Spin transfer experiments on (Ga,Mn)As/(In,Ga)As/(Ga,Mn)As tunnel junctions

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We present and discuss the results of current induced magnetic switching experiments performed on pillar-shaped (Ga,Mn)As/(In,Ga)As/(Ga,Mn)As tunnel junctions. The sign of the switching currents confirms the opposite spin polarizations of the valence band holes and Mn atoms in (Ga,Mn)As. With respect to spin transfer experiments in purely metallic structures, the magnitude of the switching currents is smaller by two orders of magnitude, which can be explained mainly by the small magnetization of (Ga,Mn)As. A striking result is the observation of current induced magnetization switching at values of the bias voltage for which the magnetoresistance of the junction has dropped to almost zero. This raises interesting questions on the different role played by voltage-induced magnon excitations on magnetoresistance and current-induced magnetization switching.

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The magnetic moment of a ferromagnetic body can be reversed or reoriented by transfer of spin angular momentum from the electrons of a spin-polarized current. This spin transfer concept has been introduced by Slonczewski[1] and Berger,[2] and has been confirmed by extensive recent experiments on pillar-shaped magnetic trilayers (for a review, see Stiles and Miltat).[3] Most experiments[4–9] have been performed on purely metallic trilayers, for example Co/Cu/Co, with detection of the magnetic switching by giant magnetoresistance (GMR). A few experiments have been performed on magnetic tunnel junctions (MTJ), generally on standard junctions with metallic magnetic electrodes,[10–12] and recently on (Ga,Mn)As/GaAs/(GaMn)As junctions by Chiba *et al.*[13] Current induced magnetization switching (CIMS) experiments on tunnel junctions bring new physical problems,[14] and are of particular interest for their promising application to the switching of the MTJ of magnetic random access memory (MRAM). However, with standard MTJ made of magnetic metal electrodes separated by an insulating material, such as alumina, the combination of large tunnel resistances with high switching current densities ($\sim 10^7$ A cm^{-2}) is a difficult obstacle for applications. In contrast, the low current density, of the order of 10^5 A cm^{-2}, needed for CIMS with (Ga,Mn)As,[13] shows the interest of magnetic semiconductors for spin transfer. In this paper, we present results of CIMS experiments on pillar-shaped (Ga,Mn)As/(In,Ga)As/(Ga,Mn)As tunnel junctions. (In,Ga)As has a smaller gap than GaAs and its choice for the insulating barrier allows us to obtain slightly smaller tunnel resistances than with GaAs. The offset of the valence band of (Ga,Mn)As above that of GaAs is estimated to 100 meV.[15] A smaller value and therefore a lower barrier is expected when GaAs is replaced by (In,Ga)As and as we will see, a tunneling behavior is still observed. After reporting on the experimental results, we will focus on the interpretation of the sign and amplitude ($\sim 10^5$ A cm^{-2}) of the switching currents and we will also discuss our observation of CIMS effects in a voltage range where the magnetoresistance (MR) has decreased to almost zero.

Our $Ga_{0.939}Mn_{0.061}As$(80 nm)/$In_{0.25}Ga_{0.75}As$(6 nm)/$Ga_{0.939}Mn_{0.061}As$(15 nm) structure is grown by molecular beam epitaxy at 250 °C on a p-doped GaAs buffer layer (p $\cong 2\times10^9$cm^3) grown on a GaAs(001) substrate. By superconducting quantum interference device (SQUID) measurements we find a typical ferromagnetic behavior for the (Ga,Mn)As layers with a Curie temperature of 80 K. For the MR and CIMS experiments, submicronic pillars were patterned in the structure by *e*-beam lithography. A circular resist mask (height=200 nm, diameter=700 nm) is first defined by *e*-beam lithography and oxygen plasma etching. The pillar is then etched down to the conducting GaAs buffer layer by ion beam etching and a Si_3N_4 layer is sputtered to cover the bottom electrode. The next step is the planarization of the surface by spin coating. The nitride layer on top of the pillar is then removed by ion etching. Finally, the top of the pillar is cleaned with an oxygen plasma and the top electrodes are fabricated by a lift-off process.

