Surface Potential versus Voltage Equation from Accumulation to Strong Inversion Region for Undoped Symmetric Double-Gate MOSFETs

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Abstract- **Surface potential is one key variable in DG MOSFET compact modeling. A complete surface potential versus voltage equation and its continuous solution from the accumulation to strong inversion region are presented in this paper for undoped (lightly doped) symmetric double-gate (DG) MOSFETs. The results are based on the exact solution of Poisson's equation with an amending mathematical condition of the continuity, allowing the surface potential to be accurately described from the accumulation region, through sub-threshold, finally to the strong inversion region. From presented surface potential solution, the dependence of the surface potential and corresponding gate capacitance on the quasi-Fermi-potential, silicon film thickness, gate oxide layer, and temperature are tested running different parameters, showing the solution continuity, smoothing, and high accuracy, compared with the 2-D numerical simulation. The presented equation and its solution will be useful in developing a complete surface potential-based DG-MOSFET compact model.**

Index terms- **Surface potential, DG-MOSFETs, device physics, compact modeling, ULSI circuit simulation**

I INTRODUCTION

Since the bulk MOSFET surface potential-based model has been chosen as the next generation industry standard, the analytic surface potential-based model studies on the non-classical multiple-gate devices have also been explored [1-3]. However, the complete surface potential equation for the DG MOSFETs has not been established well so far although various compact models, such as potential-based model, charge-based model and carrier-based model have been established [4-9] on the electrostatics analysis of the DG MOS transistor [10].

In this work, a complete surface potential versus voltage equation is presented and its continuous solution is also discussed for the undoepd symmetric DG MOSFETs from the accumulation to strong inversion region. Using the Newton's iterative method, the surface potential characteristics of DG MOSFETs have been analyzed numerically and the dependences of the surface potential solution on the quasi-Fermi-potential, temperature, the scale of the silicon film and the gate oxide layer have been also demonstrated.

II SOLUTION DEVELOPMENT

We consider an ideal undoped symmetric n-channel MOSFET in which the electrostatics is control by the back and surface gates good enough to neglect the short channel effects associated to two-dimensional effects (gradual channel approximation). Therefore, the electrostatic behaviour of the DG MOSFETs can be described by the 1-D Poisson's equation in the vertical direction.

$$\frac{d^2\phi}{dx^2} = -\frac{\rho}{\varepsilon_{si}} \tag{1}$$

Since in an undoped symmetric n-type DG-MOSFET,

$$N_a = N_d = 0 \tag{2}$$

The space and hole concentrations can be simply given by

$$\rho = q\left(p - n\right) \tag{3}$$

Electron and hole concentrations can be expressed by the potential as

$$n = n_i e\left(\frac{q(\phi - V)}{kT}\right) \tag{4}$$

$$p = n_i e\left(-\frac{q(\phi)}{kT}\right) \tag{5}$$

Poisson's equation thus takes the following form:

$$\frac{d^2\phi}{dx^2} = \frac{qn_i}{\varepsilon_{si}}\left[e^{\frac{q(\phi-V)}{kT}} - e^{\frac{-q\phi}{kT}}\right] \tag{6}$$

with the symmetric boundary conditions:

$$\frac{d\phi}{dx}(x=0) = 0, \frac{d\phi}{dx}(x = \pm\frac{T_{si}}{2}) = C_{ox}\left(V_{gs} - \phi_s - \Delta\phi_l\right) \tag{7}$$

$$\phi(x = \pm\frac{T_{si}}{2}) = \phi_s, \phi(x=0) = \phi_0 \tag{8}$$

Where ϕ_s and ϕ_0 are the surface potential at the interface between the silicon surface and the gate oxide layer and the centric potential at the silicon film centre as the coordinate origin, respectively. All other symbols have the common meanings.

