Study of spin transport in In$_{0.75}$Ga$_{0.25}$As/In$_{0.75}$Al$_{0.25}$As narrow wires

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Abstract

We systematically studied spin–orbit interaction in narrow wires with different wire widths, where the base material is a normal-type In$_{0.75}$Ga$_{0.25}$As/In$_{0.75}$Al$_{0.25}$As modulation-doped narrow-gap heterojunction. We used two different methods to make the wires and analyze their spin-dependent transports. As a first method, the wire width was defined by simply mesa-etching the samples on the same substrate. As a second method, we fabricated wire samples with side-gate. The wire width was changed by varying a voltage applied to the side-gate. For the determination of spin–orbit coupling constant, $\alpha$, we measured magneto-resistance at 1.6 K. In the first method, $\alpha$ remained almost constant in the wires with various widths longer than 0.4 $\mu$m. However, in the second method, $\alpha$ increased with decreasing the wire width down to about 1 $\mu$m. The increase of $\alpha$ observed in the side-gate structure sample might rather be attributed to the effect of the lateral electric field by the side-gate, which could enhance the effect of the vertical electric field originally existing at the hetero-interface.

Keywords: Narrow wire; Narrow-gap semiconductor; Magneto-resistance; Spin-splitting; Spin–orbit coupling constant; Vertical electric field; Lateral electric field

1. Introduction

In 1990, the concept of a spin-FET has been proposed by Datta and Das [1]. The main idea was the electric field controlled spin precession of traveling electrodes. To realize spin-FET devices, following two things are considered to be necessary: (i) Efficient spin injection and detection from (ferromagnetic) electrodes attached to the semiconductor. (ii) Control of electron spin precession by the spin–orbit interaction, that is, the external electric field. In addition to those requirements, it is pointed out that the transport should be restricted to a narrow wire structure to obtain a sufficiently large signal modulation [2,3]. As a unique and attractive feature of two-dimensional electron gas (2DEG) confined at narrow-gap heterojunctions, a new kind of spin-splitting (Rashba splitting) originated from structure induced spin–orbit interactions have recently been studied [4–6]. We so far have explored Rashba effect in an In$_{0.75}$Ga$_{0.25}$As/In$_{0.75}$Al$_{0.25}$As narrow-gap heterojunction and confirmed the existence of the effect when the wire width reduced down to 2 $\mu$m [7]. So that, in this study, we study the spin–orbit interaction in very narrow wires with the width down to sub-micrometer.

2. Sample fabrication and experimental

A detailed growth process by molecular beam epitaxy of our heterojunction has already been reported elsewhere [8]. The structure consisted of a semi-insulating GaAs (001) substrate, 30 nm thick GaAs buffer layer, In$_y$Al$_{1-y}$As ($y = 0.15–0.75$) step graded buffer (SGB) layer, 30 nm thick metamorphic In$_{0.75}$Ga$_{0.25}$As channel layer, 20 nm In$_{0.75}$Al$_{0.25}$As spacer layer, and 40 nm In$_{0.75}$Al$_{0.25}$As carrier supply layer doped by Si. On the top of the doped layer, an additional 10 nm thick Si-doped In$_{0.75}$Ga$_{0.25}$As capping layer was grown.

We used two different methods to make diffusive narrow wire structures with different widths. In the first method, the wire width was defined by simply mesa-etching the samples in various widths from 4 to 0.4 $\mu$m on the same substrate. In the first step, the layers on the SGB were removed by wet etching. For the ohmic contact, AuGeNi was deposited and thermally annealed. In the second method, the wire width...
restriction was realized by the gate voltage to a gate electrode attached to the one side of the wire, to which the negative bias voltage could be applied. The SEM image of the top view of the side-gate wire is shown in Fig. 1. The fabrication of the mesa and ohmic contact were the same as those in the first method. Finally, the side-gate electrode was deposited on the side of the wire.

We measured low-temperature (1.6 K) magneto-resistances by AC lock-in technique. In simple mesa-etched wire samples, a sheet electron density, \( n_{\text{Hall}} \); Hall; and an electron mobility, \( \mu_e \) were found to be \( 8 \times 10^{11} \text{ cm}^{-2} \) and \( 1.6 \times 10^5 \text{ cm}^2/\text{V s} \) at 1.6 K, respectively. The side-gate structure sample was found to have \( n_{\text{Hall}} \) of \( 4 \times 10^{11} \text{ cm}^{-2} \), and \( \mu_e \) of \( 1.4 \times 10^5 \text{ cm}^2/\text{V s} \) at 1.6 K.

