Pearson Effective Potential vs. Multi-Subband Monte-Carlo Simulation for Electron Transport in DG nMOSFETs

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Abstract

We present a comparison between two-different approaches to including quantum effects in a Monte-Carlo simulator. The ability of our original Pearson Effective Potential (PEP) correction to correctly account for electrostatic quantum effects has been demonstrated on double-gate nMOS capacitors with different film thicknesses. In this work, results obtained from semi-classical, PEP corrected and multi-subband Monte-Carlo approaches are reported for a double-gate nMOSFET with a channel length $L_C = 20$ nm and a silicon film thickness $T_{Si} = 8$ nm at low and high drain voltages. For the first time, excellent agreements are obtained between quantum corrected and multi-subband Monte-Carlo methods on both electrical characteristics and microscopic quantities.

1 Introduction

For the simulation of electron transport in nanoscaled MOSFET devices, Monte-Carlo (MC) approaches accounting for quantum effects are becoming of great relevance. A multi-subband particle Monte-Carlo simulator self-consistently coupled with Schrödinger's equation seems presently to be the most rigorous solution to include quantum confinement effects in a Monte-Carlo simulator [1,2]. This mode-space approach properly accounts for the quantization effects on electrostatics, conductivity mass and scattering rates in ultra-thin double-gate devices but it is computationally intensive and it may be difficult to extend it to other MOSFET architectures. An alternative to this approach is the Effective Potential method [3-7]. This quantum corrected potential method modifies the carrier "classical" trajectory during the free flight in order to assess the impact of first order quantum effect on electron transport. It does not include electron gas degeneracy and introduce the effects of quantization only on the electrostatics. In contrast to the well-known Gaussian Effective Potential (GEP) [3-7], we have demonstrated on double-gate nMOS capacitors with different film thicknesses that our original Pearson Effective Potential (PEP) is able to correctly account for electrostatic quantum effects, i.e. to accurately reproduce Schrödinger-Poisson electron density profiles [8,9]. In this work, for the first time, electron transport results from the PEP corrected Monte-Carlo and a more rigorous multi-subband Monte-Carlo [1] are compared in terms of electrical characteristics and microscopic quantities (electron density, potential, velocity) at low and high drain voltages for a 20 nm channel-long double-gate nMOSFET.

2 Pearson Effective Potential Correction

The PEP correction mainly consists in improving the particle wave-packet description: the Gaussian distribution in the usual GEP [3-7] is replaced by a Pearson IV distribution that much better fits the square modulus of the ground-subband Schrödinger's wave-function. It has been calibrated as a function of both the local electrical field and the silicon film thickness [8,9]. For a double-gate structure, it is defined (1D) as:

$$PEP(x) = \int_{T_{ox}}^{T_{Si}+T_{ox}} V_p(x') \times \text{Pearson IV}\left(R_p(E_x, T_{Si}) - x'\right) dx' \quad (1)$$

where $V_P(x')$ is the potential energy, T_{Si} and T_{ox} are the silicon film and oxide thicknesses, and E_x is the local electric field in the confinement direction.

3 Results

The simulated device is a double-gate nMOSFET with a channel length $L_C = 20$ nm, $T_{ox} = 1.1$ nm, $T_{Si} = 8$ nm, $N_A = 10^{15}$ cm^{-3} and $N_D = 10^{20}$ cm^{-3}. Both channel and source/drain extensions are covered with silicon oxide. Concerning the PEP correction, an energy barrier $E_B = 3.1$ eV is used for electrons at Si/SiO_2 interfaces and satisfies $V_{ox} = V_P - E_B$. The scattering mechanisms included in the model are acoustic intravalley phonon scattering, three *f* and *g* intervalley phonons scattering, and electron-impurity scattering. To make easier the comparison, surface roughness scattering is not included here. The simulated output characteristics resulting from semi-classical, PEP corrected and multi-subband MC simulations are plotted in Fig. 1. Excellent agreement is obtained between PEP and multi-subband results. We observe a reduction of drive current when quantum confinement effects are included (11% with PEP at $V_{GS} = 1.2$ V and $V_{DS} = 0.7$ V). It is mainly explained by a decrease of the inversion charge due to carrier repulsion at SiO_2/Si interfaces (cf. Fig. 2).

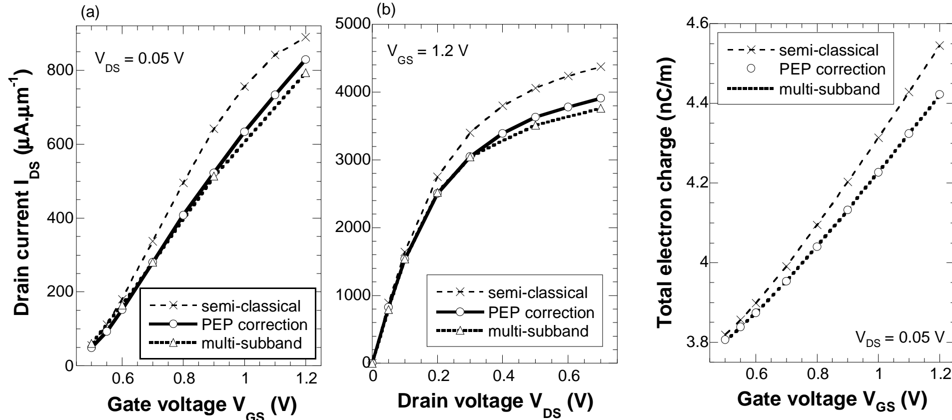

Fig. 1. Output I_D-V_{GS} (a) I_D-V_{DS} (b) characteristics from semi-classical, PEP corrected and multi-subband Monte-Carlo. $V_{DS} = 0.05$ V (a). $V_{GS} = 1.2$ V (b).

