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Quantum capacitance probing of spin and charge dynamics in a one- and two-electron double quantum dot

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Abstract

Using quantum capacitance measurements, we study charge and spin dynamics in a double quantum dot containing only one or two electrons. The measurements exploit a new technique that allows the dynamics to be investigated over a wide frequency range from hertz to a few ten gigahertz. We find a significant difference in the frequency dependence of the quantum capacitance in the one- and two-electron regimes, which reveals the relevance of spin relaxation and the Pauli spin blockade in the two-electron system.

1. Introduction

Capacitance spectroscopy is a useful technique for probing electronic properties in mesoscopic systems. In a classical conductor, the capacitance is a constant, characteristic of geometrical electrostatic configuration of the conductor. On the other hand, in mesoscopic conductors, such as two-dimensional electron gas, carbon nanotubes, and semiconductor quantum dots, quantum mechanical correlation affects the capacitance, where quantum capacitance C_Q as well as the geometrical capacitances C_g, i.e., $1/C = 1/C_g + 1/C_Q$, contribute to the total capacitance C [1]. In particular, in mesoscopic systems, such as a Cooper-pair box and a semiconductor quantum dot, C_Q is given by the first derivative of charge Q, or equivalently by the second derivative of energy E at an avoided crossing, with respect to gate voltage V_G, i.e., $C_Q \equiv \partial Q / \partial V_G \equiv \partial^2 E / \partial V_G^2$ [2].

In this paper, we study charge and spin dynamics in a double quantum dot (DQD) by measuring the frequency dependence of C_Q in one- and two-electron regimes. We use a newly developed capacitance measurement technique in which high-frequency signals are separately applied to the DQD and a quantum point contact (QPC). The capacitance associated with the charge transfer in the DQD is detected as a change in the current flowing through a nearby QPC [3]. Along the boundary of the inter-dot tunneling regime in a charge stability diagram of the DQD, C_Q is observed. The C_Q signal decreases as the frequency increases; however, we find a noticeable difference between the cases in the one- and two-electron regimes. The experimental data are well explained by numerical calculations based on master equations. Our results show that quantum capacitance is a sensitive probe for spin as well as for charge dynamics in a DQD.

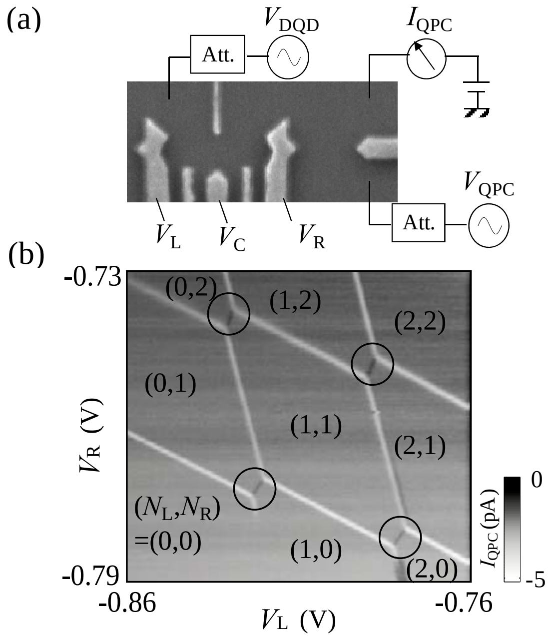

Fig. 1(a) Schematic illustration of the experimental setup. (b) I_{QPC} as a function of V_L and V_R at f_{op} =100 Hz, V_{DQD} = 0.25 mV, and V_{QPC}=0.5 mV. N_L and N_R in the brackets correspond to absolute electron numbers in the left and right dots. In the circles, the quantum capacitance is observed.

2. Capacitance measurement

Figure 1(a) shows the experimental setup. A DQD is formed in a two-dimensional electron gas at the interface of a GaAs/AlGaAs heterojunction by applying negative voltages to the surface Schottky metal gates. We use gate voltages V_L and V_R to vary the electron number in the DQD and V_C to tune the strength of the interdot tunnel coupling. A QPC formed adjacent to the DQD is employed as a charge sensor for the DQD. The principle of our capacitance measurement is as follows. Sinusoidal waves with amplitude $|V_{DQD}|$ and $|V_{QPC}|$ and the same operating frequency f_{op} are applied to the DQD and QPC, respectively. $V_{DQD}(t)$ induces single-electron tunneling, both on and off and between the dots, which results in a temporal modulation $Q_{DQD}(t)$ in the charge state of the DQD. $Q_{DQD}(t)$ modulates the conductance of the QPC, i.e., $G_{QPC}(t) \propto Q_{DQD}(t)$, because each dot is capacitively coupled to the QPC. The second

