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Anisotropic spin dynamics of two-dimensional electrons in strained n -InGaAs/AlGaAs (110) quantum wells (QWs) is investigated by a time-resolved Faraday rotation technique. Strong anisotropy of the relaxation time for the electron spins in parallel (τ_{\parallel}) and perpendicular (τ_{\perp}) to the QWs is observed ($\tau_{\perp}/\tau_{\parallel} \sim 60$) at 150 K as a result of the enhanced D'yakonov–Perel' (DP) spin relaxation mechanism. At 5 K, an anisotropic feature of the spin relaxation time is also observed in the presence of in-plane magnetic field, suggesting that the DP mechanism is effective for low-temperature spin relaxation. © 2005 American Institute of Physics. [DOI: 10.1063/1.2112193]

Recently, spin-related phenomena in semiconductor quantum structures have attracted much attention from both viewpoints of physics and applications.^{1–4} In particular, spin relaxation of conduction electrons has extensively been studied since it is a key factor for semiconductor spintronics devices: spin relaxation time must be sufficiently long for storage and processing of information encoded as spin polarization.

In zinc-blende semiconductors, it is generally accepted that the spin relaxation is governed by the D'yakonov–Perel' (DP) mechanism in the high temperature regime.^{5–7} In this mechanism, electron spins precess about the internal effective magnetic field \mathbf{B}_{eff} , which originates from the spin–orbit coupling with bulk inversion asymmetry and thus depends on the magnitude and the direction of the translational momentum \mathbf{p} of electrons. In the case of two-dimensional electrons (2DEs) confined in a quantum well (QW) potential, the effect of the DP mechanism strongly depends on the growth direction.^{8,9} In (110) QWs, for example, \mathbf{B}_{eff} orients in the growth direction, while it lies in the QW plane for 2DEs in (001) QWs. According to the theory,⁸ the spin relaxation time of 2DEs is given by $\tau_{\parallel(110)} = 4\tau_s$ and $\tau_{\perp(110)} = \infty$ for in and out of the (110) QW plane, respectively, and $\tau_{\parallel(001)} = \tau_s$ and $\tau_{\perp(001)} = \tau_s/2$ for in and out of the (001) QW plane, respectively, where τ_s is the spin relaxation time proportional to $E_1^{-2}T^{-1}\tau_p^{-1}$, E_1 the quantized kinetic energy of electrons, T the temperature, and τ_p is the momentum relaxation time.¹⁰

Experimentally, in the high temperature regime, extremely long τ_{\perp} has been observed in GaAs/AlGaAs (110) QWs^{9,11} compared to the (100) QWs^{9,12} in accordance with the above theory.⁸ On the other hand, in the low temperature

regime (<40 K), the DP mechanism is suppressed and electron-hole exchange interaction¹³ is more likely to govern the spin relaxation.^{9,14}

When an external magnetic field \mathbf{B}_{ext} is applied, electron spins start to precess about \mathbf{B}_{ext} : so far, long-retained spin precession, which can be measured by time-resolved optical techniques, has been proved a powerful tool to detect effective magnetic fields.^{15,16} It has recently been reported, however, that such an anisotropy ($\tau_{\perp}/\tau_{\parallel}$) modulates the motion of electron spins in a complex manner in the high temperature regime where the DP mechanism is dominant.¹⁴ Although a number of studies on spin relaxation in QWs have been reported, only a few works have focused on the peculiar spin relaxation anisotropy so far.^{14,17}

In the present work, we studied anisotropic spin relaxation processes of 2DEs in strained, narrow n -In_{0.08}Ga_{0.92}As/Al_{0.4}Ga_{0.6}As (110) QWs by using a time-resolved Faraday rotation (TRFR) technique. In order to enhance the effect of the DP mechanism in a wide temperature regime, the samples are designed to have deep and narrow QW potential and thus large E_1 , which decreases τ_s ($\propto \tau_{\parallel}$) and enhances the anisotropy ($\tau_{\perp}/\tau_{\parallel}$) in (110) QWs. We also employed n -doped QWs to suppress electron-hole exchange interaction and have conduction electrons with finite kinetic energy at low temperatures. We confirmed greater anisotropy of the spin relaxation time in our QWs compared to the 20 nm-thick GaAs/AlGaAs (110) QWs,¹⁴ and observed an anomalous motion of electron spins under an external magnetic field. In our samples with large anisotropy of spin relaxation, we also found that the DP mechanism is playing a role even at low temperature of 5 K, while the electron-hole

