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Quasi-analytical model of ballistic cylindrical surrounding gate nanowire MOSFET

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ABSTRACT

A quasi-analytical model bas been developed for predicting the current–voltage characteristics of a cylindrical surrounding gate metal-oxide-semiconductor field-effect-transistor (MOSFET) by taking ballistic transport and quantum confinement effects into consideration. Quantum effect was incorporated in the Poisson's equation in a self-consistent way together with the calculated subband energy levels. The model was validated with numerical simulation. Better agreements were obtained as compared with several previous models. Our results further revealed that the top of barrier (ToB) approximation is not accurate enough at large gate and drain biases; tunneling current and better electrostatic model have to be taken into account.

1. Introduction

As the gate length of metal-oxide-semiconductor field-effect-transistors (MOSFETs) has been scaled down to the decananometer region, short-channel effects (SCEs) are severer and hinder further device downsizing. Several new device structures have been proposed to replace the conventional planar MOSFET structure [1–3]. Among these structures, the surrounding gate MOSFET (SGT) has the best SCE immunity owing to its strongest control ability on the channel carriers with the gate electrode. Even without any channel doping, this structure still shows excellent capability in suppressing the SCEs. In addition, undoped channel further benefits from minimum impurity scattering and has better drive capability.

In devices with extremely small gate length with undoped channel, ballistic transport becomes the prominent charge transport mechanism [4,5]. SGTs working in ballistic regime have the best performance and ballistic mode of operation is considered as the theoretical limit of the SGT structure. Numerical models such as Non-Equilibrium Green Function (NEGF) method has been widely used in some quantum transport simulators to investigate the performance and the underlying physics of the ballistic SGTs [6–8]. It takes the quantum effects into account in both the confinement and carrier transport directions. However, it costs huge amount of computation resource and is impractical for large scale circuit simulations. In recent years several compact models for ballistic SGTs have been developed [9–12]. Among these models, most of them relied on the numerical solutions of some equations to obtain some intermediate parameters. The equations are that carrier density calculated from both electrostatics and quantum statistics of the energy subbands are equivalent. However, when calculating the electrostatic potential from the Poisson's equation, quantum effects were often neglected. In some other models, the electric potential was assumed to be some simple functions of some geometric parameters [11,13], it seems to be over-simplified.

In this work, we developed a quasi-analytical model for ballistic SGTs based on Landauer's theory [14]. The quantum effects were incorporated in the Poisson's equation so as to obtain the electric potential in the thin nanowire channel. The results of the model were compared with both numerical simulation and a previous model [15]. As will be shown later, better agreements with simulation results were obtained for our model. However, there are still some deviations from the simulation results when the gate and drain biases are large. These deviations are attributed to the source-to-drain tunneling effect as well as the inaccurate approximation of the channel potential which will be dealt with in future work.

2. Drain current model

The device structure of an n-type silicon SGT with coordinate system used for the model formulation is shown in Fig. 1. The cylindrical silicon nanowire is first wrapped by an oxide layer and then

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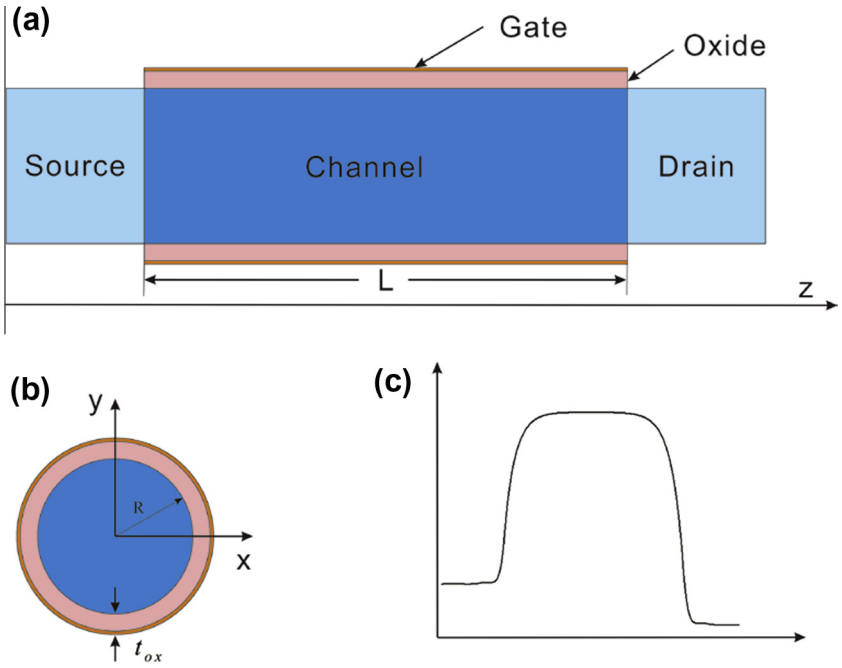

Fig. 1. Schematic structure of an n-type silicon SGT showing the definitions of various major device parameters: R the radius of the nanowire; t_{ox} the oxide thickness; L the channel length. Source and drain regions are assumed to be heavily doped with a doping concentration of 10^{20} cm^{-3}; the channel is undoped. X–Y plane is in the cross section of channel (see (b)), and Z axis is along channel direction (a). Subband energy profile along channel is also shown (see (c)).

