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Coupling Characteristics of Semiconductor Coupled Quantum Dots in Coulomb Blockade Regime

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Coupled quantum dots in series have been realized in two dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures using the surface gate, and transport measurements have been performed at the dilution refrigerator temperature. The electrical transport was found to be determined by the Coulomb blockade and the resonant tunneling. The energy width of the resonant peak can be smaller than the thermal energy when two dots are sufficiently isolated. The charge stability diagram, by changing two gates attached to each dot, was measured for weak and strong coupling conditions. The width of the current resonant peak changed significantly as the coupling was increased, while the capacitive coupling did not change so much. The experimental result was analyzed using a simple capacitance model.

KEYWORDS: coupled quantum dots, Coulomb blockade, charge stability diagram, resonant tunneling, capacitive coupling

1. Introduction

The quantum dot is a small and isolated island with discrete energy levels, in which electrons can be confined. The electrical transport through such a quantum dot is determined by the Coulomb blockade effect, when the charging energy for the single electron, $e^2/2C^2$ where e and C are elementary charge and self-capacitance, respectively, becomes larger than the thermal energy ($k_B T$). This situation is easily realized in the dot with submicron dimensions at dilution refrigerator temperatures (<1 K). For the transport measurement, the quantum dot is connected to the source and the drain. To suppress charge fluctuations in the dot, the resistance between the dot and the reservoir has to be larger than the quantum resistance ($\sim h/e^2$). This condition is realized in the semiconductor system by adjusting the gate voltage which forms the tunneling barrier. The transport mechanism in the dot is well understood by the so called orthodox theory,[1)] when the electron number is large. In the semiconductor dot, the separation between the discrete energy, ΔE, also becomes an important energy scale, and the Coulomb blockade effect is modified by it.[2,3)] When $\Delta E \gg k_B T$, the dot can be considered a quantum dot.

The coupling of quantum dots has attracted increasing interest both from the basic research and application point of view.[4)] The coupled dot system was first applied to the turnstile[5)] and pump device[6)] made from metal to realize the current standard. Recently, its application to quantum cellular automata[7)] and to the basic element of the quantum computer[8)] has been proposed. Transport through coupled quantum dots is a bit more complicated than in the single dot case, because the coupling among dots has to be considered. A simple model for the double dot system is a capacitively coupled system with a well-defined electron number in each dot, which produces a charge stability diagram. Experimentally, the coupling effect has been observed in the semiconductor double dot system as a peak splitting of Coulomb oscillations.[9,10)] Both classical capacitive coupling and quantum mechanical tunneling coupling give rise to the peak splitting, and to separate them experimentally is difficult. Although there are many theoretical studies on the coupling effect in coupled quantum dots,[4)] it has not been demonstrated enough experimentally.

In this report, we present our experimental results on the double quantum dot formed in GaAs/AlGaAs 2 dimensional electron gas (2DEG) using the surface gate technique. Resonant tunneling was observed through discrete zero-dimensional energy levels in each dot. We show that the resonant peak width may be smaller than the thermal energy, which is a unique feature in coupled quantum dots. The charge stability diagram was measured for different coupling strengths, and its effect on the capacitive and tunneling coupling is studied.

2. Experimental Procedure

The starting wafer was a MBE grown GaAs/AlGaAs heterostructure, which contains 2DEG with a sheet electron density of 1.9×10^{11} cm^{-2} and a mobility of 3×10^6 cm^2/Vs. The Ti/Au Schottky gates were formed by electron beam lithography and lift off. The schematic picture of the gate pattern is shown in Fig. 1(a). The lithographic size of the left and right dots is (320×320) nm^2 and (280×280) nm^2, respectively.

