Mechanism of extraordinary gate-length dependence of quantum dot operation in isoelectronic-trap-assisted tunnel FETs

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Current characteristics in quantum dot devices based on isoelectronic-trap-assisted tunnel field-effect transistors (TFETs) were investigated employing device simulations. It was clarified that in the case of devices with small gate lengths, the quantum-dot-intermediated tunneling distance is almost identical to the gate length, thereby causing gate-length-dependent current intensity. Furthermore, devices with larger gate lengths probabilistically lack quantum dots in the narrow desirable location, thereby hindering the operation of TFETs as quantum dot devices. This study clarifies an important operating mechanism of quantum dot devices based on TFETs and provides the design guidelines for high-temperature operating quantum bit devices. © 2020 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

Quantum computers have attracted significant attention owing to their contributions toward advancements in computational capabilities by using new computational principles.1–3 The implementation of silicon-based quantum bits (qubits) is expected to yield large-scale integration technologies in the near future. Spin qubits are the most promising silicon qubits.4,5 Recently, tunnel field-effect transistor (TFET)-type spin qubits have been proposed, and experiments have demonstrated that they are capable of operating at high temperatures of up to 10 K.6–10 Furthermore, gate-defined qubits are also capable of operating at temperatures in the order of 1 K.11,12 This type of “hot” operation is another advantage of silicon-based qubits.

Semiconductor spin qubits, which control the electron spin in a quantum dot, can be realized on quantum dot devices such as single-electron transistors. Discrete energy levels of the electrons confined within the quantum dot due to the Coulomb blockade are utilized. A quantum dot is sandwiched between electrodes via an insulating film, and the gate is used to electrostatically control the energy levels of the quantum dot. Therefore, electron transport subjected to the Coulomb blockade is governed by the energy-level spacing, electrostatic capacitance around the quantum dot, and tunnel probabilities. Scholze et al. proposed a theoretical scheme that can handle these effects quantitatively.14 The scheme involves the Schrödinger–Poisson solver and Bardeen tunneling, which can consider the energy level of the quantum dot, tunneling rate between the quantum dot and the macroscopic reservoirs, and the charging energy of the quantum dot. In addition, carrier redistribution caused by the change in gate voltage (VG) plays an important role in the electron transport of semiconductor quantum dots. Carrier redistribution alters tunneling distances between the dot and the electrodes. Therefore, to understand the operation of semiconductor dots, carrier redistribution and its effects need to be considered. In this regard, drift–diffusion transport simulations have been a powerful tool for describing the operation mechanism of semiconductor devices. Consequently, in a recent study, simulation combining drift–diffusion and quantum transport has been proposed in order to evaluate semiconductor quantum dots.15

In this letter, we report on TFET-type quantum dot devices.11 An isoelectronic trap (IET) impurity, composed of Al and N, embedded in a TFET is employed as a quantum dot in these devices. These devices were originally proposed as steep-slope devices;16–19 however, they can also operate as quantum devices. They can be used to realize single-electron transport up to room temperature as well as qubit operation up to 10 K. In the experiment, Coulomb oscillation is observed in the off region for devices with a gate length (LG) of 60–80 nm; however, oscillation is not observed when LG exceeds 100 nm. In conventional silicon TFET operation, the current characteristics are almost independent of LG because the tunneling current flows at the source-edge.20 Therefore, it is speculated that dot-intermediated tunneling also occurs at the source-edge and that the Coulomb blockade transport does not depend on LG. However, this speculation is not consistent with the experimental results. Thus, the dependence of the Coulomb blockade transport in IET-TFETs on LG is not clear. To address this issue, we calculate and analyze the quantum transport under Coulomb blockade in IET-TFET-type quantum dot devices, by utilizing a self-developed simulator employing drift–diffusion, and quantum tunneling transports.15 This enables us to easily construct models for quantum tunneling transport and is suitable for transport calculations via traps. The previous reports clarified the effect of tunneling via traps on the current characteristics of a TFET or Esaki diode using a similar method.21,22 These reports discussed the tunneling via traps, which form the tail states near the band-edge. This study aims to construct a tunneling transport model based on a relatively simple method compared with those used in previous works and clarify why the Coulomb blockade is observed experimentally only in short-channel TFETs.

