Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp948-949

Anisotropic spin dynamics of drifting electrons with coexistence of Rashba and Dresselhaus spin-orbit interactions

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Abstract

We investigated the spin dynamics of drifting electrons in high mobility two-dimensional electron gases using time- and spatially-resolved Kerr microscopy. During drift transport, electron spins precess around an effective magnetic field, which is induced by spin-orbit interactions (SOI). The precession frequency and spin decay length depend on the crystallographic direction of the drift motion, which reflects the anisotropic effective magnetic field due to the coexistence of Rashba and Dresselhaus SOIs. These characteristic spin dynamics are well reproduced by numerical simulation with experimentally extracted SOI parameters. Our results will provide a flexible technique for realizing spin transport and its manipulation.

1. Introduction

The electrical manipulation of spin-polarized carriers in solid-state systems is the key to realizing spin-based electronic devices [1-2]. By analogy with conventional semiconductor devices, electric fields are expected to play important roles in both transferring and manipulating spin information. Macroscopic spin transport under lateral electric fields in bulk GaAs measured with a magneto-optical imaging technique has already been reported [3]. However, the low electron mobility in a bulk system limits the transport velocity. In addition, the electrical control of spins by using SOIs resulting from structural inversion asymmetry, i.e. Rashba SOI, is difficult to achieve in bulk systems.

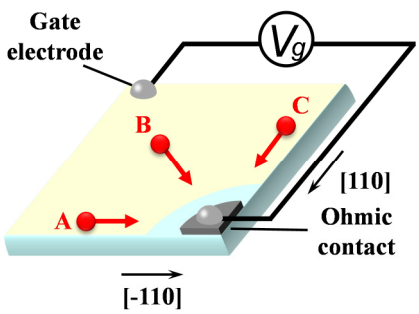

Fig.1 Schematic image of the measured samples. A, B and C indicate the positions of optical spin injection by circularly polarized pump light. Because of the finite in-plane electric field, optically-generated electron spins drift toward ohmic contact as indicated by red arrows.

In this study, we investigated the spin dynamics of drifting electrons in high mobility two-dimensional electron gas (2DEG) systems, where spins can be electrically manipulated by gate tuning the Rashba SOI [4]. We observed that the spins are transported over 200 μm. Their spin dynamics showed that the spatial precession frequency and decay length depend strongly on the moving directions. By using numerical simulations based on the Monte Carlo method, we found that the anisotropic dynamics of drifting spins results from the coexistence of the Rashba and Dresselhaus SOIs.

2. Experiment

The sample was a GaAs/AlGaAs-based high-electron-mobility transistor, which contained 2DEG in a 25-nm-wide GaAs quantum well. 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 (Fig. 1). A bias voltage applied between these two electrodes enabled us to tune the SOIs.

The spin dynamics during drift motion were measured using time- and spatially-resolved Kerr rotation microscopy with a CW Ti:sapphire laser (λ = 810-820 nm) at T = 8 K. A

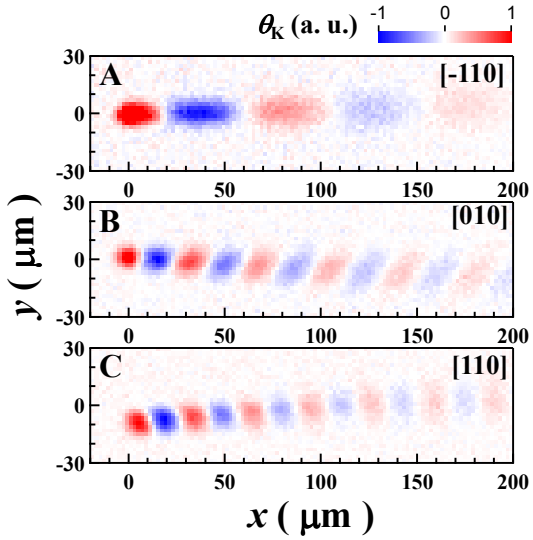

Fig. 2 Spatial imaging of drifting spins in [-110], [010], and [110] directions (A, B, and C). Red and blue signals correspond to up and down spins.

circularly polarized pump light generated spin polarized electrons at a fixed position on the 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 a normally incident probe beam was approximately 3 μm, whereas the waist size of an obliquely incident pump beam was 6 μm. Since the Kerr rotation angle θ_K is proportional to the spin density at the probe position, we can obtain two-dimensional images of the spin distribution.

