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Microelectronic Engineering 63 (2002) 129–133

MICROELECTRONIC ENGINEERING

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Direct observation of excited states in double quantum dot silicon single electron transistor

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Abstract

We report, in this paper, the detailed measurements obtained from the double quantum dot silicon single electron transistors. Both the drain current and the differential conductance measurements in large drain voltage regime show small conductance peaks—as many as seven. The differential conductance contour exhibits many small diamond-like features other than main Coulomb blockade diamonds. The extracted quantum energy of the dot is 2.52 meV, which is only six times smaller than the charging energy and the Monte-Carlo simulation results are qualitatively consistent with the measured results. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Single electron transistor; Quantum dot; Transport; Tunneling; Excited states

Many experimental studies of Coulomb blockade and single electron tunneling have been performed in last 20 years [1]. With reduction in the size of the quantum dot (QD), the quantum energy level becomes important when it is compared with the charging energy. The transport in a large source–drain bias can then reveal the single electron tunneling through the excited quantum states of the dot. Transport through the excited states was reported in the quantum dot fabricated on GaAs/AlGaAs heterostructures [2,3], and in the single electron transistors fabricated using silicon (Si) [4,5]. The current–voltage characteristics and the differential conductance contour plots exhibited small conductance peaks or negative differential conductance.

In this paper, the detailed measurement results obtained from double QD Si single electron transistor (SET) were reported. Both the drain current and differential conductance measurement as a function of drain voltage show small conductance peaks. These small conductance peaks in the large

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0167-9317/02/$ – see front matter
PII: S0167-9317(02)00622-6

drain bias regime is a clear evidence of single electron tunneling through excited states of double QD. Moreover, differential conductance contour plot exhibits many small diamond-like features other than Coulomb diamond. The Monte-Carlo simulation results are qualitatively consistent with the measured data.

Fig. 1a shows the schematic sketch of the SET used in this study and Fig. 1b shows the cross-sectional scanning electron microscope photo. The device was fabricated on a silicon-on-insulator (SOI) wafer prepared by the separation by implanted oxygen (SIMOX). The thickness of the buried oxide was 415 nm and the top Si layer was thinned to 30 nm. A quantum wire with the width of 30 nm was formed by the side-wall definition technique utilizing conventional photo-lithography [6]. For the definition of the QD, two side-wall defined depletion gates were made with the separation of 90 nm. Subsequently, a thick layer of SiO_2 and a poly Si control gate were formed for the control of the total charge in the QD. The inversion channel layer was induced by the back gate bias. More detailed information about the fabrication was reported elsewhere [7].

Fig. 2a shows a typical characterization result of the drain current–control gate voltage ($I_{DS} - V_{CG}$) measured at 4.2 K in the Coulomb blockade regime. Clear Coulomb oscillations with strong beating are observed. The oscillation periods are 70 and 150 mV. Such a strong beating and two different

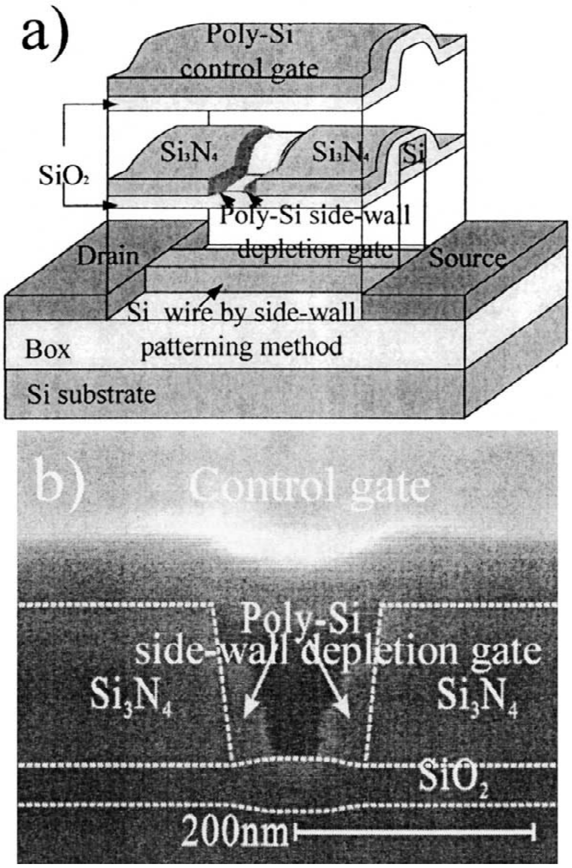

Fig. 1. (a) A schematic sketch of the fabricated Si SET. (b) An SEM photo of cross-sectional view of the fabricated SET.