The resistance of the junctions is measured with a standard dc technique between 3 K and 30 K in magnetic fields up to 6000 Oe. As shown in the inset of Fig. 1, the $I(V)$ curves exhibit the typical nonlinear behavior of tunnel junctions. The *RA* (resistance × area) product at low bias (1 mV)

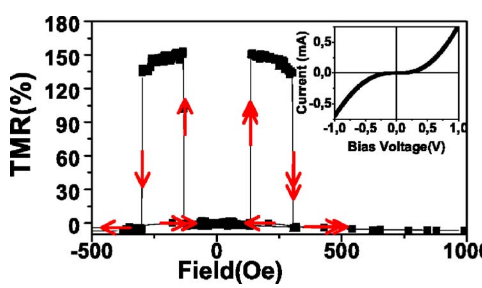

FIG. 1. (Color online) Tunnel magnetoresistance of a (Ga,Mn)As/(In,Ga)As/(Ga,Mn)As tunnel junction (diameter =700 nm) recorded at 3 K and 1 mV with the field along [100] (the first magnetic reversal corresponds to the thick magnetic layer). Inset: $I(V)$ curve at 3 K in the parallel configuration.

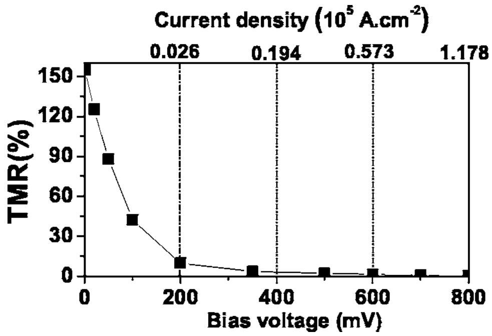

FIG. 2. Tunnel magnetoresistance versus bias voltage (bottom scale) and current density (top scale) at 3 K.

is about $1.1\times10^{-3}\ \Omega\,\mathrm{cm}^2$ at 3 K and $1.5\times10^{-3}\ \Omega\,\mathrm{cm}^2$ at 30 K (80% of the *RA* product for similar junctions with GaAs instead of (In,Ga)As). In Fig. 1, we show an example of a tunnel magnetoresistance (TMR) curve with a magnetic field applied along the easy magnetization axis [100]. The well-defined resistance plateau on the curves is characteristic of an antiparallel (AP) arrangement of the two (Ga,Mn)As layers in the field range between their respective reversal fields. The MR ratio reaches 155% at 3 K with a bias voltage of 1 mV, what is among the highest values found at this temperature with (Ga,Mn)As-based MTJ.[16,17] We also measured the variation of the resistance with an in-plane magnetic field in the field range where the magnetization of both electrodes is saturated. We observe a variation of about 3–4% (at 1 mV), which rules out any significant contribution from TAMR (Ref. 18) in our case.

In Fig. 2 we report the dependence of the MR ratio on the bias voltage applied to the junction. The TMR decreases rapidly as a function of the bias, with a reduction by a factor of two at $V_{1/2}\approx60$ mV and almost vanishes above 500 mV. Such a decrease of MR with the voltage is very generally observed in MTJ and is generally ascribed to inelastic processes involving emission of magnons or impurity scattering.[19–21] On the other hand, as it will be seen below, a voltage of about 800 mV is needed for the switching of the junctions by spin transfer, so that this switching cannot be detected directly by a clear change of resistance. Instead we use the following procedure: Starting, for example, from a parallel (P) configuration at $V=0$, the voltage is increased step by step, and, after each step, brought back to 20 mV to compare with that found at 20 mV before the step. We can check in this way whether the magnetic configuration has been irreversibly switched. Of course only irreversible switchings can be detected and the reversible changes of the "steady precession regime"[8,22] cannot be detected. Examples of results obtained with this procedure are shown in Figs. 3(b) and 3(d). By comparison with the MR curve at 20 mV of Figs. 3(a) and 3(c), one sees that the magnetic configuration is switched irreversibly from an almost parallel (P) to an almost antiparallel (AP) configuration by a positive current density (current flowing from the thin magnetic layer to the thick one), $j_{c+}=1.23\times10^5$ A cm^{-2}($V_{c+}=810$ mV) at 3 K and $j_{c+}=0.939\times10^5$ A cm^{-2}($V_{c+}=680$ mV) at 30 K. Then the configuration is switched back to parallel by a negative current above a threshold current density of the same order ($j_{c-}=-1.37\times10^5$ A cm^{-2} at 3 K and $j_{c-}=-0.986\times10^5$ A cm^{-2} at 30 K). Opposite current directions for the P to AP and AP to P transitions is the characteristic behavior of switching by spin transfer.[3–12] Reversing the initial orientation of the magnetizations does not reverse the sign of the switching current, which confirms that Oersted field effects can be ruled out. By using more complex cycling procedures, which would be too long to describe, we have checked that, as in standard CIMS experiments, the transition is due to the magnetic switching of the thin layer.