3. Results and discussion

Fig. 2(a) and (b) show the magneto-resistances \((R(B))\) and Landau plots for the second derivatives \((d^2R/dB^2)\) for simple mesa-etched wire samples with a width ranging from 4 to 0.4 \( \mu \)m. From Fig. 2(b), it is found that they show straight lines for the samples with the widths from 4 to 0.45 \( \mu \)m. Only the Landau plot of the 0.4 \( \mu \)m width wire showed the deviation from the linear dependence, suggesting formation of one-dimensional electric subbands in the wire. In Fig. 3(a), the results of fast Fourier transform (FFT) analysis of the second derivatives are shown. In those traces, it is found that ground and first excited subbands are occupied by the 2DEG and the peak corresponding to the ground subband (right peak) are likely splitting. In the wire of 0.4 \( \mu \)m width, however, no clear peaks are observed. This is probably due to the fact that conductance fluctuations probably appeared in this quasi-one-dimensional wire which might make unclear the beating oscillations, the proof of spin–orbit interaction, since both of them are observed in the low field regions. The values of spin–orbit coupling constant, \( \alpha \), calculated from the splittings are plotted in Fig. 3(b) as a function of the wire width larger than 0.45 \( \mu \)m. Simple mesa-etched wire samples measured here did not show \( \alpha \) dependence on the wire width, probably since they still remain in almost two-dimensional transport regime.

Fig. 4(a) shows the magneto-resistances \( R(B) \)s and \( d^2R/dB^2 \) vs. \( 1/B \) for side-gate structure sample. Negative gate voltage from 0 to \(-12 \text{ V}\) was applied to the side-gate electrode in this case. Zero-field resistance became large as negative gate voltage increased. We then simply calculated effective wire width from the change of zero-field resistance. As shown in Fig. 4(b), a beating pattern changed by varying negative gate voltage. Fig. 5(a) shows corresponding FFT results for the oscillation in Fig. 4(b). In all spectra, there are peak splittings and the magnitude between the splitted peaks was found to enlarge by increasing negative gate voltage. From the magnitude of...
the peak splitting, we estimated \( \alpha \). Those values as well as the effective wire widths \( w_{\text{eff}} \) are shown as a function of gate voltage \( V_G \) in Fig. 5(b). It is found that \( \alpha \) was drastically enhanced under large negative voltage conditions. The estimated \( \alpha \) (46.7 \( \times 10^{-12} \) eV m) at \( V_G = -12 \) V was about 4 times as large as that (9.8 \( \times 10^{-12} \) eV m) at \( V_G = 0 \) V.

This is probably due to that lateral electric field by the side-gate voltage created even stronger electric field thus resulting stronger effective magnetic field, which brings the enhancement of spin–orbit interaction. That is, when \( V_G = 0 \) V, only the vertical built-in electric field was existing in the system. If the negative \( V_G \) is applied, lateral electric field is created and then the total electric field (the vector sum of vertical and lateral electric fields) increases. Note here that almost no change of \( n_s \) was confirmed by the Landau plots of the Shubnikov de-Haas (SdH) oscillations (not shown), excluding the effect of \( n_s \) change on \( \alpha \). Of course, also note here that the narrow wires of side-gate structure sample studied are still in almost two-dimensional. This is obvious, since in the Landau plots of the SdH oscillations in Fig. 2(b), the deviation from the straight line is observed only in the narrowest wire of \( w = 0.45 \) \( \mu \)m, which is made by mesa-etching. From the above result, \( \alpha \) changes not by the effects of reducing the width of the wire. Increase of \( \alpha \) observed here in the side-gate structure sample could thus rather be attributed to sum up of the lateral electric field by the side-gate to the vertical electric field originally existing at the hetero-interface. Those situations are sketched in Fig. 6.

4. Summary

We have fabricated two kinds of diffusive narrow wires at narrow-gap \( \text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As} \) heterojunction interface and studied their transport properties especially focusing on spin–orbit interaction of the 2DEG. In simple mesa-etched wires with widths \( w = 4 - 0.45 \) \( \mu \)m, there occurred almost no change in the magnitude of spin–orbit interaction parameter, \( \alpha \), although the 2DEG nature still remained even in the wire of width, \( w \sim 0.45 \) \( \mu \)m. In the side-gate structure sample, where the wire width was controlled by negative gate voltage, there occurred a drastic enhancement of a value of \( \alpha \) by applying the gate voltage. This is probably due to the additional electric field by the lateral gate voltage and hence the effective magnetic field also increased by the negative gate voltage application.
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