Figure 1(a) presents the structure of the IET-TFET quantum dot device discussed in this letter. This device comprises a p-type TFET on a silicon-on-insulator wafer. The gate width (WG) is 10 nm. The acceptor concentration of the channel is 10^{15} \text{ cm}^{-2}. The donor/acceptor concentrations of the source/drain regions are 10^{20} \text{ cm}^{-2}. The quantum dot is located 10 nm from the source-edge regardless of LG and 0.3 nm below the gate interface, assuming that the quantum dot intermediated the tunneling near the source-edge.

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The current characteristics and carrier distributions are calculated by employing standard drift–diffusion equations using our homemade simulator, which is named Impulse TCAD. In IET-TFET quantum dot devices, single-electron transport can be observed at temperatures ranging from cryogenic to room temperatures; accordingly, the carrier temperature is set at 80 K, which corresponds to the median operation temperature. Generation–recombination (GR) terms of the drift–diffusion equations include Kane’s band-to-band tunneling (BTBT), and the following quantum transport term corresponding to the dot-intermediated tunneling current: 

\[
GR = \frac{2\pi}{h} \frac{\Gamma^2 \Gamma_i^2 \cosh^2 \left( \frac{\mu_0 - E_F}{\alpha k_B T} \right)}{\Gamma_1 \Gamma_2 + \Gamma_i^2}, \tag{1}
\]

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

where \(\mu_0\) is the chemical potential of a quantum dot, and \(E_F\) is the Fermi energy; the temperature \(T\) is set at 0.1 K, \(\alpha = 2\), and the spatial dispersive width \(\sigma\) is 3 nm. \(L_i\) is the tunneling distance, and \(i\) is an index indicating source-dot or dot-drain. According to Eq. (2), the dot-intermediated tunneling current increases with a decrease in the tunneling distance. We should note that, to be precise, the form of the prefactor in Eq. (1) depends on temperature. The parameters derived from the electron states of valence and conduction bands should be included in the prefactor to accurately calculate the height of the Coulomb peak. Furthermore, when resonant tunneling occurs at low temperature, different formulas are used for the prefactor. In this study, a simple formula was employed because the temperature dependence is not analyzed quantitatively. Other details of the calculation and temperature settings are described in our previous paper.

The energy level of a quantum dot influences the dot-intermediated carrier transport [Fig. 1(b)]. In conventional TFET operations, BTBT occurs between valence and conduction bands. When the IET quantum dot is introduced, a localized state is generated immediately below the conduction band of Si. Dot-intermediated tunneling current flows only when the energy level is within the tunnel window and the tunneling distance is sufficiently short. In the calculations, the energy position of a neutral quantum dot is set to be 0.8 eV higher than the valence band maximum of Si [Fig. 1(c)]. The energy level of a charged quantum dot is 0.2 eV greater than that of a neutral quantum dot; based on experimental observations.

First, we investigated the dependence of \(L_G\) on the gate voltage (\(V_{GS}\)) characteristics for several values of \(L_G\). Ambipolar BTBT currents are observed below \(V_{GS} = -1.0\) V and above \(V_{GS} = 1.0\) V; this is because the devices are not designed to avoid ambipolar characteristics. For the device with \(L_G = 40\) nm, Coulomb oscillation was observed around \(V_{GS} = 0.1\) and 0.4 V. A similar oscillation was observed in the device with \(L_G = 50\) nm; however, the current intensities were weak. Moreover, oscillation was not observed in the device with \(L_G = 60\) nm. This observation qualitatively reproduces the experimental results that Coulomb oscillations are not observed when \(L_G\) exceeds a certain value. Note that it is difficult to experimentally determine the coordinate of the quantum dot that contributes to the Coulomb oscillation because the IET quantum dot was implanted in the entire channel region by ion implantation in the previous experimental study. Therefore, herein, we cannot compare the simulation and experimental results quantitatively. We plan to investigate this in our future research.

Figures 3(a), 3(b) show the distribution of carrier GR rate caused by the dot-intermediated tunneling. Carriers are generated at the source-edge (electron) and drain-edge (hole), which indicates that electrons directly tunnel from the drain toward the source. Thus, it is clarified that, for these devices, tunneling distances are determined by \(L_G\) in the presence of Coulomb oscillations. According to Eqs. (1) and (2), GR rate decreases on increasing the tunneling distance; accordingly, devices with larger \(L_G\) exhibit smaller tunneling currents due to the tunneling length, which is determined by \(L_G\), as shown in Fig. 2.

