) is magnetic, indicated by the spin splitting $2q\zeta$ of the conduction band. The n region (right) is nonmagnetic, but spin polarized by a spin source: Filled circles, spin-polarized electrons; empty circles, unpolarized holes. If the nonequilibrium spin in the n region is oriented parallel (top figure) to the equilibrium spin in the p region, large forward current flows. If the relative orientation is antiparallel (bottom), the current drops significantly. Adapted from Žutić *et al.*, 2002.

I-V characteristics of the diodes. It is straightforward to generalize these considerations to include spin-polarized holes (Fabian *et al.*, 2002a).

The dependence of the electric current j on $q\zeta$ and δP_n was obtained by both numerical and analytical methods. Numerical calculations (Žutić *et al.*, 2002) were performed by self-consistently solving for the drift-diffusion, continuity, as well as carrier recombination and spin-relaxation equations, discussed in Sec. IV.A.4. While the numerical calculations are indispensable in the high-injection limit,[117] valuable insight and analytical formulas can be obtained in the low-injection limit, where the Shockley theory (Shockley, 1950) for ordinary p-n junctions was generalized by Fabian *et al.* (2002a) for the magnetic case.

To illustrate the I-V characteristics of MBD's, consider the low-injection limit in the configuration of Fig. 30. The electron contribution to the total electric current is (Fabian *et al.*, 2002a)

$$j_n \sim n_0(\zeta)[e^{qV/k_B T}(1+\delta P_n P_{n0})-1], \tag{114}$$

where V is the applied bias (positive for forward bias) and $n_0(\zeta)=(n_i^2/N_a)\cosh(q\zeta/k_B T)$ is the equilibrium number of electrons in the p region, dependent on the splitting, the intrinsic carrier density n_i, and the acceptor doping N_a. Equation (114) generalizes the Silsbee-Johnson spin-charge coupling (Silsbee, 1980; Johnson

[116]Not to be confused with the usual magnetic diodes, which are ordinary diodes in a magnetic field. The I-V characteristics of such diodes depend on the magnetic field through small orbital effects on diffusion coefficient, not through the spin effects described here.

[117]The small-bias or low-injection limit is the regime of applied bias in which the density of the carriers injected through the depletion layer (the minority carriers) is much smaller than the equilibrium density of the majority carriers. Here and in Sec. IV.E.2 the terms majority and minority refer to the relative carrier (electron or hole) population and not to spin. The large-bias or high-injection limit is the regime where the injected carrier density becomes comparable to the equilibrium density. This occurs at forward biases comparable to the built-in potential, typically 1 V.

and Silsbee, 1985), originally proposed for ferromagnet/paramagnet metal interfaces, to the case of magnetic p-n junctions. The advantage of the spin-charge coupling in p-n junctions, as opposed to metals or degenerate systems, is the nonlinear voltage dependence of the nonequilibrium carrier and spin densities (Fabian *et al.*, 2002a), allowing for the exponential enhancement of the effect with increasing V. Equation (114) can be understood qualitatively from Fig. 30 (Fabian *et al.*, 2002a). In equilibrium, $\delta P_n=0$ and $V=0$, no current flows through the depletion layer, as the electron currents from both sides of the junction balance out. The balance is disturbed either by applying bias or by selectively populating different spin states, making the flow of one spin species greater than that of the other. In the latter case, the effective barriers for crossing of electrons from the n to the p side is different for spin-up and spin-down electrons (see Fig. 30). Current can flow even at $V=0$ when $\delta P_n\neq 0$. This is an example of the spin-voltaic effect (a spin analog of the photovoltaic effect), in which nonequilibrium spin causes an emf (Žutić *et al.*, 2002; Žutić and Fabian, 2003). In addition, the direction of the zero-bias current is controlled by the relative signs of P_{n0} and δP_n.

MBD's can display an interesting GMR-like effect, which follows from Eq. (114) (Žutić *et al.*, 2002). The current depends strongly on the relative orientation of the nonequilibrium spin and the equilibrium magnetization. Figure 31 plots j, which also includes the contribution from holes, as a function of $2q\zeta/k_BT$ for both the unpolarized, $\delta P_n=0$, and fully polarized, $\delta P_n=1$, n region. In the first case j is a symmetric function of ζ, increasing exponentially with increasing ζ due to the increase in the equilibrium minority carrier density $n_0(\zeta)$. In unipolar systems, where transport is due to the majority carriers, such a modulation of the current is not likely, as the majority carrier density is fixed by the density of dopants.

If $\delta P_n\neq 0$, the current will depend on the sign of $P_{n0}\cdot\delta P_n$. For parallel nonequilibrium (in the n region) and equilibrium spins (in the p region), most electrons cross the depletion layer through the lower barrier (see Fig. 30), increasing the current. In the opposite case of antiparallel relative orientation, electrons experience a larger barrier and the current is inhibited. This is demonstrated in Fig. 31 by the strong asymmetry in j. The corresponding GMR ratio, the difference between j for parallel and antiparallel orientations, can also be calculated analytically from Eq. (114) as $2|\delta P_nP_{n0}|/(1-|\delta P_nP_{n0}|)$ (Fabian *et al.*, 2002a). If, for example, $|P_{n0}|=|\delta P_n|=0.5$, the relative change is 66%. The GMR effect should be useful for measuring the spin relaxation rate of bulk semiconductors (Žutić *et al.*, 2003), as well as for detecting nonequilibrium spin in the nonmagnetic region of the p-n junction.[118]

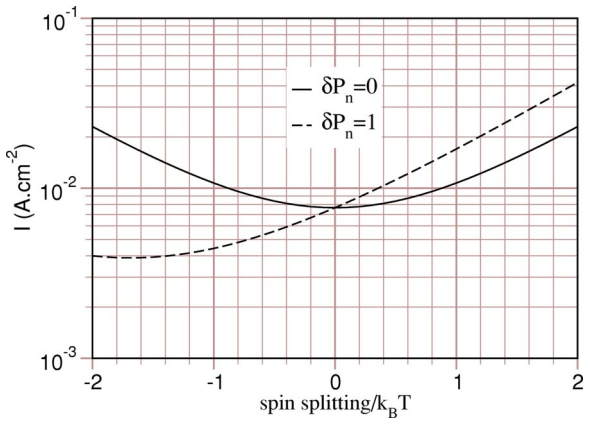

FIG. 31. (Color in online edition) Giant magnetoresistance (GMR) effect in magnetic diodes. Current/spin-splitting characteristics ($I-\zeta$) are calculated self-consistently at $V=0.8$ V for the diode from Fig. 30. Spin splitting $2q\zeta$ on the p side is normalized to k_BT. The solid curve corresponds to a switched-off spin source. The current is symmetric in ζ. With spin source on (the extreme case of 100% spin polarization injected into the n region is shown), the current is a strongly asymmetric function of ζ, displaying large GMR, shown by the dashed curve. Materials parameters of GaAs were applied. Adapted from Žutić *et al.*, 2002.

Although practical MBD's are still to be fabricated and the predicted effects tested, magnetic p-n junctions have already been demonstrated. Indeed, Wen *et al.* (1968)[119] were perhaps the first to show that a ferromagnetic p-n junction, based on the ferromagnetic semiconductor $CdCr_2Se_4$ doped with Ag acceptors and In donors, could act as a diode. Heavily doped p-GaMnAs/n-GaAs junctions were fabricated (Ohno, Arata, *et al.*, 2000; Arata *et al.*, 2001; Kohda *et al.*, 2001; Johnston-Halperin *et al.*, 2002; Van Dorpe, Liu, *et al.*, 2003) to demonstrate tunneling interband spin injection. Incorporation of (Ga,Mn)As layer in the intrinsic region of p-i-n GaAs diode was shown to lead to an efficient photodiode, in which the Mn ions function as recombination centers (Teran *et al.*, 2003). It would be interesting to see such devices combined with a spin injector in the bulk regions. Recently, Tsui *et al.* (2003) have shown that the current in p-CoMnGe/n-Ge magnetic heterojunction diodes can indeed be controlled by magnetic field. To have functioning MBD's at room temperature, and to observe the above predicted phenomena, several important challenges have to be met:

(i) Zeeman or exchange splitting needs to be sufficiently large to provide equilibrium spin polarization, $\gtrsim 1-10\,\%$. This may be difficult at room temperature, unless the effective g factor is ~ 100 at $B\sim 1$ T (Sec. II.D.3). The use of ferromagnetic semiconductors is limited by their T_C (Sec. IV.B).

(ii) For a strong spin-charge coupling [recall the discussion of Eq. (114)] a nondegenerate carrier den-

[118]This could be a way to detect spin injection into Si, where optical detection is ineffective.

[119]We thank M. Field for bringing this reference to our attention.

sity is desirable, which, while likely in (Zn,Cr)Te, is not easily realized in many other ferromagnetic semiconductors that are typically heavily doped (Sec. IV.B).

(iii) An effective integration is needed of magnetic and nonmagnetic structures into single devices (Samarth *et al.*, 2003).

(iv) The samples need to be smaller than the spin diffusion lengths, requiring high carrier mobility and long spin relaxation (easier to realize for spin-polarized electrons).

(v) The effects of actual device structures, such as two- and/or three-dimensional spin flow, interface contacts, spin-dependent band offsets and band bendings, strong spin relaxation in the depletion layers, etc., will need to be understood.

By combining two magnetic p-n junctions in series one can obtain a magnetic bipolar transistor (Sec. IV.E.2), a three terminal device which offers spin-dependent amplification.

E. Spin transistors

We review several proposals for spin transistors that have at least one semiconductor region and that aim at integrating spin and charge transport within traditional device schemes of the field-effect and junction transistors. Three important cases are discussed in detail: the Datta-Das spin field-effect transistor, the magnetic bipolar transistor, and the hot-electron spin transistor.

Various spin transistors that contain metallic (and insulating) regions have been proposed (Johnson, 1993a; You and Bader, 2000; Bauer *et al.*, 2003; Zvezdin *et al.*, 2003). There is also a large category of spin single-electron transistors, first realized by Ono *et al.* (1996), and later investigated by Barnaś and Fert (1998); Korotkov and Safarov (1999); Ciorga *et al.* (2002); and Martinek *et al.* (2002). Spin single-electron transistors can be viewed as an extension of magnetic tunneling (see Sec. IV.A.2) to double tunnel junctions, where the Coulomb blockade becomes important (Takahashi and Maekawa, 1998). For a review of spin single-electron transistors see Maekawa *et al.* (2002).

1. Spin field-effect transistors

Datta and Das (1990) proposed what became the prototypical spintronic device scheme, the Datta-Das spin field-effect transistor (SFET). The device is based on spin injection and spin detection by a ferromagnetic source and drain, and on spin precession about the built-in structure inversion asymmetry (Bychkov-Rashba) field $\mathbf{\Omega}$, Eq. (88), in the asymmetric, quasi-one-dimensional channel of an ordinary field-effect transistor. The attractive feature of the Datta-Das SFET is that spin-dependent device operation is controlled not by external magnetic fields, but by gate bias, which controls the spin precession rate.

The structure of the Datta-Das SFET is shown in Fig. 1. Consider a 2D electron gas confined along the plane of the unit vector $\mathbf{n}$. The precession axis of $\mathbf{\Omega}$ always lies in the channel plane (see Sec. III.B.2), so the results (unlike those for bulk inversion asymmetry) are insensitive to the relative orientation of $\mathbf{n}$ and the principal crystal axes. Equation (88) determines the evolution of the expectation value for a spin perpendicular to the plane, $s_n=\mathbf{s}\cdot\mathbf{n}$, and a spin parallel to the in-plane $\mathbf{k}$, $s_\parallel=\mathbf{s}\cdot\mathbf{k}/k$:

$$ds_n/dt=2\alpha_{BR}ks_\parallel, \quad ds_\parallel/dt=-2\alpha_{BR}ks_n, \tag{115}$$

where α_{BR} is the structure inversion asymmetry coefficient appearing in Eq. (88). The average spin component along $\mathbf{\Omega}$, $s_\perp=\mathbf{s}\cdot(\mathbf{k}\times\mathbf{n})/k$, is constant. As a result, $s_\parallel=s_{0\parallel}\cos(\omega t)$, where $\omega=2\alpha_{BR}k$ and the injected spin at the source is labeled with zero. If φ is the angle between $\mathbf{k}$ and the source-drain axis, the electron will reach the drain at time $t'=Lm_c/(\hbar k\cos\varphi)$, with the spin $s_\parallel$ precessing at the angle $\phi=2\alpha_{BR}m_cL/\hbar$. The average spin at the drain in the direction of magnetization is $s_\parallel(t')\cos\varphi+s_{0\perp}\mathbf{m}\cdot(\mathbf{k}\times\mathbf{n})$, so the current is modulated by $1-\cos^2\varphi\sin^2(\phi/2)$, the probability of finding the spin in the direction of magnetization $\mathbf{m}$.

Note that ϕ does not depend on the momentum (or energy) of the carriers. As the spread φ in the momenta increases, the modulation effect decreases. The largest effect is seen for $\varphi=0$, where the current modulation factor is $\cos^2(\phi/2)$. It was therefore proposed (Datta and Das, 1990) that φ be limited by further confining the electron motion along $\varphi=0$ using a one-dimensional channel as a waveguide. Spin modulation of the current becomes ineffective if transport is diffusive. Taking typical values (Nitta *et al.*, 1997; Koga *et al.*, 2002a) for $\hbar\alpha_{BR}\approx1\times10^{-11}$ eV m, and $m_c=0.1m_e$, current modulation should be observable at source-drain separations of $L\gtrsim1$ μm, setting the scale for ballistic transport. The device will work best with narrow-gap materials (Lommer *et al.*, 1988) like InAs, in which the structure inversion asymmetry dominates the spin precession (Luo *et al.*, 1988, 1990; Das *et al.*, 1989). Another option is using Si heterostructures, in which bulk inversion asymmetry is absent. However, the small magnitude of the spin-orbit interaction makes α_{BR} in Si probably rather weak.

The Datta-Das SFET is yet to be realized. There are at least four important difficulties in observing the proposed effects.

(i) The effective spin injection of spin-polarized carriers from the ferromagnetic source into a 2DEG is nontrivial (see Sec. II.D.4).

(ii) Ballistic spin-polarized transport should be realized through the channel with *uniform* α_{BR} by eliminating undesirable electric fields due to interface inhomogeneities.

(iii) The parameter α_{BR} should be effectively controllable by the gate.

(iv) The structure inversion asymmetry should dominate over the bulk inversion asymmetry, and the spin precession rate must be large enough

($\hbar\alpha_{BR} \gtrsim 10^{-11}$ eV m) to allow at least a half precession during the ballistic transport.

These four factors present a great challenge to fabricating a Datta-Das SFET at room temperature, limiting the design to special materials and very clean interfaces. However, the modulation of α_{BR} by biasing voltage (iii) has been already convincingly demonstrated in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells (Nitta *et al.*, 1997; Hu *et al.*, 1999; Grundler, 2000) (for GaAs/AlGaAs 2DEG, see also Miller *et al.*, 2003). Initial experimental investigations of magnetoresistance in the Datta-Das SFET systems were performed by Gardelis *et al.* (1999). Recently spin precession in the Datta-Das SFET, including the bulk inversion asymmetry, was investigated by Winkler (2004) using $k\cdot p$ model calculations. It is not surprising that the conductance through the transistor, in the present orientation-dependent bulk inversion asymmetry, depends rather strongly on the crystallographic orientation of the two-dimensional channel (Łusakowski *et al.*, 2003). For more discussion of the Dresselhaus bulk inversion asymmetry and the Bychkov-Rashba structure asymmetry see Sec. III.B.2.b.

The Datta-Das SFET has generated great interest in mesoscopic spin-polarized transport in the presence of structure inversion asymmetry. Model calculations using the tight-binding formulation of H_{SIA} (recall Sec. II.B.2) were reported by Pareek and Bruno (2002). Further theoretical investigations on the theme of the Datta-Das spin transistor can be found in Nikolić and Freericks (2001) and Matsuyama *et al.* (2002), and in an extensive review by Bournel (2000). Distinct SFET's have also been suggested, even in the absence of ferromagnetic regions which are replaced by a rotating external magnetic field of uniform strength (Wang, Wang, and Guo, 2003). Ciuti *et al.* (2002b) proposed a ferromagnetic-oxide-semiconductor transistor, with a nonmagnetic source and drain, but with two ferromagnetic gates in series above the base channel. The relative orientation of the gates' magnetization leads to magnetoresistance effects. An SFET that can operate in the diffusive regime, in the presence of both bulk and structure inversion asymmetry, has been considered by Schliemann *et al.* (2003).

2. Magnetic bipolar transistor

The magnetic bipolar transistor (MBT) is a bipolar transistor with spin-split carrier bands and, in general, an injected spin source (Fabian *et al.*, 2002b, 2004; Fabian and Žutić, 2004). A related device structure was already proposed by Gregg *et al.* (1997) in a push for silicon-based spintronics. In this proposal (also called SPICE for spin-polarized injection current emitter) the semiconductors have no equilibrium spin, while the spin source is provided by a ferromagnetic spin injector attached to the emitter, and another ferromagnetic metal, a spin detector, is attached to the base/collector junction

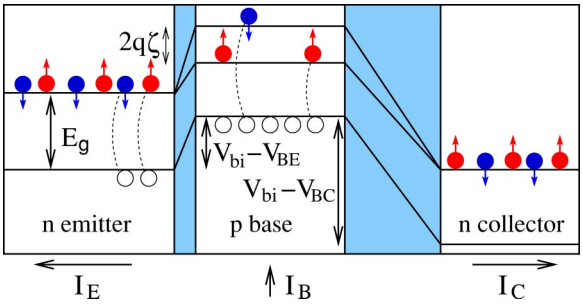

FIG. 32. (Color in online edition) Scheme of an n-p-n magnetic bipolar transistor with magnetic base B, nonmagnetic emitter E, and collector C. Conduction and valence bands are separated by the energy gap E_g. The conduction band has a spin splitting $2q\zeta$, leading to equilibrium spin polarization $P_{B0}=\tanh(q\zeta/k_BT)$. Carriers and depletion regions are represented as in Fig. 30. In the so-called forward active regime, where the transistor can amplify currents, the E-B junction is forward biased (here with voltage $V_{BE}>0$ lowering the built-in potential V_{bi}), while the B-E junction is reverse biased ($V_{BC}<0$). The directions of the current flows are indicated. Electrons flow from E to B, where they either recombine with holes (dashed lines) or continue to be swept by the electric field in the B-E depletion layer towards C. Holes form mostly the base current, I_B, flowing to the emitter. The current amplification $\beta=I_C/I_B$ can be controlled by P_{B0} as well as by the nonequilibrium spin in E. Adapted from Fabian *et al.*, 2004.

to modulate the current flow. In both configurations the aim is to control current amplification by spin and magnetic field.

A scheme of a particular MBT is shown in Fig. 32. Such a three-terminal device can be thought of as consisting of two magnetic p-n junctions connected in series. Materials considerations discussed in Sec. IV.D also apply to an MBT in order to provide a sufficient equilibrium polarization in a magnetic base P_{B0}. While nonmagnetic, the emitter has a nonequilibrium polarization δP_E from a spin source, similar to the magnetic diode case in Fig. 30. Only the spin polarization of electrons is assumed. Applying the generalized Shockley theory to include spin effects (Fabian *et al.*, 2002a), a theory of MBT was developed by Fabian *et al.* (2002b) and Fabian and Žutić (2004). Later, simplified schemes of MBT [not including the effect of nonequilibrium spin ($\delta P_E=0$)] were also considered by Flatté *et al.* (2003) and Lebedeva and Kuivalainen (2003).

The current amplification (gain) $\beta=I_C/I_B$ (see Fig. 32) is typically ~ 100 in practical transistors. This ratio depends on many factors, such as the doping densities, carrier lifetimes, diffusion coefficients, and structure geometry. In an MBT β also depends on the spin splitting $2q\zeta$ (see Fig. 32) and the nonequilibrium polarization δP_E. This additional dependence of β in an MBT is called magnetoamplification (Fabian and Žutić, 2004). An important prediction is that nonequilibrium spin can be injected at low bias all the way from the emitter, through the base, to the collector (Fabian *et al.*, 2002b; Fabian and Žutić, 2004) in order to make possible an effective control of β by δP_E.

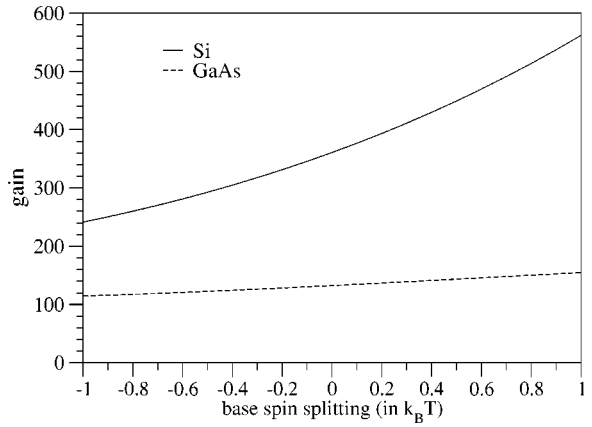

FIG. 33. Calculated gain dependence of an MBT as a function of base spin splitting $2q\zeta$, given in units of thermal energy k_BT. The nonequilibrium spin polarization in the emitter is $\delta P_E=0.9$. Si (solid) and GaAs (dashed) materials parameters were applied. Adapted from Fabian *et al.*, 2002b.

The calculated dependence of the gain on the spin splitting for $\delta P_E=0.9$ is shown in Fig. 33, for GaAs and Si materials parameters. The gain is very sensitive to the equilibrium magnetization in Si, while the rapid carrier recombination in GaAs prevents more effective control of the transport across the base. In Si it is the spin injection at the emitter-collector depletion layer which controls the current. As the spin-charge coupling is most effective across the depletion layer (see Sec. IV.D), this coupling is essential for the current in Si. In the limit of slow carrier recombination (Fabian *et al.*, 2002b),

$$\beta \sim \cosh(q\zeta/k_BT)(1+\delta P_E P_{B0}). \tag{116}$$

Both magnetic field (through ζ) and nonequilibrium spin affect the gain, an implication of the spin-voltaic effect (Žutić *et al.*, 2002; Žutić and Fabian, 2003). The sensitivity of the current to spin can be used to measure the injected spin polarization. If no spin source is present ($\delta P_E=0$), there is no spin-charge coupling in the space-charge regions, unless at least two regions are magnetic. The only remaining effects on the I-V characteristics come from the sensitivity of the carrier densities in the equilibrium magnetic regions to ζ [see Eq. (116) for the case of $\delta P_E=0$].

The MBT is, in effect, a magnetic heterostructure transistor, since its functionality depends on tunability of the band structure of the emitter, base, or collector. The advantage of the MBT, however, is that the band structure is not built in, but can be tuned during the device operation by magnetic field or spin injection signals. The challenges to demonstrate the predicted phenomena in MBT are similar to those of magnetic bipolar diodes, see Sec. IV.D.

3. Hot-electron spin transistors

Spin transistors that rely on transport of hot (nonthermalized) carriers have the potential of serving several different purposes. On the one hand, they could be used as a diagnostic tool to characterize spin- and energy-dependent interfacial properties, scattering processes, and electronic structure, relevant to spintronic devices.[120] On the other hand, hot-electron transistors are also of interest for their ability to sense magnetic fields, their possible memory applications, and their potential as a source of ballistic hot-electron spin injection. Below we discuss two representative examples, a spin-valve transistor and a magnetic tunneling transistor.

The *spin-valve or Monsma transistor* provided an early demonstration of a hot-electron spin transistor and realization of a hybrid spintronic device that integrates metallic ferromagnets and semiconductors (Monsma *et al.*, 1995, 1998). A three-terminal structure[121] consisted of a metallic base (B) made of a ferromagnetic multilayers in a CPP geometry [as depicted in Fig. 3(a)] surrounded by a silicon emitter (E) and collector (C) with two Schottky contacts, formed at E/B and B/C interfaces.[122] Forward bias V_{EB} controls the emitter current I_E of spin-unpolarized electrons, which are injected into a base region as hot carriers. The scattering processes in the base, together with the reverse bias V_{BC}, influence how many of the injected electrons can overcome the B/C Schottky barrier and contribute to the collector current I_C. Similar to the physics of GMR structures (Gijs and Bauer, 1997; Levy and Mertig, 2002), scattering in the base region strongly depends on the relative orientation of the magnetizations in the ferromagnetic layers. Electrons with spin which has magnetic moment opposite (antiparallel) to the magnetization of a ferromagnetic layer typically are scattered more than electrons with parallel magnetic moment, resulting in a spin-filtering effect which can be described in terms of a spin-dependent mean free path (Rendell and Penn, 1980; Pappas *et al.*, 1991; Hong and Mills, 2000). Generally, both elastic and inelastic scattering processes determine the effective spin-dependent mean free path,

[120]These efforts are motivated in part by the success of (spin-insensitive) ballistic electron-emission microscopy in providing high spatial and energy resolution of the properties of metal/semiconductor interfaces (Kaiser and Bell, 1988; Smith *et al.*, 2000; Bonnell, 2001). A subsequent variation—a ballistic electron-magnetic microscopy, which also uses an STM tip to inject hot carriers, is capable of resolving magnetic features at a ~10-nm length scale (Rippard and Buhrman, 1999, 2000).

[121]Similar to other hot-electron spin devices, the term transistor characterizes their three-terminal structure rather than the usual functionality of a conventional semiconductor transistor. In particular, a semiconductor bipolar transistor, which also has an emitter/base/collector structure, typically has a sizable current gain—a small change in the base current leads to a large change in the collector current (see Sec. IV.E.2). However, only a small current gain ~2 (due to large current in a metal base) was predicted in magnetic tunnel-junction-based devices (Hehn *et al.*, 2002).

[122]Another realization of a spin-valve transistor combines a GaAs emitter with a Si collector (Dessein *et al.*, 2000).

sometimes also referred to as the attenuation length.[123] The magnetoresistive response is usually expressed using magnetocurrent (MC), defined as the change in collector current, normalized to the minimum value

$$\mathrm{MC}=(I_{C\uparrow\uparrow}-I_{C\uparrow\downarrow})/I_{C\uparrow\downarrow}, \tag{117}$$

analogous to the expression for GMR or TMR structures [recall Eq. (1)], where $\uparrow\uparrow$ (parallel) and $\uparrow\downarrow$ (antiparallel) denote the relative orientation of the magnetizations. The large values[124] of MC ($>200\%$) and the sensitivity of $\sim 130\%$ per G measured at room temperature (Anil Kumar *et al.*, 2000) demonstrate a capability for magnetic-field sensors. Several important challenges, raised by the operation of the spin-valve transistor, need to be addressed to better realize the potential of hot-electron transistors. These challenges include increasing the small collector current and determining whether the spin injection of hot carriers into semiconductors is feasible. Furthermore, it would be desirable to fabricate structures in which semiconductor regions played an active role, not limited to energy selection (via Schottky barriers) of the carriers injected into the base and collector regions.

An alternative class of hot-electron transistors, often referred to as *magnetic tunneling transistors*, has a tunneling junction instead of a Schottky barrier emitter (Mizushima *et al.*, 1997; Yamauchi and Mizushima, 1998; Sato and Mizushima, 2001; van Dijken *et al.*, 2002a, 2002b, 2003c; Jiang *et al.*, 2003). The addition of a tunnel junction, combined with a variable V_{EB}, allows exploration of hot-electron transport over an energy range of several eV. At large V_{EB} bias, the ratio I_C/I_E, important for the device performance, can be substantially increased over that of the spin-valve transistor (Sato and Mizushima, 2001; van Dijken *et al.*, 2003a, 2003b).

A particular realization is depicted in Fig. 34. Different coercive fields in the regions 1 and 3 ensure independent switching of the corresponding magnetizations in the applied magnetic field. The magnetocurrent MC, defined in Eq. (117), shows a nonmonotonic behavior with V_{EB} (van Dijken *et al.*, 2003c), influenced by the conduction-band structure of a collector. In GaAs, in addition to the direct conduction-band minimum at the Γ point [recall Fig. 6(a)], there are indirect minima at L points at higher energy (Blakemore, 1982). After an initial decrease of MC with electron energy, at $V_{EB}\approx 0.3$ V larger than the base/collector Schottky barrier there is an onset of hot-electron transport into L valleys

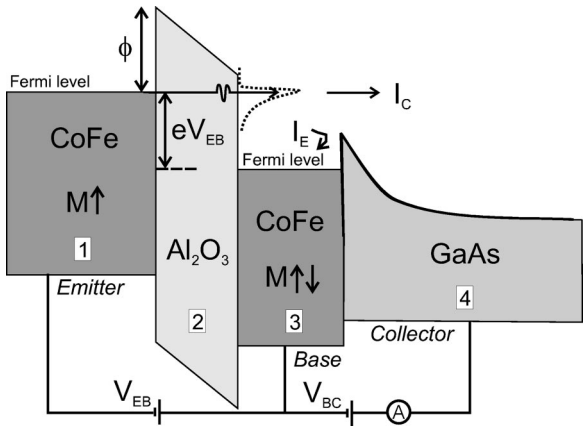

FIG. 34. Schematic energy diagram of a magnetic tunneling transistor. Region 1 is the emitter, region 2 the Al_2O_3 tunnel barrier of height ϕ, and region 3 the base. Together they form a magnetic tunnel junction. Region 4 is a semiconductor collector that has a Schottky barrier at the interface with the base. From van Dijken *et al.*, 2003c.

accompanied by an increase in MC (van Dijken *et al.*, 2003c).

