Quantum Transport in Ultra-Scaled Double-Gate MOSFETs: A Wigner Function-based Monte Carlo Approach

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Double-gate transistors are considered as an attractive option to improve the performance of logic devices and overcome some of the difficulties encountered in further downscaling of bulk MOS field-effect transistors into the decananometer regime [1]. When the channel length is reduced below approximately 25nm, quantum effects such as direct source-to-drain tunneling under the barrier start affecting the device characteristics [2]. At the same time, the scattering mean free path is still as short as a few nanometers, so that transport is not ballistic. A precise theory of ultra-scaled double-gate MOSFETs must therefore properly account for an interplay between the quantum nature of carrier propagation inside the channel and scattering processes. The nonequilibrium Green's functions method is able to solve in principle the problem. However, due to its computational complexity, the method is successfully used only for some restricted class of model scattering mechanisms [3].

An alternative approach based on the Wigner function formalism includes quantum mechanical effects in a more natural way in form of a quantum scattering operator [4]. After conventional scattering integrals are additively included, the Wigner equation approach treats scattering and quantum effects on equal footing, allowing for a solution by a Monte Carlo algorithm. However, because the kernel of the quantum scattering operator is not positively defined, the numerical stability of Monte Carlo is a critical issue. We report the improvement of stability by choosing a smooth classical component $V_c(x)$ to be an output of a low-pass filter with cut-off wave number $q_c << 2\pi / \Delta x$ applied to the potential profile $V(x)$, where Δx is the grid step. An example of such a decomposition is shown in Fig.1.

We have applied the method to a double-gate device schematically shown in Fig. 2, for various gate lengths and oxide thicknesses. A source/drain doping of 5×10^{19} cm^{-3} with abrupt doping profile and undoped channel was chosen. Metal gates with mid-gap work function have been used. The first subband profile is calculated in a post-processing step after a classical MINIMOS-NT simulation. Different geometrical parameters of double-gate MOSFETs at a gate bias 1.0V are shown in Fig. 3. The subband energy in the source increases for smaller silicon thicknesses as a result of size quantisation due to stronger confinement. Based on these subband profiles, the decomposition procedure is applied to obtain the classical and quantum-mechanical force terms. The carrier concentration in different devices resulting from a quantum Monte Carlo simulation is shown in Fig. 4. For the shortest devices we observe a carrier concentration increase of about 50% inside the channel, which is expected indeed because of an increasing density contribution of carriers tunneling under the barrier.

Output I-V characteristics are presented in Fig. 5. For 60 nm gate length, the Wigner function based calculation reproduces the classical results. For shorter channel length the difference between the Wigner equation and the classical approaches grows due to an increase of the tunneling current. Finally, the mean energy obtained from quantum and classical simulations is shown in Fig. 6 for a drain bias of 0.6 V, and two gate lengths, together with the thermal energy at 300 K. Although the difference between the classical and Wigner results is small, in a shorter gate length device the drive field is stronger, so the carriers are not fully thermalized in the drain region.

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References

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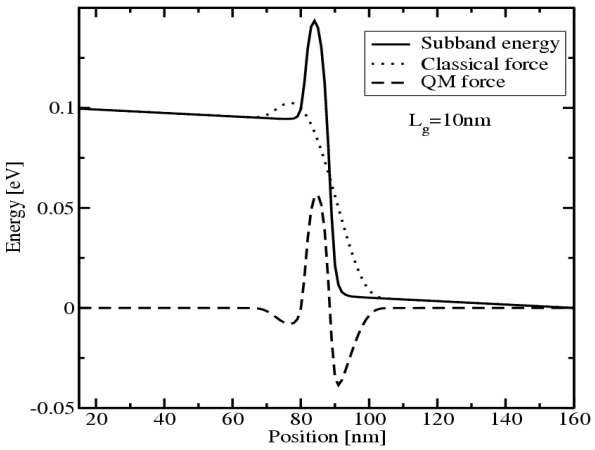

Fig. 1. Decomposition of the subband energy $V(x)$ into classical and quantum-mechanical parts.

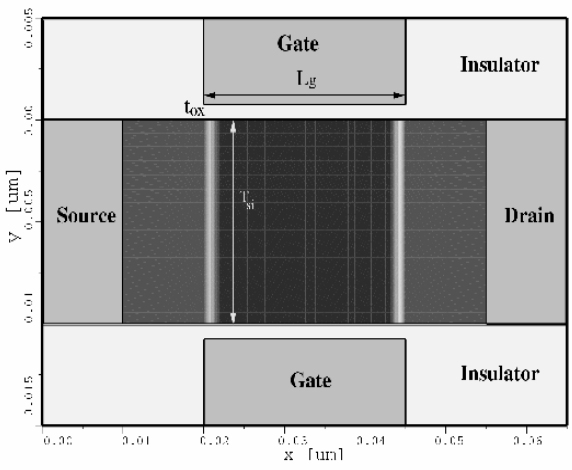

Fig. 2. Sketch of the 25 nm gate length double-gate MOSFET simulated in MINIMOS-NT

