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Anisotropic effect of in-plane magnetic field on spin interference in an InGaAs based ring array

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1. Introduction

Recently, much attention has been focused on spintronics to utilize spin as well as charge of electrons. An electrical manipulation of spins is prerequisite for spintronics and quantum computers. The time reversal symmetric (TRS) Aharonov-Casher (AC) spin interference is an invaluable effect, to electrically control and detect spin phase through spin-orbit interaction (SOI). We propose a spin-interference device [1], made of III-V compound semiconductor heterotsructures with the Rashba SOI [2]. The device consists of a ring, for electrons travelling clockwise and counter-clockwise in the loop and causing interference. Also, it is covered by gate electrode to control spin precession rate via the Rashba SOI. The spin interference has been experimentally demonstrated [3] by using a ring-array structure in order to average out universal conductance fluctuations (UCF) and orbital-phase-induced Aharonov-Bohm (AB) oscillation. Therefore, the merit of the array structure is direct observation of the AC spin interference effect, leading to simultaneous spin manipulation and detection by an electrical way. In the previous study [3], the TRS AC effect has been studied in the first subband region and has been explained only by the Rashba SOI.

III-V compound semiconductors have typically two main SOI contributions, namely the Rashba SOI due to structural inversion asymmetry and the Dresselhaus SOI [4] due to bulk inversion asymmetry. Each has isotropic in effective magnetic field (B_{eff}) strength but different vector directions. However, when two SOIs coexist, B_{eff} strength becomes anisotropic. When carrier density (N_s) increases, electrons occupy the second subband, then intersubband scattering takes place. In this study, we investigate effects of the second subband and in-plane magnetic field on the AC spin interference.

2. Experiment and discussion

InAlAs/InGaAs based semiconductor, which provides a two-dimensional electron gas (2DEG), is processed by electron-beam lithography and reactive ion etching (RIE) to fabricate an array of 40×40 rings (diameter of each ring is 1.35 μm) and a Hall bar structure with the same current path of an array, as shown in Fig. 1. The sample is covered with 200-nm-thick Al_2O_3 insulator layer, deposited by atomic layer deposition (ALD) and a 200-nm-thick Au gate electrode in order to control carrier density(N_s) and the Rashba SOI strength (α). All measurements were

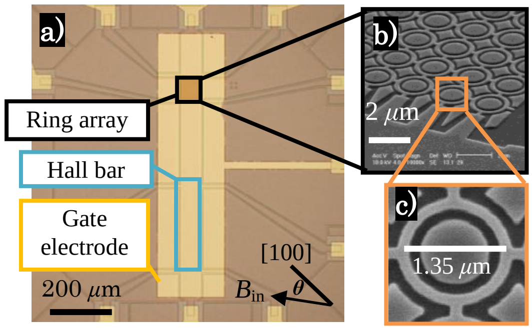

Fig. 1 SEM micrograph of the structure. a) A ring array and a Hall bar with a gate electrode. b) A ring-array structure. c) A 1.35 μm-diameter of a ring structure.

performed at a temperature of 1.6 K.

The analysis of Shubnikov – de Haas (SdH) oscillations using the Hall bar shows that if gate voltage (V_g) is higher than -0.5 V ($N_s = 1.94\times10^{12}$ cm^{-2}), the second subband is occupied. Total N_s (Fig. 2a, blue) is found to be linear function with V_g. The Rashba SOI strength was also obtained from the SdH oscillations.

Magnetoresistance of a ring array is measured as a function of V_g. The inset of Fig. 2b shows the Al`tshuler -Aronov-Spivak (AAS) interference, which has the period of magnetic flux h/2e. Graph in Fig. 2b is plotted by deducing the oscillation amplitude at zero magnetic field ($B_{perp} = 0$). The amplitudes are oscillated as a function of V_g. We found that when V_g > -0.5 V, in the second subband region, oscillation is suppressed and the amplitudes tend to be steady.

The AAS interference at $B_{perp} = 0$ is constructive since the acquired orbital phase difference along the TRS paths is zero. Therefore, the magnetoresistance should be maximum at $B_{perp} = 0$ if the spin phase does not play a role. It was found [3] that the magnetoresistance amplitude at $B_{perp} = 0$ is modulated by V_g, since the spin phase is controlled through the Rashba SOI strength. This effect is the so called AC spin interference effect. The AC oscillation period is consistent with the gate voltage dependence of the Rashba SOI strength.

