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Double quantum dot Si single-electron transistor with multiple gate electrodes fabricated by PADOX

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ABSTRACT

Double quantum dots (DQDs) are well known as devices for quantum information processing. For this usage, it is important to control the capacitive coupling between the two quantum dots. We have fabricated a DQD Si single-electron transistor (DQD Si-SET) with multiple gate electrodes and clarified the fact that the capacitive coupling of the Si-DQDs is tunable by controlling the number of electrons in QDs. The reason is attributed to the change of the effective QD size due to the change in the number of the electrons in the QDs.

1. INTRODUCTION

A double quantum-dot (DQD) system (van der Wiel 2002, Fujisawa 2004) has attracted great attention to achieve quantum information processing. It is well known that the DQD device can be made in two-dimensional electron gas (2DEG) in GaAs/AlGaAs (Hayashi 2003) or Si/SiGe (Angus 2007) hetero-interfaces and Si nanowire (Fujiwara 2006). Since the dot sizes of the DQD made of 2DEG can be controlled by potential barriers formed by electric fields produced by the gate electrodes, capacitive coupling between the dots is varied by the gate voltage. Usually, multiple gate structure placed on the 2DEG is used, in which some gate electrodes is used for defining the dot structures, and the other is used for controlling the dot potential. However, it is difficult to tune the capacitive coupling of QDs freely because any gate voltage affects defining the electronic states of the QDs. Therefore, the capacitive coupling of 2DEG-DQDs is not capable of changing independently of the electric states of QDs.

Here, in order to solve this problem, we fabricated Si-DQD single electron transistor (SET) by pattern-dependent oxidation (PADOX), and made a relatively stable QDs

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(Takahashi 1995). It was recognized that the capacitive coupling of QDs increases by increasing the number of electrons in the QDs.

2. ECPERIMENTAL DETAILS

DQD Si-SETs were fabricated by PADOX of Si-nanowire on an SOI (Silicon on Insulator) wafer at 1000 °C in the dry oxygen ambient. The schematic cross section is shown in Fig. 1.

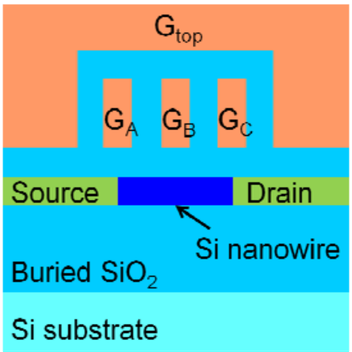

Fig. 1 Schematic cross section of Si-SET.

A Si-nanowire was formed by the use of electron-beam lithography and dry etching of the top Si layer of an SOI wafer. The wire width, length and thickness are 40, 160 and 25 nm, respectively. Then we employed the PADOX to form a Si-QD at the center of the wire with tunnel barriers at both sides. Three fine lower gate electrodes (G_A, G_B, G_C) made of P-doped poly-silicon were placed on the Si nanowire. Figure 2 shows the scanning electron microscopy (SEM) image taken just after the formation of fine lower gate electrodes.

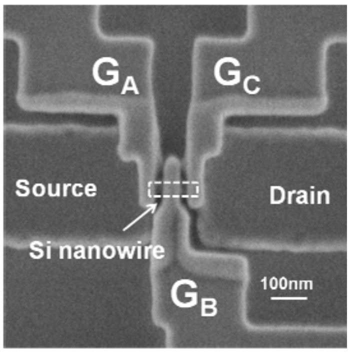

Fig. 2 SEM image of the DQD Si-SET just after the formation of lower fine gate electrodes.