The sample was mounted on the mixing chamber of the dilution refrigerator. To eliminate the high frequency noise which raises the electron temperature, all the wiring was filtered both at room temperature and at the lowest temperature, and the sample was carefully shielded at the lowest tempera-

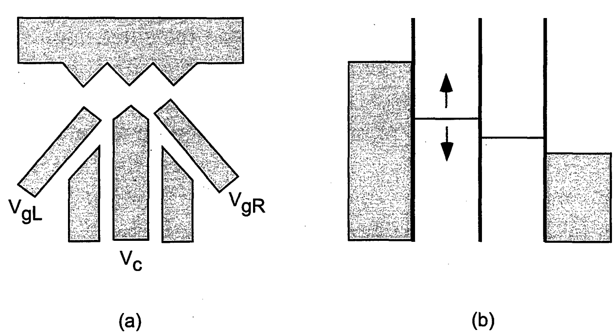


Fig. 1. (a) Schematic picture of the gate pattern: The point contact gates (V_{gL} and V_{gR}) were used to isolate the coupled dots from the reservoir, and the center gate (V_c) was used to adjust the coupling strength between two dots. (b) Energy diagram of coupled quantum dots: A much larger source drain voltage (up to 1.6 mV) than the temperature was applied. Electrons always move from the left to the right in this bias situation. The sweep of the left gate mainly shifts the potential in the left dot.

ture. The electron temperature was estimated from the peak width of the Coulomb oscillations taken in the single classical dot[2)] and was estimated to be about 50 mK, while the mixing chamber temperature was about 20 mK.

The DC current due to the fixed DC source drain voltage (V_{sd}) was measured with a current-voltage converter. After checking the pinch off characteristics of all the point contacts, they were set to form the tunneling barrier. In particular, the point contacts connecting the source and the drain were strongly closed to isolate the system from reservoirs. In most of the measurement, the left point contact gate (V_{gL}) was swept with the fixed V_{sd}. The two side gates sitting in between the left (right) point contact gates and the coupling gate were sometimes used to compensate the gate voltage change on other gates, and were kept constant during gate voltage (V_{gL}) sweep. The important effect of sweeping the gate (V_{gL}) voltage is that it shifts the energy levels in one dot relative to that of the other dot (Fig. 1(b)), but at the same time it pinches off the point contact itself. Therefore, many Coulomb oscillations could not be observed before the swept gate completely pinched off the current. The charge stability diagram was obtained by sweeping V_{gL} with different gate voltages of the right point contact (V_{gR}).

3. Results and Discussions

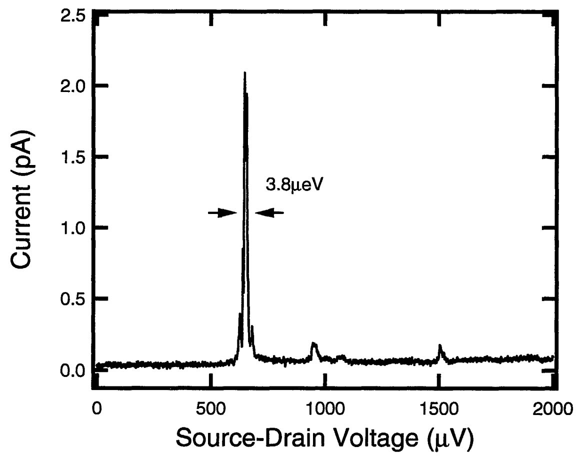
The physical parameters of left and right dots were obtained from the independent measurement of Coulomb oscillations of each dot with a different V_{sd}. The physical parameters of each dot are summarized in Table I. As seen from the table, $k_B T \ll \Delta E < E_c$ is satisfied for each dot at 50 mK ($k_B T = 4.3\,\mu$eV).

Figure 2(a) shows the plot of the current versus voltage (V_{sd}) of the coupled quantum dots. In this measurement, we tried to decouple two dots as much as possible by adjusting the point contact gates, in order to observe how narrow the zero-dimensional energy level could be. A few current peaks can be observed, which is due to the alignment of two energy levels in each dot (resonant tunneling). The first (left most) peak is larger than other peaks. This may be because the first peak arises from the ground state-ground state transition, while excited states may be involved in resulting in other peaks, and relaxation processes reduce the current height. The broadening of the quantum level in the dot is determined by the coupling between the dot and the reservoir, because this determines the lifetime of an electron in the dot. The peak width of the first peak in Fig. 2(a) using the conversion factor mentioned later is about 3.8 μeV, which is consistent with the width determined from the current measurement in which the gate voltage is swept rather than the source drain voltage (Fig. 2(b)). The peak width is a bit smaller than the electron temperature of the sample ($k_B T = 4.3\,\mu$eV at 50 mK). This fact should be distinguished from the single dot case, in which the peak width depends on the thermal broadening of the Fermi levels in the source and the drain leading to a peak width of $\sim k_B T$. In the coupled quantum dot when the source drain bias is much larger than the temperature, the current is determined by the alignment of the energy level in one dot with that in the other dot rather than its alignment to Fermi levels in the leads, and thus, the peak width is free from the thermal broadening in reservoirs. In other words, one of the two energy levels works as an energy filter to mask the thermal broadening in reservoirs. The peak shape of the following gate voltage sweep (Fig. 2(b)) is Lorentzian, which is also due to the alignment of energy levels.[11)]

