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Electrostatic coupling between two double-quantum dots studied by resonant tunneling current

Gou Shinkai[1,2,*], Toshimasa Fujisawa[1,2], Toshiaki Hayashi[1] and Yoshiro Hirayama[1,3,4]

[1]NTT Basic Research Laboratories, NTT Corporation
3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
[2] Department of Physics, Tokyo Institute of Techonology
2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552, Japan
[3] Department of Physics, Tohoku University
6-3 Aza Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan
[4]SORST-JST, 4-1-8 Honmachi, Kawaguchi, Saitama 331-0012, Japan
[*]Phone: +81-46-240-4706 E-mail: shinkai@will.brl.ntt.co.jp

1. Introduction

A semiconductor double quantum dot (DQD) provides an artificial two-level system or qubit, in which an excess electron occupies the left dot, state L, or the right dot, state R [1]. We have successfully observed coherent oscillations between the two charge states by non-adiabatically exciting the system into a non-stationary state [2]. Here, we extend the system toward two-qubit and investigate Coulomb interaction between two DQDs by analyzing resonant tunneling current through each DQD. The observed interaction is sufficiently large to perform a controlled quantum logic operation.

2. Capacitance model for coupled DQD

Figure 1(a) shows a simplified circuit diagram of two DQDs (1 and 2), each of which is connected to the source and drain electrodes to allow transport measurement. The two DQDs are coupled by capacitances C_{CR} and C_{CL}, representing the Coulomb repulsion. Then the charge state of one DQD influences the electrostatic potential of the other DQD, and vise versa. The electrochemical potential, $\mu_{in}(m)$, for charge state n (L or R) in DQD-i (1 or 2) depends on charge state m (0, L, or R) of the other DQD, which can be calculated for the capacitance model. Resonant tunneling through DQD-i is expected to appear at the resonant condition $\varepsilon_i(m) = \mu_{iL}(m) - \mu_{iR}(m) = 0$. For example, when the DQD-2 is resonant with unoccupied DQD-1 (m = 0) as shown in Fig. 1(b), charging the right dot of DQD-2 (m = R) brings the system in non-resonant condition as in Fig. 1(c). The induced energy offset $\delta_{R0} = \varepsilon_1(R) - \varepsilon_1(0)$ can be obtained from the shift of the resonant tunneling peak.

3. Transport measurement

Our coupled-DQD device is fabricated in a standard AlGaAs/GaAs heterostructure with two-dimensional electron gas (2DEG) by using electron beam lithography and dry etching techniques as shown in Fig. 2(a). By applying appropriate gate voltages on Schottky gates, two sets of DQD each connected to the source and drain electrodes are formed. Following measurements are performed in a dilution refrigerator (about 50 mK) at zero magnetic field. In order to observe resonant tunneling peaks at various charge states of the other DQD, we sweep some gate voltages of the two DQDs simultaneously at large source voltages, $V_{1S} = V_{2S}$ = 500 μV. Figure 2(b) shows current through DQD-2, I_2, with resonant tunneling peaks (α and β) associated with alignment of ground and excited states of DQD-2. The two peaks appear diagonally along equi-energy condition of $\varepsilon_i(m)$ in the V_{2R}-V_{2L} plane, but are actually fragmented into five pieces because DQD-1 takes different charge configurations during the sweep. We also measure the current through DQD-1 (data not shown), from which we can determine charge state m of DQD-1 as shown by dashed lines (boundaries of the stable charge configurations) superimposed to Fig. 2(b). Then, the peak shifts with the variation of charge states, which is consistent with the capacitance model that describes Coulomb interaction between the two DQDs. We obtain δ_{LR} = 77 μeV from peak α and δ_{L0} = 60 μeV and δ_{0R} = 13 μeV from peak β, which are consistent with the expected relation $\delta_{LR} = \delta_{L0} + \delta_{0R}$. These values correspond coupling capacitances C_{CL} = 3.8 aF and C_{CR} = 0.6 aF. Similarly, resonant tunneling peaks of DQD-1 also shift at boundaries of charge configuration of DQD-2, and the two DQDs are interacting with each other.

4. Toward two-qubit operation

For coupled-qubit application, δ_{LR} is the relevant coupling energy for interacting two charge qubits. The Hamiltonian of the two-qubit system can be written as $H = \sum_i \left(\varepsilon_i \sigma_{iz} + \frac{1}{2} T_{iC} \sigma_{ix}\right) + \frac{1}{2}\delta\sigma_{1z}\sigma_{2z}$, where σ_{ij} is the Pauli matrices ($j = x$, y, and z) and T_{iC} is the tunneling coupling for i-th qubit. Coherent oscillation for one-qubit in a similar device has been demonstrated with T_C ~ 10 μeV and $|\varepsilon|$ = 0 – 20 μeV [2]. The obtained δ_{LR} = 80 μeV is sufficiently large to allow controlled operation in the two-qubit system, and can be smaller than single-particle excitation energy (130 μeV for the present device) to restrict the system in the two-qubit Hilbert space. Therefore, two-qubit system should be feasible in semiconductor quantum dots.

