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Effect of electron-electron scattering on spin dephasing in a high-mobility low-density two-dimensional electron gas

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By utilizing time-resolved Kerr rotation techniques, we have investigated the spin dynamics of a high-mobility low density two-dimensional electron gas in a GaAs/$Al_{0.35}Ga_{0.65}As$ heterostructure in the dependence on temperature from 1.5 to 30 K. It is found that the spin relaxation/dephasing time under a magnetic field of 0.5 T exhibits a maximum of 3.12 ns around 14 K, which is superimposed on an increasing background with rising temperature. The appearance of the maximum is ascribed to that at the temperature where the crossover from the degenerate to the nondegenerate regime takes place, electron-electron Coulomb scattering becomes strongest, and thus inhomogeneous precession broadening due to the D'yakonov–Perel' mechanism becomes weakest. These results agree with the recent theoretical predictions [J. Zhou *et al.*, Phys. Rev. B **75**, 045305 (2007)], which verify the importance of electron-electron Coulomb scattering to electron spin relaxation/dephasing.

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In recent years, spin dynamics in semiconductors has attracted considerable attention because of its potential application in the spin-based devices.[1] The operation of these devices requires spin lifetime long enough to achieve storage, transport, and processing of information. Therefore, a comprehensive understanding of spin relaxation mechanisms is a key factor for the realization of these devices. It is generally accepted that the D'yakonov–Perel' (DP) mechanism is the leading spin relaxation/dephasing (R/D) mechanism in n-type zinc-blende semiconductors.[2] This is caused by a wave vector $\mathbf{k}$-dependent effective magnetic field $\mathbf{\Omega}(\mathbf{k})$ from the bulk inversion asymmetry,[3] i.e., the Dresselhaus term, and/or the structure inversion asymmetry,[4] i.e., the Rashba term. The spin relaxation rate can be determined by $\tau^{-1} = \langle \mathbf{\Omega}(\mathbf{k})^2 \rangle \tau_P(\mathbf{k})$, where $\tau_P(\mathbf{k})$ is the momentum relaxation time.[5] As the electron-electron Coulomb scattering does not contribute to the momentum relaxation time τ_p, it has long been widely believed that the electron-electron Coulomb scattering is irrelevant in the spin relaxation.[5–11] However, it was first pointed out by Wu and Ning[12] that in the presence of inhomogeneous broadening, any scattering, which includes the spin conserving electron-electron Coulomb scattering, can cause an irreversible spin relaxation and dephasing. This inhomogeneous broadening can be the energy-dependent g factor,[12] the DP term,[13,14] and even the $\mathbf{k}$-dependent spin diffusion along a spatial gradient.[15] In n-type GaAs quantum well, the importance of the electron-electron scattering to the spin relaxation was proved by Glazov and Ivchenko[16] by using perturbation theory and Weng and Wu[14] by using a fully microscopic many-body approach. In a temperature-dependent experimental study of the spin relaxation in n-type (001) quantum wells, Harley and co-workers[17,18] indirectly verified the effects of the electron-electron scattering on spin relaxation. Nevertheless, the importance of the Coulomb scattering to the spin R/D has not yet been widely accepted. Recently, Bronold *et al.*[19] and Zhou *et al.*[20] predicted that electron-electron scattering could lead to a maximum in the spin R/D time as a function of temperature at the temperature where the transition from the degenerate to the nondegenerate regime occurs. The latter particularly pointed out that this maximum is *solely* from the electron-electron Coulomb scattering in samples with low electron density but high mobility since in such samples the electron-impurity scattering and the electron-ac-phonon scattering could be effectively excluded at low temperature. An experimental observation of such a maximum helps to nail down the importance of the Coulomb scattering to the spin R/D.

In this Brief Report, we report on time-resolved measurements on such kind of high-mobility two-dimensional electron gas (2DEG) with low electron density in the low temperature regime from 1.5 to 30 K. With minimal excitation density, spin-polarized electrons are injected and probed near the Fermi energy. The ensemble spin dephasing time T_2^* is measured via time-resolved pump-probe Kerr rotation (TRKR). We find that the spin R/D time under a magnetic field of 0.5 T indeed exhibits a maximum of 3.12 ns around 14 K and a monotonic increase background from 1.03 ns at 1.5 K to 2.67 ns at 30 K. These features agree with the recent theoretical predictions,[14,19,20] which demonstrate the importance of the electron-electron Coulomb scattering to electron spin R/D in a high-mobility low-density 2DEG.