We note that the dependence of Coulomb oscillations on \(L_G\) is not caused by the so-called short-channel effect (SCE), which is a result of channel potential modulation. As you can see in the band profile for each \(L_G\) [Fig. 3(c)], the dot-intermediated tunneling occurs between source- and drain-edge, and the potential modulation on the short \(L_G\) devices does not affect the dot-intermediated tunneling, which suggests the absence of the SCE. Therefore, it was concluded that the SCE is not produced in these cases and that the SCE does not originate from the missing Coulomb oscillation in devices with large \(L_G\).
Thus far, the results indicate that Coulomb oscillation is observed only when $L_G$ is less than 60 nm and that the SCE caused by potential modulation has not occurred. Thus, we begin to consider the mechanism that Coulomb oscillation is only observed in devices with small $L_G$. In the operation of conventional TFETs, BTBT occurs at a nearby source-edge. Thus, we speculate whether the dot-intermediated tunneling current occurs near the source-edge of a device with a large $L_G$. Excluding the effects of charging energy, which are not included in this model, the occurrence of tunneling current is determined by two factors: “tunneling distance” and “whether or not the quantum dot energy level lies within the tunnel window”. The following discussion is based on the perspective of these two factors.

First, we analyze the dependence of tunneling distance on $V_{GS}$ (Fig. 4), where the tunneling distance is equivalent to the sum of two tunneling distances intermediated by the quantum dot. Similar to the case of the BTBT, there is a threshold distance at which the tunneling current is observed because the tunneling current decreases with an increase in tunneling distance. As discussed previously, the threshold for this calculation is approximately 60 nm. From $V_{GS} = 0$ up to $-0.5$ V, carriers are not generated in the channel, and the tunneling distance is nearly equal to $L_G$. Thus, the direct source-to-drain-tunneling current is only observed when the tunneling distance, that is $L_G$, is lower than the threshold. On the contrary, when $V_{GS}$ decreases to less than $-0.8$ V, both devices with large and small $L_G$ exhibit almost identical tunneling distances due to the carrier redistribution in the channel caused by the applied $V_{GS}$; the tunneling occurs near the source-edge. As conventional TFETs operate within this voltage range, the current characteristics are not influenced by the channel length.

Second, we investigate the relationship between the energy of the quantum dot and the tunnel window. Figure 5 illustrates the dependence of the energy level for various quantum dot locations in the channel region on $V_{GS}$. In the case of the device with $L_G = 40$ nm, the energy level of the quantum dot located at the center of the channel lies within the tunnel window at approximately $V_{GS} = 0.2$–0.4 V, and a tunneling current is observed in this voltage range. When the location of the dot moves toward the source-edge, the range of $V_{GS}$ for which the energy level lies within the tunnel window shifts toward lower voltage values. For instance, in the case of the quantum dot located at $x = -18$ nm, which is 2 nm away from the source-edge, the energy level lies within the tunnel window when $V_{GS}$ is $-0.4$ to $-0.1$ V. In addition, when the quantum dot is located at $x = -20$ nm, i.e. just at the source-edge, the energy level does not enter the tunnel window because the gate electrostatic control is weak at this location. This trend is independent of $L_G$. In other words, we note that, with a decrease in the negative value of $V_{GS}$, the dot location for which the energy level enters the tunnel window continues to become narrower. At approximately $V_{GS} = 0$ V, devices with large and small $L_G$ exhibit almost identical tunneling distances due to the carrier redistribution in the channel caused by the applied $V_{GS}$; the tunneling occurs near the source-edge. As conventional TFETs operate within this voltage range, the current characteristics are not influenced by the channel length.
the energy level enters the tunnel window for the quantum dots in a wide location; however, at approximately $V_{GS} = -0.7$ V or less, the energy level enters the tunnel window for the quantum dots in a considerably narrow location, which is approximately 2 nm from the source-edge.

