Electron density dependence of in-plane spin relaxation anisotropy in GaAs/AlGaAs two-dimensional electron gas

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The authors investigated the spin dynamics of two-dimensional electrons in (001) GaAs/AlGaAs heterostructure using the time-resolved Kerr rotation technique under a transverse magnetic field. The in-plane spin lifetime is found to be anisotropic below 150 K due to the interference of Rashba [J. Phys. C **17**, 6039 (1984)] and Dresselhaus [Phys. Rev. **100**, 580 (1955)] spin-orbit coupling and D'yakonov-Perel [Sov. Phys. Solid State **13**, 3023 (1972)] spin relaxation. The ratio of in-plane spin lifetimes is measured directly as a function of temperature and pump power, showing that the electron density in two-dimensional electron gas channel strongly affects the Rashba spin-orbit coupling. © *2007 American Institute of Physics*.
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The ability to manipulate the orientation and the relaxation of spin population in semiconductor two-dimensional (2D) structures via electrical or optical control is a key step toward building practical spintronics devices.[1] In the prototype device of spin field effect transistor (FET), proposed by Datta and Das,[2] the Rashba spin-orbit (SO) coupling[3] plays a central role in the controlled rotation of spin via external electric field in a two-dimensional electron gas (2DEG) system. In general, the SO coupling includes both Rashba and Dresselhaus[4] contributions in a realistic zinc-blende semiconductor 2D structure, and has the undesired effect of causing spin decoherence in 2DEG at room temperature. The underlying mechanism is the D'yakonov-Perel (DP) spin relaxation,[5,6] where electron spins randomly precess about an effective magnetic field resulted from the SO coupling and thus dependent on the electron's momentum.

Recently, methods for controlling the spin relaxation have been proposed for a robust spin FET (Ref. 7) and persistent spin helix[8] (PSH) in 2D structures. The basic idea is to tune the Rashba and the Dresselhaus terms via proper gating or structure engineering, so that they have equal strength in (001) 2D structures or have only the Dresselhaus term in rectangular (110) quantum wells (QWs).[9] The ability to determine the relative strength of the Rashba and Dresselhaus terms is, therefore, critical to the design of the spin FET and PSH devices. The ratio of Rashba and Dresselhaus terms at a fixed temperature has been measured previously by several groups.[10–12] The strengths of both Rashba and Dresselhaus SO coupling also have been investigated by applying a bias at extreme temperature of approximately millikelvin.[13,14] Theoretically speaking, both Rashba and Dresselhaus terms produce the in-plane effective magnetic field, and the interference of these two terms results in an anisotropic effective magnetic field, and hence an in-plane spin relaxation anisotropy due to DP mechanism.[15,16] Thus the anisotropy of in-plane spin lifetimes offers a direct measurement of the relative SO coupling strength. In addition, the nonequilibrium electrons are generated in a 2DEG system via spin injection during the operation of realistic spin FET and PSH devices, and the change of electron density in a 2DEG system can result in a change of relative SO coupling strength. In this letter, we use time-resolved Kerr rotation (TRKR) technique to study the anisotropic in-plane spin lifetime. We address how the electron density affects the relative strength of the Rashba and Dresselhaus terms via an elevated temperature and/or pump power. We show that the electron density in 2DEG channel will strongly affect the Rashba SO coupling.

