AN ANALYTICAL 2D MODEL FOR A SYMMETRIC DOUBLE GATE MOSFET CONSIDERING QUANTUM MECHANICAL EFFECTS

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\textbf{Abstract}: A simple and efficient model is presented to study the quantization effects in the inversion layer of symmetrical undoped Double-Gate (DG) nMOSFET. The analytical models of Quantum corrected potential and surface potential for undoped symmetrical double-gate (SDG) MOS devices are presented in this paper. The analytical models are derived under Gradual Channel Approximation (GCA) by solving the Poisson’s equation. The Poisson’s equation is used here instead of solving complex Schrodinger–Poisson’s equation. Quantum mechanical effect in ultrathin silicon film is studied by introducing quantum confinement parameter and quantum corrected potential in the Poisson’s equation. Quantum corrected potential attains its maximum value near the interface and minimum value at the centre of the silicon film. The surface potential is reduced due to quantum confinement effect.

\textbf{Keywords}: Symmetric double-gate (SDG), Gradual Channel Approximation (GCA), Quantum Mechanical Effects, Surface Potential.

\textbf{I. INTRODUCTION}

During the recent years, several technologies are proposed to keep up the scaling imposed by Moore’s law. Among these innovations are the introduction of new materials in the CMOS process, such as high-k dielectrics, metal gate electrodes and stressors that allow the build-up of mechanical stress in the silicon to increase carrier mobility. In addition to these material innovations, new transistor architectures have emerged. A silicon-on-insulator (SOI) transistor is one such example. SOI have been long known for their superior performance capabilities. Recently, one has witnessed an evolution of the SOI transistor from a classical, planar, single-gate architecture to a three dimensional structure with multiple gates (double-, triple- or quadruple-gate devices). Note that the term “double gate” refers to a single gate electrode that is present on two opposite sides of the device. The double-gate MOSFET is considered to be one of the most promising device structures to extend CMOS scaling in to the nanometre regime [1]. The key factors that limit how far a DG MOSFET can be scaled come from short-channel effects (SCEs) such as threshold voltage roll-off and drain-induced barrier lowering (DIBL). As far as short-channel effects are concerned, several models have been published [2-5].

When the gate length is scaled below deep submicron dimensions very large normal electric fields at the Si/SiO\textsubscript{2} interface may appear. Therefore a significant bending of the energy-bands at the Si/SiO\textsubscript{2} interface is produced and the potential well becomes narrow enough to quantize the motion of inversion layer carriers in the direction perpendicular to the interface [6]. Due to the quantization, the energy levels are splitted into sub bands and the lowest of the allowed energy levels for electrons in the well does not coincide with the bottom of the conduction band. On the other hand, the electron density does not reach its maximum at the Si/SiO\textsubscript{2} interface as semi classical theory predicts [7, 8], but at some distance inside the semiconductor. The quantum mechanical modeling has received less attention. [9-12]. The carrier transport with quantized energy levels requires a self-consistent solution from both the Schrodinger and Poisson’s equations. The Schrodinger–Poisson (SP) solvers need a very complex algorithm to calculate the concentration numerically which is very expensive in computing time. However, SP solvers are impractical for ultra thin SDG MOS devices because evaluation of quantum mechanical electron density is computationally more demanding [13].
In this work, we extend the state-of-the-art by proposing a simple model for the surface potential of symmetric DG-MOSFETs. We solved the Poisson equation under Gradual Channel Approximation (GCA) by introducing quantum confinement parameter and quantum corrected potential to avoid the computational complexity, which is present in SP solvers.

II. ANALYTICAL MODEL

Fig. 1, Shows the cross-section and coordinate systems of a long symmetrical undoped Double Gate (DG) nMOSFET. L is the gate length, t_{Si} is the silicon film thickness, t_{OX} is the gate-oxide thickness. The y-axis is perpendicular to the surface and the x-axis is parallel to the channel, respectively. The reference frame here, its origin at the source end of the channel and is located midway between the two gates, which is centre of the film. The same voltage V_GS is applied to the two gates and the flat band voltage are also same for both gates.

