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New Tunneling Model with Dependency of Temperature Measured in Si Nano-Dot Floating Gate MOS Capacitor

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1. Introduction

We propose a new tunneling model between nano-structure and electrode based on the measurement in Si Nano-Dot floating gate MOS capacitor. The efficient and stable electron injection from the electrode to the nano-structure is one of the most important issues for the future nano-electronic devices. The reliability of signal transport with a small number of electrons is required in such devices; whereas, the detail of the electron injection process in this system is still open to question. In this paper, we report unexpected temperature dependence of electron injection voltage in the direct tunneling region for the Si Nano-Dot floating gate MOS capacitor, and suggest that the temporal and spatial distribution of electron density in the electrode would be a crucial role in the injection process to the Si Nano-Dots. This new tunneling model would very useful for future nano-electronic devices.

2. Device Structure and Experimental Results

The schematic illustration of our sample structure is shown in Fig.1. We investigated the electron injection-emission between the substrate and the Si Nano-Dots in a Si-Nano Dots floating gate MOS capacitor with 3.5nm tunneling oxide [1]. To extract the mechanism of the electron tunneling process between the electrode and the nano-structure, we measured the transient currents as functions of the effective gate voltage [Gate Voltage (V_G) - Flatband Voltage (V_{FB})] in the conditions of 140K and 200K as shown in Fig. 2. In both conditions, the clear peaks are observed, which correspond to the electron injections and emissions between the electrode (inversion layer) and the Si Nano-Dots. Surprisingly, a large voltage shift by the temperature was observed in the injection current, whereas it was absent in the emission current. Conventionally, the tunneling probability in the direct tunneling region was thought to be determined independently from the temperature [2]. This large injection voltage shift in the peak cannot be explained by the temperature dependencies of material properties such as the change of the band gap or the shift of the Fermi level in doped Si.

3. Theoretical Analysis with 2D-Dot Tunnel Scheme

a) Electron Injection

To explain this phenomenon, we focused on the electronic state of the electrode in the electron injection process. Since, the geometry of the electrode (inversion layer) and a Dot are mismatched, where the electrode is spread two-dimensionally, whereas the Si Nano-Dots cover only a part of the electrode. Therefore, the electrons are inevitably injected from the large area to the small area in this system. We called this type of tunneling 2D-Dot Tunneling. Based on this viewpoint, we proposed that the sufficient overlap of electron density between the electronic states in the electrode and the Dot state is necessary to tunnel to the Dot as shown in Fig.3. We clarified how the spatial distribution of electronic state in the electrode affects the electron tunneling from the electrode to the Dot by Monte Carlo Simulations. Figure 4 indicates the tunnel injection voltages with temperature of our proposed tunneling model and its measurement results. We obtain a good agreement with the measurement only when we introduce a threshold tunneling density, which is defined as the electron density below the Dot when the density becomes above 10% (Fig.5). Validity setting the threshold tunneling density is discussed as follows. In our proposed tunneling model, the electronic state in the electrode fluctuates temporally and spatially due to the non-equilibrium state of the system, then the fluctuated electron satisfies high tunneling probability when the electron is localized below the Dot during time-evolution of the electronic state [Fig.6 (a)]. Our model could explain the temperature dependence of the injection voltage. Since, the ratio of the localized electron should increase with increasing temperature. This indicates that the spatial and temporal fluctuation of the electronic state in the electrode plays a crucial role for the electron tunneling process. This implies that the modulation of the spatial density distribution of electronic state in the electrode enables us to control the electron injection process.

b) Electron Emission

On the other hand, the electron emission process does not show the temperature dependence, because the electron in the Dot is already localized by spatial limitation. Thus, the overlap between the Dot state and electrode states are sufficiently large [Fig.6 (b)]. This indicates that the temperature dependence of electron tunneling cannot be observed in the emission process.

4. Conclusions

We proposed a new tunneling theory that is able to explain temperature dependence of tunneling voltage from the two-dimensional system to a Dot. It is made clear that the overlap between the electronic state in the electrode and the Dot dominates the tunneling process in the 2D-Dot tunneling. Thus, tunneling is available when the overlap electron density for the Dot becomes above 10 %. On the other hand, the electron emission process does not show the temperature dependence, because the overlap between Dot state and electrode states is sufficiently large to tunnel. From above all, we show the electronic state in the electrode strongly affect to the tunneling processes in the nano-system.

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References:

[1] S. Miyazaki *et al*, Thin Solid Films, **369** (2000) 55.
[2] Y. Takahashi *et al,* IEEE Trans. Electron Device*,* **43** (1996) 1213.

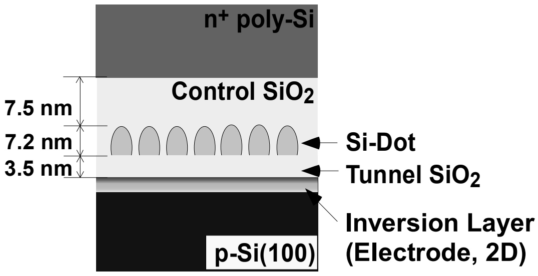

Fig. 1 Schematic illustration of Si Nano-Dots floating gate MOS capacitor.

