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Gate Control of Spatial Electron Spin Distribution in Persistent Spin Helix State

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Abstract

We demonstrated external electric field control of the persistent spin helix state in GaAs quantum wells, in which balanced Rashba and Dresselhaus spin-orbit interactions suppress the D'yakonov-Perel' spin relaxation effectively. Two-dimensional images of diffusing electron spins revealed that the spatial distribution of the spin helix is modulated by a gate bias voltage via electrical modulation of the Rashba spin-orbit interaction. Our results will advance both further research and the application of the persistent spin helix state in semiconductors.

1. Introduction

The spin-orbit interaction (SOI) in semiconductors is expected to play an important role in controlling electron spin because it induces an effective magnetic field that strongly influences spin properties. The gate control of an electron spin using Rashba SOI has been demonstrated in a semiconductor interferometer [1,2]. However, the SOI also causes undesirable spin relaxation via the D'yakonov-Perel' (DP) mechanism [3].

Recently, a lot of attention has focused on the suppression of spin relaxation in two-dimensional electron systems with balanced Rashba and Dresselhaus SOIs [4]. The characteristic spin dynamics in such an electron system result in a helical spin mode termed a persistent spin helix (PSH), which has been observed directly with the spin grating technique [5] and Kerr rotation microscopy [6]. In these studies PSH conditions have been achieved by precisely designing the heterostructures. However, to take advantage of both the gate controllability of an SOI and the long lifetime of the PSH state, the gate-controlled spatial spin distribution near the PSH condition is of great interest.

In this study, we observed the spatial distribution of electron spins in a GaAs quantum well (QW) with a top gate electrode by time- and spatially-resolved Kerr rotation microscopy. The spatial frequency of electron spin precessions in the PSH mode are modulated by the electrical modulation of a Rashba SOI, which agrees well with the results of theoretical calculation.

2. Experiment

A $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructures containing two-dimensional electrons (2DEG) are designed to allow observation of the PSH state. 2DEGs are formed in GaAs QW layer at 120 nm below the surface. To tune SOIs, width of QWs is varied from 15 nm to 25 nm. A semi-transparent Au Schottky gate was deposited on the surface of the square chip without touching the InSn ohmic contact formed in one corner. A bias voltage applied between these two electrodes enabled us to tune the SOIs [1].

The carrier density dependences of the SOI parameters calculated by the $\boldsymbol{k}\cdot\boldsymbol{p}$ formalism [7] are shown in Fig. 1. Both the Rashba and Dresselhaus SOIs depend on the carrier density, which can be tuned by controlling the gate voltage; whereas only the Dresselhaus SOI depends critically on the well width. Because the Dresselhaus SOI of a wider QW comes closer to the Rashba SOI, the calculation suggests that the 25 nm-wide QW is the most appropriate for balancing the Rashba and Dresselhaus contributions in our sample.

The spin dynamics during diffusion were measured using time- and spatially-resolved Kerr rotation microscopy with a mode-locked Ti:sapphire laser (1.5 ps, 82 MHz, 810-820 nm) at T = 8 K. A circularly polarized pump light generated spin polarized electrons at a fixed position on the

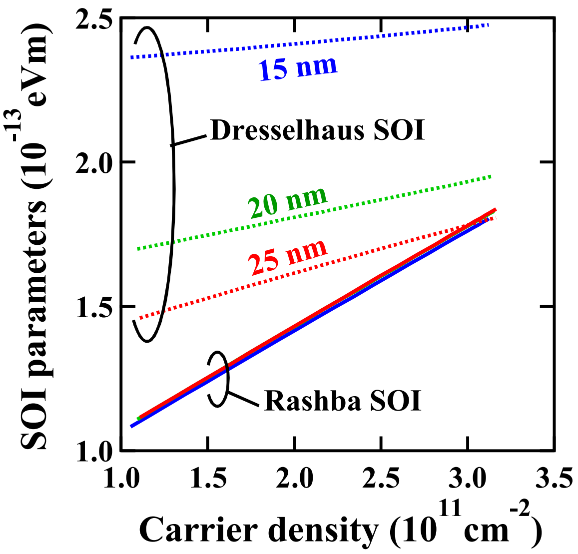

Fig. 1 Carrier density dependence of Rashba (solid lines) and Dresselhaus (dashed lines) SOIs. Blue, green, and red lines indicate 15, 20, and 25 nm-wide GaAs QWs, respectively.

sample; and a linearly polarized probe light, which can be scanned in the QW plane, was used to detect the magneto-optic Kerr effect. The full width at half maximum spot size of the normally incident probe beam was approximately 3 μm, whereas the waist size of the obliquely incident pump beam was 6 μm. Since the Kerr rotation angle is proportional to the spin density at the probe position, we can obtain two-dimensional images of the spin distribution.

