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Charge and spin manipulation in a few-electron double dot

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Abstract

We demonstrate high-speed manipulation of a few-electron double quantum dot. In the one-electron regime, the double dot forms a charge qubit. Microwaves are used to drive transitions between the (1,0) and (0,1) charge states of the double dot. A local quantum point contact charge detector measures the photon-induced change in occupancy of the charge states. Charge detection is used to measure $T_1 \sim 16$ ns and also provides a lower bound estimate for T_2^* of 400 ps for the charge qubit. In the two-electron regime we use pulsed-gate techniques to measure the singlet–triplet relaxation time for nearly-degenerate spin states. These experiments demonstrate that the hyperfine interaction leads to fast spin relaxation at low magnetic fields. Finally, we discuss how two-electron spin states can be used to form a logical spin qubit.

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Keywords: Charge qubit; Spin qubit; Rabi oscillation; Coherent manipulation

0. Introduction

Semiconducting quantum dots can be used to confine single electrons in an electrically controllable potential [1]. Coupled quantum dots, containing a single electron, create a tunable two-level system for the manipulation of single charges [2,3]. By a similar approach, when two electrons are confined to a double dot the relaxation and dephasing of singlet and triplet spin states can be studied [4–6]. Recently, we have demonstrated coherent control of two-electron spin states by using high-speed pulsed gate techniques [7]. In this paper, we review recent experiments performed by our group on few-electron quantum dots that demonstrate quantum control of just one or two electrons [3,5–8].

Samples are fabricated from a $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure grown by molecular beam epitaxy (Fig. 1(a)). Electron beam lithography and liftoff techniques are used to fabricate Ti/Au gates, which deplete the two-dimensional electron gas with electron density $2 \times 10^{11}\,cm^{-2}$ and mobility $2 \times 10^5\,cm^2/V\,s$. When the gates are appropriately biased a double well potential is formed. The electron number in the left (right) dot is varied by tuning V_L (V_R). Interdot tunnel coupling is tuned by changing the voltage V_T. Standard lock-in techniques are used to measure the double dot conductance, G_D, and the quantum point contact (QPC) conductances, $G_{S1(S2)}$. The sample is cooled to base temperature in a dilution refrigerator with an electron temperature, $T_e \sim 135$ mK, as determined from Coulomb blockade peak widths. Depending on the experimental arrangement continuous-wave (cw) microwaves are applied to gate A, or high-speed pulses are applied to gates L and R using bias tees [9] that are thermally anchored to the mixing chamber.

1. Isolating single charges

Control of the double dot using DC gate voltages is demonstrated in Fig. 1(b–d). Fig. 1(b) shows dG_{S2}/dV_L

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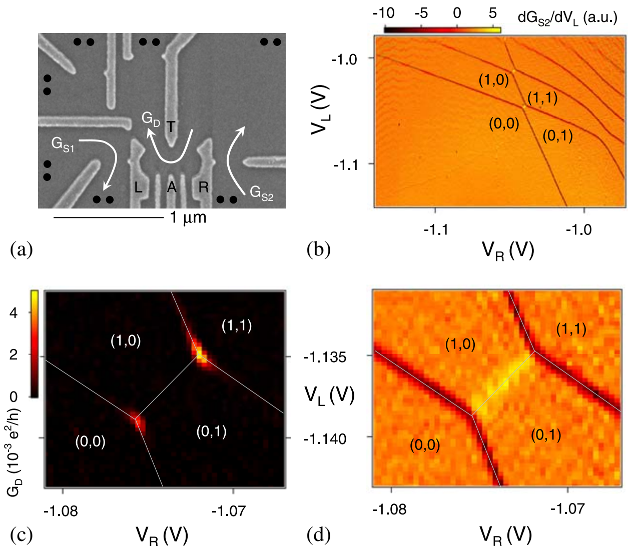

Fig. 1. Transport and charge sensing of a few-electron double dot. (a) Scanning electron microscope (SEM) image of a double dot device similar to the one used in these experiments. The double dot is flanked by two QPC charge detectors. Gates L (R) primarily change the number of electrons in the left (right) dot. Interdot tunnel coupling can easily be tuned by adjusting the voltage on gate T. • denotes an Ohmic contact. The double dot conductance, G_D, and the QPC conductances, G_{S1} and G_{S2}, are measured using standard lock-in techniques. (b) Large scale plot of dG_{S2}/dV_L as a function of V_R and V_L. Charge states are labelled (M, N), where $M(N)$ is the time-averaged number of electrons on the left (right) dot. G_D, in (c), and dG_{S2}/dV_L, in (d), as a function of V_R and V_L near the (1,0) to (0,1) transition. The gates have been slightly adjusted in (c,d) relative to (b) to allow simultaneous transport and sensing. Identical color-scales are used in (b) and (d).

