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Analysis and Control of Rashba Spin-Splitting in One-Dimensional Conductors at Narrow-Gap Single Heterojunctions

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1. Introduction

As an unique and attractive feature of two-dimensional electron gas (2DEG) confined at narrow-gap heterojunctions, a new kind of spin-splitting originated from spin-orbit interactions have recently been studied [1-3]. In those works, the magnitude and gate voltage dependency of the spin-orbit coupling constant, α, has extensively studied and the magnitude was found to be controlled by the top-gate in the range of 5~40 (x10^{-12} eVm), which roughly corresponds to a few meV splitting at the Fermi level. Although these efforts have been carried out as a first step toward the Datta-Das spin FET [4], recent simulation [5] of the device has suggested that one-dimensional or narrow-wire structure is indispensable to realize the spin-FET operation. Therefore, it is very much important to study how the Rashba splitting phenomena will appear when the sample dimension is reduced. Moreover, such one-dimensional properties can also be an interesting topic in mesoscopic physics due to its new spin degree of freedom。

In this paper, we report the results of fabrication of one-dimensional conductor and of analysis of quantum transport at low temperatures. The sample structure treated here is essentially a long diffusive wire made at modulation-doped high In-content InGaAs/InAlAs heterojunction, which has a spin-splitting of a few meV and a low temperature electron mobility of 2x10^5 cm^2/Vsec. In the wires with widths of > 0.5 μm, the transport was still quasi two-dimensional and the magnitude of spin-splitting was almost unchanged from that of the 2DEG. In wires with a side-gate electrode, in which the width can be reduced to less than 0.5μm if necessary, enhancement of the spin-splitting and hence the spin-orbit coupling constant, α, was observed, when the large side-gate voltage was applied. This is probably due to that in addition to the built-in field in the confining triangular potential, a new class of asymmetric electric field was created in the lateral direction.

2. Sample Fabrication and Experimental

Figure 1 shows sample structures fabricated and investigated in this work. Techniques of standard electron beam lithography and wet etching have been employed. First type (Fig. 1(a)) is a 40μm long diffusive wire (voltage probe spacing of 20μm) with widths from 0.3 to 10μm. Second type (Fig. 1(b)) is also a diffusive wire of 15μm long and a 10μm long side-gate electrode was attached almost to the wire center. Magnetoresistance measurements on these wires have been carried out by ac lock-in technique at 1.5 K.

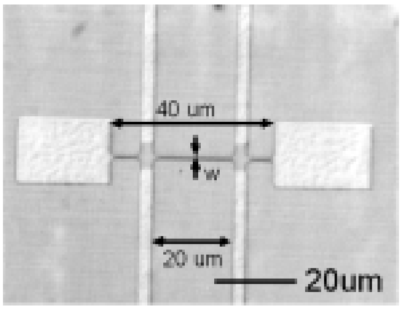

Fig.1(a) Long diffusive wire with voltage probes. Width ***W*** was changed from 0.3 to 10μm.

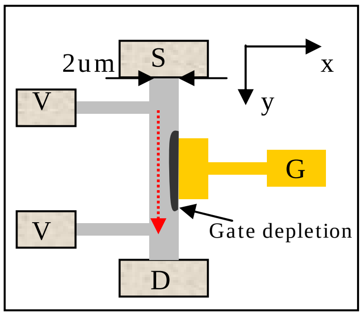

Fig.1(b) Schematic top view of diffusive wire with a side gate. Wire and gate lengths are 10 and 4μm, respectively.

3. Results and Discussions

Figure 2(a) shows Landau plots of Shubnikov de-Haas (SdH) oscillations observed in the type 1 wires with various widths. As seen in the figure, almost only the trace of w=0.4 μm shows a deviation from the straight line suggesting one-dimensional electric subbands formation in the wire. Figure 2(b) plots the value of spin-orbit coupling constant, α, deduced from the FFT analysis of the oscillations. As is expected, the value of α almost stays constant for the wires with w > 0.4 μm. This is reasonable, since the two-dimensional nature is still maintained for all the wires investigated. However, it is noted that since conductance fluctuations often appear especially at low magnetic fields in narrow wires, the FFT analysis of the magnetoresistance oscillations did not necessarily give the clear result.

