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Noise Simulation of Nanoscale Devices Based on the Non-Equilibrium Green's Function Formalism

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Abstract

A new deterministic approach to the electronic noise calculation based on the non-equilibrium Green's function formalism with the electron-phonon scattering mechanisms is presented for nanoscale devices, and the diffusion noise phenomena at zero frequency are investigated. Our approach can handle the quantum effects naturally and it gives physical insight about the noise in nanoscale devices. As an application, silicon nanowire field effect transistor is considered and the numerical results show that the Johnson-Nyquist theorem is satisfied at equilibrium and the excess noise occurs in the presence of current transport.

1 Introduction

The noise is a limiting factor of electronic device performance in the ultra small devices. Especially, the diffusion noise phenomena originated from the electron-phonon interactions are unavoidable. The diffusion noise in the nanoscale conductors have been analyzed with the help of the transmission approach [1], but it assumes that the scattering inside the device is only elastic and the fluctuations must originate solely from the thermal agitation in the contacts of the device.

In this paper, we present a new method to calculate the steady-state noise at zero frequency based on the NEGF formalism with the elastic and inelastic scattering mechanisms, which includes the fluctuations inside the device as well as on the contacts of the device. As an application, we consider the diffusion noise phenomena in the silicon nanowire transistor which have been studied as a candidate for the future device substituting the planar MOSFET [5].

2 Model of diffusion noise

In order to calculate the terminal noise current of an electronic device, we need to calculate the microscopic noise sources in the device and the transfer function which determines the influence of the noise sources on the terminal current [2]. In this work, we consider the diffusion noise source for the microscopic noise source and the transfer function will be calculated base on the NEGF formalism proposed in Ref. [3].

The solution of quantum kinetic equations gives information about the detailed motion of electrons in the device. Now, similarly to the impedance field concept [4], we define the transfer function G^c whose element G_s^c represents the ratio of the net electron out-flux through the cth contact by the electron in-flux into a state s to this in-flux. In addition, let $F_{s,s'}$ be the mean electron flux that electrons suffering a phase-breaking process at a state s' will suffer its next phase-breaking event at a state s. The derivations will not be shown here on account of space considerations.
The diffusion noise source can be modeled as the fluctuation of the electron fluxes originated from the phase-breaking electron-phonon interactions, which occur randomly and independently due to the discrete nature of carriers. Each electron flux fluctuation $\delta F_{s,s'}$ defined as the fluctuation of $F_{s,s'}$ follows Poissonian process and they are uncorrelated each other, so the cross power spectral density of the electron fluxes is

$$S_{\delta F_{s,s'},\delta F_{s^2,s^3}} = 2F_{s,s'}\delta_{s,s^2}\delta_{s',s^3}. \tag{1}$$

The occurrence of a single fluctuation $\delta F_{s,s'}$ means the same amount of electron in-flux into s' and out-flux from s, which results in the net electron out-flux $(G_{s'}^c - G_s^c)\delta F_{s,s'}$ to the cth terminal, and simultaneously, induces the external noise current at the cth terminal by $q(G_s^c - G_{s'}^c)\delta F_{s,s'}$ to satisfy the current conservation. Here, the displacement current is neglected since we are interested in the zero-frequency fluctuation.
Including all diffusion noise sources in the device, the noise current of the cth terminal can be obtained as

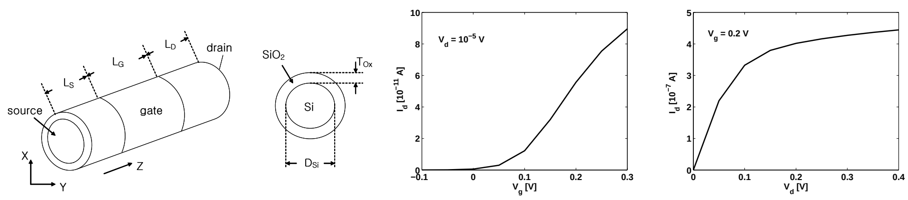
$$\delta i_c = \sum_s \sum_{s'} q(G_s^c - G_{s'}^c)\delta F_{s',s}. \tag{2}$$