The width of gate electrodes is 40 nm, and the space of these is 40 nm. After 50-nm-thick SiO_2 gate insulator was deposited, the top gate electrode (G_{top}) was covered all over the device shown in Fig. 2. The DQD was formed at the nanowire under G_A and G_B due to tunnel barriers formed by the fluctuation of the wire width since the length of the nanowire is long. Figure 3 shows an equivalent circuit of the DQD. Here, we named the two QDs near G_A and G_B as QD1 and QD2, respectively. Electrical characteristics were measured at 8K and the two gate voltage (V_A, V_B) were scanned. It should be noted that the fine gate G_C does not affect the electrical characteristics shown below because the gate is far from the Qd1 and QD2. The investigation is focused on the change of the coupling capacitive (C_{12}) between QD1 and QD2 when the number of electrons in QD1 and QD2 change.

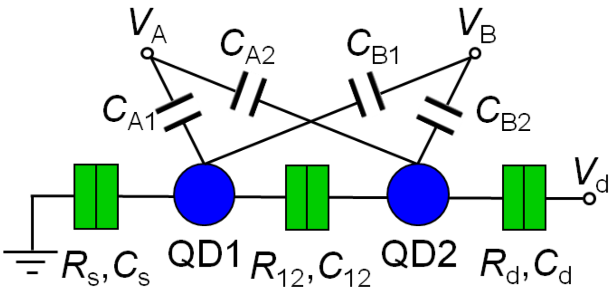

Fig. 3 Equivalent circuit model of the DQD device.

Figure 4 shows DQD stability diagram that shows honey-comb structures. Black points represent the vertex of drain currents, and the distance between the neighboring points corresponds to the coupling capacitance (C_{12}). Smaller distance corresponds to the smaller coupling capacitance C_{12}. Accordingly, we observed the change of the distance between the neighboring vertex of drain current as the increase of the number of electrons in QD1 and QD2 (n, m).

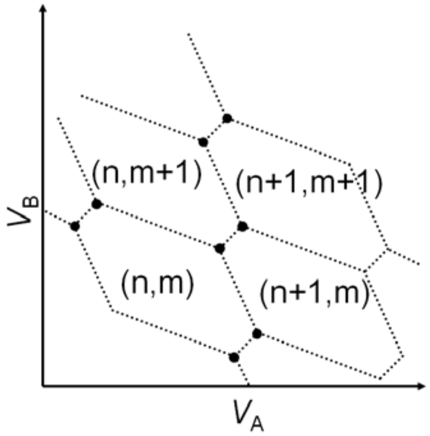

Fig. 4 DQD stability diagram
(n, m) corresponds the occupancy of electrons in QD1, QD2, respectively.

3. RESULTS AND DISCUSSION

The gray scale plots of the drain current (I_d) are shown in Fig. 5 as a function of V_A and V_B. Here, the other voltages were fixed as V_{top} = 3 V, V_C = 2 V, V_d = 1 mV. The number of electrons in QDs increases as V_A and V_B increase. Figures 5(a), (b), and (c) show the regime that the number of electrons in each QD is about 50, 60, and 80, respectively. As shown in Fig. 5, it is clear that honey-comb diagrams with various C_{12} appeared in wide V_A and V_B ranges, but C_{12} gradually increases as the number of electrons in the QDs increase. Then, In order to estimate C_{12} of each characteristics, Monte Carlo simulation (Kuwamura 1994) was used.

