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Estimation of spin-orbit interaction parameters with drifting spins in semiconductor quantum wells

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Abstract

We investigated theoretically the spin dynamics of drifting electrons in high mobility two-dimensional electron gases with a semiclassical Monte Carlo approach. Our theoretical procedure enabled us to estimate the strengths of Rashba, linear Dresselhaus and cubic Dresselhaus spin-orbit interactions (SOI) from the crystal orientation dependence of precession frequency of drifting spins without applying any external magnetic field. When applying high in-plane electric fields, we obtained the quasi-one dimensional transports of electron spins whose spin precession frequency accurately reflected the spin splitting energy induced by SOIs. This theoretical method can be applied to experimental results of drifting spins. Our results will provide a useful tool for the accurate detection of SOI parameters.

1. Introduction

Spin-orbit interaction (SOI) plays an important role as regards spin manipulation in solid-state devices. Specially, the Rashba SOI, which is induced by structural inversion symmetry, generates effective electrically-controllable magnetic fields [1]. For accurate spin precession control, it is necessary to determine the strength of SOIs in materials. In addition to the Rashba SOI, there is the Dresselhaus SOI induced by bulk inversion asymmetry. The Dresselhaus SOI has two contributions, namely, the linear and cubic terms in the electron momentum. The complicated structure of SOIs makes the accurate estimation of SOI parameters very difficult.

Previously, SOI parameters are estimated from results of magnetoconductance measurements under weak antilocalization conditions [2]. However, estimated parameters usually contain certain ambiguities since the data must be fitted with several unknown parameters. Another way of estimating SOIs is with an optical method based on time-resolved Kerr microscopy [3]. This method is very useful to directly detect effective magnetic fields which are crucial for estimating SOI parameters. However, SOI parameters cannot be determined only from experimental results because the method needs theoretically assumed parameter, e. g. a wave vector confined in a quantum well $<k_z^2>$ to distinguish three SOI terms. Moreover, these two techniques require a cumbersome experimental setup with external magnetic fields. Therefore, a direct and simple method to determine SOI parameters is required.

In this study, we propose a way of estimating strength of SOI parameters in a system with Rashba and Dresselhaus SOIs from the anisotropic precession of drifting spins. The advantages of the proposed method are that it is not necessary to apply an external magnetic field and employ a theoretical model with ambiguous values unlike previous methods. We first performed a semiclassical Monte Carlo (MC) simulation of the spin dynamics in a two-dimensional system with an in-plane electric field. The spin dynamics was simplified to one dimension when we applied a high in-plane electric field. By comparing the MC simulation and the analytical solution of the spin splitting energy, we found that drifting spins precess around an effective magnetic field with corresponding the spin splitting energy in the drifting direction. Thus, it is possible to estimate the SOI parameters from the spatial precession frequency of the drifting spins.

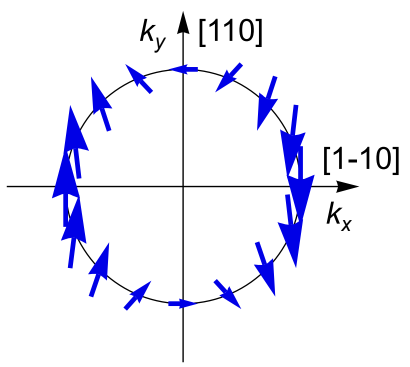

Fig. 1 Effective magnetic fields in k-space where $\alpha = 0.5$, and $\beta_1 = 1.0$, $\beta_3 = 0.14$ meVÅ.

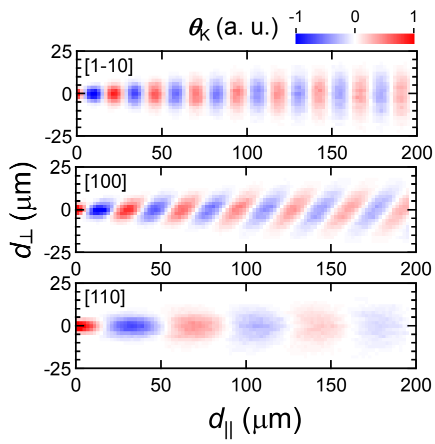

Fig. 2 Simulated spatial imaging of drifting spins in [1-10], [100], and [110] directions. Red and blue signals correspond to up and down spins.

