Compact Modeling for Inversion Charge in Nanoscale DG-MOSFETs*

Li Meng† and Yu Zhiping

(*Institute of Microelectronics, Tsinghua University, Beijing* 100084, *China*)

Abstract: A compact model for the integrated inversion charge density Q_i in double-gate (DG-) MOSFETs is developed. For nanoscale applications, quantum confinement of the inversion carriers must be taken into account. Based on the previous work of Ge, we establish an expression for the surface potential with respect to Q_i, and form an implicit equation, from which Q_i can be solved. Results predicted by our model are compared to published data as well as results from Schred, a popular 1D numerical solver that solves the Poisson's and Schrödinger equations self-consistently. Good agreement is obtained for a wide range of silicon layer thickness, confirming the superiority of this model over previous work in this field.

Key words: compact model; quantum confinement effect; double-gate MOSFETs
EEACC: 2560R; 2560B
CLC number: TN386.1 **Document code**: A **Article ID**: 0253-4177(2007)11-1717-05

1 Introduction

As the feature size of bulk MOSFETs continues to shrink, serious technical and economical hurdles have been encountered[1], necessitating new device structures that can provide improved device performance. A double-gate MOSFET is considered a promising structure due to its excellent short channel effect (SCE) immunity, near-ideal subthreshold slope, increased inversion charge density, and beneficial transport characteristics resulting from the volume inversion.

Recently, compact modeling of DG MOSFETs has attracted a great deal of interest. The integrated inversion charge density across the channel, Q_i, is a key physical quantity, and on its basis, device characteristics, such as the *I-V* and *C-V* curves, can be obtained. Thus, modeling Q_i is the first step, and a key one, in device modeling.

In Ref. [1], Baccarani proposed a model, in which the quantum-mechanical confinement of carriers in DG MOSFETs is considered. This work is based on two assumptions. One is the box-like potential, which considers only the structural confinement caused by the front- and back-gate oxide, neglecting electrical confinement due to the transverse gate electric field. The other assumption is the uniform inversion charge distribution within the channel when calculating the depletion capacitance. These two assumptions limit applications of this method to only ultra-thin silicon film and/or low gate bias conditions. For thick silicon films and high gate-bias, large errors occur.

He[2] presented a classical analytical model for undoped symmetric DG MOSFETs. Since quantum-mechanical effects are not considered in his work, significant errors result when compared to the more accurate numerical simulations for thin silicon films where quantum-mechanical effects cannot be neglected.

Ge[3] developed a quantum-mechanical model for symmetric DG-MOSFETs. The structural and electric-field confinements are both taken into account. Although it gives excellent physical insight into the device physics, this model does not account for the inversion charge density calculation.

Our work is based on Ref. [3]. By relating the surface potential to Q_i, an implicit equation is established. Solving this equation for Q_i, we obtain results that agree well with those of the numerical simulator Schred[4] for arbitrary silicon film thickness.

* Project supported by the NEDO of Japan and the State Key Development Program for Basic Research of China (No. 2006CB302700)
† Corresponding author. Email: limeng04@mails.tsinghua.edu.cn
Received 19 March 2007, revised manuscript received 21 July 2007

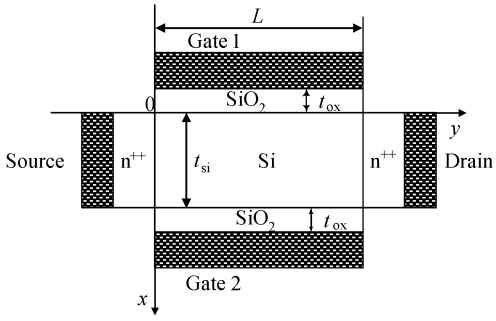

Fig. 1 Schematic of a symmetric DG MOSFET

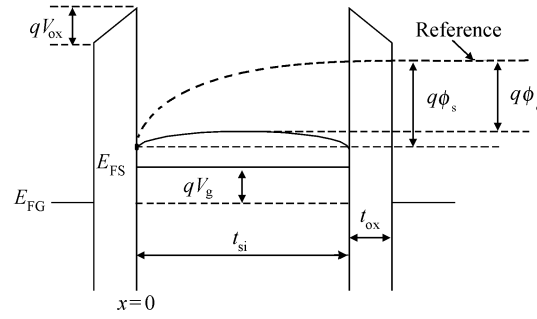

Fig. 2 Schematic of the band curvature in the direction normal to the channel for a DG MOSFET