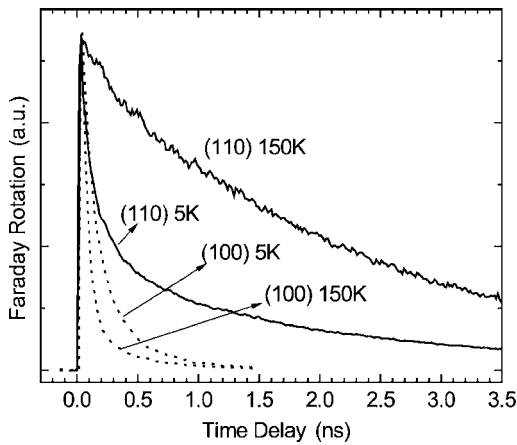


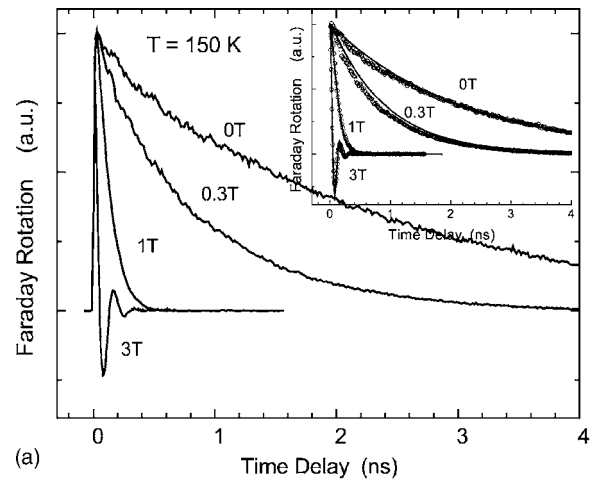
FIG. 1. TRFR angle $\theta_F(\Delta t)$ at 150 and 5 K for both (110) and (001) QW samples at zero magnetic field.

exchange interaction is more likely to govern the spin relaxation in Ref. 14.

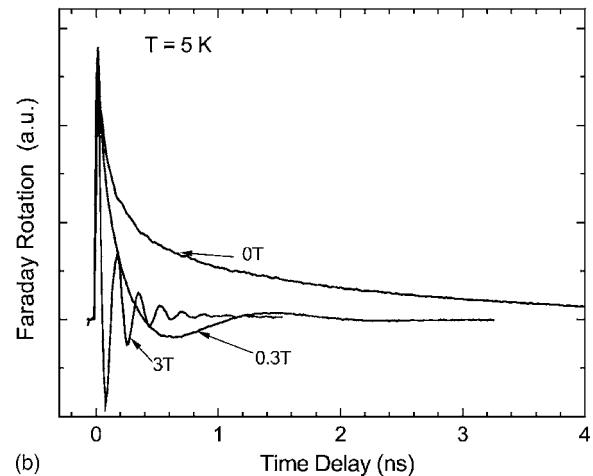
The samples studied here were grown by molecular beam epitaxy. Ten periods of 5 nm-thick $\text{In}_{0.08}\text{Ga}_{0.92}\text{As}$ QWs separated by 10 nm-thick $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ barriers were grown on (001) and (110)-oriented semi-insulating GaAs substrates, respectively. Each QW was doped with Si donors to a nominal density of $\sim 3 \times 10^{11} \text{ cm}^{-2}$ per QW. In TRFR measurements, we employed a mode-locked Ti:Al₂O₃ laser to generate an optical pulse train (~ 110 fs, 76 MHz). The center of the photon energy was tuned at the heavy-hole exciton energy at each temperature (1.521 eV at 150 K and 1.546 eV at 5 K). A normal-incident circular-polarized pump pulse (5 mW) excites spin-polarized electrons in the QW along the growth direction. We recorded the Faraday rotation angle $\theta_F(\Delta t)$ of a linear-polarized probe pulse as a function of a time delay Δt , which corresponds to the spin component normal to the QW plane.

