Compact Model of Short-channel Cylindrical ballisitic Gate-All-Around MOSFET Including the Source-to-drain Tunneling

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Abstract. One compact model of drain current valid in the subthreshold region, for short-channel cylindrical gate-all-around metal-oxide-semiconductor field-effect transistors including the source-to-drain tunneling has been proposed. From a two-dimensional analysis, the drain-induced barrier lowering effect is modeled according to our previous work. In this paper, by introducing the profile of the energy subband level along the electron transport direction into the Wentzel-Kramers-Brillouin approximation, we can numerically derive the expression of the tunneling transmission coefficients. Then, the source-to-drain tunneling current in the subthreshold region is evaluated by using the Landauer formula. The results obtained are compared with non-equilibrium Green’s function transport simulations with a good accuracy.

1. Introduction
As the dimension of semiconductor device scales down, undoped short-channel gate-all-around metal-oxide-semiconductor field-effect transistors (GAA MOSFETs) had been developed as one of the most important candidates for the next generation electronics [1-2]. Owing to their excellent gate controllability over the channel [3-5], such MOSFETs provide a better immunity to short-channel effects (SCEs), such as drain-induced barrier lowering (DIBL) and threshold voltage roll-off [1,6]. Since the gate length of the MOSFETs had reached sub-10 nm regime [7], it is widely investigated that the quantum transport has become significant of describing the properties in such devices [8]. Particularly, the quantum tunneling and ballistic transport of electrons across the source-to-drain potential barrier within GAA MOSFETs can be accurately simulated in several numerical simulators using non-equilibrium Green’s function (NEGF) formalism [8-10]. However, the simulations require significantly long computation times, which are not suitable to the circuit level simulations.

In this work, we study the source-to-drain tunneling current in the GAA MOSFET shorter than 10nm, assuming the energy subband profile of an electron along the device channel can be analytically represented using one unknown parameter according to our previous work. Then, by considering the expression of the lowest subband level, the tunneling transmission coefficients can be numerically calculated using the Wentzel-Kramers-Brillouin (WKB) approximation. Therefore, we can propose a numerical compact model of the short-channel cylindrical GAA MOSFET including the source-to-drain tunneling in the subthreshold region from the Landauer formula. Furthermore, results obtained
by this model are compared with those obtained by SILVACO NEGF simulation, successfully
demonstrating a good agreement.

2. Calculation Theory

2.1. Model structure

The cylindrical GAA-MOSFET is considered with intrinsic silicon channel surrounded by the gate
oxide and metal gate, as illustrated in figure 1. We assume that the source and drain are highly doped
n-type silicon as ideal reservoirs of electrons. Thus, we also consider that the electrons flow into the
source and drain without reflections back to the channel. In the following formulations, cylindrical
coordinate with length $z$, radius $r$, and angular component $\varphi$ is used. In addition, we also assume that
the transverse and longitudinal effective masses are fixed at $m_t = 0.19m_0$ and $m_l = 0.91m_0$, respectively,
in the (100)-oriented channel. The effective mass in the confinement cross section is represented as the
expression $2(m_t^{-1} + m_l^{-1})^{-1}$ [11].

![Figure 1. Schematic drawing of cylindrical GAA-MOSFET model considered in this work. (a) The
device structure and (b) wire cross section, where the channel length, radius, and gate oxide thickness
are denoted as $L_G$, $R$ and $T_{OX}$, respectively.](image1)

![Figure 2. (a) Representation of conduction band edge and higher energy subband profile along the $z$-
direction of channel. Electrons whose energy subband level is higher/lower than the potential barrier
in the channel contribute to the ballistic/tunneling current. Turning points $z_{MAX}$, $z_1$ and $z_2$ have literal
expressions. (b) Schematics of confinement potential energy distribution along $r$-component at $z_{MAX}$ in
the cross section.](image2)

2.2. Landauer formula

As shown in figure 2(a), the profiles of the conduction band edge and higher energy subband along $z$-
direction are illustrated. The total energy of an electron is denoted as $E_{total}$, and the source and drain
Fermi energies are denoted as $E_{F,S}$ and $E_{F,D}$, respectively. The difference in Fermi level between the
source and drain is given by $eV_{DS}$, where $V_{DS}$ is defined as voltage across the source and drain. The
maximum energy level of nth-subband along the $z$-axis at the barrier top $z_{MAX}$ is denoted as $E_{MAX,n}$,
corresponding to the discrete subband level measured from $E_{F,S}$ expressed as $E_{n\varphi,n_r}(z_{MAX})$, where
$E_{n\varphi,n_r}(z)$ represents the confinement energy level along $z$-direction with $n_\varphi$ and $n_r$ represented as the
angular and radial quantum numbers, respectively. Then, the drain current can be represented using
the Landauer formula as follows [12-14]:

$$I_D = eT \frac{1}{h} \int_{E_{F,S}}^{E_{F,D}} \left( \frac{\partial f}{\partial E} \right) dE \left( \frac{\partial E_{Total}}{\partial z} \right)$$
where $T(E_z)$ is the transmission coefficients for electrons traveling through the source-to-drain energy barrier at $E_z$. $E_z$ is the electron kinetic energy along $z$-direction, $f(E_{F,S}, E_{\text{total}})$ denotes the Fermi-Dirac distribution function in the source reservoirs. Moreover, the source-to-drain tunneling and ballistic currents are considered involving electrons with the energies $E_{\text{total}} < E_{\text{MAX},n}$ and $E_{\text{total}} > E_{\text{MAX},n}$, respectively.

Figure 2(b) illustrates the potential profile along $r$-direction in the cross section at $z_{\text{MAX}}$. Defining the electrostatic potential at the center and surface of the cylindrical channel as $w_0$ and $w_S$, the conduction band edges at the center and surface are given by $-e w_0$ and $-e w_S$, respectively. In addition, the potential is measured from $E_{F,S}$. The difference between $-e w_0$ and $-e w_S$ is described using an unknown parameter $\Delta U_G$. According to our previous work, we use $\Delta U_G(z)$ instead of $\Delta U_G$ to describe the $z$-direction dependence [13,14]. Therefore, the electron subband level $E_{n_{r,n_z}}(z)$ can be rewritten in terms of $\Delta U_G(z)$ as follows:

$$E_{n_{r,n_z}}(z) = E_{n_{r,n_z}}^0 - eV_{GS}^* + e\left(H_{n_{r,n_z}}^0 + \frac{4\pi\varepsilon CH}{C_{OX}}\right)\Delta U_G(z),$$

where $V_{GS}^* = V_{GS} - \varphi_{GC} + w_{FB}$. $V_{GS}$ is the gate-source voltage, $\varphi_{GC}$ is the work function difference between the gate and channel material, $w_{FB}$ is the conduction band edge with respect to $E_{F,s}(-e)$ under the flat-band condition, $C_{OX}$ is the gate oxide capacitance per unit length, $\varepsilon_{CH}$ is the dielectric constant of the channel, $E_{n_{r,n_z}}^0$ is the confinement energy level in one-dimensional infinite square well potential with respect to $-e w_S$. The matrix element $H_{n_{r,n_z}}$ is given by [13]

$$H_{n_{r,n_z}} = \int_0^\infty \Psi^0_{n_{r,n_z}}(r) \left(1 - \frac{r^2}{R^2}\right) \Psi^0_{n_{r,n_z}}(r) r dr,$$

where $\Psi^0_{n_{r,n_z}}(r)$ denotes unperturbed electron wave function in terms of confinement. Furthermore, $\Delta U_G(z)$ is derived based on our previous study [14]:

$$\Delta U_G(z) = A \exp(\gamma \cdot z) + B \exp(-\gamma \cdot z),$$

where coefficients $A$ and $B$ are expressed as

$$A = K \frac{(V_{bi} - V_{GS}^*) \left[1 - \exp(-\gamma \cdot L_G)\right] + V_{DS}}{2 \sinh(\gamma \cdot L_G)},$$

$$B = K \frac{(V_{bi} - V_{GS}^*) \left[\exp(\gamma \cdot L_G) - 1\right] - V_{DS}}{2 \sinh(\gamma \cdot L_G)},$$

with

$$K = \frac{\gamma^2 R^2}{4 \left(1 - \frac{\gamma^2 R^2}{4}\right)^2 + \gamma^2 R^2}.$$

Here, we define $V_{bi}$ as the built-in potential at source-channel and channel-drain junctions, $\gamma$ is the scaling parameter depending on device structure given by
Moreover, by solving the derivative of (3) equals to zero, $z_{\text{MAX}}$ is then represented by

$$z_{\text{MAX}} = \frac{1}{2\gamma} \ln \left( \frac{B}{A} \right).$$

### 2.3. Transmission coefficient calculation

The source-to-drain tunneling current cannot be neglected in a device when the channel length is shorter than 10 nm [15]. In the subthreshold region, we assume the electron transmission coefficients for each subband $T_{n\varphi,n}(E_z)$ can be calculated using the WKB approximation as follows [15,16]:

$$T_{n\varphi,n}(E_z) = \exp \left[-2\int_{z_1}^{z_2} \kappa(z,E_z) dz \right].$$

where $\kappa(z,E_z)$ is the electron wave vector inside the potential barrier at $E_z$ along the $z$-direction, which is represented as follows:

$$\kappa(z,E_z) = \frac{1}{\hbar} \left[ 2m_1 \left( E_{n\varphi,n}(z) - E_z \right) \right]^{1/2}.$$  

