Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp909-910

PS-12-01

Gate Controlled Switching between Two Different Persistent Spin Helix States and Determination of Dresselhaus Spin-orbit Interaction Parameter

Kohei Yoshizumi[1], Makoto Kohda [1,2] and Junsaku Nitta [1,2]

[1] Department of Materials Science, Tohoku University
6-6-02 Aramai-Aza, Aoba, Aoba-ku, Sendai 980-8579, Japan
E-mail: nitta@material.tohoku.ac.jp
[2] Center for Spintronics Research Network (CSRN), Tohoku University

Abstract
We demonstrate gate-controlled switching between persistent spin helix (PSH) state and inverse PSH state, which are detected by quantum interference effect on magneto-conductance. These special symmetric spin states showing weak localization effect give rise to a long spin coherence when the strength of Rashba spin-orbit interaction (SOI) are close to that of Dresselhaus SOI. Furthermore, in the middle of two persistent spin helix states, where the Rashba SOI can be negligible, the bulk Dresselhaus SOI parameter in a modulation doped InGaAs/InAlAs quantum well is determined.

1. Introduction

Spin-orbit interaction (SOI) is a key ingredient to generate, manipulate, and detect spins in semiconductors solely by electrical means [1]. However, the SOI gives rise to spin relaxation due to momentum-dependent effective magnetic fields. One of the ways to suppress spin relaxation is to utilize persistent spin helix (PSH) state where the Rashba and Dresselhaus SOIs are equal to each other in magnitude. Under the PSH state, the effective magnetic field is unidirectional, resulting in coherent spin propagation with helical spin texture [2], [3].

By changing the sign of Rashba SOI parameter through the gate, the PSH state can be reversed to an inverse PSH (*i*-PSH) state where the direction of unidirectionally-oriented effective fields becomes orthogonal to that in PSH state. Switching between the PSH and *i*-PSH states provides insightful information on coherent spin transport for future spintronic applications, and it also enables a spin complementary field effect transistor (FET). The relation between the spin Hall conductance and the Berry phase has been discussed in ballistic two dimensional electron gas (2DEG). The direction of spin current associated with the spin Hall conductance is reversed when the gate controlled Rashba SOI goes through these two PSH states, in which the Berry phase is equal to zero [4].

2. Experiments and Discussion

The semiconductor heterostructure used in this study was epitaxially grown by metal organic chemical vapor deposition on a (001) InP substrate. It consists of, from the substrate, 200 nm $In_{0.52}Al_{0.48}As$ / 6 nm $In_{0.52}Al_{0.48}As$ (Si doping with 1.2×10^{18} cm^{-3}) / 6 nm $In_{0.52}Al_{0.48}As$ / 7 nm $In_{0.53}Ga_{0.47}As$ QW / 6 nm $In_{0.52}Al_{0.48}As$ / 6 nm $In_{0.52}Al_{0.48}As$ (Si doping with 3.2×10^{18} cm^{-3}) / 10 nm $In_{0.52}Al_{0.48}As$. The band structure is designed to be symmetric potential profile where the Rashba SOI is close to the Dresselhaus SOI by inserting Si doping layers in both sides of an $In_{0.53}Ga_{0.47}As$ QW. Standard Hall bars were fabricated by photolithography and wet chemical etching techniques with Al_2O_3 (5 nm-thick) and HfO_2 (95 nm-thick) gate insulator layers and covered with a Cr/Au top-gate electrode in order to modulate the strength of Rashba SOI by the gate bias voltage (V_g). The measurement of magneto-conductance (MC) was carried out at a temperature of T = 0.26 K - 0.3 K with perpendicular magnetic field to the QW plane. All transport properties were measured by a standard lock-in technique. The V_g dependence of sheet carrier density (N_s) and mobility were evaluated from Shubnikov-de Haas oscillations. The mobility (carrier density) decreases from 5.0 $m^2/V\cdot s$ ($N_s = 2.5\times10^{16}$ m^{-2}) to 1.5 $m^2/V\cdot s$ ($N_s = 0.5\times10^{16}$ m^{-2}) as V_g changing from -1.5V to -3.5V.

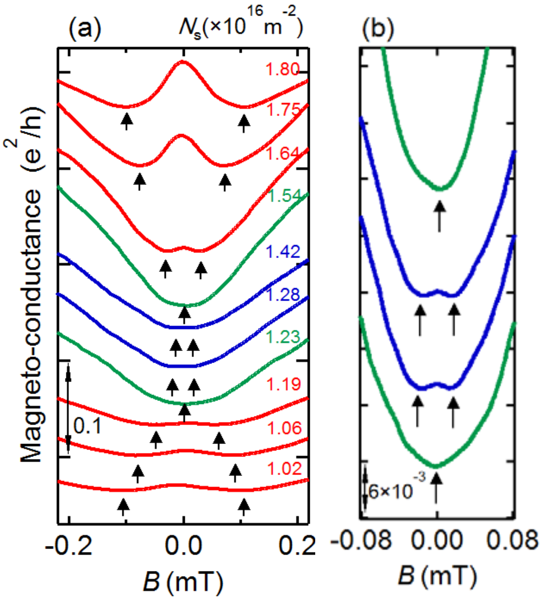

Fig. 1. (a) Magneto-conductance as a function of external magnetic field in different carrier density (*Ns*). The vertical arrows indicate magnetic field at minima of magneto-conductance. (b) Magnified magneto-conductance at *Ns*= 1.23, 1.28, 1.42, 1.54 (x 10^{16} m^{-2}) between the PSH and *i*-PSH states [5].

