A Complete Analytic Surface Potential-Based Core Model for Undoped Cylindrical Surrounding-Gate MOSFETs

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ABSTRACT

An analytic surface potential-based non-charge-sheet core model for cylindrical undoped surrounding-gate (SRG) MOSFETs is presented in this brief. Starting from the exact surface potential solution of the Poisson's equation in the cylindric surrounding-gate (SRG) MOSFETs, a single set of the analytic drain current expression in terms of the surface potential evaluated at the source and drain ends is obtasined from the Pao-Sah's dual integral without the charge-sheet approximation. It is shown that the derived drain current model is valid for all operation regions, allowing the SRG-MOSFET characteristics to be adequately described from the linear to saturation and from the sub-threshold to strong inversion region without fitting-parameters. Moreover, the model prediction is also be verified by the 3-D numerical simulation.

Keywords: non-classical MOS transistor, surrounding-gate MOSFETs, device physics, surface potential model, non-charge-sheet approximation.

1 INTRODUCTION

Extensive studies on surrounding-gate (SRG) MOSFET modelling have been performed in recent years and the related device physics have been well described by many different models [1-6]. In the channel potential-based SRG-MOSFET models, the closed-form current models are presented in terms of the intermediate variables or the potentials of the surface and centric point at the source and drain ends [3-4]. In the charge-based SRG-MOSFET models, the charge expression is developed for the SRG-MOSFETs based on a smooth function and interpolation [5]. In addition, a carrier-based approach is found to be useful in developing generic compact model for SRG-.

MOSFETs [6]. On the other hand, we also noted that the considerable attention has been focused on developing surface potential-based models in recent compact model formulations [7-8]. At present, there is a general consensus that the surface potential approach not only includes as much device physics as possible but also retains high accuracy and model continuity.

Under such a background, an analytical surface potential-based non-charge-sheet core model for obtaining the $I_{ds}(V_{gs},V_{ds})$ characteristics of the SRG-MOSFETs is proposed in this brief, based on the closed-form solution of Poisson's equation and Pao-Sah's dual integral fot the drain current formulation. We demonstrate in this paper that an analogous formulation as the proposed by J.R.Brews et al. for the single-gate (SG) Bulk MOSFET [9] can be carried out for the SRG-MOSFETs. The model has three distinctive features: (i) A single set of the surface potential voltage equation is obtained from the exact Poisson equation solution in the undoped SRG-MOSFET structure, analogous to that of the bulk MOSFETs, for which the complete surface potential equation is the beginning to develop a continuous model; (ii) the drain current, obtained from the Pao-Sah's dual integral, is described by one continuous function in terms of the surface potentials at the source and drain ends, tracing properly the transition between different SRG-MOSFET operation regions without resorting to non-physical fitting-parameters; (iii) the charge-sheet approximation, typically used in bulk MOSFET models to simplify the Pao-Sah's double integral for the current [9-10], is not invoked, properly capturing SRG-MOSFET's volume inversion effect. In order to complete the model, short-channel effects, quantum effects, low and high field transport, and more, will be added in near future.

2 ANALYTIC MODEL DEVELOPMENT

An ideal long channel SRG MOSFET without second order effects, such as poly-silicon depletion, quantum confinement, short channel effects, drain induced barrier lowering and velocity saturation is considered in this paper for simplicity. It will be possible to incorporate these second-order effects into a complete SRG MOSFET model in the near future after the core model is developed. The coordinate system used in this work is shown in Fig. 1 with r representing the radial distance from the center of the channel and $r = R$ giving the oxide silicon interface. It also assumes that the quasi-Fermi level is constant in the radial direction, so that the current flows only along the channel (y direction). The energy levels are referenced to the electron quasi-Fermi level of the source end since there is no body contact in the undoped SRG MOSFETs.

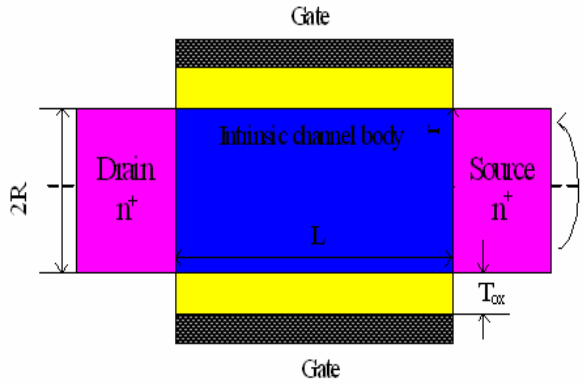

Fig.1 Diagram and coordinate of a undoped surrounding-gate MOSFET device.