For the DG-MOSFET operation above flat-band point, the electron dominates the space electron layer. In this case, only electron term is considered while the hole term is negligible is reasonable. Thus, (6) is simplified as

$$\frac{d^2\phi}{dx^2} = \frac{qn_i}{\varepsilon_{si}} e^{\frac{q(\phi-V)}{kT}} \tag{9}$$

With the boundary conditions, (9) is analytically preformed to yield. We obtain the formulation solution of the centric potential and the surface potential.

$$\phi_0 = V + \frac{kT}{q}\ln\left[e^{\frac{q(\phi_s - V)}{kT}} - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right] \tag{10}$$

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT}} e^{-\frac{q(\phi_s - V)}{2kT}} = \sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[e^{\frac{q(\phi_s - V)}{kT}} - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{11}$$

We note that (11) does not stand for the electrostatic potential close the flat-band point due to the simplification of Poisson's equation, which causes a discontinuity problem. To keep the continuity of surface potential, Eq. (11) is fixed as

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT}}\left[e^{\frac{q(\phi_s - V)}{kT}} - e^{\frac{qV}{kT}}\right] = \sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[e^{\frac{q(\phi_s - V)}{kT}} - e^{\frac{qV}{kT}} - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{12}$$

Meanwhile, to keep the surface potential derivative continuity, Eq (12) can be amended further as

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT}}\left[e^{\frac{q(\phi_s - V)}{kT}} - \left(1 - \frac{q\phi_s}{kT}\right)e^{\frac{qV}{kT}}\right]^{\frac{1}{2}} = \sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[e^{\frac{q(\phi_s - V)}{kT}} - \left(1 + \frac{q\phi_s}{kT}\right)e^{\frac{qV}{kT}} - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{13}$$

Below the flat-band point, only the hole is considered. So the expressions of the surface potential can be decided as the follows similarly.

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT}} e^{\frac{q\phi_s}{2kT}} = -\sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[e^{-\frac{q\phi_s}{kT}} - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{14}$$

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT}}\left[e^{\frac{q\phi_s}{kT}} - 1\right]^{1/2} = -\sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[e^{-\frac{q\phi_s}{kT}} - 1 - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{15}$$

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT}}\left[e^{\frac{q\phi_s}{kT}} - \left(1 + \frac{q\phi_s}{kT}\right)\right]^{\frac{1}{2}} = -\sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[e^{-\frac{q\phi_s}{kT}} - 1 + \frac{q\phi_s}{kT} - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{16}$$

According to the discussion above, a single surface potential versus voltage equation is also obtained for the symmetric DG MOSFETs from the accumulation to strong inversion region assuming some signum functions are used

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT\theta}}\left[e^{-\mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}} - \left(1 - \mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}\right)\right]^{\frac{1}{2}} = \mathrm{sgn}(\phi_s)\sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[\theta e^{\mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}} - \left(1 + \mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}\right)\theta - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{17}$$

From a combination of (14) and (23) and

$$\frac{C_{ox}(V_{gs} - \Delta\phi_f - \phi_s)}{\sqrt{2n_i\varepsilon_{si}kT\theta}}\left[e^{-\mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}} - \left(1 - \mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}\right)\right]^{\frac{1}{2}} = \mathrm{sgn}(\phi_s)\sin\left[\frac{T_{si}}{2}\sqrt{\frac{q^2 n_i}{2\varepsilon_{si}kT}\left[\theta e^{\mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}} - \left(1 + \mathrm{sgn}(\phi_s)\frac{q\phi_s}{kT}\right)\theta - \frac{C_{ox}^2(V_{gs} - \Delta\phi_f - \phi_s)^2}{2n_i\varepsilon_{si}kT}\right]}\right] \tag{18}$$

where (17) is continuous for surface potential and charge but discontinuous for the derivative of surface potential. In contrast, (18) is continuous for all related quantities, and the sgn(ϕ) is the signum function showed as the follow

$$\theta = \begin{cases} e^{-qV/kT} & \text{above flat-band point} \\ 1 & \text{flat-band or accumulation} \end{cases} \tag{19}$$

III RESULTS AND DISCUSSION

We use a Newton-Raphson iterative method to calculate the surface potential value of undoped DG MOSFET from the accumulation to the strong inversion region. Firstly, a discussion about the results of Eq. (11) & Eq. (14), Eq. (12) & Eq. (15) or Eq. (17) and Eq(13) & Eq(16) or Eq. (18) are performed as follows.