A large magnetocurrent alone, measured in various hot-electron spin transistors (Monsma *et al.*, 1995, 1998; Sato and Mizushima, 2001; van Dijken *et al.*, 2003b), is not sufficient to demonstrate spin injection in a semiconductor collector. For conclusive evidence spin detection in a collector region is needed. This was first achieved (Jiang *et al.*, 2003) using optical detection with a spin LED structure[125] added to the collector in Fig. 34. Measurements at $T=1.4$ K and $B=2.5$ T, after a background subtraction, showed majority spin injection with $P_{\mathrm{circ}}\approx 10\%$.

In another realization of a magnetic tunnel transistor, more similar to the original spin-valve transistor, the emitter was nonmagnetic (Cu) while the base was a magnetic multilayer (F1/N/F2) (van Dijken *et al.*, 2003b). The resulting strong spin-filtering effect can be inferred from the transmitted hot carriers with a spin-dependent exponential decay within the F_i, $i=1,2$ layer. Unpolarized electrons, injected from the emitter, after passing an F1 layer of thickness t acquire an effective transmitted polarization

$$P_{N1}=\frac{N_\uparrow-N_\downarrow}{N_\uparrow+N_\downarrow}=\frac{e^{-t/l_\uparrow}-e^{-t/l_\downarrow}}{e^{-t/l_\uparrow}+e^{-t/l_\downarrow}}, \tag{118}$$

where $N_\uparrow$ and $N_\downarrow$ represent the number of transmitted electrons with majority or minority spin and $l_\uparrow$ and $l_\downarrow$ are the corresponding attenuation lengths (the polarization P_{N2} has an analogous form). The resulting magnetocurrent can be expressed as (van Dijken *et al.*, 2003b)

$$\mathrm{MC}=2P_{N1}P_{N2}/(1-P_{N1}P_{N2}), \tag{119}$$

[123]For electrons with sufficiently high excess energy, a scattering process (influencing the mean free path) does not necessarily remove the electron from the collector current. The attenuation length, which can be determined by measuring the base layer thickness dependence of the collector current (see Rippard and Buhrman, 1999, 2000; Vlutters *et al.*, 2001; van Dijken *et al.*, 2002b) can therefore differ from the effective mean free path.

[124]These values substantially exceed the CPP giant magnetoresistance value for the same magnetic multilayer used in the base.

[125]Analogous to the spin LED from Fig. 12, in which a GaAs collector served as an n-type spin aligner and InGaAs/GaAs was used for a quantum well.

which is analogous to Eq. (2) for TMR using Jullière's model, but with the redefined definition of spin polarization. At $V_{EB}=0.8$ V and at $T=77$ K, the measured MC exceeds 3400%, while with Eq. (119) the polarization of the transmitted electrons can be estimated to exceed 90%, even with a ferromagnet only ~3 nm thick (van Dijken *et al.*, 2003b). A theoretical analysis of spin injection and spin filtering in magnetic tunneling transistors was given by Rashba (2003a) who extended the approach for ballistic spin injection (Kravchenko and Rashba, 2003; Sec. II.C.2) to include the effects of hot-electron transport and inelastic scattering.

Future studies of hot-electron spin transistors are expected to result in increased spin injection even at room temperatures and to utilize other semiconductor collectors. It would be particularly desirable to demonstrate hot-electron spin injection in Si and facilitate an integration with the complementary metal-oxide semiconductor technology.

F. Spin qubits in semiconductor nanostructures

A potentially revolutionary idea in spintronics is the possibility of using the two-level nature of electron spin to create a solid-state quantum computer (DiVincenzo, 1995; Nielsen and Chuang, 2000; Das Sarma, *et al.*, 2001). The basic unit in a quantum computer is the quantum bit (or qubit), the quantum analog of the binary bit in a classical digital computer. A qubit is essentially a controllable quantum two-level system (Nielsen and Chuang, 2000; Das Sarma, 2001). While the dimensionality (2^n) of the Hilbert space of n electron spins is the same as the number of configurations of a corresponding classical system, a quantum system can be in a superposition of all the basis states, effectively performing (via a unitary evolution) many classical computations in parallel. Several "spin-based" quantum computer schemes have been proposed and extensively studied.[126] A common theme in these proposals is the idea of manipulating the dynamics of a single (or a few) electron spin(s) in semiconductor nanostructures (e.g., quantum dots), with the reasonable hope that the predicted behavior will extend to many-spin systems, requisite for practical quantum computation.

The control of spin dynamics and entanglement [many-spin quantum correlations (Nielsen and Chuang, 2000)] at the single-spin level in a semiconductor quantum dot structure is a formidable task, which has not been achieved even at mK temperatures, although impressive experimental advances have recently been made (Fujisawa *et al.*, 2002; Elzerman *et al.*, 2003; Hanson, Witkamp, *et al.*, 2003). The current architectures for spin-based quantum computing employ GaAs quantum dots (Loss and DiVincenzo, 1998) or Si (or Si-Ge) systems (Kane, 1998), with different variations. The basic idea (see Fig. 35) is to manipulate the spin states of a single electron using external magnetic fields (or microwaves) for single-qubit operations and to utilize the quantum exchange coupling between two neighboring electrons to carry out two-qubit operations.

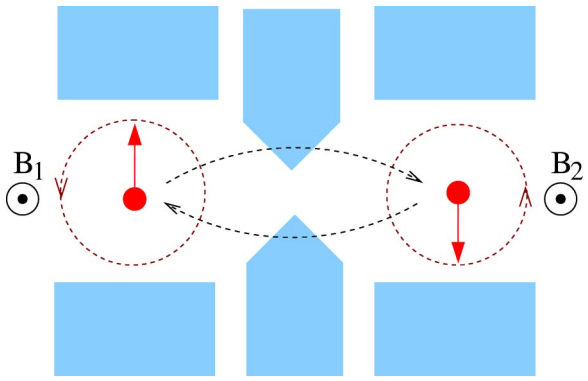

FIG. 35. (Color in online edition) The Loss and DiVincenzo (1998) proposal for spin-based solid-state quantum computing. Electrons are localized in electrostatically defined quantum dots, with coupling between electron spins—via the exchange interaction—allowed by tunneling between the dots. The tunneling is controlled by gate voltage. The figure shows two electrons localized in the regions defined by the gates (shaded). Single-qubit operations are realized by single-spin precessions (circles), performed by applying local magnetic fields (here perpendicular to the page) to each dot. Two-qubit operations are done through the exchange interaction indicated by the dashed curves. The scheme works according to the time-dependent Hamiltonian $H(t)=\Sigma'_{i,j}J_{i,j}(t)\mathbf{S}_i\cdot\mathbf{S}_j+\mu_B g\Sigma\mathbf{B}_i(t)\mathbf{S}_i$, where the first summation, over all neighboring spin pairs, describes the local exchange interaction (J is the exchange coupling), while the second describes the single-spin operations by local magnetic fields. Variations to this scheme are described by Burkard *et al.* (2000).

State-of-the-art techniques to measure a single spin in a solid, such as magnetic resonance force microscopy (Sidles *et al.*, 1995; Barbic, 2002; Mamin *et al.*, 2003) or spin-selective single-electron-transistor spectroscopy (Ono *et al.*, 2002), are still not sensitive enough for quantum computing operations. However, recently a single shot readout of the spin of an individual electron has been demonstrated using an electrical pump-probe measurement (Kouwenhoven, 2004). A single electron with unknown spin was trapped in a quantum dot for a few milliseconds. At the end of the trapping time the spin was measured by quickly shifting the Zeeman resolved spin states towards the Fermi energy. A spin to charge conversion allowed for an electrical readout of the spin. The real motivation for using the spin as a qubit is its long coherence time, microseconds or longer in operational experimental conditions (de Sousa and Das Sarma, 2003a), to be contrasted with typical picosecond coherence times for charge or orbital states in solids. Interest in spin-based quantum computing will

[126]See, for example, Kane (1998, 2000); Loss and DiVincenzo (1998); Privman *et al.* (1998); Burkard *et al.* (1999); DiVincenzo (2000); Hu and Das Sarma (2000, 2001); Vrijen *et al.* (2000); Koiller *et al.* (2002, 2003); Levy (2002); Piermarocchi *et al.* (2002); Friesen *et al.* (2003); Meier *et al.* (2003); Skinner *et al.* (2003); Troiani *et al.* (2003).

only increase as we understand more about spin coherence and relaxation from other spintronic studies. The broad subject of spin-based quantum computing, which is related to the areas of quantum measurement and quantum decoherence (Zurek, 2003), is beyond the scope of this review.

V. OUTLOOK

We have reviewed selected topics on spintronics, emphasizing both the fundamental aspects of spin dynamics, transport, and relaxation, and the potential applications. While the current push for spintronics is driven by the prospect of technological applications, the fundamental spin physics, which has a longstanding tradition in the solid-state community, is by itself exciting and worth pursuing. Furthermore, even though many proposed spintronic device schemes may turn out to be impractical in the end, their importance lies in stimulating interesting experimental and theoretical research.

There are many challenges and open questions to be tackled by future research, in particular a robust spin injection into silicon.[127] While GaAs is of great technological importance, the control of spin in silicon would raise hopes for seamless integration of spintronics with the current information technology. In addition, the small magnitude of the spin-orbit interaction and the absence of inversion symmetry lead to relatively long room-temperature spin lifetimes (of about 10 ns; see Sec. III.D.1), relaxing some constraints on the operational length and time scales. Important materials advances have been realized in improving the compatibility of Si/III-V structures (Sieg *et al.*, 1998), suggesting that the existing control of spin in GaAs or in III-V ferromagnetic semiconductors might be extended to Si.

Future progress in spin-polarized transport will be largely driven by the materials advances. In the context of semiconductors, considering all-semiconductor structures rather than the hybrid structures with metallic ferromagnets will depend on the improvements in ferromagnetic semiconductors, for example, whether they can achieve higher mobility, higher Curie temperature,[128] and a simple fabrication of high quality interfaces with nonmagnetic materials. What is missing, even in the currently available materials, is a systematic understanding of the effects of magnetic interfaces and materials inhomogeneities on spin-polarized transport. A comprehensive transport calculation in the actual devices with realistic electronic structure of the studied materials would provide valuable insights into both the spin polarization being measured and how it is reduced from the moment it was generated.

Spin relaxation and spin dephasing of conduction electrons is a mature field, with the basic principles well understood. What is needed are accurate band-structure-derived calculations of spin relaxation times, in both metals and semiconductors. The same can be said of the g factor, calculation of which from first principles is a nontrivial task that has not been accomplished even for the elemental metals. An important and still debated issue is spin relaxation and decoherence of localized or confined electrons, where the hyperfine-interaction mechanism dominates. Furthermore, single-spin relaxation and decoherence, and their relation to the ensemble spin dephasing, need to be pursued further in the context of quantum computing. A first step towards understanding single-spin relaxation is the recent experiment of Hanson, Witkamp, *et al.* (2003) in a one-electron quantum dot.

While dynamic nuclear polarization induced by electron spin can often be a nuisance for detecting intrinsic spin dynamics (Sec. III.D.3), the interaction between electron and nuclear spins (Fleisher and Merkulov, 1984a; Paget and Berkovits, 1984; Smet *et al.*, 2002; Vagner, 2003) is of fundamental importance for spintronics. An NMR of the nuclear spin polarized by spin-polarized photoexcited electrons has already been used to detect the nonequilibrium electron spin in Si (Lampel, 1968). On the other hand, an NMR signal can be detected optically by measuring changes in the circular polarization of photoluminescence due to resonant variations of the nuclear field (D'yakonov and Perel', 1984), as shown first in p-doped $Ga_{0.7}Al_{0.3}As$ (Ekimov and Safarov, 1972). The early work of Lampel (1968), and Ekimov and Safarov (1972) established the basic principles for a series of experiments that demonstrated various realizations of an all-optical NMR. The role of the resonant radio waves is played by periodically optically excited electron spins (Kalevich *et al.*, 1980, 1981; Fleisher and Merkulov, 1984b; Kalevich, 1986; Kikkawa and Awschalom, 2000; Salis, Fuchs, *et al.*, 2001). Electron-nuclear spintronics is likely to become relevant for quantum computation and for few-spin manipulations, which can benefit from long nuclear spin coherence times (even lasting minutes).

The range of potential spintronic applications goes beyond the use of large magnetoresistive effects. Rudolph *et al.* (2003), for example, have demonstrated the operation of a spin laser. The laser is a vertical-cavity surface-emitting laser (VCSEL), optically pumped in the gain medium, here two InGaAs quantum wells, with 50% spin-polarized electrons. The electrons recombine with heavy holes, which are effectively unpolarized, emitting circularly polarized light (Sec. II.B). The threshold electrical current, extracted from the pump power for the lasing operation, was found to be $0.5\ \mathrm{A\,cm^{-2}}$, which is 23% below the threshold current of the spin-unpolarized

[127]Small signals attributed to spin injection have already been reported (Jia *et al.*, 1996).

[128]There still remain many challenges in accurately predicting Curie temperature. First principles results suggest that dominant models of ferromagnetism in semiconductors cannot be used to explain a variation of Curie temperature across different materials (Erwin and Žutić, 2004). For reviews of ferromagnetic semiconductor theories outside the scope of this article see, for example, Nagaev (1983); Bhat *et al.* (2002); Dietl (2002); Sanvito *et al.* (2002); Das Sarma *et al.* (2003); König *et al.* (2003); Timm (2003).

VCSEL. Furthermore, for a fixed pump power, the emission power of the laser changed by 400% upon changing the degree of circular polarization of the pump laser. The reason for the decrease in threshold is the selective coupling of spin-polarized electrons to photons with one helicity. While the experiment was conducted at 6 K, a room-temperature operation and an electrically pumped laser should be viable as well.[129]

The demonstration that the flow of spin-polarized carriers, rather than applied magnetic field, can also be used to manipulate magnetization of ferromagnetic materials brings the exciting prospect of a novel class of spintronic devices. In addition to reversal of magnetization, which is a key element in realizing various magnetoresistive applications, the driving of a spin-polarized current can lead to coherent microwave oscillations in nanomagnets (Kiselev *et al.*, 2003). Spin-transfer torque (Sec. I.B.1) has already been realized in several experimental geometries. These include nanowires (Wegrowe *et al.*, 1999; Kelly *et al.*, 2003), point contacts (Tsoi *et al.*, 1998, 2000, 2002; Ji *et al.*, 2003), nanoconstrictions (Myers *et al.*, 1999; Rippard *et al.*, 2004), and nanopilars (Katine *et al.*, 2000; Albert *et al.*, 2002; Urazhdin *et al.*, 2003; see Fig. 36), all involving metallic ferromagnets. The common feature of all these geometries is a need for very large current densities ($\sim 10^7$ A cm^{-2}). Ongoing experiments (Munekata, 2003; Chiba *et al.*, 2004; Yamanouchi *et al.*, 2004) to demonstrate spin-transfer torque (together with other cooperative phenomena) in ferromagnetic semiconductors, which have much smaller magnetization than their metallic counterparts, are expected also to require much smaller switching currents. Based on the findings in electric-field-controlled ferromagnetism (see Fig. 27), it has been demonstrated that reversal of magnetization in (In, Mn)As can be manipulated by modifying the carrier density, using a gate voltage in a field-effect transistor structure (Chiba *et al.*, 2003).

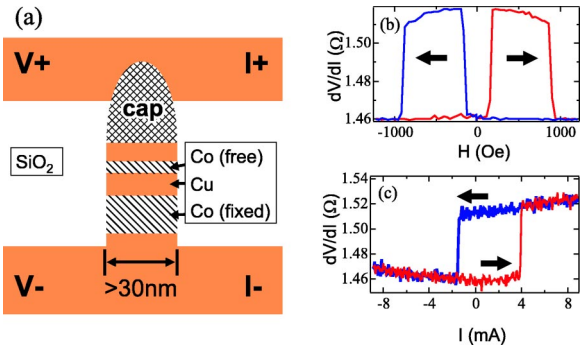

FIG. 36. (Color in online edition) Nanopilar device: (a) schematic diagram of a nanopilar device operating at room temperature. The direction of magnetization is fixed (pinned) in the thick Co film and free in the thin Co film; (b) differential resistance dV/dI of a nanopilar device as a function of applied field; (c) dV/dI of the device as a function of applied current. The arrows in panels (b) and (c) represent the direction of magnetic field and current sweeps, respectively. For positive current, electrons flow from the thin to the thick Co film. Adapted from Albert *et al.*, 2002.

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[129]The requirement is that the spin relaxation time be longer than the carrier recombination time, and that the spin injection spot and the gain medium be within the spin transport length.

REFERENCES

Abragam, A., 1961, *The Principles of Nuclear Magnetism* (Oxford University Press, London).

Abrikosov, A. A., and L. P. Gorkov, 1960, "Contribution to the theory of superconducting alloys with paramagnetic impurities," Zh. Eksp. Teor. Fiz. **39**, 1781–1796 [Sov. Phys. JETP **12**, 1243–1253 (1961)].

Adachi, T., Y. Ohno, F. Matsukura, and H. Ohno, 2001, "Spin relaxation in n-modulation doped GaAs/AlGaAs(110) quantum wells," Physica E (Amsterdam) **10**, 36–39.

Affleck, I., J.-S. Caux, and A. M. Zagoskin, 2000, "Andreev scattering and Josephson current in a one-dimensional electron liquid," Phys. Rev. B **62**, 1433–1445.

Akinaga, H., 2002, "Magnetoresistive switch effect in metal/semiconductor hybrid granular films: extremely huge magnetoresistance effect at room temperature," Semicond. Sci. Technol. **17**, 322–326.

Albert, F. J., N. C. Emley, E. B. Myers, D. C. Ralph, and R. A. Buhrman, 2002, "Quantitative study of magnetization reversal by spin-polarized current in magnetic multilayer nanopillars," Phys. Rev. Lett. **89**, 226802.

Albrecht, J. D., and D. L. Smith, 2002, "Electron spin injection at a Schottky contact," Phys. Rev. B **66**, 113303.

Albrecht, J. D., and D. L. Smith, 2003, "Spin-polarized electron transport at ferromagnet/semiconductor Schottky contacts," Phys. Rev. B **68**, 035340.

Aleiner, I. L., and Y. B. Lyanda-Geller, 1991, "Conductance and electron spin polarization in resonant tunneling," Pis'ma Zh. Eksp. Teor. Fiz. **53**, 89–92 [JETP Lett. **53**, 91–95 (1991)].

Alvarado, S. F., 1995, "Tunneling potential barrier dependence of electron spin polarization," Phys. Rev. Lett. **75**, 513–516.

Alvarado, S. F., and P. Renaud, 1992, "Observation of spin-polarized-electron tunneling from a ferromagnet into GaAs," Phys. Rev. Lett. **68**, 1387–1390.

Anderson, P. W., 1966, "Localized magnetic states and Fermi-surface anomalies in tunneling," Phys. Rev. Lett. **17**, 95–97.

Ando, T., A. B. Fowler, and F. Stern, 1982, "Electronic properties of two-dimensional systems," Rev. Mod. Phys. **54**, 437–672.

Andreev, A. F., 1964, "The thermal conductivity of the intermediate state in superconductors," Zh. Eksp. Teor. Fiz. **46**, 1823–1825 [Sov. Phys. JETP **19**, 1228–1231 (1964)].

Andreev, V. V., and V. I. Gerasimenko, 1958, "On the theory of paramagnetic resonance and paramagnetic relaxation in metals," Zh. Eksp. Teor. Fiz. **35**, 1209–1215 [Sov. Phys. JETP **35**, 846–850 (1959)].

Anil Kumar, P. S., R. Jansen, O. M. J. van 't Erve, R. Vlutters, P. de Haan, and J. C. Lodder, 2000, "Low-field magnetocurrent above 200% in a spin-valve transistor at room temperature," J. Magn. Magn. Mater. **214**, L1–L6.

Ansermet, J.-Ph., 1998, "Perpendicular transport of spin-polarized electrons through magnetic nanostructures," J. Phys.: Condens. Matter **10**, 6027–6050.

Apinyan, V., and R. Mélin, 2002, "Microscopic theory of non local pair correlations in metallic F/S/F trilayers," Eur. Phys. J. B **25**, 373–389.

Appelbaum, J., 1966, "'*s-d*' exchange model of zero-bias tunneling anomalies," Phys. Rev. Lett. **17**, 91–95.

Arata, I., Y. Ohno, F. Matsukura, and H. Ohno, 2001, "Temperature dependence of electroluminescence and I-V characteristics of ferromagnetic/non-magnetic semiconductor pn junctions," Physica E (Amsterdam) **10**, 288–291.

Aronov, A. G., 1976a, "Spin injection and polarization of excitations and nuclei in superconductors," Zh. Eksp. Teor. Fiz. **71**, 370–376 [Sov. Phys. JETP **44**, 193–196 (1976)].

Aronov, A. G., 1976b, "Spin injection in metals and polarization of nuclei," Pis'ma Zh. Eksp. Teor. Fiz. **24**, 37–39 [JETP Lett. **24**, 32–34 (1976)].

Aronov, A. G., and G. E. Pikus, 1976, "Spin injection into semiconductors," Fiz. Tekh. Poluprovodn. (S.-Peterburg) **10**, 1177–1180 [Sov. Phys. Semicond **10**, 698–700 (1976)].

Aronov, A. G., G. E. Pikus, and A. N. Titkov, 1983, "Spin relaxation of conduction electrons in p-type III-V compounds," Zh. Eksp. Teor. Fiz. **84**, 1170–1184 [Sov. Phys. JETP **57**, 680–687 (1983)].

Ashcroft, N. W., and N. D. Mermin, 1976, *Solid State Physics* (Saunders, Philadelphia).

Asnin, V. M., A. A. Bakun, A. M. Danishevskii, E. L. Ivchenko, G. E. Pikus, and A. A. Rogachev, 1979, "Circular photogalvanic effect in optically active crystals," Solid State Commun. **30**, 565–570.

Atanasov, R., A. Haché, J. L. P. Hughes, H. M. van Driel, and J. E. Sipe, 1996, "Coherent control of photocurrent generation in bulk semiconductors," Phys. Rev. Lett. **76**, 1703–1706.

Auth, N., G. Jakob, T. Block, and C. Felser, 2003, "Spin polarization of magnetoresistive materials by point contact spectroscopy," Phys. Rev. B **68**, 024403.

Averkiev, N. S., and L. E. Golub, 1999, "Giant spin relaxation anisotropy in zinc-blende heterostructures," Phys. Rev. B **60**, 15 582–15 584.

Avodin, S. A., L. A. Dmitrieva, Yu. A. Kuperin, and V. V. Sartan, 2003, "Spin-dependent transport through the finite array of quantum dots: Spin gun," cond-mat/0310632.

Awschalom, D. D., 2001, "Manipulating and storing spin coherence in semiconductors," Physica E (Amsterdam) **10**, 1–6.

Awschalom, D. D., and J. M. Kikkawa, 1999, "Electron spin and optical coherence in semiconductors," Phys. Today **52** (6), 33–38.

Awschalom, D. D., J. Warnock, and S. von Molnár, 1987, "Low-temperature magnetic spectroscopy of a dilute magnetic semiconductor," Phys. Rev. Lett. **58**, 812–815.

Baibich, M. N., J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas, 1988, "Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices," Phys. Rev. Lett. **61**, 2472–2475.

Balents, L., and R. Egger, 2000, "Spin transport in interacting quantum wires and carbon nanotubes," Phys. Rev. Lett. **85**, 3464–3467.

Balents, L., and R. Egger, 2001, "Spin-dependent transport in a Luttinger liquid," Phys. Rev. B **64**, 035310.

Barbic, M., 2002, "Magnetic resonance diffraction using the magnetic field from ferromagnetic sphere," J. Appl. Phys. **91**, 9987–9994.

Barnaś, J., and A. Fert, 1998, "Magnetoresistance oscillations due to charging effects in double ferromagnetic tunnel junctions," Phys. Rev. Lett. **80**, 1058–1061.

Bass, J., and W. P. Pratt, Jr., 1999, "Current-perpendicular (CPP) magnetoresistance in magnetic metallic multilayers," J. Magn. Magn. Mater. **200**, 274–289.

Bastard, G., and R. Ferreira, 1992, "Spin-flip scattering times in semiconductor quantum wells," Surf. Sci. **267**, 335–341.

Bauer, G. E. W., A. Brataas, and Y. T. B. J. van Wees, 2003, "Spin-torque transistor," Appl. Phys. Lett. **82**, 3928–3930.

Baylac, B., T. Amand, X. Marie, B. Dareys, M. Brousseau, G. Bacquet, and V. Thierry-Mieg, 1995, "Hole spin relaxation in n-modulation doped quantum wells," Solid State Commun. **93**, 57–60.

Bazaliy, Y. B., B. A. Jones, and S.-C. Zhang, 1998, "Modification of the Landau-Lifshitz equation in the presence of a spin-polarized current in colossal- and giant-magnetoresistive materials," Phys. Rev. B **57**, R3213–R3216.

Beck, M., P. Kiesel, S. Malzer, and G. H. Döhler, 2002, "Spin transport by giant ambipolar diffusion," Physica E (Amsterdam) **12**, 407–411.

Bennett, M. C., J. van Lierop, E. M. Berkeley, J. F. Mansfield, C. Henderson, M. C. Aronson, D. P. Young, A. Bianchi, Z. Fisk, F. Balakirev, and A. Lacerda, 2003, "The origin of weak ferromagnetism in CaB_6," cond-mat/0306709.

Berciu, M., and B. Jankó, 2003, "Nanoscale Zeeman localization of charge carriers in diluted magnetic semiconductor-permalloy hybrids," Phys. Rev. Lett. **90**, 246804.

Berger, L., 1996, "Emission of spin waves by a magnetic multilayer transversed by a current," Phys. Rev. B **54**, 9353–9358.

Bergeret, F. S., A. F. Volkov, and K. B. Efetov, 2001, "Long-range proximity effects in superconductor-ferromagnet structures," Phys. Rev. Lett. **86**, 4096–4099.

Bergmann, G., 1982, "Studies of spin-orbit scattering in noble-metal nanoparticles using energy-level tunneling spectroscopy," Z. Phys. B: Condens. Matter **48**, 5–16.

Beschoten, B., E. Johnston-Halperin, D. K. Young, M. Poggio, J. E. Grimaldi, S. Keller, S. P. DenBaars, U. K. Mishra, E. L.

