# Investigation of noise in silicon nanowire transistors through quantum simulations

Hong-Hyun Park, Soo Young Park, Hong Shick Min,
Young June Park
Electrical Engineering and Computer Science
Seoul National University, Seoul, Korea
E-mail : hhpark@isis.snu.ac.kr

Seonghoon Jin
Synopsys Inc., USA
E-mail : sjin@synopsys.com

*Abstract*—**A theoretical analysis of the drain current and its fluctuation in silicon nanowire transistors is proposed. We also suggest a general approach to the electronic noise calculation in the presence of a continuous distribution of phase-breaking scattering. Through our approach, the drain current noise characteristics with and without electron-phonon interactions are obtained at various bias conditions, and their physical origins are investigated. The non-equilibrium Green's function formalism is employed within the effective-mass and Hartree approximations. In addition, the intravalley and intervalley electron-phonon scattering mechanisms are included using the deformation potential theory and the self-consistent Born approximation.**

***Keywords - quantum transport, non-equilibrium Green's function, silicon nanowire transistor, noise***

## I. INTRODUCTION

Quantum transport simulations based on the non-equilibrium Green's function (NEGF) formalism have been widely used in order to predict the current-voltage characteristics of nanoscale transistors. On the other hand, it is also important to study the electronic noise phenomena in the scaling limit since the relative magnitude of the electronic noise power also increases with decreasing transistor size. In this work, we take the focus on the electronic noise in silicon nanowire transistors (SNWTs) with and without electron-phonon scattering. The SNWT shown in Fig.1 is a kind of nonplanar, gate-all-around metal-oxide-semiconductor field-effect transistor (MOSFET) using a silicon nanowire as a conduction channel. Since its surrounding gate can effectively control the channel potential thanks to the strong electrostatic coupling, the SNWT shows good switching characteristics even at the scaling limit and has been studied as a possible candidate for the future transistor substituting planar MOSFETs [1-5].

This paper is organized as follows: In Section II, we present a noise calculation method that takes into account phase-breaking processes such as electron-phonon scattering. Section III gives simulation results and discussions on the electronic noise in SNWTs. Conclusions will follow in Section IV.

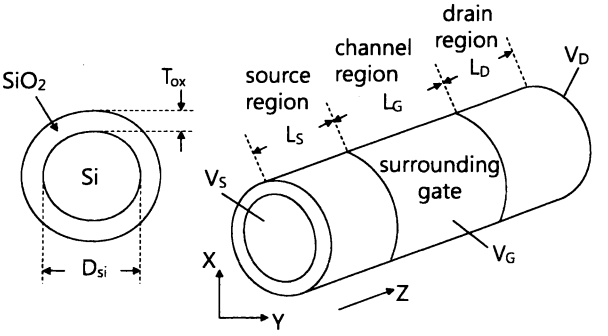

Fig. 1. Structure of silicon nanowire transistor.

## II. THEORY

In this section we present a general approach to electronic noise that takes into account a continuous distribution of phase-breaking scattering without detailed description of the NEGF formalism due to lack of space. It is assumed that the electron-phonon scattering is caused by a distribution of independent oscillators in thermal equilibrium, each of which interacts with electrons through a delta potential in space [6]. In this case, the motion of an electron will involve two elementary transport mechanisms, coherent propagation and state transition, as sketched in Fig. 2. An electron will propagate coherently and make a transition of its internal state when suffering a phase-breaking process, and propagate coherently again and so on.

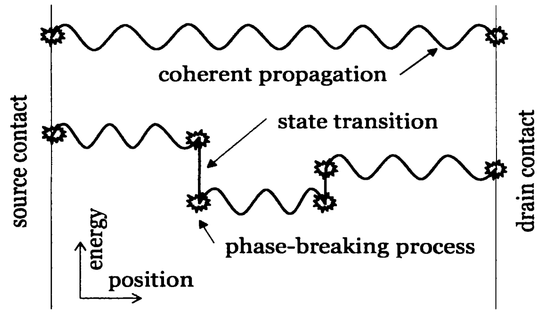

Fig. 2. Illustration of electron transport.

