Physical Mechanism of Current Fluctuation under Ultra-Small Device Structures

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1. Introduction

Unlimited miniaturization of Si-MOSFETs is successfully pursued at various leading research laboratories.[1] Without any doubt, the device size of future Si-MOSFETs continues to shrink into sub-0.1 micron regions. As the device size shrinks into the sub-0.1 micron regime, it is speculated that the fluctuations of device characteristics might be of crucial importance for future large-scale-integration. Nevertheless, very little attention has been paid on the fluctuation characteristics of the channel current for such ultra-small devices. As a result, a clear picture for the physical mechanism of the current fluctuation in Si-MOSFETs under the sub-0.1 micron regime is still missing.

Of course, the current fluctuation itself has been intensively studied since the vacuum-tube era.[2] In particular, numerical tools such as the Monte Carlo technique have been successfully applied to analyze the current noise characteristics in semiconductors.[3] However, most attention so far has been paid on the overall characteristics of the current noise in bulk or in *moderately* large device structures and, essentially, no attention has been paid for the compromised role of the diffusive and ballistic electrons on the current fluctuation, which is characteristic to such ultra-small device structures.[4]

In the present paper, we attempt to clarify the basic physical mechanism of the current fluctuation under sub-0.1 micron device structures in Si by employing Monte Carlo simulations. We demonstrate that a new current fluctuation mode, in addition to the ordinary thermal noise and hot-carrier noise under *large* devices, appears as the channel length shrinks into below 0.1 micro-meters. This fluctuation mode is peculiar to sub-0.1 micron devices since the fluctuation is closely associated with the ballistic electrons in the channel.

The present paper is organized as follows: In section 2, simulation method employed for the analyses of current fluctuation is briefly described. In section 3, the simulation results from the Monte Carlo method and discussion are presented. Conclusions are given in section 4.

2. Numerical

The present analyses are carried out for a one-dimensional Si *n-i-n* structure. The *n* region is 100 nm long and its doping is 10^{18} cm^{-3} each. The *i* region (hereafter denoted as channel) is varied from 200 to 50 nm long so that the transition from the diffusive to quasi-ballistic transport regime is covered.[5, 6] The cross-sectional area is assumed to be 0.05 μm^2. An average number of simulated electrons is thus around 10000 depending on the biasing.

The simulations are performed by using an ensemble Monte Carlo method self-consistently coupled with a one-dimensional Poisson solver. The Monte Carlo employed here is a simple and conventional one; the analytical (parabolic) electronic band structure and Si material parameters known in the literature[7] are used (see Table 1). The device is divided into equal cells of 2 nm each and the electric potential is updated at each time step of 1 fs. The electron kinetics is simulated for several hundreds ps and the device characteristics such as the channel current are sampled after a transient of 10 ps.

The channel current $I(t)$ at time t is evaluated by

$$I(t) = \frac{e}{L}\sum_{i=1}^{N(t)} v_{iz}(t) = \frac{eN(t)}{L} v_d(t), \qquad (1)$$

where e, L, N, v_{iz}, v_d are, respectively, the electronic charge, the device length over which the current is evaluated, the electron number inside L, the i-th electron velocity along the channel, and drift velocity. In the present work, the device length L is chosen to be the channel length of the diode. Notice that this choice is essential to make the current noise in the channel regions separated from the noise originated in high-doping n regions. The current fluctuation (variance) $\langle \delta I^2 \rangle$ is calculated from

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effective mass	m^*	$0.27m_e$
deformation potential	D	9 (eV)
coupling const	DK	11×10^8 (eV/cm)
optical phonon	$\hbar\omega$	63 (meV)

Table 1: Si material parameters employed for Monte Carlo simulations. m_e is the electron bare mass.

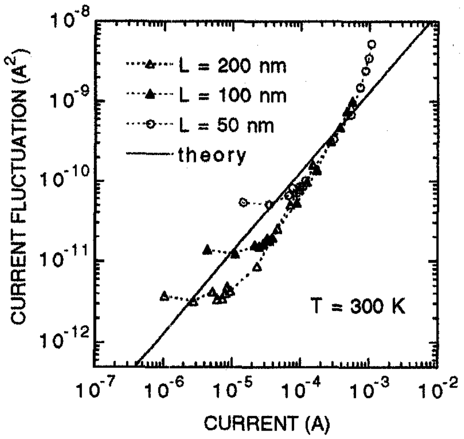

Figure 1: Current fluctuation (variance) $\langle \delta I^2 \rangle$ as a function of averaged current for $L = 200, 100,$ and 50 nm at $T = 300$ K. The solid line represents the theoretical prediction for the full shot-noise.

$$\langle \delta I^2 \rangle = \frac{1}{m} \sum_{k=1}^{m} \{I(k\Delta t) - I_{ave}\}^2 \quad , \tag{2}$$

where I_{ave} and Δt are, respectively, the average current and the time step ($\Delta t = 1$ fs) for the current sampling.

