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Spin-related transport in one-dimensional conductors made at high-in content InGaAs/InAlAs hetero-junctions

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Abstract

Results of spin-related transport observed in various one-dimensional (1D) samples made at high In-content InGaAs/InAlAs modulation-doped hetero-junctions are reported. This type of material is interesting especially from the viewpoint of non-magnetic semiconductor spintronics, since it contains two-dimensional electron gas (2DEG) which reveals large spin–orbit coupling constant (α) as well as very high electron mobility (μe) at low temperatures. 1D structures studied here are diffusive narrow wires (width, w) and quantum point contacts (QPCs) as typical example of ballistic transport regime. In the long diffusive wires with a variety of width, α is found to remain unchanged when w > 2 μm. But in the diffusive wires with side-gate (the width of the wire can thus be controlled by the side-gate voltage), α is enhanced by applying negative voltage to the side gate. This is probably due to that the side-gate voltage has enhanced asymmetric lateral electric field perpendicular to the moving direction of 2DEG. In the QPC samples defined by the wire and the finger side-gate, conductance quantization in unit of 0.5/(2e^2/h) is confirmed. This might be caused by the formation of ‘spin-related Tomonaga–Luttinger wire’, which encourages spin-polarized transport in such an ideal conductor. Finally, we propose several quantum information processing devices based on the spin-FET, that could construct a solid-state qubit and quantum computation devices and circuits.

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Keywords: Spin-related transport; One-dimensional; Spin–orbit coupling constant; Diffusive narrow wires; Quantum point contacts; Quantum information processing

1. Introduction

Spin-related transport studies in non-magnetic narrow-gap semiconductor hetero-junctions have recently attracted much attentions, since 2DEG accumulated in those hetero-junctions exhibits very high electron mobility as well as strong spin–orbit interaction originated from built-in asymmetric electric field and thus controlled by the voltage applied to the top gate, for example. Field effect transistor (FET) type device of this operation principle has been proposed [1] and is called as spin-FET. In order to realize this kind of device, first problem is to obtain a material system which contains 2DEG with high mobility and controllable and strong spin–orbit interaction at low temperatures at least. This is almost attained by several groups and the value of α recently reached over 30 (× 10^{-12} eVm), which means the shortest length necessary to give π phase precession is less than 0.5 μm [2–4]. Second problem is to find or to make source/drain electrodes which can inject and detect spins in high efficiencies, respectively. This seems, however, not to be solved yet [5]. Third item which has most rarely been discussed is the problem of the device dimension or structure. Since the spin precession angle is proportional to the electron path length, two-dimensional device, that is, the device with wide width is not suitable for spin-FET. In fact, Bournel [6] has pointed out in his calculation some improvements of the transport features in the spin-FET when the sample width is sufficiently reduced. However, how the spin–orbit interaction observed in 2DEG at present is modified, when the sample width is reduced, that is, in narrow or 1D-like conductors, is not known at present. Moreover, mesoscopic transport physics in the low dimensional systems with strong spin–orbit interaction has so far almost not been investigated and remains as a novel research field, which could be called as ‘mesoscopic spintronics’, in semiconductor physics.
In this work, spin-related transport studies in various one-dimensional conductors made at high In-content InGaAs/InAlAs hetero-junctions carried out in JAIST are reviewed. Studied 1D structures includes diffusive quantum wires as well as two-type quantum point contacts (QPCs). The high In-content InGaAs/InAlAs heterojunctions [7] have been confirmed to have a high electron mobility $\mu_e \sim 5 \times 10^5$ cm$^2$/Vs and a very large spin–orbit coupling constant, $\alpha \sim 30 \times 10^{-12}$ eVm at 1.5 K, which correspond to the electron mean free path of $\sim 6$ μm and spin splitting of $\sim 10$ meV, respectively [4]. By using this heterostructure, we have fabricated four-terminal diffusive quantum wires with a variety of widths and QPCs of side-gate and split-gate types and studied their transport at low temperatures at $\sim 1.5$ K. Modifications of spin–orbit coupling in the narrow side-gate wires and spin-polarized transport in the side-gated QPCs were confirmed and their origins were discussed. Based on the results obtained here, several quantum information processing devices based on the spin-FET are proposed at the last section. Those devices could be developed toward solid-state quantum computing devices as qubit or quantum gate, etc.

2. Rashba spin–orbit interaction in diffusive quantum wires [8]

The sample of the first case is long diffusive wires with various widths from 0.4 to 4 μm defined by simple mesa-etching. Shubnikov de-Haas (SdH) oscillations have been measured and the fast Fourier transform (FFT) analysis was carried out. The magnitude of $\alpha$ was, however, found to be almost constant for all the wires measured. In addition, Landau plots for the SdH oscillations were found to show straight lines, which means that 1D subbands were not formed in those wires. This is probably the reason for no modification of spin–orbit interaction in the wire samples, since they were still 2D. To observe the effect of reducing the dimension, the wires with even narrower widths less than $\sim 0.3$ μm should be fabricated.