The electrostatic potential ψ(x, y) in the silicon body is defined as the intrinsic potential at a point (x, y) with respect to Fermi potential at the source end. It is assumed that the quasi-Fermi level is constant across the silicon-film direction (y-direction) so that current flows only along the x-axis from source to drain. Poisson’s equation along a vertical cut perpendicular to silicon film is written as,

\[
\frac{\partial^2 \psi}{\partial y^2} = \left( \frac{q}{\varepsilon_{\text{Si}}} \right) n
\]  

(1)

Where ψ and n are the spatial electro statistics potential and mobile-electron concentration, respectively; \( \varepsilon_{\text{Si}} \) is the permittivity of silicon material. In Eq. (1) hole concentration is neglected in nMOS device. Using Boltzmann Statistics, the classical carrier concentration is given as,

\[
n = n_i e^{y - \psi_f} / V_T
\]  

(2)

Where \( n_i \) is the intrinsic carrier concentration, \( V_T = (kT/q) \) is thermal voltage (0.026V at room temperature) and \( \psi_f \) is non-equilibrium quasi-Fermi level Potential and satisfy following conditions [14, 15],

\[
\psi_f(0, y) = 0 \quad \psi_f(L, y) = V_{DS}
\]

Where, \( V_{DS} \) is the drain source voltage.

Eq. (2) shows an exponential increase of carrier concentration towards the silicon-oxide interface, however, the physically corrected quantum mechanically derived carrier concentration strongly decreases towards the interface. A quantum corrected potential term is included in Eq. (2) to adjust the classically derived concentration equal to the quantum mechanically calculated carrier concentration. The Eq. (2) is modified and expressed as [13],

\[
n_{\text{corr}} = n_i e^{(\psi - \psi_f - \psi_{\text{corr}})} / V_T
\]  

(3)

Where \( \psi_{\text{corr}} \) is a quantum corrected potential, which varies along y-direction. Including the quantum confinement effects Eq. (1) is modified as,

\[
\frac{\partial^2 \psi_{\text{corr}}}{\partial y^2} = \left( \frac{q}{\varepsilon_{\text{Si}}} \right) n_{\text{corr}}
\]  

(4)

Substituting Eq. (3) in Eq.(4),

\[
\frac{\partial^2 \psi_{\text{corr}}}{\partial y^2} = \left( \frac{q}{\varepsilon_{\text{Si}}} \right) n_i \exp \left( \frac{(\psi_{\text{class}} - \psi_f - 2 \psi_{\text{corr}})}{V_T} \right)
\]  

(5)

\[
\frac{\partial^2 \psi_{\text{corr}}}{\partial y^2} = \left( \frac{q}{\varepsilon_{\text{Si}}} \right) n_i \exp \left( (\psi - \psi_f - \psi_{\text{corr}}) / V_T \right)
\]  

(6)

Using, \( \psi = \psi_{\text{class}} - \psi_{\text{corr}} \) in the above equation,

Where substituting, \( \beta_i = \frac{q n_i}{\varepsilon_{\text{Si}}} \) and \( \beta = \frac{1}{V_T} \),

\[
\frac{\partial^2 \psi_{\text{corr}}}{\partial y^2} = \beta_i^2 \exp \left[ \beta \left( \psi_{\text{class}} - \psi_f \right) \right] \exp \left[ -2 \beta \psi_{\text{corr}} \right]
\]  

(7)
By Integrating above equation twice, we can get the variation of quantum corrected potential along y-direction. Integrating (7) once with \( \frac{d\psi_{\text{corr}}}{dy} \bigg|_{y=0} = 0 \), we have,

\[
\frac{d\psi_{\text{corr}}}{dy} = \theta \exp \left[ \frac{\beta}{2} \left( \psi_{\text{class}} - \psi_F \right) \right] \exp \left[ \frac{-2\beta\psi_{\text{corr}}}{1} \right]^{1/2} \tag{8}
\]

Where, \( \theta = \sqrt{\frac{\beta_1^2}{2\beta}} \)

In this work we assume the following dependence for the potential,

\[
\psi_{\text{class}} = \frac{k_1}{2} \left[ \left( \frac{y}{t_{\text{si}}} \right)^2 - \left( \frac{1}{4} + r \right) \right] \tag{9}
\]

Where, \( k_1 \) measures the significance of the dopant induced field and \( r \) is function of gate-oxide thickness and film thickness.

