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An Improved Compact Model for Doped Double-Gate MOSFETs Using a Rigorous Perturbation Method and Higher-Order Correction

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1. Introduction

BSIM-CMG compact model for multi-gate MOSFETs is widely adopted in the semiconductor industry for device research and development [1][2]. In BSIM double-gate (DG) MOSFET model, a superposition based approximation is applied to solve 1-D nonlinear Poisson's equation to obtain an analytic electric-potential distribution. In this paper, an analytic model with improved accuracy for doped DG MOSFETs using a rigorous perturbation method is presented. The interaction between the zeroth and first-order solutions is found to be important, and the first-order correction is used to improve the model accuracy for wider applicable conditions, especially when the doping level is high.

Unlike many other models that set the body center as the operating point for their linear approximation, we study the effect of shifting the operating point, and find that the model accuracy in predicting both surface charge density and current is significantly improved by setting the operating point at the body surface. This is consistent with the well-known properties that Taylor approximation is more accurate around the operating point, and the induced charge near the surface is the major contribution to the device current.

2. Theoretical Analysis and Derivation

The structure of a symmetric (p-type) double-gate MOSFET is shown in Fig.1. 1-D Poisson's equation including both inversion and bulk charges is:

$$\frac{\partial^2\psi(x,y)}{\partial x^2}=\frac{qn_i{}^2}{\varepsilon_{si}N_A}\cdot e^{\frac{q(\psi(x,y)-V_{ch}(y))}{KT}}+\frac{qN_A}{\varepsilon_{si}} \qquad (1)$$

where $\psi(x,y)$ is the electric potential, N_A is the body doping, $V_{ch}(y)$ is the electron quasi-Fermi potential .

Next we perform a variable transformation to remove the constant term in (1) by introducing a new variable ψ_0:

$$\psi=\psi_0+\frac{1}{2}\frac{qN_A}{\varepsilon_{si}}x^2 \qquad (2)$$

Without lose of generality, the boundary conditions of a symmetric fully-depleted double-gate MOSFET can be expressed as (only the upper half region: $0\le x\le T_{si}/2$ is needed due to the device symmetry):

$$\frac{\partial\psi}{\partial x}|_{x=0}=0 \quad \text{and} \quad \psi\left(x=\frac{T_{si}}{2},y\right)=\varphi_s(y)$$

Substituting (2) into (1) yields:

$$\frac{\partial^2\psi_0}{\partial x^2}=\frac{qn_i{}^2}{\varepsilon_{si}N_A}\cdot e^{\frac{q(\psi_0-V_{ch}(y))}{KT}}\cdot e^{\frac{1q^2N_A}{2KT\varepsilon_{si}}x^2} \qquad (3)$$

It should be kept in mind that no approximation is made to obtain (3). But when $\frac{1}{2}\frac{q^2N_A}{KT\varepsilon_{si}}x^2\ll 1$, the second exponential term $e^{\frac{1q^2N_A}{2KT\varepsilon_{si}}x^2}$ can be approximated using Taylor expansion. To estimate the accuracy of this approximation, we define a "relative error" as follows:

$$ReErr=[f(x)-f(x_0)-f'(x_0)(x-x_0)]/f(x) \qquad (4)$$

where x_0 is the operating point to expand an arbitrary function f(x).

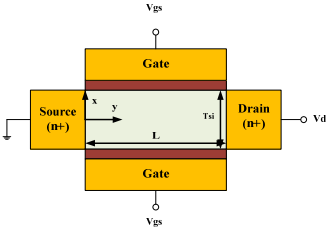


Fig. 1. Schematic diagram of a DG MOSFET.

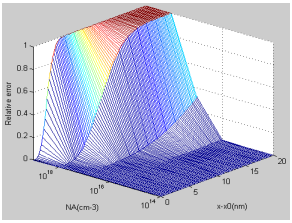


Fig. 2. Relative error (*ReErr*) as a function of x-x_0 and N_A.

The accuracy of above Taylor approximation made for a doped double-gate MOSFET, is determined by the doping density and the distance away from the operating point x_0, as shown in Fig. 2. Since the major population of mobile charges is located near the body surface, a solution to (3) with higher accuracy near the surface is preferred. Therefore, we set the operating point at $x_0=T_{si}/2$ as the relative-error index $ReErr$ grows with the distance: $x-x_0$.