In the second case, the diffusive wires with in-plane side-gate were prepared. An example of such wires is shown in Fig. 1, where the wire has two voltage probes and the width of the center $\sim 15$ μm long region can be controlled in the range less than $\sim 2$ μm (the structure width) by applying the negative voltage, $V_g$, to the side-gate. Fig. 2(a) shows SdH oscillations for various $V_g$s and traces in Fig. 2(b) are the corresponding FFT results. As shown in Fig. 2(b), although there is almost no peak splitting (hence $\alpha \sim 0$ in this case) for $V_g = +10$ and 0(V), the peak splitting appeared first for

![Fig. 1. Example of a diffusive wire with in-plane side-gate.](image)

![Fig. 2. (a) SdH oscillations in the wire with side-gate for various applied side-gate voltages ($V_g$s). $w$ is an effective width of the wire calculated from the value of resistance at $B = 0$. (b) Corresponding FFT results for the oscillations in (a). Peak splitting in the cases of $V_g = +10$ and 0(V) are very small, but it increases rapidly when $V_g$ decreases to deep minus values, suggesting the increase of spin–orbit coupling constant, $\alpha$.](image)
$V_g = -30(V)$ is found to become large as $V_g$ decreases. Finally, the value of $\alpha$ attained in this sample is 46.7 ($\times 10^{-12}$ eVm), which is the largest value ever obtained in our heterojunction samples of various types. Table 1 summarizes typical results, in which an effective wire width, $w_{\text{eff}}$, estimated by the resistance and $\alpha$ determined by SdH measurement were listed against $V_g$. It is found that there observed significant enhancements of $\alpha$ for deep gate-voltages. This seems surprising, since no size effects were expected to be observed in the diffusive wires, when the width is larger than 0.4 $\mu$m (the result found in the first case). An alternative and most plausible explanation of this enhancement is the one due to the asymmetric lateral electric field created by the applied voltage via the side-gate. This field is also perpendicular to the direction of electron flow and thus can contribute to the Rashba spin–orbit interactions of moving electrons (spins). This explanation would be plausible, since very recently we observed a similar enhancement of $\alpha$ in the side-gate wire by applying negative $V_g$, which is followed by the sudden decrease of $\alpha$ due to the decrease of $n_s$. This result should, however, be examined again by referring the results in future experiments.

### Table 1

Estimated effective width, $w_{\text{eff}}$, and spin–orbit coupling constant, $\alpha$, for the side-gate voltage varied.

| $V_G$ (V) | $w_{\text{eff}}$ (μm) | $\alpha$ ($\times 10^{-12}$ eVm) |
|-----------|------------------------|---------------------------------|
| 10        | 2                      | ~5                              |
| 0         | 2                      | ~5                              |
| −30       | 1.64                   | 33.9                            |
| −35       | 1.22                   | 41.3                            |
| −40       | 1.17                   | 46.7                            |

3. Spin transport in side-gate and split-gate QPCs [9]

Due to the difficulties of making Schottky electrodes to this heterojunction, we have made a QPC of a wire type with opposite side-gates. Fig. 3(a) shows schematically the cross-sectional structure of the sample and the top view observed by scanning electron microscope (SEM) is shown in Fig. 3(b). In this device, we observed conductance steps with 0.5($2e^2/h$) difference (Fig. 4) in samples with various dimensions. The steps separated by 0.5($2e^2/h$) becomes even clear when the perpendicular magnetic field increased. In contrast, no improvement of the clearness was observed when the parallel magnetic field was applied to the sample (not shown). Those results suggest non-Zeeman origin of the ($e^2/h$) $\times$ $n$ ($n$: integer) conductance steps. We observed, however, ($2e^2/h$) difference conductance steps in the split-gate QPC sample with a thick polyimide insulator, which is made for comparison. One difference of those two samples is a sheet electron density, 1.8 and $3.2 \times 10^{11}$ cm$^2$/Vs, for the side-gate and split-gate QPCs, respectively. So that, the origin of the 0.5($2e^2/h$) steps might be an enhanced electron–electron interaction rather than the spin-effect possibly be expected in this type of heterojunction. Another important difference is the degree of adiabatic-ness of the sample structure. In other words, the constriction realized in the split-gate QPC is rather abrupt compared with the constriction formed in the side-gate QPC. This ‘adiabatic’ QPC could become a kind of Tomonaga–Luttinger wire, in which the mode-coupling of one-dimensional sub-bands could bring a spin-polarized transport in the wire [10]. This result is very much interesting, since it means that we might have high efficiency spin-filter, if we make properly designed adiabatic QPC at the narrow-gap semiconductor heterojunctionn with strong Rashba effect.
4. Proposed quantum information processing devices based on spin-FET

Since the operation principle of the spin-FET itself is a rotation, i.e. an unitary transformation of spin as described by an equation, \( U_{so} = \exp(i\theta_0 \sigma_z) \), where \( \theta_0 = \frac{m' \alpha L \hbar^2}{2} \), \( L \) is a device length (source–drain distance) and Hamiltonian of spin–orbit interaction is \( H_{so} = i\alpha \sigma_z \), it is essentially possible to construct quantum information processing devices based on the spin-FET. For example, quantum bit (qubit) device can be realized in two different ways as shown in Fig. 5(a) and (b). Fig. 5(a) is a wire spin-FET with top and side serial gates and Fig. 5(b) is a ‘bend’ wire spin FET. In order to realize quantum mechanical superimposed state, \( \cos(\theta/2) |0> + \exp(i\Phi) \sin(\theta/2) |1> \), successive spin precession processes represented by angles \( \theta \) and \( \Phi \) with different \( B_{eff} \) axes are prepared. Moreover, quantum gate devices could also be realized by coupling the two bend type qubits as shown in Fig. 6, where the interaction between the qubits is supposed to be a dipole–dipole interaction, the magnitude of which is roughly proportional to the \( 1/(\text{distance})^6 \) between the two qubits.

Fig. 5. Example structures for realizing quantum bit operation based on spin FET. (a) Dual-gate type device and (b) Split (bend) wire type device. Arrows attached to the electrodes (the green parts) indicate the directions of magnetization of the ferromagnetic sources and drains. Gate electrodes attached on the wire region control the spin–orbit interaction.

Fig. 6. An example of coupled qubits device based on the bend spin-FET. The dipole–dipole type interaction between the qubits is here assumed.

If we make circuits by connecting those devices with each other, some level of quantum computations could be realized in the new kind regime based on the solid state devices.

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