Recall that, from the Wiener-Khintchine theorem, the current fluctuation $\langle \delta I^2 \rangle$ is linked to the current spectral density $S_I(\omega)$ as

$$\langle \delta I^2 \rangle = \int_0^\infty d\omega \; S_I(\omega) \approx S_I(0) \cdot \Delta\omega \quad , \tag{3}$$

where $\Delta\omega$ is the bandwidth and the current noise is assumed to be white up to very high frequency.[8]

3. Results and Discussion

Figure 1 shows the general trend of the current fluctuation (variance) $\langle \delta I^2 \rangle$ as a function of average current for three different channel lengths; $L = 200, 100, 50$ nm. The straight line in the figure represents the theoretical prediction if the whole noise source is due to the full shot-noise with $\Delta\omega = 4 \times 10^{12}$ (sec^{-1}). Here, the current variance due to the full shot-noise is given by

$$\langle \delta I^2 \rangle = 2 \; e \; I_{ave} \cdot \Delta\omega \quad . \tag{4}$$

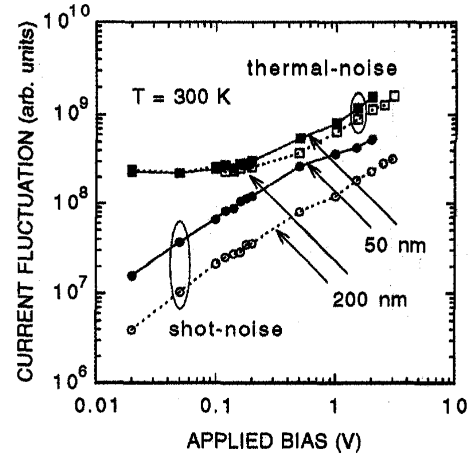

Figure 2: Bias dependence of the thermal- and shot-noise modes of the current fluctuation for $L = 200$ (solid symbols) and 50 (empty symbols) nm at $T = 300$ K.

As is already well-known[3], the current fluctuations in *large* devices are made up of two different noise sources depending on the magnitude of the average current, *i.e.*, thermal-noise that stays nearly constant at low currents and hot-carrier noise that monotonically increases at high currents. As the channel length decreases, on the other hand, the fraction of ballistic electrons in the channel increases and the current noise associated with the number fluctuation of ballistic electrons may also become significant. This is manifested in Fig. 1 such that $\langle \delta I^2 \rangle$ approaches the straight line as the channel length decreases. It is, therefore, conjectured that a new noise source related to the number fluctuation of electrons appears at the intermediate current ranges for $L = 50$ nm device.

In order to clarify the noise mechanism, the current fluctuation is decomposed into the velocity fluctuation (thermal-noise mode) and the electron number fluctuation (shot-noise mode). The results are represented in Fig. 2, where the bias dependence of each fluctuation mode is plotted for $L = 200$ and 50 nm. The linear dependence of the number fluctuation and the bias-independent velocity fluctuation at low biases, both of which are characteristics to, respectively, shot-noise and thermal noise, are well demonstrated. We would like to stress that, though the thermal-noise mode is dominated over the shot-noise mode for both devices, the relative magnitude of the shot-noise mode is greatly enhanced for $L = 50$ nm. In particular, the magnitude of the shot-noise mode is even close to that of thermal-noise at intermediate biases, at which the current fluctuation $\langle \delta I^2 \rangle$ approaches to the full shot-noise line in Fig. 1.