3. Result and discussion

We first measured the time evolutions of Kerr rotation signals under different bias conditions for each QW sample. Figure 2 shows the data under specific bias voltages, where the decay times take their maximum for each QW width. We fit the data with a simple exponential function $\theta_K(t) = \exp(t/\tau_S)$ and obtain spin relaxation times τ_S of 1.10, 1.30, and 1.96 ns for 15, 20, and 25 nm-wide QWs, respectively. These data indicate that the 25-nm-wide QW is the most likely to meet the PSH condition as expected from the calculation shown in Fig. 1.

Figure 3 shows the spatial profiles of diffusing electron spins in the 25-nm-wide QW. For all gate voltages, oscillations caused by spin precessions were observed for the electrons moving in the [110] direction, whereas no spin precession was observed along [1-10]. This anisotropic behavior of the spin precession provides clear evidence of the PSH and indicates that the spin-orbit magnetic fields exist in the [110] direction in this sample. The precession frequency observed for the [110] direction decreases as we increase the gate voltage from V_g = -2.1 to -2.4 V. We consider that this is caused mainly by the modulation of the Rashba SOI, which depends on a gate voltage stronger than the Dresselhaus SOI (Fig. 1).

4. Conclusions

We investigated the spatial distribution of optically generated electron spins in gated GaAs/AlGaAs heterostructures with time- and spatially-resolved Kerr microscopy. A maximum spin relaxation time of τ_S = 1.96 ns was observed in the 25-nm-wide QW by applying V_g = -2.7 V. The spin precession caused by the diffusive motion in a 25-nm-wide QW exhibited anisotropic behavior, which indicates the PSH mode. We achieved the gate modulation of the spin precession frequency near the PSH condition. Our experimental results will advance both further research and the application of the PSH state in semiconductors.

Acknowledgements

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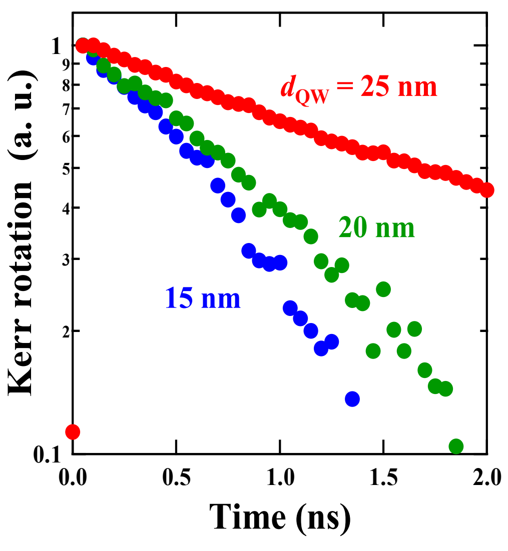

Fig.2 Time-resolved Kerr rotation signal in several QWs. Gate voltages were set for the longest spin relaxation time: V_g = -2.5 V, -2.6 V, and -2.7 V for 15, 20, and 25 nm-wide QWs.

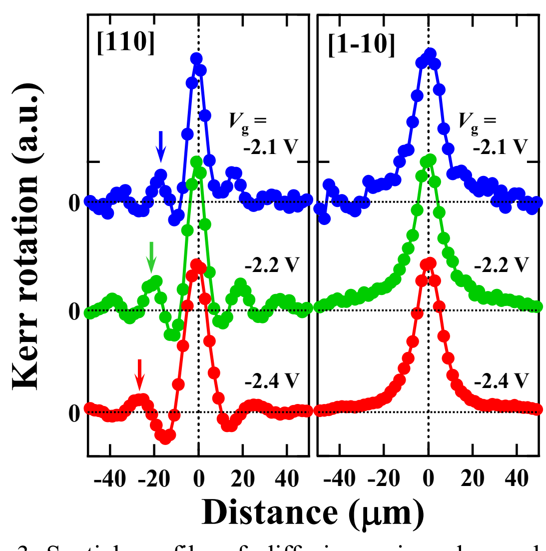

Fig.3 Spatial profile of diffusing spins observed in 25-nm wide QW along [110] and [1-10] directions for several gate voltages. Kerr rotation signals are normalized by that at the point of origin.