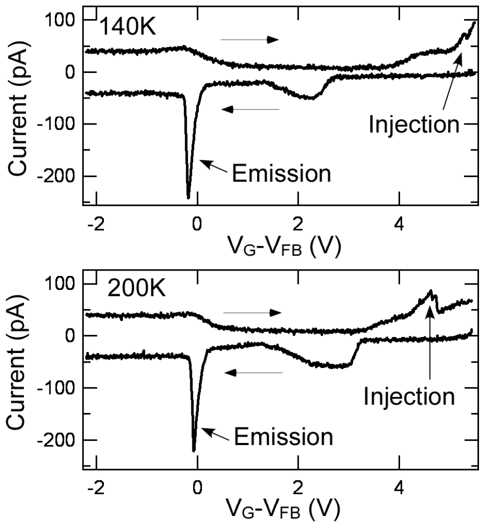

Fig. 2 Transient Currents with the effective voltage in a Si Nano -Dots floating gate MOS capacitor.

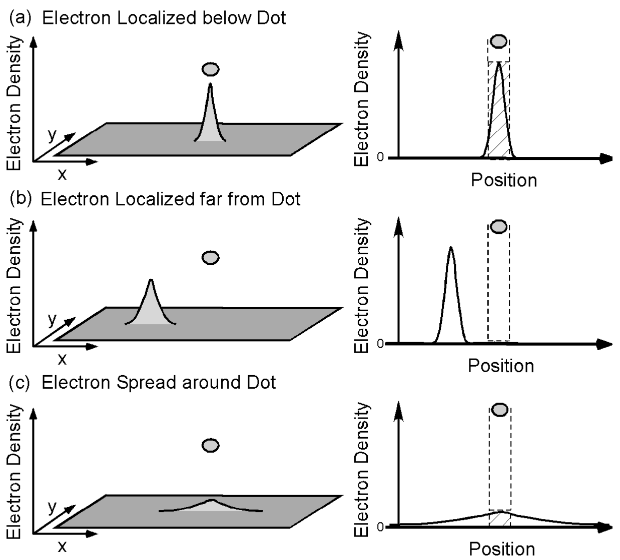

Fig. 3 Schematic illustrations of overlap between 2DEG (electrode) and Dot. (a) Electron localized below Dot. (b) Electron Localized far from Dot. (c) Electron Spread around Dot.

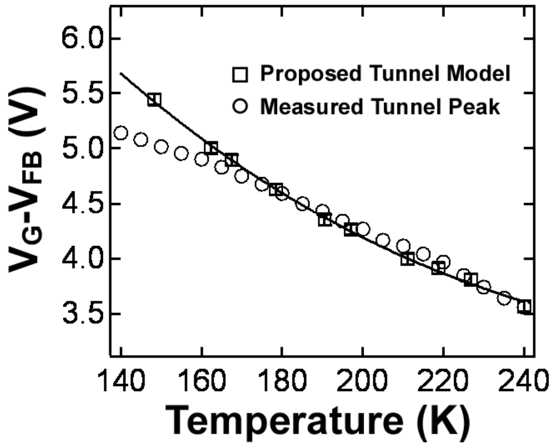

Fig. 4 Fitting results of tunnel injection voltages with temperature by our proposed tunneling model.

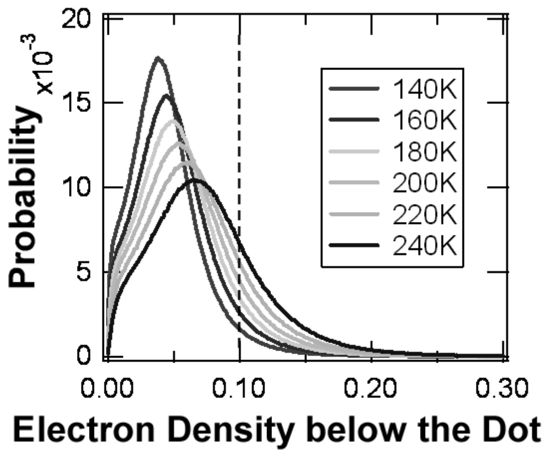

Fig. 5 The distribution of electron density below the Dot with the temperature.

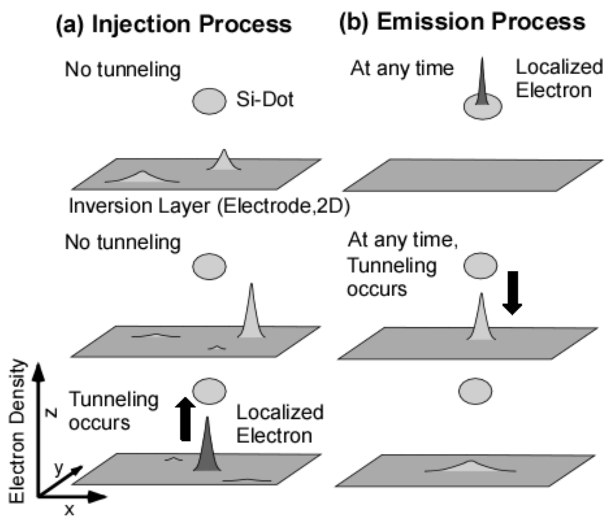

Fig. 6 Schematic illustration of considerable electron injection and emission processes.