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Citation: Journal of Applied Physics 116, 174507 (2014); doi: 10.1063/1.4901000

View online: http://dx.doi.org/10.1063/1.4901000

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A compact quantum correction model for symmetric double gate metal-oxide-semiconductor field-effect transistor

Edward Namkyu Cho, Yong Hyeon Shin, and Ilgu Yun

Department of Electrical and Electronic Engineering, 50 Yonse-ro, Seodaemun-gu, Yonsei University, Seoul 120-749, South Korea

(Received 19 September 2014; accepted 23 October 2014; published online 5 November 2014)

A compact quantum correction model for a symmetric double gate (DG) metal-oxide-semiconductor field-effect transistor (MOSFET) is investigated. The compact quantum correction model is proposed from the concepts of the threshold voltage shift (\(\Delta V_{TH}^{QM}\)) and the gate capacitance (\(C_g\)) degradation. First of all, \(\Delta V_{TH}^{QM}\) induced by quantum mechanical (QM) effects is modeled. The \(C_g\) degradation is then modeled by introducing the inversion layer centroid. With \(\Delta V_{TH}^{QM}\) and the \(C_g\) degradation, the QM effects are implemented in previously reported classical model and a comparison between the proposed quantum correction model and numerical simulation results is presented. Based on the results, the proposed quantum correction model can be applicable to the compact model of DG MOSFET.

I. INTRODUCTION

Over the past decades, metal-oxide-semiconductor field-effect transistor (MOSFET) technology has been drastically developed. However, the continuing downscaling of the conventional MOSFET has been interrupted by the growing portion of the short-channel effects.\(^{1,2}\) The multi-gate MOSFETs, such as double gate (DG) MOSFET\(^{3,4}\) and Tri-gate MOSFET\(^{5,6}\) (FinFET), have been considered to be candidates to extend the limitation of scaling capability of MOSFET. The key advantage of the multi-gate MOSFET is that it can better control channel charges than conventional MOSFET. Typically, the Si body thickness in FinFET is small compared to its height. The narrow FinFET can be approximated as a symmetric DG MOSFET.\(^{5,7}\) As the Si body thickness decreases, the quantum mechanical (QM) effects become crucial.

Due to the growing portion of the QM effects in DG MOSFET, several researchers studied on the QM effects. Previously, models of QM effects in conventional MOSFET,\(^{8}\) DG MOSFET,\(^{9}\) and FinFET\(^{10,16}\) have been reported. However, these models need to be solved numerically to calculate quantum inversion charges, which are not suitable for circuit simulation. To overcome these limitations, there have been some analytic models characterizing QM effects.\(^{11,12}\) These models had limited application on modeling quantum drain current (\(I_{DS}^{QM}\)). There were limited numbers of papers on compact modelling of \(I_{DS}^{QM}\) for DG MOSFET.\(^{13-15}\)

In this paper, we propose the compact quantum correction model for DG MOSFET. Before establishing the quantum model, we start from the classical drain current (\(I_{DS}^{CL}\)) model previously reported.\(^{16}\) From the \(I_{DS}^{CL}\) model, we implement the QM effects by applying the concepts of QM effects:\(^{14}\) (1) threshold voltage shift (\(\Delta V_{TH}^{QM}\)) and (2) gate capacitance (\(C_g\)) degradation. For the validation of proposed model, the simulation results from 1D SCHRED simulation\(^{17}\) and Silvaco 2D ATLAS simulation\(^{18}\) are used for comparison.

II. MODELING SCHEME

The schematic structure of a symmetric DG MOSFET used in our analysis is shown in Fig. 1, where \(L\) is the channel length, \(t_s\) is the channel film thickness, and \(t_{ox}\) is the gate oxide thickness. In addition, the points at \(x = 0\) and \(y = 0\) indicate the source-channel interface and the center of the channel, respectively. A uniform p-type doping concentration (\(N_A = 10^{15} \text{ cm}^{-3}\)) is assumed in the channel region. The source and drain regions are also assumed to be heavily doped with n-type doping concentration (\(N_D = 10^{20} \text{ cm}^{-3}\)) in this work.