2. Analytical expression of spin splitting energy

We selected a GaAs quantum well as a calculation model. Spin splitting due to the Rashba and Dresselhaus SOIs in a GaAs quantum well (QW) grown in the crystallographic direction [001] are characterized by the Hamiltonians,

$$H_R = \alpha(\sigma_x k_y - \sigma_y k_x),$$
$$H_D = \gamma \langle k_z^2 \rangle (\sigma_y k_y - \sigma_x k_x) + \gamma(\sigma_x k_x k_y^2 - \sigma_y k_y k_x^2),$$

where σ_x and σ_y are Pauli spin matrices and α is a Rashba parameter that depends on the constituting materials on the geometry of a quasi 2D system whereas γ is a material constant. The interplay between the Rashba and Dresselhaus SOIs meant that we obtained the anisotropic spin splitting energy,

$$\Delta E_{SO} = 2k[\alpha^2 + \beta_1^2 - \alpha(2\beta_1 - \beta_3)\sin(2\theta) - \beta_3(\beta_1 - \beta_3/4)\sin^2(2\theta)]^{1/2}, \quad (1)$$

where $\beta_1 = \gamma\langle k_z^2 \rangle$ and $\beta_3 = \gamma k^2$ are linear and cubic Dresselhaus parameters, respectively. θ is defined as an angle from the [100] direction. When we consider a fully one-dimensional model of drifting spins with a drift wave number $k_d = m^* v_d / \hbar$, the wave number k_{SO} of the spin precession is given by the following equation,

$$k_{SO} = \Delta E_{SO} m^* / \hbar^2 k_d, \quad (2)$$

where k in Eq.(1) and β_3 are substituted by k_d. Once we obtain the θ dependence of k_{SO}, we can determine the SOI parameters, α, β_1, and β_3 from Eqs. (1) and (2).

3. Monte Carlo simulation

We performed an MC simulation to validate of the SOI estimation procedure. To simplify the model, we assumed that all electrons have the same Fermi velocity and elastic scattering time. Applied in-plane electric fields drift electron spins with the drift wave number k_d. Electron spins of 10^3 are initially polarized in the z direction, and experience isotropic impurity scattering in every elastic scattering event. The SOI parameters used in the simulation were $\alpha = 0.5$, $\beta_1 = 1.0$ meVÅ, and $\gamma = 9$ eVÅ^3. Assuming electron mobility $\mu = 7$ m^2/Vs and applied in-plane electric field $E = 100$ V/cm, the wave number due to drift motion k_d becomes 4.01 x 10^7 m^{-1}, resulting in $\beta_3 = 0.14$ meVÅ. Figure 1 shows the effective magnetic fields in k-space with the SOI parameters assumed above.

Figure 2 shows the spatial distribution of drifting spins under in-plane electric fields of E = 100 V/cm along the [1-10], [100], and [110] directions. We observed the dependence of the spatial spin precession frequency on the drift directions, which reflects the anisotropic effective magnetic fields resulting from the interplay between Rashba and Dresselhaus SOIs. To extract k_{SO} from the simulated results, we performed a Fast-Fourier transform of the cross-sectional profile of the spin distribution parallel to the drift direction. The crystal orientation dependence of k_{SO} for each applied in-plane electric field is shown in Fig. 3. We found that k_{SO} values simulated by the MC method well agree with the theoretical results expressed by Eq. (2). We also observed the bias dependence of k_{SO}, which was due to the bias dependence of the cubic Dresselhaus parameters β_3. According to Fig. 3, we can determine the SOI parameters (α, β_1, and β_3) without ambiguities. Moreover, this result clearly reveals that SOI parameters will be determined from the experimentally observed k_{SO} of drifting spin. At the conference, we will discuss the estimation of the SOI parameters of GaAs quantum wells from an actual experiment.

4. Conclusions

We have presented a direct and simple method to estimate SOI parameters with theoretical analysis. This method analyzed crystal orientation dependence of spin precession frequency of drifting spins using a semilassical Monte Carlo approach. When we take the cubic Dresselhaus term into account in the simulation, the spin precession frequency exhibits bias dependence. By comparing the simulation and analytical solutions, we showed that the spin precession frequency is well described by the crystal orientation dependence of the spin splitting energy. Our results indicate that the SOI parameters in a system with Rashba and Dresselhaus SOIs can be estimated from the anisotropic spin precession of drifting spins without applying any magnetic fields and ambiguous theoretically assumed parameters. The technique for estimating SOI parameters proposed in this paper will lead to both further research and the application of spins to semiconductor devices.

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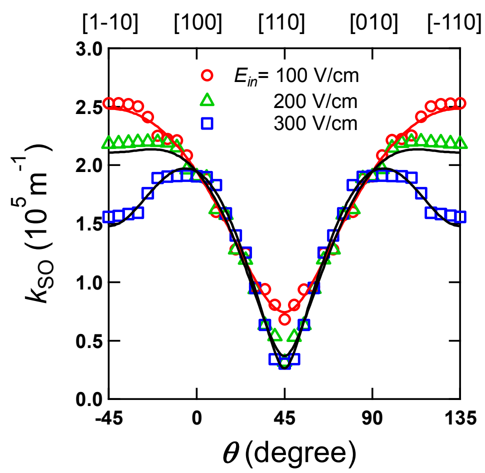

Fig. 3 Anisotropy of k_{SO} for various in-plane electric fields. Symbols and solid lines are indicate k_{SO} obtained from the MC simulation and Eq. (2), respectively.