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Large Temperature Dependence of Coulomb Blockade Oscillations in Room-Temperature Operating Silicon Single-Hole Transistor

Masaharu Kobayashi, Masumi Saitoh, and Toshiro Hiramoto

Institute of Industrial Science, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
Tel: +81-3-5452-6264, Fax: +81-3-5452-6265, E-mail: mkoba@nano.iis.u-tokyo.ac.jp

1. Introduction

Recently, large Coulomb blockade (CB) oscillations with the peak-to-valley current ratio (PVCR) larger than 10 have been observed at room-temperature (RT) in silicon single-electron/hole transistors (SETs/SHTs) fabricated by high yield process [1,2]. For device design and circuit applications of these SETs/SHTs, it is essential to clarify the transport mechanisms in an ultra-small dot and tunneling barriers. Although the transport in silicon SETs/SHTs with small PVCR at RT has been examined [3], the transport in SETs/SHTs with high PVCR remains unclear.

In this paper, we observed in a SHT with high PVCR the large temperature (T) dependence of CB oscillation peak for the first time, which is not explained by the classical CB theory. The possible origin is discussed by comparing the measured data with numerical calculation.

2. Experiments and Results

The measured device is a p-type ultra-narrow channel MOSFET that acts as a SHT [1] as shown in Fig. 1. Fig. 2 shows the Coulomb diagram measured at RT. The Coulomb charging energy (E_C), quantum level spacing (ΔE), and silicon dot size estimated from this diagram are 216meV, 173meV, and 4nm, respectively. Fig. 3 shows measured T-dependence of CB oscillations from 180K to RT. PVCR at RT is as large as 10.4. Although a single dot-like CB oscillation is observed at RT, the rapid increase in the peak current with increasing T is clearly observed.

In high T region, the strong T-dependence like this has not been reported in silicon SETs/SHTs. Based on the conventional theory on CB oscillations in a single-dot system, the peak current is constant in the conventional CB regime and inversely proportional to T in the resonant tunnel regime. Therefore, the conventional theory cannot explain the large T-dependence in Fig. 3.

3. Possible Origins of Large Temperature Dependence

There are some possible reasons for the large T-dependence. Here, we discuss three possibilities and clarify the origin.

(i) Thermally activated current: Large T-dependence would be observed if the current is thermally activated [4]. The conductance peak of this SHT is plotted against 1/T in Fig. 4. The activation energy (E_a) is 56meV. When the current is thermally activated, this energy corresponds to the tunnel barrier height, which is too low compared to the estimated charging energy and quantum level spacing. The strong T-dependence is not due to the thermally activated current.

(ii) Parasitic MOSFETs: As shown in Fig. 5, threshold voltage (V_{th}) of parasitic MOSFETs connected to SHT in series increases with decreasing T and accordingly, the peak current of CB oscillations may be suppressed [5]. In order to examine the effect of parasitic MOSFETs, substrate bias (V_{bs}) is applied. Since the SHT channel is gate-all-around, the V_{bs} dependence of SHT peak is much smaller than that of Vth of parasitic MOSFETs. Figs. 6 and 7 show the V_{bs} dependence of CB oscillations at 300K and 180K, respectively, where CB oscillations peak current remain constant around V_{bs} = 0V, even at 180K, indicating that the parasitic MOSFETs do not suppress the CB oscillations peak.

(iii) Stochastic Coulomb blockade in multiple-dot SHTs: The ultra-narrow channel SHT may be composed of series small dots with different size. It is known that a multiple-dot SET shows stochastic CB, in which CB oscillations in one small dot is suppressed by CB in another large dot and CB oscillations peak current exhibit the strong T-dependence [6], as illustrated in Fig.8. In order to examine the effect of multiple-dot stochastic CB, we simulate the double-dot SHT model [7] using master equation approach [8], assuming that double dots are composed of a small dot and a large dot. Since the RT-oscillation is caused by the small dot, parameters including E_C and obtained ΔE from measured data in Fig. 2 are applied to the small dot.