To obtain the QM effects rigorously, the coupled Poisson and Schrödinger equations are needed to be solved self-consistently described as\(^\text{a,14,19}\)

\[
\begin{align*}
\n\end{align*}
\]
\[
\frac{d^2\psi(y)}{dy^2} = \frac{q}{\varepsilon_{si}} (n + N_A), \tag{1}
\]

\[- \frac{\hbar^2}{8\pi^2m^*} \frac{d^2\psi(y)}{dy^2} + (-q\psi(y))\psi(y) = E_{sub}\psi(y), \tag{2}
\]

where \(\psi, q, \epsilon_{si}, n, h, m^*, \phi, \) and \(E_{sub}\) are the channel potential, an electron charge, the silicon permittivity, the carrier concentration, Planck constant, the effective mass, the normalized wave function, and the subband energy, respectively.

To solve the coupled Poisson and Schrödinger equations, we use 1D SCHRED simulation\(^\text{17}\) which can self-consistently solve the Poisson and Schrödinger equations for QM effects. However, 1D SCHRED simulation has limited application on calculating the drain current. Thus, Silvaco 2D ATLAS simulation\(^\text{16}\) is then used for calculating the drain current.

### III. CLASSICAL DRAIN CURRENT MODEL

From our previous work,\(^\text{16}\) we use the expression of \(I_{DS}^{CL}\) (i.e., only considering inversion charges) followed as:

\[
I_{DS}^{CL} = \frac{W}{L} \mu_n t_{ox} \frac{q^2}{\varepsilon_{ox}} \left( C_S - C_D \right) + 2 \frac{W}{L} \mu_n t_{ox} v_t \left[ \ln(C_S - C_D) + \frac{qN_A}{2\varepsilon_{ox}} \ln \left( C_S - \frac{qN_A}{2\varepsilon_{ox}} \right) \right]
\]

\[- \ln \left( C_D - \frac{qN_A}{2\varepsilon_{ox}} \right) \]

\[- \frac{W}{L} \mu_n qN_A \left[ t_{ox} v_t \frac{2}{\varepsilon_{ox}} (C_S - C_D) + V_t \left[ \ln \left( C_S - \frac{qN_A}{2\varepsilon_{ox}} \right) - \ln \left( C_D - \frac{qN_A}{2\varepsilon_{ox}} \right) \right] \right], \tag{3}
\]

where \(W, \mu_n, \varepsilon_{ox},\) and \(v_t\) are the channel width, the electron mobility, SiO\(_2\) permittivity, and the thermal voltage, respectively.

\(C_S\) and \(C_D\) can be obtained by the following expression:

\[
2C = \frac{q}{\varepsilon_{si}} \left( N_A^2 \exp \left( \frac{V_{GS} - V_{fb} - \frac{t_{ox} v_t}{\varepsilon_{ox}} C_{CL} - V}{v_t} \right) + N_A \right), \tag{4}
\]

where \(n, V_{GS}, V_{fb},\) and \(V\) are the intrinsic carrier concentration of silicon, the gate-source voltage, the flat band voltage, and the electron quasi-Fermi potential, respectively. For a given \(V_{GS}\) and \(N_A, C\) can be solved as a function of \(V, C_S\) and \(C_D\) are the solutions of Eq. (4) when \(V = 0\) and \(V = \) drain-source voltage (\(V_{DS}\)), respectively.

The total charge density can be obtained from the Gauss’ Law described as

\[
Q = 2e_{si} \left. \frac{d\psi(y)}{dy} \right|_{y = \frac{t_{ox}}{2}} = Q_{inv} + Q_d = 2e_{si} t_{si} C, \tag{5}
\]

where \(Q_{inv}\) and \(Q_d\) are the inversion charge density and the depletion charge density (i.e., \(Q_d = qN_A t_{si}\)), respectively.

