Anisotropic Electron Spin Lifetime in (In,Ga)As/GaAs (110) Quantum Wells

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Anisotropic electron spin lifetimes in strained undoped (In,Ga)As/GaAs (110) quantum wells of different width and height are investigated by time-resolved Faraday rotation and time-resolved transmission and are compared to the (001)-orientation. From the suppression of spin precession, the ratio of in-plane to out-of-plane spin lifetimes is calculated. Whereas the ratio increases with In concentration in agreement with theory, a surprisingly high anisotropy of 480 is observed for the broadest quantum well, when expressed in terms of spin relaxation times.

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In the last years, the manipulation of the electron's spin degree of freedom for information processing was explored in the new field of spintronics[1]. The most prominent proposal for a logic spin device by Datta and Das[2], the spin field effect transistor, is based on the precession of a spin in a variable electric field due to the Rashba effect. Recently, more robust devices have been suggested, which are based on the manipulation of spin relaxation leading to switchable randomization of the spin orientation[3,4,5]. Some of these proposals exploit the unique characteristics of bulk inversion asymmetry in (110)-oriented zinc-blende semiconductor quantum wells (QWs), for which a large anisotropy of electron spin relaxation time is predicted[6].

The largest spin relaxation anisotropy was found in a narrow n-doped (In,Ga)As/(Al,Ga)As QW grown in the [110] crystal direction[7]. In these zinc-blende semiconductors QWs, the spin relaxation time τ_S is mainly governed by the D'yakonov-Perel' (DP) spin dephasing mechanism, for which τ_S^{DP} of 2D confined electron spins is proportional to $T^{-1}E_g d^{-2}E_1^{-2}\tau_p^{-1}$, where T is the temperature, τ_p the momentum relaxation time, E_1 the quantized kinetic energy of electrons and E_g and d are the band gap and the thickness of the QW layer, respectively[6]. Additionally, the effect of DP strongly depends on the QW's confinement direction as well as on the spin direction[6]: For (001) QWs, the relaxation time of spins pointing in the in-plane direction $\tau^{\parallel}$ and in the out-out-plane direction $\tau^{\perp}$ is given by $\tau^{\parallel}_{S(001)} = \tau_S^{DP}$ and $\tau^{\perp}_{S(001)} = \tau_S^{DP}/2$, respectively, whereas it is $\tau^{\parallel}_{S(110)} = 4\tau_S^{DP}$ and $\tau^{\perp}_{S(110)} = \infty$ for (110) QWs, leading to infinite spin relaxation anisotropy for the latter. Indeed, large out-of-plane spin relaxation times (> 1 ns) as well as spin relaxation anisotropy were experimentally found in n-doped GaAs/$Al_{0.4}Ga_{0.6}As$ (110)[8,9] and in n-doped $In_{0.08}Ga_{0.92}As$/$Al_{0.4}Ga_{0.6}As$ (110) QWs[7,10]. Additional isotropic spin relaxation mechanisms have to be taken into account: e.g., the Bir-Aronov-Pikus (BAP) mechanism[11] based on randomly oriented hole spins acting on electron spins via exchange interaction is believed to be dominant only at low temperature in undoped and n-doped QWs[9]. However, there has been no detailed study of anisotropic spin lifetimes in shallow and strained $In_xGa_{1-x}As$/GaAs (110) QWs yet.

In the present work, we therefore investigated spin precession as a function of transverse magnetic fields of three $In_xGa_{1-x}As$/GaAs (110) QWs with different QW width and In concentration x employing the time-resolved Faraday rotation (TRFR) technique. The QWs were not intentionally doped, allowing us to separate the magnetization loss due to electron spin relaxation in the conduction band characterized by the spin relaxation time $\tau_S^{\perp,\parallel}$ and the carrier recombination processes described by the carrier lifetime τ_R. The decay of electron spin magnetization as observed by TRFR is then given by the spin lifetime $T_S^{\perp,\parallel}$[12]

