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Quantum correction for DG MOSFETs

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Abstract The characteristics of modern semiconductor devices are strongly influenced by quantum mechanical effects. Due to this fact, purely classical device simulation is not sufficient to accurately reproduce the device behavior. For instance, the classical semiconductor equations have to be adapted to account for the quantum mechanical decrease of the carrier concentration near the gate oxide. Several available quantum correction models are derived for devices with one single inversion layer and are therefore only of limited use for thin double gate (DG) MOSFETs where the two inversion layers interact. We present a highly accurate quantum correction model which is even valid for extremely scaled DG MOSFET devices. Our quantum correction model is physically based on the bound states that form in the Si film. The eigenenergies and expansion coefficients of the wave functions are tabulated for arbitrary parabolic approximations of the potential in the quantum well. Highly efficient simulation of DG MOSFET devices scaled in the decananometer regime in TCAD applications is made possible by this model.

Keywords Simulation · Confinement · Quantum correction · DG MOSFETs

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1 Introduction

Continously downscaling of the device geometry increases the influence of quantum mechanical effects on the device characteristics. Besides tunneling, the effect of quantum confinement highly affects the characteristics of bulk, silicon-on-insulator (SOI), and double gate (DG) MOSFET devices under inversion conditions.

Purely classical device simulation without adequate quantum correction is no longer sufficient to provide proper results since it predicts an exponential increase of the carrier concentration towards the gate oxide interface. However, due to quantum confinement, which affects the local density of states, the carrier concentration near the gate oxide decreases as shown in Fig. 1.

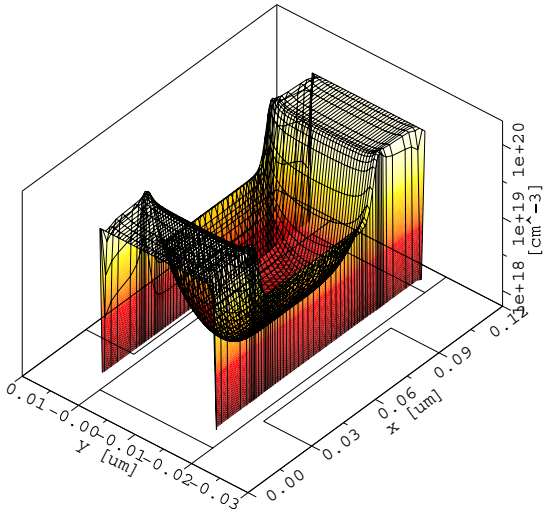

Fig. 1 Quantum mechanical electron concentration within a DG MOSFET device. The concentration strongly decreases towards the oxide interfaces due to geometrical confinement

Schrödinger Poisson (SP) solvers, which deliver a self consistent solution of a quantum mechanically calculated carrier concentration and the Poisson equation, provide accurate results for the carrier concentration within 1d slices perpendicular to the oxide interface. However, since the evaluation of the quantum mechanical electron density is computationally very demanding, the application of SP solvers is impractical.

In order to obtain proper results at significantly reduced CPU time, several quantum correction models for classical simulations have been proposed [1–5]. However, some of these corrections are based on empirical fits with numerous parameters [4, 5]. In some other models, the dependence on the electrical field adversely affects the convergence behavior [3]. Practically, the model proposed in [1] has to be recalibrated for each device. A comprehensive comparison of these models can be found in [6]. In addition, none of these models is suitable for highly scaled DG MOSFETs in the deca nanometer regime where two coupled inversion regions occur. In this work, we present a new, physically based, and more specific approach for state-of-the-art DG MOSFETs.

2 Approach

The classical carrier concentration is based on the assumption of a free 3-dimensional electron gas and Boltzmann statistics and shows exponential increase towards the semiconductor-oxide interface. However, the physically correct quantum mechanically derived carrier concentration strongly decreases towards the interface. The classically derived concentration is adjusted to be equal to the quantum mechanically calculated carrier concentration [7] by introducing the quantum correction potential φ_{corr} as

$$n_{\text{cl,corr}} = N_{\text{C}} \exp\left(-\frac{E_{\text{c}} - q\varphi_{\text{corr}} - E_{\text{f}}}{k_{\text{B}}T}\right),$$

$$n_{\text{qm}} = N_{\text{C1}} \sum_n |\Psi_n(x)|^2 \exp\left(-\frac{E_n - E_{\text{f}}}{k_{\text{B}}T}\right).$$

Here, N_{C} and N_{C1} denote the effective density of states for classical and the quantum mechanical carrier concentration, respectively. φ_{corr} describes the quantum correction potential, E_{c} the conduction band edge energy, and E_{f} the Fermi energy.