Fig. 2 shows the comparison of \(I_{DS}^{CL-V}_{GS}\) characteristics between the analytical model and ATLAS simulation with the variations of \(t_{si}\).

### IV. QUANTUM CORRECTION MODEL

In previous researches, the quantum inversion charge density \((Q_{inv}^{QM})\) is described as\(^\text{9,13,15}\)

\[
Q_{inv}^{QM} = q \sum_{n=1}^{N_s} N_s \ln \left( 1 + \frac{\exp \left( \frac{E_{nk} - E_F}{kT} \right)}{\exp \left( \frac{E_{nk} - E_F}{kT} \right) + 1} \right), \tag{6}
\]

where \(N_s, N_{inv}, N_k,\) and \(E_F\) are the number of subbands, the number of minima, the density of states in subband at energy \(E_{nk},\) and the Fermi energy, respectively. However, \(Q_{inv}^{QM}\) needs to be solved numerically which is not suitable for the compact model approach.\(^\text{9}\)

In order to implement the QM effects on our analytical model, we apply the concepts of previously reported QM effects:\(^\text{14}\) (1) \(\Delta V_{TH}^{QM}\) and (2) \(C_g\) degradation.

#### A. Threshold voltage shift

At first, we need to model \(\Delta V_{TH}^{QM}.\) In the subthreshold region, the inversion carriers are negligible which makes the DG MOSFET as an infinite square potential well.\(^\text{14,15}\) The subband energy of infinite square potential well can be analytically solved as

\[
E_{nk} = E_{c0} + \frac{(n\pi h)^2}{8\pi^2 m^* v_t}, \tag{7}
\]

where \(E_{c0}\) is the conduction band minimum energy.

We can obtain \(\Delta V_{TH}^{QM}\) from the shift of \(Q_{inv}^{QM} - V_{GS}\) curve with respect to the classical \(Q_{inv}^{CL-V}_{GS}\) curve. The charges in thin Si film which is important for modeling QM effects are mostly occupied by the lowest energy subband.\(^\text{11}\)

Therefore, \(\Delta V_{TH}^{QM}\) can be approximately expressed by only considering the lowest energy subband followed as:

\[
\Delta V_{TH}^{QM} = V_{TH}^{QM} - V_{CL}^{CL-V} = \left( E_{c0} + \frac{(n\pi h)^2}{8\pi^2 m^* v_t} \right) - E_{c0}
\]

\[
= \frac{(n\pi h)^2}{8\pi^2 m^* v_t}, \tag{8}
\]
where $V_{TH}^{QM}$ and $V_{TH}^{CL}$ are the threshold voltages ($V_{TH}$) of quantum and classical models, respectively. For silicon (100) crystal orientation, $m^* = 0.916m_0$ is used where $m_0$ is the electron mass.

Fig. 3 shows the comparison of $\Delta V_{TH}^{QM}$ obtained from the analytical model using Eq. (8) and SCHRED simulation. It is obvious that the approximation can well represent the $\Delta V_{TH}^{QM}$.

B. Gate capacitance degradation

Second, the $C_g$ degradation from QM effects needs to be modeled. The inversion charges are farther away from the SiO2/channel interface due to the quantum effects. So, the inversion layer thickness is increased resulting in the $C_g$ degradation. The $C_g$ in the DG MOSFET can be simply modeled as

$$C_g = \frac{1}{\varepsilon_{ox} + y_{inv}}$$

(9)

where $y_{inv}$ is the inversion layer centroid.

The inversion layer centroid indicates the average distance of the inversion carriers distribution and is defined as

$$y_{inv} = \frac{\frac{t_{si}}{2} \int n(y)dy}{\frac{t_{si}}{2} \int n(y)dy}.$$  

(10)

As can be seen from Eq. (10), $y_{inv}$ is an implicit function of the number of charge per unit area ($N_{inv}$) where $N_{inv} = Q_{inv}/q$. In order to obtain the $y_{inv}$ values with different device structures, the SCHRED simulation is used. We compare the classical $N_{inv}^{CL}$ calculated from our model in Eq. (5) and the SCHRED classical model as shown in Fig. 4. It is shown that our analytical model can well represent the $N_{inv}^{CL}$–$V_{GS}$ characteristics.

