Computation Efficient yet Accurate Surface Potential Based Analytic Model for Symmetric DG MOSFETs to Predict Current-Voltage Characteristics

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ABSTRACT

A computation efficient yet accurate surface potential-based analytic model for the symmetric double-gate MOSFETs is proposed to simulate double-gate device current-voltage characteristics in this paper. This model consists of a surface potential versus voltage input equation and a drain current expression, which are very similar to that proposed by J. R. Brews for the single-gate (SG) Bulk MOSFET. The model gets rid of requirement of the transcendent trigonometric function used in the previous model, thus, result in the computation efficiency. The model is also verified by extensive comparisons with rigorous numerical solutions under different operation conditions and geometry structures, thus, the new set of surface potential equation and drain current is the framework of a complete DG MOSFET model for computer-aided-design circuit purpose.

Keywords: non-classical MOS transistor, double-gate MOSFETs, device physics, surface potential model, computation efficiency.

1 INTRODUCTION

With the advance of double-gate (DG) MOSFETs fabrication technologies [1-3], compact modelling for circuit simulation using DG MOSFETs has received a lot of achievements [4-14]. Based on the intermediate variables used to calculate the output current, compact models can be categorized into three classes. The first approach uses the density of the inversion charges at the two ends of the channel and formulates the model outputs in terms of these charge densities. Some models developed using this approach includes the EKV-DG and previous BSIMDG [6-7]. These models are analytic, thus may computation efficient. However, these models may be not accurate compared with other model approaches [8]. The second approach uses the potentials at the two ends of the channel to calculate the terminal charges and currents. These models are called potential-based models and some representative models have been developed by Taur, Adelmo, and Jin et al. [9-11]. These model include as much as possible device physics, thus they are accurate compared with the 2-D numerical simulation. These models, however, suffer from the efficient computation issue because they involved into the transcendental trigonometric functions either in the surface potential or in the drain current calculation. The last approach uses the carrier concentration at the source and drain ends of the channel to calculate the drain current [12-14], which may have either accurate or the computation efficiency issue from different formulation. Since surface potential approach has been chosen to be the industrial standard for the next generation bulk MOSFET model due to its advantages, to use similar approach to model the non-classical multiple-gate devices becomes extensive studies as shown in the second approach applications [15-16].

In order to improve the present channel potential based DG-MOSFET models, a computation efficient yet accurate surface potential-based core model for the symmetric DG-MOSFET is proposed. The model results demonstrated that surface potential versus voltage relationship and the drain current expression similar to that proposed by J. R. Brews for the single-gate bulk MOSFET [17] are obtained for the symmetric DG MOSFETs. In this way the practice advantage of the new surface potential based model in itself is not only directly obvious, but also in its computation efficiency without transcendent function, leading to easier and better understanding to the device physics and flawless description of the performance of DG MOSFETs.

2 ANALYTIC MODEL DEVELOPMENT

2.1 Derivation of input-output voltage equation

Considering an ideal long channel undoped n-channel symmetric DG-MOSFET, with only electrons as the conducting carrier, Poisson's equation under the gradual-channel-approximation (GCA) takes the one-dimensional (1D) form:

$$\frac{d^2\phi}{dx^2} = \frac{qn_i}{\varepsilon_{si}} e^{\frac{q(\phi-V)}{kT}} \quad (1)$$

where ϕ is the potential, V is the quasi-Fermi potential, and other symbols bear their common meanings. The assumption that conduction is dominated by electrons is valid while hole density is negligible.

Due to the symmetry property of the DG MOSFET's structure and coordinate reference as shown in Fig.1, there is a point at the center of the silicon film where the vertical

electric field is zero. Taking this point as the origin of the coordinate system, Equation (1) has to satisfy the following boundary conditions:

$$\frac{d\phi}{dx}(x=0)=0, \qquad \phi(x=\pm\frac{T_{si}}{2})=\phi_s \tag{2}$$

Equation (1) can be analytically solved as follows [4-14]:

$$E_s=\sqrt{\frac{2n_ikT}{\varepsilon_{si}}}\sqrt{e^{\frac{q(\phi_s-V)}{kT}}-e^{\frac{q(\phi_0-V)}{kT}}} \tag{3}$$

where $\phi_0=\phi\left(x=0\right)$ is the centric potential.