To clarify our derivation, we introduce several notations as follows:

$$\begin{cases} z = q[\psi_0-V_{ch}(y)]/KT \\ a = q^2n_i{}^2e^{\frac{1q^2N_A}{2KT\varepsilon_{si}}(\frac{T_{si}}{2})^2}/KT\varepsilon_{si}N_A \\ b = q^4n_i{}^2e^{\frac{1q^2N_A}{2KT\varepsilon_{si}}(\frac{T_{si}}{2})^2}/2K^2T^2\varepsilon_{si}{}^2 \end{cases} \qquad (5)$$

Eq. (3) can be approximated as:

$$\frac{\partial^2 z}{\partial x^2}=e^z\cdot[a+b(x^2-\frac{T_{si}{}^2}{4})] \qquad (6)$$

Using the perturbation method, z can be written as the sum of the zeroth and first-order (perturbation) terms:

$$Z=Z_0+Z_1(Z_1\ll Z_0) \qquad (7)$$

Setting the operating point at the body surface, new equations and boundary conditions can be obtained as follows:

$$Z_0''=ae^{Z_0} \qquad (8)$$

$$Z_1''=[aZ_1+b(x^2-\frac{T_{si}{}^2}{4})]e^{Z_0} \qquad (9)$$

$$\begin{cases} \frac{\partial Z_0}{\partial x}|_{(x=0,y)} = 0 \ , \ \frac{\partial Z_1}{\partial x}|_{(x=0,y)} = 0 \ , Z_1\left(x = \frac{T_{si}}{2}, y\right) = 0 \\ Z_0(x = T_{Si}/2\,, y) = q\left[\varphi_s(y) - \frac{qN_A T_{Si}^2}{8\varepsilon_{si}} - V_{ch}(y)\right]/KT \end{cases} \quad (10)$$

Nonlinear eq. (8) has an analytic solution[3][4], and (9) can also be analytically solved using the approximation:

$$\frac{b}{a}\left(x^2 - \frac{T_{Si}^{\ 2}}{4}\right) = \frac{b}{a}\left(x + \frac{T_{Si}}{2}\right)\left(x - \frac{T_{Si}}{2}\right) \approx \frac{b}{a}T_{Si}\left(x - \frac{T_{Si}}{2}\right) \quad (11)$$

This approximation is highly accurate as $x \to T_{Si}/2$, where we are most concerned about. Consequently, the electric potential distribution can be obtained as:

$$\psi = qN_A x^2/2\varepsilon_{si} + V_{ch}(y) - 2\,KT/q\,ln\left[\sqrt{2a}/2p \cdot \cos(px)\right] + KTb/qa \cdot T_{Si}\frac{\tan(px) - \tan(pT_{Si}/2) + (pT_{Si}/2 - px)\tan(px)\cdot\tan(pT_{Si}/2)}{1 + pT_{Si}/2\cdot\tan(pT_{Si}/2)} - KTb/qa \cdot T_{Si}(x - T_{Si}/2) \quad (12)$$

Here, p is a constant to be determined from boundary condition and formulation of drain current follows reference [2].

3. Comparison with BSIM Model

BSIM-CMG model[1][2] takes a "superposition" approach by separating the electric potential into two parts:

$$\frac{\partial^2\psi_1(x,y)}{\partial x^2} = \frac{qn_i}{\varepsilon_{si}} \cdot e^{\frac{q\left(\psi_1(x,y) - \phi_B - V_{ch}(y)\right)}{KT}} \quad (13)$$

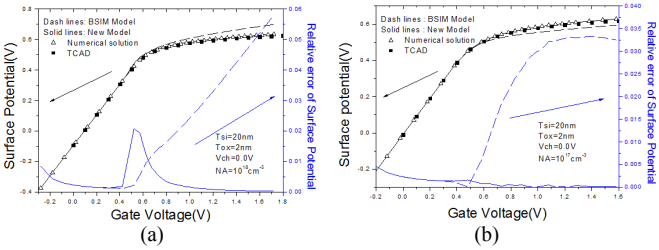
$$\frac{\partial^2\psi_2(x,y)}{\partial x^2} = \frac{qn_i}{\varepsilon_{si}} \cdot e^{\frac{q\left(\psi_1(x,y) - \phi_B - V_{ch}(y)\right)}{KT}} \cdot \left(e^{\frac{q\psi_2(x,y)}{KT}} - 1\right) + \frac{qN_A}{\varepsilon_{si}} \quad (14)$$