By substituting (3) into (11), $T_{n\varphi,n}(E_z)$ can be numerically obtained. Then, $z_1$ and $z_2$ are defined as the turning points, at which the electron energy corresponds to $E_z$, respectively. Thus, resulting that $z_1$ and $z_2$ read as the same form obtained in [11]

$$z_{1,2} = \frac{1}{\gamma} \ln \left[ -\frac{C \pm \Lambda^{1/2}}{2A} \right],$$

where the quantities $C$ and $\Lambda$ are given by

$$C = \frac{E_{n\varphi,n}^0 - eV_{GS} - E_z}{e \left( H_{n\varphi,n} + \frac{4\pi\varepsilon_{CH}}{C_{OX}} \right)},$$

$$\Lambda = C^2 - 4AB.$$  

Note that this method requires a numerical subroutine to evaluate the transmission coefficients, it makes this model become numerical. However, by substituting (11) into (3), we can derive the expression of the source-to-drain tunneling current in the subthreshold region.

### 3. Results and Discussion

In the subthreshold region, since most carriers are only exited up to the lowest subband in the channel, the tunneling current can be expressed by only considering the lowest the subband ($n_\varphi = 0, n_r = 1$). Figure 3 shows comparisons of the lowest subband profile along the channel between NEGF simulation [17] (green open circle lines) and our model (red solid lines). The dashed lines show interfaces between source/channel and drain/channel. Three lines correspond to the results with $V_{GS} = 0$, 0.2 and 0.5V, respectively. In order to achieve good agreements, channel length used in the compact model has been expanded into the source and the drain regions, respectively in [14]. It demonstrates that the potential profiles calculated using our compact model successfully capture the shape of the potential calculated by NEGF simulator in the subthreshold operating region. Figure 4 illustrates electron kinetic energy dependencies of the transmission coefficients for different gate bias. Four lines correspond to the
results with $V_{GS} = 0, 0.1, 0.2$ and $0.3$V. Note that the transmission coefficients must be 1 when $E_{total}$ of an electron becomes larger than $E_{0,1}(z_{MAX})$ under different gate bias condition correspondingly.

![Figure 3](image1.png)

**Figure 3.** Comparison results of the lowest subband profile plot between the compact model and NEGF simulation under different gate bias conditions.

![Figure 4](image2.png)

**Figure 4.** Electron kinetic energy dependence of the transmission coefficient calculated by the compact model with different gate bias.

In figure 5, for different channel length setting to 5 and 7 nm from the top, the subthreshold drain current vs. gate voltage characteristics are shown, demonstrating good accuracy with the WKB compact model. The green open circle lines and red solid lines show the results obtained by NEGF simulation and our WKB model, respectively. Note that the WKB model current decreases as $V_{GS}$ gets large. That is considered when the potential barrier height in the channel decreases, the amount of electrons tunneling through the source-to-drain potential barrier reduces. Figure 6 shows the comparison results of the subthreshold drain current between models considering the WKB tunneling (red solid lines) and our ballistic model (blue dashed lines). However, note that $T_{0,1}$ is assumed to be 1 for $E_{total} \geq E_{MAX,0,1}$ and 0 for $E_{total} < E_{MAX,0,1}$ when considering the ballistic model. As expected, the subthreshold drain current evaluated using the ballistic model is lower than the WKB tunneling current. It demonstrates that the source-to-drain tunneling becomes dominant and contributes significantly to
the current in the subthreshold region when the channel length of the GAA MOSFET decreases below 10 nm.

**Figure 5.** Comparison results of current characteristics in the subthreshold region between NEGF simulation and this WKB model.

**Figure 6.** Comparison results of current characteristics in the subthreshold region between the models considering ballistic transport and this WKB model, respectively.

4. Conclusions
We have presented a compact model of short-channel cylindrical GAA MOSFET including the source-to-drain tunneling. By using the WKB approximation to evaluate the transmission coefficients for the source-to-drain tunneling, we calculate the subthreshold drain current considering the lowest subband from the Landauer formula. In addition, this compact model has been tested against NEGF simulation, and showed a good accuracy in the subthreshold region. Furthermore, we intend to extend this tunneling current model of the GAA MOSFET using the WKB approximation with an analytical expression in our future study. Then, we can propose an analytic compact model of ballistic GAA MOSFETs for all operating regions.

5. Acknowledgment
This work has been supported by National Science and Technology Major Project of the Ministry of Science and Technology of China (Grant No. 2015ZX03003010).

6. References
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