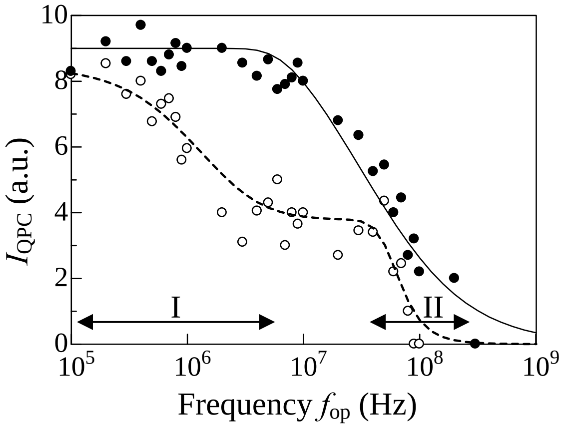

Fig. 2 C_Q as a function of f_{op} at zero magnetic field. The solid and open circles correspond to the data taken in the one- and two-electron regimes, respectively. The solid line and dashed lines correspond to the result of the simulation in the one- and two-electron regimes, respectively.

sinusoidal wave, $V_{QPC}(t)e^{i\theta}$, with a relative phase θ (set to 0 in this experiment) to $V_{DQD}(t)$ excites ac current $I_{QPC}(t)$ through the QPC. We measure dc average of the $I_{QPC}(t)$ in phase with $V_{DQD}(t)$, which is given by $I_{QPC} = \langle G_{QPC}(t)V_{QPC}(t)\rangle \propto \langle Q_{DQD}(t)V_{QPC}(t)\rangle \propto C_Q$ (or C_g)$\langle V_{DQD}(t)V_{QPC}(t)\rangle$ by noting that the capacitance C_Q (or C_g) due to Q_{DQD} is represented by $C_Q(or\ C_g) \equiv \partial Q_{DQD}/\partial V_{DQD}$. Thus, C_Q as well as C_g can be probed by measuring I_{QPC} [3]. Our previous study performed on a DQD in the many-electron regime demonstrated that this technique works over a wide frequency range from hertz to a few ten gigahertz [3].

Figure 1(b) shows the charge stability diagram of the DQD obtained through a capacitance measurement at f_{op} = 100 Hz. The honeycomb-shaped structure is characteristic of a weakly coupled DQD. Signals associated with C_Q appear along the charge boundaries corresponding to inter-dot tunneling, as indicated by the circles. These signals, which appear dark in the figure, have positive polarity, whereas those defining other charge boundaries have negative polarity as seen from their bright color. The background signal seen inside the hexagons, which appear gray, represents the contribution of C_g, which only reflects the geometry of the device and is therefore constant. The polarity of the signals reflects the relative location of the QPC and the dot. That is, the capacitance signal becomes positive (negative) if the conductance of the QPC is enhanced (reduced) by the tunneling of the charge. Note that the charge boundary between (0,0) and (1,0) is missing, which indicates that the tunneling rate is less than 100 Hz.

Figure 2 shows the frequency dependence of C_Q at zero magnetic field. The solid and open circles represent the data taken in the one- and two-electron regimes, respectively. As f_{op} is increased, capacitance signal shows a stepwise decrease in both cases. However, there is a noticeable difference in the behavior: there is only one step in the one-electron regime, whereas the signal decreases in two steps in the two-electron regime.

In order to understand these results, we simulate the spin and charge dynamics that result from the $V_{DQD}(t)$ excitation across the avoided crossing by solving master equations. We firstly study the situation in the one-electron regime, where the charge dynamics is characterized by three time scales: repetition time $T_{rep} = 1/f_{op}$ of the pulse, tunneling time T_{tunnel} across the avoided crossing, and relaxation time T_{relax} induced by phonons. The solid line in Fig. 2 represents a fit to the data, from which we obtain T_{tunnel} = 30 nsec and T_{relax} = 100 nsec. For $T_{rep} = 1/f_{op} > 10^{-7}$, the signal is independent of f_{op}, indicating that single-electron tunneling occurs at each T_{rep} because $T_{rep} > T_{tunnel}$. On the other hand, for $T_{rep} = 1/f_{op} < 10^{-7}$, the signal decreases monotonically. Since $T_{rep} < T_{tunnel}$, T_{relax} in this region, the system passes through the avoided crossing non-adiabatically. This results in the increased probability of Landau-Zener transition, which implies a reduced probability of charge transfer, i.e., a reduced capacitance signal.

In the two-electron regime, the two spins constitute spin-singlet state S and spin-triplet states T_0, T_-, and T_+ with m_S = 0, -1, and +1, respectively. At zero magnetic field, the triplets are degenerate. We assume a three-level system consisting of S(0,2), S(1,1), and T(1,1) and take into account spin-flip time T_{flip} between S(1,1) and T(1,1). The dashed line in Fig. 2 represents the best fit obtained with T_{tunnel} = 5 nsec, T_{relax} = 100 nsec, and T_{flip} = 100 nsec. The simulation shows that the second step in region II has the same origin as the step in the one-electron regime. Furthermore, it reveals that the first step in region I comes from T_{flip}. Indeed, the obtained value of T_{flip} = 100 nsec is consistent with that reported previously [4]. Because of the finite lifetime T_{flip} of S(1,1), the transition from S(1,1) to S(0,2) is partially taken over by a transition to T(1,1). Once the DQD is loaded into T(1,1), the Pauli spin blockade prohibits charge transfer, which reduces the capacitance signal.

3. Conclusions

We have performed high-frequency capacitance measurements on a DQD in one- and two-electron regimes. The obtained results show that quantum capacitance is a sensitive probe for charge and spin dynamics in a DQD.

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