$$\left(T_S^{\perp,\parallel}\right)^{-1} = \left(\tau_S^{\perp,\parallel}\right)^{-1} + \tau_R^{-1}, \tag{1}$$

when hole spins are considered to be already relaxed. Carrier lifetimes were measured using time-resolved transmission (TRTR) simultaneously to TRFR, in order to determine electron spin relaxation times from the measured spin lifetimes. All measurements were performed using a picosecond-pulsed laser with energies tuned to the lowest QW electron-hole transition confirmed independently by TRTR and photoluminescence at each temperature. The small spectral width of the picosecond laser (FWHM 0.5 nm) reduces the energetical width of occupied states and thus lowers the effect of inhomogeneous dephasing of electron spins in transverse magnetic fields[13], which otherwise may mask the anisotropy caused by the DP mechanism. In this way, investigating our broadest $In_xGa_{1-x}As$/GaAs (110) QW, we observed the highest spin relaxation anisotropy ever reported. We observed an increase of anisotropy with the increase of In-concentration which is consistent with DP and confirmed that the anisotropy does not vanish at 10 K as has been observed for a n-doped (In,Ga)As/(Al,Ga)As

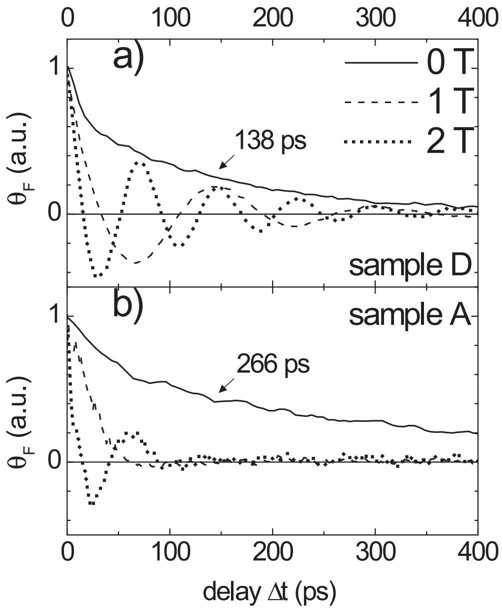

FIG. 1: Faraday rotation angle $\theta_F(\Delta t)$ of (001)-oriented sample D (a) and (110)-oriented sample A (b) for various transverse magnetic fields B_{ext} measured at 70 K.

(110) QW[7].

For all samples, the QW is formed by a single undoped and strained $In_xGa_{1-x}As$-layer sandwiched between intrinsic GaAs barriers grown by molecular-beam epitaxy. Three samples with different $In_xGa_{1-x}As$-layer thickness d and In-concentration x were grown on (110)-oriented semi-insulating GaAs substrates: samples A and B have the same $d = 8$ nm and In concentrations of $x = 11.5$ % and $x = 19$ %, respectively. Sample C has a much broader QW layer of $d = 14$ nm, but the same In concentration as sample A. Reference sample D was grown under the same conditions as sample A, but on a (001)-oriented GaAs substrate. For simultaneous TRFR and TRTR measurements we employed a mode-locked $Ti : Al_2O_3$ laser generating 1 ps optical pulses with 80 MHz repetition frequency. Normal-incident pump pulses, which were alternatingly left-circularly and right-circularly polarized by a photo-elastic modulator (PEM) working at 42 kHz and chopped at 1600 Hz frequency, excite spin-polarized electrons and holes along the growth direction. The evolution of the corresponding magnetization projected in this direction was determined by means of the Faraday rotation angle θ_F of transmitted linear-polarized probe pulses, which were delayed by a variable time Δt with respect to the pump pulses. A balanced diode-bridge was employed to measure the Faraday rotation angle and the output is locked to the PEM frequency. The evolution of the filling of the quantum well is determined by the change of transmission $\Delta\zeta(\Delta t)$ of the probe pulse and recorded by the sum of the intensities on the diode bridge locked to the chopper frequency of the pump beam.