This approach requires the knowledge of the energy levels E_n and the wavefunctions $\Psi_n(x)$ of the quantized states. To avoid the computationally expensive solution of the Schrödinger equation, we tabulate the solutions for a parabolic shaped approximation of the conduction band edge,

$$E_{\text{c}}(x) = E_{\max} - a(d/2 - x)^2,$$

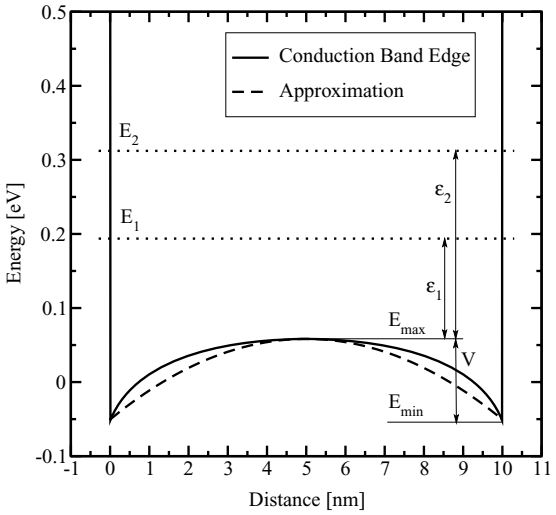

Fig. 2 A cut of the conduction band edge energy perpendicular to the semiconductor-oxide interfaces. The dashed line displays its parabolic approximation. Furthermore, Eigenenergy levels and their relative values to $E_{\max}$ and $E_{\min}$ are shown

as displayed in Fig. 2. Input parameters are the film thickness d and the curvature a which is derived from an initial classical simulation. The wave functions are expanded as

$$\Psi_n(x) = \sum_k \xi_{n,k} \sqrt{\frac{2}{d}} \sin\left(\frac{\pi}{d} kx\right).$$

Hence, the offset of the energy levels ϵ_n and the expansion coefficients of the wavefunctions $\xi_{n,k}$ can be found by interpolation of tabulated values. This allows one to estimate a correction potential φ_{corr} such that the corrected classical

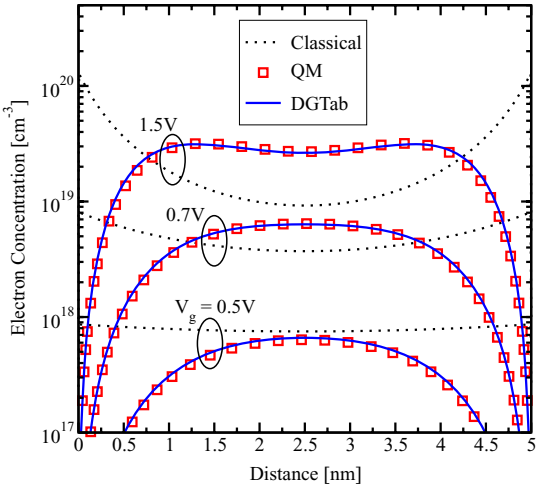

Fig. 3 The classical, the quantum mechanical, and the corrected classical electron concentration of a double gate MOSFET structure with 5 nm silicon film thickness. Gate voltages of 0.5 V, 0.7 V, and 1.5 V were applied. DGTab quantum corrected curves show outstanding agreement with quantum mechanically derived curves for all applied gate voltages

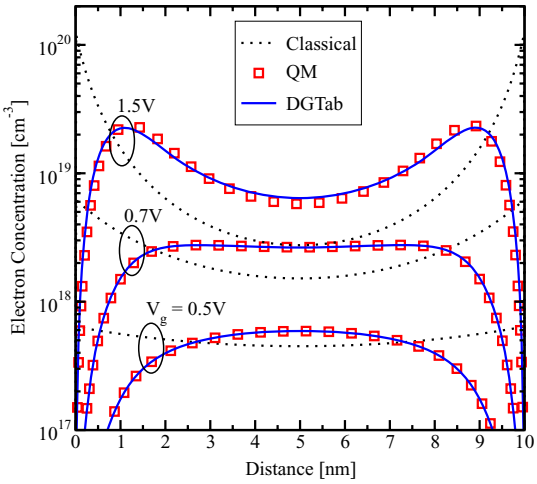

Fig. 4 The classical, the quantum mechanical, and the corrected classical electron concentration of a double gate MOSFET structure with 10 nm silicon film thickness at gate voltages of 0.5 V, 0.7 V, and 1.5 V respectively. DGTab quantum corrected curves show outstanding agreement with quantum mechanically derived curves for all applied gate voltages

carrier concentration is consistent with the SP solution

$$\exp\left(-\frac{q\varphi_{\text{corr}}}{k_{\text{B}}T}\right) = \exp\left(-\frac{a(d/2-x)^2}{k_{\text{B}}T}\right) \times \sum_m \frac{N_{\text{C1},m}}{N_{\text{C}}} \sum_n |\Psi_{m,n}(x)|^2 \exp\left(-\frac{\epsilon_{m,n}-E_{\text{f}}}{k_{\text{B}}T}\right).$$

Here, m denotes the summation over the different valley sorts (three for silicon) [8].

