Study on High-Frequency Response of Single-Electron Transistors

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Abstract of Dissertation

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Abstract:

Single-electron transistor (SET) is a three terminal device which has gained popularity in the field of nanoelectronics due to its advanced and attractive features i.e., small size, low power consumption, high functionality, etc.

Aggressive scaling of circuits with conventional scaled-down FETs have almost reach the limit and SETs have the potential to replace FETs in the circuit for further scaling. However, it should be noted that replacing conventional transistors with SETs in the circuits can have desirable and undesirable consequences, as a result careful evaluation of SETs behavior is crucial. Looking at the demand of future electronics, devices with high-speed/high-frequency operations are anticipated.

Traditionally, it was believed that SETs are slow due to high tunneling resistance (R_T > 25.8 kΩ). However, due to advanced nanofabrication technology it is now possible to fabricate SETs with capacitances in the range of attofarad. As a result, subpicosecond intrinsic time constant can be achieved bringing about an opportunity in high-speed or high-frequency operation.

Till now high-frequency operation of SETs has been discussed simply based on this small intrinsic time constant. Nevertheless, with advances in nanofabrication technology it is worthwhile to analyze the high-frequency dynamic behavior of the SET in more detail. For this reason, rectifying effect of SET at high frequencies and capacitance components in a SET at high frequencies have been discussed.

[SET as a high frequency rectifier]

It was reported that there is no cutoff frequency in the rectifying operation of SETs. Theoretical explanation behind such behavior is attempted for the first time through the simulation using SET model based on time dependent master equation. From the obtained results it was concluded that the asymmetry in the tunneling rate (rate with which electron tunnels into or out of the Coulomb island) with respect to the drain

voltage is responsible for the rectifying operation at high frequencies. In order to verify the rectifying characteristics predicted by the simulation, SETs fabricated by the pattern-dependent oxidation (PADOX) and those based on the heavily doped Si nonowire were evaluated in terms of the frequency response of the rectifying current. In the former SETs, the intrinsic SET characteristics could not be observed since the cutoff frequency f_c of the parasitic MOSFET is lower than the intrinsic f_c of the SET. In the latter SETs the f_c of the parasitic low-pass filter in the lead is sufficiently high due to its low sheet resistance, but unexpected reduction of the rectifying current at low frequencies is observed. Further research on the parasitic components that have not been considered, and on the stability of SET are necessary.

The experimental verification will lead to a clear prospect for the rectifier application of SETs in the high-frequency regime where conventional devices cannot operate.

[Capacitance components inside SET]

Understanding of the capacitance components inside the SET is crucial to discuss its high-frequency operation. For that purpose, SET model based on the time-dependent master equation by taking the dynamic gate current into account has been proposed which can represent terminal capacitances and transcapacitances.

By using this model, bias, frequency, and temperature dependences of these intrinsic capacitances are evaluated. It was concluded that, at low frequencies, the capacitances depended on the biasing but, at high frequencies, the transistor action of the SET was lifted and it acted as a passive capacitance circuit. Such a transition from the low-frequency to high-frequency characteristics of the SET could be described quantitatively by the proposed model. Also, the model could analyze the behavior of the SET covering a wide range of temperature.

In addition, the frequency response of the SET-based amplifier was investigated. The transformation from inverting amplifier at low frequencies to the capacitive divider at high frequencies was successfully described. It was also found that the Miller effect is not conspicuous in the SET-based amplifier due to the negligible feedback capacitance at the operation point.

From these results, we can expect that the proposed model can be widely used to analyze the circuits including SETs for high-frequency amplification, oscillation, detection, qubits readout by gate-based sensing, and so on.