Analytical drain current model reproducing advanced transport models in nanoscale cylindrical surrounding-gate (SRG) MOSFETs

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In this paper we extend a compact surrounding-gate MOSFET model to include the hydrodynamic transport and quantum mechanical effects, and we show that it can reproduce the results of 3D numerical simulations using advanced transport models. A template device representative for the cylindrical surrounding-gate MOSFET was used to validate the model. The final compact model includes mobility degradation, drain-induced barrier lowering, velocity overshoot, and quantum effects. Comparison between the compact model and the advanced transport modeling approaches shows good agreement within the practical range of drain voltages. © 2011 American Institute of Physics. [doi:10.1063/1.3618678]

I. INTRODUCTION

The advantages of silicon-on-insulator (SOI) MOSFETs over bulk transistors related to reduced short channel effects, lower parasitic capacitances, and increased circuit speed are well known. Among SOI devices, surrounding-gate (SRG) has become one of the most promising device structures according to the technology scaling roadmap. These devices include important features that permit more aggressive channel length scaling than to their conventional bulk counterparts. In this context, it is important to highlight the efforts currently under way in relation to multigate MOSFETS compact modeling. The continuous scaling in the IC industry makes the reduction of a cylindrical surrounding-gate MOSFET essential in the active silicon area in multigate MOSFETs. This model was derived for doped devices, but it has been demonstrated into account the mobility degradation due to scattering effects. The final compact model for the drain current includes hydrodynamic transport, mobility degradation, short channel effects such as DIBL, and quantum effects. Comparisons between the compact model and 3D advanced numerical transport models are shown.

II. dc MODEL

A. Expression for potentials

The potentials at the surface, \( \phi_s \), and in the center, \( \phi_c \), of the silicon layer are calculated analytically. The surface potential in the subthreshold \( \phi_{BT} \) regime are calculated analytically using the Lambert function as:

\[
\phi_{BT} = V_{GS} - V_{fb} - \frac{Q_{dep}}{C_s} - \phi_s \frac{Q_{dep}}{C_s} e^{\frac{V_{GS} - V_{fb}}{V_s}}
\]

and in the above threshold regime as:

\[
\phi_{SAT} = V_{GS} - V_{fb} - 2\phi_s LW \left[ \frac{1}{2C_s \phi_t} \left( \frac{Q_{dep} \varepsilon_s \phi_t}{R} \right)^{4} \right]^{\frac{1}{2}} \times \left[ 1 - \frac{1}{2} + \frac{1}{2} e^{-2\left( \frac{V_{GS} - V_{fb}}{V_s} \right)} \right],
\]

where \( V_{GS} \) is applied to the gate voltage, \( V_{fb} \) is the flatband voltage, \( Q_{dep} = qN_s R/2 \) is the fixed charge density per unit gate area, \( N_s \) is the doping concentration, \( R \) is the radius of the cylindrical silicon body, \( \phi_t = mT/q \) is the thermal voltage, \( V_{th} \) is the quasi-Fermi potential along the channel, \( \phi_e = \phi_s \), \( \phi_f = \phi_t \), \( \ln(N_s/n) \) is the Fermi potential, \( \varepsilon_s = (\phi_s - \phi_e)/\phi_t \) is the normalized difference of potentials, \( \varepsilon_s \) is the permittivity of...
silicon, and $q$ is the electric charge. The inversion centroid is a function of the inversion charge. A simple relationship between inversion centroid and inversion charge obtained by fitting numerical simulation results is given by $x = \frac{1}{e^{\frac{q}{q_{dep}N_{ID}(R)}}} + \frac{1}{e^{\frac{q}{q_{dep}N_{ID}(R)}}}$ (Ref. 7) with $a = 0.55 \text{nm}$, $b = 0.198$, $z_{so} = 5.1 \text{nm}$, $n = 0.75$, and $N_{ID}(R) = 8.26 \times 10^{12} \text{cm}^{-2} - 4.9 \times 10^{18} \text{cm}^{-3} \times R(\text{cm})$. The classical oxide capacitance $C_{ox}$ was replaced in our model by another capacitance, corrected oxide capacitance $(C_{ox}^e)$, where the capacitance of the oxide was in series with a centroid capacitance, which is the capacitance of a silicon layer, given as:

$$\frac{1}{C_{ox}^e} = \frac{1}{C_{ox}} + \frac{1}{C_{cen}},$$

(3)

where $C_{cen} = \frac{en_{so}}{(R-z_i)ln[1+q_{so}/e_{so}]}$, and $C_{ox} = \frac{en_{so}}{Rln[1+q_{so}]}$ is the oxide capacitance per unit gate area in a SRG MOSFET; $L_m$ is the oxide thickness and $e_{ox}$ is the permittivity of the oxide.