Based on Figs. 4 and 5, we can consider the mechanism whereby the tunneling current is not experimentally observed in devices with large $L_G$. When $L_G$ is large, it is difficult to tunnel directly from the source-edge to the drain-edge because the tunneling distance is significantly long. Thus, it is necessary to apply more negative values of $V_{GS}$ to shorten the tunneling distance and enable tunneling at the source-edge. However, as shown in Fig. 5, when a more negative value of $V_{GS}$ is applied, the dot location at which the energy level enters the tunnel window is limited to the range of a few nanometers from the source-edge. Furthermore, in the experiments, the concentration of Al–N IET that was introduced for the formation of quantum dots is in the order of $10^{18}$ cm$^{-3}$, which is one IET in 10 nm$^3$; therefore, the IETs are unlikely to be present within a few nanometers from the source-edge. Hence, only the devices with small $L_G$ exhibit quantum transport because the devices with large $L_G$ probabilistically lack quantum dots in the narrow desirable location, which is required for dot-intermediated tunneling.

**Fig. 3.** (Color online) (a) Generation–recombination (GR) rate distribution caused by dot-intermediated tunneling at the oscillation peaks. (a) GR distribution for the device with $L_G = 40$ nm. (b) GR distribution for the device with $L_G = 50$ nm. (c) Band profile of Si immediately below the SOI/oxide interface, where $V_{GS} = 0.1$ V.

**Fig. 4.** (Color online) Dependence of tunneling distance on $V_{GS}$. From $V_{GS} = 0$ to approximately $-0.5$ V, tunneling occurs directly from the source to the drain, as indicated in the schematic band diagram on the right. When $V_{GS}$ is approximately $-0.8$ V or less, the tunneling distance is almost identical, regardless of $L_G$. In this situation, tunneling occurs near the source-edge, as indicated in the schematic on the left.

**Fig. 5.** (Color online) Dependence of the energy level of a quantum dot on $V_{GS}$. The center of the channel is set as 0 for the coordinate of a quantum dot, as shown in Fig. 1(a). (a) Device with $L_G = 40$ nm and the varying quantum dot location at $x = -20$ to 0 and 20 nm. (b) Device with $L_G = 100$ nm and the varying quantum dot location at $x = -50$ to 0 and 50 nm. Dot-intermediated tunneling current can be observed at $V_{GS}$ such that the energy level of the quantum dot lies within the tunnel window.
Here, we would comment on design guidelines to realize high-temperature-operable IET-TFET-type quantum dot devices. The modeling approach in this work clarified that it is difficult to observe the Coulomb oscillations with large $L_G$ devices accompanied by tunneling at the source-edge, and it is easy to observe the oscillations with short $L_G$ devices accompanied by tunneling between the source and drain via a quantum dot. In addition, it is indicated that the Coulomb oscillation is observed in the device with $L_G = 40–50 \text{nm}$, while it is experimentally observed in the device with $L_G = 60–80 \text{nm}$. We believe that the discrepancy originates from the effective channel length, which is caused by the diffusion of impurities in the experiments. Because the effective channel length becomes shorter by 10–20 nm due to impurity diffusion, the devices with $L_G = 40–50 \text{nm}$ in this calculation correspond to the device with $L_G = 50–70 \text{nm}$ in the experiments. Therefore, the calculation and experiments agree well from the viewpoint of $L_G$. Indeed, the IET-TFET quantum dot devices discussed here can operate as qubits up to 10 K without dilution refrigerators and can be fabricated utilizing conventional large-scale-integration technologies enabling large-scale-integration of the qubits. The knowledge provided in this work could assist in the development of high-temperature-operable quantum computers, for which a device fabrication technology that realizes devices with short effective channel length with high yields paves a way.

In summary, we calculated and analyzed the characteristics of the Coulomb blockade transport in IET-TFET quantum dot devices using various values of $L_G$ and further clarified the operation mechanism that Coulomb blockade is not observed in devices with large $L_G$. The devices with long $L_Q$ probabilistically lack quantum dots in the narrow desirable location, which is a prerequisite for dot-intermediated tunneling. Thus, short $L_Q$ devices are desirable for observing Coulomb blockade transport. This $L_Q$ dependence is not due to the so-called SCE associated with channel potential modulation. Furthermore, the dot-intermediated tunneling current might be observable if the concentration of quantum dots increases. The results of this study clarify one of the important operation mechanisms in high-temperature-operable quantum dot devices based on TFETs. Therefore, these results are expected to facilitate design guidelines and also contribute toward the future development of such qubit devices.

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