Figure 1 displays $\theta_F(\Delta t)$ for (001)-oriented sample D and (110)-oriented sample A at various transverse magnetic fields B_{ext} applied in the [001] crystal direction. Data were taken at 70 K, at which the longest electron spin lifetime as a function of temperature was found for sample A. Fitting the curves for zero magnetic field starting from $\Delta t = 50$ ps reveal a single-exponential decay reflecting the electron spin lifetime $T_S^{\perp}$ to be 138 ps and 266 ps for samples D and A, respectively. An additional fast decay (< 10 ps at 70 K) might be caused by excitonic effects[7,11]. In a transverse magnetic field B_{ext}, spin precession is observed in the control sample D for all B_{ext}, whereas spin precession is not observed at $B_{ext} \lesssim 1$ T for the (110)-oriented sample A. Additionally, the electron spin lifetime of sample A is dramatically reduced when a transverse magnetic field is applied similar to Refs.[7,10]. The corresponding carrier lifetimes τ_R at 70 K (not shown) turned out to be independent of the applied B_{ext} and are 600 ps and 675 ps for sample D and A, respectively, which reflects that τ_R does not depend on the electron spin direction.

In order to model the complex B_{ext}-dependence for the anisotropic sample A, the magnetization of electrons spins normal ($S_\perp$) and parallel ($S_\parallel$) to the QW plane has to be considered separately. The time evolution of $\vec{S}$ in an in-plane magnetic field $\vec{B}_{ext} \perp \vec{S}$ is given by[9]

$$\frac{\partial}{\partial t}\begin{pmatrix} S_\parallel \\ S_\perp \end{pmatrix} = -\begin{pmatrix} \Gamma_\parallel & -\omega \\ \omega & \Gamma_\perp \end{pmatrix}\begin{pmatrix} S_\parallel \\ S_\perp \end{pmatrix}, \qquad (2)$$

where $\omega = g\mu_B B_{ext}/\hbar$ is the Larmor frequency. For undoped QWs the total relaxation rates $\Gamma_{\perp,\parallel} = (T_S^{\perp,\parallel})^{-1}$ are the sum of the anisotropic electron spin relaxation rates $\gamma_{\perp,\parallel} = (\tau_S^{\perp\parallel})^{-1}$ and the isotropic carrier recombination rate $(\tau_R)^{-1}$ in the QW: $\Gamma_{\perp,\parallel} = \gamma_{\perp,\parallel} + (\tau_R)^{-1}$ in accordance with Eq. 1. The solution for $S_\perp$, which is measured by TRFR, is given by

$$S_\perp(t) = \frac{S_0}{\cos(\phi)}\exp\left(-\frac{\Gamma_\perp + \Gamma_\parallel}{2}t\right)\cos(\omega' t - \phi), \qquad (3)$$

with $\tan(\phi) = (\Gamma_\perp - \Gamma_\parallel)/(2\omega')$ and the modified Larmor frequency

$$\omega' = \sqrt{\omega^2 - \left(\frac{\Gamma_\parallel - \Gamma_\perp}{2}\right)^2}. \qquad (4)$$

In order to calculate the spin lifetime anisotropy, the square of the measured modified Larmor frequency ω'^2 of sample A and D is plotted as a function of B_{ext}^2 as displayed in Figure 2. In the inset, a right-shift of the plot for sample A is obvious and indicates the suppression of precession in the (110)-oriented QW. According to Eq. 4 this shift is caused by the difference of the total spin relaxation rates $\Gamma_\parallel - \Gamma_\perp$ and thus by the spin lifetime anisotropy. From the right-shift and the slope of the linear fit, both the difference of the relaxation rates $\Gamma_\parallel - \Gamma_\perp$