The 2DEG sample used in our investigation contains a GaAs/AlGaAs heterostructure grown by molecular beam epitaxy on a (001)-oriented semi-insulating substrate. A 1400 nm GaAs buffer layer was first grown on the substrate followed by a 90 nm undoped $Al_{0.35}Ga_{0.65}As$ spacer layer, 14 nm n-doped (3.1×10^{18} cm^{-3}) $Al_{0.35}Ga_{0.65}As$, a 10 nm undoped AlGaAs barrier layer, and finally a 7 nm GaAs cap layer. The 2DEG sample has a mobility of 3.2

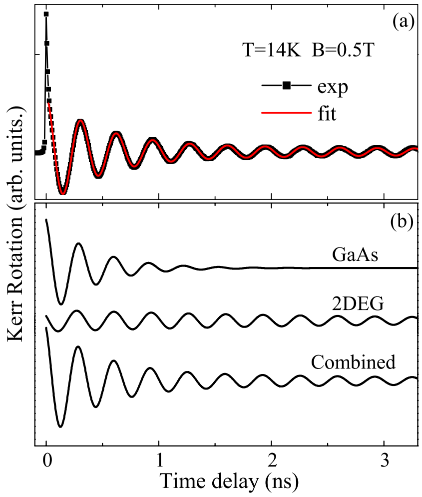

FIG. 1. (Color online) (a) Experimental TRKR trace (curve with squares) at $T=14$ K and $B=0.5$ T. The solid line is the fitting result. (b) Extracted TRKR signals of GaAs (top), 2DEG (middle), and their combined TRKR signal (bottom).

$\times 10^6$ cm^2 V^{-1} s^{-1} and a density of 9.6×10^{10} cm^{-2} at 4.2 K. The TRKR measurements were performed in a magneto-optical cryostat with a superconducting split-coil magnet. The sample was excited near normal incidence with degenerate pump and probe beams from a Ti:sapphire laser (76 MHz repetition rate). The laser pulse has a temporal duration of ~3 ps and a spectral width of ~0.5 meV, which allows for a high energy resolution. The photon energy was slightly tuned above the band gap of GaAs for the maximum Kerr rotation signal. The pump and probe beams were focused to a spot of ~100 μm in diameter, with constant powers of 200 and 20 μW, respectively. The circular polarization of the pump beam was modulated with the photoelastic modulator at 50 kHz for lock-in detection. The circularly polarized pump beam incident normal to the sample surface generated spin-polarized electrons with the spin vector along the growth direction of the sample. The Kerr rotation $\theta(\Delta t)$ of a linearly polarized pulse after a time delay Δt measures the projection of the net spin magnetization as it precesses about a magnetic field applied parallel to the sample surface (in Voigt geometry).

A typical experimental TRKR trace measured at $T=14$ K and $B=0.5$ T is presented in Fig. 1(a). The trace shows strong oscillations whose frequency, i.e., the Larmor precession frequency ω gives the electron g factor by $\omega = g\mu_B B/\hbar$, where μ_B is the Bohr magneton, B is the transverse magnetic field, and $\hbar$ is the reduced Planck's constant. The exponentially decayed envelope reflects the ensemble spin R/D time T_2^*. Quantitative analysis shows that the experimental TRKR trace in Fig. 1(a) contains oscillations with two different frequencies rather than a single frequency. This can be understood as follows. The photon energy of pump and probe beams is only a little higher than the band gap of GaAs. The 2DEG and the GaAs buffer layer are unavoidable to be simultaneously excited. Spin-polarized electrons in the 2DEG and the GaAs buffer layer both contribute to the Kerr rotation signal with distinct precession frequencies. Therefore, the TRKR trace shows two distinct precession frequencies (or g factors). We can extract the Kerr signal arising from the 2DEG or the GaAs buffer layer through their distinct electron g factors. The Kerr rotation signal $\theta_K(\Delta t)$ as a function of time delay Δt can be expressed as a superposition form of exponentially decayed harmonic functions for 2DEG and GaAs,