Hu, and D. D. Awschalom, 2001, "Spin coherence and dephasing in GaN," Phys. Rev. B **63**, 121202.
Beuneu, F., and P. Monod, 1978, "The Elliott relation in pure metals," Phys. Rev. B **18**, 2422–2425.
Bhat, R. D. R., and J. E. Sipe, 2000, "Optically injected spin currents in semiconductors," Phys. Rev. Lett. **85**, 5432–5435.
Bhat, R. N., M. Berciu, M. P. Kennett, and X. Wan, 2002, "Dilute magnetic semiconductors in the low carrier density regime," J. Supercond. **15**, 71–83.
Binasch, G., P. Grünberg, F. Saurenbach, and W. Zinn, 1989, "Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange," Phys. Rev. B **39**, 4828–4830.
Bir, G. L., A. G. Aronov, and G. E. Pikus, 1975, "Spin relaxation of electrons due to scattering by holes," Zh. Eksp. Teor. Fiz. **69**, 1382–1397 [Sov. Phys. JETP **42**, 705–712 (1976)].
Blakemore, J. S., 1982, "Semiconducting and other major properties of gallium arsenide," J. Appl. Phys. **53**, R123–R181.
Bloch, F., 1946, "Nuclear induction," Phys. Rev. **70**, 460–474.
Blonder, G. E., and M. Tinkham, 1983, "Metallic to tunneling transition in Cu-Nb point contacts," Phys. Rev. B **27**, 112–118.
Blonder, G. E., M. Tinkham, and T. M. Klapwijk, 1982, "Transition from metallic to tunneling regimes in superconducting microconstrictions: Excess current, charge imbalance, and supercurrent conversion," Phys. Rev. B **25**, 4515–4532.
Boeve, H., Š. Németh, Z. Liu, J. De Boeck, and G. Borghs, 2001, "Transport properties of epitaxial Fe-GaN-Fe tunnel junctions on GaAs," J. Magn. Magn. Mater. **226-230**, 933–935.
Boggess, T., J. T. Olesberg, C. Yu, M. E. Flatté, and W. H. Lau, 2000, "Room-temperature electron spin relaxation in bulk InAs," Appl. Phys. Lett. **77**, 1333–1335.
Boguslawski, P., 1980, "Electron-electron spin-flip scattering and spin relaxation in III-V and II-VI semiconductors," Solid State Commun. **33**, 389–391.
Bonnell D. A., 2001, Ed., *Scanning Probe Microscopy and Spectroscopy* (Wiley, New York).
Borda, L., G. Zaránd, W. Hofstetter, B. I. Halperin, and J. von Delft, 2003, "SU(4) Fermi liquid state and spin filtering in a double quantum dot system," Phys. Rev. Lett. **90**, 026602.
Boukari, H., P. Kossacki, M. Bertolini, D. Ferrand, J. Cibert, S. Tatarenko, A. Wasiela, J. A. Gaj, and T. Dietl, 2002, "Light and electric field control of ferromagnetism in magnetic quantum structures," Phys. Rev. Lett. **88**, 207204.
Bourgeois, O., P. Gandit, A. Sulpice, J. L. J. Chauss, and X. Grison, 2001, "Transport in superconductor/ferromagnet/superconductor junctions dominated by interface resistance," Phys. Rev. B **63**, 064517.
Bournel, A., 2000, "Magnéto-électronique dans des dispositifs á semiconducteurs," Ann. Phys. (Paris) **25**, 1–167.
Bournel, A., P. Dollfus, E. Cassan, and P. Hesto, 2000, "Monte Carlo study of spin relaxation in AlGaAs/GaAs quantum wells," Appl. Phys. Lett. **77**, 2346–2348.
Bowen, M., M. Bibes, A. Barthelemy, J.-P. Contour, A. Anane, Y. Lemaitre, and A. Fert, 2003, "Nearly total spin polarization in $La_{2/3}Sr_{1/3}MnO_3$ from tunneling experiments," Appl. Phys. Lett. **82**, 233–235.
Bowring, C. S., M. A. Smithard, and J. E. Cousins, 1971, "Conduction electron spin resonance in magnesium," Phys. Status Solidi B **43**, 625–630.
Braden, J. G., J. S. Parker, P. Xiong, S. H. Chun, and N. Samarth, 2003, "Direct measurement of the spin polarization of the magnetic semiconductor (Ga,Mn)As," Phys. Rev. Lett. **91**, 056602.
Brand, M. A., A. Malinowski, O. Z. Karimov, P. A. Marsden, R. T. Harley, A. J. Shields, D. Sanvitto, D. A. Ritchie, and M. Y. Simmons, 2002, "Precession and motional slowing of spin evolution in a high mobility two-dimensional electron gas," Phys. Rev. Lett. **89**, 236601.
Brandt, N. B., and V. V. Moshchalkov, 1984, "Semimagnetic semiconductors," Adv. Phys. **33**, 193–256.
Brataas, A., Y. Tserkovnyak, G. E. W. Bauer, and B. I. Halperin, 2002, "Spin battery operated by ferromagnetic resonance," Phys. Rev. B **66**, 060404.
Bratkovsky, A. M., 1997, "Tunneling of electrons in conventional and half-metallic systems: Towards very large magnetoresistance," Phys. Rev. B **56**, 2344–2347.
Bratkovsky, A. M., and V. V. Osipov, 2003, "Spin extraction from a nonmagnetic semiconductor," cond-mat/0307656.
Brehmer, D. E., K. Zhang, C. J. Schwarz, S. Chau, S. J. Allen, J. P. Ibbetson, J. P. Zhang, C. J. Palmstrøm, and B. Wilkens, 1995, "Resonant tunneling through ErAs semimetal quantum wells," Appl. Phys. Lett. **67**, 1268–1270.
Brinkman, W. F., R. C. Dynes, and J. M. Rowell, 1970, "Tunneling conductance of asymmetrical barriers," J. Appl. Phys. **41**, 1915–1921.
Britton, R. S., T. Grevatt, A. Malinowski, R. T. Harley, P. Perozzo, A. R. Cameron, and A. Miller, 1998, "Room temperature spin relaxation in GaAs/AlGaAs multiple quantum wells," Appl. Phys. Lett. **73**, 2140–2142.
Bronold, F. X., I. Martin, A. Saxena, and D. L. Smith, 2002, "Magnetic-field dependence of electron spin relaxation in *n*-type semiconductors," Phys. Rev. B **66**, 233206.
Brosig, K., K. Ensslin, R. J. Warburton, C. Nguyen, B. Brar, M. Thomas, and H. Kroemer, 1999, "Zero-field spin splitting in InAs-AlSb quantum wells revisited," Phys. Rev. B **60**, R13 989–R13 992.
Brouwer, P. W., 1998, "Scattering approach to parametric pumping," Phys. Rev. B **58**, R10 135–R10 138.
Bruno, P., 1999, "Geometrically constrained magnetic wall," Phys. Rev. Lett. **83**, 2425–2428.
Bruno, R. C., and B. B. Schwartz, 1973, "Magnetic field splitting of the density of states of thin superconductors," Phys. Rev. B **8**, 3161–3178.
Burkard, G., H. A. Engel, and D. Loss, 2000, "Spintronics and quantum dots for quantum computing and quantum communication," Fortschr. Phys. **48**, 965–986.
Burkard, G., D. Loss, and D. P. DiVincenzo, 1999, "Coupled quantum dots as quantum gates," Phys. Rev. B **59**, 2070–2078.
Busch, G., M. Campagna, P. Cotti, and H. Ch. Siegmann, 1969, "Observation of electron polarization in photoemission," Phys. Rev. Lett. **22**, 597–599.
Bussmann, K., S. F. Cheng, G. A. Prinz, Y. Hu, R. Gutmann, D. Wang, R. Beech, and J. Zhu, 1998, "CPP giant magnetoresistance of NiFeCo/Cu/CoFe/Cu multilayers," IEEE Trans. Magn. **34**, 924–926.
Bussmann, K., G. A. Prinz, S.-F. Cheng, and D. Wang, 1999, "Switching of vertical giant magnetoresistance devices by current through the device," Appl. Phys. Lett. **75**, 2476–2478.
Butler, W. H., X.-G. Zhang, T. C. Schulthess, and J. M. MacLaren, 2001, "Reduction of electron tunneling current due to lateral variation of the wave function," Phys. Rev. B **63**, 092402.

Bychkov, Yu. A., and E. I. Rashba, 1984a, "Oscillatory effects and the magnetic-susceptibility of carriers in inversion-layers," J. Phys. C **17**, 6039–6045.

Bychkov, Yu. A., and E. I. Rashba, 1984b, "Properties of a 2D electron-gas with lifted spectral degeneracy," Pis'ma Zh. Eksp. Teor. Fiz. **39**, 66–69 [JETP Lett. **39**, 78–81 (1984)].

Cacho, C., Y. Lassailly, H. Drouhin, G. Lampel, and J. Peretti, 2002, "Spin filtering of free electrons by magnetic multilayers: Towards an efficient self-calibrated spin polarimeter," Phys. Rev. Lett. **88**, 066601.

Camilleri, C., F. Teppe, D. Scalbert, Y. G. Semenov, M. Nawrocki, M. I. D'yakonov, J. Cibert, S. Tatarenko, and T. Wojtowicz, 2001, "Electron and hole spin relaxation in modulation-doped CdMnTe quantum wells," Phys. Rev. B **64**, 085331.

Campbell, I. A., A. Fert, and A. R. Pomeroy, 1967, "Evidence for two current conduction iron," Philos. Mag. **15**, 977–983.

Chadi, D. J., A. H. Clark, and R. D. Burnham, 1976, "Γ_1 conduction electron g factor and matrix elements in GaAs and $Al_xGa_{1-x}As$ alloys," Phys. Rev. B **13**, 4466–4469.

Chan, H. B., R. C. Ashoori, L. N. Pfeiffer, and K. W. West, 1999, "Tunneling into ferromagnetic quantum Hall states: Observation of a spin bottleneck," Phys. Rev. Lett. **83**, 3258–3261.

Chazalviel, J.-N., 1975, "Spin relaxation of conduction electrons in n-type indium antimonide at low temperature," Phys. Rev. B **11**, 1555–1562.

Chen, Z. Y., A. Biswas, I. Žutić, T. Wu, S. B. Ogale, R. L. Greene, and T. Venkatesan, 2001, "Spin-polarized transport across a $La_{0.7}Sr_{0.3}MnO_3/YBa_2Cu_3O_{7-x}$ interface: Role of Andreev bound states," Phys. Rev. B **63**, 212508.

Chiba, D., Y. Sato, T. Kita, F. Matsukura, and H. Ohno, 2004, "Current-driven magnetization reversal in a ferromagnetic semiconductor (Ga,Mn)As/GaAs/(Ga,Mn)As tunnel junction," cond-mat/0403500.

Chiba, D., M. Yamanouchi, F. Matsukura, and H. Ohno, 2003, "Electrical manipulation of magnetization reversal in a ferromagnetic semiconductor," Science **301**, 943–945.

Chtchelkanova, A., S. Wolf, and Y. Idzerda 2003, Eds., *Magnetic Interactions and Spin Transport* (Kluwer Academic, Dordrecht/Plenum, New York).

Chui, S. T., 1995, "Electron interaction on the giant magnetoresistance in the perpendicular geometry," Phys. Rev. B **52**, R3832–R3835.

Chui, S. T., 1997, "Bias dependence in spin-polarized tunneling," Phys. Rev. B **55**, 5600–5603.

Chui, S. T., and J. R. Cullen, 1995, "Spin transmission in metallic trilayers," Phys. Rev. Lett. **74**, 2118–2121.

Chun, S. H., S. J. Potashnik, K. C. Ku, P. Schiffer, and N. Samarth, 2002, "Spin-polarized tunneling in hybrid metal-semiconductor magnetic tunnel junctions," Phys. Rev. B **66**, 100408.

Chung, S. H., M. Munoz, N. Garcia, W. F. Egelhoff, and R. D. Gomez, 2002, "Universal scaling of ballistic magnetoresistance in magnetic nanocontacts," Phys. Rev. Lett. **89**, 287203.

Chye, Y., M. E. White, E. Johnston-Halperin, B. D. Gerardot, D. D. Awschalom, and P. M. Petroff, 2002, "Spin injection from (Ga,Mn)As into InAs quantum dots," Phys. Rev. B **66**, 201301.

Ciorga, M., M. Pioro-Ladriere, P. Zawadzki, P. Hawrylak, and A. S. Sachrajda, 2002, "Tunable negative differential resistance controlled by spin blockade in single-electron transistors," Appl. Phys. Lett. **80**, 2177–2179.

Ciuti, C., J. P. McGuire, and L. J. Sham, 2002a, "Ferromagnetic imprinting of spin polarization in a semiconductor," Phys. Rev. Lett. **89**, 156601.

Ciuti, C., J. P. McGuire, and L. J. Sham, 2002b, "Spin-dependent properties of a two-dimensional electron gas with ferromagnetic gates," Appl. Phys. Lett. **81**, 4781–4783.

Clark, A. H., R. D. Burnham, D. J. Chadi, and R. M. White, 1975, "Spin relaxation of conduction electrons in $Al_xGa_{1-x}As$," Phys. Rev. B **12**, 5758–5765.

Clark, W. G., and G. Feher, 1963, "Nuclear polarization in InSb by a dc current," Phys. Rev. Lett. **10**, 134–138.

Cochrane, R. W., M. Plischke, and J. O. Ström-Olsen, 1974, "Magnetization studies of $(GeTe)_{1-x}(MnTe)_x$ pseudobinary alloys," Phys. Rev. B **9**, 3013–3021.

Cohen-Tannoudji, C. and A. Kostler, 1966, in *Progress in Optics, Vol. 25*, edited by E. Wolf (North-Holland, Amsterdam), p. 33.

Cortez, S., A. Jbeli, X. Marie, O. Krebs, R. Ferreira, T. Amand, P. Voisin, and J. M. Gerard, 2002, "Spin polarization dynamics in n-doped InAs/GaAs quantum dots," Physica E (Amsterdam) **13**, 508–511.

Cousins, J. E., and R. Dupree, 1965, "Electron spin resonance of conduction electrons in beryllium," Phys. Lett. **19**, 464–465.

Crooker, S. A., D. D. Awschalom, J. J. Baumberg, F. Flack, and N. Samarth, 1997, "Optical spin resonance and transverse spin relaxation in magnetic semiconductor quantum wells," Phys. Rev. B. **56**, 7574–7588.

Damay, P., and M. J. Sienko, 1976, "Conduction-electron spin resonance in metallic lithium," Phys. Rev. B **13**, 603–606.

Dargys, A., 2002, "Luttinger-Kohn Hamiltonian and coherent excitation of the valence-band holes," Phys. Rev. B **66**, 165216.

Das, B., D. C. Miller, S. Datta, R. Reifenberger, W. P. Hong, P. K. Bhattacharya, J. Singh, and M. Jaffe, 1989, "Evidence for spin splitting in $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ heterostructures as $B \rightarrow 0$," Phys. Rev. B **39**, 1411–1414.

Das Sarma, S., 2001, "Spintronics," Am. Sci. **89**, 516–523.

Das Sarma, S., J. Fabian, X. Hu, and I. Žutić, 2000a, "Issues, concepts, and challenges in spintronics," 58th DRC (Device Research Conference) Conference Digest (IEEE, Piscataway) 95–98, cond-mat/0006369.

Das Sarma, S., J. Fabian, X. Hu, and I. Žutić, 2000b, "Spintronics: electron spin coherence, entanglement, and transport," Superlattices Microstruct. **27**, 289–295.

Das Sarma, S., J. Fabian, X. Hu, and I. Žutić, 2000c, "Theoretical perspectives on spintronics and spin-polarized transport," IEEE Trans. Magn. **36**, 2821–2826.

Das Sarma, S., J. Fabian, X. Hu, and I. Žutić, 2001, "Spin electronics and spin computation," Solid State Commun. **119**, 207–215.

Das Sarma, S., E. H. Hwang, and A. Kaminski, 2003, "Temperature-dependent magnetization in diluted magnetic semiconductors," Phys. Rev. B **67**, 155201.

Datta, S., and B. Das, 1990, "Electronic analog of the electro-optic modulator," Appl. Phys. Lett. **56**, 665–667.

Daughton, J. M., A. V. Pohm, R. T. Fayfield, and C. H. Smith, 1999, "Applications of spin dependent transport materials," J. Phys. D **32**, R169–R177.

Davis, A. H., and K. Bussmann, 2003, "Organic luminescent devices and magnetoelectronics," J. Appl. Phys. **93**, 7358–7360.

de Andrada e Silva, E. A., and G. C. La Rocca, 1999, "Electron-spin polarization by resonant tunneling," Phys. Rev. B **59**, R15 583–R15 585.

de Andrada e Silva, E. A., G. C. La Rocca, and F. Bassani, 1997, "Spin-orbit splitting of electronic states in semiconductor asymmetric quantum wells," Phys. Rev. B **55**, 16 293–16 299.

De Boeck, J., R. Oesterholt, A. Van Esch, H. Bender, C. Bruynseraede, C. Van Hoof, and G. Borghs, 1996, "Nanometer-scale magnetic MnAs particles in GaAs grown by molecular beam epitaxy," Appl. Phys. Lett. **68**, 2744–2746.

De Boeck, J., W. Van Roy, J. Das, V. F. Motsnyi, Z. Liu, L. Lagae, H. Boeve, K. Dessein, and G. Borghs, 2002, "Technology and materials issues in semiconductor-based magnetoelectronics," Semicond. Sci. Technol. **17**, 342–354.

de Gennes, P. G., 1989, *Superconductivty of Metals and Alloys* (Addison-Wesley, Reading MA).

de Gennes, P. G., and D. Saint James, 1963, "Elementary excitations in the vicinity of a normal metal-superconducting metal contact," Phys. Lett. **4**, 151–152.

de Groot, R. A., A. G. Janner, and F. M. Mueller, 1983 Dutch Patent No. 8, 300, 602, Canadian Patent No. 1,216,375.

de Groot, R. A., F. M. Mueller, P. G. van Engen, and K. H. J. Buschow, 1983, "New class of materials: Half-metallic ferromagnets," Phys. Rev. Lett. **50**, 2024–2027.

de Jong, M. J. M., 1994, "Transition from Sharvin to Drude resistance in high-mobility wires," Phys. Rev. B **49**, 7778–7781.

de Jong, M. J. M., and C. W. J. Beenakker, 1995, "Andreev reflection in ferromagnet-superconductor junctions," Phys. Rev. Lett. **74**, 1657–1660.

de Sousa, R., and S. Das Sarma, 2003a, "Electron spin coherence in semiconductors: Considerations for a spin-based solid-state quantum computer architecture," Phys. Rev. B **67**, 033301.

de Sousa, R., and S. Das Sarma, 2003b, "Theory of nuclear-induced spectral diffusion: Spin decoherence of phosphorous donors in Si and GaAs quantum dots," Phys. Rev. B **68**, 115322.

de Sousa, R., and S. Das Sarma, 2003c, "Gate control of spin dynamics in III-V semiconductor quantum dots," Phys. Rev. B **68**, 155330.

De Teresa, J., A. Barthelemy, A. Fert, J. Contour, R. Lyonnet, F. Montaigne, P. Seneor, and A. Vaurès, 1999, "Inverse tunnel magnetoresistance in $Co/SrTiO_3/La_{0.7}Sr_{0.3}MnO_3$: New ideas on spin-polarized tunneling," Phys. Rev. Lett. **82**, 4288–4291.

Dediu, V., M. Murgia, F. C. Matacotta, C. Taliani, and S. Barbanera, 2002, "Room temperature spin polarized injection in organic semiconductor," Solid State Commun. **122**, 181–184.

Demler, E. A., G. B. Arnold, and M. R. Beasley, 1997, "Superconducting proximity effects in magnetic metals," Phys. Rev. B **55**, 15 174–15 182.

Deshmukh, M. M., and D. C. Ralph, 2002, "Using single quantum states as spin filters to study spin polarization in ferromagnets," Phys. Rev. Lett. **89**, 266803.

Dessein, K., H. Boeve, P. S. A. Kumar, J. D. Boeck, J. C. Lodder, L. Delaey, and G. Borghs, 2000, "Evaluation of vacuum bonded GaAs/Si spin-valve transistors," J. Appl. Phys. **87**, 5155–5157.

Deutscher, G., and D. Feinberg, 2000, "Coupling superconducting-ferromagnetic point contacts by Andreev reflections," Appl. Phys. Lett. **76**, 487–489.

Dieny, B., V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Maur, 1991, "Giant magnetoresistive in soft ferromagnetic multilayers," Phys. Rev. B **43**, 1297–1300.

Dietl, T., 1994, in *Handbook of Semiconductors, Vol. 3*, edited by T. S. Moss and S. Mahajan (North-Holland, New York), p. 1251.

Dietl, T., 2002, "Ferromagnetic semiconductors," Semicond. Sci. Technol. **17**, 377–392.

DiVincenzo, D. P., 1995, "Quantum computation," Science **270**, 255–261.

DiVincenzo, D. P., 1999, "Quantum computing and single-qubit measurements using the spin-filter effect," J. Appl. Phys. **85**, 4785–4787.

DiVincenzo, D. P., 2000, "The physical implementation of quantum computation," Fortschr. Phys. **48**, 771–783.

Dobers, M., K. von Klitzing, and G. Weimann, 1988, "Electron-spin resonance in the two-dimensional electron gas of GaAs-$Al_xGa_{1-x}As$ heterostructures," Phys. Rev. B **38**, 5453–5456.

Dong, Z. W., R. Ramesh, T. Venkatesan, M. Johnson, Z. Y. Chen, S. P. Pai, V. Talyansky, R. P. Sharma, R. Shreekala, C. J. Lobb, and R. L. Greene, 1997, "Spin-polarized quasiparticle injection devices using $Au/YBa_2Cu_3O_7/LaAlO_3/Nd_{0.7}Sr_{0.3}MnO_3$ heterostructures," Appl. Phys. Lett. **71**, 1718–1720.

Dresselhaus, G., 1955, "Spin-orbit coupling effects in zinc blende structures," Phys. Rev. **100**, 580–586.

Dugaev, V. K., Yu. Vygranenko, M. Vieira, V. I. Litvinov, and J. Barnas, 2003, "Modeling of magnetically controlled Si-based optoelectronic devices," Physica E (Amsterdam) **16**, 558–562.

Duke, C. B., 1969, in *Solid State Physics, Supplement 10*, edited by F. Seitz, D. Turnbull, and H. Ehrenreich (Academic, New York).

Dupree, R., and B. W. Holland, 1967, "The range of g factors and the breakdown of motional narrowing in conduction electron spin resonance," Phys. Status Solidi **24**, 275–279.

D'yakonov, M. I., and V. Y. Kachorovskii, 1986, "Spin relaxation of two-dimensional electrons in noncentrosymmetric semiconductors," Fiz. Tekh. Poluprovodn. (S.-Peterburg) **20**, 178–181 [Sov. Phys. Semicond. **20**, 110–112 (1986)].

D'yakonov, M. I., V. A. Marushchak, V. I. Perel', and A. N. Titkov, 1986, "The effect of strain on the spin relaxation of conduction electrons in III-V semiconductors," Zh. Eksp. Teor. Fiz. **90**, 1123–1133 [Sov. Phys. JETP **63**, 655–661 (1986)].

D'yakonov, M. I., and V. I. Perel', 1971a, "Current-induced spin orientation of electrons in semiconductors," Phys. Lett. **35A**, 459–460.

D'yakonov, M. I., and V. I. Perel', 1971b, "Feasibility of optical orientation of equilibrium electrons in semiconductors," Pis'ma Zh. Eksp. Teor. Fiz. **13**, 206–208 [JETP Lett. **13**, 144–146 (1971)].

D'yakonov, M. I., and V. I. Perel', 1971c, "Possibility of orienting electron spins with current," Pis'ma Zh. Eksp. Teor. Fiz. **13**, 657–660 [JETP Lett. **13**, 467–469 (1971)].

D'yakonov, M. I., and V. I. Perel', 1971d, "Spin orientation of electrons associated with the interband absorption of light in semiconductors," Zh. Eksp. Teor. Fiz. **60**, 1954–1965 [Sov. Phys. JETP **33**, 1053–1059 (1971)].

D'yakonov, M. I., and V. I. Perel', 1971e, "Spin relaxation of conduction electrons in noncentrosymetric semiconductors," Fiz. Tverd. Tela **13**, 3581–3585 [Sov. Phys. Solid State **13**, 3023–3026 (1971)].

D'yakonov, M. I., and V. I. Perel', 1973a, "Influence of an electric field and deformation on the optical orientation in semiconductors," Fiz. Tekh. Poluprovodn. (S.-Peterburg) **7**, 2335–2339 [Sov. Phys. Semicond. **7**, 1551–1553 (1974)].

D'yakonov, M. I., and V. I. Perel', 1973b, "Optical orientation in a system of electrons and lattice nuclei in semiconductors Theory," Zh. Eksp. Teor. Fiz. **38**, 362–376 [Sov. Phys. JETP **38**, 177–183 (1973)].

D'yakonov, M. I., and V. I. Perel', 1976, "Theory of the Hanle effect in optical orientation of electrons in n-type semiconductors," Fiz. Tekh. Poluprovodn. (S.-Peterburg) **10**, 350–353 [Sov. Phys. Semicond. **10**, 208–210 (1976)].

D'yakonov, M. I., and V. I. Perel', 1984, in *Optical Orientation, Modern Problems in Condensed Matter Science, Vol. 8*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam), pp. 11–71.

D'yakonov, M. I., V. I. Perel', V. L. Berkovits, and V. I. Safarov, 1974, "Optical effects due to polarization of nuclei in semiconductors," Zh. Eksp. Teor. Fiz. **67**, 1912–1924 [Sov. Phys. JETP **40**, 950–955 (1975)].

Dyson, F. J., 1955, "Electron spin resonance absorption in metals. II. Theory of electron diffusion and the skin effect," Phys. Rev. **98**, 349–359.

Dzero, M., L. P. Gor'kov, A. K. Zvezdin, and K. A. Zvezdin, 2003, "Even-odd effects in magnetoresistance of ferromagnetic domain walls," Phys. Rev. B **67**, 100402.

Dzhioev, R. I., K. V. Kavokin, V. L. Korenev, M. V. Lazarev, B. Y. Meltser, M. N. Stepanova, B. P. Zakharchenya, D. Gammon, and D. S. Katzer, 2002, "Low-temperature spin relaxation in n-type GaAs," Phys. Rev. B **66**, 245204.

Dzhioev, R. I., V. L. Korenev, I. A. Merkulov, B. P. Zakharchenya, D. Gammon, A. L. Efros, and D. S. Katzer, 2002, "Manipulation of the spin memory of electrons in n-GaAs," Phys. Rev. Lett. **88**, 256801.

Dzhioev, R. I., V. L. Korenev, B. P. Zakharchenya, D. Gammon, A. S. Bracker, J. G. Tischler, and D. S. Katzer, 2002, "Optical orientation and the Hanle effect of neutral and negatively charged excitons in GaAs/$Al_xGa_{1-x}As$ quantum wells," Phys. Rev. B **66**, 153409.

Dzihoev, R. I., B. P. Zakharchenya, K. V. Kavokin, and M. V. Lazarev, 2003, "The Hanle effect in nonuniformly doped GaAs," Fiz. Tverd. Tela (S.-Peterburg) **45**, 2153–2160 [Phys. Solid State **45**, 2225–2263 (2003)].

Dzhioev, R. I., B. P. Zakharchenya, V. L. Korenev, D. Gammon, and D. S. Katzer, 2001, "Long electron spin memory times in gallium arsenide," Pis'ma Zh. Eksp. Teor. Fiz. **74**, 182–185 [JETP Lett. **74**, 200–203 (2001)].

Dzhioev, R. I., B. P. Zakharchenya, V. L. Korenev, and M. N. Stepanova, 1997, "Spin diffusion of optically oriented electrons and photon entrainment in n-gallium arsenide," Fiz. Tverd. Tela (S.-Peterburg) **39**, 1975–1979 [Phys. Solid State **39**, 1765–1768 (1997)].

Dzyaloshinskii, I., 1958, "A thermodynamic theory of 'weak' ferromagnetism of antiferromagnetics," Phys. Chem. Solids **4**, 241–255.

Efros, Al. L., E. I. Rashba, and M. Rosen, 2001, "Paramagnetic ion-doped nanocrystal as a voltage-controlled spin filter," Phys. Rev. Lett. **87**, 206601.

Egelhoff, W. F., Jr., M. D. Stiles, D. P. Pappas, D. T. Pierce, J. M. Byers, M. B. Johnson, B. T. Jonker, S. F. Alvarado, J. F. Gregg, J. A. C. Bland, and R. A. Buhrman, 2002, "Spin polarization of injected electrons," Science **296**, 1195.

Egues, C. J., 1998, "Spin-dependent perpendicular magnetotransport through a tunable ZnSe/$Zn_{1-x}Mn_xSe$ heterostructure: A possible spin filter?" Phys. Rev. Lett. **80**, 4578–4581.

Eickhoff, M., B. Lenzmann, G. Flinn, and D. Suter, 2002, "Coupling mechanisms for optically induced NMR in GaAs quantum wells," Phys. Rev. B **65**, 125301.

Ekimov, A. I., and V. I. Safarov, 1970, "Optical orientation of carriers in interband transitions in semiconductors," Pis'ma Zh. Eksp. Teor. Fiz. **12**, 293–297 [JETP Lett. **12**, 198–201 (1970)].

Ekimov, A. I., and V. I. Safarov, 1971, "Observation of optical orientation of equilibrium electrons in n-type semiconductors," Pis'ma Zh. Eksp. Teor. Fiz. **13**, 251–254 [JETP Lett. **13**, 177–179 (1971)].

Ekimov, A. I., and V. I. Safarov, 1972, "Optical detection of dynamic of nuclei in semiconductors," Pis'ma Zh. Eksp. Teor. Fiz. **15**, 257–261 [JETP Lett. **15**, 179–181 (1972)].

Elezzabi, Y., M. R. Freeman, and M. Johnson, 1996, "Direct measurement of the conduction electron spin-lattice relaxation time T_1 in gold," Phys. Rev. Lett. **77**, 3220–3223.

Elliott, R. J., 1954, "Theory of the effect of spin-orbit coupling on magnetic resonance in some semiconductors," Phys. Rev. **96**, 266–279.

Elzerman, J. M., R. Hanson, J. S. Greidanus, L. H. Willems van Beveren, S. D. Franceschi, L. M. K. Vandersypen, S. Tarucha, and L. P. Kouwenhoven, 2003, "Few-electron quantum dot circuit with integrated charge read out," Phys. Rev. B **67**, 161308.

Endo, T., K. Sueoka, and K. Mukasa, 2000, "Electron spin-relaxation times in p-type δ-doped GaAs/AlGaAs double heterostructures," Jpn. J. Appl. Phys., Part 1 **39**, 397–401.

Engels, G., J. Lange, Th. Schäpers, and H. Lüth, 1997, "Experimental and theoretical approach to spin splitting in modulation-doped $In_xGa_{1-x}As$/InP quantum wells for $B\rightarrow 0$," Phys. Rev. B **55**, R1958–R1961.

Epstein, A. J., 2003, "Organic-based magnets: Opportunities in photoinduced magnetism, spintronics, fractal magnetism and beyond," MRS Bull. **28**, 492–499.

Erlingsson, S. I., Y. V. Nazarov, and V. I. Falko, 2001, "Nucleus-mediated spin-flip transitions in GaAs quantum dots," Phys. Rev. B **64**, 195306.

Erwin, S. C., S. Lee, and M. Scheffler, 2002, "First-principles study of nucleation, growth, and interface structure of Fe/GaAs," Phys. Rev. B **65**, 205422.

Erwin, S. C., and I. Žutić, 2004, "Tailoring ferromagnetic chalcopyrites," Nature Mater. (London) (in press), cond-mat/0401157.

Esaki, L., P. Stiles, and S. von Molnár, 1967, "Magnetointernal field emission in junctions of magnetic insulators," Phys. Rev. Lett. **19**, 852–854.

Escorne, M., A. Ghazalli, and P. Leroux-Hugon, 1974, in *Proceedings of the 12th International Conference on the Physics of Semiconductors*, edited by M. H. Pilkuhn (Teubner, Stuttgart), p. 915.