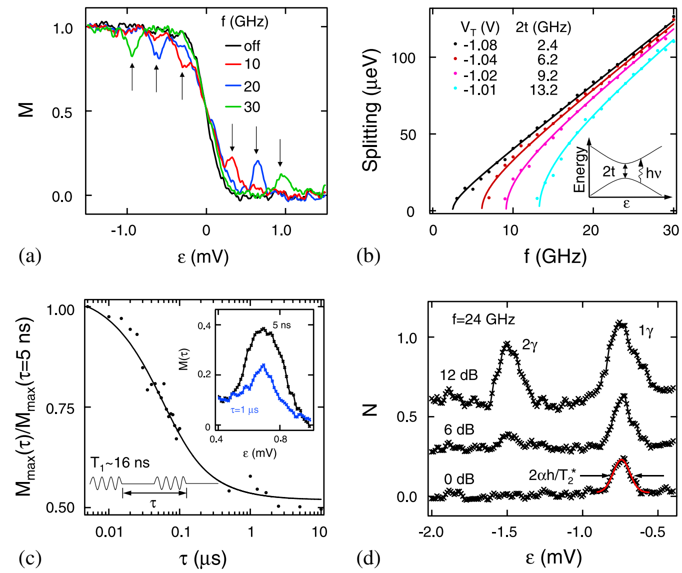

Fig. 2. Microwave spectroscopy of a one-electron double dot. (a) Charge occupancy of the left dot, M, as a function of ε for several microwave frequencies. (b) One-half of the resonance peak splitting as a function of f for several values of V_T. Solid lines are best fits to the experimental data using the theory outlined in the text. Inset: Two-level system energy level diagram. (c) Amplitude of the resonance, expressed as $M_{max}(\tau)/M_{max}(\tau = 5\,ns)$, as a function of chopped cw period, τ, with $f = 19\,GHz$. Theory gives a best fit $T_1 = 16\,ns$ (solid line, see text). Inset: Single photon peak shown in a plot of M as a function of ε for $\tau = 5\,ns$ and 1 µs. (d) Power dependence of the resonance for $f = 24\,GHz$. Widths are used to extract the ensemble-averaged charge dephasing time T_2^*. At higher microwave powers multiple photon processes occur. Curves are offset by 0.3 for clarity.

(numerically differentiated) as a function of V_R and V_L. When an electron enters or leaves the double dot, or moves from one dot to the other, the QPC conductance changes. Gate voltage derivatives of G_{S1} and G_{S2} clearly show these changes and map out the double dot charge stability diagram [10,11]. The nearly horizontal lines are due to charge transitions in the left dot, while the nearly vertical lines correspond to charge transitions in the right dot. For very negative values of V_L and V_R (see the lower left corner of the charge stability diagram) charge transitions no longer occur, indicating that the double dot is completely empty, denoted (0,0). Transport through the double dot can be correlated with simultaneous charge sensing measurements. Fig. 1(c) shows a color scale plot of G_D near the (1,0) to (0,1) charge transition. A charge stability diagram, simultaneously acquired, is shown in Fig. 1(d). Near the (1,0) to (0,1) charge transition the system behaves as an effective two-level system. Crossing this transition by making V_L more positive transfers a single electron from the right dot to the left dot.

2. Microwave manipulation of a single charge

Near the (0,1) to (1,0) interdot transition, the double dot forms a two-level charge system that can be characterized by the detuning parameter, ε, and the tunnel coupling, t (see inset of Fig. 2(b)) [12]. We have used microwave spectroscopy to characterize this two-level system [3]. Microwaves drive transitions in the double dot when the photon frequency is equal to the energy separation between the (1,0) and (0,1) charge states [13–15]. This microwave-induced charge state repopulation can be directly measured using the QPC charge sensors [16,17]. The black curve in Fig. 2(a) shows the measured charge on the left dot, M, as a function of ε, in the absence of microwave excitation. As expected, increasing ε transfers a single charge from the left dot to the right dot. Application of microwaves to gate A results in resonant peaks in M vs. ε that move to larger |ε| with increasing frequency. This resonant peak corresponds to a single photon process that drives an electron from the (1,0) ground state (for negative ε) into the (0,1) excited state, or vice versa.

The frequency dependence of the resonance condition can be used to map out the energetics of the charge two-level system. Detailed measurements of the resonant peak position as a function of microwave frequency, f, are used to extract t for various V_T (see Fig. 2(b)) [18]. At high frequencies the peak positions move linearly with f. For small frequencies, probing the region near the (0,1)–(1,0) charge transition, the interdot tunnel coupling modifies the linear dependence. Changing the interdot tunnel coupling modifies the frequency dependence of the resonant peak