The final surface potential in all regimes are calculated as:

$$\phi_s = \phi_{BT} + \frac{1}{2} \left[ 1 - \tanh[10(V_{GS} - V_T - V_{ch})] \right]$$

$$+ \phi_{sat} + \frac{1}{2} \left[ 1 + \tanh[10(V_{GS} - V_T - V_{ch})] \right],$$

(4)

where $V_T$ is the threshold voltage as shown in Ref. 8.

**B. Mobile charge**

Mobile charge $q_s$ is a function of the surface potential is obtained by solving Poisson’s equation. Their normalized values at the source, $q_{sd}$, and at the drain, $q_{sd}$, are given by the following expressions as in Ref. 8:

$$q_{S(D)} = \sqrt{\frac{4q_{dep,si}}{C_{ox}^eR}} \sqrt{\frac{1}{2} + \left[ \frac{1}{2} + \frac{1}{2} e^{-\frac{\phi_s - \phi_{BT} - \phi_{sat}}{e_{ox} e_{si}}} \right]} - q_{dep},$$

(5)

where $q_{dep} = \frac{Q_{seff}}{C_{ox}^e q_{tr}}$ is the normalized fixed charge density per unit gate area.

**C. DIBL effect**

The drain-induced barrier lowering (DIBL) is considered through a threshold voltage correction $\Delta V_T$ as:

$$\Delta V_T = \sigma \phi_F \left( \frac{L_m}{L} \right)^2 \left[ 1 - e^{\left( \frac{V_{ch}}{3.6\phi_F} \right)} \right] \left[ 1 + \frac{\left| V_{ch} \right|}{3.6\phi_F} - e^{\left( \frac{V_{sat}}{3.6\phi_F} \right)} \right],$$

(6)

where $\sigma$ is the fitting parameter, $L_m$ is a reference length $= 1 \times 10^{-3} \text{cm}$ and $L_c = \sqrt{2e_oxR_{so} ln[1+q_{so}]+z_{so}R^2}$ is the characteristic length. 12

One of the most used expressions for the saturation potential $\frac{V_{dssat}}{V_{sat}}$ has been corrected as:

$$V_{dssat} = \left( \frac{Q_{seff}}{C_{ox}^e} \right) \left( \frac{V_{sat}}{2LC_{ox}^e} \right) + V_{sat},$$

(7)

with

$$Q_{seff} = q + 4kT \frac{C_{ox}^e}{q_s} \left( \frac{V_{sat}}{v_{sat}} - \frac{kT}{q} \left( \frac{v_{sat}}{L} \right) \right),$$

(8)

where $V_{sat}$ is the saturation velocity.

The effective drain voltage valid in the linear and saturated region is calculated as:

$$V_{Def} = V_{dssat} + \frac{1}{2} \left[ (V_{ch} - V_{dssat}) - \phi_s \right]$$

$$- \sqrt{(V_{ch} - V_{dssat} - \phi_s)^2 + 4\phi_s V_{dssat}}.$$  

(9)

In the subthreshold region, the effective voltage must be adjusted to represent the real behaviors, so a complementary effective drain voltage is defined as:

$$V_{Def} = V_{dssat} + \frac{1}{2} \left[ 1 - \tanh[5(V_{GS} - V_T)] \right]$$

$$+ V_{Def} \frac{1}{2} \left[ 1 + \tanh[5(V_{GS} - V_T)] \right].$$

(10)

A smoothing function is used to interpolate $V_{dss}$:

$$V_{dss} = V_{Def} - \frac{kT \ln[1 + \exp\left( A(V_{Def} - V_{dssat})/(kT/q) \right)]}{q}.$$  

(11)

where A is the parameter that controls the transition between saturated and nonsaturated channels.