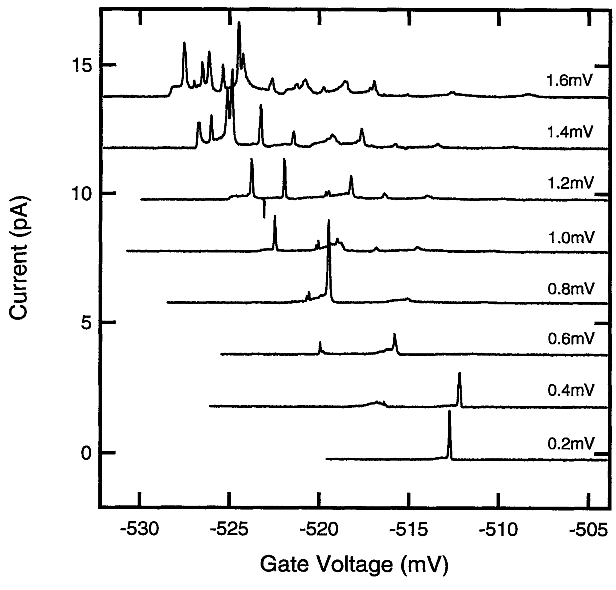
Table I. Parameters in each dot

	Left dot	Right dot
size (nm^2)	320 × 320	280 × 280
ΔE (meV)	0.26	0.28
E_c (meV)	1.5	2.2
C_g (aF)	9.2	5.8

ΔE: average energy level separation
E_c: charging energy. C_g: capacitance between left (right). PC gate and left (right) dot.



(a)



(b)

Fig. 2. (a) Current-voltage characteristics: In this measurement, the two dots were isolated as much as possible by applying a large negative voltage on V_c. For $V_{sd} < 600\,\mu$V, the current does not flow due to the Coulomb blockade and the misalignment of two energy levels. (b) Gate voltage dependence of the current: V_{sd} is changed from 0.2 mV to 1.6 mV with a step of 0.2 mV. Each trace is shown with an offset of 2 pA between adjacent traces.

In Fig. 2(b), the gate voltage (V_{gL}) sweep is shown with different source drain voltages. For $V_{sd} < 200\,\mu$V, no current peak is observed. This is due to the fact that there is no chance for two levels to align, because one of the dots is still in the Coulomb blockade regime. As V_{sd} increases, more and more peaks can be observed, because the chance that two levels align increases in the widened energy window. For a large V_{sd}, many excited states take part in forming current peaks, and complicated relaxation processes happen, which makes it difficult to assign each peak. The right most peak, which moves slowly to the right as the bias voltage is increased, seems to be the ground state-ground state peak.

The absolute value of $\Phi_L - \Phi_R$, the relative potential difference in the left and right dots, is the function of all gate voltages and the source drain voltage (V_{sd}) as shown in the following equation.

$$\Phi_L - \Phi_R = A_{sd}V_{sd} + A_{gL}V_{gL} + A_{gR}V_{gR} + \text{(contributions from other existing gates)} \quad (1)$$

where A_j (j = sd, gL, gR, ...) is the energy-voltage conversion factor with respect to the specific voltage (j). The specific peak shifts systematically in a linear fashion as V_{sd} changes. The shift of the specific peak along with the energy dispersion relationship, obtained in the microwave spectroscopy experiment,[12] gives $A_{sd} = 52$ (meV/V) and $A_{gL} = 127$ (meV/V). These values were used to determine the energy width from the current peak width mentioned before.

