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RAPID COMMUNICATION

Multi sub-band Monte Carlo simulation of an ultra-thin double gate MOSFET with 2D electron gas

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Abstract

A new two-dimensional self-consistent Monte Carlo simulator including multi sub-band transport in 2D electron gas is described and applied to thin-film SOI double gate MOSFETs. This approach takes into account both out of equilibrium transport and quantization effects. Our method allows us to significantly improve microscopic insight into the operation of deep sub-100 nm CMOS devices. We compare and analyse the results obtained with and without quantization effects for a 15 nm long DGMOS transistor.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Double gate (DG) structures are promising architectures likely to overcome short channel effects in a nanometre scaled MOSFET. Using a form factor L_G/T_{Si} greater than 3, where L_G is the gate length and T_{Si} is the Si body thickness between the two gate stacks, good performances in both off- and on-states may be obtained without the need of sub-nanometre equivalent oxide thickness [1]. Thus, in sub-50 nm MOSFETs, T_{Si} should be typically less than 10 nm and quantization effects in the transverse direction are expected to be more and more significant. Quantization effects may degrade charge control [2] and modify carrier transport [3, 4]. Besides, in nanotransistors where the channel length is comparable to the electron mean free path, quasi-ballistic effects are also known to strongly influence the device performance [5]. However, scattering phenomena may not be neglected in any part of the channel [5]. Therefore, to design a MOSFET suitable for the next CMOS generations, a transport model in which both scatterings and quantum vertical confinement in the channel are accurately taken into account is highly desirable.

In this context, we present results obtained using Monte Carlo simulation of a DG MOSFET self-consistently coupled with the Schrödinger equation in order to properly include

quantization effects. For the first time, results obtained from this 2Dk simulator are compared to those resulting from a classical Monte Carlo approach (3Dk).

2. Model

2.1. The simulator principle

The simulator principle is inspired by both the mode-space approach of quantum transport [6] and the MC technique developed in [7]. In our model, the x -axis, along which the carrier movement is supposed to be semi-classical, is separated from the z -axis, along which the energy is quantized in the whole device. For each x_0 -slice of the channel schematized in figure 1, the time-independent 1D Schrödinger equation along the z -axis is solved, which provides the eigenenergies E_n and wavefunctions $\xi_n(z)$ associated with all sub-bands numbered ' n '.

2.2. Self-consistent Monte Carlo simulation

During each time step, the classical transport equation of the 2Dk electron gas is solved along the x -axis by a Monte Carlo algorithm as summarized in figure 2. According to the mode-space approach, the electric field undergone by a

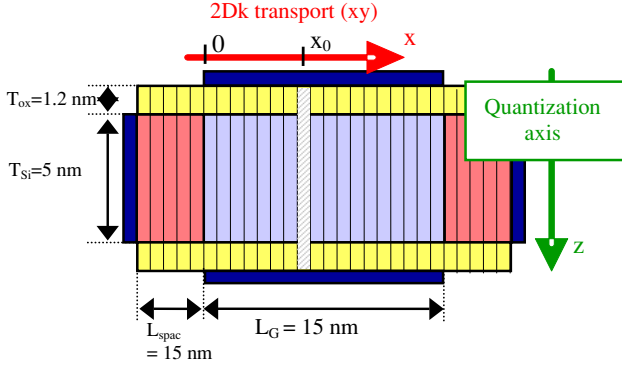


Figure 1. Schematic of the DG MOS structure.

carrier belonging to sub-band ‘ n ’ is given by the x -derivative of the associated energy $E_n(x)$. This transport algorithm provides the number of electrons present in each sub-band of the ‘Schrödinger’ x_0 -slice at the end of the time step. The electron density is then calculated by distributing the charge of each electron along its x_0 -slice according to the appropriate probability density $|\xi_n(x_0, z)|^2$. Next, a new loop can start from a new 2D Poisson’s equation solution followed by a 1D Schrödinger’s equation solution, and so on. By this method, the 1D Schrödinger, 2D Poisson and Boltzmann equations are solved self-consistently.

2.3. 2D scattering mechanisms

Scattering mechanisms included in the simulation are bulk phonon (acoustic intra-valley and intervalley phonons as described in [8]) and impurity scatterings, taking non-parabolic and ellipsoidal band structures into account. Details on the calculation of 2Dk scattering rates may be found in [9]. The same phonon coupling constants are used for the 2Dk and 3Dk electron gases. In order to facilitate the comparison between 2Dk and 3Dk simulations, roughness scattering is not included in the present work.

3. Results

The simulated DG MOS device, described in figure 1, has a gate length L_G equal to 15 nm. The SiO_2 gate oxide T_{ox}

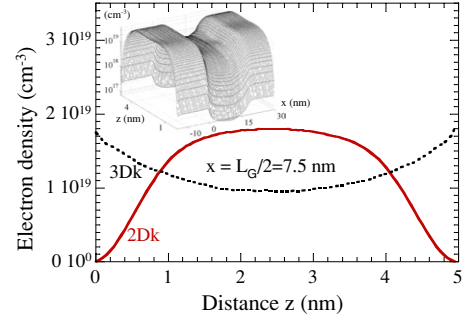


Figure 3. Electron density versus distance z perpendicular to the gate stack in the middle of the channel ($x = L_G/2$) at the on-state ($V_{\text{GS}} = V_{\text{DS}} = V_{\text{DD}}$). Inset: 2D cartography of electron density at the on-state.