From Eq. (3), we obtain the surface potential and surface field as follows [4-14]:

$$\phi_s=\phi_0-2\frac{kT}{q}\ln[\cos(\sqrt{\frac{n_iq^2}{2kT\varepsilon_{si}}e^{\frac{q(\phi_0-V)}{kT}}}\frac{T_{si}}{2})] \tag{4}$$

Gauss's law is obeyed between surface potential, induced charge and applied voltage

$$C_{ox}\left(V_{gb}-\phi_s\right)=E_s \tag{5}$$

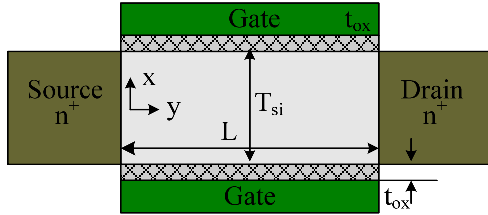

Fig.1 Diagram and coordinate of an undoped double-gate MOSFET device.

Once the centric potential is eliminated from Eqs.(3), (4) and (5), we have the following surface potential versus input voltage equation

$$\frac{C_{ox}(V_{gs}-\Delta\varphi-\phi_s)}{\sqrt{2n_i\varepsilon_{si}kT}}e^{-\frac{q(\phi_s-V)}{2kT}}=\sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2n_i}{2\varepsilon_{si}kT}\left[e^{\frac{q(\phi_s-V)}{kT}}-\frac{C_{ox}^2(V_{gs}-\Delta\varphi-\phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{6}$$

Eq.(6) is a fully rigorous surface potential-voltage equation of the DG MOSFETs [4], which can be solved by the Newton–Raphson (NR) method to get the accurate surface potential value. However, Eq.(6) is not evident to elucidate the dependence of the surface potential on bias and the structure parameters. This is precisely the aim of this work to provide a direct and clear dependence of the surface potential on bias and structure factors. Since the right hand side of Eq.(6) is a trigonometric function and the augment value inside it has to take the positive value based on the requirement of its physical meaning, it can be approximated by two times of the first-order Talyor expansion as shown in Eq.(7)

$$\frac{2C_{ox}(V_{gs}-\Delta\varphi-\phi_s)}{qn_iT_{si}}+\frac{C_{ox}^2(V_{gs}-\Delta\varphi-\phi_s)^2}{4n_i\varepsilon_{si}kT}=\frac{1}{2}e^{\frac{q(\phi_s-V)}{kT}} \tag{7}$$

Since two times of Taylor expansions are involved into the same exponential function item, which is directly related to the accuracy of the surface potential in the strong inversion region, we would like to show later from the comparison between the calculation results and the numerical solution that Taylor expansions of the original surface potential equation have a good accuracy either for surface potential or the drain current calculation. Due to the multiple root characteristics of Eq.(7) with respect to $V_{gs}-\Delta\varphi$, we make use of the solution procedure of general quadratic equation to derive a DG-MOSFET surface potential versus voltage equation with single a root as shown in Eq.(4)

$$\frac{q\left(V_{gs}-\Delta\varphi-\phi_s\right)}{kT}=\frac{4\varepsilon_{si}}{T_{si}C_{ox}}\sqrt{1+\frac{T_{si}^2}{8L_i^2}e^{\frac{q(\phi_s-V)}{kT}}}-\frac{4\varepsilon_{si}}{T_{si}C_{ox}} \tag{8}$$

It is easily found from Eq.(8) that the derived DG-MOSFET surface potential versus voltage equation is very analogous to that of the bulk MOSFETs, which can be solved by numerical iteration such as Newton–Raphson (NR) or approximate analytic solution [18] to obtain the surface potential. Compared with other previous works [9~14], this equation does not involve any intermediate variables and transcendental trigonometric function, its computation efficiency should be comparable with that of the bulk MOSFET surface potential versus voltage equation. In fact, we can directly use the bulk MOSFET surface potential methods such as HISIM, PSP and ULTRAS to get the DG MOSFET solution.

2.2 Drain current expression derivation

From Pao-Sah's dual integral [19], integrating $I_{ds}dy$ from the source to the drain and expressing dV/dy as $(dV/d\phi_s)\left(d\phi_s/dy\right)$, the non-charge-sheet drain current of the SRG-MOSFETs is written as

$$I_{ds}=\frac{\mu W}{L}\int_0^{V_{ds}}Q(V)dV=\frac{\mu W}{L}\int_{\phi_{ss}}^{\phi_{SL}}Q(\phi_s)\frac{dV}{d\phi_s}d\phi_s \tag{9}$$

where ϕ_{SS} and ϕ_{SL} are the solutions to (8) corresponding to V=0 and V= V_{ds} respectively. The parameter μ is the effective mobility.

