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Characteristics of Silicon Single Electron Transistors Controlled by Charge Injection into Silicon Nano-Crystal Floating Dots

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1. Introduction

Silicon single electron transistors (SETs) are promising for future ultra low power and high density integrated devices. However, it has been impossible to fabricate SETs whose peak positions of Coulomb blockade oscillations are precisely designed because of size fluctuations of the quantum dot, background charges, and quantum confinement effect [1,2]. For practical integration of SETs, it is very important to develop a new SET structure in which the peak positions of Coulomb blockade oscillations are precisely controlled. To adjust the peak positions, we have already proposed an idea of SET that has a memory effect due to Si nano-crystal floating gates [1]. In this paper, we experimentally demonstrate this idea and successfully control the peak positions at various temperatures. In addition, the influence of potential fluctuations caused by random distribution of the Si nano-crystals is discussed from the obtained temperature dependence of Coulomb blockade oscillations.

2. Device Structure

The fabricated device is schematically shown in Figure 1. The point-contact channel MOSFET that acts as a SET [2] is used. Si nano-crystals are formed on the SET. This structure is usually used for non-volatile memory applications [3,4], and we use this structure for the adjustment of the peak positions. The point contact channel width is less than 10 nm. 4.4 nm-thick tunnel oxide is formed by thermal oxidation, on which Si nano-crystals and 30 nm-thick gate oxide are formed by low-pressure chemical vapor deposition (LPCVD). The average diameter of Si nano-crystals is 7nm and density is about 10^{12}cm^{-2}

3. Results and Discussions

Figure 2, 3, and 4 show I_d-V_g characteristics of a fabricated device at room temperature, 50 K, and 20 K, respectively. After applying various gate voltages, the I_d-V_g characteristics are measured. The Coulomb blockade oscillations are clearly observed. At each temperature, when the gate voltage larger than 4.5 V is applied, the peak positions of the oscillations are shifted. The shift becomes larger as the applied gate voltage is larger. On the other hand, when negative voltage (-6V) is applied, the I_d-V_g curve returns to the initial position. In this system, the potential of the channel dots is raised by the electrons injected into the floating dots, which results in the shift of threshold voltage of the device. Because of the high density of the floating dots, the potential of the channel dots is determined by many electrons in a large number of Si nano-crystals, resulting in the continuous shift of the I_d-V_g curves. This feature is suitable and important for the adjustment of the peak positions of Coulomb blockade oscillations.

The I_d-V_g curves at 20 K (Fig.4) indicate that there are two serial dots in the channel. These curves not only shift but also change in shape at 20 K after electrons are injected into the floating dots. The change of the oscillation curve has also been reported in a SET having one floating gate [5], where the injected charges are located at rim, resulting in stronger confinement of electrons in the SET. In our device, however, the oscillations period is almost the same at 20 K and the shapes of curves do not change above 50 K. This is because the injected electrons are located in silicon nano-crystal floating dots which are distributed on the SET. Therefore the potential confinement in the channel dots would not change before and after the electron injection in our device. This is also a suitable feature for peak position adjustment and the change of curve shape at 20 K would be caused by different origin from Ref. [5].

The change of the curve shape at 20 K is explained by the random distribution of the floating dots which are injected with electrons as shown in Figure 5. In contrast to the case of regular distribution (Fig.5(c)), when the distribution is random, the potential change in two dots due to the injected electrons is different and I_d-V_g curve changes in shape (Fig.5(d)). When temperature is raised and the thermal energy is larger than the difference of the potential change, the shape of the I_d-V_g curve does not change as shown in Figure 2 and 3. Therefore, at practical high temperatures, in term of the shape of I_d-V_g curves, potential fluctuations caused by the random dot distribution have only a slight influence on device operation.

4. Conclusions

We have demonstrated the control of the peak positions of Coulomb blockade oscillations in a SET using floating Si nano-crystal dots. In addition, it is found that the potential fluctuations caused by random distribution of Si nano-crystals have only a slight influence on the shape of the I_d-V_g curves at practical high temperatures.

References

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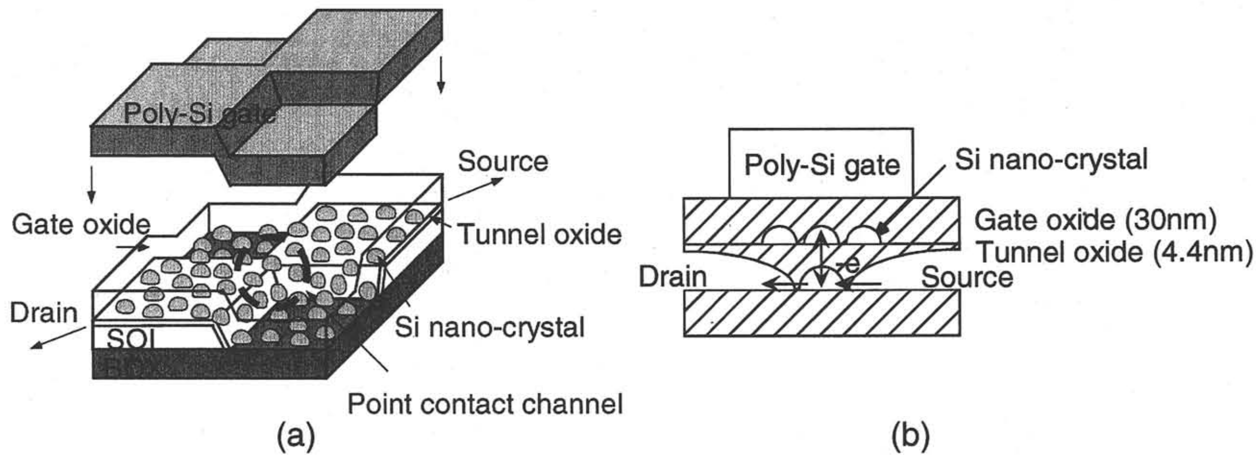

Fig.1 Schematics of the fabricated SET with Si nano-crystal floating gates. (a) Bird's-eye view. (b) Cross section. The average diameter of Si nano-crystals is 7 nm and the density is about $10^{12}cm^{-2}$.