A coherent propagation from (r',E) to (r,E) can be written as

$$F_p(r,r';E) = f(r';E)T(r,r';E)/2\pi\hbar\,, \qquad (1)$$

where f(r;E) is an occupation probability at (r,E), and T(r,r';E) is a transmission probability between (r',E) and (r,E). A state transition from (r,E') to (r,E) can be written as

$$F_t(r;E,E') = D(E-E')p(r;E)n(r;E')/\hbar, \qquad (2)$$

where n(r;E) and p(r;E) are the electron and hole densities per unit energy, and D(ε) is a function related with electron-phonon scattering with phonon energy ε.

From the above, the drain current is obtained as simply a difference between in- and out-flow through the drain,

$$I_D = \int dE \int dr \int_{\Omega_D} dr' q\left[F_p(r,r';E) - F_p(r',r;E)\right], \qquad (3)$$

where $\Omega_D$ is the volume of drain contact. The current equation looks like an extension of the Buttiker formula to a continuous distribution of probes [6].

On the other hand, the drain current fluctuates even in the steady-state due to the random occurrence of phase-breaking processes which cause the fluctuation in the coherent propagations and the state transitions. For the calculation of the drain current noise, we first calculate non-local current fluctuations between each and every pair of phase-breaking sites, and calculate the influence of the non-local fluctuations on the drain. The non-local current fluctuation between two phase-breaking sites (r,E) and (r',E') can be written as

$$S(r,r';E,E') = \frac{q^2}{\pi\hbar}\left\{\begin{aligned} & f(r;E)[1-f(r;E)] \\ & + f(r';E)[1-f(r';E)] \\ & + [f(r;E)-f(r';E)]^2 T(r,r';E) \end{aligned}\right\} T(r,r';E)\delta(E-E')$$
$$+ 2q^2\left[F_t(r;E,E') + F_t(r;E',E)\right]\delta(r-r')\,, \qquad (4)$$

where the first and the second parts are due to the fluctuations of coherent propagation and state transitions, respectively. The fluctuation of the coherent propagation has been well established by the scattering theory [7-11], and the fluctuation of state transitions have been assumed to follow the Poisson process [12,13]. Now we need to convert the non-local current fluctuations into the drain fluctuation. To make it simple, we characterize a small-signal coherent propagation and phase-breaking transition between two phase-breaking sites as the simultaneous events of the same amount of in- and out-scattering of electrons at the two phase-breaking sites. In connection with this, let us introduce a drain transfer function $T_D(r;E)$ defined as a small-signal response in the net electron out-flow through drain terminal to a unit electron in-scattering rate into (r,E). Due to the linearity of the small-signal analysis, the transfer function for the electron out-scattering out of (r,E) has the same magnitude as $T_D(r;E)$ but the opposite sign. The Langevin approach is applied to obtain the transfer function based on the steady-state NEGF formalism. Then, the fluctuation of drain current due to a unit small-signal coherent propagation or phase-breaking transition current from (r',E') to (r,E) can be written as $[T_D(r;E)-T_D(r';E')]$. Similarly, the contribution of a non-local current fluctuation S(r,r';E,E') to the drain terminal should be $[T_D(r;E)-T_D(r';E')]^2$ S(r,r';E,E').

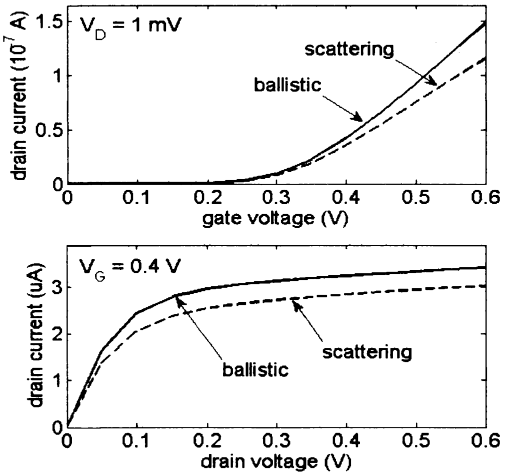

Fig. 3. $I_D$ vs. $V_G$ and $I_D$ vs. $V_D$ characteristics.

We therefore obtain the drain terminal short-circuit current noise power as

$$S_D = \frac{1}{2}\int dE \int dE' \int dr \int dr' \left[T_D(r;E) - T_D(r';E')\right]^2 S(r,r';E,E'), \qquad (5)$$

where the factor 1/2 is inserted to avoid duplication of noise contribution. In case of not being of phase-breaking scattering inside the device, our theory reduces to the conventional scattering approach.