**D. Velocity overshoot**

In extremely short channel multigate MOSFET the transport regime is quasi-ballistic, thus an important overshoot velocity is expected. Using a simplified energy-balance model, the electron mobility is a function of the electron temperature related to the average energy of the carriers. The electron temperature $T_e$ is governed by the following equation:

$$\frac{dT_e}{dx} + \frac{T_e - T_0}{\tau_e} = - \frac{q}{2k} E_e(x),$$

(12)

where the energy-relaxation length is defined as $\lambda_e \approx 2v_{sat} \tau_e$, $\tau_e$ being the energy relaxation time constant, $v_{sat}$ the saturation velocity, and $E_e(x)$ is the lateral electric field.

The velocity increases along the channel, and at the saturation voltage, the velocity reaches a saturation velocity. Assuming that the velocity is saturated we can divide the channel into two sections: the first section $0 < x < L_e = L - L_{sat}$, and the saturation region, $x > L_{sat}$. In contrast with classical drift-diffusion models, the saturated velocity in the saturation region due to nonstationary effects can achieve several times the stationary saturation velocity, $V_{sat}$. This phenomenon is known as velocity overshoot. The velocity overshoot has been modeled through a hydrodynamic transport model.

**E. Drain current**

The drain-current in a SRG MOSFET is calculated as a function of the mobile-charge densities at the source $Q_s$ and at the drain $Q_d$.
\[ I_{DS} = \frac{W \mu_{eff}}{L_c(1 + \gamma_n V_{DS})} \left[ 2(q_S - q_D) + \frac{q_S^2 - q_D^2}{2} + 2q_{dep} \ln \left( \frac{q_D + 2q_{dep}}{q_S + 2q_{dep}} \right) \right]. \]  

(13)

The effective mobility is defined as: \[ \mu_{eff} = \frac{\mu_o}{1 + \theta_1 \beta \log(1 + \exp(1 + (V_{GS} - V_T)/\beta)) + \theta_2 \beta^2 \log(1 + \exp(1 + (V_{GS} - V_T)/\beta)^2}, \]  

(14)

where \( \mu_o \) is the low-field mobility, and \( \theta_1 \) and \( \theta_2 \) are the mobility attenuation coefficients of the first and second orders, respectively, which can be considered as fitting parameters, \( \gamma_n = \frac{\mu_{sat}}{\frac{1}{L} \left( \frac{1}{2} \right)} \); \( V_{dsat} \) is equal to \( V_{Def} \) for a nonsaturated channel and \( V_{dsat} = V_{dssat} \) for a saturated channel; \( L_c = L - \Delta L \) and \( W = 2nR \) are the device effective length and width respectively, where the saturated channel length is given by \( \Delta L = L_c \arcsin \frac{V_{Def} - V_{dsat}}{E_{sat} L_c} \), and \( E_{sat} \) is the saturation field when velocity reaches the saturation velocity.

III. SIMULATED DEVICE AND APPROACHES

We consider the cylindrical SRG MOSFET shown in Fig. 1. It has a physical gate length of 6 nm and a gate stack consisting of 2 nm of HfO2 on top of 0.7 nm of SiO2 [Effective oxide thickness (EOT) = 1 nm]. The channel is lowly doped \( (10^{15} \text{ cm}^{-3}) \). The channel diameter is 4 nm.

Each model is identified with the acronym of the main developer. The possible modeling approaches range from modifications of the conventional drift-diffusion (DD) model used in commercial TCAD tools to advanced Monte Carlo models. The different numerical models used by the different groups \(^{14-17} \) differ in terms of scattering mechanisms, simulation approaches, and so on. In order to compare, all simulators have been calibrated first to reproduce the curves in silicon devices.

A. SNPS (Synopsis Switzerland LLC)

In the SNPS model, \(^{14} \) at low drain bias, the effect of mobility degradation is seen at higher gate voltages.

B. SNPS with ion impurities (II)

In SNPS with ion impurities (II), \(^{14} \) the drain current has a stronger mobility degradation effect compared to the other groups. The effect of ion impurity scattering has a strong influence on the drain current and, hence, the drain current is lower than in the other groups.

C. IUNET (Consorzio Nazionale Interuniversitario per la Nanoelettronica)-University of Bologna (quantum ballistic)

The tight-binding approach is employed to work out the system Hamiltonian on quantum transport under ballistic condition. \(^{15} \) The mobility degradation is not significant. It can be seen that the velocity saturation takes place at higher values.