In order to see the PSH and *i*-PSH transitions in the present sample, we experimentally measure MC by tuning the strength of Rahsba SOI (α) via gate voltage. The gate voltage modifies N_s as well as α. Figures 1 (a) and (b) show the obtained MC as a function of N_s. The WAL gradually weakens with decreasing N_s (red curves) and WL appears around N_s=1.54×10^{16} m^{-2} (green curve) and back to WAL (blue curves) again. The appearance of WL reflects the suppressed spin relaxation indicating the PSH state. The weak WAL (blue curves) corresponds to the enhanced spin relaxation caused mainly by the Dresselhaus SOI. In addition to the first WAL-WL-WAL transition, we observed the second transition by further decreasing N_s. WL (green curve) around N_s=1.23×10^{16} m^{-2} is another sign of suppressing spin relaxation, corresponding to the *i*-PSH state [5].

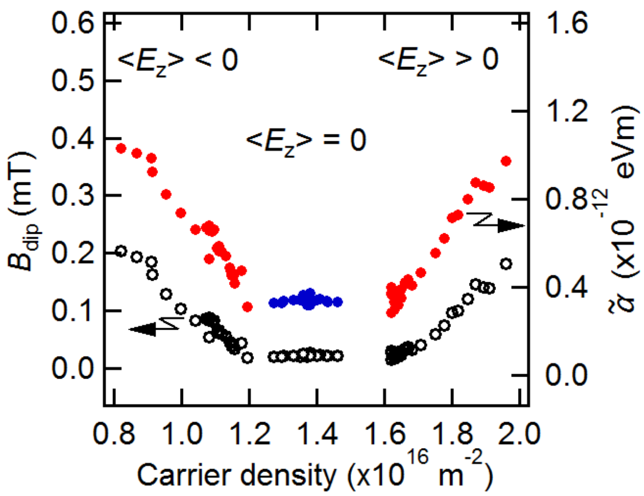

Fig. 2 Magnetic field at minimum magneto-conductance (open circles) and strength of spin orbit interaction (filled circles) as a function of carrier density [5].

To compare the experimental MC data with numerical simulation (not shown), we also evaluate B_{dip} as a function of N_s from measured MC. Evolution of B_{dip} with N_s shows a similar behavior to numerical results. We also evaluate SOI parameter according to the following relationship $\tilde{\alpha} = \sqrt{e\hbar^3 B_{dip}/m^*}$ (eVm) in Fig. 2, since the characteristic magnetic field H_{so} obtained from Knap theory [6] shows almost the same value to B_{dip} , i.e. $H_{so} \approx B_{dip}$ [7]. In the higher and lower N_s regions corresponding to the Rashba SOI dominance, the SOI strength shows a linear increase being consistent with the fact that the Rashba SOI linearly depends on internal electric field <E_z>. In 1.28×10^{16} m^{-2} < N_s < 1.46×10^{16} m^{-2}, the Dresselhaus SOI becomes dominant, showing the constant SOI strength since the Dresselhaus SOI does not strongly depends on carrier density. This is also reproduced in the numerical simulation. As a result, evolution of MC between WL and WAL indicates the gate-controlled switching between PSH and *i*-PSH states [5].

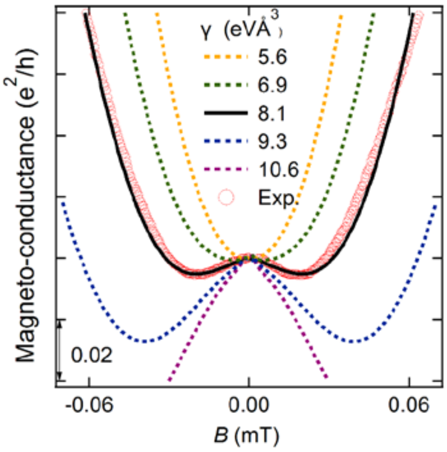

Fig. 3 Magneto-conductance at *Ns*= 1.38 x 10^{16} m^{-2} with negligible Rashba SOI and WAL analysis to obtain bulk Dresselhaus SOI parameter.

By using the transition from PSH and *i*-PSH states, carrier density for vanishing Rashba SOI (α= 0), where <E_z>= 0, is determined as N_s= 1.38×10^{16} m^{-2}. This enables us to precisely evaluate the bulk Dresselhaus SOI parameter $|\gamma|$ by comparing between the experimental MC and the Knap theory as $|\gamma|$= 8 eVÅ^3. It is interesting to note that $|\gamma|$ in InGaAs QW is a little bit smaller than that in GaAs [8].

3. Conclusions

We demonstrate the gate-controlled switching between the PSH and *i*-PSH states using transport measurements and roughly determine the bulk Dresselhaus SOI parameter in an InGaAs QW. The material parameter γ is of crucial for designing semiconductor spintronic devices such as the complementary spin-FET, and our results also provide useful information for Berry phase related phenomena such as the spin Hall effect.

Acknowledgements

This work was supported by the Japan Society for the Promotion of Science with Grants-in-Aid (15H05699, 15H02099 and 25220604) and JSPS Core-to-Core Program.

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