Naturally, the shot-noise enhancement in sub-0.1 micron device described above must be associated with ballistic electrons. However, the scenario to explain this enhancement is not quite trivial. Figure 3 shows the spatial

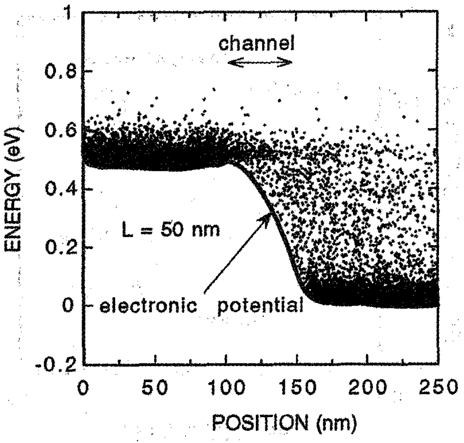

Figure 3: Spatial distribution of electrons as a function of energy inside the device for $L = 50$ nm. The applied bias is $V = 0.5$ V, around which shot-noise is most actualized. The solid line represents the electronic potential.

distribution of electrons inside the devices as a function of energy. The applied bias is $V = 0.5$ V, around which shot-noise is most actualized for $L = 50$ nm. A great increase of the quasi-ballistic electrons for $L = 50$ nm is obvious. The number of electrons emitted from the source (the left n) region could be restricted due to the potential dip existed at the source (the left n) edge. This could lead to the ordinary shot-noise on the current, as pointed out very recently by Gonzalez *et al.*[9] However, this is not the whole story; Since the quasi-ballistic electrons injected into the drain (the right n) region require some time to relax to their thermal-equilibrium states, they diffuse to the channel or even to the source (the left n) regions. This process could also lead to the fluctuation of electron number in the channel region and, hence, lead to the shot-noise like fluctuation in the current. Notice that this process is possible only if the electrons travel the channel quasi-ballistically and is a unique characteristic in ultra-small device structures.

The normalized current fluctuation (Fano factor) $\langle \delta I^2 \rangle / I_{ave}$ is re-plotted as a function of the applied voltage for the three different diodes $L = 200, 100$, and 50 nm in Fig. 4. From Eq. (4), $\langle \delta I^2 \rangle / I_{ave}$ for the full shot-noise is independent of the biasing and gives a constant;

$$\frac{\langle \delta I^2 \rangle}{I_{ave}} = 2e\Delta\omega \approx 1.3 \times 10^{-6} \quad [\text{A}] \ . \tag{5}$$

Employing the Nyquist theorem,[2] the thermal-noise at low bias regions is also expressed as

$$\frac{\langle \delta I^2 \rangle}{I_{ave}} = \frac{4\,k_B\,T_e}{V} \cdot \Delta\omega \ , \tag{6}$$

where T_e is the electron noise temperature and approximately equal to the lattice temperature (300 K). Equations (5) and (6) are also plotted in Fig. 4 with, respectively, dotted and solid lines. The transition of the noise source is well demonstrated; in *large* devices the current fluctuation makes a direct transition from thermal-noise at low voltages to hot-carrier noise at high voltages. However, shot-noise like fluctuation becomes significant in the intermediate voltages for $L = 50$ nm. This is consistent with the results described above.

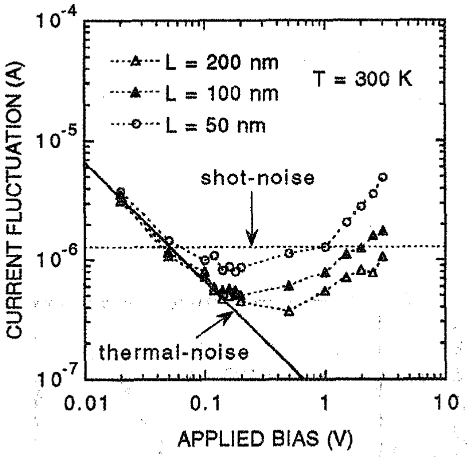

Figure 4: Normalized current fluctuation (Fano factor) $\delta I^2/I_{\text{ave}}$ as a function of the applied voltage at $T = 300$ K for $L = 200$ nm (empty triangles), 100 nm (solid triangles), and 50 nm (empty circles). The dotted and solid lines represent the full noise levels for, respectively, shot-noise and thermal-noise.

4. Conclusions

Monte Carlo analyses of the current fluctuation in Si *n-i-n* structures have been carried out with varying the length of the i (channel) region so that the diffusive to quasi-ballistic transport is covered. It has been demonstrated that the current fluctuation is dominated by thermal-noise at low bias regions and makes a direct transition to hot-carrier noise in *moderately large* devices. On the other hand, a new fluctuation mode appears under sub-0.1 micron device structures. This is associated with the fluctuation of the electron number in the i (channel) region and results from both the ballistic electrons emitted from the left n (source) region and the electrons diffused from the right n (drain) region.

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