Figure 1 shows $\theta_F(\Delta t)$ measured at 150 and 5 K for both (110) and (001) QW samples without applying in-plane magnetic fields. At the initial stage ($\Delta t < 0.3$ ns), we observed fast decay in $\theta_F(\Delta t)$ for both (110) and (001) QWs at 5 K, which might not come from the spin relaxation of conduction electrons but from some excitonic effect.¹³ Thus we evaluated $\tau_{\perp(110)}$ and $\tau_{\perp(001)}$ by fitting the experimental data of $\theta_F(\Delta t)$ for $\Delta t > 0.3$ ns with a single exponential decay function. At 150 K, we observed a large difference between $\tau_{\perp(110)}$ and $\tau_{\perp(001)}$: $\tau_{\perp(110)} \sim 2.3$ ns, which is about 25 times larger than $\tau_{\perp(001)} \sim 90$ ps. This is consistent with the previous experimental result in GaAs/AlGaAs QWs.⁹ At 5 K, we also observed a distinct difference between $\tau_{\perp(110)}$ and $\tau_{\perp(001)}$: $\tau_{\perp(110)} \sim 2.1$ ns is about 10 times longer than $\tau_{\perp(001)} \sim 0.22$ ns. This indicates that the electron-hole exchange interaction, which does not strongly depend on the growth direction, is suppressed even at low temperature because of the existence of donor-induced background electrons.^{7,11,18} Instead, the DP mechanism is most likely governing the spin relaxation even at the low temperature of 5 K.

In order to examine the anisotropic spin relaxation of 2DEs in (110) QWs, we applied an in-plane magnetic field B_{ext} along the $[\bar{1}10]$ direction. Figures 2(a) and 2(b) show the B_{ext} -dependence of $\theta_F(\Delta t)$ in the (110) QWs measured at 150 and 5 K, respectively. We first notice that with increasing B_{ext} the decay of $\theta_F(\Delta t)$ becomes faster for both 150 and



(a)



(b)

FIG. 2. TRFR angle $\theta_F(\Delta t)$ measured at different magnetic fields B_{ext} at 150 K (a) and at 5 K (b) in (110) QWs. The inset shows the reproduced theoretical curves (solid lines) with the experimental results (open circles).

5 K. Furthermore, we did not observe any oscillation in $\theta_F(\Delta t)$ at 150 K when $B_{\text{ext}} < 1$ T, while we observed clear oscillations at 5 K as $B_{\text{ext}} > 0.3$ T. This is not due to the temperature dependence of the electron g -factor: At 3 T, for example, the Larmor frequencies are nearly the same at 150 and 5 K.

By introducing the effective spin relaxation time $T_S(B_{\text{ext}})$, $\theta_F(\Delta t)$ can be expressed as

$$\theta_F(\Delta t) = C_0 \cdot e^{-\Delta t/T_S(B_{\text{ext}})} \cdot \cos\{(1/\hbar)g\mu_B B_{\text{ext}}\Delta t\}, \quad (1)$$

where C_0 is a constant, g is an element of the g -tensor \hat{g} along B_{ext} , μ_B is the Bohr magnetron, and \hbar the reduced Planck constant. In the present case, however, the anisotropic spin relaxation due to the DP mechanism is switched on with applying B_{ext} , and the fact that $\tau_{\perp} > \tau_{\parallel}$ should result in the B_{ext} -dependence of $T_S(B_{\text{ext}})$. Figure 3 shows the B_{ext} -dependence of $T_S(B_{\text{ext}})$, which is obtained from the data in Figs. 2(a) and 2(b) by fits using Eq. (1). At 5 K, rapid decrease of $T_S(B_{\text{ext}})$ was observed at lower magnetic field $B_{\text{ext}} < 0.1$ T, while $T_S(B_{\text{ext}})$ decreases slowly with further increase of B_{ext} . On the contrary, $T_S(B_{\text{ext}})$ decreases slowly with B_{ext} at 150 K up to $B_{\text{ext}} = 1$ T, but then $T_S(B_{\text{ext}})$ becomes almost constant as $B_{\text{ext}} > 1$ T.