$$\theta_K(\Delta t) = A_1 \exp\left(-\frac{\Delta t}{T_{21}^*}\right)\cos(\omega_1 \Delta t + \phi_1) + A_2 \exp\left(-\frac{\Delta t}{T_{22}^*}\right)\cos(\omega_2 \Delta t + \phi_2), \tag{1}$$

where A_1 is the initial magnitude of electron spin polarization in 2DEG, T_{21}^* is the spin R/D time in 2DEG, ω_1 is the Larmor precession frequency in 2DEG, and ϕ_1 is a phase offset. A_2, T_{22}^*, ω_2, and ϕ_2 are the corresponding parameters of GaAs.

Fitting the experimental data with Eq. (1) yields the solid curve in Fig. 1(a). It is clearly seen that the fitting curve agrees very well with the experimental data. A decomposition of the KR signal is shown in Fig. 1(b). The decomposition uses the parameters obtained from the fitting results in Fig. 1(a). The TRKR signal of 2DEG indicates an electron spin R/D time of 3.12 ns and an electron g factor of 0.407, while the TRKR signal of GaAs indicates an electron spin R/D time of 0.40 ns and an electron g factor of 0.434. The combined signal of 2DEG and GaAs gives the fitting curve in Fig. 1(a). Note the very fast decay of the TRKR signal within the first few picoseconds. We attribute this to the spin relaxation of the photoexcited holes, which lose their initial spin orientation very fast.[21] Here, we do not consider this fast decay, i.e., hole spin relaxation.

Figure 2(a) shows TRKR traces under a magnetic field of 0.5 T at different temperatures of 4, 14, and 16 K. One can find that the oscillatory envelope decay becomes much slower from 4 to 14 K and a little faster from 14 to 16 K [see the inset of Fig. 2(a)]. These clearly indicate that the spin R/D time exhibits a maximum around 14 K. As the temperature was increased, we tuned the photon energy of the pump and probe beams slightly above the band gap of GaAs for the maximum Kerr rotation signal at a fixed time delay of 12 ps. Figure 2(b) displays the electron g factors in 2DEG and GaAs as a function of temperature from 1.5 to 30 K. One can clearly see that the electron g factor in GaAs at low temperatures is about 0.44, which is a commonly accepted value in GaAs.[22–24] The electron g factor in 2DEG is smaller than that in GaAs. This is because the wave function of electrons in the triangle quantum well penetrates into the potential barrier AlGaAs. Except for the temperature of 1.5 K, the electron g factors in 2DEG and GaAs are clearly resolved. From the distinct g factors in 2DEG and GaAs, we can obtain the corresponding electron R/D time in 2DEG and GaAs. Figure 2(c) shows the temperature dependence of electron R/D time in 2DEG and GaAs from 1.5 to 30 K. A maximum of 3.12 ns is clearly seen around 14 K in the electron spin R/D time of 2DEG as a function of temperature. The maximum is superimposed on an increasing spin R/D time background from 1.03 ns at 1.5 K to 2.67 ns at 30 K. The electron spin R/D time in GaAs at different temperatures is around 0.4 ns with