the metal gate electrode. Source and drain regions are heavily doped. As a result of quantum confinement, the electrons in the nanowire are confined in discrete subbands. The subband energy profile along channel is illustrated in Fig. 1(c). As shown in the figure, a barrier exists between the source and drain. It is assumed that electrons can transmit through the channel if their kinetic energy is higher than the barrier, otherwise they are reflected back. That is, at the top of barrier (ToB), there are two electron fluxes in opposite directions: electrons transmitting from the source towards the drain; while the opposite electron flux is injected from drain. These two electron fluxes are assumed to be in equilibrium with the region from which they are injected. Current can be calculated as the net difference of the two fluxes, i.e. [9]

$$I_{DS} = \frac{q}{\pi\hbar}\sum_{\upsilon,s} g_\upsilon \int_0^\infty T(E)[f(E,E_{FS}) - f(E,E_{FD})]dE_z \tag{1}$$

where q is the magnitude of electron charge; $\hbar$ is the reduced Planck constant; υ represents the valley in which subbands reside; g_υ is the degeneracy of the valley; s represents the specific subband. $f(E,E_F)$ is the Fermi–Dirac distribution function with E_F as the Fermi level. E_{FS} and $E_{FD} = E_{FS} - qV_{DS}$ are the source and drain Fermi levels, respectively. For electrons with energy larger than the subband energy at ToB, transmission coefficient $T(E) = 1$, otherwise $T(E) = 0$. Substituting these values into (1), the drain current can be calculated as [10]:

$$I_{DS} = \frac{qk_BT}{\pi\hbar}\sum_{\upsilon,s} g_\upsilon \ln\left[\frac{1+e^{(E_{FS}-E_{\upsilon s})/k_BT}}{1+e^{(E_{FD}-E_{\upsilon s})/k_BT}}\right] \tag{2}$$

where the subband energy levels $E_{\upsilon,s}$ are the critical parameters for calculating drain current. They are obtained by solving the two-dimensional Schrödinger's equation in the cross-section of the nanowire at the ToB as follows:

$$-\frac{\hbar^2}{2m_\upsilon}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}\right]\psi(r,\theta) - q\phi(r,\theta)\psi(r,\theta) = E_{\upsilon s}\psi(r,\theta) \tag{3}$$

where $\phi(r,\theta)$ is the electric potential; $\psi(r,\theta)$ is the subband wavefunction. m_υ is the confinement effective mass in the specific valley. In the device illustrated in Fig. 1, channel is along the [100] direction of the crystalline silicon, the six equivalent energy valleys are separated into two groups: primed and unprimed valleys with degeneracy of 2 and 4, respectively. Isotropic effective masses of m_T and $\sqrt{m_L m_T}$ were used for characterizing the subband energy levels in primed and unprimed valleys [16–19]. Here m_L and m_T are, respectively, the longitudinal and the transverse effective mass of silicon.

In flatband situation, the subband energy levels and their corresponding wavefunctions can be solved analytically by considering a flat bottom cylindrical quantum well. The depth of quantum well was often considered as infinite. However, finite well depth still has influence on the subband energy levels [20] and was taken into account in this model. The resulting wavefunctions and subband energy levels are shown below [20]. Different wavefunctions were used for the channel and the oxide regions because of the large conduction band discontinuity between these two regions:

$$\psi_{\upsilon s}(r,\theta) = \begin{cases} A_{\upsilon s}J_{n_s}(\eta_{\upsilon s}r/R)e^{-in_s\theta} & 0 < r \leqslant R \\ B_{\upsilon s}K_{n_s}(\zeta_{\upsilon s}r/R)e^{-in_s\theta} & R < r \leqslant R + t_{ox} \end{cases} \tag{4}$$

$$\eta_{\upsilon s} = \frac{R}{\hbar}\sqrt{2m_\upsilon E_{\upsilon s}} \tag{5}$$

$$\xi_{\upsilon s} = \frac{R}{\hbar}\sqrt{2m_{ox}(E_{ox} - E_{\upsilon s})} \tag{6}$$

where $J_n(x)$ and $K_n(x)$ are the n-th order first kind Bessel function and second kind modified Bessel function, respectively. n_s is the order of Bessel function for the specific subband. m_{ox} is the electron effective mass in the oxide and is assumed to be half of free electron mass [21]. E_{ox} is the affinity difference between silicon and oxide. Subband energy is the solution of the following equation [20]:

$$\frac{\eta_{\upsilon s}[J_{n_s-1}(\eta_{\upsilon s}) - J_{n_s+1}(\eta_{\upsilon s})]}{m_\upsilon J_{n_s}(\eta_{\upsilon s})} + \frac{\xi_{\upsilon s}[K_{n_s-1}(\xi_{\upsilon s}) + K_{n_s+1}(\xi_{\upsilon s})]}{m_{ox}K_{n_s}(\xi_{\upsilon s})} = 0 \tag{7}$$