Fabian, J., and S. Das Sarma, 1998, "Spin relaxation of conduction electrons in polyvalent metals: theory and a realistic calculation," Phys. Rev. Lett. **81**, 5624–5627.

Fabian, J., and S. Das Sarma, 1999a, "Band-structure effects in the spin relaxation of conduction electrons," J. Appl. Phys. **85**, 5075–5079.

Fabian, J., and S. Das Sarma, 1999b, "Phonon-induced spin relaxation of conduction electrons in aluminum," Phys. Rev. Lett. **83**, 1211–1214.

Fabian, J., and S. Das Sarma, 1999c, "Spin relaxation of conduction electrons," J. Vac. Sci. Technol. B **17**, 1708–1715.

Fabian, J., and S. Das Sarma, 2002, "Spin transport in inhomogeneous magnetic fields: a proposal for Stern-Gerlach-like experiments with conduction electrons," Phys. Rev. B **66**, 024436.

Fabian, J., and I. Žutić, 2004, "Spin-polarized current amplification and spin injection in magnetic bipolar transistors," Phys. Rev. B **69**, 115314.

Fabian, J., I. Žutić, and S. Das Sarma, 2002a, "Theory of spin-polarized bipolar transport in magnetic *p-n* junctions," Phys. Rev. B **66**, 165301.

Fabian, J., I. Žutić, and S. Das Sarma, 2002b, "Theory of magnetic bipolar transistor," eprint cond-mat/0211639.

Fabian, J., I. Žutić, and S. D. Sarma, 2004, "Magnetic bipolar transistor," Appl. Phys. Lett. **84**, 85–87.

Falicov, L. M., D. T. Pierce, S. D. Bader, R. Gronsky, K. B. Hathaway, H. J. Hopster, D. N. Lambeth, S. S. P. Parkin, G. Prinz, M. Salamon, I. K. Schuller, and R. H. Victora, 1990, "Surface, interface, and thin-film magnetism," J. Mater. Res. **5**, 1299–1340.

Fal'ko, V. I., C. J. Lambert, and A. F. Volkov, 1999, "Andreev reflections and magnetoresistance in ferromagnet-superconductor mesoscopic structures," Pis'ma Zh. Eksp. Teor. Fiz. **69**, 497–503 [JETP Lett. **69**, 532–538 (1999)].

Fanciulli, M., T. Lei, and T. D. Moustakas, 1993, "Conduction-electron spin resonance in zinc-blende GaN thin films," Phys. Rev. B **48**, 15 144–15 147.

Fang, C. M., G. A. de Wijs, and R. A. de Groot, 2002, "Spin-polarization in half-metals," J. Appl. Phys. **91**, 8340–8344.

Feher, G., 1959, "Nuclear polarization via 'hot' conduction electrons," Phys. Rev. Lett. **3**, 135–137.

Feher, G., and E. A. Gere, 1959, "Electron spin resonance experiments on donors in silicon: II. electron spin relaxation effects," Phys. Rev. **114**, 1245–1256.

Feher, G., and A. F. Kip, 1955, "Electron spin resonance absorption in metals. I. Experimental," Phys. Rev. **98**, 337–348.

Feng, J.-F., and S.-J. Xiong, 2003, "Tunneling resonances and Andreev reflection in transport of electrons through a ferromagnetic metal/quantum dot/superconductor system," Phys. Rev. B **67**, 045316.

Ferreira, R., and G. Bastard, 1991, "Spin-flip scattering of holes in semiconductor quantum wells," Phys. Rev. B **43**, 9687–9691.

Fert, A., and I. A. Campbell, 1968, "Two-current conduction in nickel," Phys. Rev. Lett. **21**, 1190–1192.

Fert, A., and H. Jaffres, 2001, "Conditions for efficient spin injection from a ferromagnetic metal into a semiconductor," Phys. Rev. B **64**, 184420.

Fert, A., and S.-F. Lee, 1996, "Theory of the bipolar spin switch," Phys. Rev. B **53**, 6554–6565.

Fiederling, R., P. Grabs, W. Ossau, G. Schmidt, and L. W. Molenkamp, 2003, "Detection of electrical spin injection by light-emitting diodes in top- and side-emission configurations," Appl. Phys. Lett. **82**, 2160–2162.

Fiederling, R., M. Kleim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L. W. Molenkamp, 1999, "Injection and detection of a spin-polarized current in a light-emitting diode," Nature (London) **402**, 787–790.

Filip, A. T., B. H. Hoving, F. J. Jedema, B. J. van Wees, B. Dutta, and S. Borghs, 2000, "Experimental search for the electrical spin injection in a semiconductor," Phys. Rev. B **62**, 9996–9999.

Filip, A. T., P. LeClair, C. J. P. Smits, J. T. Kohlhepp, H. J. M. Swagten, B. Koopmans, and W. J. M. de Jonge, 2002, "Spin-injection device based on EuS magnetic tunnel barriers," Appl. Phys. Lett. **81**, 1815–1817.

Filipe, A., H. Drouhin, G. Lampel, Y. Lassailly, J. Nagle, J. Peretti, V. I. Safarov, and A. Schuhl, 1998, "Spin-dependent transmission of electrons through the ferromagnetic metal base of a hot-electron transistorlike system," Phys. Rev. Lett. **80**, 2425–2428.

Fisher, M. E., 1967, "Interfacial, boundary, and size effects at critical points," Phys. Rev. Lett. **19**, 169–172.

Fishman, G., and G. Lampel, 1977, "Spin relaxation of photoelectrons in *p*-type gallium arsenide," Phys. Rev. B **16**, 820–831.

Flatté, M. E., and J. M. Byers, 2000, "Spin diffusion in semiconductors," Phys. Rev. Lett. **84**, 4220–4223.

Flatté, M. E., and G. Vignale, 2001, "Unipolar spin diodes and transistors," Appl. Phys. Lett. **78**, 1273–1275.

Flatté, M. E., Z. G. Yu, E. Johnston-Halperin, and D. D. Awschalom, 2003, "Theory of semiconductor magnetic bipolar transistors," Appl. Phys. Lett. **82**, 4740.

Fleisher, V. G., and I. A. Merkulov, 1984a, in *Optical Orientation, Modern Problems in Condensed Matter Science, Vol. 8*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam), pp. 173–258.

Fleisher, V. G., and I. A. Merkulov, 1984b, in *Optical Orientation, Modern Problems in Condensed Matter Science, Vol. 8*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam), pp. 198–208.

Flensberg, K., T. S. Jensen, and N. A. Mortensen, 2001, "Diffusion equation and spin drag in spin-polarized transport," Phys. Rev. B **64**, 245308.

Folk, J. A., R. M. Potok, C. M. Marcus, and V. Umansky, 2003, "A gate-controlled bidirectional spin filter using quantum coherence," Science **299**, 679–682.

Fominov, Ya. V., 2003, "Proximity and Josephson effects in superconducting hybrid structures," Ph.D. thesis (Universiteit Twente).

Fraser, J. M., A. I. Shkrebtii, J. E. Sipe, and H. M. van Driel, 1999, "Quantum interference in electron-hole generation in noncentrosymmetric semiconductors," Phys. Rev. Lett. **83**, 4192–4195.

Friesen, M., P. Rugheimer, D. E. Savage, M. G. Lagally, D. W. van der Weide, R. Joynt, and M. A. Eriksson, 2003, "Practical design and simulation of silicon-based quantum-dot qubits," Phys. Rev. B **67**, 121301.

Frustaglia, D., M. Hentschel, and K. Richter, 2001, "Quantum transport in nonuniform magnetic fields: Aharonov-Bohm ring as a spin switch," Phys. Rev. Lett. **87**, 256602.

Fu, C. C., Z. Huang, and N. C. Yeh, 2002, "Spin-polarized quasiparticle transport in cuprate superconductors," Phys. Rev. B **65**, 224516.

Fujisawa, T., D. G. Austing, Y. Tokura, Y. Hirayama, and S. Tarucha, 2002, "Allowed and forbidden transitions in artificial hydrogen and helium atoms," Nature (London) **419**, 278–281.

Fulde, P., 1973, "High field superconductivity in thin films," Adv. Phys. **22**, 667–719.

Furdyna, J. K., 1988, "Diluted magnetic semiconductors," J. Appl. Phys. **64**, R29–R64.

Gadzuk, J. W., 1969, "Band-structure effects in the field-induced tunneling of electrons from metals," Phys. Rev. **182**, 416–426.

Gaj, J. A., 1988, in *Semiconductors and Semimetals, Vol. 25*, edited by J. K. Furdyna and J. Kossut (Academic, New York), p. 286.

Ganichev, S. D., S. N. Danilov, V. V. Belkov, E. L. Ivchenko, M. Bichler, W. Wegscheider, D. Weiss, and W. Prettl, 2002, "Spin-sensitive bleaching and monopolar spin orientation in quantum wells," Phys. Rev. Lett. **88**, 057401.

Ganichev, S. D., E. L. Ivchenko, V. V. Belkov, S. A. Tarasenko, M. Sollinger, D. Weiss, W. Wegschelder, and W. Prettl, 2002, "Spin-galvanic effect," Nature (London) **417**, 153–156.

Ganichev, S. D., E. L. Ivchenko, S. N. Danilov, J. Eroms, W. Wegscheider, D. Weiss, and W. Prettl, 2001, "Conversion of spin into directed electric current in quantum wells," Phys. Rev. Lett. **86**, 4358–4561.

Ganichev, S. D., and W. Prettl, 2003, "Spin photocurrents in quantum wells," J. Phys.: Condens. Matter **15**, R935–R983.

Ganichev, S. D., P. Schneider, V. V. Bel'kov, E. L. Ivchenko, S. A. Tarasenko, W. Wegscheider, D. Weiss, D. Schuh, B. N. Murdin, P. J. Phillips, C. R. Pidgeon, D. G. Clarke, M. Merrick, P. Murzyn, E. V. Beregulin, and W. Prettl, 2003, "Spin-galvanic effect due to optical spin orientation in *n*-type GaAs quantum well structures," Phys. Rev. B **68**, 081302.

Garbuzov, D. Z., A. I. Ekimov, and V. I. Safarov, 1971, "Measurement of the lifetime and of the spin-relaxation time of electrons in semiconductors by the optical-orientation method," Pis'ma Zh. Eksp. Teor. Fiz. **13**, 36–40 [JETP Lett. **13**, 24–26 (1971)].

Garcia, N., M. Munoz, and Y.-W. Zhao, 1999, "Magnetoresistance in excess of 200% in ballistic Ni nanocontacts at room temperature and 100 Oe," Phys. Rev. Lett. **82**, 2923–2926.

Gardelis, S., C. G. Smith, C. H. W. Barnes, E. H. Linfield, and D. A. Ritchie, 1999, "Spin-valve effects in a semiconductor field-effect transistor: A spintronic device," Phys. Rev. B **60**, 7764–7767.

Geux, L. S., A. Brataas, and G. E. W. Bauer, 2000, "Scattering theory of the Johnson spin transistor," Acta Phys. Pol. A **97**, 119–128.

Giaever, I., and K. Megerle, 1961, "Study of superconductors by electron tunneling," Phys. Rev. **122**, 1101–1111.

Giazotto, F., F. Taddei, R. Fazio, and F. Beltram, 2003, "Ferromagnetic resonant tunneling diodes as spin polarimeters," Appl. Phys. Lett. **82**, 2449–2451.

Gibson, G. A., and R. Meservey, 1985, "Properties of amorphous germanium tunnel barriers," J. Appl. Phys. **58**, 1584–1596.

Gijs, M. A. M., and G. E. W. Bauer, 1997, "Perpendicular giant magnetoresistance of magnetic multilayers," Adv. Phys. **46**, 285–445.

Gim, Y., A. W. Kleinsasser, and J. B. Barner, 2001, "Current injection into high-temperature superconductors: Does spin matter?" J. Appl. Phys. **90**, 4063–4077.

Glazov, M. M., and E. L. Ivchenko, 2002, "Precession spin relaxation mechanism caused by frequent electron-electron collisions," Pis'ma Zh. Eksp. Teor. Fiz. **75**, 476–478 [JETP Lett. **75**, 403–405 (2002)].

Glazov, M. M., and E. L. Ivchenko, 2003, "D'yakonov-Perel' spin relaxation under electron-electron collisions in QWs," cond-mat/0301519.

Goldman, A. M., K. Nikolaev, P. Kraus, V. Va'sko, A. Bhattacharya, and W. Cooley, 2001, "Spin injection and transport in magnetic-superconducting oxide heterostructures," J. Supercond. **14**, 283–290.

Goldman, A. M., V. Va'sko, P. Kraus, K. Nikolaev, and V. A. Larkin, 1999, "Cuprate/manganite heterostructures," J. Magn. Magn. Mater. **200**, 69–82.

Gordon, J. P., and K. D. Browers, 1958, "Microwave spin echoes from donor electrons in silicon," Phys. Rev. Lett. **1**, 368–370.

Gorelenok, A. T., V. G. Gruzdov, V. A. Marushchak, and A. N. Titkov, 1986, "Spin splitting of the conduction band of InP," Fiz. Tekh. Poluprovodn. (S.-Peterburg) **20**, 347–350 [Sov. Phys. Semicond. **20**, 216–218 (1986)].

Gorkov, L. P., and P. L. Krotkov, 2003, "Spin relaxation and antisymmetric exchange in *n*-doped III-V semiconductors," Phys. Rev. B **67**, 033203.

Gotoh, H., H. Ando, T. Sogawa, H. Kamada, T. Kagawa, and H. Iwamura, 2000, "Effect of electron-hole interaction on electron spin relaxation in GaAs/AlGaAs quantum wells at room temperature," J. Appl. Phys. **87**, 3394–3398.

Governale, M., D. Boese, U. Zülicke, and C. Schroll, 2002, "Filtering spin with tunnel-coupled electron wave guides," Phys. Rev. B **65**, 140403.

Governale, M., F. Taddei, and R. Fazio, 2003, "Pumping spin with electrical fields," Phys. Rev. B **68**, 155324.

Graeff, C. F. O., M. S. Brandt, M. Stutzmann, M. Holzmann, G. Abstreiter, and F. Schäffler, 1999, "Electrically detected magnetic resonance of two-dimensional electron gases in Si/SeGe heterostructures," Phys. Rev. B **59**, 13 242–13 250.

Gregg, J., W. Allen, N. Viart, R. Kirschman, C. S. J.-P. Schille, M. Gester, S. Thompson, P. Sparks, V. Da Costa, K. Ounadjela, and M. Skvarla, 1997, "The art of spin electronics," J. Magn. Magn. Mater. **175**, 1–9.

Griffin, A., and J. Demers, 1971, "Tunneling in the normal-metal-insulator-superconductor geometry using the Bogoliubov equations of motion," Phys. Rev. B **4**, 2202–2208.

Grimaldi, C., and P. Fulde, 1996, "Spin-orbit scattering effects on the phonon emission and absorption in superconducting tunneling junctions," Phys. Rev. Lett. **77**, 2550–2553.

Grimaldi, C., and P. Fulde, 1997, "Theory of screening of the phonon-modulated spin-orbit interaction in metals," Phys. Rev. B **55**, 15 523–15 530.

Griswold, T. W., A. F. Kip, and C. Kittel, 1952, "Microwave spin resonance absorption by conduction electrons in metallic sodium," Phys. Rev. **88**, 951–952.

Gruber, T., M. Kein, R. Fiederling, G. Reuscher, W. Ossau, G. Schmidt, and L. W. Molenkamp, 2001, "Electron spin manipulation using semimagnetic resonant tunneling diodes," Appl. Phys. Lett. **78**, 1101–1103.

Grundler, D., 2000, "Large Rashba splitting in InAs quantum wells due to electron wave function penetration into the barrier layers," Phys. Rev. Lett. **84**, 6074–6077.

Gu, J. Y., J. A. Caballero, R. D. Slater, R. Loloee, and W. P. Pratt, 2002, "Direct measurement of quasiparticle evanescent waves in a dirty superconductor," Phys. Rev. B **66**, 140507.

Guettler, T., A. L. Triques, L. Vervoort, R. F. P. Roussignol, P. Voisin, D. Rondi, and J. C. Harmand, 1998, "Optical polarization in $In_xGa_{1-x}As$-based quantum wells: Evidence of the interface symmetry-reduction effect," Phys. Rev. B **58**, R10 179–R10 182.

Guo, Y., J.-Q. Lu, B.-L. Gu, and Y. Kawazoe, 2001, "Spin-resonant splitting in magnetically modulated semimagnetic semiconductor superlattices," Phys. Rev. B **64**, 155312.

Gupta, J. A., D. D. Awschalom, A. L. Efros, and A. V. Rodina, 2002, "Spin dynamics in semiconductor nanocrystals," Phys. Rev. B **66**, 125307.

Gupta, J. A., D. D. Awschalom, X. Peng, and A. P. Alivisatos, 1999, "Spin coherence in semiconductor quantum dots," Phys. Rev. B **59**, 10 421–10 424.

Gurzhi, R. N., A. N. Kalinenko, A. I. Kopeliovich, and A. V. Yanovskii, 2001, "Nonmagnetic spinguides and spin transport in semiconductors," Fiz. Nizk. Temp. **27**, 1332–1334 [Low Temp. Phys. **27**, 985–986 (2001)].

Gurzhi, R. N., A. N. Kalinenko, A. I. Kopeliovich, A. V. Yanovsky, E. N. Bogachek, and U. Landman, 2003, "Spin-guide source for the generation of the high spin-polarized current," Phys. Rev. B **68**, 125113.

Gustavsson, F., J.-M. George, V. H. Etgens, and M. Eddrief, 2001, "Structural and transport properties of epitaxial Fe/ZnSe/FeCo magnetic tunnel junctions," Phys. Rev. B **64**, 184422.

Guth, M., A. Dinia, G. Schmerber, and H. A. M. van den Berg, 2001, "Tunnel magnetoresistance in magnetic tunnel junctions with a ZnS barrier," Appl. Phys. Lett. **78**, 3487–3489.

Haché, A., Y. Kostoulas, R. Atanasov, J. L. P. Hughes, J. E. Sipe, and H. M. van Driel, 1997, "Observation of coherently controlled photocurrent in unbiased, bulk GaAs," Phys. Rev. Lett. **78**, 306–309.

Hägele, D., M. Ostreich, W. W. Rühle, N. Nestle, and K. Eberl, 1998, "Spin transport in GaAs," Appl. Phys. Lett. **73**, 1580–1582.

Hall, K. C., S. W. Leonard, H. M. van Driel, A. R. Kost, E. Selvig, and D. H. Chow, 1999, "Subpicosecond spin relaxation in GaAsSb multiple quantum wells," Appl. Phys. Lett. **75**, 4156–4158.

Halterman, K., and O. T. Valls, 2002, "Proximity effects at ferromagnet-superconductor interfaces," Phys. Rev. B **65**, 014509.

Hammar, P. R., B. R. Bennett, M. J. Yang, and M. Johnson, 1999, "Observation of spin injection at a ferromagnet-semiconductor interface," Phys. Rev. Lett. **83**, 203–206.

Hammar, P. R., B. R. Bennett, M. J. Yang, and M. Johnson, 2000, "A reply to the comment by F. G. Monzon and H. X. Tang and M. L. Roukes," Phys. Rev. Lett. **84**, 5024–5025.

Hammar, P. R., and M. Johnson, 2000, "Potentiometric measurements of the spin-split subbands in a two-dimensional electron gas," Phys. Rev. B **61**, 7207–7210.

Hammar, P. R., and M. Johnson, 2001, "Spin-dependent current transmission across a ferromagnet-insulator-two-dimensional electron gas junction," Appl. Phys. Lett. **79**, 2591–2593.

Hammar, P. R., and M. Johnson, 2002, "Detection of spin-polarized electrons injected into a two-dimensional electron gas," Phys. Rev. Lett. **88**, 066806.

Hanbicki, A. T., and B. T. Jonker, 2002, "Response to comment on 'Efficient electrical spin injection from a magnetic metal/tunnel barrier contact into a semiconductor,' " Appl. Phys. Lett. **81**, 2131.

Hanbicki, A. T., B. T. Jonker, G. Itskos, G. Kioseoglou, and A. Petrou, 2002, "Efficient electrical spin injection from a magnetic metal/tunnel barrier contact into a semiconductor," Appl. Phys. Lett. **80**, 1240–1242.

Hanbicki, A., O. M. J. van t Erve, R. Magno, G. Kioseoglou, C. H. Li, B. T. Jonker, G. Itskos, R. Mallory, M. Yasar, and A. Petrou, 2003, "Analysis of the transport process providing spin injection through an Fe/AlGaAs Schottky barrier," Appl. Phys. Lett. **82**, 4092–4094.

Hanle, W., 1924, "Über magnetische Beeinflussung der Polarisation der Resonanzfluoreszenz," Z. Phys. **30**, 93–105.

Hanson, R., L. M. K. Vandersypen, L. H. W. van Beveren, J. M. Elzerman, I. T. Vink, and L. P. Kouwenhoven, 2003, "Semiconductor few-electron quantum dot operated as a bipolar spin filter," cond-mat/0311414.

Hanson, R., B. Witkamp, L. M. K. Vandersypen, L. H. Willems van Beveren, J. M. Elzerman, and L. P. Kouwenhoven, 2003, "Zeeman energy and spin relaxation in a one-electron quantum dot," Phys. Rev. Lett. **91**, 196802.

Hao, X., J. S. Moodera, and R. Meservey, 1990, "Spin-filter effect of ferromagnetic europium sulfide tunnel barriers," Phys. Rev. B **42**, 8235–8243.

Happer, W., 1972, "Optical pumping," Rev. Mod. Phys. **44**, 169–249.

Hartman, U., 2000, Ed., *Magnetic Multilayers and Giant Magnetoresistance* (Springer, Berlin).

Hass, N., M. Covington, W. L. Feldmann, L. H. Greene, and M. Johnson, 1994, "Transport properties of $YBa_2Cu_3O_{7-\delta}$/ferromagnetic interfaces," Physica C **235-240**, 1905–1906.

Hayashi, T., M. Tanaka, T. Nishinaga, H. Shimada, T. Tsuchiya, and Y. Otuka, 1997, "(GaMn)As: GaAs-based III-V diluted magnetic semiconductors grown by molecular beam epitaxy," J. Cryst. Growth **175/176**, 1063–1068.

Heberle, A. P., J. J. Blaumberg, E. Binder, T. Kuhn, K. Köhler, and K. H. Ploog, 1996, "Coherent control of exciton density and spin," IEEE J. Sel. Top. Quantum Electron. **2**, 769–775.

Heberle, A. P., W. W. Rühle, and K. Ploog, 1994, "Quantum beats of electron Larmor precession in GaAs wells," Phys. Rev. Lett. **72**, 3887–3890.

Heersche, H. B., T. Schäpers, J. Nitta, and H. Takayanagi, 2001, "Enhancement of spin injection from ferromagnetic metal into a two-dimensional electron gas using a tunnel barrier," Phys. Rev. B **64**, 161307.

Hehn, M., F. Montaigne, and A. Schuhl, 2002, "Hot-electron three-terminal devices based on magnetic tunnel junction stacks," Phys. Rev. B **66**, 144411.

Heida, J. P., B. J. van Wees, J. J. Kuipers, T. M. Klapwijk, and G. Borghs, 1998, "Spin-orbit interaction in a two-dimensional electron gas in a InAs/AlSb quantum well with gate-controlled electron density," Phys. Rev. B **57**, 11 911–11 914.

Heide, C., 2001, "Spin currents in magnetic films," Phys. Rev. Lett. **87**, 197201.

Hermann, C., G. Lampel, and V. I. Safarov, 1985, "Optical pumping in semiconductors," Ann. Phys. (Paris) **10**, 1117–1138.

Hershfield, S., and H. L. Zhao, 1997, "Charge and spin transport through a metallic ferromagnetic-paramagnetic-ferromagnetic junction," Phys. Rev. B **56**, 3296–3305.

Hertz, J. A., and K. Aoi, 1973, "Spin-dependent tunneling from transition-metal ferromagnets," Phys. Rev. B **8**, 3252–3256.

Hilton, D. J., and C. L. Tang, 2002, "Optical orientation and femtosecond relaxation of spin-polarized holes in GaAs," Phys. Rev. Lett. **89**, 146601.

Hirohata, A., Y. B. Xu, C. M. Guertler, J. A. C. Bland, and S. N. Holmes, 2001, "Spin-polarized electron transport in

ferromagnet/semiconductor hybrid structures induced by photon excitation," Phys. Rev. B **63**, 104425.
Hirota, E., H. Sakakima, and K. Inomata, 2002, *Giant Magneto-Resistance Devices* (Springer, Berlin).
Hirsch, J. E., 1999, "Spin Hall effect," Phys. Rev. Lett. **83**, 1834–1837.
Hong, J., and D. L. Mills, 2000, "Spin dependence of the inelastic electron mean free path in Fe and Ni: Explicit calculations and implications," Phys. Rev. B **62**, 5589–5600.
Hu, C.-M., and T. Matsuyama, 2001, "Spin injection across a heterojunction: A ballistic picture," Phys. Rev. Lett. **87**, 066803.
Hu, C.-M., J. Nitta, T. Akazaki, H. Takayanagi, J. Osaka, P. Pfeffer, and W. Zawadzki, 1999, "Zero-field spin splitting in an inverted $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure: Band non-parabolicity influence and the subband dependence," Phys. Rev. B **60**, 7736–7739.
Hu, C.-M., J. Nitta, A. Jensen, J. B. Hansen, and H. Takayanagi, 2001, "Spin-polarized transport in a two-dimensional electron gas with interdigital-ferromagnetic contacts," Phys. Rev. B **63**, 125333.
Hu, C. R., 1994, "Midgap surface states as a novel signature for $d_{x_a^2-x_b^2}$-wave superconductivity," Phys. Rev. Lett. **72**, 1526–1529.
Hu, C.-R., 1998, "Origin of the zero-bias conductance peaks observed ubiquitously in high-T_c superconductors," Phys. Rev. B **57**, 1266–1276.
Hu, C.-R., and X.-Z. Yan, 1999, "Predicted giant magnetic moment on non-{$n0m$} surfaces of d-wave superconductors," Phys. Rev. B **60**, R12573–R12576.
Hu, G., and Y. Suzuki, 2002, "Negative spin polarization of Fe_3O_4 in magnetite/manganite-based junctions," Phys. Rev. Lett. **89**, 276601.
Hu, X., and S. Das Sarma, 2000, "Hilbert-space structure of a solid-state quantum computer: two-electron states of a double-quantum-dot artificial molecule," Phys. Rev. A **61**, 062301.
Hu, X., and S. Das Sarma, 2001, "Spin-based quantum computation in multielectron quantum dots," Phys. Rev. A **64**, 042312.
Hu, X., R. de Sousa, and S. Das Sarma, 2001, "Decoherence and dephasing in spin-based solid state quantum computers," cond-mat/0108339.
Hübner, J., W. W. Rühle, M. Klude, D. Hommel, R. D. R. Bhat, J. E. Sipe, and H. M. van Driel, 2003, "Direct observation of optically injected spin-polarized currents in semiconductors," Phys. Rev. Lett. **90**, 216601.
Imamura, H., N. Kobayashi, S. Takahashi, and S. Maekawa, 2000, "Conductance quantization and magnetoresistance in magnetic point contacts," Phys. Rev. Lett. **84**, 1003–1006.
Inoue, J., and S. Makeawa, 1999, "Effects of spin-flip and magnon-inelastic scattering on tunnel magnetoresistance," J. Magn. Magn. Mater. **198**, 167–169.
Ionicioiu, R., and I. D'Amico, 2003, "Mesoscopic Stern-Gerlach device to polarize spin currents," Phys. Rev. B **67**, 041307.
Isaković, A. F., D. M. Carr, J. Strand, B. D. Schultz, C. J. Palmstrøm, and P. A. Crowell, 2001, "Optical pumping in ferromagnet-semiconductor heterostructures: Magneto-optics and spin transport," Phys. Rev. B **64**, 161304.
Itoh, H., A. Shibata, T. Kumazaki, J. Inoue, and S. Maekawa, 1999, "Effects of randomness on tunnel conductance and magnetoresistance in ferromagnetic tunnel junctions," J. Phys. Soc. Jpn. **68**, 1632–1639.
Ivchenko, E. L. and G. E. Pikus, 1997, *Superlattices and Other Heterostructures, Symmetry and Optical Phenomena*, 2nd ed. (Springer, New York).
Izyumov, Yu. A., Yu. N. Proshin, and M. G. Khusainov, 2002, "Competition between superconductivity and magnetism in ferromagnet/superconductor heterostructures," Usp. Fiz. Nauk **172**, 113–154 [Phys. Usp. **45**, 109–148 (2002)].
Jánossy, A., 1980, "Resonant and nonresonant conduction-electron-spin transmission in normal metals," Phys. Rev. B **21**, 3793–3810.
Jánossy, A., O. Chauvet, S. Pekker, J. R. Cooper, and L. Forró, 1993, "Conduction electron spin resonance in Rb_3C_{60}," Phys. Rev. Lett. **71**, 1091–1094.
Jansen, A. G. M., A. P. van Gelder, and P. Wyder, 1980, "Point-contact spectroscopy in metals," J. Phys. C **13**, 6073–6118.
Jansen, R., 2002, "Comment on 'Efficient electrical spin injection from a magnetic metal/tunnel barrier contact into a semiconductor,' " Appl. Phys. Lett. **81**, 2130.
Jansen, R., and J. S. Moodera, 2000, "Magnetoresistance in doped magnetic tunnel junctions: Effect of spin scattering and impurity-assisted transport," Phys. Rev. B **61**, 9047–9050.
Jedema, F. J., 2002, "Electrical spin injection in metallic mesoscopic spin valves," Ph.D. thesis (Rijksuniversiteit Groningen).
Jedema, F. J., M. V. Costache, H. B. Heersche, J. J. A. Baselmans, and B. J. van Wees, 2002, "Electrical detection of spin accumulation and spin precession at room temperature in metallic spin valves," Appl. Phys. Lett. **81**, 5162–5164.
Jedema, F. J., A. T. Filip, and B. J. van Wees, 2001, "Electrical spin injection and accumulation at room temperature in an all-metal mesoscopic spin valve," Nature (London) **410**, 345–348.
Jedema, F. J., H. B. Heersche, A. T. Filip, J. J. A. Baselmans, and B. J. van Wees, 2002a, "Electrical detection of spin precession in a metallic mesoscopic spin valve," Nature (London) **416**, 713–716.
Jedema, F. J., H. B. Heersche, A. T. Filip, J. J. A. Baselmans, and B. J. van Wees, 2002b, "Spintronics (communication arising): Spin accumulation in mesoscopic systems," Nature (London) **416**, 810.
Jedema, F. J., M. S. Nijboer, A. T. Filip, and B. J. van Wees, 2002, "Spin injection and spin accumulation in permalloy-cooper mesoscopic spin valves," J. Supercond. **15**, 27–35.
Jedema, F. J., M. S. Nijboer, A. T. Filip, and B. J. van Wees, 2003, "Spin injection and spin accumulation in all-metal mesoscopic spin valves," Phys. Rev. B **67**, 085319.
Jedema, F. J., B. J. van Wees, B. H. Hoving, A. T. Filip, and T. M. Klapwijk, 1999, "Spin-accumulation-induced resistance in mesoscopic ferromagnet-superconductor junctions," Phys. Rev. B **60**, 16 549–16 552.
Ji, Y., C. L. Chien, and M. D. Stiles, 2003, "Current-induced spin-wave excitations in a single ferromagnetic layer," Phys. Rev. Lett. **90**, 106601.
Ji, Y., G. J. Strijkers, F. Y. Yang, C. L. Chien, J. M. Byers, A. Anguelouch, G. Xiao, and A. Gupta, 2001, "Determination of the spin polarization of half-metallic CrO_2 by point-contact Andreev reflection," Phys. Rev. Lett. **86**, 5585–5588.
Jia, Y. Q., R. C. Shi, and S. Y. Chou, 1996, "Spin-valve effects in nickel/silicon/nickel junctions," IEEE Trans. Magn. **32**, 4707–4709.
Jiang, H. W., and E. Yablonovitch, 2001, "Gate-controlled electron spin resonance in $GaAs/Al_xGa_{1-x}As$ heterostructures," Phys. Rev. B **64**, 041307.