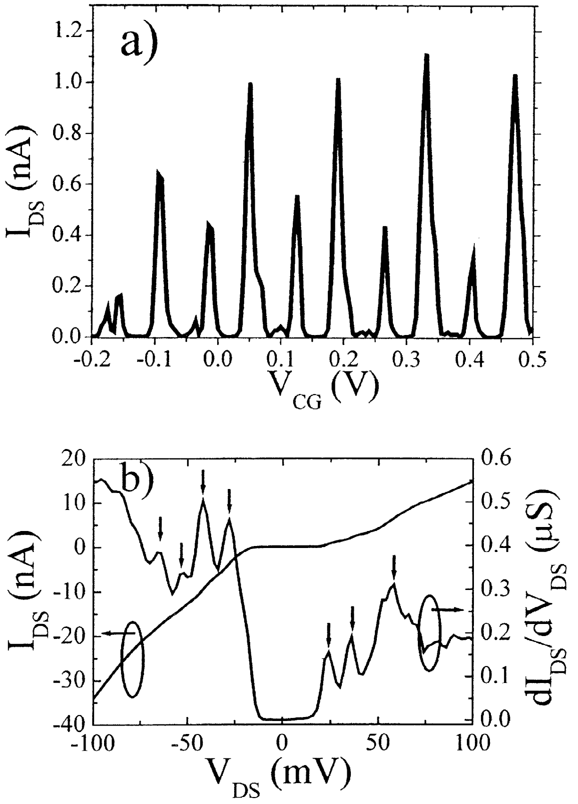

Fig. 2. (a) The $I_{\mathrm{DS}} - V_{\mathrm{CG}}$ characteristics measured at 4.2 K. The oscillation periods of I_{DS} are 70 and 150 mV, respectively. (b) The $I_{\mathrm{DS}} - V_{\mathrm{DS}}$ and $\mathrm{d}I_{\mathrm{DS}}/\mathrm{d}V_{\mathrm{DS}} - V_{\mathrm{DS}}$ characteristics at finite V_{CG}.

oscillation periods are clear manifestation of the double dot charge transport. Since the device has single dot structure, the observed double dot transport behavior suggests the existence of an accidentally formed dot. Some devices from the same die exhibit similar double dot transport behavior and the origin and possible locations were reported elsewhere [8]. There is only a small possibility that the unintentional defect could create another quantum dot near the intentionally fabricated quantum dot because the total length of the Si quantum wire is 7 μm and the defects density at the top Si layer and buried oxide interface is 1–2/cm^2. Another possibility is that an accidental defect in the thermally grown side-wall depletion gate oxide wrapping the Si quantum wire creates a tunnel barrier. Here, the gate capacitances between the control gate and the dots are estimated to be 1.06 and 2.29 aF from the oscillation periods of 70 and 150 mV.

Fig. 2b shows the I_{DS} – drain voltage (V_{DS}) and the differential conductance ($\mathrm{d}I_{\mathrm{DS}}/\mathrm{d}V_{\mathrm{DS}}$) – V_{DS} measured from the same devices. A series of conductance peak spaced about 10 mV can be clearly seen in the bias range $|V_{\mathrm{DS}}| \geq 25$ mV. The number of small conductance peaks is much larger than in the single dot case [9]. These conductance peaks in the large V_{DS} region is clear evidence of single electron tunneling through excited states of the double dot.

Fig. 3 shows the logarithmic gray scale plot of the $\mathrm{d}I_{\mathrm{DS}}/\mathrm{d}V_{\mathrm{DS}}$ as a function of V_{CG} at various values of V_{DS}. In this figure, V_{DS} is converted into the effective value considering parasitic resistance between

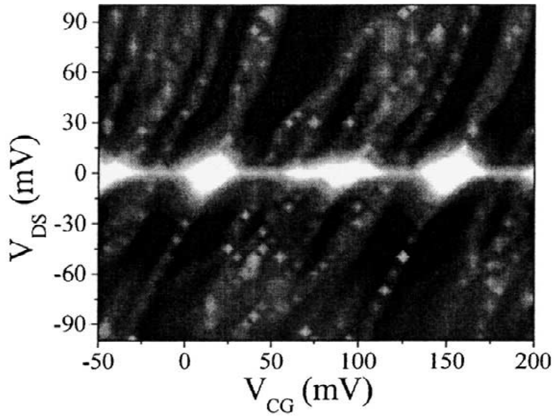

Fig. 3. Logarithmic gray scale plot of dI_{DS}/dV_{DS} as a function of V_{CG} for various values of of V_{DS}. The white regions denote the blockade regions with the dI_{DS}/dV_{DS} below 0.1 μS and the black regions denote conducting region with the dI_{DS}/dV_{DS} above 0.5 μS. The small gray diamond observed in large V_{DS} values represented the series of conductance peaks and valleys observed in Fig. 2b.