At single subband occupancy, the advantage of the AC spin interference is that the oscillation amplitude is not smeared out even in the multi-mode channel. This is because the spin precession angle does not depend on the wave number. However, in the second subband region

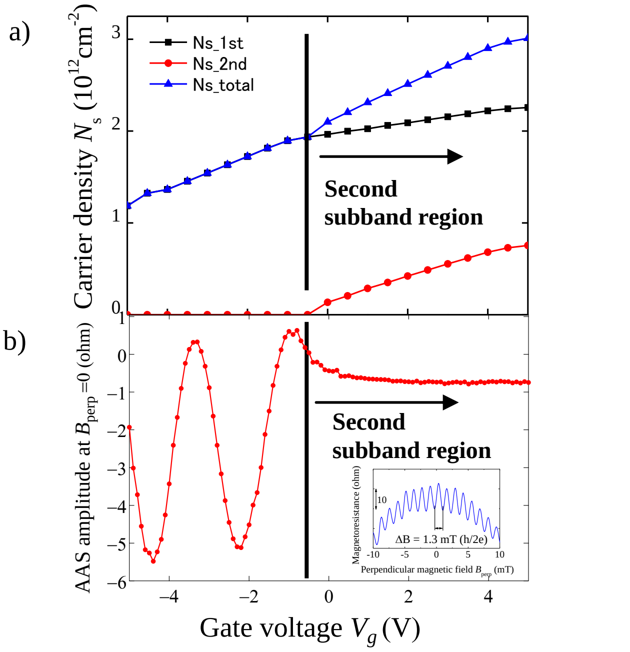

Fig. 2 (a) V_g dependence of carrier density N_s. At V_g > -0.5 V, electrons occupy the second subband region. (b) V_g dependence of AAS oscillation amplitude at B_{perp} = 0. AAS oscillation is suppressed in the second subband region. (Inset) Raw data of AAS magnetoresistance oscillation at V_g = -2 V.

with intersubband scattering, the acquired spin phases along the TRS paths in different rings are fluctuated. This is because the second subband has a different Rashba SOI strength [5] and the intersubband scatterings in different rings occur at random places. As a result, the spin interferences of the ring array are randomized and averaged out. It is theoretically pointed out [6] that due to the SO scattering, the amplitude of quantum interference is reduced by a factor of -1/2. Furthermore, the intersubband scattering enhances the electron-electron scattering rate [7], leading to the destruction of interferences. Thus, the suppression of the AC spin interference in the second subband region is explained by the randomization of the spin phase and the decoherence due to the electron-electron scattering.

Coexistence of both Rashba and Dresselhaus SOIs leads to the anisotropy of B_{eff}. When we apply an in-plane magnetic field (B_{in}), B_{in} and B_{eff} are in parallel to 2DEG plane. Various directions of B_{in} lead to different total parallel magnetic fields. With a fixed α parameter (a fixed V_g), the AC spin interference effect depends on the total parallel magnetic field. It is theoretically predicted [8] that, in the coexistence of Rashba and Dressehaus SOIs, the dephasing rate ($1/\tau_H$) of interference takes maximum or minimum when the angles of B_{in} from [100] direction are $\pi/4$ or $3\pi/4$.

To investigate the Dresselhaus SOI effect, we measured the AAS interference as a function of B_{in} angle from [100] direction. At V_g = -1.9 V, in the first subband region, we applied 1T of B_{in}, the amplitude of interference shows clear anisotropy with a dip at $\pi/4$ and a peak at $3\pi/4$, as shown in Fig. 3 (red dots).

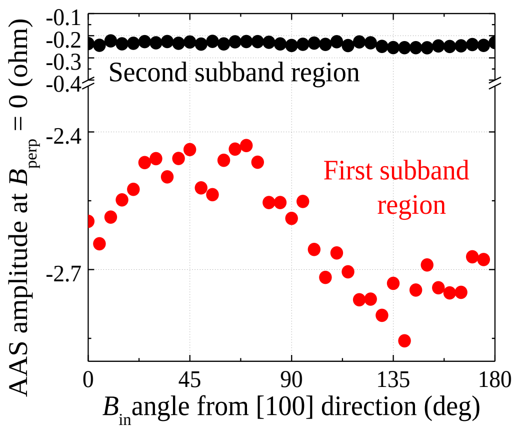

Fig. 3 Angle direction of in-plane magnetic field dependence of AAS amplitude at B_{perp} = 0. (Red dots) Anisotropy of the AC spin interference appears in B_{in} = 1.0 T, at V_g = -1.9 V, in the first subband region. (Black dots) In B_{in} = 0.4 T, at 2.3 V of V_g in the second subband region, anisotropy is suppressed.

This anisotropy suggests that the Dresselhaus SOI is not negligible. On the other hand, at V_g = 2.3 V, in the second subband region, as shown in the black dots of Fig. 3, anisotropy of AC spin interference effect becomes not clear.

It is noted that the applied B_{in} was 0.4 T for the measurement of the second subband, while B_{in} was 1.0 T for that of the first subband. The in-plane magnetic field of 1.0 T completely suppressed the AAS oscillation in the second subband region. Additional randomization of spin phase is expected since the linear Dresselhaus SOI strength in the second subband region should be different from that in the first subband. It is suggested that observed isotropic AAS oscillation amplitude at B_{perp} = 0 is related to the randomization of spin phase.

3. Conclusions

The effect of in-plane magnetic field on the spin interference was investigated both in the first and second subband regions. The AC spin interference observed in the first subband region shows anisotropy by changing in-plane magnetic field direction. This indicates that the Dresselhaus SOI is not negligible. In the second subband region, with intersubband scattering, AC spin oscillation is suppressed and becomes isotropic with in-plane magnetic field. These results are explained by the randomization of spin phase.

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