Jiang, X., R. Shelby, R. Wang, R. M. Macfarlane, S. Bank, J. Harris, and S. S. P. Parkin, 2004, "Highly spin polarized tunnel injector for semiconductor spintronics using MgO(100)," preprint.

Jiang, X., R. Wang, S. van Dijken, R. Shelby, R. Macfarlane, G. S. Solomon, J. Harris, and S. S. P. Parkin, 2003, "Optical detection of hot-electron spin injection into GaAs from a magnetic tunnel transistor source," Phys. Rev. Lett. **90**, 256603.

Johnson, M., 1991, "Analysis of anomalous multilayer magnetoresistance within the thermomagnetic system," Phys. Rev. Lett. **67**, 3594–3597.

Johnson, M., 1993a, "Bipolar spin switch," Science **260**, 320–323.

Johnson, M., 1993b, "Spin accumulation in gold films," Phys. Rev. Lett. **70**, 2142–2145.

Johnson, M., 1994, "Spin coupled resistance observed in ferromagnet-superconductor-ferromagnet trilayers," Appl. Phys. Lett. **65**, 1460–1462.

Johnson, M., 2000, "Dynamic nuclear polarization by spin injection," Appl. Phys. Lett. **77**, 1680–1682.

Johnson, M., 2001, "Spin injection: A survey and review," J. Supercond. **14**, 273–281.

Johnson, M., 2002a, "Spin injection into metals and semiconductors," Semicond. Sci. Technol. **17**, 298–309.

Johnson, M., 2002b, "Spintronics (communication arising): Spin accumulation in mesoscopic systems," Nature (London) **416**, 809–810.

Johnson, M., 2003, in *Magnetic Interactions and Spin Transport*, edited by A. Chtchelkanova, S. Wolf, and Y. Idzerda (Kluwer Academic, Dordrecht/Plenum, New York), pp. 515–564.

Johnson, M., and J. Byers, 2003, "Charge and spin diffusion in mesoscopic metal wires and at ferromagnet/nonmagnet interfaces," Phys. Rev. B **67**, 125112.

Johnson, M., and J. Clarke, 1990, "Spin-polarized scanning tunneling microscope: Concept, design, and preliminary results from a prototype operated in air," J. Appl. Phys. **67**, 6141–6152.

Johnson, M., and R. H. Silsbee, 1985, "Interfacial charge-spin coupling: Injection and detection of spin magnetization in metals," Phys. Rev. Lett. **55**, 1790–1793.

Johnson, M., and R. H. Silsbee, 1987, "Thermodynamic analysis of interfacial transport and of the thermomagnetoelectric system," Phys. Rev. B **35**, 4959–4972.

Johnson, M., and R. H. Silsbee, 1988a, "Coupling of electronic charge and spin at a ferromagnetic-paramagnetic metal interface," Phys. Rev. B **37**, 5312–5325.

Johnson, M., and R. H. Silsbee, 1988b, "Electron spin injection and detection at a ferromagnetic-paramagnetic interface," J. Appl. Phys. **63**, 3934–3939.

Johnson, M., and R. H. Silsbee, 1988c, "Ferromagnet-nonferromagnet interface resistance," Phys. Rev. Lett. **60**, 377.

Johnson, M., and R. H. Silsbee, 1988d, "Spin injection experiment," Phys. Rev. B **37**, 5326–5335.

Johnston-Halperin, E., D. Lofgreen, R. K. Kawakami, D. K. Young, L. Coldren, A. C. Gossard, and D. D. Awschalom, 2002, "Spin-polarized Zener tunneling in (Ga,Mn)As," Phys. Rev. B **65**, 041306.

Jonker, B. T., 1999, U.S. Patent No. 5,874,749 (23 February 1999).

Jonker, B. T., S. C. Erwin, A. Petrou, and A. G. Petukhov, 2003a, "Electrical spin injection and transport in semiconductor spintronic devices," MRS Bull. **28**, 740–748.

Jonker, B. T., O. J. Glembocki, R. T. Holm, and R. J. Wagner, 1997, "Enhanced carrier lifetimes and suppression of midgap states in GaAs at a magnetic metal interface," Phys. Rev. Lett. **79**, 4886–4889.

Jonker, B. T., A. T. Hanbicki, Y. D. Park, G. Itskos, M. Furis, G. Kioseoglou, A. Petrou, and X. Wei, 2001, "Quantifying electrical spin injection: Component-resolved electroluminescence from spin-polarized light-emitting diodes," Appl. Phys. Lett. **79**, 3098–3100.

Jonker, B. T., A. T. Hanbicki, D. T. Pierece, and M. D. Stiles, 2003b, "Spin nomenclature for semiconductors and magnetic metals," cond-mat/030445.

Jonker, B. T., Y. D. Park, B. R. Bennett, H. D. Cheong, G. Kioseoglou, and A. Petrou, 2000, "Robust electrical spin injection into a semiconductor heterostructure," Phys. Rev. B **62**, 8180–8183.

Joshi, S. K., D. Sahoo, and A. M. Jayannavar, 2001, "Aharonov-Bohm oscillations and spin-polarized transport in a mesoscopic ring with a magnetic impurity," Phys. Rev. B **64**, 075320.

Jullière, M., 1975, "Tunneling between ferromagnetic films," Phys. Lett. **54A**, 225–226.

Kainz, J., U. Rössler, and R. Winkler, 2003, "Anisotropic spin splitting and spin relaxation in asymmetric zinc-blende semiconductor quantum structures," Phys. Rev. B **68**, 075322.

Kaiser, W. J., and L. D. Bell, 1988, "Direct investigation of subsurface interface electronic structure by ballistic-electron-emission microscopy," Phys. Rev. Lett. **60**, 1406–1409.

Kalevich, V. K., 1986, "Optically induced nuclear magnetic resonance in semiconductors," Fiz. Tverd. Tela **28**, 3462–3465 [Sov. Phys. Solid State **28**, 1947–1949 (1986)].

Kalevich, V. K., V. D. Kul'kov, and V. G. Fleisher, 1980, "Manifestation of the sign of the *g* factor of conduction electrons in resonant cooling of the nuclear spin system of a semiconductor," Fiz. Tverd. Tela **22**, 1208–1211 [Sov. Phys. Solid State **22**, 703–705 (1980)].

Kalevich, V. K., V. D. Kul'kov, and V. G. Fleisher, 1981, "Manifestation of the sign of the *g* factor of conduction electrons in resonant cooling of the nuclear spin system of a semiconductor," Fiz. Tverd. Tela **23**, 1524–1526 [Sov. Phys. Solid State **23**, 892–893 (1981)].

Kalt, H., D. Tröndle, S. Wachter, I. J. Blewett, G. Brown, and I. Galbraith, 2000, "The role of spin orientation and relaxation in exciton-exciton scattering," Phys. Status Solidi B **221**, 477–480.

Kane, B. E., 1998, "A silicon based nuclear spin quantum computer," Nature (London) **393**, 133–137.

Kane, B. E., 2000, "Silicon-based quantum computation," Fortschr. Phys. **48**, 1023–1041.

Kane, B. E., L. N. Pfeiffer, and K. W. West, 1992, "Evidence for an electric-field-induced phase transition in a spin-polarized two-dimensional electron gas," Phys. Rev. B **46**, 7264–7267.

Kaplan, J. I., 1959, "Application of the diffusion-modified Bloch equation to electron spin resonance in ordinary and ferromagnetic metals," Phys. Rev. **115**, 575–577.

Kashiwaya, S., and Y. Tanaka, 2000, "Tunneling effects on surface bound states in unconventional superconductors," Rep. Prog. Phys. **63**, 1641–1724.

Kashiwaya, S., Y. Tanaka, N. Yoshida, and M. R. Beasley, 1999, "Spin current in ferromagnet-insulator-superconductor junctions," Phys. Rev. B **60**, 3572–3580.

Kastler, A., 1950, "Quelques suggestions concernant la production optique et la détection optique d'une inegalité de population des niveaux de quantification spatiale des atomes—application à l'experience de Stern et Gerlach et à la resonance magnetique," J. Phys. (Paris) **11**, 255–265.

Kasuya, T., and A. Yanase, 1968, "Anomalous transport phenomena in Eu-chalcogenide alloys," Rev. Mod. Phys. **40**, 684–696.

Katine, J. A., F. J. Albert, R. A. Buhrman, E. B. Myers, and D. Ralph, 2000, "Current-driven magnetization reversal and spin-wave excitations in Co/Cu/Co pillars," Phys. Rev. Lett. **84**, 3149–3152.

Kato, Y., R. C. Myers, D. C. Driscoll, A. C. Gossard, J. Levy, and D. D. Awschalom, 2003, "Gigahertz electron spin manipulation using voltage-controlled g-tensor modulation," Science **299**, 1201–1204.

Kauschke, W., N. Mestres, and M. Cardona, 1987, "Spin relaxation of holes in the split-hole band of InP and GaSb," Phys. Rev. B **35**, 3843–3853.

Kavokin, K. V., 2001, "Anisotropic exchange interaction of localized conduction-band electrons in semiconductors," Phys. Rev. B **64**, 075305.

Kavokin, K. V., 2002a, "Optical manifestations of electron spin transport and relaxation in semiconductors," Phys. Status Solidi A **190**, 221–227.

Kavokin, K. V., 2002b, "Symmetry of anisotropic exchange interactions in semiconductor nanostructures," cond-mat/0212347.

Keldysh, L. V., 1964, "Diagram technique for nonequilibrium processes," Zh. Eksp. Teor. Fiz. **47**, 1515–1527 [Sov. Phys. JETP **20**, 1018–1026 (1965)].

Kelly, D., J.-E. Wegrowe, T. k. Truong, X. Hoffer, and J.-P. Ansermet, 2003, "Spin-polarized current-induced magnetization reversal in single nanowires," Phys. Rev. B **68**, 134425.

Kessler, J., 1976, *Polarized Electrons* (Springer, New York).

Khaetskii, A. V., 2001, "Spin relaxation in semiconductor mesoscopic systems," Physica E (Amsterdam) **10**, 27–31.

Khaetskii, A. V., D. Loss, and L. Glazman, 2002, "Electron spin decoherence in quantum dots due to interaction with nuclei," Phys. Rev. Lett. **88**, 186802.

Khaetskii, A. V., D. Loss, and L. Glazman, 2003, "Electron spin evolution by interaction with nuclei in a quantum dot," Phys. Rev. B **67**, 195329.

Khaetskii, A. V., and Y. V. Nazarov, 2000, "Spin relaxation in semiconductor quantum dots," Phys. Rev. B **61**, 12 639–12 642.

Khaetskii, A. V., and Y. V. Nazarov, 2001, "Spin-flip transitions between Zeeman sublevels in semiconductor quantum dots," Phys. Rev. B **64**, 125316.

Kikkawa, J. M., 2003, private communication.

Kikkawa, J. M., and D. D. Awschalom, 1998, "Resonant spin amplification in n-type GaAs," Phys. Rev. Lett. **80**, 4313–4316.

Kikkawa, J. M., and D. D. Awschalom, 1999, "Lateral drag of spin coherence in gallium arsenide," Nature (London) **397**, 139–141.

Kikkawa, J. M., and D. D. Awschalom, 2000, "All-optical magnetic resonance in semiconductors," Science **287**, 473–476.

Kikkawa, J. M., J. A. Gupta, I. Malajovich, and D. D. Awschalom, 2001, "Spin coherence in semiconductors: storage, transport, and reduced dimensionality," Physica E (Amsterdam) **9**, 194–201.

Kikkawa, J. M., I. P. Smorchkova, N. Samarth, and D. D. Awschalom, 1997, "Room-temperature spin memory in two-dimensional electron gases," Science **277**, 1284–1287.

Kikuchi, K., H. Immamura, S. Takahashi, and S. Maekawa, 2002, "Conductance quantization and Andreev reflection in narrow ferromagnet/superconductor point contacts," Phys. Rev. B **65**, 020508.

Kimel, A. V., F. Bentivegna, V. N. Gridnev, V. V. Pavlov, R. V. Pisarev, and T. Rasing, 2001, "Room-temperature ultrafast carrier and spin dynamics in GaAs probed by the photoinduced magneto-optical Kerr effect," Phys. Rev. B **63**, 235201.

Kimel, A. V., V. V. Pavlov, R. V. Pisarev, V. N. Gridnev, F. Bentivegna, and T. Rasing, 2000, "Ultrafast dynamics of the photo-induced magneto-optical Kerr effect in CdTe at room temperature," Phys. Rev. B **62**, R10 610–R10 613.

Kirczenow, G., 2001, "Ideal spin filters: A theoretical study of electron transmission through ordered and disordered interfaces between ferromagnetic metals and semiconductors," Phys. Rev. B **63**, 054422.

Kiselev, A. A., and K. W. Kim, 2000, "Progressive suppression of spin relaxation in two-dimensional channels of finite width," Phys. Rev. B **61**, 13 115–13 120.

Kiselev, A. A., and K. W. Kim, 2001, "T-shaped ballistic spin filter," Appl. Phys. Lett. **78**, 775.

Kiselev, S. I., J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman, and D. C. Ralph, 2003, "Microwave oscillations of a nanomagnet driven by a spin-polarized current," Nature (London) **425**, 380–383.

Kittel, C., 1963, *Quantum Theory of Solids* (Wiley, New York).

Kittel, C., 1996, *Introduction to Solid State Physics*, 7th ed. (Wiley, New York).

Kivelson, S. A., and D. S. Rokhsar, 1990, "Bogoliubov quasiparticles, spinons, and spin-charge decoupling in superconductors," Phys. Rev. B **41**, 11 693–11 696.

Knap, W., C. Skierbiszewski, A. Zduniak, E. Litwin-Staszewska, D. Bertho, F. Kobbi, J. L. Robert, G. E. Pikus, F. G. Pikus, S. V. Iordanskii, V. Mosser, *et al.*, 1996, "Weak antilocalization and spin precession in quantum wells," Phys. Rev. B **53**, 3912–3924.

Kobayashi, K. L., T. Kimura, H. Saweda, K. Terakura, and Y. Tokura, 1998, "Room-temperature magnetoresistance in an oxide material with an ordered double-perovskite structure," Nature (London) **395**, 677–680.

Koga, T., J. Nitta, T. Akazaki, and H. Takayanagi, 2002a, "Rashba spin-orbit coupling probed by the weak antilocalization analysis in InAlAs/InGaAs/InAlAs quantum wells as a function of quantum well asymmetry," Phys. Rev. Lett. **89**, 046801.

Koga, T., J. Nitta, H. Takayanagi, and S. Datta, 2002b, "Spin-filter device based on the Rashba effect using a nonmagnetic resonant tunneling diode," Phys. Rev. Lett. **88**, 126601.

Kohda, M., Y. Ohno, K. Takamura, F. Matsukura, and H. Ohno, 2001, "A spin Esaki diode," Jpn. J. Appl. Phys., Part 2 **40**, L1274–L1276.

Koiller, B., X. Hu, and S. Das Sarma, 2002, "Exchange in silicon-based quantum computer architecture," Phys. Rev. Lett. **88**, 027903.

Koiller, B., X. Hu, and S. Das Sarma, 2003, "Disentangling the exchange coupling of entangled donors in the Si quantum computer architecture," Phys. Rev. Lett. **90**, 067401.

Kolbe, W., 1971, "Spin relaxation time of conduction electrons in bulk sodium metal," Phys. Rev. B **3**, 320–323.

König, J., M. C. Bønsager, and A. H. MacDonald, 2001, "Dissipationless spin transport in thin film ferromagnets," Phys. Rev. Lett. **87**, 187202.

König, J., and J. Martinek, 2003, "Interaction-driven spin precession in quantum-dot spin valves," Phys. Rev. Lett. **90**, 166602.

König, J., J. Schliemann, T. Jungwirth, and A. H. MacDonald, 2003, in *Electronic Structure and Magnetism of Complex Materials*, edited by D. J. Singh and D. A. Papaconstantopoulos (Springer, Berlin), pp. 163–211.

Korenblum, B., and E. I. Rashba, 2002, "Classical properties of low-dimensional conductors: Giant capacitance and non-Ohmic potential drop," Phys. Rev. Lett. **89**, 096803.

Korotkov, A. N., and V. I. Safarov, 1999, "Nonequilibrium spin distribution in a single-electron transistor," Phys. Rev. B **59**, 89–92.

Koshihara, S., A. Oiwa, M. Hirasawa, S. Katsumoto, Y. Iye, S. Urano, H. Takagi, and H. Munekata, 1997, "Ferromagnetic order induced by photogenerated carriers in magnetic III-V semiconductor heterostructures of (In,Mn)As/GaSb," Phys. Rev. Lett. **78**, 4617–4620.

Kouwenhoven, L. P., 2004, private communication.

Kravchenko, V. Ya., 2002, "The electric conductivity of a laminated metal system (alternating magnetic and nonmagnetic layers)," Zh. Eksp. Teor. Fiz. **121**, 703–727 [Sov. Phys. JETP **94**, 603–626 (2002)].

Kravchenko, V. Ya., and E. I. Rashba, 2003, "Spin injection into a ballistic semiconductor microstructure," Phys. Rev. B **67**, 121310.

Krenn, H., K. Kaltenegger, T. Dietl, J. Spalek, and G. Bauer, 1989, "Photoinduced magnetization in dilute magnetic (semimagnetic) semiconductors," Phys. Rev. B **39**, 10 918–10 934.

Krenn, H., W. Zawadzki, and G. Bauer, 1985, "Optically induced magnetization in a dilute magnetic semiconductor: $Hg_{1-x}Mn_xTe$," Phys. Rev. Lett. **55**, 1510–1513.

Kreuzer, S., J. Moser, W. Wegscheider, D. Weiss, M. Bichler, and D. Schuh, 2002, "Spin polarized tunneling through single-crystal GaAs(001) barriers," Appl. Phys. Lett. **80**, 4582–4584.

Krey, U., 2004, "On the significance of quantum effects and interactions for the apparent universality of Bloch laws for $M_s(T)$," J. Magn. Magn. Mater. **268**, 277–291.

Krinichnyi, V. I., 2000, "2-mm waveband electron paramagnetic resonance spectroscopy of conducting polymers," Synth. Met. **108**, 173–221.

Krishnamurthy, S., M. van Schilfgaarde, and N. Newman, 2003, "Spin life-times of electrons injected into GaAs and GaN," Appl. Phys. Lett. **83**, 1761–1763.

Kuzma, N. N., P. Khandelwal, S. E. Barrett, L. N. Pfeiffer, and K. W. West, 1998, "Ultraslow electron spin dynamics in GaAs quantum wells probed by optically pumped NMR," Science **281**, 686–690.

LaBella, V. P., D. W. Bullock, Z. Ding, C. Emery, A. Venkatesan, W. F. Oliver, G. J. Salamo, P. M. Thibado, and M. Mortazavi, 2001, "Spatially resolved spin-injection probability for gallium arsenide," Science **292**, 1518–1521.

LaBella, V. P., D. W. Bullock, Z. Ding, C. Emery, A. Venkatesan, W. F. Oliver, G. J. Salamo, P. M. Thibado, and M. Mortazavi, 2002, "Spin polarization of injected electrons (reply)," Science **292**, 1195.

Lamari, S., 2003, "Effect of the doping concentration on the zero-field splitting and Rashba parameter in a *p*-InAs MOSFET," Phys. Rev. B **67**, 165329.

Lambert, C. J., and R. Raimondi, 1998, "Phase-coherent transport in hybrid superconducting nanostructures," J. Phys.: Condens. Matter **10**, 901–941.

Lampel, G., 1968, "Nuclear dynamic polarization by optical electronic saturation and optical pumping in semiconductors," Phys. Rev. Lett. **20**, 491–493.

Lang, J., W. Eisenmenger, and P. Fulde, 1996, "Phonon-induced spin flip in extremely thin superconducting Al tunneling junctions in high magnetic fields," Phys. Rev. Lett. **77**, 2546–2549.

Lau, W. H., and M. E. Flatté, 2002, "Tunability of electron spin coherence in III-V quantum wells," J. Appl. Phys. **91**, 8682–8684.

Lau, W. H., J. T. Olesberg, and M. E. Flatté, 2001, "Electron-spin decoherence in bulk and quantum-well zinc-blende semiconductors," Phys. Rev. B **64**, 161301.

Lebedeva, N., and P. Kuivalainen, 2003, "Modeling of ferromagnetic semiconductor devices for spintronics," J. Appl. Phys. **93**, 9845–9864.

LeClair, P., J. T. Kohlhepp, C. H. van de Vin, H. Wieldraaijer, H. J. M. Swagten, W. J. M. de Jonge, A. H. Davis, J. M. MacLaren, J. S. Moodera, and R. Jansen, 2002, "Band structure and density of states effects in Co-based magnetic tunnel junctions," Phys. Rev. Lett. **88**, 107201.

Lee, W. Y., S. Gardelis, B.-C. Choi, Y. B. Xu, C. G. Smith, C. H. W. Barnes, D. A. Ritchie, E. H. Linfield, and J. A. C. Bland, 1999, "Magnetization reversal and magnetoresistance in a lateral spin-injection device," J. Appl. Phys. **85**, 6682–6685.

Lenczowski, S. K. J., R. J. M. van de Veerdonk, M. A. M. Gijs, J. B. Giesbers, and H. H. J. M. Janssen, 1994, "Current-distribution effects in microstructures for perpendicular magnetoresistance experiments," J. Appl. Phys. **75**, 5154–5159.

Lepine, D. J., 1970, "Spin resonance of localized and delocalized electrons in phosphorus-doped silicon between 20 and 30 K," Phys. Rev. B **2**, 2429–2439.

Lepine, D. J., 1972, "Spin-dependent recombination on silicon surface," Phys. Rev. B **6**, 436–441.

Levitov, L. S., Y. V. Nazarov, and G. M. Éliashberg, 1984, "Magnetoelectric effects in conductors with mirror isomer symmetry," Zh. Eksp. Teor. Fiz. **88**, 229–236 [Sov. Phys. JETP **61**, 133–137 (1973)].

Levitov, L. S., and E. I. Rashba, 2003, "Dynamical spin-electric coupling in a quantum dot," Phys. Rev. B **67**, 115324.

Levy, J., 2002, "Universal quantum computation with spin-1/2 pairs and Heisenberg exchange," Phys. Rev. Lett. **89**, 147902.

Levy, P. M., and I. Mertig, 2002, in *Spin Dependent Transport in Magnetic Nanostructures*, edited by S. Maekawa and T. Shinjo (Taylor and Francis, New York), pp. 47–111.

Linder, N., and L. J. Sham, 1998, "Theory of the coherent spin dynamics in magnetic semiconductor quantum wells," Physica E (Amsterdam) **2**, 412–416.

Lommer, G., F. Malcher, and U. Rössler, 1988, "Spin splitting in semiconductor heterostructures for $B \rightarrow 0$," Phys. Rev. Lett. **60**, 728–731.

Long, W., Q.-F. Sun, H. Guo, and J. Wang, 2003, "Gate-controllable spin battery," Appl. Phys. Lett. **83**, 1397–1399.

Loraine, D. R., D. I. Pugh, H. Jenniches, R. Kirschman, S. M. Thompson, W. Allen, C. Sirisathikul, and J. F. Gregg, 2000,

"Effect of silicon crystal structure on spin transmission through spin electronic devices," J. Appl. Phys. **87**, 5161–5163.

Loss, D., and D. P. DiVincenzo, 1998, "Quantum computation with quantum dots," Phys. Rev. A **57**, 120–122.

Lubzens, D., and S. Schultz, 1976a, "Conduction-electron spin resonance in aluminum at 79 GHz," Phys. Rev. B **14**, 945–950.

Lubzens, D., and S. Schultz, 1976b, "Observation of an anomalous frequency dependence of the conduction-electron spin resonance in Al," Phys. Rev. Lett. **36**, 1104–1106.

Luo, J., H. Munekata, F. F. Fang, and P. J. Stiles, 1988, "Observation of the zero-field spin splitting of the ground electron subband in GaSb-InAs-GaSb quantum wells," Phys. Rev. B **38**, 10 142–10 145.

Luo, J., H. Munekata, F. F. Fang, and P. J. Stiles, 1990, "Effects of inversion asymmetry on electron energy band structures in GaSb/InAs/GaSb quantum wells," Phys. Rev. B **41**, 7685–7693.

Łusakowski, A., J. Wróbel, and T. Dietl, 2003, "Effect of bulk inversion asymmetry on the Datta-Das transistor," Phys. Rev. B **68**, 081201.

MacDonald, A. H., 1999, "Spin bottlenecks in the quantum Hall regime," Phys. Rev. Lett. **83**, 3262–3265.

MacDonald, A. H., T. Jungwirth, and M. Kasner, 1998, "Temperature dependence of itinerant electron junction magnetoresistance," Phys. Rev. Lett. **81**, 705–708.

MacLaren, J. M., X.-G. Zhang, and W. H. Butler, 1997, "Validity of the Jullière model of spin-dependent tunneling," Phys. Rev. B **56**, 11 827–11 832.

MacLaren, J. M., X.-G. Zhang, W. H. Butler, and X. Wang, 1999, "Layer KKR approach to Bloch-wave transmission and reflection: Application to spin-dependent tunneling," Phys. Rev. B **59**, 5470–5478.

Maekawa, S., and U. Gäfvert, 1982, "Electron tunneling between ferromagnetic films," IEEE Trans. Magn. **18**, 707–708.

Maekawa, S., S. Takahashi, and H. Imamura, 2001, "Spin-polarized tunneling and spin injection in superconductor-ferromagnet junctions," Mater. Sci. Eng., B **84**, 44–48.

Maekawa, S., S. Takahashi, and H. Imamura, 2002, in *Spin Dependent Transport in Magnetic Nanostructures*, edited by S. Maekawa and T. Shinjo (Taylor and Francis, New York), pp. 143–236.

Majewski, J. A., and P. Vogl, 2003, in *Physics of Semiconductors 2002*, edited by A. R. Long and J. H. Davies (IOP, Bristol), p. 305.

Maialle, M. Z., 1996, "Spin relaxation of electrons in *p*-doped quantum wells via the electron-hole exchange interaction," Phys. Rev. B **54**, 1967–1974.

Maialle, M. Z., and M. H. Degani, 1997, "Electron-spin relaxation in *p*-type quantum wells via the electron-hole exchange interaction: the effects of the valence-band spin mixing and of an applied longitudinal electric field," Phys. Rev. B **55**, 13 771–13 777.

