Effect of Spin-orbit Interaction in an InGaAs-based Aharonov-Bohm Ring Structure

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Abstract

The interference effect in a gate controlled mesoscopic Aharonov-Bohm ring structure is studied in the presence of spin-orbit interaction. After ensemble averaging, the Fourier spectrum of h/2e oscillations as a function of gate voltage showed an oscillatory behavior. The oscillatory behavior is possibly due to the Aharonov-Casher type interference.

Key words: Aharonov-Bohm structure; spin-orbit interaction;spin interference

Much attention is focused on the effects of spin-orbit interaction (SOI) on mesoscopic transport. For example, a spin-orbit induced Berry phase in Aharonov-Bohm (AB) structures was predicted theoretically [1], [2]and was investigated experimentally in the Fourier (FFT) spectrum [3],[4]. It has been predicted that the FFT spectrum shows an oscillatory behavior as a function of the SOI parameter α [2]. In addition to the geometrical Berry phase, we have shown that a dynamical spin phase [5] is induced in the presence of Rashba SOI [6]. It has been demonstrated experimentally that the SOI in InGaAs two-dimensional electron gas (2DEG) systems can be controlled by a gate voltage [7]. Recently, the cross-over from weak antilocalization (WAL) to weak localization has been observed by controlling the asymmetry of the InGaAs quantum wells [8]. This leads to possibilities of studying spin-controlled transport as well as for novel spin device applications [9].

We have performed gate-controlled AB experiments in the presence of Rashba SOI. The actually fabricated AB-ring structures using InGaAs-based 2DEG are not completely ballistic and not completely symmetric (i.e. the channels have not exactly the same length). We focus on the ensemble averaged h/2e oscillations to eliminate the sample-specific features and interference from electron part of wave function due to this asymmetric effect.

The heterostructure used in the present experiment is an InAs-inserted InGaAs/InAlAs system [10]. The SOI parameter α was deduced from the analysis of the beating pattern that appeared in the Shubnikov-de Haas (SdH) oscillations [10]. The AB-ring structures were fabricated by electron beam lithography (EBL) and electron cyclotron resonance (ECR) dry etching. The Au/Ti gate electrode covered the entire area of the AB-ring. The radius and channel width of the fabricated AB-ring are 0.79 μm and 0.24 μm, respectively. The magnetoresistance *R(B)* measurements were performed at T= 0.3 K using conventional lock-in techniques.

The *R(B)* curves were measured as a function of gate voltage Vg from -0.4 V to 0.4 V in 0.01 V step. The AB-ring showed clear magnetoresistance oscillations as a function of magnetic field B. This is a signature of a phase coherent device. The phase of the h/e oscillations is sample-specific, whereas the h/2e oscillations, which contain a contribution from time-reversed tra-

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jectories, have a sample-independent phase. To eliminate the sample-specific feature, we averaged *R(B)* by summing the neighboring 5 sets of data with different *Vg* values. If the ensemble averaging range is smaller than the spin phase shift of π, the ensemble average does not wash out the spin phase information. Figure 1 shows the h/e and h/2e oscillations as a function of *Vg*.

We performed the FFT and filtering analysis to pick up the h/2e oscillations $\Delta R(B)$ from the magnetoresistance *R(B)*. The values of $\Delta R(B)$ always showed the minimum at B= 0 in the whole range of applied gate voltages. By increasing the sampling number for the ensemble average, it was found that the amplitude of the FFT spectrum with h/e oscillations was decreasing, whereas the one with h/2e oscillations was almost constant. It was also found that the h/2e oscillation amplitude after ensemble averaging was rapidly damped with increasing magnetic field *B*. These results suggest that the main contribution to h/2e oscillations is due to the Altshuler-Aronov-Spivak (AAS) oscillations [12], and the minima at B= 0 can be attributed to the WAL affected by the spin-orbit scattering. Figure 2 shows the FFT spectrum of h/2e oscillations as a function of *Vg*. The FFT spectrum shows an oscillatory behavior as a function of *Vg*. The typical period is around $\Delta\, Vg$= 0.1-0.18 V.

It is shown that the effects of SOI in disordered conductors are manifestations of Aharanov-Casher (AC) effect in the same sense as the effects of weak magnetic field are manifestation of AB-effect[11]. The spin phase shift for h/2e oscillations due to the SOI is given by $\Delta\varphi = 4\pi r\alpha m^*/\hbar^2$, where r is the radius of the ring, m^* is the electron effective mass. The SOI of this heterostructure changes almost linearly with the value of *Vg*. If we use the experimentally obtained relation of $\Delta\alpha/\Delta\, Vg$= 0.93 x 10^{-11} eVm/V [10], the expected period of the spin-interference is 0.12 V, which is close to the experimental result. This implies that this oscillatory behavior in the FFT spectrum as a function of *Vg* is possibly due to the spin-interference that is induced by the SOI.

In summary, we have measured the h/2e magnetoresistance oscillations in AB-ring structure by changing the gate voltage, and therefore, the SOI. The observed minima of magnetoresistance of h/2e oscillations at B= *0* can be explained in terms of WAL. We also observed an oscillatory behavior in FFT spectrum of h/2e oscillations as a function of *Vg*. This could be attributed to the spin interference that is induced by the SOI.

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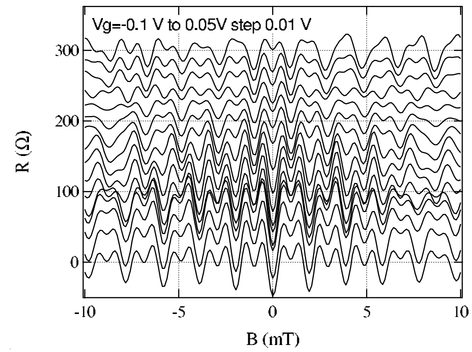

Fig. 1. The h/e and h/2e oscillations as a function of *Vg* after averaging 5 *R(B)* data and filtering.

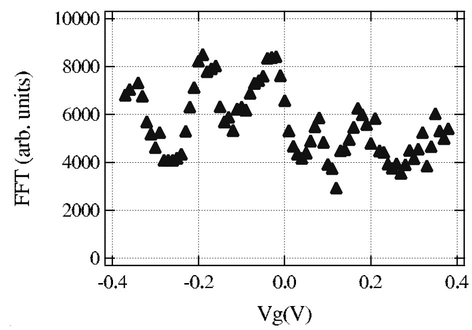

Fig. 2. The FFT spectrum of h/2e oscillation as a function of gate voltage *Vg* after averaging 5 *R(B)* data.

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