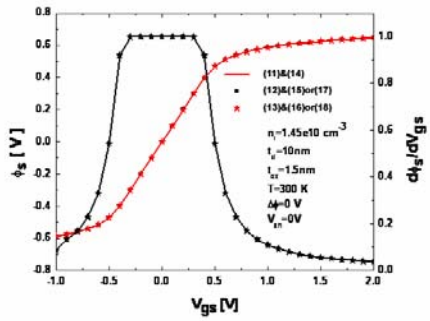

Fig.1 Plot of surface potential and surface potential derivative of the three equation pairs

Fig.1 plots the calculated ϕ_s (left) and $d\phi_s / V_{gs}$ (right) versus V_{gs} for wide gate voltage range from three equation pairs. The results from three equation pairs match well in a large gate voltage range indicating that the modification to Eqs. (11) & (14) is reasonable.

Fig.2 demonstrates the calculated result of ϕ_s versus V_{gs} curve near the flat-band point in a refined gate voltage region. Eq. (11) & (14) results in a discontinuity problem of, thus the calculated surface potential cannot pass through the flat-band point smoothly. ϕ_s calculated by using (17) can pass through the flat-band point smoothly even considering non-zero V_{ch}. (18) also demonstrates continuous characteristic and it fits the result of (17) so well that no difference can be observed.

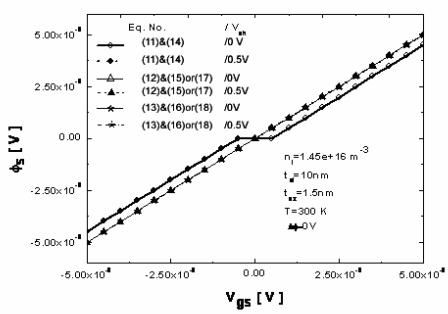

Fig. 2. Plot of ϕ_s versus V_{gs} near flat-band point among three equation pairs for different V_{ch}.

Fig.3 plots the calculation of $d\phi_s / dV_{gs}$ fromEq. (17) and Eq.(18). As expected, Eq.(17) results in a discontinuous derivative close to the flat-band point when $V_{ch} \neq 0$, indicating that Eq.(17) cannot be used to predict the capacitance-voltage characteristics of the DG-MOSFETs. Eq.(18) has to be used and the resultant $d\phi_s / dV_{gs}$ pass the flat-band point smoothly either for V_{ch}=0.0V or V_{ch}=0.5V.

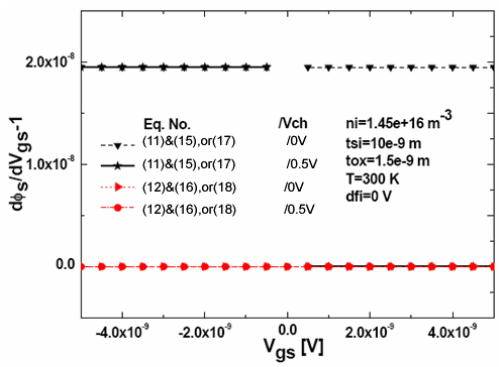

Fig. 3 The comparison of $d\phi_s / dV_{gs} - 1$ versus V_{gs} near the flat-band point between Eq. (17) and (18)

All surface potential equation predictions in the following discussion are based on (18), and the corresponding central potentials (ϕ_0) are from (4) and (11) using Newton-Raphson iterative method. The 3-D numerical simulation is performed from a device simulator, ULTRAS-SRG, from Institute of Microelectronics, Peking University[11].

