Suppression of Aharonov-Casher spin interference in an InGaAs ring array

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Abstract. An Aharonov-Casher (AC) spin interference is studied in a gate-fitted InGaAs ring array. The AC interference period is consistent with gate voltage dependence of Rashba spin-orbit interaction parameter in a single subband occupied region. However, the AC interference amplitude and oscillations are suppressed above a particular gate voltage where the second subband is occupied. This suppression is attributed to the decoherence induced by inter-subband scattering.

1. Introduction

An electron acquires a phase around magnetic flux due to the vector potential leading to Aharonov-Bohm (AB) effect [1] in an interference loop. From the view point of inherent symmetries between magnetic field and electric field in the Maxwell equations, Aharonov and Casher have predicted that a magnetic moment acquires a phase around charge flux line [2]. It should be noted that the original Aharonov-Casher (AC) effect has been proposed for charge neutral particles since the electric field modifies the charged particles in the same sense as the original AB effect was predicted in the situation where the magnetic flux should not exist in an electron path. It is pointed out that the AC phase shift can be derived from spin-orbit interaction (SOI) [3]. The major difference between the AB and AC effects is that the AC effect is not observable if the electric field is not in the electron paths. Cimmino et al. [4] managed to perform the AC interference experiment in a neutron (having spin 1/2 but no charge) beam loop using a voltage of 45 kV to create the electric field. However, the modified AC phase shift was only 2.2 mrad since the SOI is not strong in vacuum.

Mathur and Stone have theoretically shown that the effects of SOI in disordered conductors are manifestation of the AC effect in the same sense as the effects of weak magnetic fields are manifestation of AB effect [5]. They have proposed the electronic AC effect in a mesoscopic interference loop made of GaAs 2DEG with the Dresselhaus SOI [6]. It is emphasized that a thousand-fold improvement in its experiment can be expected in the electronic AC effect since the SOI in semiconductors is much enhanced compared with that in vacuum. We have proposed an AC spin interference in a mesoscopic ring [7] based on the gate controlled Rashba SOI [8], [9]. However, the spin interference is not easily observable since the gate electric field tunes not only SOI but also carrier density, namely electron wave length which affects the interference. In this paper, we have measured time reversal symmetric Al’tshuler-Aronov-Spivak (AAS) oscillations [10] in an array of mesoscopic loops in order to distinguish spin interference from other spurious effects. The AAS oscillation amplitude which does not depend on the electron wavelength but depends on spin
precession shows an oscillatory behaviour as a function of the gate voltage. The observed AC spin interference is consistent with the gate voltage dependence of the Rashba SOI. This result shows that the spin precession can be controlled by the gate voltage. However, the AC spin interference amplitude and oscillatory behaviour are suppressed in the second subband occupied gate voltage region. The spin decoherence induced by inter-subband scattering results in this suppression.

2. Experiment and Discussion

The resistance of a mesoscopic ring is affected by different quantum interference effects. The well known AB effect results in a resistance oscillation with a magnetic flux period of h/e. The AB effect is sample specific and very sensitive to the Fermi wavelength, therefore, the interference pattern is rapidly changed by the gate voltage. In order to detect the AC effect we used another quantum interference phenomenon, the AAS effect. The AAS effect is an AB effect of time reversal symmetric paths, where the two wave function parts go all around back to the origin on identical paths, but in opposite directions. In this situation, any phase which is due to path geometry will be identical and will not affect the interference. This also means that it is independent of the Fermi energy (and consequently the carrier density $N_s$). However, the AAS effect is sensitive to the spin phase when the SOI plays a role. If there is magnetic flux inside the paths the resistance will oscillate with the period of h/2e. When the flux is increased the resistance oscillates with the period h/2e, but the AAS oscillation amplitude decays after a several periods because of averaging between different paths in the ring, with different areas. If there is SOI in the ring, the electron spin will start precessing around the effective magnetic field and change the interference at the entry point. Note that the effective magnetic field due to the SOI is much stronger than the external magnetic field to pick up AAS oscillations. The precession axes for the two parts of the wave function are opposite and therefore the relative precession angle is twice the angle of each part. If the relative precession angle is $\pi$ the spins of the two parts are opposite and can not interfere, and the AAS oscillations disappear. If the relative angle is $\pi/2$ the two parts will have the same spin but opposite signs because of the 1/2 spin quantum laws (a $4\pi$ rotation is required to return to the original wave function), effectively changing the phase of the AAS oscillations by $\pi$, which we interpret as a negative amplitude. By using arrays rather than single rings we get a stronger spin signal and we average out some of the universal conductance fluctuations (UCF) and sample specific AB oscillations.