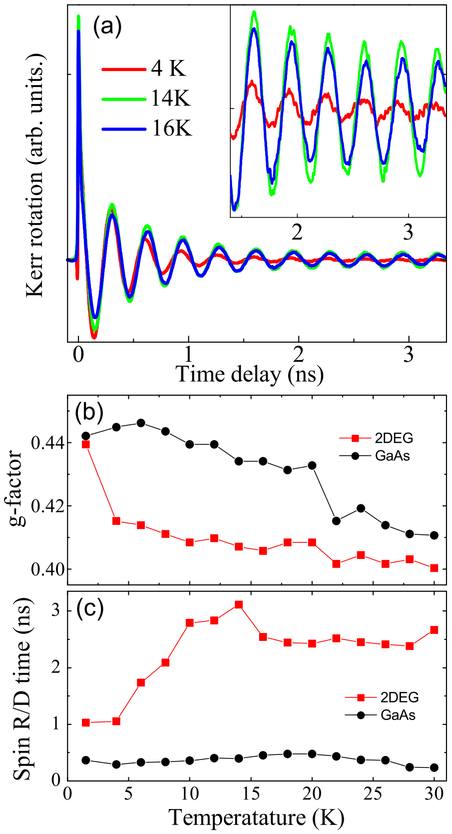

FIG. 2. (Color online) (a) TRKR traces at different temperatures of 4 K (red), 14 K (green), and 16 K (blue). Inset: zoomed picture of the same curve for the time delays between 1.4 and 3.34 ns. (b) Electron g factor as a function of temperature for 2DEG (squares) and GaAs (circles). (c) Electron spin R/D time as a function of temperature for 2DEG (squares) and GaAs (circles). All of the data were taken at $B=0.5$ T and powers of pump:probe=200:20 μW.

moderate fluctuation. Similar temperature dependence of the electron spin R/D time in bulk GaAs has been observed in the previous work at low temperatures.[24]

The 2DEG sample used here is of high mobility, and thus the electron-impurity scattering is weak. In addition, the electron-impurity scattering has a very weak temperature dependence. At very low temperature, the electron-ac-phonon scattering is negligible.[26] Therefore, the appearance of the maximum in the spin R/D time as a function of temperature in Fig. 2(c) originates from the electron-electron Coulomb scattering, which dominates the scattering process at low temperature. It is understood that electron-electron Coulomb scattering has a nonmonotonic dependence on temperature: at low temperature (degenerate limit), the electron-electron scattering time $\tau_{ee} \propto T^{-2}$, while at high temperature (nondegenerate limit), $\tau_{ee} \propto T$.[27,28] The minimum of τ_{ee} appears at the transition temperature where the crossover from the degenerate to the nondegenerate regime occurs. Therefore, the contribution of electron-electron Coulomb scattering to inhomogeneous precession broadening due to the DP mechanism has a minimum at the transition temperature. Consequently, the spin R/D time versus temperature curve exhibits a maximum. This feature agrees with the recent theoretical prediction.[19,20] Note that the Fermi temperature (T_F) of the 2DEG estimated from the electron density is about 40 K, while the transition temperature is around 14 K. This deviation can be attributed to that the Fermi–Dirac distribution function is strongly affected by the electron-electron scattering in the intermediate temperature regime $T \sim 0.5T_F$.[29,30] Thus, the transition temperature between the degenerate and the nondegenerate regimes in the 2DEG investigated here is close to $0.5T_F$.

We now turn to discuss the increasing spin R/D time background with rising temperature. For a low initial spin polarization, a large increase in the spin R/D time with rising temperature was already observed by Brand *et al.*[17] and Stich *et al.*[31] This behavior was discussed from the kinetic spin Bloch approach by Weng and Wu[14] in the high temperature regime and by Zhou *et al.*[20] in the low temperature regime. With both experiment and calculation, Stich *et al.*[31] showed that the spin R/D time increases with rising temperature for low initial spin polarization in low temperature regime, except that the spin R/D time peak was not observed in their case. By using the method in Ref. 25 and by taking into account the absorption ratio between 2DEG and GaAs in this measurement, we estimate an initial spin polarization degree of about 0.8%. For such low initial spin polarization, the inhomogeneous broadening determined by momentum scattering in DP mechanism plays a dominant role.[31] An increasing temperature led to stronger momentum scattering, in other words, a shorter momentum scattering time τ_P. This, in turn, induced an increasing spin R/D time via DP mechanism. Consequently, there is an increasing spin R/D time background with rising temperature.

In conclusion, we have performed time-resolved Kerr rotation measurements on a high-mobility low-density two-dimensional electron gas at low temperatures. We observe that as temperature is increased, the spin R/D time exhibits a peak of 3.12 ns around 14 K, superimposed on an increasing background from 1.03 ns at 1.5 K to 2.67 ns at 30 K. The appearance of the peak is ascribed to the electron-electron Coulomb scattering. As temperature approaches the point where the crossover from the degenerate to the nondegenerate regime occurs, the electron-electron scattering becomes strongest. This results in a peak in spin R/D time versus temperature curve due to the DP mechanism. Our results nail down the importance of the Coulomb scattering to the spin R/D due to the DP mechanism.

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