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Charge polarization effect on single-hole-characteristics in a two-dimensional Si multidot structure

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1. Introduction

Two-dimensional (2D) quantum multidot structure has attracted interest because of its importance both in physics and device applications. In applying multidot system to new functional devices such as quantum cellular automata (QCA) [1] and photoimaging device [2], it is necessary to study the electrical transport properties of 2D array of the dots. In particular, capacitively-coupled two double-dot systems are important, because they works as bases in QCA and other single-electron tunneling circuits. Recently, characteristics of two double-dot systems have been studied both in experimental and theoretical points of view [3, 4].

In this paper, we present a significant current switching event in single-hole characteristics of 2D Si multidot channel field-effect transistor (FET) and study the charge polarization effect in a naturally-formed two double-dot system.

2. Experiment results

The device used in this experiment is 2D Si multidot FET fabricated on the silicon-on-insulator (SOI) substrate (Fig. 1). The fabrication procedure is described in our previous work [5]. Figure 2 shows the drain current (I_d) versus backgate voltage (V_{bg}) characteristics for hole carrier at 15 K. The current oscillations due to Coulomb blockade (CB) effect are clearly observed. As proposed in previous work [5, 6], CB oscillations occur based on the current percolation path formed in the 2D multidot channel and the highest resistance tunnel junctions dominate the carrier transport.

Figure 3 shows I_d versus drain voltage (V_d) characteristics at 15 K when the V_g is varied from -19.0 V to –19.9 V in a 0.1 V step. It is found that the I_d-V_d curves with current switching events as noises are clearly detected in the negative V_d. Such behavior probably arises from the charge polarization in the vicinity of the current percolation path.

3. Simulation model and results

We construct a simplified equivalent circuit of the 2D multidot structure, as shown in Fig. 4(a). The circuit consists of two double-dot sets (quantum cellular automata structure), in which one set (dots 1 and 2) is just in the current percolation path and the other (dots 3 and 4) represents the adjacent dots. We assume that the tunneling is also allowed between dots 1 and 3 and between dots 2 and 4. Moreover, each dot is connected to voltage (V_g) through each capacitor (C_{g1}, C_{g2}, C_{g3}, C_{g4}) representing buried SiO_2.

Assuming that the charge distribution at the dots 3 and 4 is indicated by (l r) (l and r are number of charges in the dots 3 and 4, respectively), in the (1 0) state, a dipole pointing right is lying along the current path, and a dipole pointing left appears in the (0 1) state. The CB condition in the current path is sensitively influenced by the charge polarization, which is evidenced by a simulation mentioned below.

We calculate the single-hole characteristics of the circuit at 0K by employing a Monte Carlo method. The calculation procedure is the same as in our previous works [2, 7].

Figure 5 shows a typical resultant I_d contour plot for various V_g and V_d, where we set the circuit parameters of C_{s1}=C_{12}=C_{2d}= 5 aF, C_{13}=C_{24}=C_{34}= 3 aF, C_{g1}=C_{g2}= 0.05 aF, C_{g3}=C_{g4}= 6 aF, R_{s1}=R_{12}=R_{2d}= 100 kΩ, and R_{13}=R_{24}=R_{34}= 100 MΩ. In this figure, bright region corresponds to low tunneling currents. It is clearly found that the region with current fluctuation just outside the CB region (region A) and that the one without fluctuation (region B) appear periodically for V_g. The I_d-V_d characteristics picked out from the contour plot for V_g= -27 mV, -9 mV, 3 mV, 14 mV and 25 mV are shown in Fig. 6. It can be seen that the curves with current switching events as fluctuation noises are observed for region A, but not observed for region B. This calculated result qualitatively provides the basis of the experimental results shown in Fig. 3.

The (l r) states indicated in Fig. 5 is the charge distribution at a stationary state in the CB region. It is seen that the distribution changes for V_g as well as regions A and B. Comparing the charge distribution on the dots 3 and 4 and the current behavior, it is confirmed that the current switching event is found only when charge polarity between dots 3 and 4 changes with applying drain current. This means that the change of the charge polarity at the different dots, for example (0 0)→(1 0)→(0 1), strongly modify the current level, as shown in Fig. 4(b). More detailed study is necessary to clarify the current behavior in positive V_d.

4. Conclusions

We have measured the current switching event in single-hole characteristics of 2D Si multidot channel FET. From the Monte Carlo simulation based on charge polarization effect model, it is evident that single-hole-tunneling is modified by the dipole polarity adjacent to the current path.

Acknowledgements

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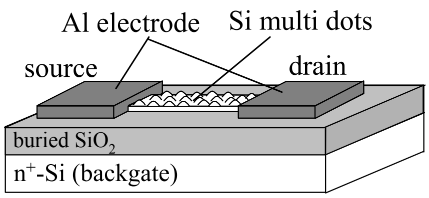

Fig. 1 Schematic view of Si multidot FET.