![Figure 1. (a) SEM photograph of fabricated InGaAs ring array. The whole area of the sample is covered with gate electrode to control the Rashba SOI parameter. (b) AAS oscillation measured at $V_g = -2.4$ V. AB oscillation is suppressed by ensemble averaging due to 40x40 rings.](image)
The sample was epitaxially grown on (100) InP substrate by metal organic chemical vapour deposition. The quantum well (QW) channel consists of 2.5 nm In_{0.53}Ga_{0.47}As / 10 nm In_{0.7}Ga_{0.3}As for QW / 2.5 nm In_{0.53}Ga_{0.47}As. The epitaxial wafer was processed by a reactive ion etching (RIE) into a 40×40 ring array as shown in Fig. 1 (a). The ring array is placed close to the Hall bar to measure the carrier density and the strength of the Rashba SOI. For a gate insulator, a 100 nm Al_{2}O_{3} was deposited on the whole sample area by atomic-layer deposition (ALD). All the measurements were preformed with a ^3He cryostat refrigerator at $T = 0.27$ K. We measured magnetoresistance oscillations in the ring array by changing gate bias voltages, $V_g$. The external magnetic field was applied perpendicular to the QW plane. Figure 1 (b) shows an example of magnetoresistance oscillation measured at $V_g = -2.4$ V. By increasing the magnetic field, the amplitude of the oscillation is decreasing. This is because the time reversal symmetry is broken by the magnetic field, and it is an essential feature of the AAS interference. The period of AAS oscillation is given by quantized magnetic flux of $\hbar/2e$, and the experimentally obtained periodic magnetic field is about $\Delta B = 1.7$ mT, which is consistent with the ring radius of 0.62 μm. The sample specific AB oscillation which has $\hbar/e$ period is almost completely suppressed because of the ensemble averaging effect by the 40x40 ring array.

Sheet carrier density, $N_s$, as a function of gate voltage $V_g$ was determined from Shubnikov de Haas (SdH) oscillations in the Hall bar. The results are shown in Fig. 2. The total carrier density is linearly increasing with the gate voltage. It should be noted that the second subband is occupied above the gate voltage of $V_g = -1$ V. The effective mass $m^* = 0.05$ was derived from the temperature dependence of SdH oscillation amplitude. The Rashba SOI parameter $\alpha$ was obtained from the weak antilocalization analysis of the magnetoresistance measurement in the weak magnetic field region. The Rashba SOI parameter is almost linearly decreased such as

$$\alpha (10^{-12} \text{ eVm}) = 7.81 - 3.32 \times N_s (10^{12} \text{ cm}^{-2})$$

Figure 3 shows color-scale plots of the gate voltage dependence of AAS oscillations. It is clearly found that the AAS oscillation phase is periodically changed as increasing the gate voltage. This AAS oscillation phase change can be attributed to the AC spin interference effect where the spin phase is modified by the gate electric field. However, we can see almost no gate voltage dependence above $V_g = -1$ V, which corresponds to the second subband occupied region.

To investigate it more clearly, the AAS oscillation amplitude at $B = 0$ mT as a function of the gate voltage (AC spin interference ) is plotted as shown in Fig. 4. As is clearly seen, the AC oscillation is suppressed above $V_g = -1$ V although a clear periodic AC oscillation is observed under a single subband region. The suppression of the AC interference which is reproducible in other two samples.
will be discussed below. Another interesting feature of this experiment is that the AC oscillation has negative bias of about -3.5 \( \Omega \). This negative bias was not observed in our previous AC spin interference experiment with 4x4 and 5x5 ring arrays [11]. It is known that randomization of spin phase in time reversal symmetric interference loops gives rise to positive magnetoresistance near zero magnetic field (resistance dip), and is called the weak antilocalization. The negative bias is explained by the weak antilocalization effect appeared in the large number of rings.

The modulation of an AC oscillation amplitude in a time reversal interference ring can be expressed as a function of the Rashba SOI parameter \( \alpha \),

\[
\frac{\partial R}{\partial R_{\alpha}} = \cos \left[ 2\pi \sqrt{1 + \left( \frac{2m^* \alpha}{\hbar^2} \right)^2} \right] R
\]

where \( \partial R_{\alpha} \) and \( \partial R_{\alpha=0} \) is the AC amplitude with and without SOI, respectively. A dashed line in Fig. 4 is a calculated result on the basis of the above equation. All parameters used in the calculation are experimentally obtained ones. Here, we assume the negative bias resistance of -3.5 \( \Omega \). The experimentally observed AC period is consistent with the theoretical one. However, there is a phase difference between the experiment and the calculation in the AC oscillations. A possible reason is that there exists a finite Dresselhaus SOI which is expected in the III-V compound semiconductors. A phase shift in the AC oscillation is predicted in the presence of the Dresselhaus SOI [12].
It should be noted that the spin precession angle does not depend on the wave vector. This is an advantage of the spin interference device [7]. The most surprising feature in the present experiment is that the AC oscillation is suppressed in the second subband occupied region. The Rashba parameter $\alpha$ in the second subband is different from that in the first subband [13]. This is because the electric fields which are felt by the first and second subbands are different in a QW due to the difference in electron distributions. It is also expected that the Dresselhaus SOI parameters are different among two subbands because the electron confinement in the QW is crucial for the Dresselhaus SOI. These two subbands provide electron spins with different spin precession angles. **We could not observe any oscillatory behaviours in the second subband region.** Further theoretical analysis is required for the AC spin interference in the second subband occupied region.

3. Summary

We have investigated AC spin interference in a gate-fitted InGaAs ring array. The AC interference period is consistent with the gate voltage dependence of the Rashba SOI parameter in a single subband occupied region. The AC interference amplitude and oscillations are suppressed in the second subband occupied region. This suppression is attributed to the dephasing induced by inter-subband scattering. Further theoretical analysis is required.

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