2 Description of modeling approach

Figure 1 shows the schematic of a symmetric DG MOSFET. We first try to establish an implicit equation for Q_i. Considering the quantum confinement of carriers in the direction normal to the channel, the coupled Poisson's and Schrödinger equations have to be solved. For the computational efficiency that is required in compact modeling, proper approximation can be adopted to decouple the two equations. Here we take the Schrödinger equation as the starting point, and are concerned only about the ground state in the carrier distribution.

Using a similar approach to that in Ref. [3], the 1D trial eigenfunction in the x-direction, which is transverse to the channel, can be written as

$$\Psi_j(x) = \frac{a_j}{2}\sqrt{\frac{2}{t_{si}}}\sin\left(\frac{(j+1)\pi x}{t_{si}}\right)\times \left(e^{-b_j x/t_{si}} + e^{-b_j(t_{si}-x)/t_{si}}\right), \quad j = 0,1,2,\cdots \tag{1}$$

where b_j is a parameter dependent upon the transverse electric field E_x at the interface between the silicon and the gate oxide, a_j is the normalization factor as shown below, and t_{si} is the thickness of the silicon film.

$$b_j \cong t_{si}\left(\frac{qm_x\pi^2\left(qN_A t_{si} + \frac{5}{6}Q_i\right)}{(j+1)\varepsilon_{si}\hbar^2}\right)^{1/3}, j=0,1,2,\cdots \tag{2}$$

$$a_j = \frac{2}{\sqrt{2e^{-b_j} + \frac{[(j+1)\pi]^2(1-e^{2b_j})}{b_j[b_j^2 + ((j+1)\pi)^2]}}} \tag{3}$$

The electron distribution is approximated by considering the eigenfunction at the ground level only. This simplification has been justified in Ref. [3], and by solving the 1D Poisson's equation,

$$\frac{d^2}{dx^2}\phi(x) = \frac{q}{\varepsilon_{si}}(N_A + n(x)) = \frac{q}{\varepsilon_{si}}\left(N_A + \frac{Q_i}{q}|\Psi_0(x)|^2\right) \tag{4}$$

$\phi(x) - \phi_s$ can be expressed as the function of Q_i, where the surface potential $\phi_s = \phi(0)$. Note that the ground-level wavefunction, $\Psi_0(x)$, has been normalized across the channel.

In Ref. [5], the inversion charge density is related to the gate voltage and the central potential of the silicon film via the following equation:

$$Q_i = 2C_{Gf}(V_g - V_{tf}) \tag{5}$$

with

$$C_{Gf} = \frac{C_{ox}}{1 + \frac{\varepsilon_{ox}}{\varepsilon_{si}}\times\frac{x_i}{t_{ox}}} \tag{6}$$

$$V_{tf} = \Phi_{MS} + \phi_c + \frac{qN_A t_{si}}{2C_{ox}}\left(1 + \frac{C_{ox}}{4C_{si}}\right) \tag{7}$$

where $C_{ox} = \varepsilon_{ox}/t_{ox}$, $C_{si} = \varepsilon_{si}/t_{si}$, Φ_{MS} is the contact potential difference between the gate and the silicon film due to the workfunction difference, and $\phi_c = \phi(t_{si}/2)$ is the central potential of the silicon film referenced to the neutral body as shown in Fig. 2. That is when the center of the silicon remains neutral (e.g., at the flatband condition), $\phi_c = 0$. And x_i is the centroid of the half inversion layer, which can be defined as

$$x_i = \frac{\int_0^{t_{si}/2} xn(x)dx}{\int_0^{t_{si}/2} n(x)dx} = \frac{\int_0^{t_{si}/2} xQ_i|\Psi_0(x)|^2dx}{Q_i/2} = 2\int_0^{t_{si}/2} x|\Psi_0(x)|^2dx \tag{8}$$