To explain these peculiar features of the spin dynamics in (110) QWs, we solved the equation of motion for electron spin S involving a strong anisotropy of spin relaxation, as

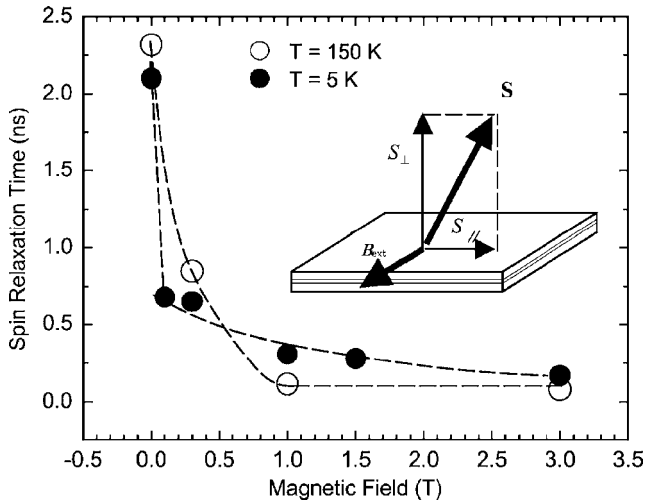


FIG. 3. The magnetic field dependence of $T_S(B_{\text{ext}})$ in (110) QWs at 150 K (open circles) and 5 K (filled circles). Dashed curves are a guided for the eye. The inset shows the illustration of motion for electron spin \mathbf{S} involving spin relaxation anisotropy under in-plane magnetic field.

depicted in the inset of Fig. 3. Taking into account the anisotropy of spin relaxation,¹⁴ the spin components normal (S_{\perp}) and parallel (S_{\parallel}) to the QW plane under in-plane magnetic fields are given by

$$\frac{\delta}{\delta t} \begin{pmatrix} S_{\parallel} \\ S_{\perp} \end{pmatrix} = - \begin{pmatrix} \gamma_{\parallel} & -\omega \\ \omega & \gamma_{\perp} \end{pmatrix} \begin{pmatrix} S_{\parallel} \\ S_{\perp} \end{pmatrix}, \quad (2)$$

where $\omega = g\mu_B B_{\text{ext}}/\hbar$ is the Larmor frequency, $\gamma_{\parallel} = 1/\tau_{\parallel}$ and $\gamma_{\perp} = 1/\tau_{\perp}$ are the spin relaxation rates. The solution for S_{\perp} in Eq. (2) is given by

$$S_{\perp} = S_0 e^{-(\gamma_{\parallel} + \gamma_{\perp})t/2} \cdot (C_1 e^{-\sqrt{\alpha}t} + C_2 e^{\sqrt{\alpha}t}), \quad (3)$$