Substituting Eq. [9] in Eq. [8],

\[
\frac{d\psi_{\text{corr}}}{dy} = \lambda_{11} \exp \left[ \theta_{11} y^2 \right] \exp \left[ \frac{-2\beta\psi_{\text{corr}}}{1} \right]^{1/2} \tag{10}
\]

Where, \( \theta_{11} = \frac{\beta k_1}{4 t_{\text{si}}} \) and \( \lambda_{11} = \theta \exp \left[ \frac{-\beta}{2} \left( \frac{1}{4} + r \right) - \psi_F \right] \).

Integrating above equation again from 0 to \( y \), and taking \( \psi_{\text{corr}} (y=0) = 0 \)

\[
\psi_{\text{corr}} (y) = -\frac{1}{\beta} \ln \cos \left[ B_{11} \left\{ \exp(\theta_{11} y^2) \left( \theta_{11} y^2 - 1 \right) + 1 \right\} \right] \tag{11}
\]

Where, \( B_{11} = \frac{\lambda_{11} \beta}{\sqrt{\theta_{11}}} \)

Equation [11] gives the variation of quantum corrected potential. The variation of carrier concentration along y-direction is given by [15],

\[
n(y) = n_0(y) e^{-A y^2} = n_{\text{corr}} \tag{12}
\]

Where, \( A \) is the quantum confinement parameter, which is used to measure the strength of quantum confinement.

The confinement parameter \( A \) is determined by Boundary condition,
Surface potential $\hat{E}_s$ is obtained by substituting $y = t_s/2$ in the above equation.

\[
\psi_s = \psi \left( \frac{t_s}{2} \right) = \frac{1}{\beta} \ln \left( \frac{n_o \left( \frac{t_s}{2} \right)}{n_i} \right) - \frac{1}{\beta} A \left( \frac{t_s}{2} \right)^2 + \psi_{\text{corr}} \left( \frac{t_s}{2} \right) \tag{15}
\]

Where, $n_o \left( \frac{t_s}{2} \right)$ and $\psi_{\text{corr}} \left( \frac{t_s}{2} \right)$ are obtained by substituting $y = t_s/2$ in Eq. [11] and Eq. [13]

### III. RESULTS AND DISCUSSION

The quantum confinement effect is more pronounced in ultrathin silicon film. The quantum confinement parameter reduces with silicon film as well as gate voltage. Due to quantum confinement effect, the mobile carrier density as well as surface potential is lower than the classical one. Quantum confinement effect on threshold voltage cannot be ignored for $t_s < 3\text{nm}$. We have simulated the surface potentials in the silicon channel as a function of Silicon thickness and doping concentration. Based on the equation present in the last section, surface potential can be obtained for DG MOSFETs with quantum corrected potential and quantum confinement parameter. Figures 2 and 3 demonstrate the influences of quantum mechanical effects (QMEs) on surface potential. Figure 2 can be seen that Surface potential increases with silicon thickness and the increases gets more significant as drain source voltage decreases. In quantum mechanical theory, the wave nature of inversion carrier’s results in a peak of charge density separated from the interface and an increased width of inversion layer. Thus, the same charge density would results in a higher surface potential in the semi classical cases. The variation of surface potential affects the electric field in gate oxide and then the tunnelling current through gate oxide [16] and its reliability.

Figure 3 shows that the surface potential increases with increasing the doping concentration and also for minimum value of $t_s$. Clearly shows that, it is necessary to consider QMEs in the simulation and design of modern MOSFET since the substrate doping level in realistic MOSFETs is very important parameter. The results in Figs. 2 and 3 shows that QMEs have considerable influence on surface potential. Therefore, the model of this work provides a useful method to study Quantum mechanical effects on surface potential.

### IV. CONCLUSION

The Calculation for $\psi_s$ - presented here is fully analytical calculations, takes into account the quantum mechanical effects present in ultra small channel length MOSFETs, and the complexity of the calculations reduced marginally over the SP solvers. This approach leads to a physics-based model, which does not need any additional parameter with respect to the basic $\hat{E}_s$-model. Based on extensive comparisons with self-consistent Schrodinger-Poisson simulations for a large range of substrate doping and oxide thickness, the complexity of the calculations reduced. An excellent agreement was found for both measurement sets, which confirms the validity of our modeling approach. Our developed model is suitable for under-standing the behaviour of Symmetric Double Gate device in presence of quantum effect without considering the Schrodinger-Poisson equation.

### REFERENCES