source and drain. The white regions denote the blockade regions with the dI_{DS}/dV_{DS} below 0.1 μS and the black regions denote conducting region with the dI_{DS}/dV_{DS} above 0.5 μS. The large white diamonds correspond to the Coulomb blockade region and the shape of the diamonds alternate. This is consistent with the beating observed in Fig. 2a. From the slopes of the diamonds and assuming a simple coupled dot model [1], we can extract the drain capacitance (C_D), the source capacitance (C_S) and the coupling capacitance (C_C). The extracted C_D, C_S, and C_C are 2.30, 2.97 and 7.34 aF, respectively. The charging energies of dot 1 and dot 2 obtained from the total capacitance ($C_{dot1} = 10.6$ aF, $C_{dot2} = 12.6$ aF) are 15.0 and 12.7 meV, respectively. These correspond to dot diameters of 24 and 30 nm, respectively. A value of 24 nm is consistent with the geometrical size of the intentionally fabricated dot considering a finite depletion width (~47 nm) [10] due to the side gate voltage.

Other than the large diamonds corresponding to the blockade region, there are a series of small diamond in the conduction region. The small gray diamond observed in large V_{DS} values represented the series of conductance peaks and valleys observed in Fig. 2b. The half-diagonal of these small diamonds is 2.94 mV. This value can be converted into the energy scale of 2.52 meV using $(1 - C_D/C_{TOTAL})$ [1]. This value is only about six times smaller than the charging energy.

Fig. 4 shows the Monte-Carlo simulation result of $I_{DS} - V_{DS}$ and the $dI_{DS}/dV_{DS} - V_{DS}$. All parameters used in this simulation are the same extracted from the measured result. From the simulation result, a series of conductance peak in the large V_{DS} regions are clearly observed like the measured result in Fig. 2b. It is qualitatively confirmed the measured result which represent single electron tunneling through the excited states.

We report, in this paper, the detailed measurements obtained from double QDs Si SET. Both the $I_{DS} - V_{DS}$ and the $dI_{DS}/dV_{DS} - V_{DS}$ in the large V_{DS} regime show small conductance peaks—as many as seven. The number of small conductance peaks is much larger than the single dot case, which is clear evidence of single electron tunneling through excited states of double dot. The dI_{DS}/dV_{DS} contour exhibits many small diamond-like features other than the main Coulomb diamonds. This observation is different from the evidence of the excited states which were reported previously. The

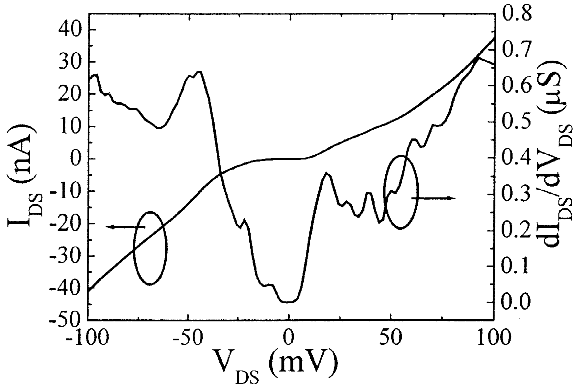

Fig. 4. The Monte-Carlo simulation result of $I_{DS} - V_{DS}$ and the $dI_{DS}/dV_{DS} - V_{DS}$. The parameters used in this simulation are the same extracted from the measured results.

extracted quantum energy of the dot is 2.52 meV, which is only six times smaller than the charging energy. The Monte-Carlo simulation results showed small conductance peaks, which are qualitatively consistent with the measured results.

Acknowledgements

This work is supported by the Korea Ministry of Science and Technology through the Creative Research Initiatives program under contact No. 00-C-CT-01-C-35. The work at Korea University is supported by Brain Korea 21 Program 2002. The work at SNU was supported by the National Program for 'Tera-bit Level Nano Device Project' as a part of 21st Century Frontier Project.

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