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Room-Temperature Charge Stability Modulated by Quantum Effect in a Sub-5nm Coulomb Blockade Device

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An ultra-small Coulomb blockade device has been made by scaling the size of a fin-FET structure down to an ultimate limiting form, resulting in the reliable formation of a sub-5nm Coulomb island. The charge stability at 300K exhibits a substantial change in slopes and diagonal size of each successive Coulomb diamond, but its main feature persists even at low temperature down to 5.3K except for additional Coulomb peak splitting. This key feature of the charge stability with additional fine structures of Coulomb peaks are modeled by including the interplay between Coulomb interaction, valley splitting, and strong quantum confinement, which leads to the substantial modulation of the room-temperature charge stability.

Tunneling through an ultra-small quantum dot system can provide a rich experimental environment for studying quantum transport phenomena [1]. Previously, these quantum effects have been investigated using relatively large devices at low temperatures, where they give rise to additional fine structures on the Coulomb oscillations. However, as temperature increases up to 300K such fine structures observed at low temperature normally vanish together with Coulomb peaks themselves because of the weak Coulomb charging energy due to the relatively large dot size. Here, we report on an extensive transport measurement performed on a room-temperature-operating Coulomb blockade device with an ultra-small silicon island of sub-5nm size.

The Coulomb blockade device used in transport measurement has been fabricated by scaling a state-of-the-art finFET structure down to an ultimate form, by using deep-trench and subsequent oxidation-induced strain [2, 3]. Figure 1(a) shows a SEM image of the SET device whose active channel is detailed as a schematic 3-D layout (Fig. 1(b). Note how the top-Si nanowire, exposed by the nano-gap between the source and the drain, is further etched down to 30 nm in depth by dry etching and gate oxidation. This key process, different from the conventional finFET, enables a Coulomb island to be formed with nearly identical tunnel barriers in a self-aligned manner.

Figure 2 shows temperature dependence of the I-Vg characteristics of the SET measured for various temperatures down to 5.3K for a bias 50mV. As seen in Fig. 2(a), the main feature of the Coulomb oscillations of 300K persists even at low temperature down to 5.3K, except for additional splitting observed in each Coulomb peak. This temperature-dependent feature is quite new and remarkable because the peak splitting so far observed at low-temperatures have been reported to vanish together with Coulomb peaks themselves with increasing temperature. Charge stability plots are seen in Fig. 2b-2d, where successive Coulomb diamonds are clearly seen. Note that substantial change in slopes and diagonal size of each successive diamond is observed, implying that the charging energy is not constant over the gate voltage range studied. This behavior could be accounted for by strong interplay of the Coulomb interaction and additional quantum effects associated with very low electron number on the island.

Figure 3a and 3b are charge stability data at 5.3K. They illustrate the fine structure of the bias dependence of the Coulomb oscillations, showing typical behaviour of increasing splitting with bias window. For more clarity, we present Fig. 3c and 3d, reproducing Id-Vg for some specific bias voltages in the charge stability data. Strong bias dependences of peak splitting are clearly seen, which can be accounted for by the non-linear transport made through many excited levels associated with each dot occupancy N.

The unusual energy separation between Coulomb diamonds and the fine splitting of each Coulomb peak are accounted for by including quantum many-body interactions, leading to the substantial modulation of Coulomb diamonds at 300K [3]. Fig. 4 shows addition charging energies for N=1 up to N=4, estimated from the many-body Hamiltonian, where a confinement potential along the wire <110> are adapted. The low energy level spectrum associated with each dot occupancy N successfully explains the observed fine structure in each main Coulomb peak. These excited states become enhanced in the sub-5nm ultra-small scale and persist even at 300K in the form of cluster, leading to the substantial modulation of charge stability. This further supports the reliability in our CMOS-compatible implementation of the ultra-small SET that enables the multi-bit functionality at room-temperature.

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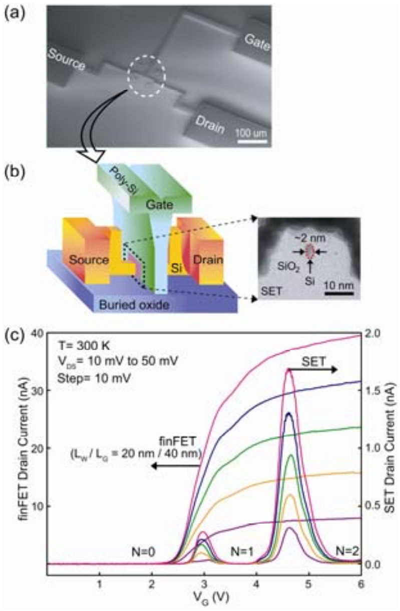

Fig.1. **(a)** SEM image of the Coulomb blockade SET device. (**b**) Schematic 3-D layout of the active channel area of the device and a cross-sectional TEM images along the channel, showing Coulomb island size of ~2nm. (**c**) Comparison of the I-Vg characteristics of SET with those of the conventional nano finFET for drain bias up to 50mV at 300K.

