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Periodic Coulomb oscillation in highly doped Si single-electron transistor

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1. Introduction

Single-electron devices utilizing the Coulomb blockade effect are promising candidate for the basic elements of future low power, high density integrated circuits [1-4].

Recently the single-electron transistors (SETs) using highly doped silicon-on-insulator (SOI) films have been fabricated, where carriers are generated from the dopant [4-6]. Since a highly doped SET has a large number of carriers, periodic Coulomb oscillations are expected to be observed when the SET has only one Coulomb island [4]. On the other hand, Coulomb blockade effects have been reported in highly doped SOI nanoscale wires where there are no obvious artefacts that form Coulomb islands. In these wires, Coulomb-island-like structures are naturally formed by random fluctuations in dopant concentration. Usually, these fluctuations lead to SETs with serially connected multiple Coulomb islands. Consequently, these devices mostly lack clear periodicity in observed Coulomb oscillations because the charging energy levels in each island can rarely be aligned with each other in such a multiple Coulomb island system [5]. However, periodic Coulomb oscillations have been reported even in highly doped SOI wires of nanoscale width [6]. As explained above, the conduction mechanism for highly doped nanoscale structures has not yet been fully understood.

To further examine the conduction mechanism in highly doped nanoscale structures, we fabricated a one-dimensional regular array of geometrically-defined multiple nanoscale islands in this study. Contrary to our anticipation, we observed clear periodicity in the Coulomb oscillations at 4.2 K. A Coulomb island was considered to be produced by random fluctuations in dopant concentration somewhere in the channel region, and other channel regions act as simple resistances in our SET.

2. Device Fabrication

We fabricated a one-dimensional regular array of 22 nanoscale islands using EB in a SOI layer. Figure 1 shows the schematic diagram and the resist pattern of a SET with geometrically defined multiple nanoscale islands. Doping of the top Si layer was carried out by $POCl_3$ diffusion at 850 °C. The doping level was about 2 x 10^{20} cm^{-3}. After dry etching using an electron cyclotron resonance etcher with the resist pattern as a mask, subsequent isotropic wet etching in a $NH_4OH/H_2O_2/H_2O$ solution reduced the dimensions of the device [7]. The final thickness of the top Si layer was about 20 nm. The width of the island and that of the region between adjacent islands were about 20 and 10 nm, respectively. The width of the islands fluctuated between 20 nm and 30 nm from device to device.

3. Electrical Characterization

Figure 2 shows the drain current (I_d) vs gate voltage (V_g) characteristics at a drain voltage (V_d) of 0.015 V at 4.2 K. Clear periodic I_d oscillation can be observed in the V_g region from 0 to 11 V. The observed period is 1.55±0.1 V. From this value, the capacitance C_{gi} between the side gate and the Coulomb island was evaluated to be 0.10 aF .

Figure 3 shows I_d vs V_d characteristics as a function of V_g at 4.2 K. A clear zero-current Coulomb gap region and the modulation of the gap by V_g can periodically be observed. We can see that the gap is maximum at V_g's of 0.6, 2.1, and 3.7 V. Also, the gap completely disappears at V_g's of 1.3, 2.9, and 4.5 V. The periodicity (1.6 V) agrees with that of peak position in Fig. 2. This suggests a single Coulomb island in our SET because the Coulomb gap cannot disappear in a multiple Coulomb island system.

Figure 4 shows the contour plot of I_d as a function of V_g and V_d at 4.2 K. We can see periodically repeated Coulomb-blockade diamonds in which I_d is suppressed.

4. Discussion

We estimated the size of the Coulomb island from the C_{gi} value. The periodic feature of Coulomb oscillation in Fig. 2 implies that only a single island is effective for a SET. Assuming only one cubic Coulomb island of various sizes, we estimated the C_{gi} value numerically. We solved the Laplace equation numerically by the iterative method under the proper boundary conditions for an island of a certain size to obtain the electrostatic potential. Then, the accumulated charge and capacitance between the island and side gate were obtained by using the equation of continuity. We found that an island with a size of 1 nm corresponded to a measured C_{gi} value of 0.1 aF. This is quite different from the geometrically defined island size of 20 nm. We speculated that a Coulomb island is due to fluctuations in dopant concentration.

From the symmetry of the contour plot (Fig.4), we can conclude that the source capacitance C_s and the drain capacitance C_d are almost equal (=C). Thus, the slope of the Coulomb-blockade diamonds can be approximated by C_{gi}/C. Since the observed slope from Fig. 4 is 0.07 and C_{gi} is 0.10 aF from Fig. 2, a C of 1.4 aF was obtained.

Using the C value we calculated length d of the tunnel barrier. When area S of the cross section of the barrier is taken as 1 x 1 nm^2 according to the island size (1 nm) estimated from Coulomb oscillation and using C = 1.4 aF, d is calculated as 0.1 nm. This is very much smaller than the distance between the whole channel length (about 5 μm). The upper limit for S is about 10 x 10 nm^2 because the area of the junction caused by dopant fluctuation is smaller than that geometrically defined. Even at this upper limit, d is calculated to be 10 nm, which is much smaller than the whole channel length. Therefore, in our sample, most channel regions except those around the Coulomb island are considered to act as simple resistances.