By substituting Eqs. (1~3) into Eq. (8), x_i can be related to Q_i.

Note that ϕ_c in Eq. (7) is undetermined, and if this quantity can be related to Q_i, then substituting Eqs. (6)~(8) into Eq. (5), an implicit equation

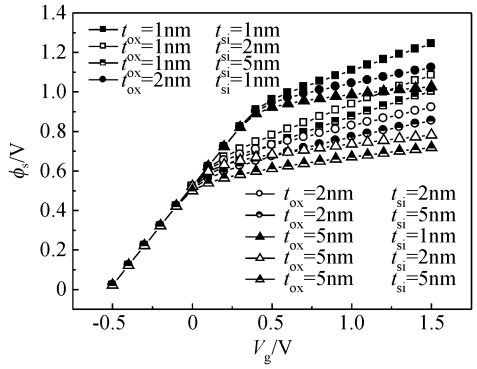

Fig. 3　Simulated surface potential ϕ_s versus gate bias using Schred　The device parameters are t_{ox} = 1nm, t_{si} = 1, 2, 5nm, and N_A = 1cm^{-3} (undoped case).

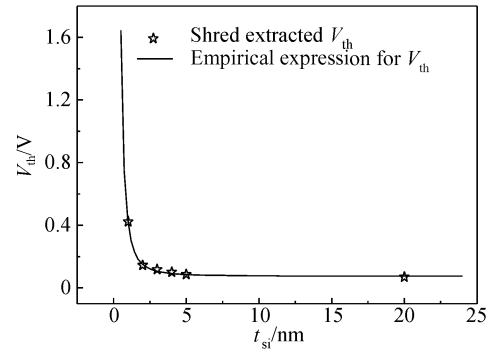

Fig. 4　V_{th} predicted by the empirical expression with respect to t_{si} (solid line)　The Shred extracted data are marked as symbols. t_{ox} = 1nm.

on Q_i will be established. Since $\phi_c - \phi_s$ can be obtained by integrating Eq. (4) twice, the subsequent work is to find an expression of ϕ_s in terms of Q_i.

Figure 3 shows the simulated ϕ_s versus the gate voltage using Schred at different t_{si}, t_{ox} and doping density N_A. From the figure, we note that in the subthreshold and strong inversion regions, ϕ_s is linearly dependent on V_g. And the threshold voltage V_{th} can be defined as the intersection of the two extrapolated lines.

For simplicity, here we consider only the undoped case.

$$\phi_s + V_{ox} = V_g - \Phi_{MS}$$
$$\phi_s = V_g - \Phi_{MS} - Q_i/2C_{ox} \tag{9}$$

In the subthreshold region, $Q_i \approx 0$, so,

$$\phi_s = V_g - \Phi_{MS} \tag{10}$$

In the strong inversion region, ϕ_s can be written as

$$\phi_s = V_{th} - \Phi_{MS} + k(V_g - V_{th}) \tag{11}$$

Here k is the slope of the ϕ_s-V_g curve in strong inversion region. Substituting Eq. (5) into Eq. (9) and setting $N_A = 0$, we get

$$\begin{aligned}\phi_s &= V_g - \Phi_{MS} - Q_i/2C_{ox} \\ &= V_g - \Phi_{MS} - \frac{C_{Gf}}{C_{ox}}(V_g - \Phi_{MS} - \phi_c) \\ &= \left(1 - \frac{C_{Gf}}{C_{ox}}\right)(V_g - \Phi_{MS}) + \frac{C_{Gf}\phi_c}{C_{ox}}\end{aligned} \tag{12}$$

As verified in Ref. [5], for $t_{si} > 2.5$nm, $d\phi_c/dV_g \approx 0$. Comparing Eq. (11) to Eq. (12), we can conclude that for $t_{si} > 2.5$nm, $k = 1 - C_{Gf}/C_{ox}$.