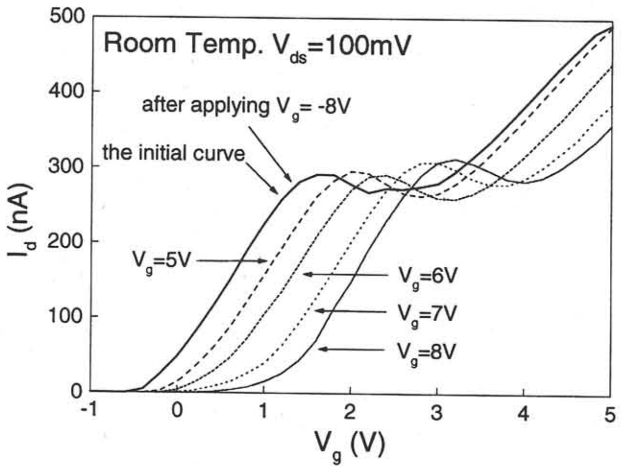

Fig.2 Gate voltage dependence of drain current at room temperature. The peak position of I_d-V_g curves is adjusted by applying various gate voltage while the shape of the curve does not change.

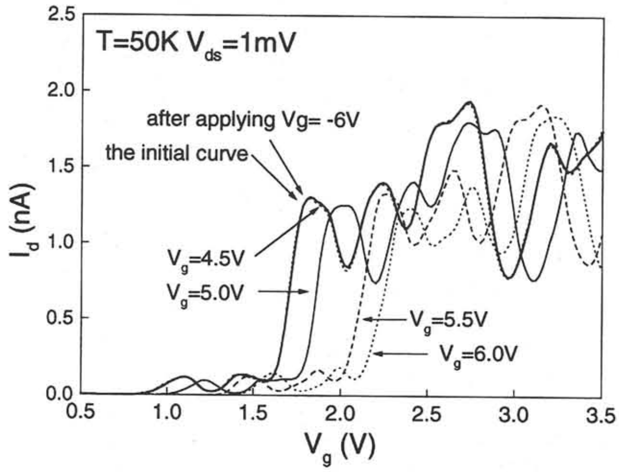

Fig.3 I_d-V_g characteristics at 50 K. The peak positions are adjusted by applying gate voltage. The I_d-V_g curve shows only a little change in shape.

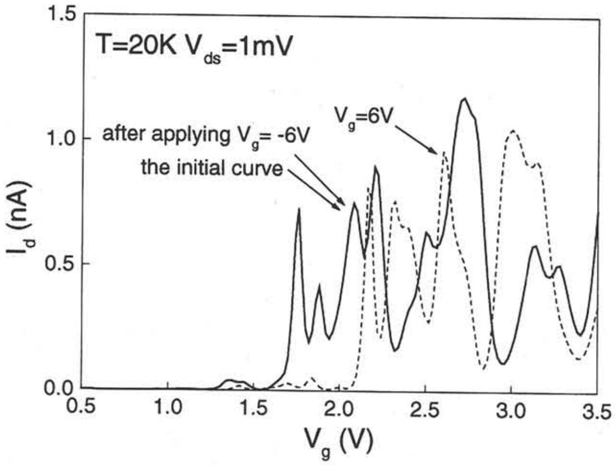

Fig.4 I_d-V_g characteristics at 20 K. The split peaks indicate two serial dots in the channel. The shape of I_d-V_g curve changes after the injection of electrons into floating dots due to the difference in potential variations in the two dots.

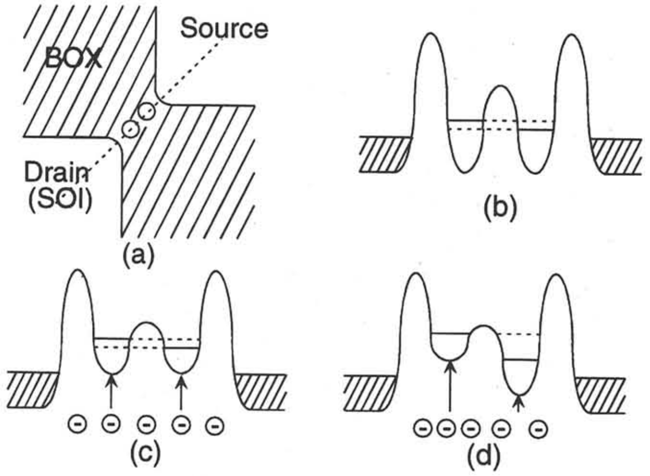

Fig.5 (a) A schematic of the top view of two serial dots. (b) Initial potential profile of the two serial dots. (c) The potential profile after electrons are injected into the floating dots. When the floating dots are regularly distributed, the I_d-V_g curve does not change in shape. (d) When the floating dots are randomly distributed, the I_d-V_g curve changes in shape.