3. Results and discussion

Figure 2 shows the spatial mapping of drifting spins injected by a pump light into a 25-nm-wide quantum well. The gate voltage was fixed at -4.0 V. By changing the pump position, the spin flowed toward the ohmic contact due to the in-plane electric field (Fig. 1). In contrast to the bulk samples [3], the directionality of the spin flows was improved and a long spin transport of over 200 μm was observed. The spatial frequency of the spin precession depends significantly on the crystal orientation of the spin flow, which reflects the fact that both Rashba and Dresselhaus SOIs exist and are of comparable strength.

To discuss the effects of the coexistence of the Rashba and Dresselhaus SOIs quantitatively, we analyzed the oscillation periods and the decays of θ_K for the different transport directions. We fitted the cross-sectional data along the drift direction with a function,

$$\theta_K = A\exp\left(-\frac{x}{l_S}\right)\cos\left(\frac{2\pi x}{L_{SO}}\right),$$

where l_S is the spin decay length and L_{SO} is the spin precession length, in which the electron spins rotate a full cycle. We obtained L_{SO} values for the [-110], [010], and [110] directions of 86.0, 35.8, and 30.5 μm, respectively. By using L_{SO} and neglecting the cubic term of the Dresselhaus SOI, the Rashba and Dresselhaus SOI parameters, α and β, can be estimated to be 0.384 and 0.805 meVÅ, respectively. These SOIs create effective magnetic fields as indicated in Fig. 3. From Figs. 2 and 3, it is clear that electron spins propagating in the [110] direction experience strong effective magnetic fields, resulting in a faster spin precession than spins moving in [-110] direction.

We found that the anisotropy of the spin dynamics also appears in l_S, and was 42.2, 68.4, and 67.5 μm for [-110], [010], and [110], respectively. The dependence of l_S on the drift direction is well reproduced by a semi-classical Monte Carlo simulation (Fig. 4), in which we used the α and β values estimated above. A further simulation with different values for the SOI parameters (not shown here) revealed that the ratio α/β determines the anisotropy of the spin precession and the decay length for the drifting electrons.

4. Conclusions

We investigated the spatial distribution of drifting spins in GaAs/AlGaAs heterostructures with time- and spatially-resolved Kerr microscopy. The spin precession period and spin decay length depend significantly on the spin propagation direction. The experimental results are well reproduced by numerical simulation, which indicates that the spin dynamics during drift transport is determined by the anisotropic effective magnetic field induced by the coexistence of the Rashba and Dresselhaus SOIs. Our experimental results will advance both further research and the application of spins to semiconductor devices.

Acknowledgements

This work was supported by JSPS KAKENHI (No. 24686004 and 23310097).

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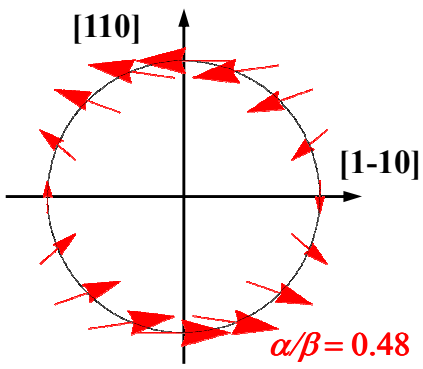

Fig. 3 Effective magnetic fields in k-space where α = 0.384, and β = 0.805 meVÅ.

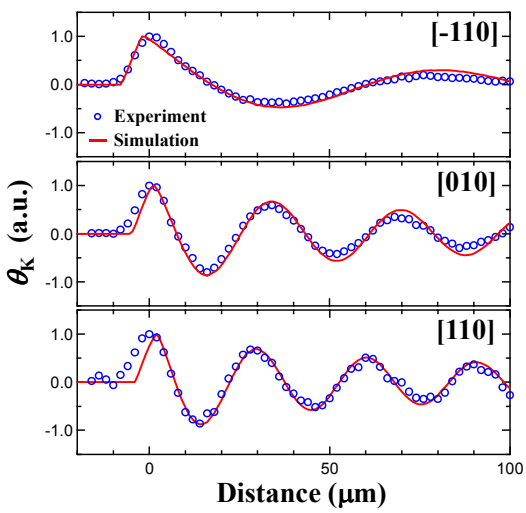

Fig. 4 Cross-sectional patterns of spatial imaging of drifting spins for [-110], [010] and [110] directions. Open circles and solid lines indicate experimental data and numerically simulated results.