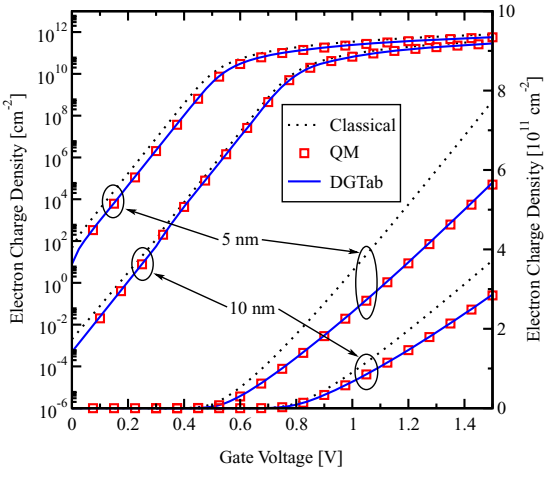

Fig. 5 The total amount of the inversion charge as a function of the gate voltage for DG MOSFETs with film thicknesses of 5 nm and 10 nm respectively. The upper left curves are plotted in logarithmic scale, the lower right ones in linear scale. DGTab quantum corrected curves show outstanding agreement with quantum mechanically derived curves in the entire range of gate voltages

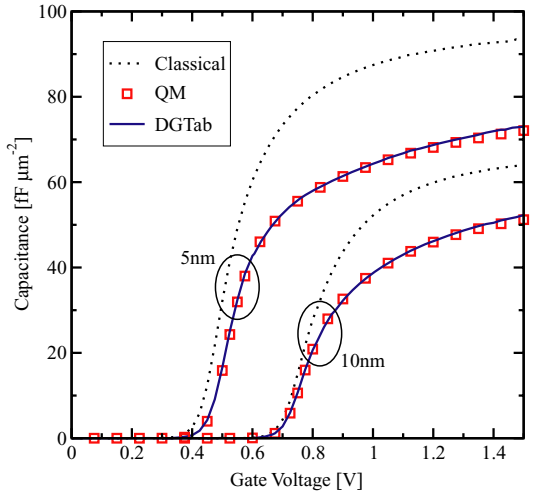

Fig. 6 The resulting gate capacitance as a function of the gate voltage for DG MOSFETs with film thicknesses of 5 nm and 10 nm, respectively. DGTab quantum corrected curves show outstanding agreement with quantum mechanically derived curves for both film thicknesses

3 Results

We implemented this model in our general purpose device simulator MINIMOS-NT [9]. Our SP simulator VSP was used to derive the reference QM curves. The applied iteration scheme of an initial classical simulation followed by a single quantum correction step and a final classical simulation with corrected bandedges delivers results in the same accuracy as a complete self consistent simulation.

Figures 3 and 4 show the electron concentration at different bias points for DG MOSFETs with 5 nm and 10 nm film thickness. Outstanding agreement between the QM and the corrected classical curves (DGTab) is achieved.

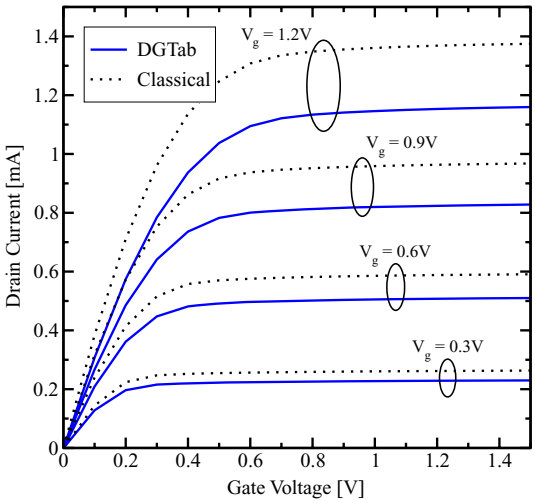

Fig. 7 Output characteristics of a double gate MOSFET device with a Si film thickness of 20 nm. The current is overestimated by a purely classical simulation because of the exponentially increasing carrier concentration near the oxide interfaces

Both the inversion charge and the gate capacitance shown in Fig. 5 and Fig. 6 demonstrate excellent agreement between DGTab and S/P curves for a wide range of gate voltages and relevant film thicknesses. Since the derived inversion charge is based on the accurate carrier concentration, no further fitting parameters had to be introduced.

Figure 7 displays the output characteristics of a double gate MOSFET with a silicon film thickness of 20 nm. Purely classical simulation overestimates the current in the entire range because of the increased carrier concentration near the oxide interfaces.

4 Conclusion

We derived a quantum correction model specifically for double gate MOSFETs based on the bound states that form in the silicon film. The model accurately reproduces both the carrier concentration distribution and gate capacitance characteristics as well as the total inversion charge even for extremely scaled DG MOSFET devices. Due to its computational efficiency, the model is well suited for TCAD simulation environments.

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