Fig.4 is the result comparison of ϕ_s and ϕ_0 versus V_{gs} curve between the 2-D simulation and the surface potential equation prediction for different quasi-Fermi-potential. The equation prediction agrees with the 2-D simulation very well. The error is less than 3%, indicating the accuracy of (18). The quasi-Fermi-potential comes into effect only when operation goes into the strong inversion region. The curve of 0φmerges with ϕ_s in the sub-threshold region, but diverges from ϕ_s when $|V_{gs}|$ is large enough, saturating into a constant value.

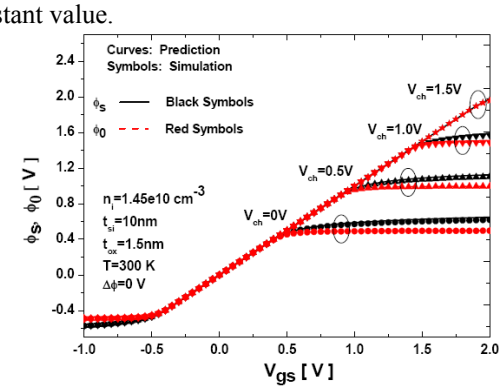

Fig.4 Comparison of ϕ_s and ϕ_0 versus V_{gs} between the 2-D simulation and surface potential equation prediction for different V_{ch} in a DG MOSFET.

Fig.5 plots the comparison of the gate capacitance curves between the surface potential equation and the 2-D simulation for different quasi-Fermi-potential. The equation predicted gate capacitance keeps continuous and smooth in the whole operation region, and matches the simulation very well.

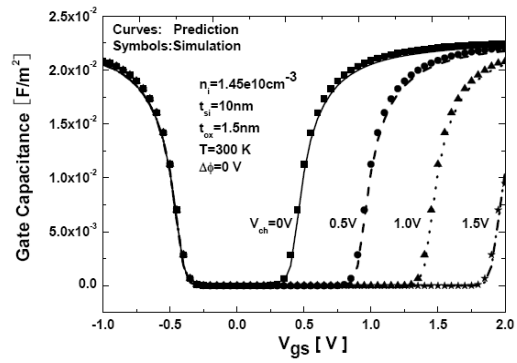

Fig.5 Comparison of the gate capacitance versus V_{gs} between the 2-D simulation and surface potential equation prediction for different V_{ch} in a DG MOSFET.

Fig.6, Fig.7 and Fig. 8 compare ϕ_s versus V_{gs} curves between the 2-D simulation and the surface potential equation prediction for different gate oxide thickness (t_{ox}), silicon film thickness(t_{si}) and temperature(T). The error is less than 4.5%, thus, the presented equation correctly predicts the surface potential dependence on device geometry and the operation temperature. The variation of t_{ox} affects ϕ_s, while ϕ_0 almost remains constant. It is found from Fig.7 that the variation of the silicon thickness makes the surface potential less conspicuous but the central potential decrease with increase of silicon thickness. In Fig. 8, it is also noted a higher temperature results in a higher surface and central potential absolute value either in accumulation region or in the strong inversion region

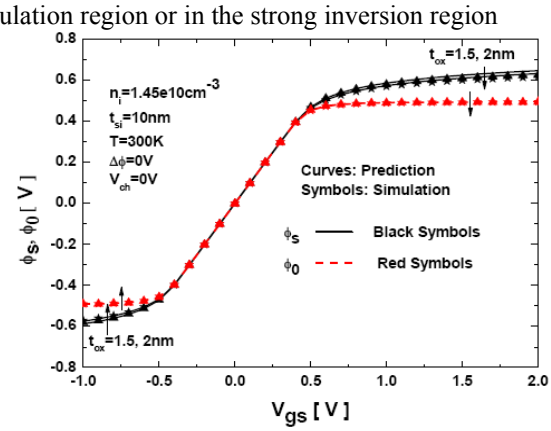

Fig.6 Comparison of ϕ_s and ϕ_0 versus V_{gs} between the 2-D simulation and surface potential equation prediction for different thickness of gate oxide in a DG MOSFET.