. Following the gradual-channel-approximation (GCA), Poisson's equation takes the one-dimensional (1-D) form:

$$\frac{d^2\phi}{dr^2}+\frac{1}{r}\frac{d\phi}{dr}=\frac{kT}{qL_i^2}e^{\frac{q(\phi-V)}{kT}} \tag{1}$$

Where all symbols have common physics meanings as shown in [3-6]

n_i is the silicon intrinsic carrier concentration ($1.14\times10^{10}\,cm^{-3}$ at room temperature).

n_0 is the induced carrier concentration at the reference coordinate point (at the center of the silicon channel in this study).

$\Delta\phi_i$ is the work function difference between the gate and the channel silicon body.

V is the quasi-Fermi-potential with $V_{ch}=0$ at the source end and $V_{ch}=V_{ds}$ at the drain.

$L_i^{-2}=q^2n_i/kT\varepsilon_{si}$ is the square of the intrinsic silicon Debye length.

Equation (1) satisfies the following boundary conditions at the surface and centric point for the cooridate choice with the origin point at the silicon film middle:

$$\left.\frac{d\phi}{dr}\right|_{r=0}=0,\quad \phi|_{r=R}=\phi_s,\quad \phi|_{r=0}=\phi_0 \tag{2}$$

Then equation (1) can be analytically solved yielding [4-6]:

$$\phi_s=\phi_0-\frac{2kT}{q}\ln\left[1-\frac{R^2}{8L_i^2}\exp\left[\frac{q(\phi_0-V)}{kT}\right]\right] \tag{3}$$

and

$$\left.\frac{d\phi}{dr}\right|_{r=R}=\frac{RkT}{2qL_i^2}\frac{\exp\left[\frac{q(\phi_0-V)}{kT}\right]}{\left[1-\frac{R^2}{8L_i^2}\exp\left[\frac{q(\phi_0-V)}{kT}\right]\right]} \tag{4}$$

From Gauss's law, the following relation exsits between the charge, potential and the gate volgage:

$$C_{ox}(V_{gs}-\Delta\varphi-\phi_s)=Q=\varepsilon_{si}\left.\frac{d\phi}{dr}\right|_{r=R} \tag{5}$$

Where $C_{ox}=\frac{\varepsilon_{ox}}{R\ln(1+t_{ox}/R)}$ and $\Delta\varphi$ is the work-function difference.

Substituting the resuklts from (3) and (4) into (5) leads to

$$C_{ox}(V_{gs}-\Delta\varphi-\phi_s)=\frac{\sqrt{2}\varepsilon_{si}kT}{qL_i}\exp\left[\frac{q(\phi_s-V)}{2kT}\right]\sqrt{1-\exp\left[-\frac{q(\phi_s-\phi_0)}{2kT}\right]} \tag{6}$$

Moreover, substituting (3) into (6) leads to

$$C_{ox}(V_{gs}-\Delta\varphi-\phi_s)=\frac{R\varepsilon_{si}kT}{2qL_i^2}\exp\left[\frac{q(\phi_s+\phi_0-2V)}{2kT}\right] \tag{7}$$

From (7), we obtain the centric potential expression:

$$\phi_0=2V-\phi_s+\frac{2kT}{q}\ln\left[\frac{2L_i^2C_{ox}q(V_{gs}-\Delta\varphi-\phi_s)}{R\varepsilon_{si}kT}\right] \tag{8}$$

Then (8) is submitted to (3), so we have

$$\frac{q(V_{gs}-\Delta\varphi-\phi_s)e^{-\frac{q(\phi_s-V)}{kT}}}{kT}\left[\frac{1}{R}+\frac{qC_{ox}(V_{gs}-\Delta\varphi-\phi_s)}{4\varepsilon_{si}kT}\right]=\frac{\varepsilon_{si}}{2L_i^2C_{ox}} \tag{9}$$

(9) is a fully rigorous surface potential-voltage equation of the SRG MOSFETs [4], which can be solved by the Newton–Raphson (NR) method to get the accurate surface potential value. In order to test the analytic surface potential model, we have compared the result of (9) prediction for long-channel SRG-MOSFETs with the numerical simulation from DESSIS-ISE®. We have assumed a channel length (L) of 1 μm, silicon oxide thickness (t_{ox}) of 2 nm, and a mid-gap gate structure. A constant effective mobility of 400 cm^2/V-s has been used for calculations both in the model and in the simulation..

