Spin-flip Process and Quantum Decoherence in a Quantum Dot

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Abstract

We studied coherence of electrons traversing a quantum dot (QD) by using an Aharonov-Bohm (AB) interferometer. It was found that for the so-called "spin-pair" peaks of Coulomb oscillations the amplitude of the AB oscillation is different between one and the other side of each peaks and that the amplitude is smaller for the sides facing with each other than the outer ones. Similar result was obtained for a QD in the Kondo state. These observations agree with the theoretical model that relates a spin-flip process of traversing electrons through a QD to the decoherence.

Key words: Aharonov-Bohm effect, quantum dot, spin-flip process, decoherence
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1. Introduction

Quantum coherence of electrons plays a central role in mesoscopic transport phenomena such as weak localization, universal conductance fluctuation, and Aharonov-Bohm (AB) effect [1]. So the understanding of microscopic mechanisms that degrade quantum coherence has been a significant issue not only for fundamental physics but also for challenges to quantum devices. Coherent transport through a quantum dot (QD) embedded in one of arms of an AB ring gives an optimal experimental stage to explore quantum coherence associated with a single tunable scatterer.

Such a system has been studied for several years, and it is known that the coherence survives through QDs [2–6]. In terms of quantum decoherence, current flowing a quantum point contact coupled to a QD was proved to deteriorate interference signal by measuring "which-path" an electron passed [7].

In this paper, we present an experiment focusing on an influence of the spin degree of freedom in a QD on the AB interference [8,9]. We consider the simplest situation where spin-degenerate single-particle levels distribute with an equal spacing in a QD. When the number of electrons in the QD is odd, the topmost level has an excess electron, say with spin-up, as depicted in Fig. 1(a). After an electron with down-spin enter the QD, there arises two possibilities for the QD to let go of an electron (Fig. 1(b)). If the up-spin electron goes away from the QD (Fig. 1(c)), coherence will be lost since it leaves "traces" in the QD, so the interference effect is degraded. This process is the most primitive case of quantum decoherence caused by spin scattering. Because this occurs only when the number of electrons in the QD is odd [8,9], the interference signal should be reduced at sides of a Coulomb oscillation peak facing the Coulomb blockade valley of odd number of electrons, producing an asymmetry of coherence for one Coulomb peak and its an even-odd behavior for successive Coulomb peaks (Fig. 1(d)).

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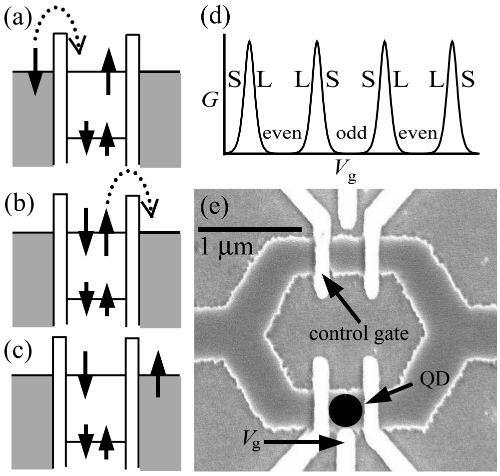

Fig. 1. (a), (b), and (c) Schematic drawings of energy diagram of a QD and the dephasing process of a traversing electron by flipping its spin. (d) Illustration of Coulomb peaks and the expected magnitude of AB interference signal indicated by letters "L" (large) and "S" (small). Because the parity of the number of electrons in the QD changes by turns for successive Coulomb peaks as changing the gate voltage V_g, the direction of the asymmetry changes alternately. (e) Scanning electron micrograph that has the same geometry with measured sample.

2. Experiment

We prepared a QD-AB-ring system fabricated on a two-dimensional electron gas (mobility 90 m^2/Vs and sheet carrier density $3.8 \times 10^{15}\ \mathrm{m}^{-2}$) in GaAs/AlGaAs heterostructure by using electron beam lithography, wet etching and vapor deposition of metallic gates (Fig. 1(e)). A QD was formed in the lower arm of the AB ring by negatively biasing both sides of the three gates, the middle one (V_g) was used to control the electrostatic potential of the QD, and the one of the upper gates was used to tune the transmission bypassing the QD. The sample was cooled in a dilution refrigerator with base temperature of 30 mK and was measured by standard lock-in technique (80 Hz frequency and 10 μV excitation voltage) in the two-terminal setup. A superconducting solenoid was used to apply the magnetic field (B) perpendicular to the sample.