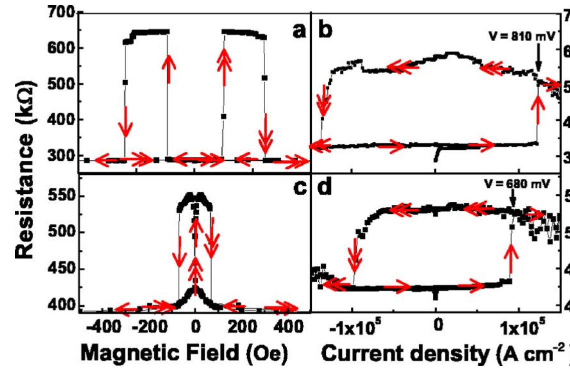

FIG. 3. (Color online) (a) Resistance versus magnetic field at 3 K and 20 mV. (b) Resistance versus current density at 3 K (initial temperature at low current density) in a field of 13.5 Oe (the initial state has parallel magnetizations in the positive field direction). (c) Same as (a) but at 30 K. (d) Same as (b) but at 30 K.

The sign of the switching currents is the same as for standard metallic pillars (typically Co/Cu/Co).[3,4,6,7] This can be explained by two successive changes of sign. First, the spin polarization of the valence band of (Ga,Mn)As is opposite to that of the Mn atoms, so that the valence subband of spin parallel to the global spin direction of (Ga,Mn)As is less filled (the respective filling of the spin subbands in Co is inverse). Second, with hole conduction in (Ga,Mn)As, the less-filled valence subband contributes more to the conduction, in contrast with a better conduction by the more filled subband in a metal like Co. The sign of the switching currents is thus characteristic of the inversion between the valence band and global spin polarization in agreement with the negative value of the *p*-*d* exchange integral β in (Ga,Mn)As, as already reported.[23,24]

A significant difference with respect to the behavior with magnetic metals is that CIMS curves similar to those of Fig. 3 can be obtained only in a small field window of 2–3 Oe around 13 Oe at 3 K. Let us first say that from an analysis of the shifts of minor MR cycles, we found that the dipolar field generated by the thick (Ga,Mn)As layer and acting on the thin layer is close to 13 Oe at 3 K, so that $H_{app}=13$ Oe corresponds to approximately an effective field $H_{eff}=0$ Oe on the thin layer when the moment of the thick one is in the positive direction (Fig. 3). The behavior of Fig. 3 in a field range of a couple of Oe around $H_{eff}=0$ Oe can be explained by the combined effects of the Joule heating and temperature dependence of the magnetic properties. From SQUID and TMR measurements, we know that the anisotropy and coercive field of the thin layer drops to a couple of Oe above 30 K [see Fig. 4(a)], or, equivalently, by heating the sample

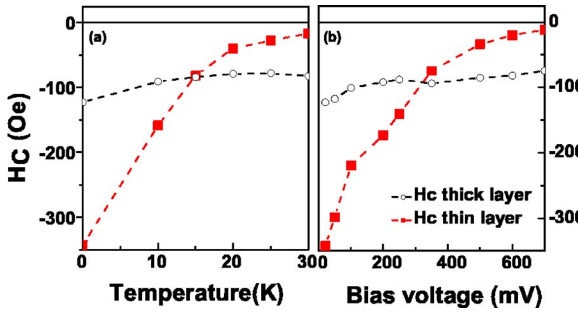

FIG. 4. (Color online) Coercive field of the thick (dots) and thin layers (squares) (a) versus temperature from MR cycles at low bias and (b) versus voltage from MR cycles under several bias at 3 K (initial temperature at low bias). The coercive field is corrected for the dipole field acting on each layer, that is $H_c = H_c^{exp} - H_{dip}$ (the dipole field H_{dip}, acting on each layer, is derived from minor MR cycles).

with a bias voltage value of about 700 mV [see Fig. 4(b)]. Suppose, for example, a P state with both magnetizations in the direction of positive H with $H_{app}=9$ Oe or, equivalently, $H_{eff} \cong -4$ Oe. If, at a current I^* smaller than the critical current for CIMS, the heating of the sample reduces the magnitude of the coercive field of the thin layer to 4 Oe or below, the effective field of −4 Oe switches the configuration to AP when the current reaches I^* or $-I^*$. This behavior, with switching to AP by positive as well as by negative currents, is what we observe for H_{app} below the window centered on $H_{app}=13$ Oe. Suppose now the same P state with $H_{app}=17$ Oe or, equivalently $H_{eff}=+4$ Oe. If heating the sample reduces the anisotropy field below 4 Oe, we enter the regime of reversible switching[3,5,7,9] that we cannot detect. Consistently, we cannot detect any switching for H_{app} above the window. We conclude that, with respect to CIMS with magnetic metals, the dramatic variation of the properties of (Ga,Mn)As with temperature, combined with the heating of the sample, introduces significant complications in CIMS experiments with (Ga,Mn)As and limits the observation of CIMS by spin transfer to a narrow field range.

