Cotunneling current in Si single-electron transistor based on multiple islands

Kensaku Ohkura, Tetsuya Kitade,[a] and Anri Nakajima[b]
Research Center for Nanodevices and Systems, Hiroshima University, 1-4-2 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

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The authors fabricated highly doped Si single-electron transistors (SETs) with three islands. The valley current of the obtained Coulomb oscillation was systematically investigated in comparison with the cotunneling theory. The temperature dependence of the valley current was well described by the inelastic cotunneling theory above 40 K in the low drain voltage region. Since the inelastic cotunneling current was confirmed to be dominant in the high temperature region and is exponentially suppressed by multiplexing islands, SETs with multiple islands are promising for the practical application such as reliable circuit operations. © *2006 American Institute of Physics*.
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Single-electron devices utilizing the Coulomb blockade effect are promising candidates for use as basic elements of future low-power and high-density integrated circuits.[1–6] To develop these devices into commercial products, the use of Si for their construction is important because of Si's compatibility with conventional fabrication techniques for large-scale integrated devices.

We have proposed Si single-electron transistors (SETs) with serially connected islands having an advantage for high temperature operation and suppression of the cotunneling current.[7,8] As far as high temperature operation, we realized 77 K and room-temperature operations of SET circuits by multiplexing islands.[9,10] However, for reliable operation of SET circuits, suppression of cotunneling is also necessary. Electron cotunneling has received considerable attention in recent years.[11–16] In Coulomb blockade regime, the cotunneling process gives rise to leakage current, where an electron tunnels from an initial state to a final state via virtual intermediate states. There are two types of cotunneling, namely, elastic and inelastic cotunnelings. In elastic cotunneling, one electron tunnels via virtual intermediate states in islands. On the other hand, in inelastic cotunneling, different electrons tunnel into and out of different states in islands. Though many experimental results were reported for SETs with a single island, cotunneling through multiple islands has hardly been investigated experimentally.[12,14] Therefore, in this letter, we systematically analyzed the valley current of the measured Coulomb oscillation in comparison with the cotunneling theory, especially in Si SETs with multiple islands for the practical use.

Figure 1 shows a schematic diagram of the fabricated SET having three islands. The thickness of the initial top Si layer and the buried oxide on the silicon-on-insulator wafers were 50 and 400 nm, respectively. Doping of the top Si layer was done by $POCl_3$ diffusion at 900 °C for 10 min. We measured the sheet resistance by a four-point probe method at room temperature to determine the doping level. The doping level obtained was about 1×10^{20} cm^{-3}. The fabrication process included electron-beam lithography using a negative resist and dry etching using an electron cyclotron resonance etcher with the resist pattern as a mask. Subsequent isotropic wet etching in an $NH_4OH/H_2O_2/H_2O$ solution at 70 °C reduced the dimensions of the device and the damage introduced during the dry etching process.[15] The final thickness of the top Si layer was about 10 nm. Each island was about 20 nm wide and the distance between the centers of adjacent islands was 250 nm; the width of constricted region between adjacent islands was about 10 nm. The constrictions between islands are expected to work as tunnel barriers. The distance between the channel wire and the side gates was 240 nm.[8] After the interlayer dielectrics were deposited, the device fabrication was completed by the formation of Ohmic contacts. We measured the low temperature current-voltage characteristics with an HP 4156B semiconductor parameter analyzer and a cryogenic manipulated probe system (HYTT-01).

Figure 2 shows the temperature dependence of the Coulomb oscillation of the SET with three islands as a function of gate voltage V_g in the temperature range from T=4.2 to 100 K. Valley current tends to increase as temperature increases. Figure 3 shows the drain current I_d as a function of drain voltage V_d at V_g=1.2 V. Clear negative differential conductance is observed up to 60 K. This is attributed to the drain conduction via quantum levels in islands. The relevant quantum level spacing is roughly estimated to be 5 meV.

For inelastic cotunneling through N islands, the drain current is roughly proportional to $(g_T e^2/h)^{N+1}$, where e is the elementary charge, h Planck's constant, and g_T the tunnel

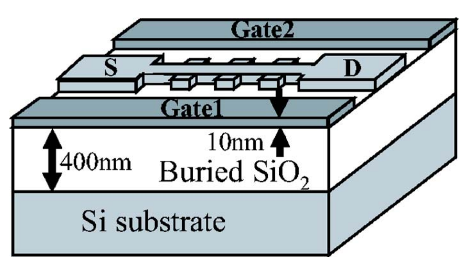

FIG. 1. (Color online) Schematic diagram of the fabricated SET with three islands. S and D stand for source and drain. Only one of the two gates was used in the electrical measurements.