Fig. 9 compares the gate capacitance between the 2-D simulation and the surface potential equation prediction for different operation temperature. The results match well, almost overlapping. At a higher temperature, the curve ascends and descends more smoothly, and represents a lower capacitance value. Still, the curves converge when the gate voltage is high or low enough.

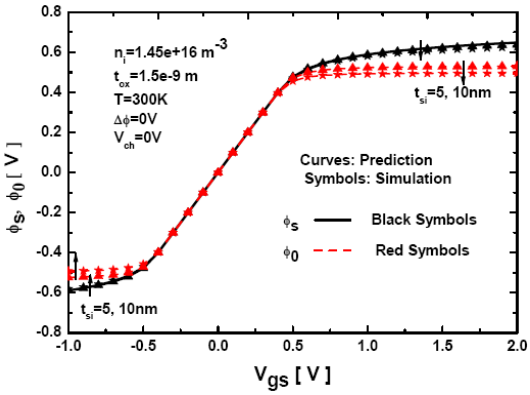

Fig.7 Comparison of ϕ_s and ϕ_0 versus V_{gs} between the 2-D simulation and surface potential equation prediction for different silicon film thickness in a DG MOSFET

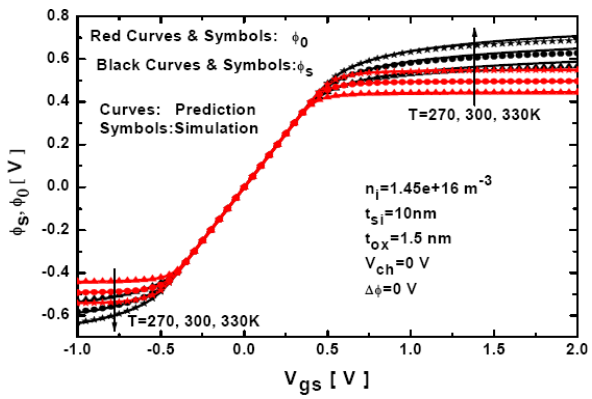

Fig.8 Comparison of ϕ_s and ϕ_0 versus V_{gs} between the 2-D simulation and surface potential equation and the resultant error of ϕ_s for different operation temperature in a DG MOSFET.

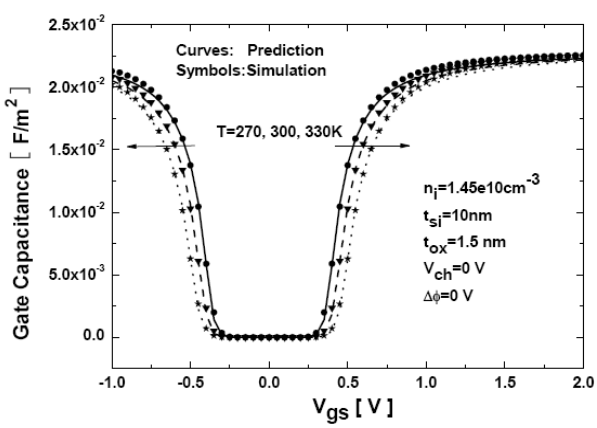

Fig.9 Comparison of the gate capacitance versus gate voltage curves between the 2-D simulation and surface potential equation prediction for different operation temperature in a DG MOSFET.

IV CONCLUSIONS

The complete surface potential versus voltage equation and its continuous solution have been proposed in this paper for the undoped symmetric DG MOSFETs from the accumulation region to the strong inversion region. The equation accuracy and its solution continuity have been widely verified from the surface potential, charge and trans-capacitance calculation. The presented results may be useful for the understating of the DG-MOSFET device physics and developing next generation advanced surface potential model.

Acknowledgements

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