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Quantum Correction for DG MOSFETs

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INTRODUCTION

Due to the strong impact of quantum mechanical effects on the characteristics of todays semiconductor devices, purely classical device simulation is no longer sufficient to provide proper results.

Schrödinger Poisson (SP) solvers, delivering a self consistent solution of the quantum mechanical carrier concentration and the Poisson equation, accurately determine quantum confinement, but they are computationally demanding. 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 [3, 4]. In some other models, the dependence on the electrical field adversely affects the convergence behavior [2]. Practically, the model proposed in [1] has to be recalibrated for each device. A comprehensive comparison of these models can be found in [5]. 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.

APPROACH

The value of the classical carrier concentration with quantum confinement correction is adjusted to be equal to the quantum mechanically calculated carrier concentration by introducing the quantum correction potential $\varphi_{\rm corr}$ as

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

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

Here, $N_{\rm C}$ and $N_{\rm C1}$ denote the effective density of states for classical and the quantum mechanical carrier concentration, respectively, $\varphi_{\rm corr}$ the quantum correction potential, $E_{\rm c}$ the conduction band edge energy, and $E_{\rm f}$ 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 conduction band edge, $E_{\rm c}(x) = E_{\max} - a(d/2-x)^2$, as displayed in Fig. 1. 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

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

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 $\varphi_{\rm corr}$ such that the corrected classical carrier concentration is consistent with the SP solution

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

Here, m denotes the summation over the different valley sorts (three for silicon) [6].

RESULTS

We implemented this model in the general purpose device simulator MINIMOS-NT [7]. Our SP simulator VSP was used to derive the reference QM curves. Fig. 2 and Fig. 3 show the electron concentration at different bias points for DG MOSFETs with $5\,\mathrm{nm}$ and $10\,\mathrm{nm}$ film thickness. Outstanding agreement between the QM and the corrected classical curves (DGTab) is achieved. Both the inversion charge and the gate capacitance shown in Fig. 4 and Fig. 5 demonstrate excellent agreement for a wide range of gate voltages and relevant film thicknesses.

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CONCLUSION

We derived a physically based quantum correction model which accurately reproduces both carrier concentrations and gate capacitance characteristics 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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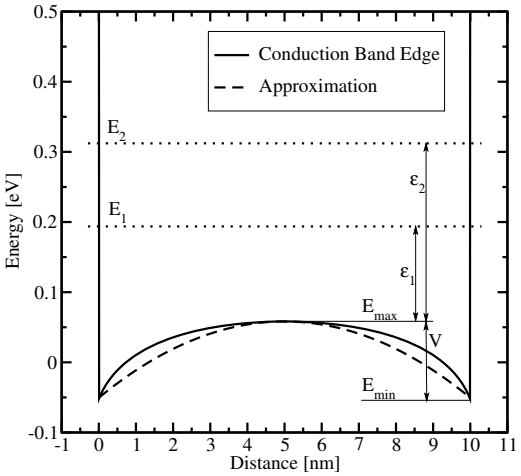

Fig. 1. Conduction band edge energy approximation and eigenenergies

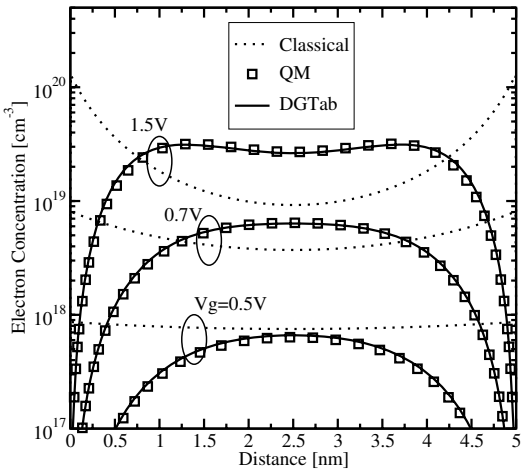

Fig. 2. Electron concentrations for a 5 nm DG MOSFET

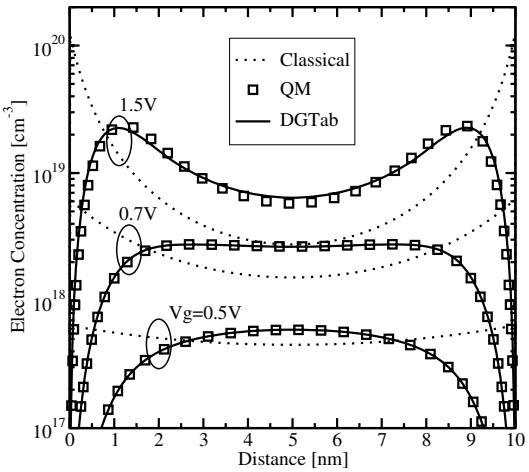

Fig. 3. Electron concentrations for a 10 nm DG MOSFET

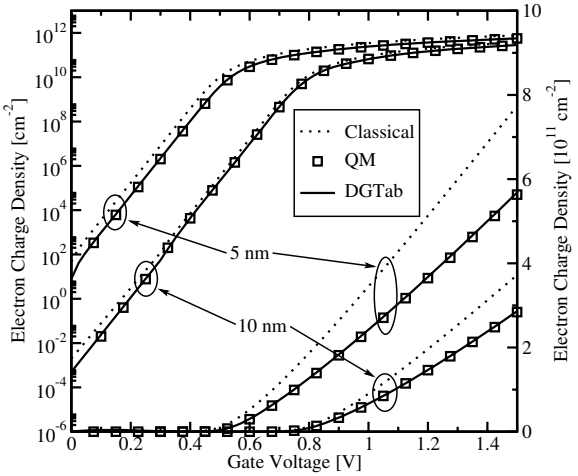

Fig. 4. Electron charge density per unit area. Logarithmic scale in the upper left part, linear scale in the lower right part.

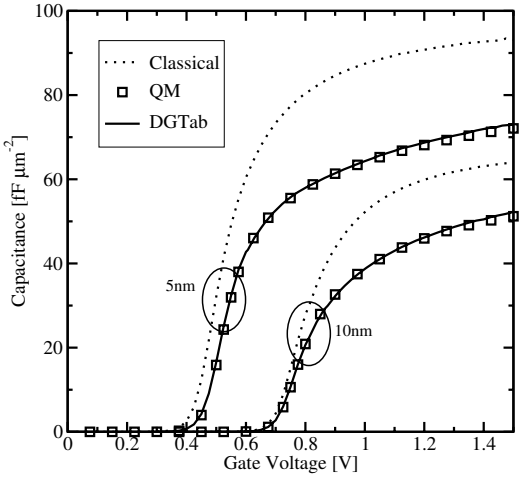

Fig. 5. Gate capacitance per unit area versus gate voltage