Analytic Potential Solution for Modeling the Symmetric DG Accumulation Mode MOSFETs

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ABSTRACT

This paper presents a potential model for symmetrical DG accumulation mode MOSFETs. The proposed model is derived from complete 1-D Poisson-Boltzmann equation and takes three components of net charge density (fixed charge, holes and electrons) into account. This model provides a smooth potential solution from subthreshold to accumulation regions. The solved potentials are verified by numerical results for various bias condition and different structure parameters. In order to model short channel effects like CLM and DIBL, a linear shift in flatband voltage using a fitting parameter is included. The presented potential solution provides the framework of a physically-based DG AMOSFET compact model for circuit simulation.

Keywords: symmetric DGMOSFET, analytic potential model

1 INTRODUCTION

As the continuous scaling down of integrated circuits calls for aggressive demand to conventional devices, novel devices are gaining attention for their potential to become an alternative to traditional counterparts. Among them, accumulation mode MOSFETs (AMOSFETs), which shows their merits including higher transconductance [1], lower vertical field [2], lower sensitivity to oxide thickness variations [2] and better short channel effects like CLM and DIBL, are under study in a wide range. Device fabrication and tests have been conducted using SOI and nanowire (NW) AMOSFETs. The experimental data is in favor of the advantages of AMOSFETs aforementioned. Simulation results by numerical simulator like TCAD are also verified [4]. However, previously published analytic models on AMOSFETs failed to account for all three terms, namely fixed charge and minority carriers, thus introduce inaccuracy in the subthreshold region for doped devices. R. Muruli provided short channel modeling of bulk AMOFETs in the subthreshold region and performed analysis on threshold voltage rolling off, with only fixed charge considered [7]. This model can only be used to analyze device performance in subthreshold and is not able to predict saturation current.

To build a current model which can provide accurate simulation results both in subthreshold and saturation region, it is necessary to solve complete Poisson-Boltzmann equation to obtain potential distribution in advance. This paper aims to provide such a potential model taking fixed charge, electrons and holes into account for symmetrical DG AMOSFETs, as the prerequisite to current model. The calculation method is described in detail in Section II. Section III presents simulated potentials provided by the proposed model and verified them with numerical results and Section IV concludes the whole paper.

2 POTENTIAL MODEL

For p-type symmetric DG structure, the general 2-D Poisson-Boltzmann equation can be written as:

\[ \frac{d^2 \psi}{dx^2} + \frac{d^2 \psi}{dy^2} = \frac{qN_d}{\epsilon} \left[ 1 - e^{\beta(V_{sd} - \psi)} + e^{\beta(V_g - 2\psi)} \right] \]  (1)

With the boundary condition given by:

\[ \frac{d\psi}{dx}\bigg|_{x=0}, \frac{d\psi}{dy}\bigg|_{y=\frac{L}{2}} = \frac{C}{\epsilon} (V_{sd} - V_D - \psi) \]

In this paper, the x-axis and y-axis are chosen to be normal to and along the channel direction, respectively. The x-coordinate of the center of channel is set to 0 while the surface’s is ±twa/2.

To simplify, Gradual-Channel-Approximation (GCA) where electrical field along y-direction can be neglected is adopted, making the 2-D equation to 1-D form as:

\[ \frac{d^2 \psi}{dx^2} = \frac{qN_d}{\epsilon} \left[ 1 - e^{\beta(V_{sd} - \psi)} + e^{\beta(V_g - 2\psi)} \right] \]  (2)

To accurately model the I-V characteristics for DG AMOSFETs, any of the three terms of the right hand side of Eq.(2) should not be neglected. However, to the author’s knowledge, no analytic solution to Eq.(2) has been found yet. Previously published papers on AMOSFETs either used a regional method with smooth function [8] or neglected fixed charge (substrate doping) to obtain an analytic solution [5-6].

For a given bias voltage, only surface potential \( \psi_s \) and central potential \( \psi_0 \) at both source and drain end are important to model drain current in AMOSFETs. Considering this fact, we proposed the following method to obtain \( \psi_s \) and \( \psi_0 \) as the function of \( V_{sd} \) and \( V_{g,t} \).