Maialle, M. Z., E. A. de Andrada e Silva, and L. J. Sham, 1993, "Exciton spin dynamics in quantum wells," Phys. Rev. B **47**, 15 776–15 788.

Maki, K., 1964, "Pauli paramagnetism and superconducting state. II," Prog. Theor. Phys. **32**, 29–36.

Malajovich, I., J. J. Berry, N. Samarth, and D. D. Awschalom, 2001, "Persistent sourcing of coherent spins for multifunctional semiconductor spintronics," Nature (London) **411**, 770–772.

Malinowski, A., R. S. Britton, T. Grevatt, R. T. Harley, D. A. Ritschie, and M. Y. Simmons, 2000, "Spin relaxation in $GaAs/Al_xGa_{1-x}As$ quantum wells," Phys. Rev. B **62**, 13 034–13 039.

Mal'shukov, A. G., C. S. Tang, C. S. Chu, and K. A. Chao, 2003, "Spin-current generation and detection in the presence of an ac gate," Phys. Rev. B **68**, 233307.

Mamin, H. J., R. Budakian, B. W. Chui, and D. Rugar, 2003, "Detection and manipulation of statistical polarization in small spin ensembles," Phys. Rev. Lett. **91**, 207604.

Margulis, A. D., and V. A. Margulis, 1994, "Effect of spin injection on the CESR at a ferromagnet-semiconductor contact," Physica B **193**, 179–187.

Martin, I., 2003, "Spin-drift transport and its applications," Phys. Rev. B **67**, 014421.

Martinek, J., J. Barnas, S. Maekawa, H. Schoeller, and G. Schön, 2002, "Spin accumulation in ferromagnetic single-electron transistors in the cotunneling regime," Phys. Rev. B **66**, 014402.

Marushchak, V. A., M. N. Stepanova, and A. N. Titkov, 1984, "Spin relaxation of conduction electrons in moderately doped gallium arsenide crystals," Fiz. Tverd. Tela **25**, 3537–3542 [Sov. Phys. Solid State **25**, 2035–2038 (1983)].

Masterov, V. F., and L. L. Makovskii, 1979, "Spin-dependent recombination on injection of electrons from a ferromagnet into a semiconductor," Fiz. Tekh. Poluprovodn. (S.-Peterburg) **13**, 2042–2044 [Sov. Phys. Semicond. **13**, 1192–1193 (1979)].

Mathon, J., and A. Umerski, 1997, "Tight-binding theory of tunneling giant magnetoresistance," Phys. Rev. B **56**, 11 810–11 819.

Mathon, J., and A. Umerski, 1999, "Theory of tunneling magnetoresistance in a junction with a nonmagnetic metallic interlayer," Phys. Rev. B **60**, 1117–1121.

Mathon, J., and A. Umerski, 2001, "Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction," Phys. Rev. B **63**, 220403.

Matsubara, K., T. Tsuzuku, and K. Sugihara, 1991, "Electron spin resonance in graphite," Phys. Rev. B **44**, 11 845–11 851.

Matsuyama, T., C.-M. Hu, D. Grundler, G. Meier, and U. Merkt, 2002, "Ballistic spin transport and spin interference in ferromagnetic/InAs(2DES)/ferromagnetic devices," Phys. Rev. B **65**, 155322.

Mattana, R., J.-M. George, H. Jaffres, F. Nguyen Van Dau, A. Fert, B. Lepine, A. Guivarc'h, and G. Jezequel, 2003, "Electrical detection of spin accumulation in a *p*-type GaAs quantum well," Phys. Rev. Lett. **90**, 166601.

Mavropoulos, P., O. Wunnicke, and P. H. Dederichs, 2002, "Ballistic spin injection and detection in Fe/semiconductor/Fe junctions," Phys. Rev. B **66**, 024416.

Mazin, I. I., 1999, "How to define and calculate the degree of spin polarization in ferromagnets," Phys. Rev. Lett. **83**, 1427–1430.

Mazin, I. I., A. A. Golubov, and B. Nadgorny, 2001, "Probing spin polarization with Andreev reflection: A theoretical basis," J. Appl. Phys. **89**, 7576–7578.

McCombe, B. D., and R. J. Wagner, 1971, "Electric-dipole-excited electron spin resonance in InSb," Phys. Rev. B **4**, 1285–1288.

Meier, F., J. Levy, and D. Loss, 2003, "Quantum computing with spin cluster qubits," Phys. Rev. Lett. **90**, 047901.

Meier, F., and B. P. Zakharchenya 1984, Eds., *Optical Orientation* (North-Holland, New York).

Mélin, R., and D. Feinberg, 2002, "Transport theory of multiterminal hybrid structures," Eur. Phys. J. B **26**, 101–114.

Mendez, E. E., L. Esaki, and W. I. Wang, 1998, "Resonant magnetotunneling in GaAlAs-GaAs-GaAlAs heterostructures," Phys. Rev. B **33**, R2893–R2896.

Merkulov, I. A., A. L. Efros, and M. Rosen, 2002, "Electron spin relaxation by nuclei in semiconductor quantum dots," Phys. Rev. B **65**, 205309.

Meservey, R., D. Paraskevopoulos, and P. M. Tedrow, 1976, "Correlation between spin polarization of tunnel currents from 3D ferromagnets and their magnetic moments," Phys. Rev. Lett. **37**, 858–860.

Meservey, R., and P. M. Tedrow, 1978, "Surface relaxation times of conduction-electron spins in superconductors and normal metals," Phys. Rev. Lett. **41**, 805–808.

Meservey, R., P. M. Tedrow, and J. S. Brooks, 1982, "Tunneling characteristics of amorphous Si barriers," J. Appl. Phys. **53**, 1563–1570.

Meservey, R., P. M. Tedrow, and J. S. Moodera, 1983, "Electron spin polarized tunneling study of ferromagnetic thin films," J. Magn. Magn. Mater. **35**, 1–6.

Miller, J. B., D. M. Zumbühl, C. M. Marcus, Y. B. Lyanda-Geller, D. Goldhaber-Gordon, K. Campman, and A. C. Gossard, 2003, "Gate-controlled spin-orbit quantum interference effects in lateral transport," Phys. Rev. Lett. **90**, 076807.

Mills, D. L., 1971, "Surface effects in magnetic crystals near the ordering temperature," Phys. Rev. B **3**, 3887–3895.

Mireles, F., and G. Kirczenow, 2001, "Ballistic spin-polarized transport and Rashba spin precession in semiconductor nanowires," Phys. Rev. B **64**, 024426.

Miyazaki, T., 2002, in *Spin Dependent Transport in Magnetic Nanostructures*, edited by S. Maekawa and T. Shinjo (Taylor and Francis, New York), pp. 143–236.

Miyazaki, T., and N. Tezuka, 1995, "Giant magnetic tunneling effect in $Fe/Al_2O_3/Fe$ junction," J. Magn. Magn. Mater. **139**, L231–L234.

Mizushima, K., T. Kinno, T. Yamauchi, and K. Tanaka, 1997, "Energy-dependent hot electron transport across a spin-valve," IEEE Trans. Magn. **33**, 3500–3504.

Monod, P., and F. Beuneu, 1979, "Conduction-electron spin flip by phonons in metals: Analysis of experimental data," Phys. Rev. B **19**, 911–915.

Monod, P., and A. Janossy, 1977, "Conduction electron spin resonance in gold," J. Low Temp. Phys. **26**, 311–316.

Monod, P., and S. Schultz, 1982, "Conduction electron spin-flip scattering by impurities in copper," J. Phys. (Paris) **43**, 393–401.

Monsma, D. J., J. C. Lodder, T. J. A. Popma, and B. Dieny, 1995, "Perpendicular hot electron spin-valve effect in a new magnetic field sensor: The spin-valve transistor," Phys. Rev. Lett. **74**, 5260–5263.

Monsma, D. J., and S. S. P. Parkin, 2000a, "Spin polarization of tunneling current from ferromagnet/Al_2O_3 interfaces using copper-doped aluminum superconducting films," Appl. Phys. Lett. **77**, 720–722.

Monsma, D. J., and S. S. P. Parkin, 2000b, "Temporal evolution of spin-polarization in ferromagnetic tunnel junctions," Appl. Phys. Lett. **77**, 883–885.

Monsma, D. J., R. Vlutters, and J. C. Lodder, 1998, "Room temperature-operating spin-valve transistors formed by vacuum bonding," Science **281**, 407–409.

Monzon, F. G., M. Johnson, and M. L. Roukes, 1997, "Strong Hall voltage modulation in hybrid ferromagnet/semiconductor microstructures," Appl. Phys. Lett. **71**, 3087–3089.

Monzon, F. G., and M. L. Roukes, 1999, "Spin injection and the local Hall effect in InAs quantum wells," J. Magn. Magn. Mater. **199**, 632–635.

Monzon, F. G., H. X. Tang, and M. L. Roukes, 2000, "Magnetoelectronic phenomena at a ferromagnet-semiconductor interface," Phys. Rev. Lett. **84**, 5022.

Moodera, J. S., X. Hao, G. A. Gibson, and R. Meservey, 1988, "Electron-spin polarization in tunnel junctions in zero applied field with ferromagnetic EuS barriers," Phys. Rev. B **42**, 8235–8243.

Moodera, J. S., L. R. Kinder, J. Nowak, P. LeClair, and R. Meservey, 1996, "Geometrically enhanced magnetoresistance in ferromagnet-insulator-ferromagnet tunnel junctions," Appl. Phys. Lett. **69**, 708–710.

Moodera, J. S., L. R. Kinder, T. M. Wong, and R. Meservey, 1995, "Large magnetoresistance at room temperature in ferromagnetic thin film tunnel junctions," Phys. Rev. Lett. **74**, 3273–3276.

Moodera, J. S., and G. Mathon, 1999, "Spin polarized tunneling in ferromagnetic junctions," J. Magn. Magn. Mater. **200**, 248–273.

Moodera, J. S., R. Meservey, and X. Hao, 1993, "Variation of the electron-spin polarization in EuSe tunnel junctions from zero to near 100% in a magnetic field," Phys. Rev. Lett. **70**, 853–856.

Moodera, J. S., J. Nassar, and G. Mathon, 1999, "Spin-tunneling in ferromagnetic junctions," Annu. Rev. Mater. Sci. **29**, 381–432.

Moodera, J. S., J. Nowak, and R. J. M. van de Veerdonk, 1998, "Interface magnetism and spin wave scattering in ferromagnet-insulator-ferromagnet tunnel junctions," Phys. Rev. Lett. **80**, 2941–2944.

Moriya, R., K. Hamaya, A. Oiwa, and H. Munekata, 2003, "Effect of electrical spin injection on magnetization reversal in (Ga,Mn)As/AlAs/(Ga,Mn)As trilayer structures," preprint.

Moriya, T., 1960, "Anisotropic superexchange interaction and weak ferromagnetism," Phys. Rev. **120**, 91–98.

Motsnyi, V. F., V. I. Safarov, J. De Boeck, J. Das, W. Van Roy, E. Goovaerts, and G. Borghs, 2002, "Electrical spin injection in a ferromagnet/tunnel barrier/semiconductor heterostructure," Appl. Phys. Lett. **81**, 265–267.

Motsnyi, V. F., P. Van Dorpe, W. Van Roy, E. Goovaerts, V. I. Safarov, G. Borghs, and J. De Boeck, 2003, "Optical investigation of electrical spin injection into semiconductors," Phys. Rev. B **68**, 245319.

Mott, N. F., 1936a, "The electrical conductivity of transition metals," Proc. R. Soc. London, Ser. A **153**, 699–717.

Mott, N. F., 1936b, "The resistance and thermoelectric properties of the transition metals," Proc. R. Soc. London, Ser. A **156**, 368–382.

Mott, N. F., and H. S. W. Massey, 1965, *The Theory of Atomic Collisions*, 3rd ed. (Clarendon, Oxford).

Moussa, J., L. R. Ram-Mohan, A. C. H. Rowe, and S. A. Solin, 2003, "Response of an extraordinary magnetoresistance read head to a magnetic bit," J. Appl. Phys. **94**, 1110–1114.

Mucciolo, E. R., C. Chamon, and C. M. Marcus, 2002, "An adiabatic quantum pump of spin polarized current," Phys. Rev. Lett. **89**, 146802.

Munekata, H., 2003, private communication.
Munekata, H., H. Ohno, R. R. Ruf, R. J. Gambino, and L. L. Chang, 1991, "P-type diluted magnetic III-V semiconductors," J. Cryst. Growth **111**, 1011–1015.
Munekata, H., H. Ohno, S. von Molnár, A. Segmüller, L. L. Chang, and L. Esaki, 1989, "Diluted magnetic III-V semiconductors," Phys. Rev. Lett. **63**, 1849–1852.
Munekata, H., A. Oiwa, Y. Mitsumori, R. Moriya, and T. Slupinski, 2003, "Rotation of ferromagnetically coupled Mn spins in (Ga,Mn)As by hole spins," J. Supercond. **16**, 411–414.
Munoz, L., E. Perez, L. Vina, and K. Ploog, 1995, "Spin relaxation in intrinsic GaAs quantum wells: influence of excitonic localization," Phys. Rev. B **51**, 4247–4257.
Murakami, S., N. Nagosa, and S.-C. Zhang, 2003, "Dissipationless quantum spin current at room temperature," Science **301**, 1348–1351.
Myers, E. B., D. C. Ralph, J. A. Katine, R. N. Louie, and R. Buhrman, 1999, "Current-induced switching of domains in magnetic multilayer devices," Science **285**, 867–870.
Nadgorny, B., I. I. Mazin, M. Osofsky, J. R. J. Soulen, P. Broussard, R. M. Stroud, D. J. Singh, V. G. Harris, A. Arsenov, and Y. Mukovskii, 2001, "Origin of high transport spin polarization in $La_{0.7}Sr_{0.3}MnO_3$: Direct evidence for minority spin states," Phys. Rev. B **63**, 184433.
Nadgorny, B., R. J. Soulen, Jr., M. S. Osofsky, I. I. Mazin, G. Laprade, R. J. M. van de Veerdonk, A. A. Smits, S. F. Cheng, E. F. Skelton, and S. B. Qadri, 2000, "Transport spin polarization of Ni_xFe_{1-x}: Electronic kinematics and band structure," Phys. Rev. B **61**, R3788–R3791.
Nagaev, E. L., 1983, *Physics of Magnetic Semiconductors* (Mir, Moscow).
Nazmul, A. M., S. Sugahara, and M. Tanaka, 2003, "Ferromagnetism and high Curie temperature in semiconductor heterostructures with Mn delta-doped GaAs and *p*-type selective doping," Phys. Rev. B **67**, 241308.
Ngai, J., Y. C. Tseng, P. Morales, J. Y. T. Wei, F. Chen, and D. D. Perovic, 2004, "Scanning tunneling spectroscopy under pulsed spin injection," Appl. Phys. Lett. **84**, 1907–1909.
Nielsen, M. A., and I. L. Chuang, 2000, *Quantum Computation and Quantum Information* (Cambridge University, Cambridge, NY).
Nikolić, B., and P. B. Allen, 1999, "Electron transport through a circular constriction," Phys. Rev. B **60**, 3963–3969.
Nikolić, B. K., and J. K. Freericks, 2001, "Mesoscopics in spintronics: Conductance fluctuations of spin-polarized electrons," cond-mat/0111144.
Nishikawa, Y., A. Tackeuchi, S. Nakamura, S. Muto, and N. Yokoyama, 1995, "All-optical picosecond switching of a quantum well etalon using spin-polarization relaxation," Appl. Phys. Lett. **66**, 839–841.
Nitta, J., T. Akazaki, H. Takayanagi, and T. Enoki, 1997, "Gate control of spin-orbit interaction in an inverted $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure," Phys. Rev. Lett. **78**, 1335–1338.
Oberli, D., R. Burgermeister, S. Riesen, W. Weber, and H. C. Siegmann, 1998, "Total scattering cross section and spin motion of low energy electrons passing through a ferromagnet," Phys. Rev. Lett. **81**, 4228–4231.
Oestreich, M., M. Brender, J. Hübner, D. H. W. W. Rühle, T. H. P. J. Klar, W. Heimbrodt, M. Lampalzer, K. Voltz, and W. Stolz, 2002, "Spin injection, spin transport and spin coherence," Semicond. Sci. Technol. **17**, 285–297.
Oestreich, M., J. Hübner, D. Hägele, P. J. Klar, W. Heimbrodt, W. W. Rühle, D. E. Ashenford, and B. Lunn, 1999, "Spin injection into semiconductors," Appl. Phys. Lett. **74**, 1251–1253.
Ohno, H., 1998, "Making nonmagnetic semiconductors ferromagnetic," Science **281**, 951–956.
Ohno, H., D. Chiba, F. Matsukura, T. O. E. Abe, T. Dietl, Y. Ohno, and K. Ohtani, 2000, "Electric-field control of ferromagnetism," Nature (London) **408**, 944–946.
Ohno, H., H. Munekata, T. Penney, S. von Molnár, and L. L. Chang, 1992, "Magnetotransport properties of *p*-type (In, Mn)As diluted magnetic III-V semiconductors," Phys. Rev. Lett. **68**, 2664–2667.
Ohno, H., A. Shen, F. Matsukura, A. Oiwa, A. End, S. Katsumoto, and Y. Iye, 1996, "(Ga,Mn)As: A new diluted magnetic semiconductor based on GaAs," Appl. Phys. Lett. **69**, 363–365.
Ohno, Y., I. Arata, F. Matsukura, K. Ohtani, S. Wang, and H. Ohno, 2000, "MBE growth and electroluminescence of ferromagnetic/non-magnetic semiconductor pn junctions based on (Ga,Mn)As," Appl. Surf. Sci. **159-160**, 308–312.
Ohno, Y., R. Terauchi, T. Adachi, F. Matsukura, and H. Ohno, 2000, "Electron spin relaxation beyond D'yakonov-Perel' interaction in GaAs/AlGaAs quantum wells," Physica E (Amsterdam) **6**, 817–820.
Ohno, Y., R. Terauchi, F. Matsukura, and H. Ohno, 1999, "Spin relaxation in GaAs(110) quantum wells," Phys. Rev. Lett. **83**, 4196–4199.
Ohno, Y., D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, 1999, "Electrical spin injection in a ferromagnetic semiconductor heterostructure," Nature (London) **402**, 790–792.
Oiwa, A., Y. Mitsumori, R. Moriya, T. Supinski, and H. Munekata, 2002, "Effect of optical spin injection on ferromagnetically coupled Mn spins in the III-V magnetic alloy semiconductor (Ga,Mn)As," Phys. Rev. Lett. **88**, 137202.
Oiwa, A., R. Moriya, Y. Mitsumori, T. Slupinski, and H. Munekata, 2003, "Manifestation of local magnetic domain reversal by spin-polarized carrier injection in (Ga,Mn)As thin films," J. Supercond. **16**, 439–442.
Oleinik, I. I., E. Yu. Tsymbal, and D. G. Pettifor, 2000, "Structural and electronic properties of $Co/Al_2O_3/Co$ magnetic tunnel junction from first principles," Phys. Rev. B **62**, 3952–3959.
Olesberg, J. T., W. H. Lau, M. E. Flatté, C. Yu, E. Altunkaya, E. M. Shaw, T. C. Hasenberg, and T. F. Boggess, 2001, "Interface contributions to spin relaxation in a short-period InAs/GaSb superlattice," Phys. Rev. B **64**, 201301.
Ono, K., D. G. Austin, Y. Tokura, and S. Tarucha, 2002, "Current rectification by Pauli exclusion in a weakly coupled double quantum dot system," Science **297**, 1313–1317.
Ono, K., H. Shimada, S. Kobayashi, and Y. Outuka, 1996, "Magnetoresistance of Ni/NiO/Co small tunnel junctions in Coulomb blockade regime," J. Phys. Soc. Jpn. **65**, 3449–3451.
Orchard-Webb, J. H., A. J. Watts, M. A. Smithard, and J. E. Cousins, 1970, "The effect of concentration gradients of impurities on the temperature dependence of the spin-lattice relaxation time in lithium and beryllium," Phys. Status Solidi **41**, 325–332.
Osipov, V. V., and A. M. Bratkovsky, 2003, "Efficient nonlinear room-temperature spin tunneling-emission in ferromagnet-semiconductor heterostructures with extended penetration depth," cond-mat/0307030.

Osipov, V. V., N. A. Viglin, I. V. Kochev, and A. A. Samokhvalov, 1990, "Microwave-absorption at a junction between the ferromagnetic semiconductor $HgCr_2Se_4$ and the semiconductor InSb," Pis'ma Zh. Eksp. Teor. Fiz. **52**, 996–998 [JETP Lett. **52**, 386–389 (1990)].

Osipov, V. V., N. A. Viglin, and A. A. Samokhvalov, 1998, "Investigation of heterostructure ferromagnetic semiconductor-semiconductor in the millimeter and submillimeter microwave range," Phys. Lett. A **247**, 353–359.

Oskotskij, B. D., A. V. Subashiev, and Y. A. Mamaev, 1997, "Polarized photoemission spectra of the strained semiconductor layers," Phys. Low-Dimens. Semicond. Struct. **1/2**, 77–87.

Osofsky, M., 2000, "Spin-injection," J. Supercond. **13**, 209–219.

Ott, H. R., J. L. Gavilano, B. Ambrosini, P. Vonlanthen, E. Felder, L. Degiorgi, D. P. Young, Z. Fisk, and R. Zysler, 2000, "Unusual magnetism of hexaborides," Physica B **281/282**, 423–427.

Overhauser, A. W., 1953a, "Paramagnetic relaxation in metals," Phys. Rev. **89**, 689–700.

Overhauser, A. W., 1953b, "Polarization of nuclei in metals," Phys. Rev. **92**, 411–415.

Paget, D., and V. L. Berkovits, 1984, in *Optical Orientation, Modern Problems in Condensed Matter Science, Vol. 8*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam), pp. 381–421.

Paget, D., G. Lampel, B. Sapoval, and V. I. Safarov, 1977, "Low field electron-nuclear spin coupling in gallium arsenide under optical pumping conditions," Phys. Rev. B **15**, 5780–5796.

Paillard, M., X. Marie, P. Renucci, T. Amand, A. Jbeli, and J. M. Gerard, 2001, "Spin relaxation quenching in semiconductor quantum dots," Phys. Rev. Lett. **86**, 1634–1637.

Panguluri, R. P., K. C. Kur, N. Samarth, T. Wojtowicz, X. Liu, J. K. Furdyna, I. I. Mazin, and B. Nadgorny, 2003, "Andreev reflection and pair breaking effects at the superconductor/ferromagnetic (Ga,Mn)As interface," (preprint).

Panguluri, R. P., B. Nadgorny, T. Wojtowicz, W. L. Lim, X. Liu, and J. K. Furdyna, 2004, "Measurement of spin polarization by Andreev reflection in $In_{1-x}Mn_xSb$ epilayers," cond-mat/0403451.

Panguluri, R. P., G. Tsoi, B. Nadgorny, S. H. Chun, N. Samarth, and I. I. Mazin, 2003, "Point contact spin spectroscopy of ferromagnetic MnAs epitaxial films," Phys. Rev. B **68**, 201307.

Pankove, J. I., 1971, *Optical Processes in Semiconductors* (Prentice-Hall, Englewood Cliffs, NJ).

Pannetier, B., and H. Courtois, 2000, "Andreev reflection and proximity effect," J. Low Temp. Phys. **118**, 599–615.

Pappas, D. P., K. Kämper, B. P. Miller, H. Hopster, D. E. Fowler, C. R. Brundle, and A. C. Luntz, 1991, "Spin-dependent electron attenuation by transmission through thin ferromagnetic film," Phys. Rev. Lett. **66**, 504–507.

Pareek, T. P., and P. Bruno, 2002, "Spin coherence in a two-dimensional electron gas with Rashba spin-orbit interaction," Phys. Rev. B **65**, 241305.

Park, J.-H., E. Vescovo, H.-J. Kim, C. Kwon, R. Ramesh, and T. Venkatesan, 1998a, "Direct evidence for a half-metallic ferromagnet," Nature (London) **392**, 794–796.

Park, J.-H., E. Vescovo, H.-J. Kim, C. Kwon, R. Ramesh, and T. Venkatesan, 1998b, "Magnetic properties at surface boundary of a half-metallic ferromagnet $La_{0.7}Sr_{0.3}MnO_3$," Phys. Rev. Lett. **81**, 1953–1956.

Park, Y. D., A. T. Hanbicki, S. C. Erwin, C. S. Hellberg, J. M. Sullivan, J. E. Mattson, T. F. Ambrose, A. Wilson, G. Spanos, and B. T. Jonker, 2002, "A group-IV ferromagnetic semiconductor: Mn_xGe_{1-x}," Science **295**, 651–654.

Park, Y. D., B. T. Jonker, B. R. Bennett, G. Itskos, M. Furis, G. Kioseoglou, and A. Petrou, 2000, "Electrical spin injection across air-exposed epitaxially regrown semiconductor interfaces," Appl. Phys. Lett. **77**, 3989–3991.

Parker, J. S., S. M. Watts, P. G. Ivanov, and P. Xiong, 2002, "Spin polarization of CrO_2 at and across an artificial barrier," Phys. Rev. Lett. **88**, 196601.

Parkin, S. S. P., 1993, "Origin of enhanced magnetoresistance of magnetic multilayers: Spin-dependent scattering from magnetic interface states," Phys. Rev. Lett. **71**, 1641–1644.

Parkin, S. S. P., 2002, in *Spin Dependent Transport in Magnetic Nanostructures*, edited by S. Maekawa and T. Shinjo (Taylor and Francis, New York), pp. 237–271.

Parkin, S. S. P., R. Bhadra, and K. P. Roche, 1991, "Oscillatory magnetic exchange coupling through thin copper layers," Phys. Rev. Lett. **66**, 2152–2155.

Parkin, S. S. P., X. Jiang, C. Kaiser, A. Panchula, K. Roche, and M. Samant, 2003, "Magnetically engineered spintronic sensors and memory," Proc. IEEE **91**, 661–680.

Parkin, S. S. P., C. Kaiser, A. Panchula, P. Rice, M. Samant, and S.-H. Yang, 2004, "Giant room temperature tunneling magnetoresistance in magnetic tunnel junctions with MgO(100) tunnel barriers," preprint.

Parkin, S. S. P., Z. G. Li, and D. J. Smith, 1991, "Giant magnetoresistance in antiferromagnetic Co/Cu multilayers," Appl. Phys. Lett. **58**, 2710–2712.

Parkin, S. S. P., K. P. Roche, M. G. Samant, P. M. Rice, R. B. Beyers, R. E. Scheuerlein, E. J. O'Sullivan, S. L. Brown, J. Bucchigano, D. W. Abraham, Y. Lu, M. Rooks, *et al.*, 1999, "Exchange-biased magnetic tunnel junctions and application to nonvolatile magnetic random access memory," J. Appl. Phys. **85**, 5828–5833.

Parsons, R. R., 1969, "Band-to-band optical pumping in solids and polarized photoluminescence," Phys. Rev. Lett. **23**, 1152–1154.

Pearton, S. J., C. R. Abernathy, M. E. Overberg, G. T. Thaler, D. P. Norton, N. Theodoropoulou, A. F. Hebard, Y. D. Park, F. Ren, J. Kim, and L. A. Boatner, 2003, "Wide band gap ferromagnetic semiconductors and oxides," J. Appl. Phys. **93**, 1–13.

Pederson, R. J., and F. L. Vernon, Jr., 1967, "Effect of film resistance on low-impedance tunneling measurements," Appl. Phys. Lett. **10**, 29–31.

Pejaković, D. A., C. Kitamura, J. S. Miller, and A. J. Epstein, 2002, "Photoinduced magnetization in the organic-based magnet $Mn(TCNE)_x \cdot y(CH_2Cl_2)$," Phys. Rev. Lett. **88**, 057202.

Perel', V. I., S. A. Tarasenko, I. N. Yassievich, S. D. Ganichev, V. V. Bel'kov, and W. Prettl, 2003, "Spin-dependent tunneling through a symmetric semiconductor barrier," Phys. Rev. B **67**, 201304.

Pershin, Y. V., and V. Privman, 2003a, "Focusing of spin polarization in semiconductors by inhomogeneous doping," Phys. Rev. Lett. **90**, 256603.

Pershin, Y. V., and V. Privman, 2003b, "Propagation of spin-polarized electrons through interfaces separating differently doped semiconductor regions," cond-mat/0306041.

Pershin, Y. V., and V. Privman, 2003c, "Spin relaxation of conduction electrons in semiconductors due to interaction with nuclear spins," Nano Lett. **3**, 695–700.

Petta, J. R., and D. C. Ralph, 2001, "Studies of spin-orbit scattering in noble-metal nanoparticles using energy-level tunneling spectroscopy," Phys. Rev. Lett. **87**, 266801.

Petukhov, A. G., 1998, "Transmission coefficients of GaAs/ErAs resonant tunneling diodes in strong magnetic fields," Appl. Surf. Sci. **123**, 385–390.

Petukhov, A. G., A. N. Chantis, and D. O. Demchenko, 2002, "Resonant enhancement of tunneling magnetoresistance in double-barrier magnetic heterostructures," Phys. Rev. Lett. **89**, 107205.

Pfeffer, P., 1997, "Spin splitting of conduction energies in GaAs-$Ga_{0.7}Al_{0.3}$As heterojunctions at $B=0$ and $B\neq 0$ due to inverstion asymmetry," Phys. Rev. B **55**, 7359–7362.