Note that $dV/d\phi_s$ can also be expressed as a function of ϕ_s From Eq. (8). For example, the quasi-Fermi-Potential is given from (8) :

$$V=\phi_S+\frac{2kT}{q}\ln\left[\frac{2\varepsilon_{si}}{C_{ox}L_i}\right]-\frac{kT}{q}\ln\left[\frac{q(V_{gs}-\Delta\varphi-\phi_S)}{kT}+\frac{8\varepsilon_{si}}{C_{ox}T_{si}}\right]-\frac{kT}{q}\ln\left(\frac{q(V_{gs}-\Delta\varphi-\phi_S)}{kT}\right) \tag{10}$$

Differentiating (10) gives the quasi-Fermi-potential derivative. By using (9) and replacing it into (5), the total mobile charge per unit gate area expressed in terms of ϕ_s yields $Q(\phi_s)$ .Substituting these factors in (5), we have

$$I_{ds}=\frac{W\mu C_{ox}}{L}\int_{\phi_{SS}}^{\phi_{SL}}\left[\left(V_{gs}-\Delta\varphi-\phi_s\right)+\frac{2kT}{q}-\frac{kT}{2q}\left(1+\frac{C_{ox}qT_{si}\left(V_{gs}-\Delta\varphi-\phi_s\right)}{8\varepsilon_{si}kT}\right)^{-1}\right]d\phi_s \tag{11}$$

The integration of (11) is performed analytically to yield:

$$I_{ds}=\frac{W\mu C_{ox}}{L}\left[\left((V_{gs}-\Delta\varphi)\phi_s-\frac{\phi_s^2}{2}\right)+\frac{2kT\phi_s}{q}+\left(\frac{kT}{q}\right)^2\frac{4\varepsilon_{si}}{T_{si}C_{ox}}\ln\left(1+\frac{C_{ox}qT_{si}\left(V_{gs}-\Delta\varphi-\phi_s\right)}{8\varepsilon_{si}kT}\right)\right]\Bigg|_{\phi_{SS}}^{\phi_{SL}} \tag{12}$$

Where ϕ_{SS} and ϕ_{SL} are the solutions to (8) corresponding to V=0 and V=V_{ds} respectively.

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Based on the developed model, DG MOSFET current-voltage characteristics can be calculated using equation (12) with the surface potential calculated using equation (8). The model calculation is compared with the rigorous numerical solution from [5] from both accuracy and computation efficiency. We would like to point out that (12) is different from the previous all DG MOSFET expressions, which don't need any intermediate variables, auxiliary functions, complicated spatial integration , and the transcendental trigonometric function[5-14], but it direct the relates to the drain current to the source and drain end surface potentials. More important, it also gives almost exact the drain current prediction as other complex functions.

3 RESULTS AND DISCUSSION

The presented surface potential based model of the undoped DG-MOSFETs has three distinctive features: (i) A single set of the elemental function based surface potential versus voltage equation is obtained in analogous to that of the bulk MOSFETs, for which the complete surface potential equation is a base to develop a continuous model; (ii) the drain current, obtained from Pao-Sah's dual integral, is described by one continuous function in the terms of the surface potentials at the source and drain, tracing properly transition between different operation regions without resorting to non-physical fitting-parameters; (iii) the derived surface potential and drain current equations properly capture DG-MOSFET's specific device physics features without charge-sheet approximation while significantly improve the previous model efficiency .

In order to test the analytic surface potential equation, we have compared the result of (8) prediction for symmetric long-channel DG-MOSFETs with the numerical simulation from [9]. We have assumed a channel length (L) of 1 μm, silicon oxide thickness (tox) of 2 nm, and a mid-gap gate structure. A constant effective mobility of 400 cm2/V-s has been used for calculations both in the model and in the simulation. Result comparison with the numerical solutions of (8) are shown in from Fig.2 to Fig.4 for the surface potential and the inversion charge curves with different gate oxide and the silicon film thickness.

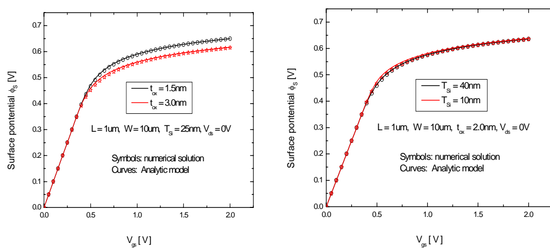

Fig.2 The surface potential versus gate voltage curves with different gate oxide and silicon film thickness, obtained from Eq.(8), compared with the numerical solution.

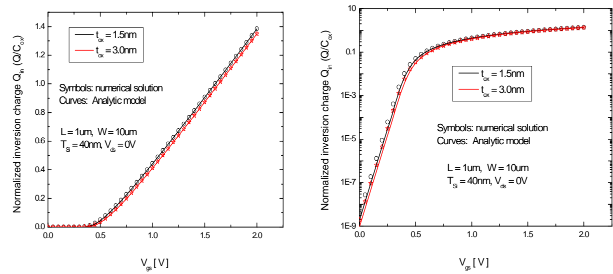

Fig.3 The comparison of the inversion charge versus gate voltage curves between the analytic model and the numerical solution for different gate oxide thickness.