Fig. 9 shows simulated T-dependence of I_d-V_g characteristics. The strong T-dependence of CB oscillations is successfully reproduced. Based on the theory of stochastic CB, E_a in double-dot SHT corresponds to E_C in the larger dot, which suppresses CB oscillations in the smaller dot. E_C of the large dot in this calculation is 20meV, which roughly agrees with the measured E_a in Fig. 4. The discrepancy would be due to the assumption that SHT is a double-dot system, instead of multiple-dot, in the calculation. Note that we simulated only at low gate voltage because the thermally activated current becomes dominant as the tunnel barriers are lowered at high gate voltage.

4. Summary

We observed large T-dependence of CB oscillations peak current in a RT-operating silicon SHT with large PVCR for the first time. It is concluded that the strong T-dependence is mainly due to multiple-dot stochastic CB.

References

[1] M. Saitoh et al., *IEDM*, p.753, 2003. [2] M. Saitoh et al., *IEDM*, p.187, 2004. [3] M. Saitoh et al., *IEEE Trans. Nanotechnol.*, **1**, 214, 2002. [4] K. A. Matveev et al., *Phys. Rev. B*, **54**, 10339, 1996. [5] A. Fujiwara et al., *Jpn. J. Appl. Phys.*, **37**, 3257, 1998. [6] I. M. Ruzin et al., *Phys. Rev. B*, **45**, 13469, 1992. [7] W. G. van der Wiel et al., *Rev. Mod. Phys.*, **75**, 1, 2003. [8] C. W. J. Beenakker, *Phys. Rev. B*, **44**, 1646, 1991.

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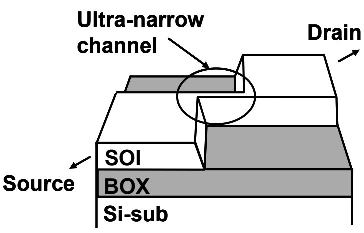

Fig. 1 : A schematic of the ultra-narrow channel SHT. The size of the silicon dot fabricated in the channel is estimated to be 4 nm.

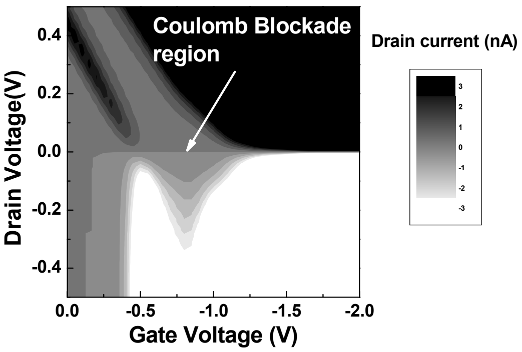

Fig. 2 : Measured Coulomb diagram of SHT at RT. From this diagram, the charging energy and quantum level spacing are estimated to be 216meV and 173meV, respectively.

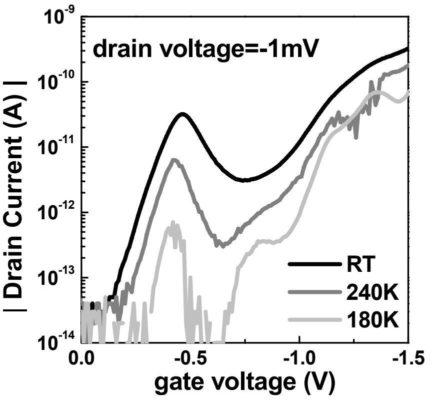

Fig. 3 : Measured T-dependence of CB oscillations in a SHT. The rapid increase in CB oscillation peak current is observed from 180K to RT.

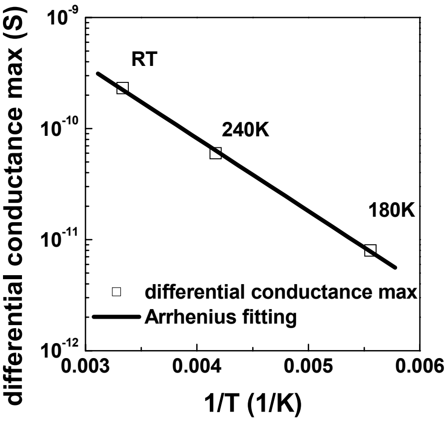

Fig. 4 : Plots of peak conductance as a function of 1/T. These plots are fitted to thermally activated form and the thermal activation energy is estimated to be 56meV.