As mentioned previously, $y_{inv}$ is an implicit function and is difficult to be calculated by an analytical form. Therefore, we use a simple empirical relationship between $y_{inv}$ and $N_{inv}$ described as

$$C_g^{CL} = \frac{1}{\varepsilon_{ox} + y_{inv}}$$

(12)

$$C_g^{QM} = \frac{1}{\varepsilon_{ox} + y_{inv}}$$

(13)

Regarding the drain current is proportional to the $C_g$, we propose a simple quantum correction factor implementing the $C_g$ degradation which is different with the previously reported methods. The $C_g$ degradation can be simply modeled by defining the quantum correction $t_{ox} (t_{ox}^{QM})$ and it can be expressed by multiplying the ratio of ($C_g^{CL}/C_g^{QM}$) to $t_{ox}$ described as

$$t_{ox}^{QM} = t_{ox} \times \frac{C_g^{CL}}{C_g^{QM}}.$$  

(14)
The appropriateness of our proposed tox-QM will be demonstrated in Sec. IV C below.

C. Quantum drain current model

\( I_{DS}^{QM} \) can be simply calculated from our analytical model as follows:

1. Replace \( V_{fb} \) parameter in Eq. (4) indicating the threshold voltage shift described as

\[
V_{fb}^{QM} = V_{fb} + \Delta V_{TH}^{QM},
\]

(15)

2. Replace \( V_{fb} \) and \( t_{ox} \) parameters in Eq. (4) as

\[
V_{fb}^{QM} = V_{fb} + \Delta V_{TH}^{QM}, \quad t_{ox}^{QM} = t_{ox} + \frac{e_{ox} y_{inv}}{e_{si} y_{inv}^{CL}} + \frac{e_{ox} y_{inv}^{CL}}{e_{si} y_{inv}}.
\]

(16)

(17)

3. Calculate the quantum correction \( C_S (C_S^{QM}) \) and quantum correction \( C_D (C_D^{QM}) \) from (2).

4. Applying the calculated \( C_S^{QM}, C_D^{QM} \), and \( t_{ox}^{QM} \) to Eq. (3), \( I_{DS}^{QM} \) can be simply calculated.

It can be noted that if \( y_{inv}^{CL} \) goes to 0 in Eq. (17), the equation is identical to previously reported research.\(^{15}\) In Fig. 6, we compare the \( I_{DS}^{QM} - V_{GS} \) analytical modeling results with Silvaco 2D ATLAS numerical simulation and previously reported Lázaro et al.\(^{15}\) model results. Scatters, lines, and dashed lines represent the simulation, analytical model, and Lázaro et al. model results, respectively. It is shown that the previously reported model\(^{15}\) overestimates \( t_{ox}^{QM} \) resulting in less \( I_{DS}^{QM} \) than our analytical model. Our proposed model well represents the 2D numerical simulation result for all the ranges of \( t_{ox} \) thickness.

V. CONCLUSION

In this paper, the proposed compact quantum correction model for DG MOSFET was presented. At first, we modeled the threshold voltage shift induced by QM effects. \( \Delta V_{TH}^{QM} \) was calculated by only considering the lowest energy sub-band. The \( C_S \) degradation was then modeled by introducing the inversion layer centroid. Since the inversion layer centroid was difficult to be calculated by an analytical model, we proposed an empirical model. With \( \Delta V_{TH}^{QM} \) and the \( C_S \) degradation, we implemented the QM effects on our previously reported classical model. The results were compared with numerical simulation tools indicating that the proposed quantum analytical model well represented the numerical simulation results. Therefore, the proposed quantum correction model can be applicable to the compact model of DG MOSFET.
ACKNOWLEDGMENTS

This work was supported by the IT R&D program of MKE/KEIT, [10039174, Technology Development of 22-nm level Foundry Devices and PDK].

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