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# Mechanism of Gate-Length Dependence of Quantum Dot Operation in Isoelectronic-Trap-Assisted Tunnel FETs

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**Abstract**

**Current characteristics of quantum dot devices based on isoelectronic-trap-assisted tunnel FETs (IET-TFETs), which can operate up to room temperature as a single electron transistor and also operate up to 10 K as a qubit, were investigated employing device simulations. The Coulomb oscillation is experimentally observed only with short $L_G$ devices while conventional TFET characteristics are almost independent of $L_G$. We clarified that the $L_G$ dependence is attributed to the probabilistic lack of quantum dots in the narrow desirable location, and not to the short-channel effect associated with potential modulation. These results facilitate the design guidelines of IET-TFET-based qubit devices.**

## 1. Introduction

Quantum computers have attracted significant attention, and Si quantum bits (qubits), with the advantages of high-temperature operation or large-scale-integration, are being investigated as one of the building block candidates. Isoelectronic-trap-assisted tunnel field-effect transistors (IET-TFETs) [1] can operate as quantum dot devices, owing to the strong electron confinement in the quantum dot formed by Al-N complex impurity. Recent experiments have demonstrated that they are capable of operating as single-electron transistors up to room temperature, and also as qubits up to 10 K [2].

The Coulomb oscillation, which is a carrier transport through a quantum dot, is not observed in the IET-TFETs when the gate length ($L_G$) exceeds 100 nm in the experiment [2]. In conventional TFET operation, current characteristics are almost independent of $L_G$ because the tunneling current occurs at the source-edge. It is speculated that dot-intermediated tunneling also occurs at the source-edge and that the Coulomb oscillation does not depend on $L_G$. However, this speculation is not consistent with the experimental results. In this study, therefore, we analyzed the $L_G$ dependence of current characteristics in IET-TFET-type quantum dot devices employing device simulations and clarified the mechanism of the disappearance of the Coulomb oscillation in the long $L_G$ devices.

## 2. Calculation model and method

Figure 1(a) shows the schematic structure of the IET-TFET quantum dot device discussed in this paper. This device comprises a p-type TFET on a silicon-on-insulator wafer, where the gate width is 10 nm. The acceptor concentration of the channel is $10^{15}$ cm$^{-3}$ and the donor/acceptor concentrations of the source/drain regions are $10^{20}$ cm$^{-3}$. The quantum dot is located at a distance of 10 nm from the source-edge regardless of $L_G$ and 0.3 nm below the oxide/silicon interface.

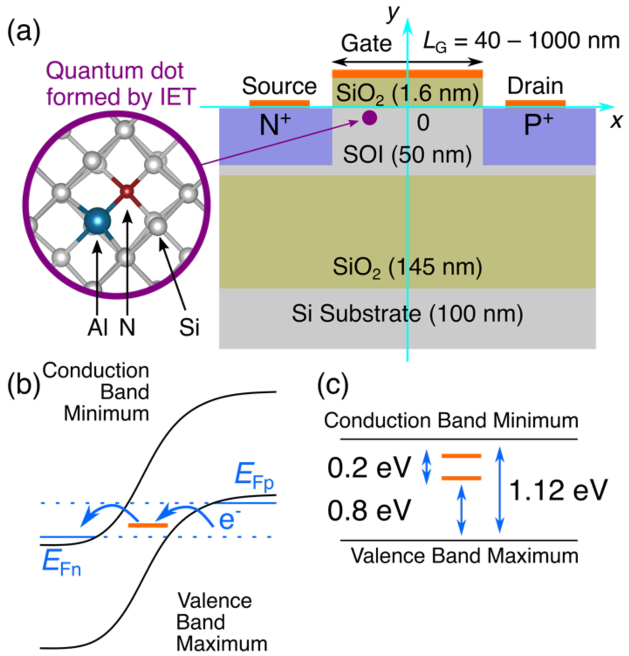


Fig.1 (a) Structure of the IET-TFET quantum dot device. (b) Schematic band diagram of the quantum dot-intermediated tunneling. (c) Schematic of energy levels within the Si bandgap.

Current characteristics and carrier distributions are calculated employing drift-diffusion equations using Impulse TCAD [3]. To reproduce the dot-intermediated tunneling as shown in Fig. 1(b), the following dot-intermediated tunneling term is introduced in Generation-Recombination (GR) term [4-6]:

$$GR = \frac{2\pi}{\hbar}\frac{\Gamma_1^2\Gamma_2^2}{\Gamma_1^2+\Gamma_2^2}\cosh^{-2}\left(\frac{\mu_0-E_F}{2k_BT}\right) \quad (1)$$

$$\Gamma_i = \gamma_i \exp\left(-\frac{L_i}{\sigma}\right), i = 1,2 \quad (2)$$

where $\Gamma_i$ depends on the tunnel distance ($L_i$) and tunnel current increases with a decrease in the $L_i$. The energy position of a quantum dot is set to be 0.8 eV higher than the valence band maximum of Si and the charging energy is 0.2 eV based on the experimental observations [2], as shown in Fig. 1(c).