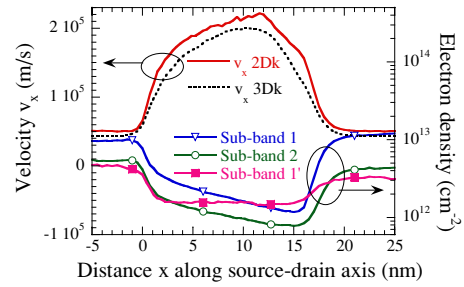


Figure 4. Average velocity v_x for both 2Dk and 3Dk simulations, and surface density of the first sub-bands versus distance x along the S–D direction at the on-state. N.B: $E_1' > E_2 > E_1$.

and Si body T_{Si} thicknesses are equal to 1.2 nm and 5 nm, respectively. The doping density is $N_D = 5 \times 10^{19} \text{ cm}^{-3}$ in the N^+ source–drain regions and $N_A = 2 \times 10^{15} \text{ cm}^{-3}$ in the body. The work function of the gate material is 4.46 eV. The supply voltage V_{DD} is 0.7 V.

Figure 3 indicates that the electron density is strongly modified by the quantization along the z -axis. Electrons are moved away from the Si/SiO₂ interface due to quantum repulsion in the whole structure even in the source and drain regions.

Figure 4 shows that the velocities in the channel for both 2Dk and 3Dk simulations are much higher than the stationary saturation velocity (about 10^5 m s^{-1}). The transport

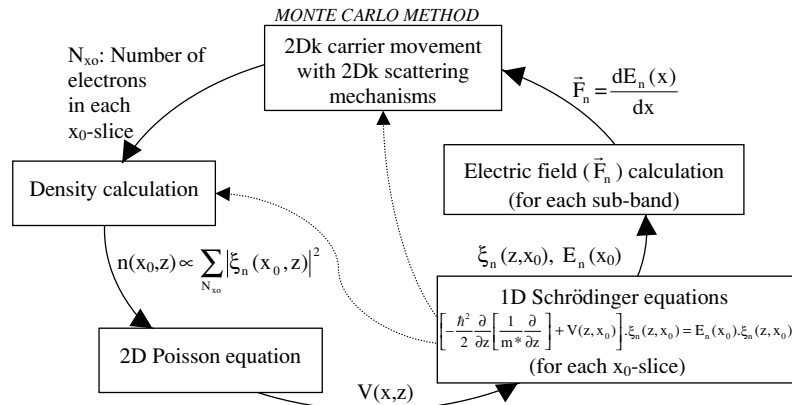


Figure 2. Multi sub-band Monte Carlo algorithm during one time step.

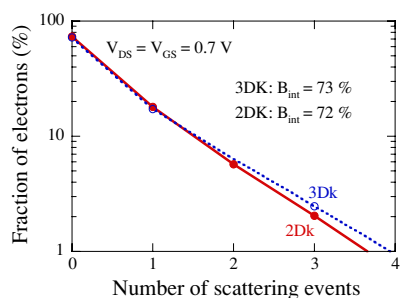


Figure 5. Fraction of electrons versus the number of scattering events undergone at the on-state.

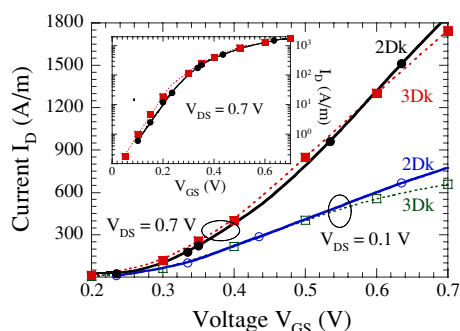


Figure 6. Drain current I_D versus gate voltage V_{GS} at $V_{DS} = 0.1$ V and 0.7 V.

is therefore far from equilibrium in this 15 nm long channel. Moreover, figure 4 exhibits hot electron transfer from the lowest energy sub-band to higher sub-bands, in particular near the drain region. Indeed, the first primed sub-band (primed and unprimed sub-bands have a quantization mass of $0.916m_0$ and $0.19m_0$, respectively) with high energy ($E'_1 > E_2 > E_1$) is less occupied than lower sub-bands in the near-equilibrium source region. However, due to inter sub-band phonon scattering, it becomes relatively more and more populated as the drain is reached.

For both 3Dk and 2Dk simulations at the on-state, we have calculated the number of scattering events N_{scatt} experienced by each carrier crossing the channel from source-end to drain-end. The resulting scattering spectra are plotted in figure 5 as a function of N_{scatt} . The exponential decay of the number of electrons with increasing N_{scatt} illustrates the quasi-ballistic behaviour of carrier transport. The fraction of ballistic electrons B_{int} reaches 72% and 73% in 2Dk and 3Dk curves, respectively. The effect of bulk phonon scattering in the channel is thus similar in 2Dk and 3Dk electron gases.

At last, figure 6 presents the evolution of the drain current as a function of the gate voltage for both 3Dk and 2Dk simulations. First, we observe that the current is only softly

modified by quantization effects. The subthreshold curves plotted in the inset of figure 6 show a weak threshold voltage shift ($\Delta V_T = 10$ mV) and a slight degradation of subthreshold behaviour induced by quantization: the subthreshold slope increases from 75 to 82 mV/dec for, respectively, 3Dk and 2Dk simulations.

4. Conclusion

We have developed a multi sub-band MC simulator for n-MOS transistors that extends the quantum confinement calculation to the whole device region. It also uses a simple and effective self-consistent iterative method that gives meaningful results with good convergence. The simulation of a 15 nm long DGMOS reveals that the transport is strongly far from equilibrium which justifies the use of the Monte Carlo approach. Multi sub-band description opens up the possibility of detailed investigation of nanoscale device physics. However, for the 5 nm thick DGMOS studied in this work, all other things being equal, the I - V characteristics are weakly modified by quantum confinement.

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