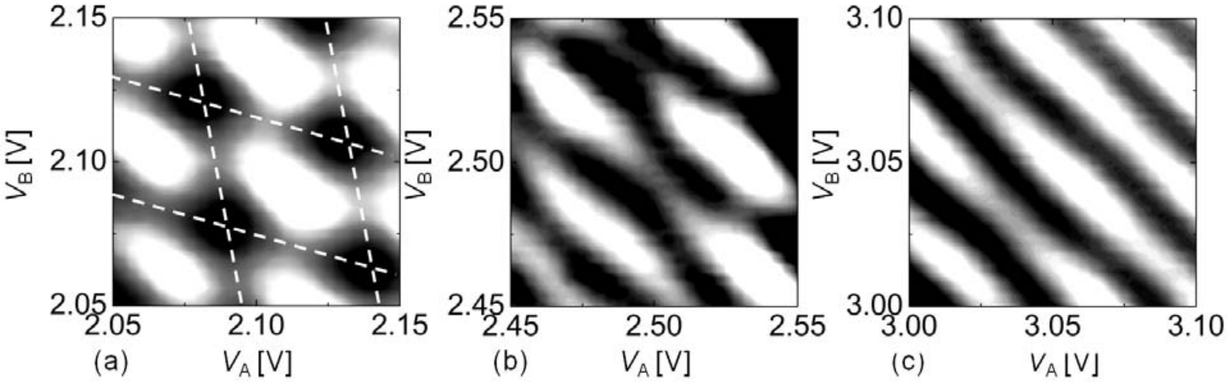

Fig. 5 Measured stability diagram shown by the use of contour plot of drain current I_d measured at 8K.

Figures 6(a), (b), and (c) show simulated results when C_{12} is 4, 15, and 25 aF, respectively. The other parameters used for the simulation were show in the following table (Table. 1). The gate capacitances were evaluated from the slopes and spaces of white dotted lines shown in Fig. 5(a), in which we can assume that the two QDs are almost independent since the coupling capacitance between the QD1 and QD2 is very small. The simulated results shown in Figs. 6(a)-(c) almost coincide with the experimental ones shown in Figs. 5(a)-(c).

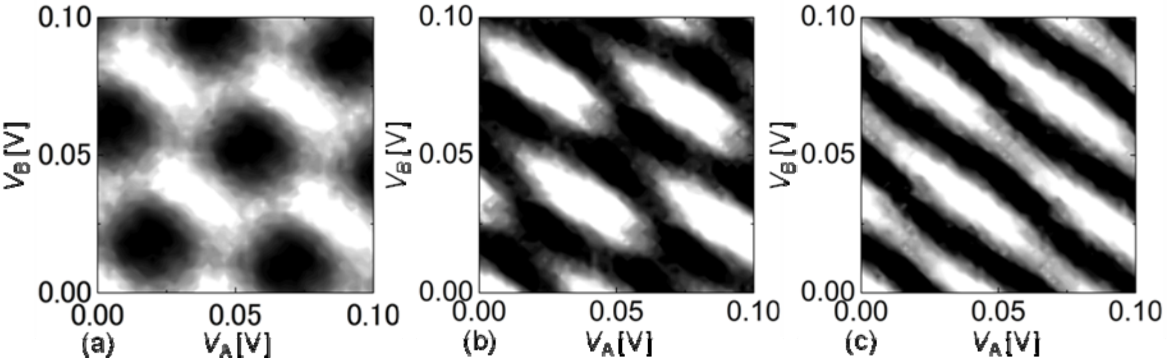

Fig. 6 Simulated results of stability diagram by the use of contour plot of drain current I_d. The capacitive coupling (C_{12}) is (a) 4 aF, (b) 15 aF, (c) 25 aF.

Table. 1 The parameters used for Monte Carlo simulation

C_{A1}	3.34 aF
C_{A2}	1.14 aF
C_{B1}	0.67 aF
C_{B2}	3.95 aF
C_s, C_d	10 aF
R_s, R_d	0.5 GΩ
V_d	1 mV
T	8 K

These results clearly show that the increase of the number of electrons in QDs gradually strengthens the capacitive coupling between QD1 and QD2. This phenomenon thought to be occurred because the effective QD size becomes larger as the increase of the number of electrons in QD. As a result, since the distance of the two small QDs is short, coupling capacitance become large as increase of the number of electrons in the QDs.

4. Summary

We successfully fabricated DQD Si-SETs with multiple electrostatic gates by PADOX and observed clear and stable honey-comb structure in the stability diagram with a relatively wide gate-voltage range. In addition, we confirmed that the coupling capacitance between the QDs increases gradually as the number of electrons in QDs increase, which is caused by the increase of effective size of QDs. The results clearly show that we can control the coupling of DQD by simply changing the gate voltages.

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