Anisotropic spin splitting in InGaAs wire structures

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Abstract

We report anisotropic spin splitting in gate-fitted InGaAs wires along different crystal orientations. Anisotropic magnetoconductance minima reflecting spin splitting is observed by decreasing wire width at the same carrier density. Anisotropy of spin splitting is reduced by applying negative gate voltages, while the strength of spin splitting is enhanced in the present InGaAs wire structures. This gate voltage dependence of spin splitting shows qualitative agreements with the theoretical calculations taking both Rashba SOI and Dresselhaus SOI into account.

Keywords: Quantum wire; Spin-orbit interaction; weak antilocalization

1. Introduction

In the field of spintronics, spin functional devices have attracted significant interest due to the possibility of miniaturization as well as operation at speeds higher than possible with conventional electric devices [1]. Spontaneous spin splitting of the conduction band in two-dimensional electron gas (2DEG), i.e., spin-orbit interaction (SOI), plays an important role for utilizing the spin degree of freedom. For example, electrical manipulation of the spin precession can be achieved by the gate control of Rashba SOI [2]. However, the SOI causes spin relaxation during multiple scattering events of electrons. To realize spin functional devices, much attention is being focused on the suppression of spin relaxation in the presence of SOIs.

In a narrow gap semiconductor such as InGaAs, the spin relaxation is governed by the D’yakonov-Perel’ mechanism [3] through the Rashba SOI caused by structure inversion asymmetry [4] and the Dresselhaus SOI caused by bulk inversion asymmetry [5]. When the Rashba parameter $\alpha$ is equal to the linear Dresselhaus parameter $\beta$ by gate modulation of Rashba SOI [6], an effective magnetic field can be aligned in the [110] direction, leading to a persistent spin helix (PSH) state and infinite spin lifetime [7-9]. Therefore, both the long spin relaxation length and electrical spin manipulation are realized near the PSH state [10]. For confirmation of the PSH state by gate modulation of Rashba SOI, it is necessary to determine strengths of $\alpha$ and $\beta$ by transport measurement. We have proposed transport measurement of wire structures to determine the rates between $\alpha$ and $\beta$ by using an in-plane magnetic field [11]. However, a remaining problem is whether the cubic Dresselhaus term $\gamma$ contributes to spin...
relaxation or not in wire structures since the cubic Dresselhaus term may induce additional spin relaxation [12]. Anisotropic spin splitting due to the cooperation between the Rashba and the Dresselhaus SOIs can potentially be used to obtain information on the cubic Dresselhaus SOI. Spin lifetime in the InGaAs-wire structure has been optically investigated with no gate modulation [13]. It is clear that investigation of the anisotropy of spin splitting under gate modulation of the Rashba SOI is significantly important for obtaining further information on spin splitting and realization of spin functional devices.

In this work, we investigated anisotropy of spin splitting with different gate bias voltages in gate-fitted InGaAs wire structures by weak antilocalization (WAL) analysis. Anisotropy of magnetococonductance (MC) becomes much stronger by decreasing wire width at the same carrier density. Our experimental results also indicate that anisotropy of spin splitting is reduced by applying negative gate voltages due to the increase of structure inversion symmetry inside the quantum well, while the strength of spin splitting is enhanced. This gate voltage dependence of spin splitting shows qualitative agreements with theoretical calculations taking both Rashba and Dresselhaus SOIs into account. In the present sample, the cubic Dresselhaus SOI contribution was found to be much smaller than Rashba and linear Dresselhaus contributions.