[a]Present address: ROHM Co., Ltd., 21 Saiin Mizosaki-cho, Ukyo-ku, Kyoto 615-8585, Japan.

[b]Author to whom correspondence should be addressed; electronic mail: nakajima@sxsys.hiroshima-u.ac.jp

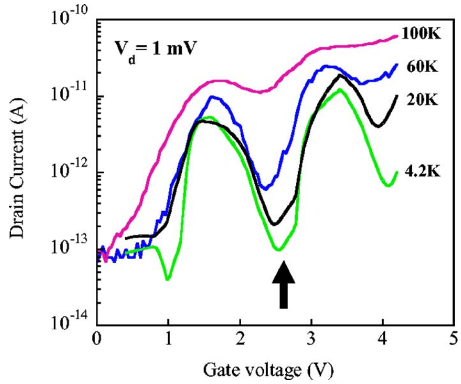

FIG. 2. (Color online) Temperature dependence of the Coulomb oscillation for the SET with three islands in the temperature range from 4.2 to 100 K at a drain voltage of 1 mV. One of the valleys of the Coulomb oscillation is marked by a thick arrow.

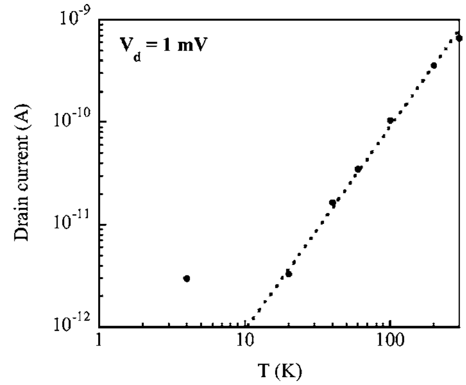

FIG. 4. Relation between temperature and drain current for the SET with a single island at a V_g of a valley of the Coulomb oscillation. Here, V_d is 1 mV. The dotted line shows a logarithmical fit of measured I_d above 20 K where fitting parameter is the proportional constant in Eq. (1).

conductance of a single junction.[18] The factor $(g_T e^2/h)$ is multiplied everytime an electron tunnels through a junction. In weak tunneling regime, where Coulomb blockade of single-electron tunneling dominates, the factor $(g_T e^2/h)$ should be much smaller than 1. Hence, the cotunneling current quickly decreases as N increases. Our system is in this regime. For a comparison, I_d-T characteristics at a V_g of the valley of the Coulomb oscillation for the SET with a single island are shown in Fig. 4. The inelastic cotunneling current for an island[12] is expressed as

$$I_d \propto eV_d\{(eV_d)^2 + (2\pi k_B T)^2\}. \tag{1}$$

Above 20 K, the measured I_d data are fitted by Eq. (1) which is shown by the dotted line. This line is almost a straight one with a slope of 2. This agrees with the behavior $I_d \propto T^2$ predicted by Eq. (1) in the high temperature region. For the SET with three islands,[17]

$$I_d \propto \frac{1}{5040}(eV_d)^7 + \frac{1}{90}(\pi k_B T)^2 (eV_d)^5 + \frac{7}{45}(\pi k_B T)^4 (eV_d)^3 + \frac{16}{35}(\pi k_B T)^6 (eV_d). \tag{2}$$