where S_0 is a constant, $C_1 = (\gamma_{\perp} - \gamma_{\parallel} + \sqrt{\alpha})/2\sqrt{\alpha}$, $C_2 = (-\gamma_{\perp} + \gamma_{\parallel} + \sqrt{\alpha})/2\sqrt{\alpha}$, and $\alpha = (\gamma_{\perp} - \gamma_{\parallel})^2 - 4\omega^2$, respectively. When B_{ext} is large enough, i.e., $|B_{\text{ext}}| > (\hbar/g\mu_B)|\gamma_{\perp} - \gamma_{\parallel}|/2$ ($\alpha < 0$), Eq. (3) becomes equivalent to Eq. (1) with $T_S(B_{\text{ext}}) = 2(1/\tau_{\perp} + 1/\tau_{\parallel})^{-1}$. At 150 K, it is reasonable to assume that τ_{\perp} and τ_{\parallel} do not depend on B_{ext} because $T_S(B_{\text{ext}})$ is almost constant at high B_{ext} . Taking $\tau_{\perp} = 2.3$ ns, which is obtained from the fitting at $B_{\text{ext}} = 0$, and $|g|$ and τ_{\parallel} as fitting parameters, we fitted the experimental data in Fig. 2(a). As shown by solid lines in the inset of Fig. 2(a), the fitted curves using Eq. (3) reproduced the experimental results. Here, we obtained $|g| = 0.16 \pm 0.01$ and $\tau_{\parallel} = 0.035 \pm 0.005$ ns, respectively. The strong anisotropy ($\tau_{\perp}/\tau_{\parallel} \sim 60$) of the present sample, which is about 6 times greater than that reported in 20 nm-thick GaAs/AlGaAs(110) QWs,¹⁴ explains the absence of oscillation when $B_{\text{ext}} < 1$ T in Fig. 2(a), where $|B_{\text{ext}}| < (\hbar/g\mu_B)|\gamma_{\perp} - \gamma_{\parallel}|/2$ and thus $\alpha > 0$ in Eq. (2).

For the data at 5 K, the rapid decrease of $T_S(B_{\text{ext}})$ observed at $B_{\text{ext}} < 0.1$ T in Fig. 3 clearly shows the presence of spin relaxation anisotropy. We observed, however, the B_{ext} -dependence of $T_S(B_{\text{ext}})$ in Fig. 3 as $B_{\text{ext}} > 0.1$ T, where B_{ext} is high enough for spins to precess. While we cannot fully reproduce $\theta_F(\Delta t)$ in Fig. 2(b) by using Eq. (3) as long as τ_{\perp} and τ_{\parallel} are assumed to be independent of B_{ext} , we evaluated the degree of anisotropy by applying Eq. (3) assuming that τ_{\perp} is constant in moderated $B_{\text{ext}} (< 3$ T). Taking $\tau_{\perp} = T_S(B_{\text{ext}} = 0) = 2.1$ ns, we obtained $|g| = 0.14 \pm 0.01$ and $\tau_{\parallel} = 0.15$ ns at $B_{\text{ext}} = 3$ T and 0.45 ns at $B_{\text{ext}} = 0.3$ T by fitting,

respectively. It is probable that some fundamental parameters such as τ_p become B_{ext} -dependent and both τ_{\perp} and τ_{\parallel} might be modified for $B_{\text{ext}} > 0.1$ T. Although the spin relaxation due to the electron-hole exchange interaction is suppressed in our sample, as it is revealed by long $T_S(B_{\text{ext}} = 0) = 2.1$ ns at 5 K, the possibility of having contributions from other mechanisms at low temperatures cannot be ruled out completely. Nevertheless, it is hard to expect that the other spin relaxation mechanisms except for the DP mechanism can induce such an anisotropy of the spin relaxation $\tau_{\perp}/\tau_{\parallel} = 4.5 - 14$ at 5 K, indicating that the DP mechanism is still playing a role at this temperature regime.

In conclusions, the effect of spin relaxation anisotropy was investigated in 5 nm-thick n -In_{0.08}Ga_{0.92}As/Al_{0.4}Ga_{0.6}As (110) QWs. Because of the strong effect of the DP mechanism, the motion of the electron spin was found strongly modulated at both high (150 K) and low (5 K) temperatures. The anisotropy of the spin relaxation time $\tau_{\perp}/\tau_{\parallel}$ reaches 60 at 150 K, which is about 6 times larger than that in a 20 nm-thick GaAs/AlGaAs (110) QWs. We have also observed anisotropic features of the spin relaxation at 5 K due most likely to the DP mechanism. The presence of magnetic field dependence of the spin relaxation may be an indication of modulation of parameters in the DP mechanism.

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¹⁰Throughout this Letter the notation τ_{\parallel} and τ_{\perp} are used for the spin relaxation time of parallel and perpendicular to the QW, respectively, according to Ref. 8.

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