Pfeffer, P., and W. Zawadzki, 1995, "Spin splitting of conduction subbands in GaAS-$Ga_{0.7}As_{0.3}$As heterostructures," Phys. Rev. B **52**, R14 332–R14 335.

Pfeffer, P., and W. Zawadzki, 1999, "Spin splitting of conduction subbands in III-V heterostructures due to inversion asymmetry," Phys. Rev. B **59**, R5312–R5315.

Pfeffer, P., and W. Zawadzki, 2003, "Bychkov-Rashba spin splitting and its dependence on magnetic field in InSb/$In_{0.91}Al_{0.09}$Sb asymmetric quantum wells," Phys. Rev. B **68**, 035315.

Pickett, W. E., and J. S. Moodera, 2001, "Half metallic magnets," Phys. Today **54** (5), 39–44.

Pierce, D. T. and R. J. Celotta, 1984, in *Optical Orientation, Modern Problems in Condensed Matter Science, Vol. 8*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam), pp. 259–294.

Pierce, D. T., R. J. Celotta, J. Unguris, and H. C. Siegmann, 1982, "Spin-dependent elastic scattering of electrons from a ferromagnetic glass, $Ni_{40}Fe_{40}B_{20}$," Phys. Rev. B **26**, 2566–2574.

Pierce, D. T., and F. Meier, 1976, "Photoemission of spin-polarized electrons from GaAs," Phys. Rev. B **13**, 5484–5500.

Piermarocchi, C., P. Chen, L. J. Sham, and D. G. Steel, 2002, "Optical RKKY interaction between charged semiconductor quantum dots," Phys. Rev. Lett. **89**, 167402.

Pikus, F. G., and G. E. Pikus, 1995, "Conduction-band spin splitting and negative magnetoresistance in A_3B_5 heterostructures," Phys. Rev. B **51**, 16 928–16 935.

Pikus, G. E. and A. N. Titkov, 1984, in *Optical Orientation, Modern Problems in Condensed Matter Science, Vol. 8*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam), p. 109.

Pines, D., and C. P. Slichter, 1955, "Relaxation times in magnetic resonance," Phys. Rev. **100**, 1014–1020.

Pohn, A. V., J. M. Daughton, C. S. Comstock, H. Y. Yoo, and J. Hur, 1987, "Threshold properties of 1, 2 and 4 μm multilayer magneto-resistive memory cells," IEEE Trans. Magn. **23**, 2575–2577.

Pohn, A. V., J. S. T. Huang, J. M. Daughton, D. R. Krahn, and V. Mehra, 1988, "The design of a one megabit non-volatile M-R memory chip using 1.5×5 μm cells," IEEE Trans. Magn. **24**, 3117–3119.

Potok, R. M., J. A. Folk, C. M. Marcus, and V. Umansky, 2002, "Detecting spin-polarized currents in ballistic nanostructures," Phys. Rev. Lett. **89**, 266602.

Pratt, W. P., Jr., S.-F. Lee, J. M. Slaughter, R. Loloee, P. A. Schroeder, and J. Bass, 1991, "Perpendicular giant magnetoresistances of Ag/Co multilayers," Phys. Rev. Lett. **66**, 3060–3063.

Preskill, J., 1998, "Reliable quantum computers," Proc. R. Soc. London, Ser. A **454**, 385–410.

Prins, M. W. J., H. van Kempen, H. van Leuken, R. A. de Groot, W. van Roy, and J. De Boeck, 1995, "Spin-dependent transport in metal/semiconductor tunnel junctions," J. Phys.: Condens. Matter **7**, 9447–9464.

Prinz, G., 1995, "Spin-polarized transport," Phys. Today **48** (4), 58–63.

Prinz, G., 1998, "Magnetoelectronics," Science **282**, 1660–1663.

Privman, V., I. D. Vagner, and G. Kventsel, 1998, "Quantum computation in quantum-Hall systems," Phys. Lett. A **239**, 141–146.

Puller, V. I., L. G. Mourokh, and N. J. M. Horing, 2003, "Electron spin relaxation in a semiconductor quantum well," Phys. Rev. B **67**, 155309.

Qi, Y., and S. Zhang, 2003, "Spin diffusion at finite electric and magnetic fields," Phys. Rev. B **67**, 052407.

Rammer, J., and H. Smith, 1986, "Quantum field-theoretical methods in transport theory of metals," Rev. Mod. Phys. **58**, 323–359.

Ramsteiner, M., H. Y. Hao, A. Kawaharazuka, H. J. Zhu, M. Kästner, R. Hey, L. Däweritz, H. T. Grahn, and K. H. Ploog, 2002, "Electrical spin injection from ferromagnetic MnAs metal layers into GaAs," Phys. Rev. B **66**, 081304.

Rashba, E. I., 1960, "Properties of semiconductors with an extremum loop. 1. Cyclotron and combinational resonance in a magnetic field perpendicular to the plane of the loop," Fiz. Tverd. Tela **2**, 1109 [Sov. Phys. Solid State **2**, 1224–1238 (1960)].

Rashba, E. I., 2000, "Theory of electrical spin injection: Tunnel contacts as a solution of the conductivity mismatch problem," Phys. Rev. B **62**, R16 267–R16 270.

Rashba, E. I., 2002a, "Complex impedance of a spin injecting junction," Appl. Phys. Lett. **80**, 2329–2331.

Rashba, E. I., 2002b, "Diffusion theory of spin injection through resistive contacts," Eur. Phys. J. B **29**, 513–527.

Rashba, E. I., 2002c, "Spintronics: Sources and challenge," J. Supercond. **15**, 13–17.

Rashba, E. I., 2002d, private communication.

Rashba, E. I., 2003a, "Inelastic scattering approach to the theory of a tunnel magnetic transistor source," Phys. Rev. B **68**, 241310.

Rashba, E. I., 2003b, "Spin currents in thermodynamic equilibrium: The challenge of discerning transport currents," Phys. Rev. B **68**, 241315.

Rashba, E. I., and Al. L. Efros, 2003, "Orbital mechanisms of electron-spin manipulation by an electric field," Phys. Rev. Lett. **91**, 126405.

Rashba, E. I., and V. I. Sheka, 1961, "Combinational resonance of zonal electrons in crystals having a zinc blende lattice," Fiz. Tverd. Tela **3**, 1735–1749 [Sov. Phys. Solid State **3**, 1257–1267 (1961)].

Rashba, E. I., and V. I. Sheka, 1991, in *Landau Level Spectroscopy, Modern Problems in Condensed Matter Science, Vol. 27*, edited by G. Landwehr and E. I. Rashba (North-Holland, Amsterdam), pp. 131–206.

Rashba, E. I., and E. Ya. Sherman, 1988, "Spin-orbital band splitting in symmetric quantum wells," Phys. Lett. A **129**, 175–179.

Recher, P., E. V. Sukhorukov, and D. Loss, 2000, "Quantum dot as spin filter and spin memory," Phys. Rev. Lett. **85**, 1962–1965.

Rendell, R. W., and D. R. Penn, 1980, "Spin dependence of the electron mean free path in Fe, Co, and Ni," Phys. Rev. Lett. **45**, 2057–2060.

Rippard, W. H., and R. A. Buhrman, 1999, "Ballistic electron magnetic microscopy: Imaging magnetic domains with nanometer resolution," Appl. Phys. Lett. **75**, 1001–1003.

Rippard, W. H., and R. A. Buhrman, 2000, "Spin-dependent hot electron transport in Co/Cu thin films," Phys. Rev. Lett. **84**, 971–974.

Rippard, W. H., A. C. Perrella, F. J. Albert, and R. A. Buhrman, 2002, "Ultrathin aluminum oxide tunnel barriers," Phys. Rev. Lett. **88**, 046805.

Rippard, W. H., M. R. Pufall, S. Kaka, S. E. Russek, and T. J. Silva, 2004, "Direct-current induced dynamics in $Co_{90}Fe_{10}/Ni_{80}Fe_{20}$ point contacts," Phys. Rev. Lett. **92**, 027201.

Rowe, A. C., J. Nehls, R. A. Stradling, and R. S. Ferguson, 2001, "Origin of beat patterns in the quantum magnetoresistance of gated InAs/GaSb and InAs/AlSb quantum wells," Phys. Rev. B **63**, 201307.

Rudolph, J., D. Hägele, H. M. Gibbs, G. Khitrova, and M. Oestreich, 2003, "Laser threshold reduction in a spintronic device," Appl. Phys. Lett. **82**, 4516–4518.

Rzchowski, M. S., and X. W. Wu, 2000, "Bias dependence of magnetic tunnel junctions," Phys. Rev. B **61**, 5884–5887.

Safarov, V. I., and A. N. Titkov, 1980, "Spin relaxation of conduction electrons in p-type semiconductors," J. Phys. Soc. Jpn. **49**, 623–626.

Saikin, S., D. Mozyrsky, and V. Privman, 2002, "Relaxation of shallow donor electron spin due to interaction with nuclear spin bath," Nano Lett. **2**, 651–655.

Saikin, S., M. Shen, M. C. Cheng, and V. Privman, 2003, "Semiclassical Monte-Carlo model for in-plane transport of spin-polarized electrons in III-V heterostructures," J. Appl. Phys. **94**, 1769–1775.

Saito, H., W. Zaets, S. Yamagata, Y. Suzuki, and K. Ando, 2002, "Ferromagnetism in II-VI diluted magnetic semiconductor $Zn_{1-x}Cr_xTe$," J. Appl. Phys. **91**, 8085–8087.

Saito, H., V. Zayets, S. Yamagata, and K. Ando, 2003, "Room-temperature ferromagnetism in a II-VI diluted magnetic semiconductor $Zn_{1-x}Cr_xTe$," Phys. Rev. Lett. **90**, 207202.

Sakharov, V. I., A. N. Titkov, N. G. Ermakova, E. M. Komova, I. F. Mironov, and E. I. Chaikina, 1981, "Spin relaxation of conduction electrons in degenerate p-type gallium antimonide crystals. the Bir-Aronov-Pikus mechanism," Fiz. Tverd. Tela **23**, 3337–3342 [Sov. Phys. Solid State **23**, 1938–1940 (1981)].

Salis, G., D. T. Fuchs, J. M. Kikkawa, D. D. Awschalom, Y. Ohno, and H. Ohno, 2001, "Optical manipulation of nuclear spin by a two-dimensional electron gas," Phys. Rev. Lett. **86**, 2677–2680.

Salis, G., Y. Kato, K. Ensslin, D. C. Driscoll, A. C. Gossard, and D. D. Awschalom, 2001, "Electrical control of spin coherence in semiconductor nanostructures," Nature (London) **414**, 619–622.

Samarth, N., S. H. Chun, K. C. Ku, S. J. Potashnik, and P. Schiffer, 2003, "Hybrid ferromagnetic/semiconductor heterostructures for spintronics," Solid State Commun. **127**, 173–179.

Sanada, H., I. Arata, Y. Ohno, Z. Chen, K. Kayanuma, Y. Oka, F. Matsukura, and H. Ohno, 2002, "Relaxation of photoinjected spins during drift transport in GaAs," Appl. Phys. Lett. **81**, 2788–2790.

Sanderfeld, N., W. Jantsch, Z. Wilamowski, and F. Schäffler, 2000, "ESR investigations of modulation-doped Si/SiGe quantum wells," Thin Solid Films **369**, 312–315.

Sandhu, J. S., A. P. Heberle, J. J. Baumberg, and J. R. A. Cleaver, 2001, "Gateable suppression of spin relaxation in semiconductors," Phys. Rev. Lett. **86**, 2150–2153.

Sanvito, S., G. Theurich, and N. A. Hill, 2002, "Density functional calculations for III-V diluted ferromagnetic semiconductors: A review," J. Supercond. **15**, 85–104.

Sato, R., and K. Mizushima, 2001, "Spin-valve transistor with an Fe/Au/Fe(001) base," Appl. Phys. Lett. **79**, 1157–1159.

Schäpers, Th., G. Engels, J. Lange, Th. Klocke, M. Hollfelder, and H. Lüth, 1998, "Effect of the heterointerface on the spin splitting in modulation doped $In_xGa_{1-x}As/InP$ quantum wells for $B\rightarrow 0$," J. Appl. Phys. **83**, 4324–4333.

Schep, K. M., J. B. A. N. van Hoof, P. J. Kelly, and G. E. W. Bauer, 1997, "Interface resistances of magnetic multilayers," Phys. Rev. B **56**, 10 805–10 808.

Schliemann, J., J. C. Egues, and D. Loss, 2003, "Non-ballistic spin field-effect transistor," Phys. Rev. Lett. **90**, 146801.

Schmidt, G., D. Ferrand, L. W. Molenkamp, A. T. Filip, and B. J. van Wees, 2000, "Fundamental obstacle for electrical spin injection from a ferromagnetic metal into a diffusive semiconductor," Phys. Rev. B **62**, R4790–R4793.

Schmidt, G., C. Gould, P. Grabs, A. Lunde, G. Richter, A. Slobodskyy, and L. W. Molenkamp, 2002, "Spin injection in the non-linear regime: band bending effects," cond-mat/0206347.

Schmidt, G., and L. W. Molenkamp, 2002, "Spin injection into semiconductors, physics and experiments," Semicond. Sci. Technol. **17**, 310–321.

Schmidt, G., G. Richter, P. Grabs, C. Gould, D. Ferrand, and L. W. Molenkamp, 2001, "Large magnetoresistance effect due to spin injection into a nonmagnetic semiconductor," Phys. Rev. Lett. **87**, 227203.

Schultz, S., and C. Latham, 1965, "Observation of electron spin resonance in copper," Phys. Rev. Lett. **15**, 148–151.

Schultz, S., and M. R. Shanabarger, 1966, "Observation of electron spin resonance in rubidium and cesium," Phys. Rev. Lett. **16**, 178–181.

Schumacher, H. W., C. Chappert, P. Crozat, R. C. Sousa, P. P. Freitas, J. Miltat, J. Fassbender, and B. Hillebrands, 2003a, "Phase coherent precessional magnetization reversal in microscopic spin valve elements," Phys. Rev. Lett. **90**, 017201.

Schumacher, H. W., C. Chappert, R. C. Sousa, P. P. Freitas, and J. Miltat, 2003b, "Quasiballistic magnetization reversal," Phys. Rev. Lett. **90**, 017204.

Scifres, D. R., R. M. W. B. A. Huberman, and R. S. Bauer, 1973, "A new scheme for measuring itinerant spin polarization," Solid State Commun. **13**, 1615–1617.

Seck, M., M. Potemski, and P. Wyder, 1997, "High-field spin resonance of weakly bound electrons in GaAs," Phys. Rev. B **56**, 7422–7427.

Semenov, Y. G., and K. W. Kim, 2003, "Effect of external magnetic field on electron spin dephasing induced by hyperfine interaction in quantum dots," Phys. Rev. B **67**, 073301.

Seufert, J., G. Bacher, H. Schömig, A. Forchel, L. Hansen, G. Schmidt, and L. W. Molenkamp, 2004, "Spin injection into a single self-assembled quantum dot," Pys. Rev. B **69**, 035311.

Seymour, R. J., M. R. Junnarkar, and R. R. Alfano, 1981, "Spin relaxation of photogenerated electron distributions in GaAs," Phys. Rev. B **24**, 3623–3625.

Sham, L. J., 1993, "Spin relaxation in semiconductor quantum wells," J. Phys.: Condens. Matter **5**, A51–A60.

Sham, L. J., T. Östreich, and K. Schönhammer, 1998, "Spin coherence in semiconductor heterostructures," Physica E (Amsterdam) **2**, 388–393.

Shang, C. H., J. Nowak, R. Jansen, and J. S. Moodera, 1998, "Temperature dependence of magnetoresistance and surface magnetization in ferromagnetic tunnel junctions," Phys. Rev. B **58**, R2917–R2920.

Sharma, P., and C. Chamon, 2003, "Adiabatic charge and spin transport in interacting quantum wires," Phys. Rev. B **68**, 035321.

Sharvin, Y. V., 1965, "A possible method for studying Fermi surfaces," Zh. Eksp. Teor. Fiz. **48**, 984–985 [Sov. Phys. JETP **21**, 655–656 (1965)].

Sherman, E. Ya., 2003a, "Random-spin-orbit coupling and spin relaxation in symmetric quantum wells," Appl. Phys. Lett. **82**, 209–211.

Sherman, E. Ya., 2003b, "Minimum of spin-orbit coupling in two-dimensional structures," Phys. Rev. B **67**, 161303.

Shinjo, T., 2002, in *Spin Dependent Transport in Magnetic Nanostructures*, edited by S. Maekawa and T. Shinjo (Taylor and Francis, New York), pp. 1–46.

Shinshi, T., F. Kato, A. Shimokohbe, H. Noguchi, and H. Munekata, 2003, "Light-driven microcantilever actuator based on photoenhanced magnetization in a GaAs-Fe composite film," Appl. Phys. Lett. **83**, 3425–3427.

Shockley, W., 1950, *Electrons and Holes in Semiconductors* (Van Nostrand, Princeton, NJ).

Si, Q., 1997, "Spin conductivity and spin-charge separation in the high-T_c cuprates," Phys. Rev. Lett. **78**, 1767–1770.

Si, Q., 1998, "Spin injection into a Luttinger liquid," Phys. Rev. Lett. **81**, 3191–3194.

Sidles, J. A., J. L. Garbini, K. J. Bruland, D. Rugar, O. Züger, S. Hoen, and C. S. Yannoni, 1995, "Magnetic resonance force microscopy," Rev. Mod. Phys. **67**, 249–265.

Sieg, R. M., J. A. Carlin, J. J. Boeckl, S. A. Ringel, M. T. Currie, S. M. Ting, T. A. Langdo, G. Taraschi, E. A. Fitzgerald, and B. M. Keyes, 1998, "High minority-carrier lifetimes grown on low-defect-density Ge/GeSi/Si substrates," Appl. Phys. Lett. **73**, 3111–3113.

Silsbee, R. H., 1980, "Novel method for the study of spin transport in conductors," Bull. Magn. Reson. **2**, 284–285.

Silsbee, R. H., 2001, "Theory of the detection of current-induced spin polarization in a two-dimensional electron gas," Phys. Rev. B **63**, 155305; **68**, 159902(E) (2003).

Silsbee, R. H., and F. Beuneu, 1983, "Model calculation of the frequency and temperature dependence of the electron-spin-resonance linewidth of aluminum," Phys. Rev. B **27**, 2682–2692.

Simon, F., A. Jánossy, T. Fehér, F. Murányi, S. Garaj, L. Forró, C. Petrovic, S. L. Budko, G. Lapertot, V. G. Kogan, and P. C. Canfield, 2001, "Anisotropy of superconducting MgB_2 as seen in electron spin resonance and magnetization data," Phys. Rev. Lett. **87**, 047002.

Skinner, A. J., M. E. Davenport, and B. E. Kane, 2003, "Hydrogenic spin quantum computing in silicon: A digital approach," Phys. Rev. Lett. **90**, 087901.

Slichter, C. P., 1989, *Principles of Magnetic Resonance*, 3rd ed. (Springer, Berlin).

Slobodskyy, A., C. Gould, T. Slobodskyy, C. R. Becker, G. Schmidt, and L. W. Molenkamp, 2003, "Voltage-controlled spin selection in a magnetic resonant tunneling diode," Phys. Rev. Lett. **90**, 246601.

Slonczewski, J. C., 1976, "Magnetic bubble tunnel detector," IBM Tech. Discl. Bull. **19**, 2328–2330.

Slonczewski, J. C., 1989, "Conductance and exchange coupling of two ferromagnets separated by a tunneling barrier," Phys. Rev. B **39**, 6995–7002.

Slonczewski, J. C., 1996, "Current-driven excitation of magnetic multilayers," J. Magn. Magn. Mater. **159**, L1–L7.

Smet, J. H., R. A. Deutschmann, F. Ertl, W. Wegscheider, G. Abstreiter, and K. von Klitzing, 2002, "Gate-voltage control of spin interactions between electrons and nuclei in a semiconductor," Nature (London) **415**, 281–286.

Smith, D. L., M. Kozhevnikov, E. Y. Lee, and V. Narayanamurti, 2000, "Scattering theory of ballistic-electron-emission microscopy at nonepitaxial interfaces," Phys. Rev. B **61**, 13 914–13 922.

Smith, D. L., and R. N. Silver, 2001, "Electrical spin injection into semiconductors," Phys. Rev. B **64**, 045323.

Sogawa, T., H. Ando, and S. Ando, 2000, "Spin-transport dynamics of optically spin-polarized electrons in GaAs quantum wires," Phys. Rev. B **61**, 5535–5539.

Sogawa, T., P. V. Santos, S. K. Zhang, S. Eshlaghi, A. D. Wieck, and K. H. Ploog, 2001, "Transport and lifetime enhancement of photoexcited spins in GaAs by surface acoustic waves," Phys. Rev. Lett. **87**, 276601.

Solin, S. A., D. R. Hines, A. C. H. Rowe, J. S. Tsai, Y. A. Pashkin, S. J. Chung, N. Goel, and M. B. Santos, 2002, "Nonmagnetic semiconductors as read-head sensors for ultra-high-density magnetic recording," Phys. Rev. Lett. **80**, 4012–4014.

Solin, S. A., T. Thio, D. R. Hines, and J. J. Heremans, 2000, "Enhanced room-temperature geometric magnetoresistance in inhomogeneous narrow-gap semiconductors," Science **289**, 1530–1532.

Solomon, I., 1976, "Spin-dependent recombination in a silicon p-n junction," Solid State Commun. **20**, 215–217.

Song, P. H., and K. W. Kim, 2002, "Spin relaxation of conduction electrons in bulk III-V semiconductors," Phys. Rev. B **66**, 035207.

Soulen, R. J., Jr., J. M. Byers, M. S. Osofsky, B. Nadgorny, T. Ambrose, S. F. Cheng, P. R. Broussard, C. T. Tanaka, J. Nowak, J. S. Moodera, A. Barry, and J. M. D. Coey, 1998, "Measuring the spin polarization of a metal with a superconducting point contact," Science **282**, 85–88.

Stearns, M. B., 1977, "Simple explanation of tunneling spin-polarization of Fe, Co, Ni and its alloys," J. Magn. Magn. Mater. **5**, 167–171.

Stein, D., K. v. Klitzing, and G. Weimann, 1983, "Electron spin resonance on GaAs-$Al_xGa_{1-x}As$ heterostructures," Phys. Rev. Lett. **51**, 130–133.

Stesmans, A., and J. Witters, 1981, "Fermi-surface structure effects revealed by the observation of conduction-electron-spin resonance in Zn," Phys. Rev. B **23**, 3159–3163.

Stevens, M. J., A. L. Smirl, R. D. R. Bhat, A. Najmaie, J. E. Sipe, and H. M. van Driel, 2003, "Quantum interference control of ballistic pure spin currents in semiconductors," Phys. Rev. Lett. **90**, 136603.

Stiles, M. D., 1996, "Spin-dependent interface transmission and reflection in magnetic multilayers," J. Appl. Phys. **79**, 5805–5810.

Stiles, M. D., 2004, in *Utrathin Magnetic Structures III*, edited by B. Heinrich and J. A. C. Bland (Springer, New York, in press).

Stiles, M. D., and D. R. Penn, 2000, "Calculation of spin-dependent interface resistance," Phys. Rev. B **61**, 3200–3202.

Stiles, M. D., and A. Zangwill, 2002, "Anatomy of spin-transfer torque," Phys. Rev. B **66**, 014407.

Story, T., R. R. Galazka, R. B. Frankel, and P. A. Wolff, 1986, "Carrier-concentration-induced ferromagnetism in PbSnMnTe," Phys. Rev. Lett. **56**, 777–779.

Strand, J., B. D. Schultz, A. F. Isaković, C. J. Palmstrøm, and P. A. Crowell, 2003, "Dynamical nuclear polarization by electrical spin injection in ferromagnet-semiconductor heterostructures," Phys. Rev. Lett. **91**, 036602.

Stroud, R. M., A. T. Hanbicki, Y. D. Park, A. G. Petukhov, and B. T. Jonker, 2002, "Reduction of spin injection efficiency by interface defect spin scattering in ZnMnSe/AlGaAs-GaAs spin-polarized light-emitting diodes," Phys. Rev. Lett. **89**, 166602.

Sugamo, S., and N. Kojima 2000, Eds., *Magneto-optics* (Springer, Berlin).

Suhl, H., 2002, "Proposal for *in situ* enhancement of electron spin polarization in semiconductors," cond-mat/0206215.

Sun, J. Z., 2000, "Spin-current interaction with a monodomain magnetic body: A model study," Phys. Rev. B **62**, 570–578.

Sze, S. M., 1981, *Physics of Semiconductor Devices* (Wiley, New York).

Tackeuchi, A., Y. Nishikawa, and O. Wada, 1996, "Room-temperature electron spin dynamics in GaAs/AlGaAs quantum wells," Appl. Phys. Lett. **68**, 797–799.

Takahashi, S., H. Imamura, and S. Maekawa, 1999, "Spin imbalance and magnetoresistance in ferromagnet/superconductor/ferromagnet double tunnel junctions," Phys. Rev. Lett. **82**, 3911–3915.

Takahashi, S., and S. Maekawa, 1998, "Effect of Coulomb blockade on magnetoresistance in ferromagnetic tunnel junctions," Phys. Rev. Lett. **80**, 1758–1761.

Takahashi, S., and S. Maekawa, 2003, "Spin injection and detection in magnetic nanostructures," Phys. Rev. B **67**, 052409.

Takahashi, S., T. Yamashita, T. Koyama, and S. Maekawa, 2001, "Joule heating generated by spin current through Josephson junctions," J. Appl. Phys. **89**, 7505–7507.

Tanaka, M., 2002, "Ferromagnet (MnAs)/III-V semiconductor hybrid structures," Semicond. Sci. Technol. **17**, 327–341.

Tanaka, M., and Y. Higo, 2001, "Large tunneling magnetoresistance in GaMnAs/AlAs/GaMnAs ferromagnetic semiconductor tunnel junctions," Phys. Rev. Lett. **87**, 026602.

Tanaka, Y., and S. Kashiwaya, 1995, "Theory of tunneling spectroscopy of *d*-wave superconductors," Phys. Rev. Lett. **74**, 3451–3454.

Tang, H. X., F. G. Monzon, F. J. Jedema, A. T. Filip, B. J. van Wees, and M. L. Roukes, 2002, in *Semiconductor Spintronics and Quantum Computation*, edited by D. Awschalom, D. Loss, and N. Samarth (Springer, New York), pp. 31–92.

Tatara, G., N. Garcia, M. Munoz, and Y.-W. Zhao, 1999, "Domain wall scattering explains 300% ballistic magnetoconductance of nanocontacts," Phys. Rev. Lett. **83**, 2030–2033.

Tedrow, P. M., and R. Meservey, 1971a, "Direct observation of spin-mixing in superconductors," Phys. Rev. Lett. **27**, 919–921.

Tedrow, P. M., and R. Meservey, 1971b, "Spin-dependent tunneling into ferromagnetic nickel," Phys. Rev. Lett. **26**, 192–195.

Tedrow, P. M., and R. Meservey, 1973, "Spin polarization of electrons tunneling from films of Fe, Co, Ni, Gd," Phys. Rev. B **7**, 318–326.

Tedrow, P. M., and R. Meservey, 1994, "Spin-polarized electron tunneling," Phys. Rep. **238**, 173–243.

Tedrow, P. M., R. Meservey, and P. Fulde, 1970, "Magnetic field splitting of the quasiparticle states in superconducting aluminum films," Phys. Rev. Lett. **25**, 1270–1272.

Tehrani, S., B. Engel, J. M. Slaughter, E. Chen, M. DeHerrera, M. Durlam, P. Naji, R. Whig, J. Janesky, and J. Calder, 2000, "Recent developments in magnetic tunnel junction MRAM," IEEE Trans. Magn. **36**, 2752–2757.

Teran, F. J., L. X. Zhao, A. Patanè, R. P. Campion, C. T. Foxon, L. Eaves, and B. L. Gallagher, 2003, "Investigation of radiative recombination from Mn-related states in $Ga_{1-x}Mn_xAs$," Appl. Phys. Lett. **83**, 866–868.

Tešanović, Z., M. V. Jarić, and S. Maekawa, 1986, "Quantum transport and surface scattering," Phys. Rev. Lett. **57**, 2760–2763.

Thomson, W., 1857, "On the electro-dynamic qualities of metals: Effects of magnetization on the electric conductivity of nickel and of iron," Proc. R. Soc. London **8**, 546–550.

Thurber, K. R., L. E. Harrelli, R. Fainchtein, and D. D. Smith, 2002, "Spin polarization contrast observed in GaAs by force-detected nuclear magnetic resonance," Appl. Phys. Lett. **80**, 1794–1796.

Thurber, K. R., and D. D. Smith, 2003, "170 nm nuclear magnetic resonance imaging using magnetic resonance force spectroscopy," J. Magn. Reson. **162**, 336–340.

Timm, C., 2003, "Disorder effects in diluted magnetic semiconductors," J. Phys.: Condens. Matter **15**, R1865–R1896.

Ting, D. Z.-Y., and X. Cartoxià, 2002, "Resonant interband tunneling spin filter," Appl. Phys. Lett. **81**, 4198–4200.