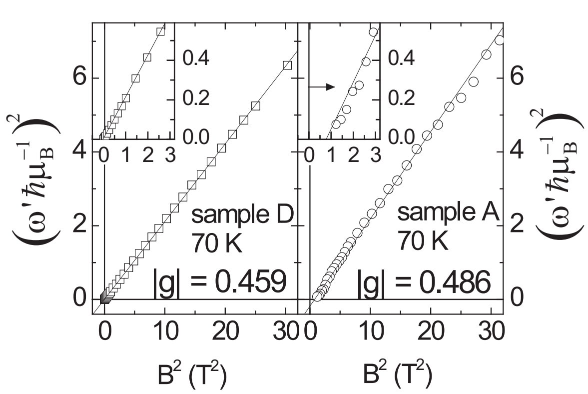

FIG. 2: Square of measured Larmor-frequency $\omega'^2(B_{ext}^2)$ for (001)-oriented sample D (squares) and (110)-oriented sample A (circles) measured at 70 K; solid lines are linear fits; zoom near $B = 0$ T in the insets.

and the absolute electron g-factor can be determined, respectively. Using $\Gamma_\parallel - \Gamma_\perp$ and assuming $T_S^\perp = 266$ ps to be independent of B_{ext}[7], the in-plane spin lifetime is calculated to be $T_S^\parallel = (13 \pm 2)$ ps. Thus, the anisotropy of the spin lifetime $T_S^\perp / T_S^\parallel$ turns out to be 21 ± 2 for sample A. The last assumption is justified, since the exponential decay in Eq. 3 is observed to be independent of the magnetic field in the oscillatory regime and simulations using constant $T_S^\perp$ fit well in the non-oscillatory regime, which is demonstrated here for sample C in Figure 3a).

In the following, this result is compared to the other (110)-oriented QWs. Figure 3 shows $\theta_F(\Delta t)$ at various B_{ext} for sample C as well as $\omega'^2(B_{ext}^2)$for sample C and B. Data were taken at 110 K and 70 K for sample B and sample C, respectively, at which the maximum of $T_S^\perp = 335$ ps and $T_S^\perp = 440$ ps was measured. Comparing $\theta_F(\Delta t)$ of sample C to sample A (see Fig. 1(b)), $T_S^\perp$ of sample C is found to be much longer, but spin precession turns out to be even more suppressed, which indicates a higher anisotropy. The same can be concluded from the pronounced right-shift of $\omega'^2(B_{ext}^2)$ (see Fig. 3(b)). Using the derivation explained above, the anisotropy of the spin lifetime $T_S^\perp / T_S^\parallel$ follows to be 52 ± 10 and 54 ± 6 with $T_S^\parallel = (6.5 \pm 0.8)$ ps and $T_S^\parallel = (8.2 \pm 0.5)$ ps for sample B and C, respectively. Compared to the calculated value of sample A, the result for the deeper QW B has the correct tendency, since DP is more dominant for the latter according to theory. However, the high anisotropy for the broadest QW C is surprising and needs further discussion. The effectiveness of DP should be reduced for sample C, since $\tau_S^{DP} \propto d^{-2} E_1^{-2} \propto d^2$. The increased spin lifetime as well as the higher anisotropy compared to sample A might than be explained by a reduction of an isotropic spin relaxation channel. Scattering at the barrier interfaces, which has not been considered yet, might be a suitable candidate, since it can be assumed to be dependent on the volume to interface ratio and thus less pronounced for the broadest QW C.