In solving $\psi_2(x,y)$, a function $a(x,y) = \frac{q^2 n_i}{\varepsilon_{si} KT} \cdot e^{\frac{q\left(\psi_1(x,y) - \phi_B - V_{ch}(y)\right)}{KT}}$ is treated as a constant without an explicit explanation and a linear approximation is made to simplify eq. (14):

$$e^{\frac{q\psi_2(x,y)}{KT}} \approx 1 + \frac{q\psi_2(x,y)}{KT}, \left(\frac{q\psi_2(x,y)}{KT} \ll 1\right) \quad (15)$$

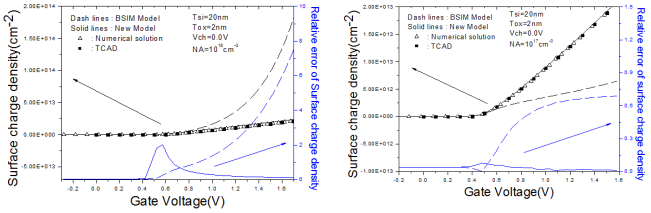
In our approach, the transformation technique (2) lumps the effects of depletion and inversion charges together to avoid the errors of superposition. The superposition method does consider the coupling of depletion and inversion charges (i.e.,ψ_1 and ψ_2), but is not able to handle higher-order nonlinearity of equation itself; therefore, it is not a rigorous perturbation approach. Moreover, unlike our Taylor approximations in which we can readily identify their applicable conditions by examining x-x_0 and N_A, it is unclear how accurate their approximations are. For example, it remains to be verified that the ratio of $\psi_2(x,y)$ to the thermal voltage (~0.026V) in (15) is much smaller than one.

We calculate the static ($V_{ch} = 0$) surface potential and surface charge density of a DG MOSFET using our new model, and compare them with the numerical solution to 1-D eq. (1) and TCAD 2-D simulations. The results are shown in Figs. 3-4 (using channel length L=1um and mid-gap work function gate material). Fig. 3 shows the surface-potential error from our new model drops rapidly when the gate voltage increases. The error from BSIM model, however, grows with the gate voltage and reaches the maximum in strong inversion region. The same trend can also be observed in the surface density (integration along x-direction) of the induced inversion charges in the body, as shown in Fig. 4. As a result, drain current given by BSIM model significantly deviates from our TCAD results when the gate voltage is large, as shown in Fig. 5. On the other hand, it can be seen that our new model has higher accuracy in all regions when predicting the drain current. Apparently, fewer approximations are made in our model and a more relevant operating point (body surface) is set, making its accuracy higher. It should be pointed out that BSIM[2] model introduces a simplified variable ψ_{pert} to replace ψ_2, while it is unclear how ψ_{pert} is formulated. In our BSIM calculation, we simply consider a fully-depleted DG MOSFET and keep using ψ_2. However, we still were not able to repeat their extremely small errors of surface potential (e.g., ~ nV) compared with TCAD simulation.



(a) (b)

Fig. 3. Surface potential and its relative error of a DG-MOSFET for different doping conditions.



(a) (b)

Fig. 4. Surface charge density and relative error of a DG-MOSFET for different body doping concentrations.

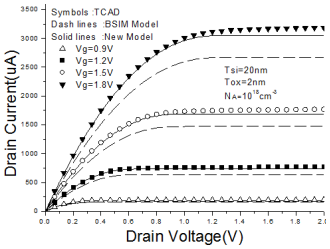


Fig. 5. Comparison of drain current calculated using our new model, BSIM model and TCAD simulation.

4. Conclusions

In this paper, we present an analytical model for doped double-gate MOSFET. By using a rigorous perturbation method to solve 1-D Poisson's equation, more accurate surface potential can be obtained to improve its capability to predict the drain current. Both numerical solution to 1-D Poisson's equation and 2-D TCAD simulation confirm that the accuracy of our model is higher than the widely adopted BSIM-CMG model, especially when the doping level is high.

References

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