Anisotropic spin transport affected by competition between spin orbit interaction and Zeeman effect in an InGaAs based wire

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Abstract. Spin transport affected by competition between Zeeman effect and spin-orbit interaction (SOI) is investigated in order to check a proposed method to deduce the Rashba SOI $\alpha$ and Dresselhaus SOI $\beta$ ratio. The experimentally obtained ratio $\alpha/\beta$ of the present sample is about 4 from angle dependence of magnetoconductance under in-plane magnetic field. The proposed method to detect the ratio by transport measurement is promising although further improvement of sample fabrication and measurement is required.

1. Introduction

The spin dynamics in solid is mainly governed by competition between the Zeeman effect and the spin-orbit interaction (SOI). In transport measurements, quantum interference such as weak anti-localization (WAL) is sensitive to the spin dynamics, and WAL analysis is often used to deduce the spin relaxation length. In III-V semiconductor heterostructures, the dominant mechanisms for SOI are the Dresselhaus SOI [1] caused by a bulk inversion asymmetry and the Rashba SOI [2] caused by a structural inversion asymmetry. When both strength of the Rashba and Dresselhaus SOIs become equal with each other, the D’yakonov-Perel’ (DP) spin relaxation [3] is completely suppressed, and spin relaxation time is significantly enhanced, generating persistent spin helix state (PSH) [4], [5]. We have observed large enhancement of spin relaxation time by making the Rashba SOI parameter close to the Dresselhaus SOI parameter [6]. To realize the PSH state in semiconductor two dimensional electron gas (2DEG), precise control and electrical detection of the relative strength of the Rashba and Dresselhaus SOIs are of great importance. It is possible to determine the ratio between Rashba and Dresselhaus SOIs by using optical techniques [7-9], this is not always an option. If, e.g., the semiconductor heterostructure is covered with a top gate to tune the Rashba SOI strength, it is very difficult to carry out optical measurements. Recently, we have proposed a method to determine the relative strength of these two SOIs from transport measurements with competition between the SOIs and the Zeeman effect [10]. In this paper, we discuss the all-electrical determination of the relative strength of Rashba and Dresselhaus SOIs in an InGaAs wire structure.
2. Experiment and Discussion

Recent theories [11], [12] have predicted that a narrow wire can suppress the DP spin relaxation, and the wire can be treated as quasi-one dimensional if the wire width is shorter than the spin diffusion length. The effective magnetic field direction induced the Rashba SOI is perpendicular to the electron momentum direction, while the effective field direction due to the Dresselhaus SOI is \([x, -y]\) direction with the electron momentum direction \([x, y]\). If the wire is quasi-one dimensional, the total effective field with both the Rashba and Dresselhaus SOIs is opposite for electron travelling in opposite wire directions. In this uni-axial effective field condition, the spin is conserved quantity. Therefore, no additional phase in the wave function is acquired by electrons returning to their original position and WAL is suppressed, leading to weak localization (WL). However, the uni-axial field condition is broken when a finite in-plane magnetic field is applied. If the direction of the in-plane field is in parallel to the SOIs total effective field, the uni-axial condition is preserved. Here we can expect the conductance minimum with this special in-plane field direction, which is given by the following equation [10]. The in-plane field should be the same order but sufficiently smaller than the effective field originated from the SOIs in order to obtain the accurate value of \(\alpha/\beta\) ratio.

\[
\theta_{min} = \arctan \left( \frac{-\alpha \cos \phi + \beta \sin \phi}{\beta \cos \phi + \alpha \sin \phi} \right)
\]  

(1)

Here, \(\phi\) and \(\theta\) are the angles for wire and applied in-plane field directions from \([100]\) orientation of the crystal. \(\theta_{min}\) is the special angle of in-plane field which provides the conductance minimum.