The sample studied here consists of GaAs/AlGaAs heterostructure grown on a (001)-oriented semi-insulating GaAs substrate by molecular beam epitaxy. A 500 nm GaAs buffer layer first was grown on the substrate followed by a 14 nm $Al_{0.24}Ga_{0.76}As$ spacer layer, 25 nm $Al_{0.24}Ga_{0.76}As$ Si-doped 4×10^{18} cm^3, and finally a 1 nm GaAs Si-doping cap layer. The standard Hall measurement gives the electron concentration $n=6.0\times 10^{11}$ cm^{-2} at room temperature, and $n=4.5\times 10^{11}$ cm^{-2} at 150 K. We also prepared a GaAs bulk sample from the same substrate wafer. Two cleaved edges oriented along $[110]$ and $[1\bar{1}0]$ axes were prepared for all samples. The TRKR experiment was carried out in an Oxford magneto-optical cryostat supplied with a 7 T split-coil superconducting magnet. The sample was excited near normal incidence with degenerate pump and delayed probe pulses from a Coherent mode-locked Ti:sapphire laser (~120 fs, 76 MHz). The center of the photon energy was tuned for the maximum Kerr rotation signal for each sample and temperature setting. The laser beams were focused to a spot size of ~100 μm, and the pump and probe beams have average power of 5.0 and 0.5 mW, respectively. The helicity of linearly polarized pump beam was modulated at 50 kHz by a photoelastic modulator for lock-in detection. The circularly polarized pump pulse incident normal to the sample creates spin-polarized electrons with the spin vector along the growth direction of samples. The temporal evolution of the electron spins was recorded by measuring Kerr rotation angle $\theta_K(\Delta t)$ of the linearly polarized probe pulse while sweeping

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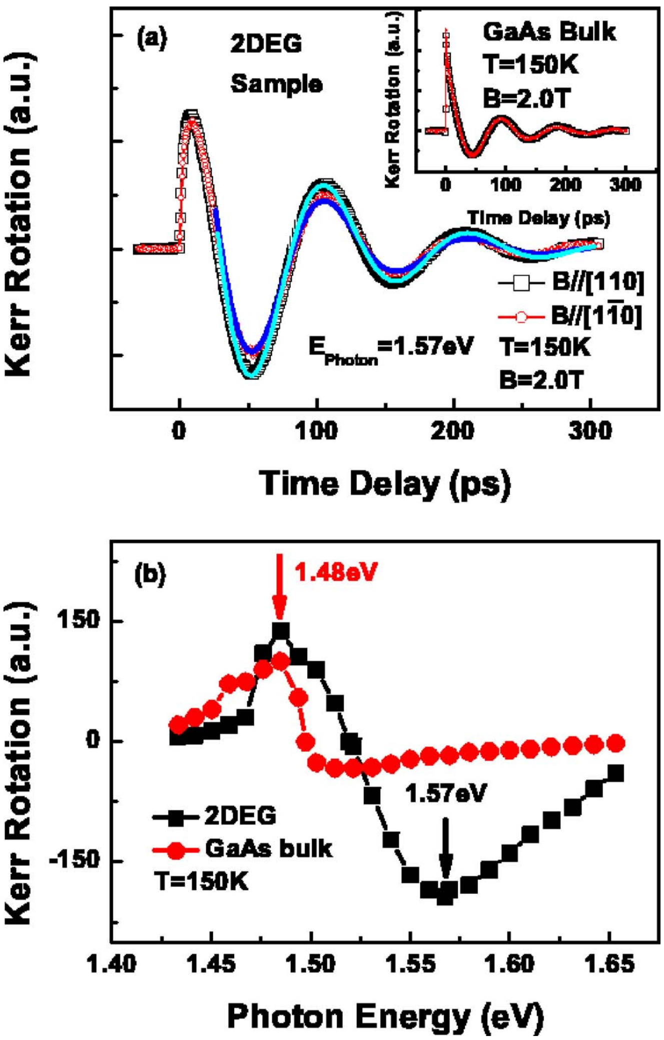

FIG. 1. (Color online) (a) TRKR angle $\theta_K(\Delta t)$ for 2DEG sample measured at a magnetic field of $B=2.0$ T and $T=150$ K. (b) The spectrum-dependent TRKR angle at $\Delta t=30$ ps for both 2DEG and GaAs bulk samples. The black (red) arrow indicates the excitation laser energy for TRKR measurement of 2DEG (GaAs bulk) sample. The inset shows the TRKR signal for GaAs bulk sample at $B=2.0$ T and $T=150$ K.

Δt, which correspond to the net spin component normal to the sample plane.