The order of magnitude of the switching current densities ($\sim 10^5$ A cm^{-2}) is consistent with that in metallic structures ($\sim 10^7$ A cm^{-2}) when one takes into account the difference in the magnitude of the magnetization between (Ga,Mn)As and a metal like Co (this has been already discussed in this way by Chiba *et al.*).[13] The switching currents at zero (or low) field are expected to be given by an expression which, in its simplest form, can be written in the form:[6,7] $I^{P(AP)} = G^{P(AP)} \alpha t M [2\pi M + H_K]$, where $G^{P(AP)}$ is a coefficient depending on the current spin polarization, α is the Gilbert damping coefficient, t is the layer thickness, and H_K is the anisotropy field. The main difference with respect to a standard Co-base pillar comes from the factor $tM[2\pi M + H_K]$. With $t=15$ nm, $M=0.035$ T, and a negligible H_K after heating, for the junctions of this paper and $t=2.5$ nm, $M=1.78$ T, $H_K=0.02$ T for a typical Co/Cu/Co pillar,[4–6] we find that the factor $tM[2\pi M + H_K]$ is larger by a factor of 500 for the metallic structure. This is more than enough to explain the difference by two orders of magnitude. Additional factors should come from the current spin polarization (probably higher with (Ga,Mn)As) and the Gilbert coefficient (probably larger by almost an order of magnitude for (Ga,Mn)As grown at low temperature),[25] but a quantitative prediction is not possible. In addition, the reduction of the critical current densities observed may also have an additional contribution from a better efficiency of the transfer of the total angular momentum carried by the holes ($J=3/2$ instead of $S=1/2$).

The last question, regarding CIMS with standard MTJ:[12] why do we observe switching by spin transfer in a bias voltage range (≈ 800 mV) where the very strong reduction of MR suggests that the current has lost a major part of its polarization? Answering this question precisely is difficult since we do not know exactly why, in our MTJ, the MR drops rapidly to zero at increasing bias. In MTJ with metallic electrodes, the decrease of the MR with the bias is generally ascribed to electron-magnon scattering (emission and annihilation of magnons)[19] and to other types of spin dependent inelastic scatterings[21] that flip the spins of the tunneling electrons. Spin flips allow the spin up (spin down) electrons to reach the spin down (spin up) density of states of the collecting electrode. The situation is probably more complex in our junctions since, with a bias voltage of 800 mV larger than the barrier height, the junction is far from being in a standard tunneling regime. Here, however, we will consider the mechanism based on electron-magnon scattering to show how it can suppress the MR without affecting the spin transfer. By flipping the spins of the electrons, the electron-magnon scattering makes that the spin-polarized electron flux, tunneling through the barrier and entering the collecting electrode, is randomly directed to the spin up and spin down bands of this electrode. For the current, there will be no difference between the P and AP configurations (no MR). However, the scattering by magnons is due to electron-magnon exchange interactions, that is to spin conserving interactions which conserve the total spin of the global system composed of the spin system of the layer and the flowing electrons. Therefore, the transverse component of the spin polarized tunneling current cannot be lost and should be finally transferred to the magnetic moment of the layer.

In conclusion, we have reported on experiments of switching by spin transfer in (Ga,Mn)As/(In,Ga)As/(Ga,Mn)As tunnel junctions. The sign of the switching currents confirms the opposite orientations of the spin polarization of the valence band and the global spin polarization of (Ga,Mn)As. The critical current density for switching is smaller than in metallic structures by two orders of magnitude, which can be explained mainly by the smaller manetization of (Ga,Mn)As. There are two other differences with respect to CIMS in metallic pillars. First, the strong temperature dependence of the magnetic properties of (Ga,Mn)As combined with heating effects, makes the CIMS irreversible cycle observable only in a narrow window around zero effective field. Second, as in tunnel junctions with metallic electrodes, CIMS is observed in a voltage range where, from the strong reduction of the MR, one would expect a strong reduction of the spin polarization. We have argued that exchange-induced electron-magnon collisions reduce MR by mixing the spin channels but conserve the total spin and should not affect the spin transfer.

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