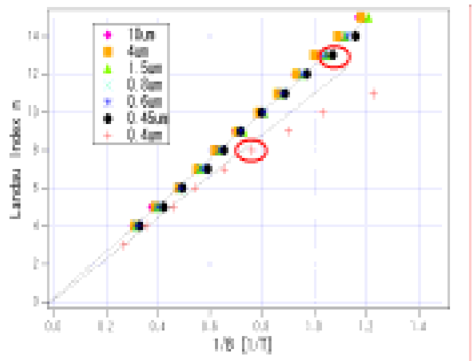

Fig.2(a) Landau plots for the SdH oscillations observed in various type 1 wires.

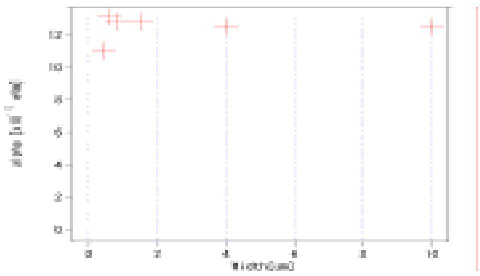

Fig.2(b) Spin-orbit coupling constant, α, plotted against the width of wire. Those are deduced from FFT analysis of the SdH oscillations.

Table1 Results of analysis of type 2 wire sample

Side Gate Voltage [V]	Effective Width of wire [um]	α [x10^{-12}eVm]	Spin-Spitting Δ_R[meV]
0	2	—	—
-30	1.5	31.7	9.8
-40	1.1	38.6	12.2
-45	0.8	44.5	13.6

Table 1 summarizes the results for the second type wire sample, in which the effective wire width estimated by the zero-field resistance, spin-orbit coupling constant, α, deduced from FFT analysis of the SdH oscillations and spin –splitting, $\Delta_R = 2\alpha k_f$ are included. When no side-gate voltage was applied, the spin-splitting was not so clearly identified. By applying large side-gate voltages > 30 V, however, the value of α likely increased as the voltage increased. This enhancement of α and hence Δ_R is probably originated from the lateral electric field > 20x10^6 V/m due to the side-gate voltage, since the value becomes almost compatible to that in the triangular potential well in the growth direction. Those situations are sketched in Fig. 3, where a new regime of spin-orbit interaction due to the lateral electric field was added in the type 2 wire sample.

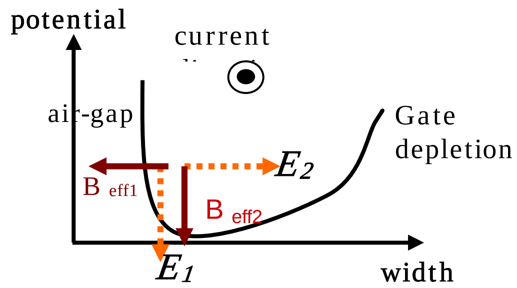

Fig. 3 Sketch of situation of spin-orbit interaction in side-gated diffusive wire. Lateral electric field, E_2, and associated effective magnetic field, B_{eff2} are suggested.

4. Summary

We have fabricated two kind diffusive quantum wires made at narrow-gap InGaAs/InAlAs heterojunction interface and studied their transport properties especially focusing on spin-orbit interaction of the 2DEG. In a mesa-etched wires with widths *w* = 0.3 ~ 10 μm, there occurred almost no change in the magnitude of spin-orbit coupling constant, α, although the 2DEG nature still remained even in the wire with *w* ~ 0.5 μm. In the wire, the width was controlled by the side-gate electrode, the enhancement of α was observed when the sample width was reduced by the side-gate voltage. This is probably due to the additional electric field and hence the effective magnetic field by the side-gate voltage application.

References

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