Figure 1(a) shows $\theta_K(\Delta t)$ measured at 150 K for a 2DEG sample with an in-plane magnetic field of $B=2.0$ T applied along axes [110] and [1$\bar{1}$0], respectively. The data show strong oscillations corresponding to the spin precession with an exponential decay envelope. We found that the amplitude of oscillation signal of the 2DEG sample with the magnetic field direction along [110] was larger than that with magnetic field direction along [1$\bar{1}$0]. The measured signal of the 2DEG sample may include the contribution of GaAs substrate because the photon energy of laser is above the band gap of GaAs bulk. To verify the possible contribution from the GaAs substrate, we measure the spectrum-dependent Kerr rotation signals at 30 ps time delay for both 2DEGs and GaAs bulk samples at the same excitation power with zero magnetic field. As shown in Fig. 1(b), the signal of the 2DEG sample reaches the maximum at 1.57 eV photon energy, which is far from the band gap of GaAs at 150 K. It is more than ten times greater than that of pure GaAs bulk sample at this excitation energy. At the photon energy of 1.48 eV, the signal of both 2DEG and GaAs bulk is almost identical. This energy corresponds to the band gap of GaAs bulk at 150 K. Thus by setting the excitation beam at 1.57 eV for our TRKR measurements of the 2DEG sample as shown in Fig. 1(a), the effect of GaAs substrate can be safely neglected. Furthermore, we check the TRKR signal at the different sample locations with magnetic field along a fixed direction, for instance, [110] axis. The oscillation signals at all detection positions are essentially the same (data not shown here), hence we can exclude possible effect due to sample inhomogeneity in the data reported here. Thus, the data of Fig. 1(a) indicate that the in-plane spin lifetimes are different between spins oriented along [110] and [1$\bar{1}$0].

The spin component normal ($S_\perp$) to the 2DEG plane can be expressed by[17,18]

$$S_\perp(\Delta t) = S_0 e^{-(1/\tau_\perp + 1/\tau_\parallel)\Delta t/2} \cos(g\mu_B B\Delta t/\hbar), \quad (1)$$

where S_0 is a constant, $\tau_\parallel(\tau_\perp)$ is the in-plane (out-of-plane) spin lifetime, g is the electron g factor, μ_B is the Bohr magnetron, and $\hbar$ is reduced Planck's constant. The out-of-plane spin lifetime $\tau_\perp$ can be obtained by fitting the experimental data at $B=0$ T with a single exponential decay, which is around $\sim$110 ps at $T=150$ K. Using this value, and $|g|$ and $\tau_\parallel$ as fitting parameters, we obtain good fits of Eq. (1) to the data in Fig. 1(a) shown in cyan and blue lines, respectively. While $|g|=0.36$ for both spectra taken with magnetic fields along [110] and [1$\bar{1}$0] axes, the in-plane spin lifetimes are about 30% different; however, for spins oriented along [110] and [1$\bar{1}$0]: $\tau_{\parallel[110]}=50$ ps and $\tau_{\parallel[1\bar{1}0]}=65$ ps. Here, we did not observe the anisotropy of the in-plane electron g factor as reported by Oesreich *et al.*[19] because Rashba term is predominant in (001) 2DEG heterostructure.[13] As a control experiment, we measured the in-plane spin lifetimes in pure GaAs bulk with magnetic field of $B=2.0$ T along [110] and [1$\bar{1}$0], respectively, as shown in the inset of Fig. 1(a). There is no change of signal amplitudes, and the same in-plane spin lifetimes of $\tau_\parallel=80$ ps are obtained for both applied magnetic field directions. In bulk GaAs, the spin splitting originates from the Dresselhaus term, which results in an isotropic effective magnetic field. As a consequence, the spin relaxation time in GaAs bulk is isotropic. Thus, the difference in the in-plane spin lifetimes is related to anisotropic in-plane relaxation in the 2DEG structure.