For V_{th} in Eq. (11), we first collected enough data for certain t_{ox} with t_{si} ranging from 1 to 20nm from Shred, and then we constructed an empirical expression using t_{si} to fit the Schred-extracted results.

$$V_{th} = at_{si}^b + c \tag{13}$$

Using curve fitting tools, the fitting parameters a, b and c can be extracted.

Figure 4 shows the Shred extracted V_{th} for different t_{si} with t_{ox} = 1nm. The results predicted by Eq. (13) are also plotted in the same figure. With proper fitting parameters, Equation (13) fits the Shred data very well. Here a = 0.336, b = −2.419, and c = 0.8498 are used as the fitting parameters.

To create a smooth transition between subthreshold and strong inversion regions, we employ the smoothing function to obtain the unified expression of Eqs. (10) and (11).

$$\phi_s = V_{th}^* - \frac{V_{th}^*}{B}\ln\left(1 + e^{A\left(1 - \frac{(1-k)V_g}{V_{th}^*}\right)}\right) - \Phi_{MS} + kV_g \tag{14}$$

where $V_{th}^* = (1-k)V_{th}$, $B = \ln(1 + e^A)$, and A is a constant characterizing the steepness of the transition. A larger value of A represents a steeper transition as shown in Fig. 5. In our model, we set A = 1.

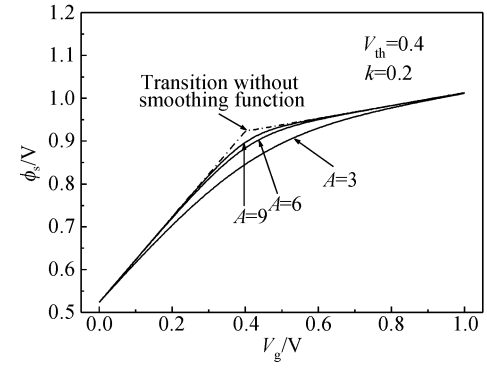

Fig. 5　Smoothing function with different values of A

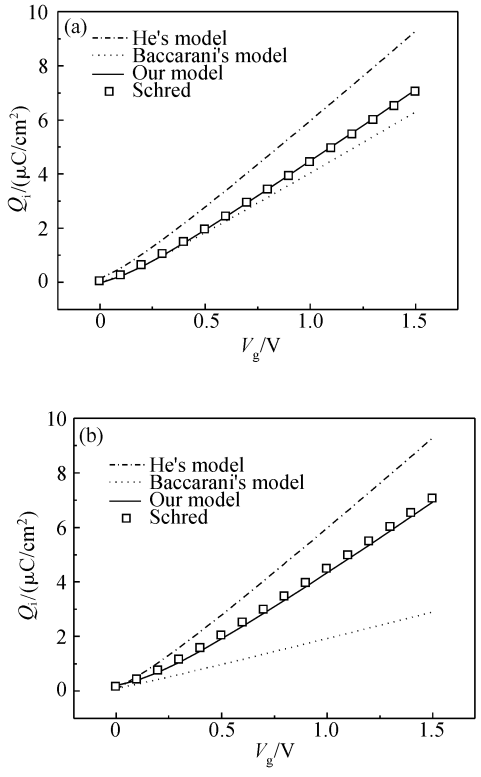

Fig. 6 Model-predicted inversion-charge density Q_i versus gate bias (solid line) (a) t_{ox} = 1nm, t_{si} = 4nm; (b) t_{ox} = 1nm, t_{si} = 20nm Schred-simulated results are marked as symbols and results from He's and Baccarani's models are also given for comparison.