2. Experimental

The InGaAs-based heterostructure was epitaxially grown on (001) InP substrate by metal organic chemical vapor deposition. 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 $N_d = 4.0 \times 10^{18}$ cm$^{-3}$) / 15 nm In$_{0.52}$Al$_{0.48}$As / 2.5 nm In$_{0.53}$Ga$_{0.47}$As / 10 nm In$_{0.5}$Ga$_{0.5}$As (quantum well) / 2.5 nm In$_{0.52}$Ga$_{0.48}$As / 3 nm InP / 20 nm In$_{0.52}$Al$_{0.48}$As / 1.5 mm AlAs / 5 mm In$_{0.52}$Al$_{0.48}$As. The epitaxial wafer was processed into sets of wires which were aligned in [110], [100] and [1-10] directions using electron beam lithography and reactive ion etching, as shown in Figs. 1(a) and (b). Each sample consisted of 100 identical wires (200-μm-long) with different wire widths. Geometrical widths $W_{SEM}$ of the wire defined by scanning electron microscopy were 541, 649, 740, and 956 nm. Processed samples were covered with 150-nm-thick AuGeNi as a gate electrode isolated by 200-nm-thick Al$_2$O$_3$ grown by atomic layer deposition. MC measurement was performed by employing the AC lock-in technique for all sets of wires as well as for Hall bars at 1.7 K. A schematic image of the measurement configuration is shown in Fig. 1(c). Carrier density $N_i$ and mobility $\mu$ were deduced from sheet resistance and the fast Fourier transformation of Shubnikov-de Haas (SdH) oscillation. It should be noted that we estimated depletion width $W_{dep} = 313$ nm from the width dependence of conductance at zero external magnetic field and effective width $W_{eff} = W_{SEM} - W_{dep}$ are used to derive mobility. The detail of this analysis is shown in reference [14].

Fig.1 (a) Scanning electron micrograph (SEM) image of InGaAs wire structure. (b) SEM images of the cross section of InGaAs wire structure. (c) Schematic illustration of measurement configuration. Sets of wires along each direction were connected in series and their MCs were measured at the same time.
3. Results and discussion

MC data observed at \( N_s = 1.4 \times 10^{12} \text{ cm}^{-2} \) for the wire of \( W_{\text{SEM}} = 956 \text{ nm} \) and that of 541 nm are shown in Fig. 2(a). In the case of the 956-nm-wide wire, WAL was observed for all crystal orientations. On the contrary, for the 541-nm-wide wire, weak localization (WL) was observed for the [1-10] direction although WAL was dominant for the [100] and [110] directions. Figure 2(a) shows that the anisotropy of MC is more predominant in the narrowest wire than in the widest wire. Since conductance minima indicated by arrows in Fig. 2(a) correspond to the magnetic field on which crossover from WAL to WL occurs and destructive interference due to SOI is completely randomized by external magnetic field, spin splitting due to SOI can be qualitatively deduced from the value of conductance minima. In this paper, we used conductance minima as indexes of strength of SOI. Minimal values of the magnetic field \( B_{\text{min}} \) are extracted from the MC data and plotted in Fig. 2(b) as a function of crystal orientation. It should be noted that we assumed twofold symmetry of MC when drawing Fig. 2(b), which is the lowest symmetry due to SOI and theoretically ensured [15]. This assumption is based on a previous study which showed that the cubic Dresselhaus SOI is negligibly small in the present sample structures [14]. In fact, fourfold symmetry based on the cubic Dresselhaus SOI was not observed in the present wire samples, indicating that the cubic Dresselhaus SOI is much smaller than Rashba and linear Dresselhaus SOIs. As shown in Fig. 2(b), crystal anisotropy becomes much stronger with the decrease of wire width. This enhanced anisotropy is probably because the time-reversal closed path, which contributes to WAL and WL, is elongated due to dimensional confinement and quasi-ballistic transport due to the longer mean free path \( l_{\text{me}} = 4.23 \pm 1.4 \mu\text{m} \) than the wire width. Furthermore, anisotropic \( B_{\text{min}} \) originates from cooperation between Rashba SOI and Dresselhaus SOI as previously mentioned [15]. If one of the SOIs is dominant, spin splitting is isotropic. In the direction of [1-10], \( B_{\text{min}} \) decreases by decreasing the wire width, which indicates that spin relaxation due to SOI is suppressed by the dimensional confinement effect for the narrower wire comparable to the bulk spin precession length \( L_{\text{SO}} = h/2m_{\text{e}}c \), where \( m_{\text{e}} \) is electron mass. However, unexpected enhancement of \( B_{\text{min}} \) under the dimensional confinement was observed for the wire in the [100] and [110] directions, which directly indicates that spin relaxation is enhanced. This enhancement of spin relaxation in the wire in the [100] and [110] directions occurs because the electron moving along an elongated time-reversal closed path is selectively contributed by the much stronger effective magnetic field in the [100] and [110] directions rather than by the averaged effective magnetic field in 2DEG. The result is not explained by the existing theory [12] and shows that spin relaxation is not always suppressed due to dimensional confinement in ballistic wire structure.
We now turn to the carrier density dependence of anisotropic MC. Carrier density dependence of MC was measured for the wire of $W_{sem} = 956 \text{ nm}$, modulating carrier density from $1.2 \times 10^{12} \text{ cm}^{-2}$ through gate bias. It should be noted that the second subband level is partially occupied at $N_s = 1.8 \times 10^{12} \text{ cm}^{-2}$. The results are shown in Fig. 3. As shown in Fig. 3, conductance minima decrease by increasing gate voltages for all the directions, indicating that the decrease of strength of the Rashba SOI is due to the reduction of structure inversion asymmetry inside a quantum well. The polar plot of conductance minima $B_{min}$ for various gate voltages is shown in Fig. 4(a), which corresponds to the strength of spin splitting. By decreasing carrier density from $1.8 \times 10^{12} \text{ cm}^{-2}$, the strength of spin splitting becomes more isotropic due to the enhancement of the Rashba SOI contribution. This indicates that the Rashba SOI becomes much stronger and is finally more dominant rather than the Dresselhaus SOI by decreasing gate voltage. Spin splitting in the [110] direction is the largest value of all the directions due to constructive cooperation between Rashba and linear Dresselhaus SOIs in contrast to destructive cooperation along [1-10] direction. According to Winkler [15], crystal orientation dependence of spin splitting energy in the presence of both Rashba SOI and linear Dresselhaus SOI is given by