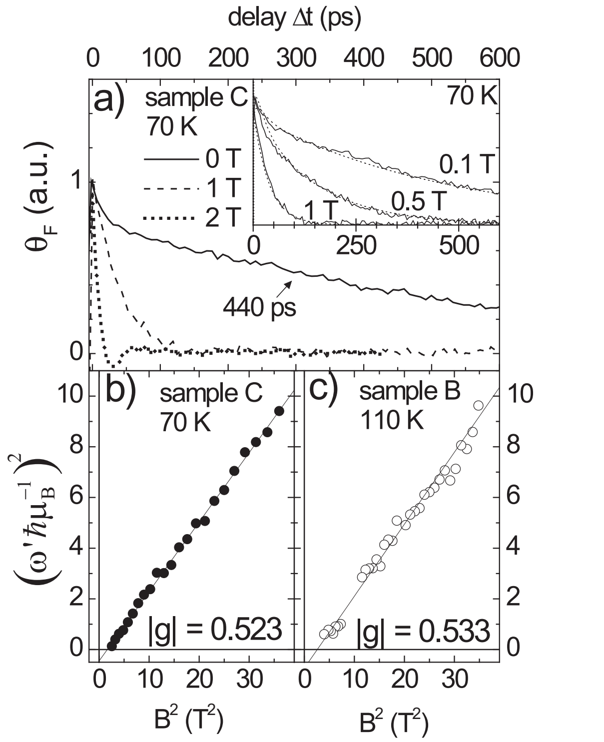

FIG. 3: (a) Faraday rotation angle $\theta_F(\Delta t)$ for the broad (110) QW C at various transverse magnetic fields B_{ext}^2; inset: measurements (line) and simulations (dotted line) for imaginary ω'; (b) Larmor frequency $\omega'^2(B_{ext})$ for the broad (110) QW C and (c) for the deep (110) QW B measured at 70 K and 110 K, respectively; solid lines are linear fits.

We now check the consistency of our results with our simple model and with DP-theory by varying the temperature and the direction of the magnetic field. Since for the derivation of $\Gamma_\parallel - \Gamma_\perp$ and the g factor only the oscillatory curves are considered as explained above, consistency of raw data with Eq. 3 is checked for imaginary ω'. With only the amplitude S_0 as a free parameter left, the simulations fit well to the measured $\theta_F(\Delta t)$ curves of sample C, as can be seen from the inset of Figure 3. Furthermore, we measured the anisotropy of sample C at 10 K, at which the isotropic BAP is considered to be dominant and thus the anisotropy of spin lifetimes should be reduced. Indeed, a lower anisotropy of $T_S^\perp / T_S^\parallel = 39 \pm 9$ is found for sample C at 10 K[14]. Since the anisotropy does not vanish, DP is still present at 10 K as was already observed for an (In,Ga)As/(Al,Ga)As (110) QW[7]. Finally, we checked for any in-plane anisotropy of the spin lifetime by rotating the sample in-situ around the growth direction in a transverse magnetic field. Figure 4 (b) displays no systematic changes of the decay for sample C at 70 K in the oscillatory ($B_{ext} = 4$ T) regime. Thus, in consistency with theory[6,15], spin relaxation is equivalent for all spin directions in the plane of the QW.

In the end, we express the calculated anisotropy of spin lifetimes in terms of spin relaxation times using the