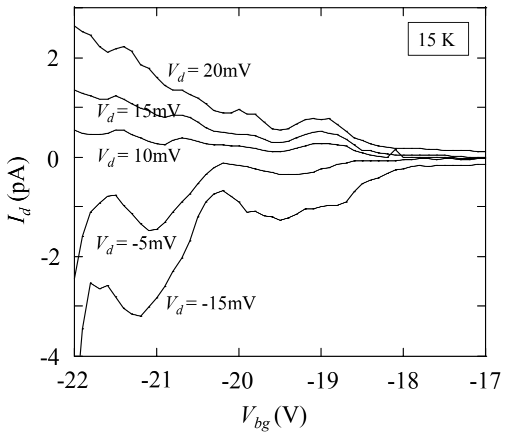

Fig. 2 I_d-V_{bg} of the single-hole characteristics at 15 K.

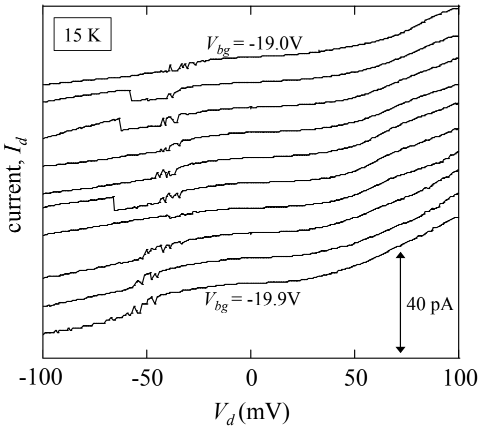

Fig. 3 I_d-V_d of the single-hole characteristics for various V_{bg}. The curves are offset vertically by 10 pA.

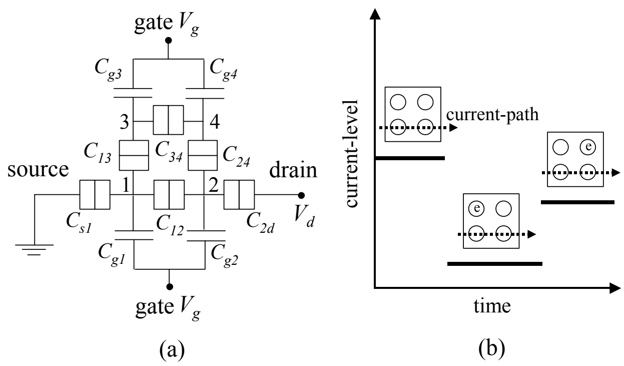

Fig.4 (a) Equivalent circuit of 2D multidot structure and (b) quantum cellular automata structure model.

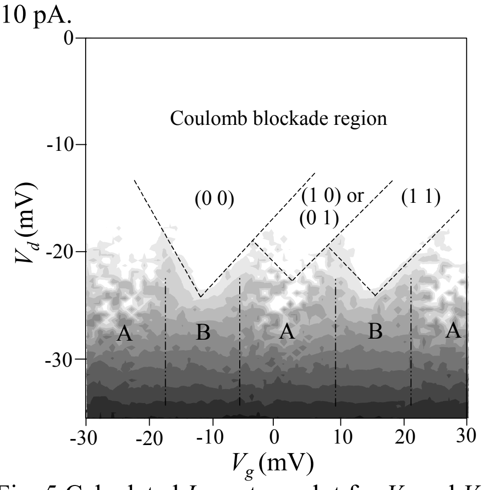

Fig. 5 Calculated I_d contour plot for V_g and V_d at 0 K. (l r) indicates the charge states at the dots 3 and 4 in the Coulomb blockade region.

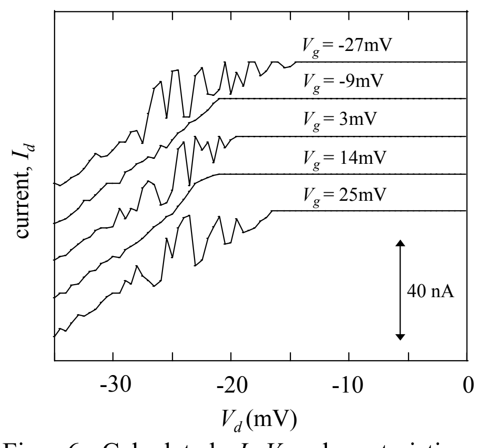

Fig. 6 Calculated I_d-V_d characteristics for V_g=-27 mV, -9 mV, 3 mV, 14 mV and 25 mV. The curves are offset vertically by 15 nA.