The above observed anisotropy of the in-plane spin relaxation can be attributed to the interference of Rashba and Dresselhaus SO coupling in the 2DEG heterostructure.[15,16] It should be enhanced when the strength of both SO coupling is equal, or reduced when one of the SO coupling terms dominates in a 2DEG system. Thus we can use the change of the anisotropy, i.e., the ratio of $\tau_{\parallel[110]}$ and $\tau_{\parallel[110]}$, to monitor the relative change of SO coupling strength. To test this interpretation, we tune the relative strength of SO coupling by manipulating the electron density via pump power and/or temperature without a gate bias. The advantage of a pure optical control is that the relationship between the SO coupling and the electron density can be obtained without a change of the band structure due to an external electrical field. Figure 2 shows the power dependence of anisotropy with a fixed probe power (0.5 mW) under a magnetic field of $B=2.0$ T and $T=150$ K. It is evident that the ratio decreases from 1.3 to 1.0 when the pump power is above 5 mW. This means

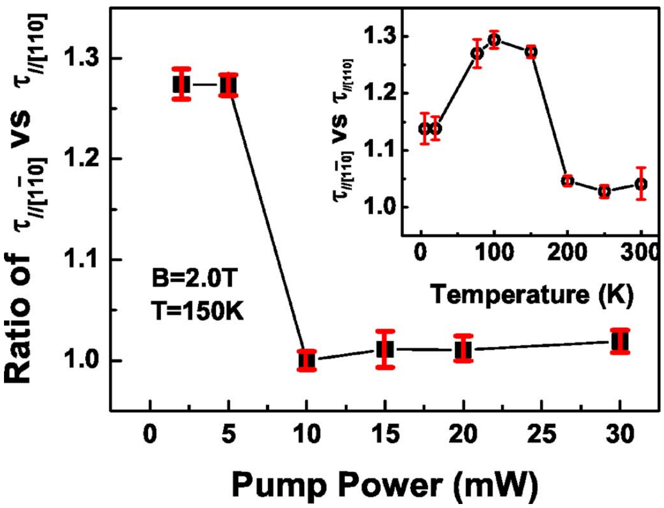

FIG. 2. (Color online) Ratio of in-plane spin lifetimes measured at $B = 2.0$ T and $T = 150$ K vs pump power. Inset: the ratio of in-plane spin lifetimes measured at $B = 2.0$ T as a function of temperature.

that one of the SO coupling overwhelms the other. At high pump power, only the electron density is changed in 2DEG, which can affect both the Rashba and Dresselhaus SO coupling.[13,14] The change of anisotropy in our experiment, however, indicates a different degree of their response to the increasing electron density. Since the Rashba effect is the main source of spin splitting in (001) 2DEG heterostructure,[13] the trend suggests that the higher electron density mainly enhance the strength of Rashba term. We believe that the higher electron density will increase the electric field of confinement potential and hence the strength of Rashba SO coupling is increased as well.

Alternatively, the electron density can be raised at elevated sample temperature in a 2DEG system, and the DP spin relaxation mechanism dominates in the high temperature regime. The inset of Fig. 2 presents the temperature-dependent anisotropy at a fixed pump power of ~5 mW. Initially, the ratio increases from 1.15 to 1.3 with temperature up to 150 K. When the temperature is above 200 K, this ratio drops to 1.0. The electron density at room temperature is larger than that at low temperature in our 2DEG system. This observation further supports that the higher electron density mainly increases the strength of Rashba term. Below 77 K, the ratio is smaller than that in the high temperature regime (77–150 K). This means that other spin relaxation mechanisms such as Elliot and Yafet[20] and Bir, Aronov, and Pikus[21] will compete with DP mechanism. Between 77 and 150 K, the DP mechanism dominates. It is consistent with the results obtained in (110) QWs.[17]

In conclusion, we observed an anisotropy of the in-plane spin lifetimes in the (001)-oriented GaAs/AlGaAs 2DEG heterostructure, which exhibits strong electron density dependence. In particular, the Rashba term dominates the Dresselhaus term at higher electron density in the 2DEG sample. These findings could be exploited in future design of spin-related electronic devices.

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