Moreover, since high temperature oxidation was not carried out in our SET, no segregation effects occurred in our SET, at least laterally [6]. Thus, we speculated that a potentially confined region connected with tunnel barriers was produced by random dopant fluctuations.

5. Summary

We fabricated a highly doped Si SET with a series of geometrically defined nanoscale Si islands. The SET exhibited the periodic Coulomb oscillations and repeated Coulomb diamonds at 4.2 K. From periodicity and numerical calculations, we estimated the Coulomb island to be 1 nm, which differs greatly from the geometrically defined size. A Coulomb island was considered to be produced by random fluctuations in dopant concentration somewhere in the channel region, and other channel regions act as simple resistances in our SET. Such SETs with periodic Coulomb oscillation have a great advantage of making circuit design easy.

References

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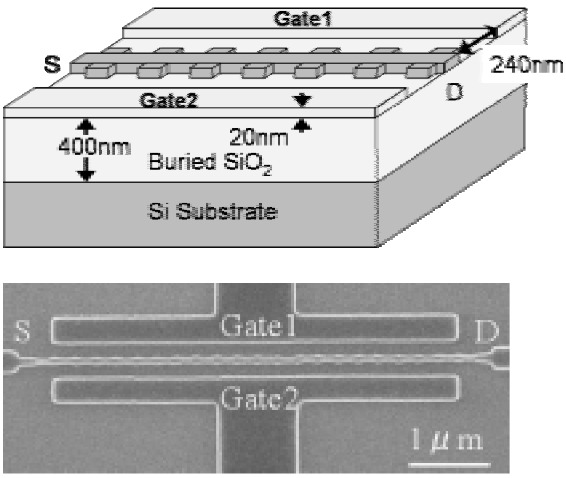

(a) (b)

Fig.1 (a) Schematic diagram and (b) Plan view of scanning electron microscopy (SEM) micrograph of resist pattern of fabricated SET. In the electrical measurements, only one of the two gates was used. S and D stand for source and drain.

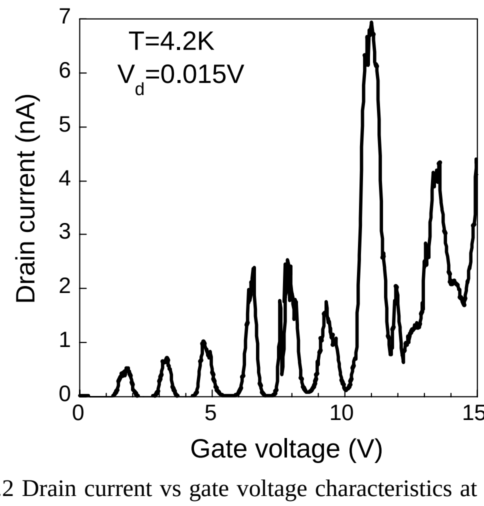

Fig.2 Drain current vs gate voltage characteristics at 4.2 K (drain voltage V_d=0.015 V).

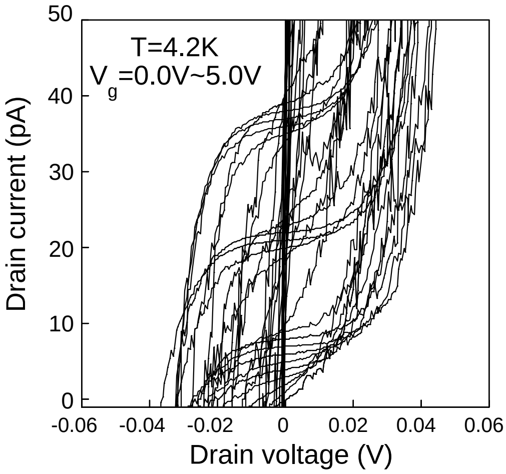

Fig.3 Drain current vs drain voltage characteristics as a function of gate voltage (V_g) at 4.2 K. V_g from 0.0 V to 5.0 V in V_g steps of 0.1 V. Each curve is offset by 1 pA per 0.1 V of Vg for clarity.

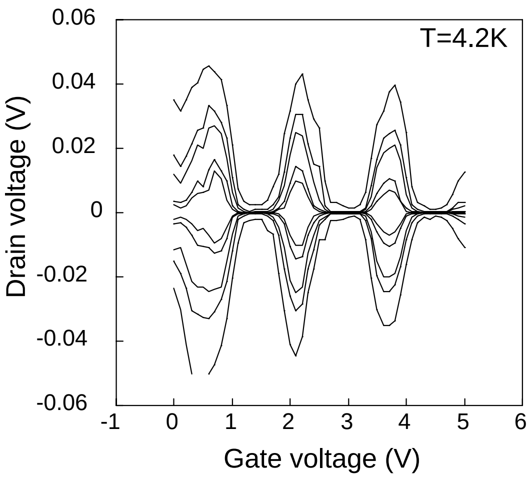

Fig.4 Relation between gate voltage and drain voltage, which gives absolute values of drain current of 50 pA, 10 pA, 5.0 pA, 1.0 pA, and 0.5 pA at 4.2 K.