Fig. 2. Total electron charge from semi-classical, PEP corrected and multi-subband Monte-Carlo. $V_{DS} = 0.05$ V.

Cartographies of electron density obtained by MC simulations corrected by the PEP at $V_{GS} = 1.2$ V and $V_{DS} = 0.05$ V or $V_{DS} = 0.7$ V are shown in Fig. 3a and 3b, respectively. At these same applied voltages, we also compare electron density and potential profiles resulting from semi-classical, PEP correction and multi-subband MC simulation along the confinement and the transport directions. An excellent agreement is found between PEP and multi-subband results regarding electron density and potential all along the device, not only at low but also at high drain voltage. It is consistent with the very good agreement obtained on the output characteristics. Comparisons with semi-classical results also highlight the impact of quantum confinement effects: two conduction channels at about 0.9 nm from SiO_2/Si interfaces and a gradual reduction of confinement effects along the channel under high drain voltage are observed.

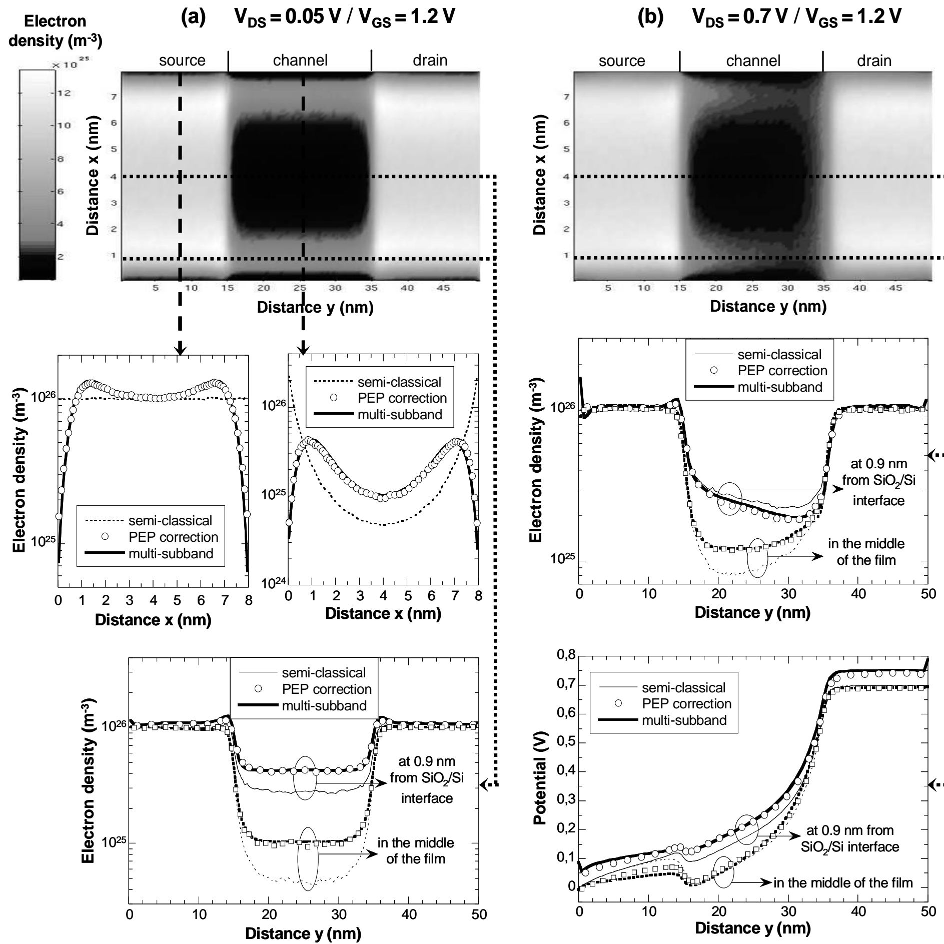

Fig. 3. Cartography of the electron density resulting from the PEP correction at $V_{GS} = 1.2$ V and $V_{DS} = 0.05$ V (a) or $V_{DS} = 0.7$ V (b). Electron density and potential profiles extracted in different slices of the device along either gate-to-gate or source-drain directions for semi-classical (thin lines), PEP corrected (symbols) and multi-subband Monte-Carlo (thick lines) simulations.

4 Conclusion

A new effective potential based on Pearson IV distribution has been developed to account for quantum confinement effects in nanoscaled devices using a Monte-Carlo simulator. For the first time, excellent agreements on both electrical characteristics and microscopic quantities between quantum corrected and multi-subband Monte-Carlo simulation are shown on a nanoscaled double-gate nMOSFET at low and high drain voltages. Thanks to a judicious calibration dependent on the local electric field in the confinement direction, our Pearson Effective Potential correction properly describes the impact of quantum confinement, not only for electrostatics but also for electron transport.

Acknowledgements

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