We finally obtain the power spectral density of the cth terminal noise current from eq. (1) and eq. (2),

$$S_{\delta i_c} = \sum_s \sum_{s'} 2q^2 F_{s',s}|G_s^c - G_{s'}^c|^2. \tag{3}$$

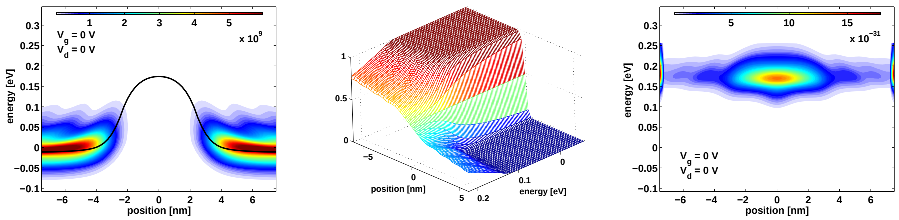
3 Simulation results

For the sake of numerical simplicity, we used the mode-space NEGF method [6] which neglects the gate tunneling current and we simulate the silicon devices with a single valley, but the electron-phonon interaction strengths are chosen to be reasonable compared with six-valley bulk silicon. These simplifications do not matter in the investigation of noise phenomena, and the extension to rigorous simulation is straightforward.
The simulated silicon nanowire field effect transistor and its I_d vs V_g and I_d vs V_d characteristics are shown in Fig. 1. The threshold voltage is about $0.05V$.
Fig. 2 shows the simulation results at equilibrium. The electrons having energy higher than the gate potential barrier can pass the channel region easily, whereas the low energy electrons hardly pass that region. So, considering the spectrum of electron density, the source transfer functions are regarded as physically reasonable results. As we expected, the resistive factors such as the contact injection, the potential barrier and the interference effect much contribute to the diffusion noise.
The excess noise phenomena are also investigated and the results are shown in Fig. 3. The interpretations can be done similar manner to those of the results at equilibrium.



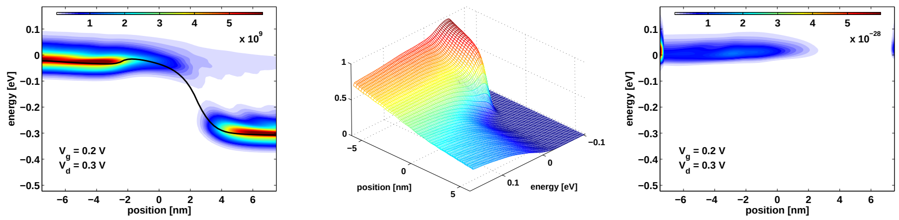
(a) (b) (c)

Figure 1: (a) Simulated silicon nanowire field effect transistor, where $L_G = 5nm$, $L_{S/D} = 5nm$, $D_{Si} = 2nm$, and $T_{Ox} = 0.5nm$. The gate material is the ideal n^+ poly-silicon whose work function is equal to the conduction band edge. The n^+ source and drain region regions are uniformly doped at $10^{20}/cm^3$, and the channel region is intrinsic. (b) I_d vs V_g and (c) I_d vs V_d characteristics.



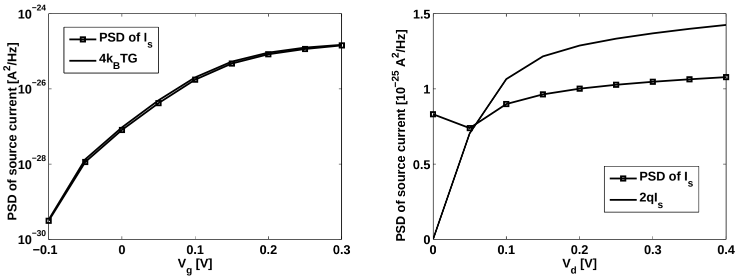
(a) (b) (c)

Figure 2: (a)Energy spectrum of the one-dimensional electron density along the z-direction with minimum subband(thick solid line) and (b) the transfer function for source contact and (c) energy spectrum of the noise contribution along the z-direction at a bias of $V_g = 0V$, $V_d = 0V$.



(a) (b) (c)

Figure 3: (a)Energy spectrum of the one-dimensional electron density along the z-direction with minimum subband(thick solid line) and (b) the transfer function for source contact and (c) energy spectrum of the noise contribution along the z-direction at a bias of $V_g = 0.2V$, $V_d = 0.3V$.



(a) (b)

Figure 4: Bias dependence of power spectral density of the source current noise evaluated by the simulation and (a) by the Nyquist theorem and (b) by $2qI_S$.

Fig. 4(a) shows that the simulated results from our model agree with the Johnson-Nyquist theorem at equilibrium, where the small differences are seem to be from the discretization error in numerical simulation. In Fig. 4(b), we compare the drain bias dependence of the short-circuit source noise current power and $2qI_S$. In the case of long channel planar MOSFETs, it has been known that the short-circuit drain noise current power decreases with increasing the drain bias and holds nearly constant in saturation [7]. However, our simulation on nanoscale device shows excess noise at high current levels, but not so-called full shot noise because of much phase-breaking scattering inside the device.

4 Conclusion

In this work, we present a new model for the diffusion noise calculation based on the NEGF formalism including the electron-phonon scattering. It is shown that the calculated diffusion noise at zero frequency agrees with the the Johnson-Nyquist theorem at equilibrium and the excess noise occurs at high current conditions.

Acknowledgements

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