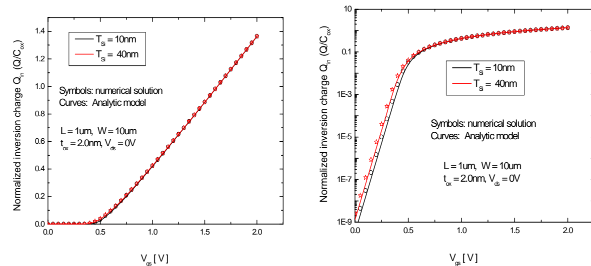

Fig.4 The inversion charge versus gate voltage curves with different silicon film thickness, obtained from the analytic model, compared with the numerical solution.

It is easily found from all these comparisons that the developed analytic surface potential equation not only give the accurate surface potential prediction, but also give precise inversion charge calculation, compared with the numerical solution either for different gate oxide thickness, but also for different silicon film thickness. It is very interesting to observe the silicon film thickness has a little impact on the surface potential either in the sub-threshold region, but also in the strong inversion region. In contrast, the inversion charge density is almost proportional to the silicon film thickness in the sub-threshold region while a little changing in the strong inversion region, obtained from both the analytic model and the numerical solution. Similar, From Fig.5 to Fig.7 shows good agreement of drain current and trans-conductance curves between model prediction and the numerical solution for different gate oxide and silicon film thickness.

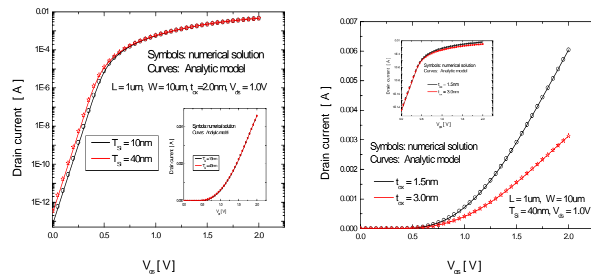

Fig.5 The drain current versus gate voltage curves with different silicon film and gate oxide thickness, obtained from the analytic model, compared with the numerical

solution.

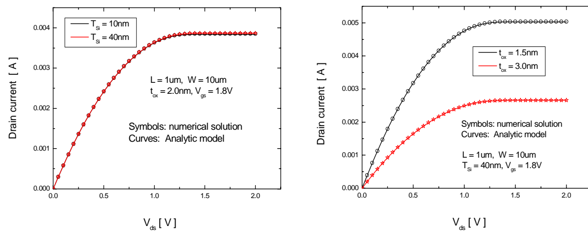

Fig.6 The comparison of drain current versus drain voltage curves with different silicon film and gate oxide thickness between the analytic model and the numerical solution.

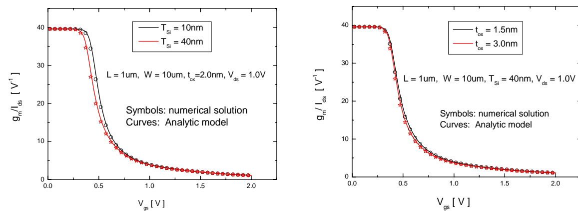

Fig.7 The comparison of trans-conductance over drain current versus gate voltage curves with different silicon film and gate oxide thickness between the analytic model and the numerical solution.

Compared to the numerical computation of the surface potential and then the drain current [5], The CPU time of the new surface potential based model required is reduced by approximately a factor of 1.6 for the voltage variables of the gate and drain in the tested range from 0 to 2.V with gate voltage step of 0.05V for three transfer curves, corresponding to drain voltage equalling to 0.5V, 1V and 2V, and with the drain voltage step of 0.05V for three output curves, corresponding to gate voltage equalling to 0.5V, 1V and 2V. The test details are as follows: The calculation recycles with six thousand times are designed in a SUN Blade workstation coming from the SUN Microsystem Co. for both models and the recorded time demonstrated separate model computation time. Of course, a rigorous test should be done for the same VLSI circuits, which will be made once two models are available in the commercial VLSI circuit simulators.

4 CONCLUSIONS

In summary, a computation efficient yet accurate surface potential-based model for undoped symmetric DG-MOSFETs is presented. The model has been verified by extensive comparisons with the numerical solutions under different operation conditions with different geometry, proving its high precise and computation efficiency. Thus, it will be a good base for us to develop surface potential based compact models for DG MOSFETs.

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