Acknowledgements

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References
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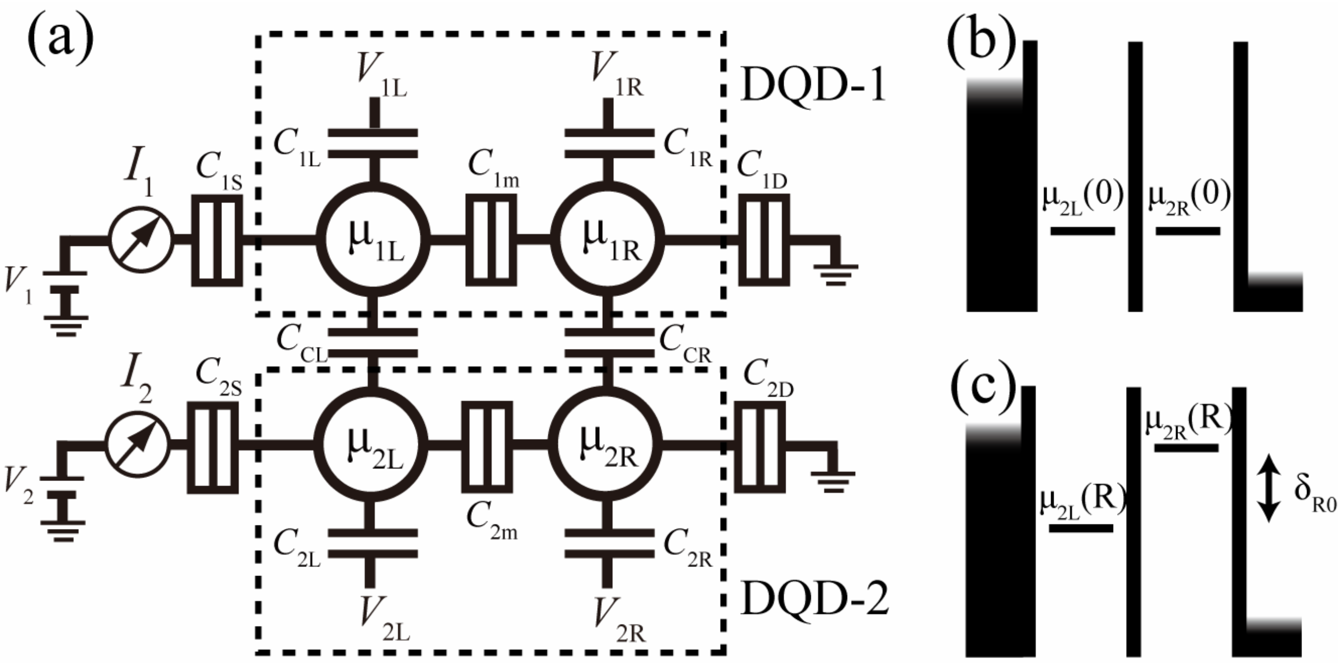

Fig. 1. (a) Schematic diagram of two-qubit system consisting of two DQDs and coupling capacitances. (b) and (c) Energy diagrams at the resonant condition when the other DQD is charge state m = 0 (b) and at the off-resonant condition for m = R

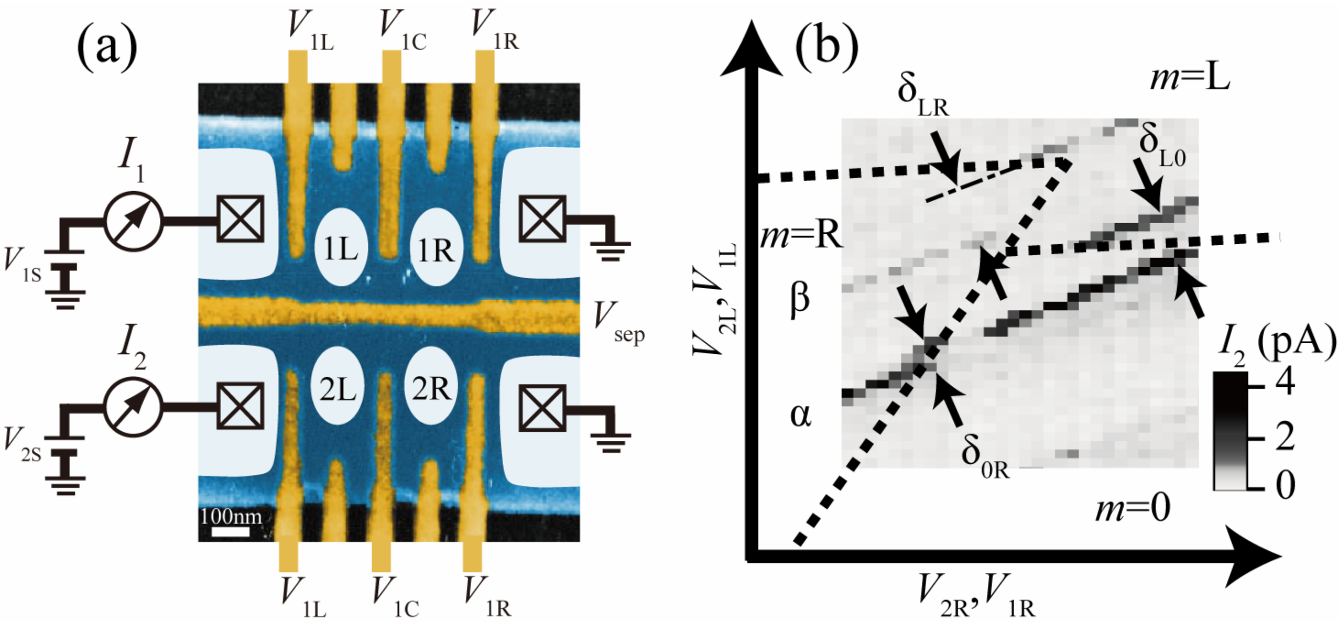

Fig. 2 (a) Scanning electron micrograph of the coupled DQD device. Four quantum dots (1L, 1R, 2L, and 2R) are formed at appropriate voltages. (b) Current through DQD-2, I_2, as a function of simultaneously swept V_{1R} and V_{2R} (horizontal axis) and V_{1L} and V_{2L} (vertical axis). Dashed lines are boundaries of charge states m = 0, L, and R of DQD-2.