It should be mentioned that we assume that the fluctuation due to long-range Coulomb interactions is negligible. This long-range Coulomb interaction is known as a significant suppression factor of shot noise when a potential barrier that controls current depends on the current [14,15]. In this work, we do not consider the fluctuation due to long-range Coulomb interaction since the potential barrier inside the SNWT is strongly controlled by the surrounding gate and there is little space-charge effect on the current transmission. It has been reported that the long-range Coulomb effect on the noise power is minor even in dual gate MOSFETs [16].

## III. SIMULATION RESULTS AND DISCUSSIONS

The sizes of the SNWT structure are chosen to be close to the physical and theoretical limit of MOS structures [17,18]. The diameter of the silicon body ($D_{si}$) is 4 nm and the gate oxide thickness ($T_{ox}$) is 1 nm. The lengths of the source ($L_S$), drain ($L_D$), and channel ($L_G$) regions are 10 nm each. The source and drain regions are n-type doped to $10^{20}$/cm$^3$ and the channel region is intrinsic. The gate work function is set to 4.35 eV in order to achieve an adequate threshold voltage. Throughout the simulations, the silicon nanowire is along the [100] orientation and the lattice temperature (T) is fixed at 300 K, and $V_S$ = 0 V.

Fig. 3 shows the $I_D$ vs. $V_G$ and $I_D$ vs. $V_D$ characteristics of the SNWT with and without electron-phonon scattering. The SNWT shows similar current-voltage characteristics to the conventional MOSFETs with the threshold voltage about 0.3 V. The SNWT has less short-channel effects and good sub-threshold slope for its channel length because the surrounding gate structure has an advantage of electrostatic control of the channel region than the planar gate structure.

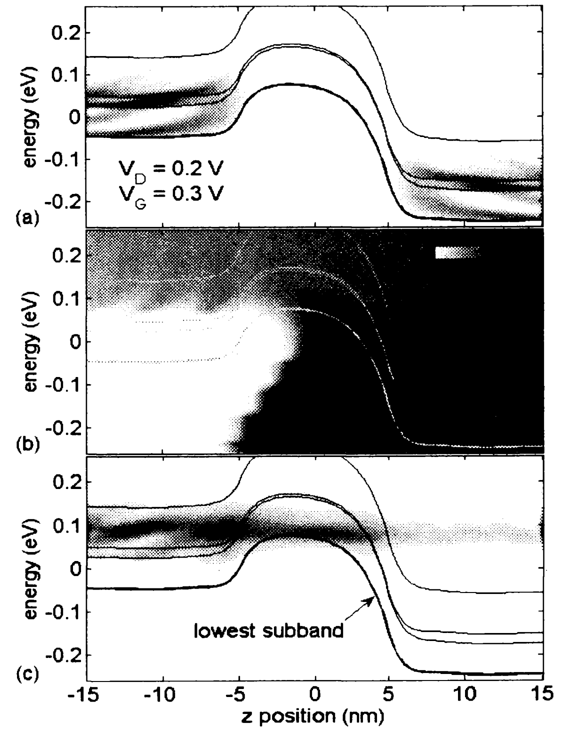

Fig. 4. (a) Intensity of the non-local current fluctuation and (b) the drain transfer function, and (c) the drain noise contribution at a bias of $V_G$ = 0.3 V, $V_D$ = 0.2 V.

According to Eq. (5), the drain noise can be obtained by adding non-local contributions of every pair of phase-breaking sites, each of which is the product of the non-local current fluctuation and the difference of drain transfer function between the sites. Since the local current fluctuations originate from random occurrence of phase-breaking process of electrons, the intensity of the non-local fluctuation is high where many electrons exist, and especially on contacts as shown in Fig. 4(a). On the other hand, the drain transfer function is a measure of probability that an electron inside the device transfers to the drain terminal. Roughly speaking, the drain transfer function below the gate potential barrier is nearly zero in the source region and nearly unity in the drain region, but the drain transfer function above the gate potential barrier gradually decreases from the drain to the source contact as shown in Fig. 4(b). As shown in Fig. 4(c), only the non-local fluctuations in the energy range around the top of gate potential barrier transfer to the drain terminal effectively.