Next, we move on to the Coulomb blockade characteristics of the double dot system. Figure 3 shows the charge stability diagram measurements in $V_{gL} - V_{gR}$ plane for the weak (b) and strong (c) coupling conditions. These data were measured with a fixed $V_{sd} = 100\,\mu$V. In both cases, two triangular regions are observed where the current flows. Other regions are Coulomb blockaded. The size of the triangular regions depends on V_{sd}, and becomes zero at $V_{sd} = 0$. This is the characteristic feature of the coupled dot system first observed by Pothier *et al.*[6] The distance between the two regions depends on the strength of the capacitive coupling of the two dots.

To estimate the coupling capacitance, a simple model of the double coupled dot is considered in Fig. 3(a) for zero V_{sd}.[13] Two dots are isolated from the reservoirs, and are connected together by the capacitance (C_c). Each dot is connected to the gate voltage (V_{gL}, V_{gR}) through the gate capacitance (C_{gL}, C_{gR}). The dot-reservoir capacitances are ignored in the simple model since they are usually smaller than the gate-dot capacitances in surface gate semiconductor dots. The total electrostatic energy is expressed by[14]

$$U(N_L, N_R, V_{gL}, V_{gR}) = Q_{gL}^2/2C_{gL} + Q_{gR}^2/2C_{gR} + Q_c^2/2C_c + Q_{gL}V_{gL} + Q_{gR}V_{gR}, \quad (2)$$

where Q_j (j = gL, gR, c) is the surface charge on each capacitor, and N_L and N_R are the number of excess charges in the left and right dots, respectively. Q_j is determined by the following equations.

$$Q_c - Q_{gL} = N_L e, \quad -Q_c - Q_{gR} = N_R e,$$
$$Q_c/C_c + Q_{gL}/C_{gL} - Q_{gR}/C_{gR} = V_{gL} - V_{gR} \quad (3)$$

Then, U is calculated as follows:

