Spin-flip Process and Quantum Decoherence in a Quantum Dot

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The experiments of transport through Aharonov-Bohm (AB) rings with quantum dots (QD's) have established that quantum coherence of traversing electrons survives even after experiencing strong Coulomb interactions with other electrons in a QD [1]. Then a natural and important question arises: What causes quantum decoherence in the QD? In Ref. 2, they reported that an artificial "environment" leads to decoherence. Here we present experimental results, which suggest that the exchange interaction between the traversing electrons and the ones in the QD leads to a significant reduction of coherence through spin-flip processes.

When a QD has an electron, say with up-spin, in its topmost spin-degenerate energy level, only an electron with down-spin can tunnel into the QD (Fig. 1(b)). When the electron with up-spin tunnels off and escapes away from the dot, the coherence is lost (Fig. 1(d)) because the dot memorizes the path of the electrons as its total spin. This can be viewed as spin-flip process inside the QD, and occurs only when the number of electron in the QD is odd [3]. Since the number of electrons in a QD changes by one at the peaks of Coulomb oscillation, the spin-flip decoherence should alter the amplitude of AB oscillation at the Coulomb peaks.

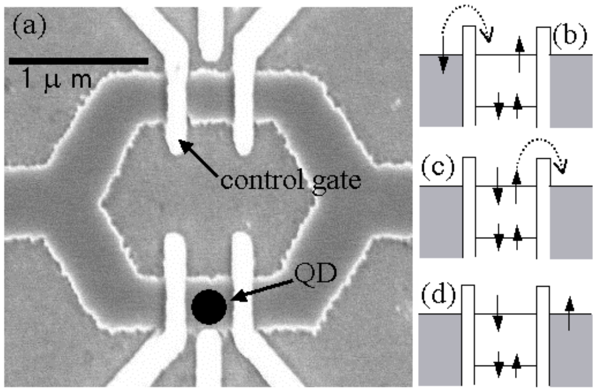

Fig. 1: (a) Scanning electron micrograph of the sample. By tuning the gates (white region), a quantum dot can be formed in one arm of the AB ring. The one of gates on the other arm was used to control the transmission bypassing the QD. Schematic drawings from (b) to (d) represent an electron traversing through a QD with its spin flipped, which causes decoherence (see text).

To look for the effect, we prepared a QD embedded in an AB ring (Fig. 1(a)) that was fabricated by wet etching of a two-dimensional electron gas (mobility 90 m^2/Vs and sheet carrier density 3.8×10^{15} m^{-2}) at a GaAs/AlGaAs interface and depositing metallic gates.

The experiments were performed with a base temperature of 30 mK. As shown in Figs. 2(a) and (c), Coulomb oscillations with offsets by the bypass arm appeared versus the center gate voltage of the dot. Figures 2(b) and (d) show AB oscillations measured at the points indicated by the arrows and characters A-E. In the experiment of Fig. 2(a) and (b), the magnetic field was around 0.23 T. The amplitude of the AB oscillation clearly changes at the Coulomb peak. This is in accordance with the prediction of the above spin-flip model. Many of the Coulomb peaks show in the low magnetic field region, where the Zeeman splitting is smaller enough than both the temperature and the lifetime broadening of the energy level in the QD. In the high field region, on the other hand, we found the asymmetry got weakened (Fig. 2(c) and (d)) in many of the peaks, supporting that the effect depends on the spin state in the QD.

However such naive interpretation fails to explain the variation of the AB amplitude for successive Coulomb peaks. That is, the amplitude should change large and small by turns as the number of electrons in the dot changes, while the results show much more complicated behavior. This might be due to the fact that the many-body states in the dot cannot be expressed as simple spin-pair ladder as described in Figs. 1(b)-(d).

Hence to get more sound evidence, we should look for the states where "spin-pair" approximation works well. Such spin-pair states can be found in two ways. One is to observe the magnetic field dependence of position and height of the neighboring Coulomb peaks as the energy levels in the same orbital states are supposed to respond similarly to the magnetic field. The other is a QD in the Kondo regime [4].

Figure 3(a) shows the results for such "spin-pair" states identified by the former method. In order to exclude artifacts due to multi-channel beating etc., we show the averaged amplitude versus the center gate voltage. The amplitude is clearly diminished between the successive Coulomb peaks, where the dot has odd number of electrons thus spin 1/2. The dips in the amplitude just at the peaks are due to an artifact so-called "phase-lapse" [1]. This is clear evidence that the spin-flip reduction of coherence certainly exists. We also observed the same tendency for a state in Kondo regime.

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[2] E. Buks *et al.*, Nature **391,** 871 (1998).
[3] H. Akera, PRB **47**, 6835 (1993); J. König, and Y. Gefen, PRL **86**, 3855 (2001).
[4] D. Goldharber-Gordon *et al.*, Nature **391**, 156 (1998).