3. Results and discussions

Successive occupation of a spin-degenerate level in a QD by up-spin and down-spin electrons, which is the underlying assumption for the even-odd behavior of the asymmetry, is known to occur rarely in semiconductor QDs [10–12]. Therefore, it is necessary firstly to search for ideal condition, a so-called "spin-pair" state, which can be found by observing the B-dependence of position and height of Coulomb peaks; a spin-pair appears as a pair of adjacent peaks with the same variation in their position and height as a function of B because they belong to the same orbital state.

We measured the Coulomb oscillations as sweeping V_g at fixed B's. The parametric variations of the position and height of nine successive Coulomb peaks as a function of B are summarized in Figs. 2 (a) and (b), respectively. These were obtained by fitting each Coulomb peak to the conductance form $G_\mathrm{h} \cosh^{-2}((V_\mathrm{g} - V_\mathrm{p})/w) + G_\mathrm{ref}$ where G_h, V_p, w, and G_ref are the peak height, peak position, the peak width in unit of V_g, and the conductance of the reference arm, respectively. As seen in Figs. 2(a) and (b), the behaviors of the peak 5 and the peak 6 are correlated far better than the other sets of peaks, indicating that these two are a spin-pair in this range of B. The small peak spacing between them (see Fig. 2 (a)) also agrees with the intuition that the addition energy is small for successive occupation of the same energy level because it does not require level spacing energy to put an electron.

For more quantitative analysis, we calculated the standard deviation of peak spacing (ΔV_p) from Fig. 2(a) and the root-mean-square (rms) value of difference of neighboring peak height (ΔG_h) from Fig. 2(b), and they are plotted in Fig. 2(c) as the vertical and the horizontal axes, respectively. Because both of them are expected to be simultaneously small for the spin-paired peaks, we conclude that the peak 5 and the peak 6 originate from a spin-pair state. We note that the presence of such spin-pair peaks is scarce as reported previously [12] and the typical ratio of finding a spin-paired peak out of all the Coulomb peaks is less than 10 %.

Next, we measured the AB oscillations as sweeping B at fixed V_g's to get the magnitude of coherence of the spin-pair peaks 5 and 6 in Fig. 2. Figure 3(a) is

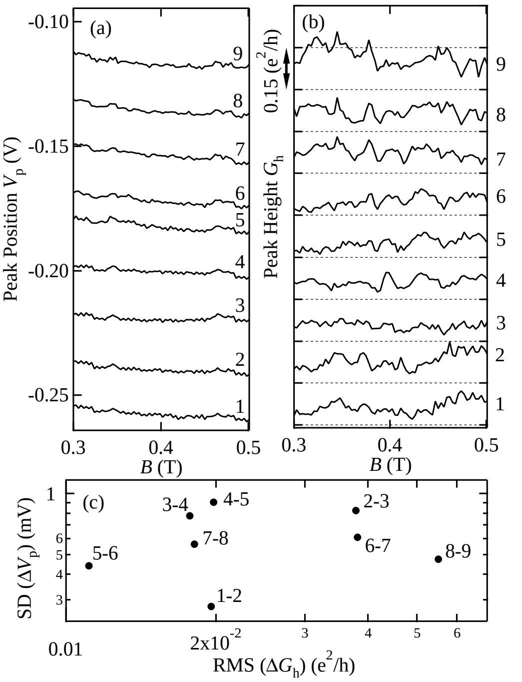

Fig. 2. Magnetic field dependence of (a) position and (b) height of nine successive Coulomb peaks as a function of B. The peaks are numbered as shown in the plot. (c) Standard deviation (SD) of the difference of peak position (ΔV_p) in (a) is plotted against the root mean square (RMS) value of the difference of peak height (ΔG_h) in (b). Because the points closer to the origin indicate higher correlation between the peaks, we can regard the peak 5 and 6 as a spin-pair peak as well as from the small peak spacing in (a).

a gray-scale plot of the extracted AB component by using fast Fourier transform as a function of V_g and B. The vertical lines indicate the peak positions. The phase of the AB oscillation shows abrupt change by π near each Coulomb peak, reflecting the two-terminal setup of our measurement [13,14]. In Fig. 3(b), we plot the amplitude of the AB oscillation averaged over ten AB periods around $B = 0.485$ T as a function of V_g. We selected the field range where the peak position does not shift largely as sweeping B. The dip in the AB amplitude at the peak position is due to the phase jump of the AB oscillation. Therefore, the data can be viewed that the averaged AB amplitude for one Coulomb peak is composed of of two sub-peaks with a dip in between.