The measured I_d data are also fitted by Eq. (2) which is shown by the dotted line in Fig. 5 above 40 K. This line is almost a straight one with a slope of 6. This also agrees with the behavior $I_d \propto T^6$ predicted by Eq. (2) in the high temperature region. Thus, I_d-T characteristics for one and three islands are well described by the inelastic cotunneling current in the high temperature region. Moreover, we can see that the measured I_d for three islands is less than one-tenth of I_d for an island by comparing Fig. 5 with Fig. 4. Indeed, the valley current is found to be well suppressed by multiplexing islands. On the other hand, for the low temperature region, the theoretical curve does not match the measured I_d. This is probably because other kind of current such as the elastic cotunneling current contributes to the measured I_d. Figure 6 shows I_d-V_d characteristics at low temperature (T=4.2 K) for the SET with three islands at a V_g of the valley marked in Fig. 2. The predicted curve of the inelastic cotunneling current given by Eq. (2) is also shown. Here, the proportional constant of Eq. (2) is set to the same value as the one for the dotted line in Fig. 5. The measured I_d fairly agrees with the predicted curve in the high drain voltage region (>30 mV). However, in the low drain voltage region (1–10 mV), the measured I_d cannot be explained by the inelastic cotunneling theory. Since the elastic cotunneling theory gives rise to a linear I_d-V_d characteristics,[15] which leads to a straight line with a slope of 1 in Fig. 6, the measured I_d at low drain voltages in the low temperature region is probably due to elastic cotunneling. It is noted that even if the fabricated SET has geometrically defined three islands, it is not guaranteed that it electrically works as a SET with three islands. Our SET has three islands also from the electrical viewpoint be-

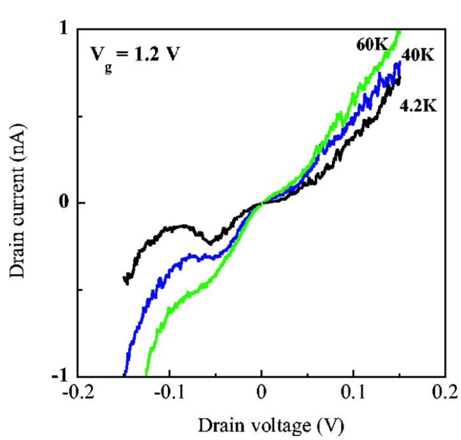

FIG. 3. (Color online) Drain current as a function of drain voltage for the SET with three islands at a gate voltage of 1.2 V.

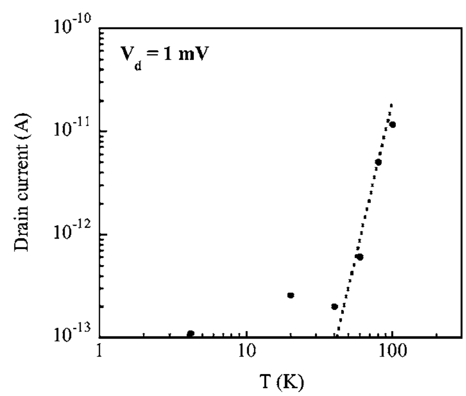

FIG. 5. Relation between temperature and drain current for the SET with three islands at a V_g of the valley marked by the thick arrow in Fig. 2. Here, V_d is 1 mV. The dotted line shows a logarithmical fit of measured I_d above 40 K where fitting parameter is the proportional constant in Eq. (2).

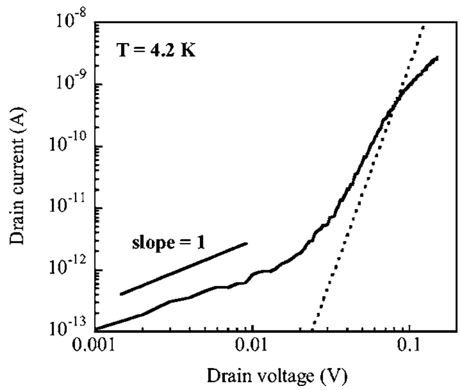

FIG. 6. Drain current as a function of drain voltage for the SET with three islands at a V_g of the valley marked in Fig. 2. In the low voltage region, the measured drain current data almost lie in a straight line with a slope of 1. The dotted line shows the theoretical prediction of inelastic cotunneling current given by Eq. (2), where the proportional constant is set to the same value as the one for the dotted line in Fig. 5.

cause of good and fair agreements of the above experimental results (I_d-T and I_d-V_d characteristics) with the theoretical predictions.

In summary, we fabricated SETs with three islands. In this device, the temperature dependence of the valley current of the Coulomb oscillation is well described by the inelastic cotunneling theory above 40 K in the low drain voltage region. In the low temperature and low drain voltage region, the elastic cotunneling component dominantly contributes to the valley current. Therefore, suppression of the inelastic cotunneling component in the low drain voltage region is important because high temperature operation of SETs is inevitable for the practical use. Since the inelastic cotunneling current is exponentially suppressed by multiplexing islands, SETs with multiple islands are promising for the practical application such as reliable circuit operations.

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