Multiplying both side of Eq.(2) with 2d\psi, and integrating from \( x = \theta \) to \( x = \theta/2 \) gives:

\[ 2d\psi \int_{\theta}^{\theta/2} d\theta = \frac{qN_d}{\epsilon} \left[ 1 - e^{\beta(V_{sd} - \psi)} + e^{\beta(V_g - 2\psi)} \right] \]
Thus the integrating can be done by a series of iteration \[10\] local approximation to obtain a solution with acceptable error.

Using a numerical method. However, it is possible to adopt the channel.

Equation is needed. Integrating Eq.(1) from \(x = 0\) to \(x = t_x/2\) twice gives;\[9\]

\[
\psi_0 = \psi_{o} + \frac{qN_x t_x^2}{8e} \int_0^{t_x} \int_0^{x'} \left[ 1 - e^{\beta(x-x')} + e^{\beta(x-x')-2x'} \right] dx' dx
\]

Where \(x' = 2x/t_x\) is normalization of vertical position in the channel.

The integrating in Eq.(5) can not be conducted unless using a numerical method. However, it is possible to adopt the local approximation to obtain a solution with acceptable error. Thus the integrating can be done by a series of iteration \[10\].

The iteration starts from a rough approximation: \(\psi \approx \psi_0\). By Substituting \(\psi\) with \(\psi_0\) in Eq.(5) and integrating, a better approximation is given by:

\[
h = \beta \frac{qN_x t_x^2}{8e} \left[ 1 - e^{\beta(x-x')} + e^{\beta(x-x')-2x'} \right]
\]

Repeating the substituting and integrating again gives an even more accurate approximation that:

\[
\psi_0 = \psi_{o} + \frac{qN_x t_x^2}{8e} \left[ 1 - S_x e^{\beta(x-x')} + 2S_x e^{\beta(x-x')-2x'} \right]
\]

Where \(S_x = \sum_{n=0}^{\infty} (-h)'(2n+1)(2n+2)\) and \(S_0 = \sum_{n=0}^{\infty} h'(2n+1)(2n+2)\).

It is obvious that further iteration makes the solution more precise but requires more a complex expression and longer computing time. As simulation results indicate that Eq.(6) is enough for provide good agreement with numerical solutions shown in Section III, iteration is ended at Eq.(6).

By solving the equation group consists of Eq.(4) and Eq.(6) using Newton-Raphson (NR) method, a continuous and smooth potential solution is obtained. In this paper, an analytic potential solution \[5\] taking only majority carrier into account is used as the initial guess for \(\psi_x\) and \(\psi_0\). Then \(\psi_0\) is updated by Eq.(6) using first-order NR method. After that, \(\psi_x\) is updated by Eq.(4) using second-order NR method. This loop continues until both \(\psi_x\) and \(\psi_0\) convergence.

### 3 SIMULATION RESULTS

In this section, a numerical simulator to solve for static potential in DG AMOSFETS is used to verify the surface potential \(\psi_x\) and central potential \(\psi_x\) obtained with the method described in Section II. This numerical simulator solves 1-D Poisson-Boltzmann Equation with its boundary condition using central difference method (CDM). If not specified, a mid-gap gate electrode is assumed, so that:

\[
V_x = \phi_m = kT \ln \frac{N_i}{q n_i}
\]

Fig.1 presents \(\psi_x\) and \(\psi_0\) obtained from solution to Eq.(4) and Eq.(6) and compares the potential with numerical results. From Fig.1, good agreement is achieved for \(\psi_x\) and \(\psi_0\) in all regions (from accumulation to inversion). There are slight differences between \(\psi_0\) curves between numerical results at strong accumulation or inversion regions, which come from the approximations made in Eq.(6). However, such small error in \(\psi_0\) only brings little inaccuracy to drain current in the simulation.

For varying structure parameters like \(T_{si}\) and \(T_{ox}\), Fig.2 and Fig.3 present corresponding potential obtained as a function of applied gate voltage \(V_{gs}\) with numerical results (dots) for symmetric DG AMOSFETS. The thickness of silicon film is 20nm, and the thickness of oxide layer is 2nm. Channel doping ranges from \(10^{11}\)cm\(^{-3}\) (intrinsic) to \(10^{17}\)cm\(^{-3}\).