$$
\Delta E = \pm \hbar \sqrt{\alpha^2 - 2\alpha \beta \sin(2\phi) + \beta^2}.
$$

(a) $B_{min} (\text{mT})$

(b) $\Delta E (\text{meV})$

Fig. 3. Crystal direction dependence of MC observed for the wire of $W_{sem} = 956 \text{ nm}$ at carrier density $N_s = (a) 1.2 \times 10^{12} \text{ cm}^{-2}$, (b) $1.5 \times 10^{12} \text{ cm}^{-2}$, and (c) $1.8 \times 10^{12} \text{ cm}^{-2}$. Arrows indicate conductance minima $B_{min}$.

Fig. 4. (a) Crystal direction dependence of $B_{min}$ for various carrier densities, assuming twofold symmetry of $B_{min}$ (b) Spin splitting energy calculated by Eq. (1).
Here, $k_\parallel$ is momentum in the in-plane direction. $\varphi$ is defined as the angle from the [100] direction. $\beta$ is a spin-orbit parameter originating from the linear Dresselhaus SOI. Spin splitting energy evaluated from Eq. (1) is shown in Fig. 4(b). It should be noted that $\alpha$ is derived from the $kp$ method according to Schäpers et al. [16] and that the parameter of the linear Dresselhaus SOI $\beta = 0.893 \times 10^{-12}$ eVm estimated from $\beta = \gamma (k_\parallel^2)$, where the parameter of the cubic Dresselhaus term $\gamma = 2.73 \times 10^{-29}$ eV m$^3$ [17] and $k_\perp$ is momentum in the out of plane direction. By comparison between Fig. 4(a) and 4(b), qualitative agreement between experimental result and theoretical calculation is found, which indicates that our experimental results show the existence of both Rashba and linear Dresselhaus SOIs. However, a new model describing quantum correction of conductivity SOI in quasi-ballistic wire is necessary for further quantitative discussion of spin splitting energy.

4. Conclusion

We here in reported on the anisotropy of WAL in gate-fitted InGaAs wires having different crystal orientations. Anisotropic MC becomes much stronger by decreasing wire width at the same carrier density. Our experimental results indicate that anisotropy of spin splitting is enhanced by applying positive gate voltages in the present InGaAs wire structure. This gate voltage dependence of the spin splitting shows qualitative agreement with the results of theoretical calculation taking both Rashba and Dresselhaus SOIs into account. For further quantitative discussion, a theoretical model describing quantum correction of the conductivity in a narrow wire structure under the ballistic regime is required.

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References