To apply (9) to current and charge modelling, ϕ_s needs to be evaluated at the source (y=0) and drain (y=L) ends with $V=0$ and $V=V_{ds}$, respectively. The results are separately labelled as $\phi_s=\phi_{SS}$ and $\phi_s=\phi_{SL}$. Fig.2 shows the surface potential versus gate voltage curves calculated from (9) for the source and drain ends, compared with the 3-D simulation. The solution given by (9) is continuously and smoothly valid for all regions of the SRG-MOSFET operation. It is found that the results from (9) shows in an agreement with the 3-D simulation in all operation regions for both the source and drain potentials. Fig.3 plots the comparison of the inversion charge density between the model prediction and the 3-D simulation for different silicon body radii. It is observed from Fig.3 that the agreement between the model and simulation is very good. In addition, the sub-threshold charge increases with the increase of the silicon radius. A unique "volume inversion effect", is also predicted from the presented model, coinciding with non-classical MOSFET device physics.

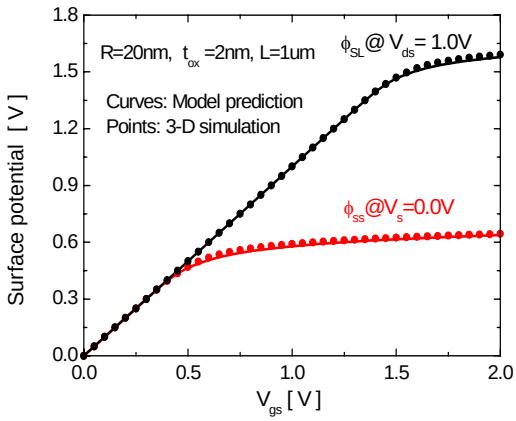

Fig.2. Comparison of source and drain end surface potentials obtained from (9) (solid lines) compared with the 3-D numerical result (points).

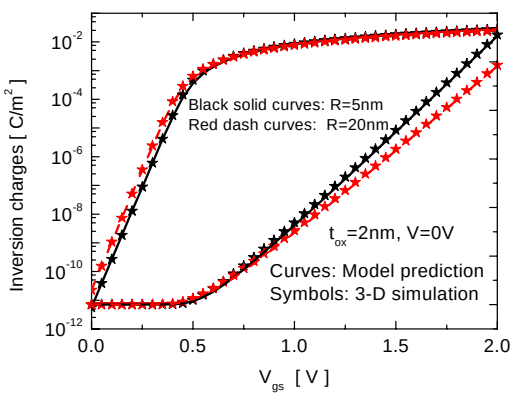

Fig.3. Inversion charge characteristics obtained from (5) (solid and dash lines) based on calculated surface potential, compared with the 3-D numerical simulation (points).or a given V_{gs}, ϕ_s can be solved from (9) as a function of V.

Note that V varies from the source to the drain. The functional dependence of $V(y)$ and ϕ_s (y) is determined by the current continuity equation. From the Pao-Sah's dual integral [10], integrating $I_{ds}dy$ from the source to the drain and expressing dV/dy as $(dV/d\phi_s)(d\phi_s/dy)$, the non-charge-sheet drain current of the SRG-MOSFETs is written as

$$I_{ds} = \mu \frac{2\pi R}{L} \int_0^{V_{ds}} Q(V)dV = \mu \frac{2\pi R}{L} \int_{\phi_{ss}}^{\phi_{SL}} Q(\phi_s) \frac{dV}{d\phi_s} d\phi_s \tag{10}$$

Where ϕ_{SS} , ϕ_{SL} are the solutions to (9) corresponding to V=0 and V=V_{ds} respectively. The parameter μ is the effective mobility. By using (9) and replacing it into $Q = C_{ox}(V_{gs} - \Delta\varphi - \phi_s)$, the total mobile charge per unit gate area expressed in terms of ϕ_s yields $Q(\phi_s)$. Note that $dV/d\phi_s$ can also be expressed as a function of ϕ_s by differentiating (9). Substituting these factors in (10), we have

$$I_{ds} = \frac{2\pi R\mu C_{ox}}{L} \int_{\phi_{SS}}^{\phi_{SL}} \left[(V_{gs} - \Delta\varphi - \phi_s) + \frac{2kT}{q} - \frac{kT}{q}\left(1 + \frac{C_{ox} qR(V_{gs} - \Delta\varphi - \phi_s)}{4\varepsilon_{si} kT}\right)^{-1} \right] d\phi_s \tag{11}$$

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

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

3 RESULTS AND DISCUSSION

From (12), the SRG-MOSFET drain current can be easily computed. In the following, the SRG-MOSFET operation regions are derived from this continuous surface potential-based analytical model:

(i) Linear region above threshold: In this region the drift current component dominates the device performance. Hence, we observe that the total drain current can be approximated by first two terms only above the threshold as shown in (13).