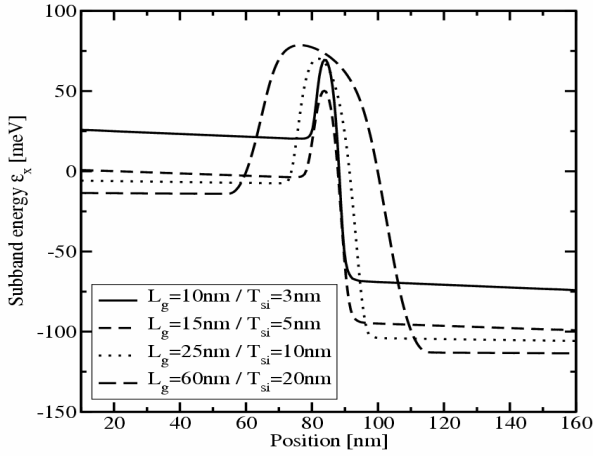

Fig. 3. First longitudinal subband ($m_l = 0.91\ m_0$) for devices with different gate lengths and Si thicknesses at $V_{SD} = 0.1$ V

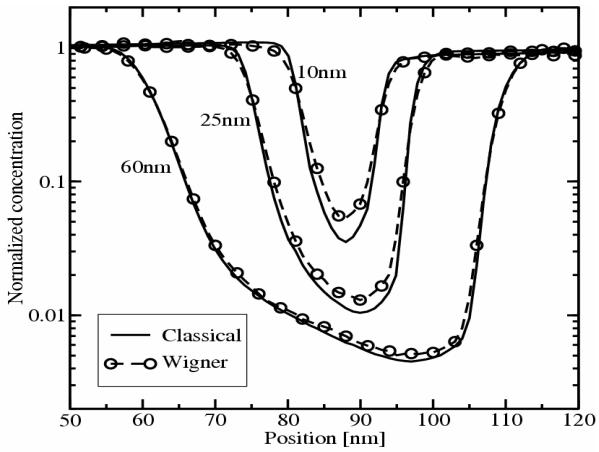

Fig. 4. Carrier concentration in 10 nm, 25 nm, and 60 nm gate length devices at 0.6 V drain bias obtained from classical and Wigner simulations.

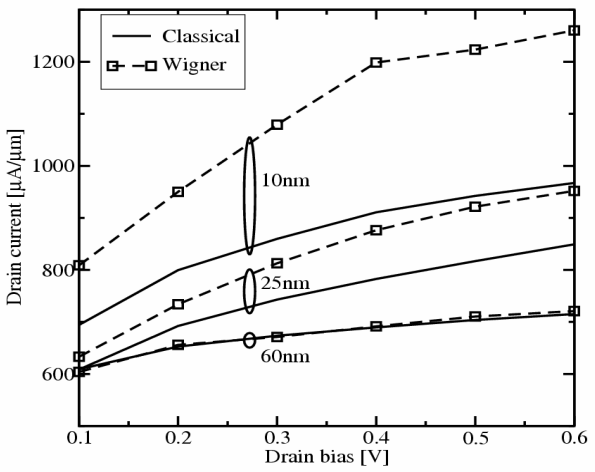

Fig. 5. Output I-V characteristics for 10 nm, 25 nm, and 60 nm gate length device at 1.0 V gate bias calculated with classical and Wigner equation approaches. For shorter gate length a tunneling current contribution emerges.

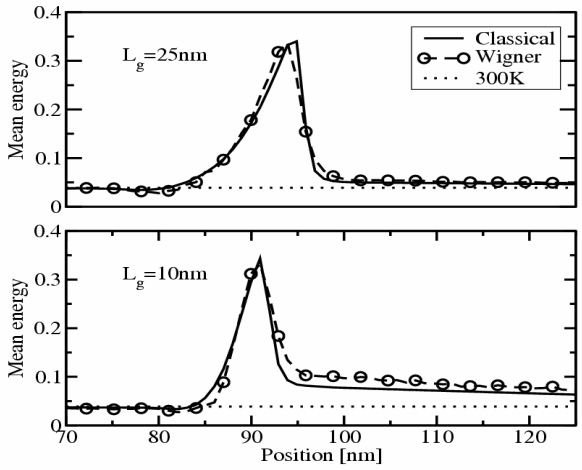

Fig. 6. The mean particle energy in 25 nm (upper panel) and in 10 nm (lower panel) gate length devices at 0.6 V drain bias, obtained from the classical and Wigner simulations.