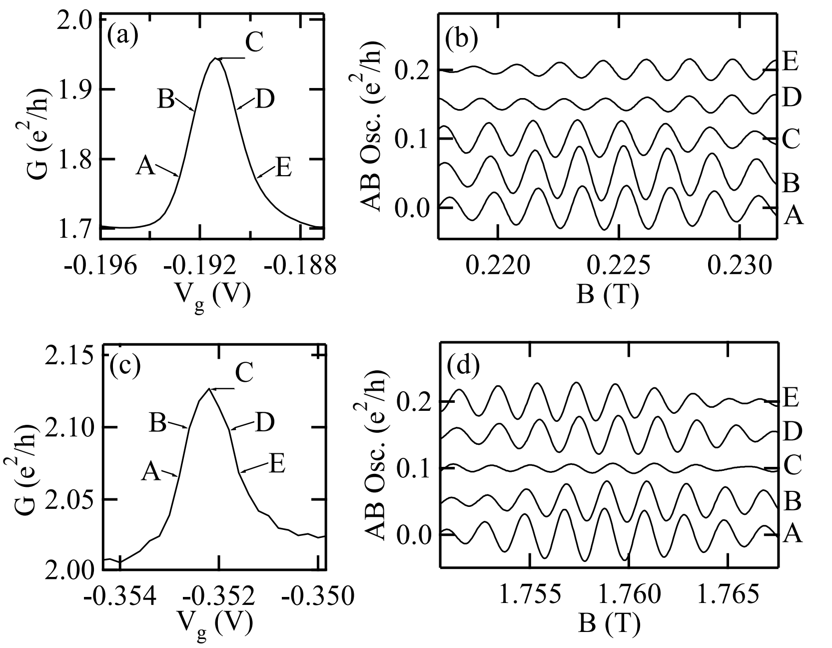

Fig. 2: (a) Coulomb oscillation peak taken at ~ 0.225 T where the Zeeman splitting is much smaller than $k_B T$ and lifetime broadening of the energy level in the QD. (b) AB oscillation component taken at each point A – E in (a). The amplitude in A and B is larger than that in D and E. (c), (d) Corresponding data taken at higher field. The asymmetry of the amplitude is reduced to almost the same level between A, B and D, E. The data are displayed with offset in (b) and (d).

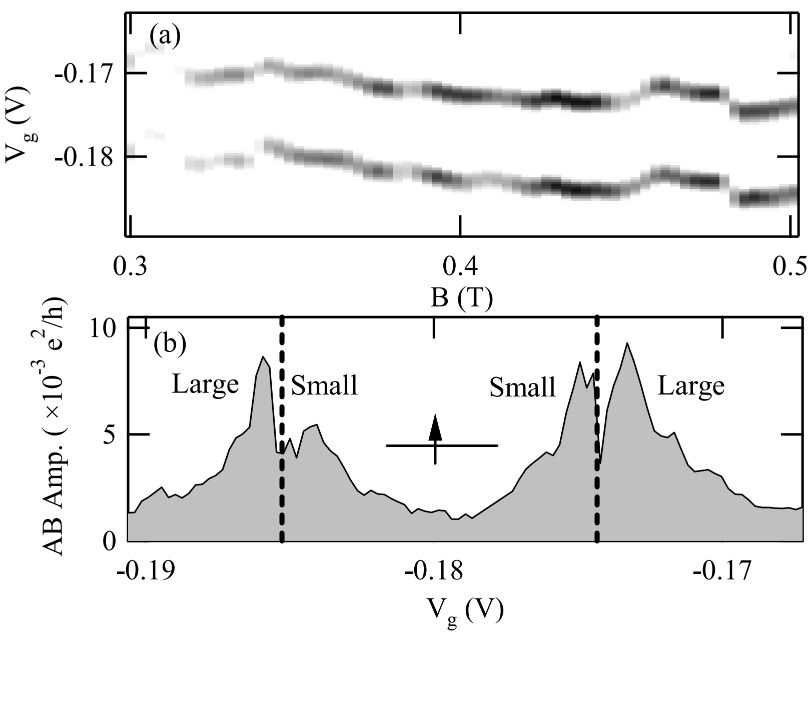

Fig. 3: (a) Gray scale plot of the magnetic field dependence of position and height of two successive Coulomb peaks (black color indicates high conductance). They are identified as "spin-pair" state. (b) AB oscillation amplitude as a function of the gate voltage for the "spin-pair" peaks taken around 0.49 T. At the valley in the middle of two peaks, where the single electron occupies the spin degenerate level, the amplitude is reduced due to the spin-flip process. The vertical lines represent the peak positions.