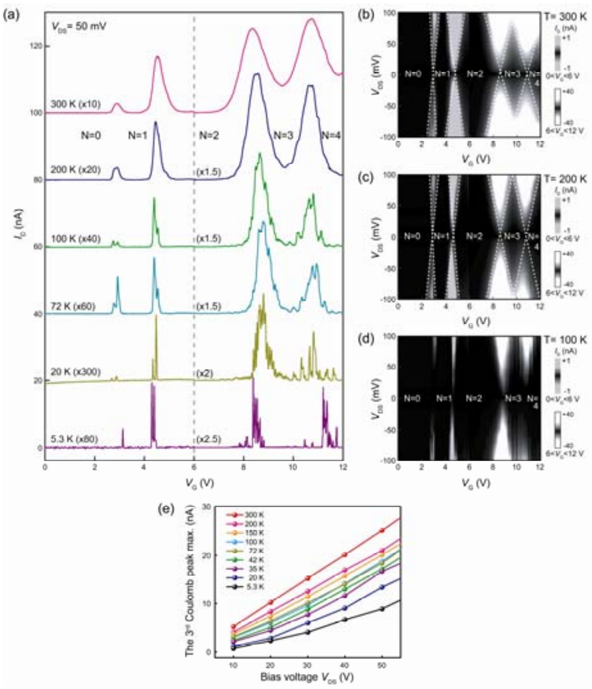

Fig.2. **(a)** Temperature dependence of the I-Vg characteristics measured for temperatures down to 5.3K for a bias Vd=50mV. **(b)-(d)** Charge stability plot for temperatures down to 100K. Each Coulomb diamond corresponds to a stable charge configuration state with fixed electron occupancy. **(e)** Temperature-dependent magnitude of the 3rd Coulomb peak for each bias up to 50mV.

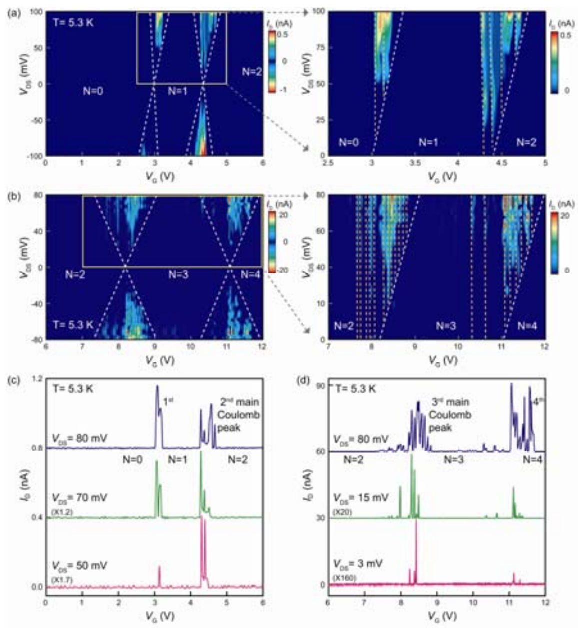

Fig. 3 Charge stability plot at 5.3K and specific bias dependence of each main Coulomb peak; (**a**) & (**b**) Charge stability plot at 5.3K, showing typical behaviour of increasing splitting with bias window. **(c) & (d)** I-Vg characteristics for some specific bias voltages, which are reproduced from the charge stability data.

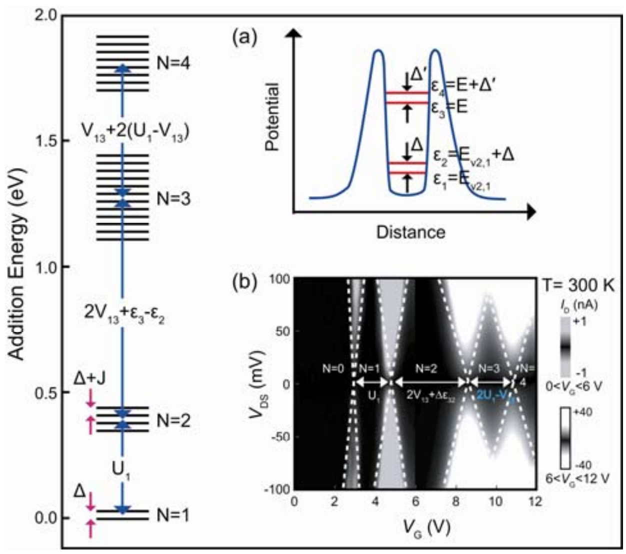

Fig. 4 Addition charging energies of N=1 ⟶ 2, 2 ⟶ 3, and 3 ⟶ 4, estimated from the many-body Hamiltonian. (**a**) illustrates a confinement potential along the wire where the energy levels of valleys are quantized.**T**he calculated addition charging energies, approximately $U_1 \approx 0.38$eV, $2V_{13}+\varepsilon_3-\varepsilon_2 \approx 0.9$eV, and $V_{13}+2(U_1-V_{13}) \approx 0.46$eV (for N=1 ⟶ 2, 2 ⟶ 3, and 3 ⟶ 4, respectively) are denoted by arrows in inset **(b),** which are in the same range as those of the charge stability data observed at 300K.