Fig 1: Comparison of calculated (lines) surface potential \(\psi_x\), (a) and central potential \(\psi_x\) (b) at various applied gate voltage \(V_{gs}\) with numerical results (dots) for symmetric DG AMOSFETS. The thickness of silicon film is 20nm, and the thickness of oxide layer is 2nm. Channel doping ranges from \(10^{11}\)cm\(^{-3}\) (intrinsic) to \(10^{17}\)cm\(^{-3}\).

For varying structure parameters like \(T_{si}\) and \(T_{ox}\), Fig.2 and Fig.3 present corresponding potential obtained as a function of applied gate voltage. In typical situations, terms including \(\psi_x\) in Eq.(4) can be neglected, so \(\psi_x\) largely depends on the solution of the following equation:

\[
[C_{ov}(V_{gs} - V_{o} - \psi_x)]^2 = 2eN_x \left[ \frac{1}{\beta} e^{\beta(x-x')} + \frac{1}{\beta} e^{\beta(x-x')-2x'} \right]
\]

Further simplification can be achieved by neglecting fixed charge and electrons in accumulation region that:

\[
C_{ov}(V_{gs} - V_{o} - \psi_x) = \sqrt{2eN_x \frac{1}{\beta} e^{\beta(x-x')}}
\]

\(T_{si}\) does not have direct influence on the constants.
appeared in Eq.(8). As a result, $T_{si}$ has little control over $\psi_s$, which can be verified by Fig.2(a) where surface potential for different $T_{si}$ overlap. On the contrary, the solution of Eq.(8) is affected by $T_{si}$ for the reason that gate capacity $C_{ox}$ follows the change in $T_{si}$. For thinner $T_{si}$, $C_{ox}$ increases, leading to an increment in the exponential term and causing $\psi_s$ to be more negative. This tendency can be observed from Fig.3(a).

Both Fig.2 and Fig.3 can be understood from a more physical angle. In the accumulation region, $\psi_s$ is fixed for the same reason that $\psi_s$ is fixed in the vicinity of $2\psi_s$ in strong inversion. And thicker $T_{si}$ tends to lower the electrical field in the channel, resulting in decreasing $\psi_s$.

Similar analysis on Eq.(6) can account for changes in $\psi_s$.

By neglecting fixed charge and electrons in accumulation region, Eq.(6) transform to:

$$\psi_s = \psi_s \frac{qN_e}{4\epsilon} - \frac{e^{(V_{gs} - \psi_s)} \sum_{x=0}^{n-1} (-h)^n}{n!(2n + 1)(2n + 2)}$$  \hspace{1cm} (9)

Where $h = -\beta qN_e t_e^2 e^{(V_{gs} - \psi_s)} / 8\epsilon$.

When $T_{si}$ increases, $\psi_s$ does not change, so the right hand side of Eq.(9) should stay the same, causing $\psi_s$ to be more positive. This tendency is verified by Fig.2(b).
assumed in derivation of Eq.(2-6), the proposed model fails to account for short channel effects like Channel Length Modulation (CLM) and Drain Induced Barrier Lower (DIBL). But with a linear shift in the flatband voltage $V_{fb}$ proportional to the channel potential $V_{ch}$ adopted [8, 11], this model can thus account for both CLM and DIBL. An empirical constant $K$ is used and now $V_{fb}$ is given by $V_{fb} = V_{gs} - K \times V_{ch}$, where $V_{gs}$ denotes the flatband voltage at $V_{ch} = 0$.

Fig.6 presents simulation results for $K$ with different values. Both $\psi_s$ and $\psi_0$ no longer saturate even at high $|V_{ch}|$, but continue to be more negative, which would result in finite output resistance in the saturation.

4 CONCLUSION

In this work, a potential model for symmetric DG AMOSFETs taking both fixed charge and mobile carriers is proposed. Verification is done by comparing the model to numerical results for devices with different structure parameters and various bias conditions. Good agreement is achieved for all situations, which demonstrates the accuracy of the proposed model. Moreover, a fitting constant $K$ is introduced to the model to account for CLM and DIBL. This potential model can be served to calculate accurate surface potential and central potential needed for drain current model which will be reported in another work.

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