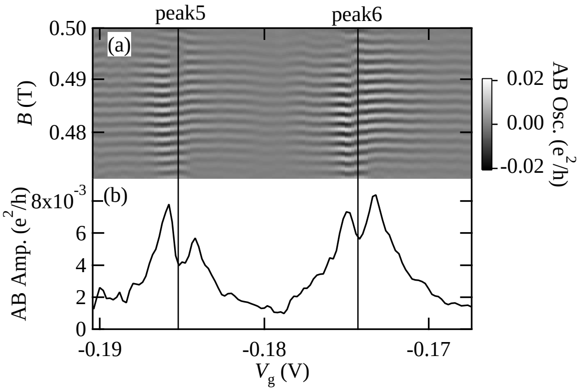

Fig. 3. (a) Gray-scale plot of the AB oscillation component for the spin-pair peaks in Fig. 3 against the gate voltage V_g and the magnetic field B. (b) Averaged amplitude of the AB oscillation measured at each V_g. Vertical lines represent the center of the Coulomb oscillation peaks where the π phase jump degrades the AB amplitude in our two-terminal setup. The AB amplitude is asymmetric with respect to the center of the peak.

The point is that the two sub-peaks composing the AB amplitude for one Coulomb peak are different in its height, showing the asymmetry of the interference signal. Moreover, the direction of the asymmetry is reversed between the adjacent spin-paired Coulomb peaks as is expected from the successive occupation of a spin-degenerate level as depicted in Fig. 1(d). These results stand for the predicted effect of spin-flip process on the coherence.

Another evidence was obtained from a measurement when the Kondo effect appears. Because ordinary Kondo effect emerges from spin-flip scattering, the conditions for spin-flip process should be fulfilled in Kondo valleys. Figures. 4(a) and (b) show the temperature and the bias-voltage dependence of the QD with the reference arm closed, respectively. From analyses similar to the reported one [4,15], we find the temperature dependence is consistent with the Kondo effect for the QD with spin 1/2 and the Kondo temperature is estimated to be $T_\mathrm{K} \sim 450$ mK at the middle of the valley. This result guarantees that a spin-pair state exists in this energy range and works as the source of the Kondo effect.

Next, we opened the reference arm and measured the AB oscillation. In Fig. 4(c), we plotted the averaged conductance (●) and AB amplitude (○) as a function of V_g. Except for the absence of the dip structure at the conductance peak because of the unique phase shift for the Kondo QD, we found qualitatively the same result

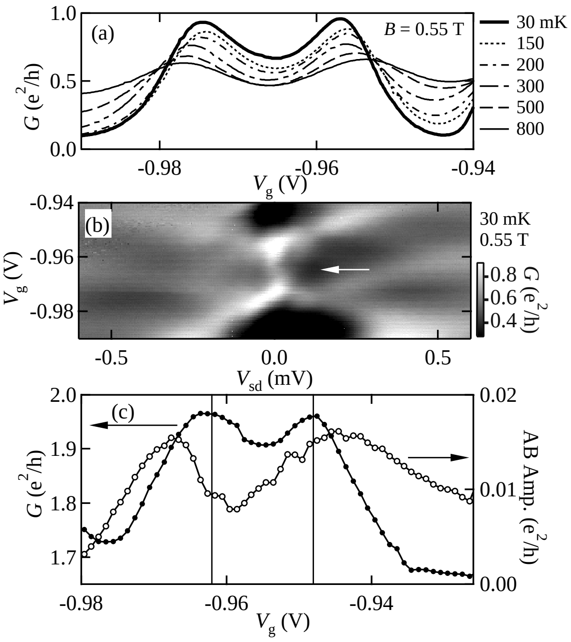

Fig. 4. (a) Temperature dependence and (b) bias-voltage dependence of the Coulomb oscillation with the other arm of the ring was pinched off, both showing clear sign of the Kondo effect. White arrow in (b) indicates the Kondo resonance at zero bias. (c) Measured conductance (filled circle) and AB amplitude (open circle) averaged between $B = 0.525$ T and $B = 0.585$ T are plotted against V_g. The vertical lines are drawn along the conductance peaks.

on the spin-pair peaks; the AB amplitude is reduced at the Kondo valley, yielding the asymmetry of the interference signal and its even-odd behavior.

4. Conclusion

In conclusion, we observed the asymmetry of the AB interference signal through a QD with respect to the center of the Coulomb peak. The measurement on the spin-pair peak and the Kondo QD indicate that the spin-flip process in the QD is a possible cause of excess dephasing. The present study is the first experimental demonstration that the interference effect through a single scatterer is reduced depending on its spin state, which is a microscopic and fundamental process of spin-scattering induced quantum decoherence.

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