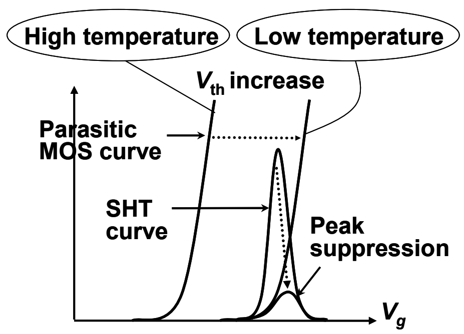

Fig. 5 : Mechanism of possible suppression of CB oscillation peak current by the increase in V_{th} in parasitic MOSFETs at low temperature.

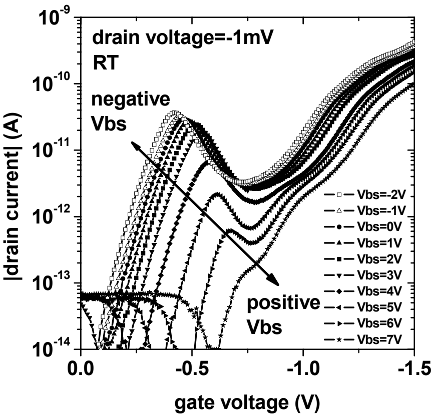

Fig. 6 : V_{bs} dependence of CB oscillations in a SHT measured at RT. When negative V_{bs} is applied, CB oscillations peak current is not increased.

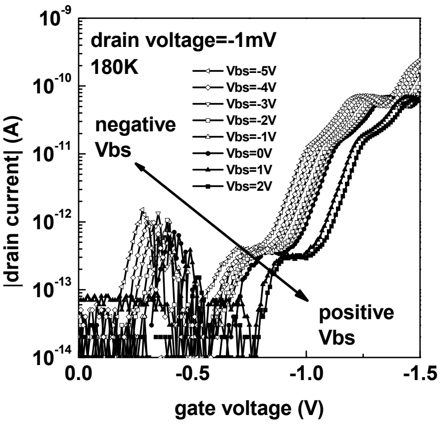

Fig. 7 : V_{bs} dependence of CB oscillations in a SHT measured at 180K. When negative V_{bs} is applied, CB oscillations peak current is not increased.

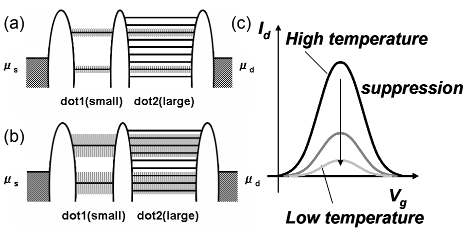

Fig. 8 : Mechanism of multiple-dot stochastic CB. The larger dot has smaller E_C than the smaller dot. (a) SHT current is suppressed at low T by the larger dot, and (b) SHT current is not suppressed at high T, resulting in strong T-dependence of peak current. (c) A schematic of the suppression of CB oscillatios peak which corresponds to (a) and (b).

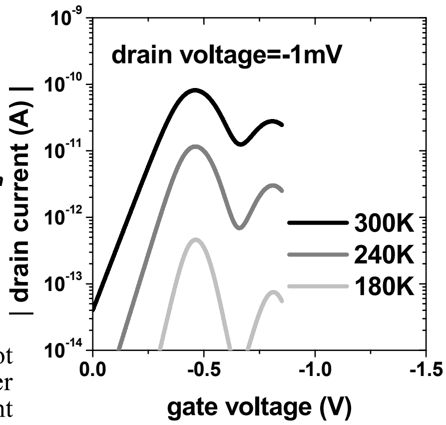

Fig. 9 : Calculated T-dependence of CB oscillations in SET. This simulation reproduces the strong T-dependence of the peak current.