High-speed operation of Si single-electron transistor

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High-speed and low-power devices are desired for future electronics. Single-electron transistor (SET) can be a candidate because electrons are transported by tunneling and its internal electrical capacitances can be made very small. On the contrary, many researchers believe that operation speed of SETs should be low due to the high tunneling resistance that is lower bounded by the resistance quantum. Moreover, high-frequency characteristics have not been measured, mainly because the voltage applied to the drain terminal was limited to be small so as to keep the Coulomb blockade condition.

Here, we propose a new method to measure the high-frequency characteristics by the use of special rectifying effect of SETs. It is well known that the rectification occurs, according as the gate voltage is swept through the peak of drain conductance, due to the asymmetry of Coulomb diamond when alternating current (AC) voltage is applied to the drain or source terminal [1]. Using this phenomenon, we evaluated the cut-off frequency of SETs. In addition, we obtained Si SETs with relatively large tunnel conductance, which is favorable for high-frequency operation.

The Si SETs were fabricated by pattern-dependent oxidation (PADOX) method [2] which converts a Si nanowire formed in a top Si layer of SOI to a small Si island together with tunnel barriers on both sides of the island. Fig. 1 shows typical source-drain conductance as a function of gate voltage measured at 8 K and drain voltage of 5 mV. Clear conductance oscillation can be seen and the peak conductance G is about 7 μS. The gate capacitance C_g of the SET is evaluated to be 2.3 aF. If a cut of frequency f_c of the device is defined as

$$f_c = G/2\pi C_g ,$$

f_c will be about 500 GHz. Note that this f_c is thought to be higher than the real one, since source, drain and other parasitic capacitances are added in reality. Is it true? We evaluated this idea by applying high-frequency voltage to the drain and measuring the rectifying current at 8 K.

In our measurement system, since highest applicable frequency is limited to 50 MHz, SETs with low peak conductance were selected so as to attain the f_c lower than 50 MHz. Specifically, we used Si SETs fabricated using a SOI wafer with thinner top Si layer to get relatively high tunnel resistance. In addition, we employed the first electron peak in which the tunneling probability expected to be low because the wave function should diminish due to the smallest number of excessive electron in the island.

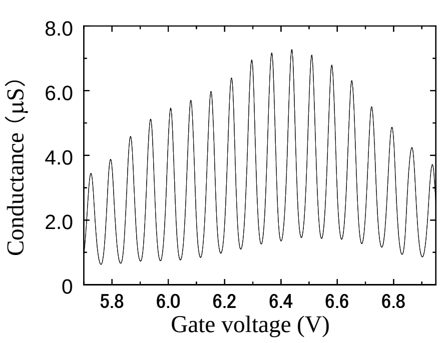

Fig. 1. Source-drain conductance as a function of gate voltage of a SET fabricated by the PADOX process, and measured at 8 K and drain voltage of 5 mV.

Fig. 2 shows the drain current (I_d) oscillation characteristics as a function of gate voltage (V_g). The peak conductance of the first peak is about $4x10^{-12}$ S, and the gate capacitance is about 0.6 aF, which enable us to attain the f_c of 1 MHz.

When AC voltage is applied to a drain of a SET, rectification effect occurs due to the asymmetry of the Coulomb diamond. We thought that the transport of electrons through the SET is inhibited when the AC frequency becomes higher than f_c. As a result, the rectification effect is also suppressed. Measured rectifying current is shown in Fig. 3. There is no reduction of rectifying current even in the frequency higher than f_c.

These results indicate that there is no cutoff frequency set by the capacitance and tunneling resistance in the Coulomb blockade of SETs, leading to the rectifying effect usable beyond the THz regime. It should be noted that tunneling event itself is limited by C/G time but the time does not put frequency limit on rectifying effect in the accumulative measurement as presented in this work.

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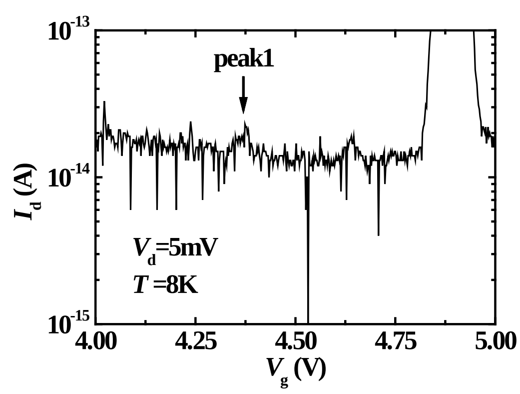

Fig. 2. Drain current I_d-V_g characteristics of a SET used for rectification measurements in a high frequency region.

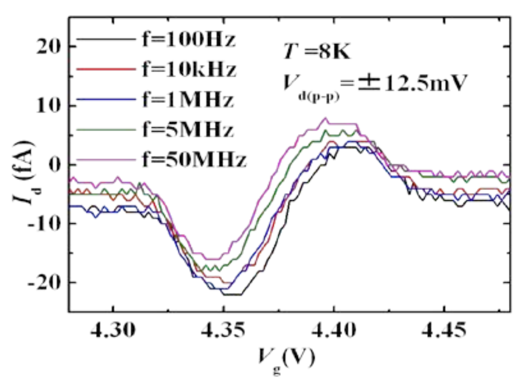

Fig. 3. Rectifying I_d-V_g characteristics of a SET at several frequencies measured at $V_{d(p-p)}$ = ± 12.5 mV