## 3. Results and discussions

Figure 2 shows the drain current ($I_D$)-gate voltage ($V_G$) characteristics for several values of $L_G$. In the device with $L_G$ = 40 nm, Coulomb oscillation was observed around $V_G$ = 0.1 V and 0.4 V in the OFF region of TFET operation. The oscil-

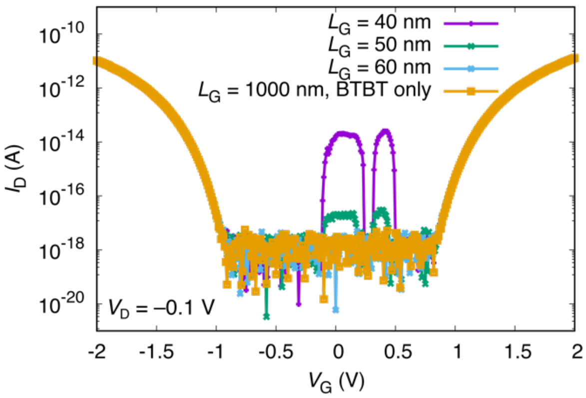


Fig.2 $I_D$-$V_G$ characteristics for several $L_G$. The Coulomb oscillation was observed around $V_G$ = 0.1 and 0.4 V.

lation intensities were weaker for $L_G$ = 50 nm and the oscillation was not observed for $L_G$ = 60 nm. This observation qualitatively reproduces the experimental results. Taking GR rate analysis in the device (*not shown*), it is clarified that electrons directly tunnel from the drain toward the source and the current intensity is determined by $L_G$, which is almost identical to tunnel distance, thereby causing the $L_G$-dependence. Furthermore, we confirmed that this $L_G$-dependence is not caused by short-channel effects associated with potential modulation because tunnel distance is not affected by the potential modulation due to the $L_G$ decrease.

Next, to clarify whether the dot-intermediated tunneling occurs near the source-edge in large $L_G$ devices, we investigated "tunnel distance" and "whether or not the quantum dot energy level lies within the tunnel window", which determine the occurrence of dot-intermediated tunneling. Firstly, Fig. 3(a) shows the $V_G$ dependence of tunnel distance. In the $V_G$ range of 0 to around –0.5 V, tunnel distance is almost identical to the $L_G$, thus the Coulomb oscillation cannot be observed in the large $L_G$ devices due to long tunnel distance. Around $V_G$ = –1.0 V, tunnel distance becomes sufficiently short for both devices; however, the Coulomb oscillation peaks are superposed by ON current of TFET operation. Therefore, the Coulomb oscillation in the large $L_G$ devices can be observed only around $V_G$ = –0.7 V, which is indicated by the area filled in blue in Fig. 3(a). Secondly, Fig. 3(b) shows the $V_G$ dependence of the energy level for various quantum dot locations in the channel region. Each red line represents the energy level for various quantum dot locations, and the tunneling occurs when the red line lies within the tunnel window. Around $V_G$ = 0 V, the energy level of the quantum dot in a wide location enters the tunnel window. However, around $V_G$ = –0.7 V, where the Coulomb oscillation can be observed even in the long $L_G$ device as discussed above, the energy level of a quantum dot enters the tunnel window only when the quantum dot is located in a considerably narrow location, which is approximately 2 nm from the source-edge. Namely, the large $L_G$ devices probabilistically lack quantum dots in the narrow desirable location, which is required for dot-intermediated tunneling.

Therefore, the short $L_G$ devices are suitable for observing the Coulomb oscillation and the qubit operation beyond it, and the Coulomb oscillation might be observable in the long $L_G$ devices if the concentration of quantum dots increases.

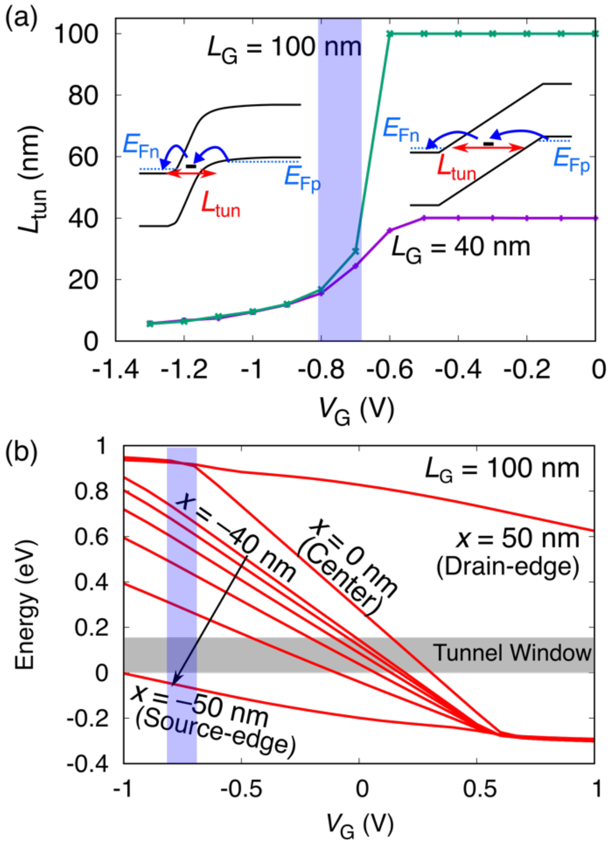


Fig.3 (a) $V_G$ dependence of tunnel distance. (b) $V_G$ dependence of the energy level of a quantum dot at various locations in the channel region. The dot-intermediated tunneling occurs when the energy level of the quantum dot lies within the tunnel window.

## 4. Summary

We investigated the Coulomb blockade transport in IET-TFET-type quantum dot devices with several values of $L_G$ by device simulation to clarify the mechanism of Coulomb oscillation disappearance for long $L_G$. This $L_G$ dependence is attributed to the probabilistic lack of quantum dots in a narrow desirable location, and not to the short-channel effects associated with potential modulation. These results clarify one of the operational mechanisms in IET-TFET-type quantum dot devices, which are capable of operating at high temperature and facilitate design guidelines for TFET-based quantum dot devices.

## Acknowledgments

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