At non-equilibrium conditions, the drain noise is not simply determined by conductance measurement. One of the interesting topics is the shot noise whose power is proportional to the current, $S_D = \gamma 2qI_D$, where $\gamma$ is called the Fano factor or suppression factor. According to experimental and theoretical studies, full shot noise is a consequence of unilateral flow of electrons following the Poisson process. From the previous work on the ballistic noise in SNWTs, it has been found that the electrons in the low-occupied states follow the Poisson process [5].

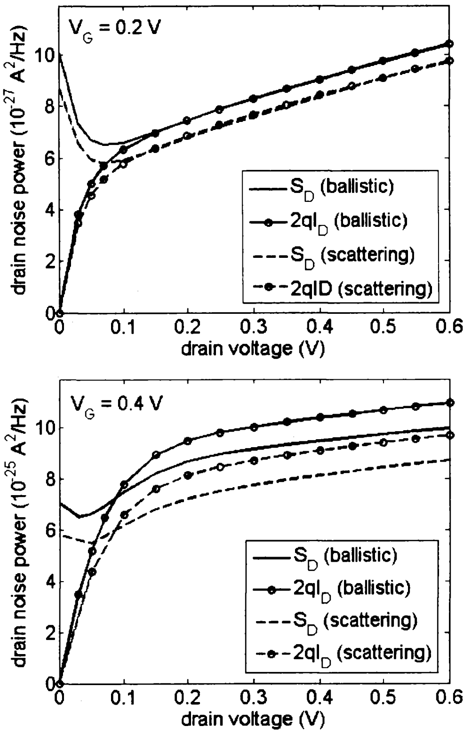

Fig. 5. Drain voltage dependence of the drain noise power with gate voltage of 0.2 V and 0.4 V.

Fig. 5(a) shows the drain voltage dependence of the drain noise power under sub-threshold regime, where the drain noise is equal to the Johnson-Nyquist noise at equilibrium, and slightly decreases with applying small drain voltage, and then increases following the full shot noise level under large drain voltage. The high gate potential barrier and the large drain voltage lead to unilateral flow of electrons from the low-occupied states in the source region to the drain, which makes the drain current fluctuation follow the Poisson process. This manifestation of full shot noise is similar to that of conventional MOSFETs in the sub-threshold operation. On the other hand, the drain noise after threshold is qualitatively different from that of sub-threshold as shown Fig. 5(b), where the drain noise in saturation regime is somewhat suppressed in comparison with the full shot noise level. This suppression is due to the increased electron occupation probabilities in the transport states, which violates the shot noise condition. In the short-channel MOSFETs, similarly to our results, a significant drain shot noise component has been reported [19]. For the long-channel MOSFETs, however, the drain noise power remains at approximately two-third of the equilibrium noise power [20-22].

Fig. 6 shows the gate bias dependence of the Fano factor with a large drain voltage. The Fano factor is nearly unity in the sub-threshold and decreases after the threshold as explained. Provided electrons flow unilaterally in the transport energy range by large drain voltage, the Fano factor strongly depends on the gate bias. The electron-phonon scattering which has been known as a suppression factor of shot noise enhances the shot noise in strong-inversion regime through band broadening effect.

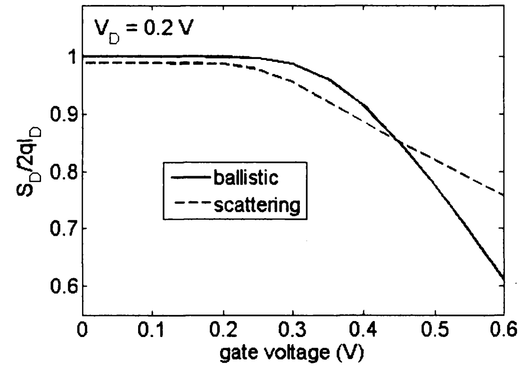

Fig. 6. Gate bias dependence of Fano factor with $V_D = 0.2$ V.

## IV. CONCLUSION

We have presented a noise calculation method considering the phase-breaking processes in the device, where the non-local current fluctuations between every two phase-breaking sites are considered and its influences on the drain terminal are obtained by employing the Langevin approach. Through our approach implemented by the non-equilibrium Green's function formalism, we have investigated the drain noise characteristics of silicon nanowire transistor at various bias conditions. In addition, we have studied the shot noise and its suppression mechanisms in the silicon nanowire transistor.

## ACKNOWLEDGMENT

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