\[\begin{align*}
2.5 \text{ nm In}_{0.53}\text{Ga}_{0.47}\text{As} & \text{ for spacer} \\
6 \text{ nm } n-\text{In}_{0.52}\text{Al}_{0.48}\text{As} & \text{ for carrier supply (Si doping: } N_d = 4 \times 10^{18}\text{cm}^{-3}) \\
200 \text{ nm } \text{In}_{0.52}\text{Al}_{0.48}\text{As} & \text{ for buffer layer. The epitaxial wafer was processed into wires along [100] direction by electron beam lithography as shown in Fig. 1. This is because the cubic Dresselhaus SOI effect, which has four-fold symmetry, is minimized along [100] direction. The width of the wire is 480 nm and the sample consists of 120 wires to reduce the universal conductance fluctuation.}
\end{align*}\]
We measured magnetoresistance in the fabricated wires with a fixed gate bias voltage, $V_g = -4.5$ V. The external magnetic field was applied perpendicular to the QW plane. The Rashba SOI parameter $\alpha$ was derived to be $3.9 \times 10^{-12}$ eVm from the WAL of the magnetoresistance measurement in an ordinary Hall bar device made of the same wafer. It should be noted that the Rashba parameter is negative value because of the inverted type modulation doped heterostructure. Sheet carrier density and electron mobility are determined to be $N_s = 8.7 \times 10^{11}$ cm$^{-2}$ and $\mu = 87,900$ cm$^2$/Vs by Shubnikov de Haas oscillations and sheet resistance for the Hall bar device. All the measurements were performed with a He$^4$ cryostat refrigerator at $T = 1.7$ K.

The magnetoconductance data as a function of in-plane field strength for parallel and perpendicular to the wires are shown in Fig. 2 (a) and (b). A transition from WAL to weak localization (WL) was observed in both cases. The transition occurred around $B_{in} = 0.9$ T for the parallel case while it was observed around $B_{in} = 0.6$ T for the perpendicular case. This anisotropy shows that the Dresselhaus SOI coexists with the Rashba SOI. The difference in the transition field indicates that the Rashba SOI field is stronger than the Dresselhaus one. This is because the Rashba SOI field direction is perpendicular to the wire while the Dresselhaus one is parallel. The applied in-plane field was decided to be 0.45 T for more detailed angle dependence measurement since the magnetoconductance data in both directions showed clear anisotropy at $B_{in} = 0.45$ T.

Figure 3 shows a color plot for the in-plane field angle dependence of magnetoconductance with $B_{in} = 0.45$ T. The angle dependence shows two-fold symmetry about 360 deg rotation. It is clear that WAL peaks are most and least suppressed at $\theta = 75$ deg and $\theta = 165$ deg, respectively. As expected from Fig. 3, the spin relaxation lengths obtained from WAL analysis for narrow wire [9] are maximum at $\theta = 75$ deg and minimum at $\theta = 165$ deg. This result suggests that the total SOI induced field is directed along $\theta = 75$ deg. From eq. (1), $\alpha/\beta$ ratio is obtained to be about $3 - 5.4$ by considering that the angle accuracy of in-plane field is $\pm 4$ deg. The experimentally obtained Dresselhaus SOI parameter $\beta$ is $0.7 \times 10^{-12} - 1.3 \times 10^{-12}$ eVm.
The Dresselhaus parameter is theoretically given by
\[ \beta = \gamma \left( k_z^2 \right) \approx \gamma (\pi / d_{QW})^2 \]
and is estimated to be 0.88 x 10^{-12} eVm with an assumption of cubic Dresselhaus parameter \( \gamma = 27.38 \times 10^{-30} \text{eVm}^3 \) [13]. The experimentally obtained \( \beta \) is consistent with the estimated value. However, the cubic Dresselhaus parameter in GaAs has been reported in a wide range of \( \gamma = 5 \times 10^{-30} - 27 \times 10^{-30} \text{eVm}^3 \) among experiments and theories. The value of cubic Dresselhaus parameter \( \gamma \) should be material constant. The obtained value \( \gamma \) in this experiment is rather high comparing with recent data (\( \gamma = 5 \times 10^{-30} \text{eVm}^3 \)) obtained in GaAs [5]. In the present InGaAs channel is not lattice matched to the InP substrate. We have to think about the possibility of a strain induced SOI effect which is reported not to be negligible in lattice mismatch systems [14]. It should be also noted that the wire width should be 5 times smaller than the spin precession length \( L_{so} = h^2 / m' \alpha \). The effective width \( W \) of the present sample is \( W = L_{so} / 2.5 \). Further improvement of sample fabrication is required.

3. Summary
We have investigated spin transport affected by competition between Zeeman effect and SOIs. The angle dependence of magnetoconductance under in-plane magnetic field shows anisotropy, leading to the \( \alpha/\beta \) ratio. The proposed method to detect the ratio by this transport measurement is promising although further improvement of sample fabrication and measurement is required. It is possible to confirm the PSH condition by the present method. The PSH state will be realized by controlling the Rashba SOI by a gate voltage [15].

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