FIG. 1. (Color online) Structure of the cylindrical SRG MOSFET template used in this work.

FIG. 2. (Color online) Transfer characteristics of the cylindrical SRG MOSFET (Fig. 1) for low (top) and high (bottom) \( V_{GS} \). 3D numerical simulation data by Synopsys (SNPS; Ref. 14), University of Bologna (IUNET-BO; Refs. 15 and 16), and IMEP (Ref. 17).
D. IUNET-BO (semiclassical ballistic)

Scattering events are accounted for via relaxation-time approximation, which holds for elastic collisions only. The mobility degradation is not significant.

E. IUNET-BO (acoustic phonon and surface roughness)

In IUNET-BO with acoustic phonon (AP) and surface roughness (SR), the mobility degradation has a slight influence on the drain current. Also, the effect of velocity saturation is stronger than in the other groups, which can be seen clearly.

F. IMEP (Institut de Microélectronique, Electromagnétisme et Photonique), Grenoble (France)

In IMEP model, the drain current is higher than other models considered in this paper. It considers backscattering. The effect of mobility degradation is lower when compared to other models which consider scattering.

IV. RESULTS AND DISCUSSION

The results of the compact model have been compared with the 3D numerical simulation data obtained by several research groups using advanced transport models. Figure 2 shows the transfer characteristics of the cylindrical SRG MOSFET at low and high VDS. A good agreement between the compact model and the 3D numerical simulations is obtained by considering the low field mobility and for a fitted saturation velocity. In the transfer characteristics it can be clearly noted that the mobility degradation at low drain voltages is significantly reproduced by the compact model. In the IMEP model it can be observed that the effect of the mobility degradation parameter is lower when compared to the other models, which may be due to the fact that surface roughness scattering is not considered in the IMEP model.

Figure 3 shows the transfer characteristics of a longer channel cylindrical SRG MOSFET at high VDS. A good agreement between the compact model and the 3D numerical simulation data is obtained both in subthreshold and above threshold by considering the low field mobility and for a fitted saturation velocity.

Figure 4 shows the transfer characteristics of an LG = 13 nm cylindrical SRG MOSFET at high VDS. Also, a good agreement between the compact model and the 3D numerical simulation data is obtained both in subthreshold and above threshold by considering the low field mobility and for a fitted saturation velocity.

Table I indicates the mobility degradation and velocity saturation parameter values that have been considered in the model to fit the different numerical simulations of the SRG MOSFET shown in Fig. 1. From the Table I parameters it can be seen that a strong mobility degradation is observed with the SNPS (ion impurities) model. It can be seen that a lower mobility degradation is observed with the IMEP model, as discussed before.

<table>
<thead>
<tr>
<th>Model</th>
<th>V_{sat} (cm/sec)</th>
<th>θ₁ (V⁻¹)</th>
<th>θ₂ (V⁻²)</th>
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<tr>
<td>SNPS</td>
<td>1.5</td>
<td>3.35</td>
<td>0.7</td>
</tr>
<tr>
<td>SNPS (Ion Impurities)</td>
<td>1.65</td>
<td>6.15</td>
<td>1.1</td>
</tr>
<tr>
<td>IUNET-BO (Quantum Ballistic)</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IUNET-BO (Semiclassical Ballistic)</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IUNET-BO (Acoustic Phonon and Surface Roughness)</td>
<td>1.45</td>
<td>5.25</td>
<td>2.55</td>
</tr>
<tr>
<td>IMEP</td>
<td>1.35</td>
<td>3.25</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table II. Parameters used in the proposed analytical model in order to fit the simulations obtained from advanced transport models.
Table II shows the mobility degradation and velocity saturation parameter values that have been used to fit the numerical simulations of Ref. 18, which is a longer-channel device SRG MOSFET.

V. CONCLUSIONS

We have extended our previous cylindrical SRG MOSFET model to include hydrodynamic transport, short channel effects, mobility degradation due to scattering mechanisms, velocity overshoot, and quantum effects. The comparisons between the advanced numerical transport models and the compact model for the drain current in cylindrical SRG MOSFET show that if our compact model includes the hydrodynamic transport model it can reproduce those simulation results based on 3D advanced transport models. The model is valid and continuous in all regimes.

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