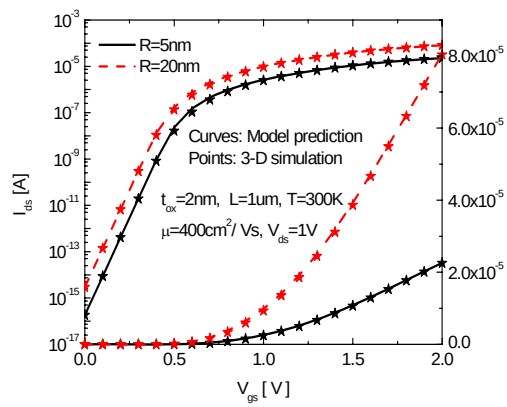

Fig. 4 Transfer characteristics obtained from the surface potential-based model for two silicon film radius (solid and dashed lines), compared with numerical simulations from DESSIS-ISE® (points).

$$I_{ds} \approx \frac{2\pi R\mu C_{ox}}{L} \left[(V_{gs} - \Delta\varphi)(\phi_{SL} - \phi_{SS}) - \frac{1}{2}(\phi_{SL}^2 - \phi_{SS}^2) \right] \tag{13}$$

This current expression is just the drift component of the traditional surface potential-based bulk MOSFET models, thus dominates in the strong inversion region;

(ii) Subthreshold region: Below threshold the SRG MOSFET current picture has a little difference from the bulk MOSFET model. Here, the first two components are negligible in this region. As a result, the total drain current is described by

$$I_{ds} \approx \frac{2\pi R\mu C_{ox}}{L} \left[\frac{2kT}{q}(\phi_{SL} - \phi_{SS}) + \left(\frac{kT}{q}\right)^2 \frac{4\varepsilon_{si}}{RC_{ox}} \ln\left[\frac{4\varepsilon_{si} kT + C_{ox} qR(V_{gs} - \Delta\varphi - \phi_{SL})}{4\varepsilon_{si} kT + C_{ox} qR(V_{gs} - \Delta\varphi - \phi_{SS})} \right] \right] \tag{14}$$

This drain expression can be simplified into:

$$I_{ds} = \mu \frac{\pi R^2}{L} n_i kTe^{\frac{q(V_{GS}-\Delta\varphi)}{kT}} \left(1 - e^{\frac{-qV_{DS}}{kT}}\right) \quad (15)$$

The sub-threshold current in (15) is proportional to the cross-section area of the SRG-MOSFET and independent of t_{ox}. This is a characteristic of the volume inversion effect that cannot be captured by the standard charge-sheet based models;

(iii) Saturation region: This regime occurs when the contribution of the drain end is little to the drain current. Hence, the drain current is expressed as

$$I_{ds} = \mu \frac{\pi R}{L} (Q_S + \frac{4C_{ox}kT}{q})(\phi_{SL} - \phi_{SS}) \quad (16)$$

The saturation current mainly depends on the source inversion charge density as expected for a bulk MOSFET.

In order to verify the presented drain current model, the comparison of drain current curves between the model prediction and the 3-D simulation is also completed as done for the surface potential and inversion charge. Fig.4 shows the SRG-MOSFET transfer curves and Fig.5 plots the SRG-MOSFET output curves, calculated from the surface potential-based model and the 3-D numerical simulation. Again, good agreement is observed without using any fitting parameter in both figures. Especially, the volume inversion effect of SRG-MOSFET demonstrated in Fig.4 is well described by the presented model, matching the 3-D numerical simulation.

4 CONCLUSIONS

In summary, we have presented an analytical surface potential-based non-charge-sheet core model current-voltage model suitable for compact modeling of undoped (lightly doped) SRG-MOSFETs. All the operation regions and the transitions are correctly described by preserving the physics. In particular, the volume inversion effect, that cannot be captured by using the traditional charge-sheet approximation, is well accounted of in this model.

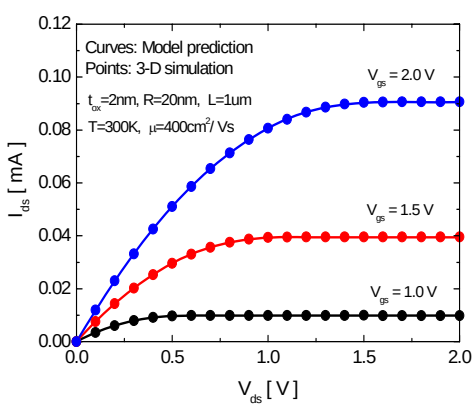

Fig.5 Output characteristics obtained from the surface potential model (solid lines) compared with numerical simulations from DESSIS-ISE® (points).

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