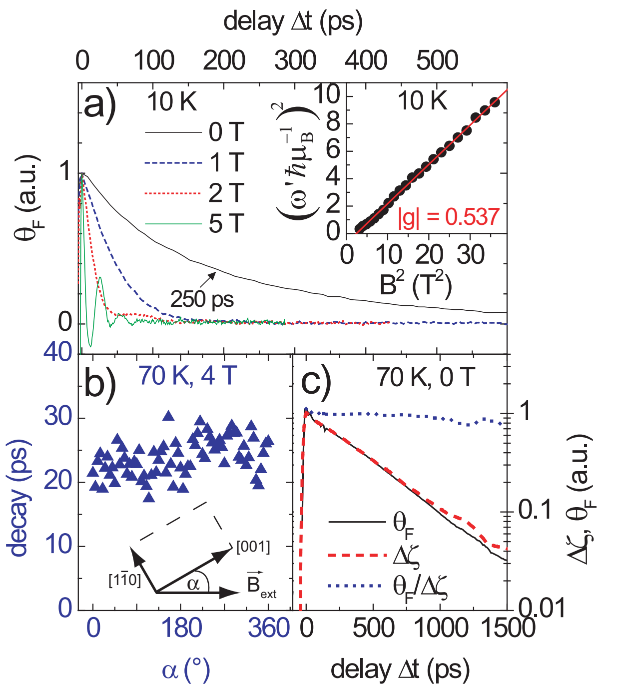

FIG. 4: (a) Faraday rotation angle $\theta_F(\Delta t)$ and fitted Larmor frequency $\omega'^2(B_{ext})$ (inset) for broad (110) QW C at various transverse magnetic fields B_{ext} measured at 10 K; (b) fitted decay of $\theta_F(\Delta t)$ measured as a function of angle α between B_{ext} and [001] crystal direction at 4 T and 70 K for sample C; (c) comparison of $\theta_F(\Delta t)$ and $\Delta\zeta(\Delta t)$ at 0 T and 70 K for sample C: the spin lifetime $T_S^{\perp}$ is limited by the carrier recombination τ_R and the ratio $\theta_F/\Delta\zeta(\Delta t)$ reveals the spin relaxation time $\tau_S^{\perp}$ to be > 4 ns.

carrier lifetime τ_R. Since $\Delta\zeta(\Delta t)$ is found to be independent of the transverse magnetic field and thus τ_R does not change with the spin direction, we can use Eq. 1 for our undoped QWs. The difference of the in-plane and out-of-plane electron relaxation rates $\gamma_{\parallel} - \gamma_{\perp} = \Gamma_{\parallel} - \Gamma_{\perp}$ can be easily seen from the right-shift of the linearly fitted $\omega'^2(B_{ext}^2)$ leading to the anisotropy of spin relaxation times. For sample C, $\Delta\zeta(\Delta t)$ and $\theta_F(\Delta t)$ are measured simultaneously at zero magnetic field and at 70 K as displayed in Figure 4 (c). Fitting $\Delta\zeta(\Delta t)$ and $\theta_F(\Delta t)$, we obtained $\tau_R = (450 \pm 20)$ ps and $T_S^{\perp} = (440 \pm 20)$ ps leading to $\tau_S^{\perp} > 4$ ns. Since $\tau_R \gg T_S^{\parallel}$, the limitation of the carrier lifetime for the calculation of $\tau_S^{\parallel}$ is negligible according to Eq. 1. Expressing the anisotropy in terms of spin relaxation times, we thus obtain $\tau_S^{\perp}/\tau_S^{\parallel} > 480$ for sample C at 70 K. This lower limit of the anisotropy is by a factor of eight higher than the maximum anisotropy observed so far[7]. As the carrier lifetime $\tau_R = 675$ ps of sample A is considerably higher than its out-of-plane spin lifetime $T_S^{\perp} = 266$ ps there is not much difference found when the anisotropy is expressed instead of spin lifetime in terms of spin relaxation time: $\tau_S^{\perp}/\tau_S^{\parallel} = 34 \pm 7$.

In conclusion, we observed anisotropic electron spin lifetimes in strained and undoped InGaAs/GaAs (110) QWs by the suppression of spin precession. Increasing the In concentration enhances the dominating DP mechanism and leads to a higher anisotropy consistent with theory. The broadest QW exhibit longest $T_S^{\perp}$ as well as a surprisingly large anisotropy, which in terms of spin relaxation times exceeds 480 and even does not vanish at low temperatures, when the isotropic BAP is believed to be most relevant. No in-plane anisotropy was found and the anomalous spin motion can be readily described by $T_S^{\perp}, T_S^{\parallel}$ and the electron g-factor in a transverse magnetic field.

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14. Curve fitting is more complex at low temperatures, since the additional decay in $\theta_F(\Delta t)$, which is contributed to excitonic effects, increases with the decrease of the temperature. This component does not show any oscillations even for $B_{ext} = 5$ T and its relaxation time is independent of B_{ext}. Thus, evaluation of spin precession is still reasonable as can be seen from the inset of Figure 4.

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