Ting, D. Z.-Y., and X. Cartoixà, 2003, "Bidirectional resonant tunneling spin pump," Appl. Phys. Lett. **83**, 1391–1393.

Torrey, H. C., 1956, "Bloch equations with diffusion terms," Phys. Rev. **104**, 563–565.

Troiani, F., E. Molinari, and U. Hohenester, 2003, "High-finesse optical quantum gates for electron spins in artificial molecules," Phys. Rev. Lett. **90**, 206802.

Tromp, H. J., P. van Gelderen, P. J. Kelly, G. Brocks, and P. A. Bobbert, 2001, "CaB_6: A new semiconducting material for spin electronics," Phys. Rev. Lett. **87**, 016401.

Tsoi, M., A. G. M. Jansen, J. Bass, W.-C. Chiang, M. Seck, V. Tsoi, and P. Wyder, 1998, "Excitation of a magnetic multilayer by an electric current," Phys. Rev. Lett. **80**, 4281–4284; **81**, 493(E).

Tsoi, M., A. G. M. Jansen, P. Wyder, W.-C. Chiang, V. Tsoi, and P. Wyder, 2000, "Generation and detection of phase-coherent current-driven magnons in magnetic multilayers," Nature (London) **406**, 46–49.

Tsoi, M., V. Tsoi, J. Bass, A. G. M. Jansen, and P. Wyder, 2002, "Current-driven resonances in magnetic multilayers," Phys. Rev. Lett. **89**, 246803.

Tsu, R., and L. Esaki, 1973, "Tunneling in a finite superlattice," Appl. Phys. Lett. **22**, 562–564.

Tsubokawa, I., 1960, "On the magnetic properties of a $CrBr_3$ single crystal," J. Phys. Soc. Jpn. **15**, 1664–1668.

Tsuei, C. C., and J. R. Kirtley, 2000, "Pairing symmetry in cuprate superconductors," Rev. Mod. Phys. **72**, 969–1016.

Tsui, D. C., R. E. Dietz, and L. R. Walker, 1971, "Multiple magnon excitation in NiO by electron tunneling," Phys. Rev. Lett. **27**, 1729–1732.

Tsui, F., L. Ma, and L. He, 2003, "Magnetization-dependent rectification effect in a Ge-based magnetic heterojunction," Appl. Phys. Lett. **83**, 954–956.

Tsukagoshi, K., B. W. Alphenaar, and H. Ago, 1999, "Coherent transport of electron spin in a ferromagnetically contacted carbon nanotube," Nature (London) **401**, 572–574.

Tsymbal, E. Yu., and D. G. Pettifor, 1997, "Modeling of spin-polarized electron tunneling from 3d ferromagnets," J. Phys.: Condens. Matter **9**, L411–L417.

Tyryshkin, A. M., S. A. Lyon, A. V. Astashkin, and A. M. Raitsimring, 2003, "Electron spin relaxation times of phosphorus donors in silicon," Phys. Rev. B **68**, 193207.

Uenoyama, T., and L. J. Sham, 1990a, "Carrier relaxation and luminescence polarization in quantum wells," Phys. Rev. B **42**, 7114–7123.

Uenoyama, T., and L. J. Sham, 1990b, "Hole relaxation and luminescence polarization in doped and undoped quantum wells," Phys. Rev. Lett. **64**, 3070–3073.

Upadhyay, S. K., R. N. Louie, and R. A. Buhrman, 1999, "Spin filtering by ultrathin ferromagnetic films," Appl. Phys. Lett. **74**, 3881–3883.

Upadhyay, S. K., A. Palanisami, R. N. Louie, and R. A. Buhrman, 1998, "Probing ferromagnets with Andreev reflection," Phys. Rev. Lett. **81**, 3247–3250.

Urazhdin, S., N. O. Birge, W. P. Pratt, Jr., and J. Bass, 2003, "Current-driven magnetic excitations in permalloy-based multilayer nanopillars," Phys. Rev. Lett. **91**, 146803.

Vagner, I. D., 2003, "Nuclear spintronics," cond-mat/0308244.

Valet, T., and A. Fert, 1993, "Theory of the perpendicular magnetoresistance in magnetic multilayers," Phys. Rev. B **48**, 7099–7113.

van Dijken, S., X. Jiang, and S. S. P. Parkin, 2002a, "Room temperature operation of a high output current magnetic tunnel transistor," Appl. Phys. Lett. **80**, 3364–3366.

van Dijken, S., X. Jiang, and S. S. P. Parkin, 2002b, "Spin-dependent hot electron transport in $Ni_{81}Fe_{19}$ and $Co_{84}Fe_{16}$ films on GaAs(001)," Phys. Rev. B **66**, 094417.

van Dijken, S., X. Jiang, and S. S. P. Parkin, 2003a, "Comparison of magnetocurrent and transfer ratio in magnetic tunnel transistors with spin-valve bases containing Cu and Au spacer layers," Appl. Phys. Lett. **82**, 775–777.

van Dijken, S., X. Jiang, and S. S. P. Parkin, 2003b, "Giant magnetocurrent exceeding 3400% in magnetic tunnel transistors with spin-valve base," Appl. Phys. Lett. **83**, 951–953.

van Dijken, S., X. Jiang, and S. S. P. Parkin, 2003c, "Nonmonotonic bias voltage dependence of the magnetocurrent in GaAs-based magnetic tunnel transistors," Phys. Rev. Lett. **90**, 197203.

Van Dorpe, P., Z. Liu, W. V. Roy, V. F. Motsnyi, M. Sawicki, G. Borghs, and J. De Boeck, 2003, "Very high spin polarization in GaAs by injection from a (Ga,Mn)As Zener diode," preprint.

Van Dorpe, P., V. Motsnyi, M. Nijboer, E. Goovaerts, V. Safarov, J. Das, W. Van Roy, G. Borghs, and J. De Boeck, 2003, "Highly efficient room temperature spin injection in a metal-insulator-semiconductor light emitting diode," Jpn. J. Appl. Phys., Part 2 **42**, L502–L504.

Van Esch, A., L. Van Bockstal, J. De Boeck, G. Verbanck, A. S. van Steenbergen, P. J. Wellmann, B. Grietens, R. Bogaerts, F. Herlach, and G. Borghs, 1997, "Interplay between the magnetic and transport properties in the III-V diluted magnetic semiconductors," Phys. Rev. B **56**, 13 103–13 112.

van Houten, H., C. W. J. Beenakker, J. G. Williamson, M. E. I. Broekaart, P. H. M. van Loosdrecht, B. J. van Wees, J. E. Mooij, C. T. Foxon, and J. J. Harris, 1989, "Coherent electron focusing with quantum point contacts in a two-dimensional electron gas," Phys. Rev. B **39**, 8556–8575.

van Son, P. C., H. van Kempen, and P. Wyder, 1987, "Boundary resistance of the ferromagnetic-nonferromagnetic metal interface," Phys. Rev. Lett. **58**, 2271–2273.

van Wees, B. J., 2000, "Comment on 'Observation of spin injection at a ferromagnet-semiconductor interface,' " Phys. Rev. Lett. **84**, 5023.

Vasilev, A. M., F. Daiminger, J. Straka, A. Forchel, V. P. Kochereshko, G. L. Sandler, and I. N. Uraltsev, 1993, "Optical orientation of holes and electrons in strained layer InGaAs/GaAs quantum-wells," Superlattices Microstruct. **13**, 97–100.

Vas'ko, V. A., V. A. Larkin, P. A. Kraus, K. R. Nikolaev, D. E. Grupp, C. A. Nordman, and A. M. Goldman, 1997, "Critical current suppression in a semiconductor by injection of spin-polarized carriers from a ferromagnet," Phys. Rev. Lett. **78**, 1134–1137.

Vas'ko, V., K. Nikolaev, V. Larkin, P. Kraus, and A. Goldman, 1998, "Differential conductance of the ferromagnet/semiconductor interface of $DyBa_2Cu_3O_7/La_{2/3}Ba_{1/3}MnO_3$ heterostructures," Appl. Phys. Lett. **73**, 844–846.

Vekua, V. L., R. I. Dzhioev, B. P. Zakharchenya, and V. G. Fleisher, 1976, "Hanle effect in optical orientation of electrons in n-type semiconductors," Fiz. Tekh. Poluprovodn. (S.-Peterburg) **10**, 354–357 [Sov. Phys. Semicond. **10**, 210–212 (1946)].

Versluijs, J. J., M. A. Bari, and J. M. D. Coey, 2001, "Magnetoresistance of half-metallic oxide nanocontacts," Phys. Rev. Lett. **87**, 026601.

Vescial, F., N. S. VanderVen, and R. T. Schumacher, 1964, "Spin-lattice relaxation time of conduction electrons in sodium metal," Phys. Rev. **134**, A1286–A1290.

Viglin, N. A., V. V. Osipov, and A. A. Samokhvalov, 1991, "Increase in the transmission of microwave power through a ferromagnetic semiconductor $HgCr_2Se_4$ in a strong electric field," Fiz. Tverd. Tela **30**, 2695–2698 [Sov. Phys. Solid State **33**, 1523–1525 (1991)].

Viglin, N. A., V. V. Osipov, A. A. Samokhvalov, and O. G. Reznitskikh, 1997, "Generation in the millimeter band for the semiconductor-ferromagnetic semiconductor heterostructure," Phys. Low-Dimens. Semicond. Struct. **1/2**, 89–94.

Vignale, G., and I. D'Amico, 2003, "Coulomb drag, magnetoresistance, and spin-current injection in magnetic multilayers," Solid State Commun. **127**, 829–834.

Vina, L., M. D. Martin, and G. Aichmayr, 2001, "Spin dynamics and spin-dependent interactions in semiconductor heterostructures," Physica B **298**, 376–383.

Vlutters, R., O. M. J. van 't Erve, R. Jansen, S. D. Kim, and J. C. Lodder, 2001, "Modeling of spin-dependent hot-electron transport in the spin-valve transistor," Phys. Rev. B **65**, 024416.

von Molnár, S., and S. Methfess, 1967, "Giant negative magnetoresistance in ferromagnetic $Eu_{1-x}Gd_xSe$," J. Appl. Phys. **38**, 959–964.

Voskoboynikov, A., S. S. Liu, and C. P. Lee, 1998, "Spin-dependent electronic tunneling at zero magnetic field," Phys. Rev. B **58**, 15 397–15 400.

Voskoboynikov, A., S. S. Liu, and C. P. Lee, 1999, "Spin-dependent tunneling in double-barrier semiconductor heterostructures," Phys. Rev. B **59**, 12 514–12 520.

Vrijen, R., E. Yablonovitch, K. Wang, H. W. Jiang, A. Balandin, V. Roychowdhury, T. Mor, and D. DiVincenzo, 2000, "Electron-spin-resonance transistors for quantum computing in silicon-germanium heterostructures," Phys. Rev. A **62**, 012306.

Vurgaftman, I., and J. R. Meyer, 2003, "Spin-polarizing properties of the InAs/(AlSb)/GaMnSb/(AlSb)/InAs ferromagnetic resonant interband tunneling diode," Phys. Rev. B **67**, 125209.

Waag, A., T. Gruber, G. Reuscher, R. F. W. Ossau, G. Schmidt, and L. W. Molenkamp, 2001, "Spin manipulation using magnetic II-VI semiconductors," J. Supercond. **14**, 291–298.

Wagner, J., H. Schneider, D. Richards, A. Fischer, and K. Ploog, 1993, "Observation of extremely long electron-spin-relaxation times in p-type δ-doped GaAs/$Al_xGa_{1-x}As$ double heterostructures," Phys. Rev. B **47**, 4786–4789.

Wagoner, G., 1960, "Spin resonance of charge carriers in graphite," Phys. Rev. **118**, 647–653.

Waintal, X., E. B. Myers, P. W. Brouwer, and D. C. Ralph, 2000, "Role of spin-dependent interface scattering in generating current-induced torques in magnetic multilayers," Phys. Rev. B **62**, 12 317–12 327.

Wald, K. R., L. P. Kouwenhoven, P. L. McEuen, N. C. van der Vaart, and C. T. Foxon, 1994, "Local dynamic nuclear polarization using quantum point contacts," Phys. Rev. Lett. **73**, 1011–1014.

Walsh, W. M., L. W. Rupp, and P. H. Schmidt, 1966a, "g value of potassium conduction electrons," Phys. Rev. **142**, 414–417.

Walsh, W. M., L. W. Rupp, and P. H. Schmidt, 1966b, "g values of rubidium and cesium conduction electrons," Phys. Rev. Lett. **16**, 181–183.

Wang, B., J. Wang, and H. Guo, 2003, "Quantum spin field effect transistor," Phys. Rev. B **67**, 092408.

Wang, D., M. Tondra, C. Nordman, Z. Qian, J. M. Daughton, E. Lange, D. Brownell, L. Tran, and J. Schuetz, 2002, "Prototype spin-dependent tunneling isolators integrated with integrated circuit electronics," J. Appl. Phys. **91**, 8405–8407.

Wang, J., G. A. Khodaparast, J. Kono, T. Slupinski, A. Oiwa, and H. Munekata, 2003, "Ultrafast softening in InMnAs," cond-mat/0305017.

Wang, Q., and C.-R. Hu, 2002, "Resonant Andreev reflection in a FIDI'D' system where F is a spin-polarized and DI'D' is a d-wave superconductor containing a {100}|{110} grain boundary," preprint.

Wangsness, R. K., and F. Bloch, 1953, "The dynamical theory of nuclear induction," Phys. Rev. **89**, 728–739.

Watson, S. K., R. M. Potok, C. M. Marcus, and V. Umansky, 2003, "Experimental realization of a quantum spin pump," Phys. Rev. Lett. **91**, 258301.

Weger, M., 1963, "Nuclear polarization in homogeneous InSb by a direct current," Phys. Rev. **132**, 581–588.

Wegrowe, J.-E., 2000, "Thermokinetic approach of the generalized Landau-Lifshitz-Gilbert equation with spin-polarized current," Phys. Rev. B **62**, 1067–1074.

Wegrowe, J. E., D. Kelly, Y. Jaccard, P. Guittienne, and J. P. Ansermet, 1999, "Current-induced magnetization reversal in magnetic nanowires," Europhys. Lett. **45**, 626–632.

Wei, J. Y. T., 2002, "Spin-injection quasiparticle nonequilibrium in cuprate/manganite heterostructures," J. Supercond. **15**, 67–70.

Wei, J. Y. T., N.-C. Yeh, C. C. Fui, and R. P. Vasquez, 1999, "Tunneling spectroscopy study of spin-polarized quasiparticle injection effects in cuprate/manganite heterostructures," J. Appl. Phys. **85**, 5350–5352.

Wei, J. Y. T., N.-C. Yeh, D. F. Garrigus, and M. Strasik, 1998, "Directional tunneling and Andreev reflection on $YBa_2Cu_3O_{7-\delta}$ single crystals: Predominance of d-wave pairing symmetry verified with the generalized Blonder, Tinkham, and Klapwijk theory," Phys. Rev. Lett. **81**, 2542–2545.

Weisbuch, C., and C. Hermann, 1977, "Optical detection of conduction-electron spin resonance in GaAs, $Ga_{1-x}In_xAs$, and $Ga_{1-x}Al_xAs$," Phys. Rev. B **15**, 816–822.

Weisbuch, C. and B. Vinter, 1991, *Quantum Semiconductor Structures—Fundamentals and Applications* (Academic, New York).

Wen, C. P., B. Hershenov, H. von Philipsborn, and H. L. Pinch, 1968, "Device application feasibility of single-crystal $CdCr_2Se_4$, a ferromagnetic semiconducting spinel," IEEE Trans. Magn. **4**, 702–704.

Werthamer, N. R., 1969, in *Superconductivity, Vol. 1*, edited by R. D. Parks (Dekker, New York), pp. 321–370.

Wexler, G., 1966, "Size effect and non-local Boltzmann transport equation in orifice and disk geometry," Proc. Phys. Soc. London **89**, 927–941.

Wiesendanger, R., 1998, in *Scanning Probe Microscopy*, edited by R. Wiesendanger (Springer, New York), pp. 71–95.

Wiesendanger, R., H.-J. Güntherodt, G. Güntherodt, R. J. Gambino, and R. Ruf, 1990, "Observation of vacuum tunneling of spin-polarized electrons with the scanning tunneling microscope," Phys. Rev. Lett. **65**, 247–250.

Wilamowski, Z., and W. Jantsch, 2002, "ESR studies of the Bychkov-Rashba field in modulation doped Si/SiGe quantum wells," Physica E (Amsterdam) **12**, 439–442.

Wilamowski, Z., and W. Jantsch, 2004, "Suppression of spin relaxation of conduction electrons by cyclotron motion," Phys. Rev. B **69**, 035328.

Wilamowski, Z., W. Jantsch, H. Malissa, and U. Rössler, 2002, "Evidence and evaluation of the Bychkov-Rashba effect in SiGe/Si/SiGe quantum wells," Phys. Rev. B **66**, 195315.

Winkler, R., 2004, "Spin orientation and spin precession in inversion-asymmetric quasi two-dimensional electron systems," Phys. Rev. B **69**, 045317.

Wissinger, L., U. Rössler, R. Winkler, B. Jusserant, and D. Richards, 1998, "Spin splitting in the electron subband of asymmetric GaAs/$Al_xGa_{1-x}As$ quantum wells: The multiband envelope function approach," Phys. Rev. B **58**, 15 375–15 377.

Wolf, S. A., D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnár, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, 2001, "Spintronics: A spin-based electronics vision for the future," Science **294**, 1488–1495.

Wolf, S. A., and D. Treger, 2000, "Spintronics: A new paradigm for electronics for the new millennium," IEEE Trans. Magn. **36**, 2748–2751.

Wong, H.-S. P., D. J. Frank, P. M. Solomon, C. H. J. Wann, and J. J. Welser, 1999, "Nanoscale CMOS," Proc. IEEE **87**, 537–570.

Worledge, D. C., and T. H. Geballe, 2000a, "Maki analysis of spin-polarized tunneling in an oxide ferromagnet," Phys. Rev. B **62**, 447–451.

Worledge, D. C., and T. H. Geballe, 2000b, "Negative spin-polarization of $SrRuO_3$," Phys. Rev. Lett. **85**, 5182–5185.

Wu, M. W., 2001, "Kinetic theory of spin coherence of electrons in semiconductors," J. Supercond. **14**, 245–259.

Wu, M. W., and M. Kuwata-Gonokami, 2002, "Can D'yakonov-Perel' effect cause spin dephasing in GaAs(110) quantum wells?" Solid State Commun. **121**, 509–512.

Wu, M. W., and H. Metiu, 2000, "Kinetics of spin coherence of electrons in an undoped semiconductor quantum well," Phys. Rev. B **61**, 2945–2955.

Wu, M. W., and C. Z. Ning, 2000, "D'yakonov-Perel' effect on spin dephasing in n-type GaAs," Phys. Status Solidi B **222**, 523–534.

Wunnicke, O., P. Mavropoulos, R. Zeller, P. H. Dederichs, and D. Grundler, 2002, "Ballistic spin injection from Fe(001) into ZnSe and GaAs," Phys. Rev. B **65**, 241306.

Xia, K., P. J. Kelly, G. E. W. Bauer, and I. Turek, 2002, "Spin-dependent transparency of ferromagnet/superconductor interfaces," Phys. Rev. Lett. **89**, 166603.

Xiang, X. H., T. Zhu, J. Du, G. Landry, and J. Q. Xiao, 2002, "Effects of density of states on bias dependence in magnetic tunnel junctions," Phys. Rev. B **66**, 174407.

Xie, S. J., K. H. Ahn, D. L. Smith, A. R. Bishop, and A. Saxena, 2003, "Ground-state properties of ferromagnetic metal/conjugated polymer interfaces," Phys. Rev. B **67**, 125202.

Xiong, Z. H., D. Wu, Z. V. Vardeny, and J. Shi, 2004, "Giant magnetoresistance in organic spin-valves," Nature (London) **427**, 821–824.

Yafet, Y., 1961, "Hyperfine interactions due to orbital magnetic moment of electrons with large g factors," J. Phys. Chem. Solids **21**, 99–104.

Yafet, Y., 1963, in *Solid State Physics, Vol. 14*, edited by F. Seitz and D. Turnbull (Academic, New York), p. 2.

Yamanouchi, M., D. Chiba, F. Matsukara, and H. Ohno, 2004, "Current-induced domain-wall switching in a ferromagnetic semiconductor structure," Nature (London) **428**, 539–541.

Yamashita, T., H. Imamura, S. Takahashi, and S. Maekawa, 2003, "Andreev reflection in ferromagnet/superconductor/ferromagnet double junction systems," Phys. Rev. B **67**, 094515.

Yamashita, T., S. Takahashi, H. Imamura, and S. Maekawa, 2002, "Spin transport and relaxation in superconductors," Phys. Rev. B **65**, 172509.

Yamashita, T., S. Takahashi, and S. Maekawa, 2003, "Crossed Andreev reflection in structures consisting of a superconductor with ferromagnetic leads," Phys. Rev. B **68**, 174504.

Yamauchi, T., and K. Mizushima, 1998, "Theoretical approach to the spin-dependent hot-electron transport in a spin valve," Phys. Rev. B **58**, 1934–1939.

Yan, X.-Z., H. Zhao, and C.-R. Hu, 2000, "Electron transport in normal-metal/superconductor junctions," Phys. Rev. B **61**, 14 759–14 764.

Yeh, N.-C., R. P. Vasquez, C. C. Fu, Y. L. A. V. Samoilov, and K. Vakili, 1999, "Nonequilibrium superconductivity under spin-polarized quasiparticle currents in perovskite ferromagnet-insulator-superconductor heterostructures," Phys. Rev. B **60**, 10 522–10 526.

You, C.-Y., and S. D. Bader, 2000, "Voltage controlled spintronic devices for logic applications," J. Appl. Phys. **87**, 5215–5217.

Young, D. K., E. Johnston-Halperin, D. D. Awschalom, Y. Ohno, and H. Ohno, 2002, "Anisotropic electrical spin injection in ferromagnetic semiconductor heterostructures," Appl. Phys. Lett. **80**, 1598–1600.

Young, D. P., D. Hall, M. E. Torelli, Z. Fisk, J. L. Sarrao, J. D. Thompson, H.-R. Ott, S. B. Oseroff, R. G. Goodrich, and R. Zysler, 1999, "High-temperature weak ferromagnetism in a low-density free-electron gas," Nature (London) **397**, 412–414.

Yu, Z. G., and M. E. Flatté, 2002a, "Electric-field dependent spin diffusion and spin injection into semiconductors," Phys. Rev. B **66**, 201202.

Yu, Z. G., and M. E. Flatté, 2002b, "Spin diffusion and injection in semiconductor structures: Electric field effects," Phys. Rev. B **66**, 235302.

Yuasa, S., T. Nagahama, and Y. Suzuki, 2002, "Spin-polarized resonant tunneling in magnetic tunnel junctions," Science **297**, 234–237.

Yusof, Z., J. F. Zasadzinski, L. Coffey, and N. Miyakawa, 1998, "Modeling of tunneling spectroscopy in high-T_c superconductors incorporating band structure, gap symmetry, group velocity, and tunneling directionality," Phys. Rev. B **58**, 514–521.

Zakharchenya, B. I., V. G. Fleisher, R. I. Dzhioev, Y. P. Veshchunov, and I. B. Rusanov, 1971, "Effect of optical orientation of electron spins in a GaAs crystal," Pis'ma Zh. Eksp. Teor. Fiz. **13**, 195–197 [JETP Lett. **13**, 137–139 (1971)].

Zawadzki, W., and P. Pfeffer, 2001, "Average forces in bound and resonant quantum states," Phys. Rev. B **64**, 235313.

Zeng, Z. Y., B. Li, and F. Claro, 2003, "Non-equilibrium Green's-function approach to electronic transport in hybrid mesoscopic structures," Phys. Rev. B **68**, 115319.

Zerrouati, K., F. Fabre, G. Bacquet, J. B. J. Frandon, G. Lampel, and D. Paget, 1988, "Spin-lattice relaxation in p-type gallium arsenide single crystals," Phys. Rev. B **37**, 1334–1341.

Zhang, S., 2000, "Spin Hall effect in the presence of spin diffusion," Phys. Rev. Lett. **85**, 393–396.

Zhang, S., P. M. Levy, A. C. Marley, and S. S. P. Parkin, 1997, "Quenching of magnetoresistance by hot electrons in magnetic tunnel junction," Phys. Rev. Lett. **79**, 3744–3747.

Zhao, B., I. Mönch, H. Vinzelberg, T. Mühl, and C. M. Schneider, 2002, "Spin-coherent transport in ferromagnetically contacted carbon nanotubes," Appl. Phys. Lett. **80**, 3144–3146.

Zhao, H. L., and S. Hershfield, 1995, "Tunneling, relaxation of spin-polarized quasiparticles, and spin-charge separation in superconductors," Phys. Rev. B **52**, 3632–3638.

Zawadzki, W., and P. Pfeffer, 2001, "Average forces in bound and resonant quantum states," Phys. Rev. B **64**, 235313.

Zheng, W., J. Wu, B. Wang, J. Wang, Q. f. Sun, and H. Guo, 2003, "Parametric quantum spin pump," Phys. Rev. B **68**, 113306.

Zhitomirskii, V. E., V. E. Kirpichev, A. I. Filin, V. B. Timofeev, B. N. Shepel, and K. von Klitzing, 1993, "Optical detection of spin relaxation of 2D electrons during photoexcitation," Pis'ma Zh. Eksp. Teor. Fiz. **58**, 429–434 [JETP Lett. **58**, 439–444 (1993)].

Zhu, H. J., M. Ramsteiner, H. Kostial, M. Wassermeier, H.-P. Schönherr, and K. H. Ploog, 2001, "Room-temperature spin injection from Fe into GaAs," Phys. Rev. Lett. **87**, 016601.

Zhu, J.-X., B. Friedman, and C. S. Ting, 1999, "Spin-polarized quasiparticle transport in ferromagnet-d-wave-superconductor junctions with a 110 interface," Phys. Rev. B **59**, 9558–9563.

Zhu, Y., Q.-f. Sun, and T.-h. Lin, 2002, "Andreev reflection through a quantum dot coupled with two ferromagnets and a superconductor," Phys. Rev. B **65**, 024516.

Ziese, M. and M. J. Thornton 2001, Eds., *Spin Electronics* (Springer, New York).

Zudov, M. A., J. Kono, Y. H. Matsuda, T. Ikaida, N. Miura, H. Munekata, G. D. Sanders, Y. Sun, and C. J. Stanton, 2002, "Ultrahigh field electron cyclotron resonance absorption in $In_{1-x}Mn_xAs$ films," Phys. Rev. B **66**, 161307.

Zurek, W. H., 2003, "Decoherence, einselection, and the quantum origins of the classical," Rev. Mod. Phys. **75**, 715–775.

Žutić, I., 2002a, "Novel aspects of spin-polarized transport and spin dynamics," J. Supercond. **15**, 5–12.

Žutić, I., 2002b, Ed., "Proceedings of Spintronics 2001 International Conference on Novel Aspects of Spin-Polarized Transport and Spin Dynamics, Washington, D.C.," J. Supercond. **15**, 1–104.

Žutić, I., and S. Das Sarma, 1999, "Spin-polarized transport and Andreev reflection in semiconductor/superconductor hybrid structures," Phys. Rev. B **60**, R16 322.

Žutić, I., and J. Fabian, 2003, "Spin-voltaic effect and its implications," Mater. Trans., JIM **44**, 2062–2065.

Žutić, I., J. Fabian, and S. Das Sarma, 2001a, "A proposal for a spin-polarized solar battery," Appl. Phys. Lett. **79**, 1558–1560.

Žutić, I., J. Fabian, and S. Das Sarma, 2001b, "Spin injection through the depletion layer: a theory of spin-polarized *p-n* junctions and solar cells," Phys. Rev. B **64**, 121201.

Žutić, I., J. Fabian, and S. Das Sarma, 2002, "Spin-polarized transport in inhomogeneous magnetic semiconductors: theory of magnetic/nonmagnetic *p-n* junctions," Phys. Rev. Lett. **88**, 066603.

Žutić, I., J. Fabian, and S. Das Sarma, 2003, "Proposal for all-electrical measurement of T_1 in semiconductors," Appl. Phys. Lett. **82**, 221–223.

Žutić, I., and O. T. Valls, 1999, "Spin polarized tunneling in ferromagnet/unconventional superconductor junctions," Phys. Rev. B **60**, 6320–6323.

Žutić, I., and O. T. Valls, 2000, "Tunneling spectroscopy for ferromagnet/superconductor junctions," Phys. Rev. B **61**, 1555–1566.

Zvezdin, A. K. and V. A. Kotov, 1997, *Modern Magnetooptics and Magnetooptical Materials* (Institute of Physics, Bristol/Philadelphia).

Zvezdin, A. K., A. S. Mishchenko, and A. V. Khval'kovskii, 2003, "Current-voltage characteristic of a spin half-metallic transistor," Zh. Tekh. Fiz. **48**, 53–58 [Tech. Phys. **4**, 431–436 (2003)].

Zwierzycki, M., K. Xia, P. J. Kelly, G. E. W. Bauer, and I. Turek, 2003, "Spin injection through an Fe/InAs interface," Phys. Rev. B **67**, 092401.

Zwolak, M., and M. Di Ventra, 2002, "DNA spintronics," Appl. Phys. Lett. **81**, 925–927.