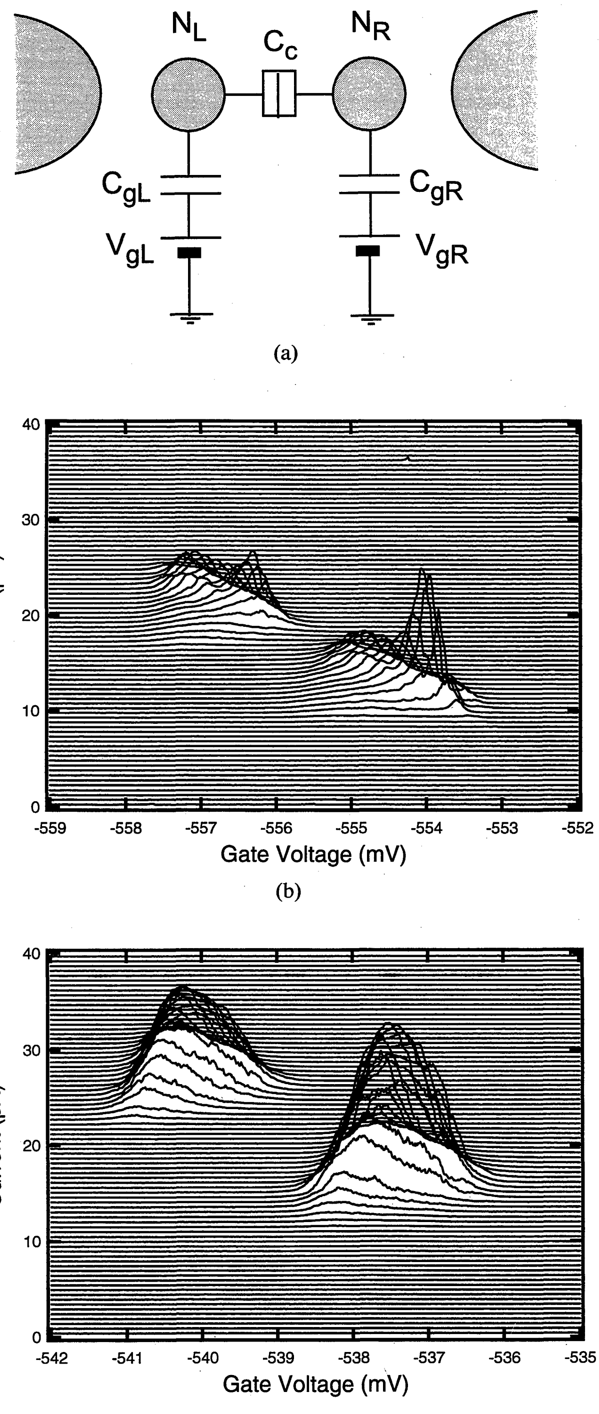


Fig. 3. (a) Simple model for the coupled dot: The capacitance between the dot and the reservoir is neglected. This assumption is reasonable for the surface gate semiconductor dot, where the dot-to-gate capacitance is dominant. The charge state of the system is defined by (N_L, N_R), where N_L and N_R are the number of excess electrons in the left and right dots, respectively. (b) and (c): charge stability diagram measurements for weak coupling conditions (b) and strong coupling conditions (c) In both cases, V_{gR} was changed in 0.1 mV steps between traces, and the current trace is shown with an offset of 0.5 pA between adjacent traces.

$$U = (N_L e - C_{gL}V_{gL})^2/2C_{\Sigma L} + (N_R e - C_{gR}V_{gR})^2/2C_{\Sigma R} + (N_L e - C_{gL}V_{gL})(N_R e - C_{gR}V_{gR})/C_{LR} + \text{const (independent on } N_L \text{ and } N_R), \quad (4)$$

where

$$C_{\sum j} = (C_{gL}C_{gR} + C_c(C_{gL} + C_{gR}))/(C_c + C_j) \quad (j = L, R)$$
$$C_{LR} = (C_{gL}C_{gR} + C_c(C_{gL} + C_{gR}))/C_c. \quad (5)$$

Two possible mechanisms for the current flow are suggested by ref. 19, and at these gate voltage conditions, three charge configurations are degenerate as follows:

$$U(N_L, N_R) = U(N_L, N_R - 1) = U(N_L - 1, N_R)$$
$$U(N_L - 1, N_R) = U(N_L - 1, N_R - 1 = U(N_L, N_R - 1). \quad (6)$$

From eq. (6), ΔV_L and ΔV_R are determined, where ΔV_{gL} and ΔV_{gR} are the distances between two current flow positions. Equivalently, the coupling capacitance, C_c, can be obtained from the experimentally measured ΔV_{gL} and ΔV_{gR}, by the following equation.

$$C_c = C_{gL}C_{gR}\Delta V_{gL}(\text{or}\Delta V_{gR})/(e - C_{gL}\Delta V_{gL} - C_{gR}\Delta V_{gR}) \quad (7)$$

Note that $\Delta V_{gL} = \Delta V_{gR}$ in this model.

Small cross-capacitances, which are not included in the above simple model, exist in the sample, such as the one between the left point contact gate (V_{gL}) and the right dot. These are assumed to be constant, and are estimated to be about 0.1 aF, which is small compared to the direct gate-dot capacitance (C_{gL}, C_{gR}). Then, if we apply this model to the results of Figs. 3(b) and 3(c), we get $C_c = 0.7$(aF) for (b) and 0.8(aF) for (c). The importance of this result is that the capacitance between two dots does not change very much as the coupling gate voltage (V_c) is changed,[15] however, the peak width increases dramatically as the coupling is increased. In the strong coupling condition in Fig. 3(c), the peak width could be limited by the Coulomb blockade, not by the tunneling coupling. This observation is reasonable because the capacitance between two disks (dots) located on the same plane seems to depend weakly on the distance between them, while the tunneling probability depends exponentially on it.

4. Conclusion

To conclude, we have measured the DC transport characteristics of the coupled quantum dots formed in GaAs/AlGaAs 2DEG. The transport mechanism is determined by the resonant tunneling between discrete energy levels and Coulomb blockade effect. Various parameters of the coupled dot system were experimentally derived. The obtained resonant width was found to be smaller than the electron temperature, which is a unique feature of coupled quantum dots. The coupling strength between two dots affects the width of the resonant peak strongly, but has a weak effect on the coupling capacitance.

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