Substituting Eq. (14) into Eq. (7), a complete implicit equation on Q_i is obtained. By solving this nonlinear equation, we can obtain the value of Q_i for any given V_g.

3 Model comparison and validation

To validate our model, we apply it to undoped symmetric DG MOSFETs with a gate oxide thickness ranging from 1 to 5nm and a silicon film thickness from 4 to 20nm. We compared the model-predicted inversion charge density with those obtained from the numerical solver Schred. Results calculated using He's and Baccarani's models are also included for comparison.

Figure 6 shows the three model-predicted inversion charge density and Schred-simulated results versus the gate bias with (a) $N_A = 1cm^{-3}$, t_{ox} = 1nm, t_{si} = 4nm and (b) t_{si} = 20nm. Note that He's model is the classical one, so it overestimates the inversion charge density in all cases presented. Baccarani's model has limited applications, providing good predictions only at low gate bias and in thin silicon film thickness conditions. Our model, on the other hand, is more general and agrees well with Schred results not only in thin silicon film conditions but also in relatively thick ones.

4 Summary

A quantum analytical model for the inversion charge density in undoped symmetric DG MOSFETs has been presented. By modeling the surface potential, referenced to the neutral body in all operation modes using a unified expression, a complete implicit equation for Q_i is established. Since both the structural and the transverse electric-field confinements have been taken into account, the model is accurate for both thin and thick silicon films and has excellent agreement with simulated results.

Acknowledgement The collaboration with NDMI members is greatly appreciated.

References

[1] Baccarani G, Reggiani S. A compact double-gate MOSFET model comprising quantum-mechanical and nonstatic effects. IEEE Trans Electron Devices, 1999, 46(8): 1656

[2] He J, Zhang X, Wang Y. A complete carrier-based non-charge-sheet analytic model for nano-scale undoped symmetric double-gate MOSFETs. Proceedings of IEEE Conference on Electron Devices and Solid-State Circuits, 2005: 247

[3] Ge L, Fossum J G. Analytical modeling of quantization and volume inversion in thin Si-film DG MOSFETs. IEEE Trans Electron Devices, 2002, 49(2): 287

[4] Schred 2.1 Tutorial. https://www. nanohub. org/tools/schred/

[5] Lopez-Villanueva J A, Catujo-Cassinello P, Gamiz F, et al. Effects of the inversion-layer centroid on the performance of double-gate MOSFET's. IEEE Trans Electron Devices, 2000, 47(1): 141

纳米尺度双栅 MOS 器件反型层电荷的集约建模*

李　萌†　余志平

（清华大学微电子学研究所，北京　100084）

摘要：建立了双栅 MOS 器件反型层积分电荷 Q_i 的集约模型.该模型考虑了反型层载流子的量子限制效应，使其适用于纳米尺度的器件应用.基于以前关于 Ge 的研究，通过建立关于 Q_i 的表面势表达式，可得到一个隐含 Q_i 的方程，从而求得 Q_i 的值.将该模型计算结果与目前已发表的模型计算结果以及自洽求解一维泊松方程和薛定锷方程的数值模拟程序 Schred 的模拟结果进行了比较.结果表明，该模型在较大的硅层厚度变化范围内均与数值模拟程序的计算结果吻合得很好，显示出其相对与目前发表的其他模型的优越性.

关键词：集约模型；量子限制效应；双栅 MOS 器件

EEACC：2560R；2560B

中图分类号：TN386.1　　**文献标识码**：A　　**文章编号**：0253-4177(2007)11-1717-05

* 日本 NEDO 基金和国家高技术研究发展基金资助项目（批准号：2006CB302700）

† 通信作者.Email：limeng04@mails.tsinghua.edu.cn

2007-03-19 收到，2007-07-21 定稿