Simulation of a double-gate MOSFET by a non parabolic energy-transport subband model based on MEP including crystal heating

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Summary. A nanoscale double-gate MOSFET is simulated by using a model based on the maximum entropy principle (MEP) by including the heating of the crystal lattice. The influence of this latter on the electrical performace of the device is discussed.

1 Mathematical model and simulations

The main aim of the paper is to simulate the nanoscale silicon double gate MOSFET (hereafter DG-MOSFET) reported in Fig. 1, by including also the crystal heating which can influence the electrical properties of the device and pose severe restrictions on its performance. In fact the phonons emitted by hot electrons create a phonon hot spot which increases the generated power density of the integrated circuits. This effect is becoming crucial by shrinking the dimension of the devices which is now below 100 *nm*, a length comparable with the wavelength of acoustic phonons [1,2].

We consider a DG-MOSFET with length L_x= 40 nm, the width of the silicon layer $L_z = 8$ nm and the oxide thickness t_{ox} = 1 nm. The n^+ regions are 10 nm long. The doping in the n^+ regions is $N_D(x) = N_D^+ = 10^{20}$ cm^{-3} and in the n region is $N_D(x) = N_D^- = 10^{15}$ cm^{-3}, with a regularization at the two junctions by a hyperbolic tangent profile.

Due to the symmetries and the dimensions of the device, the transport is, within a good approximation, one dimensional and along the longitudinal direction with respect the two oxide layers, while the electrons are quantized in the transversal direction. Six equivalent valleys are considered with a single effective mass $m^* = 0.32 m_e$, m_e being the free electron mass.

Since the longitudinal length is of the order of a few tents of nanometers, the electrons as waves achieve equilibrium along the confining direction in a time which is much shorter than the typical transport time. Therefore we adopt a quasi-static description along the confining direction by a coupled Schrödinger-Poisson system which leads to a subband decomposition, while the transport along the longitudinal direction is described by a semiclassical Boltzmann equation for each subband.

Numerical integration of the Boltzmann-Schrödinger-Poisson system is very expensive from a computational point of view, for computer aided design (CAD) purposes (see references quoted in [3, 4]) In [3] we have formulated an energy transport model for the charge transport in the subbands by including the non parabolicity effects through the Kane dispersion relation. The model has been obtained, under a suitable diffusion scaling, from the Boltzmann equations by using the moment method and closing the moment equations with the Maximum Entropy Principle (MEP). Scatterings of electrons with acoustic and non polar optical phonons are taken into account. The parabolic subband case has been treated and simulated in [4].

The crystal heating is included adding a further equation for the lattice temperature T_L in the same spirit as in ref.s [5, 6]

$$\rho c_V \frac{\partial T_L}{\partial t} - \mathrm{div}\,[K(T_L)\nabla T_L] = H, \qquad (1)$$

with ρ and c_V silicon density and specific heat respectively. H is the phonon energy production given by

$$H = -(1+P_S)\, n C_W + P_S\, \mathbf{J}\cdot\mathbf{E}, \qquad (2)$$

where P_S plays the role of a thermopower coefficient, nC_W is the electron energy production term with n electron density, and $\mathbf{J}$ is the current. The electron density is related to the surface density in each subband by the relation

$$n = \sum_\nu \rho_\nu |\phi_\nu|^2$$

where ϕ_ν are the envelope functions obtained solving the Schrödinger-Poisson system. In [5] a more general model for H has been proposed.

We stress that the lattice temperature enters into the electron-phonon scattering and in turn in the production terms of the balance equations for the electron variables. The main aim of the present paper is to address the importance of the crystal heating on the electric performance of the device.

A suitable modification of the numerical scheme for the MEP energy transport-Schrödinger-Poisson

system developed in [4] is proposed which includes also the discretization of the lattice temperature balance equation via an ADI approach. Since the characteristic time of the crystal temperature is about one or two orders of magnitude longer than that of electrons, a multirate time step method is employed as in [6].

In the figures we report some preliminary results. It is possible to see a tremendous raise of the crystal energy $k_B T_L$, which at room temperature is about 0.0259 eV, near the drain where the electron energy has its maximum values due to the high electric field present there. It is likely that the lattice temperature reaches the silicon melting temperature. This poses severe restrictions on the source/drain and sorce/gate voltages with stringent design constraints.

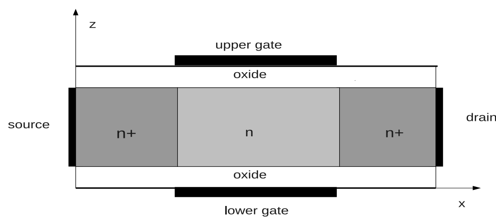

Fig. 1. Schematics representation of the simulated DG-MOSFET

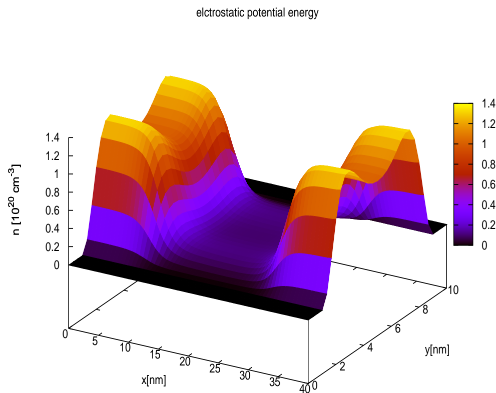

Fig. 2. Electron density when the applied potential between sorce and drain is V_{SD} = 0.1 V and sorce and gate are equipotential

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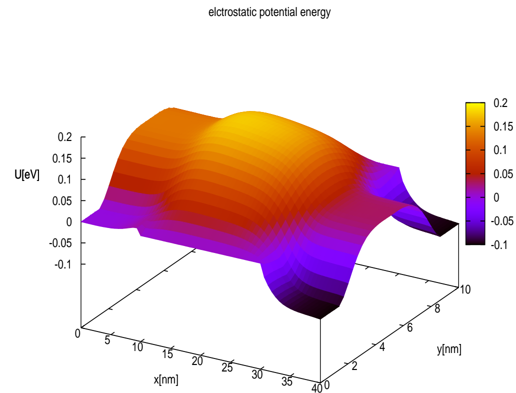

Fig. 3. Electrostatic energy when the applied potential between sorce and drain is V_{SD} = 0.1 V and sorce and gate are equipotential

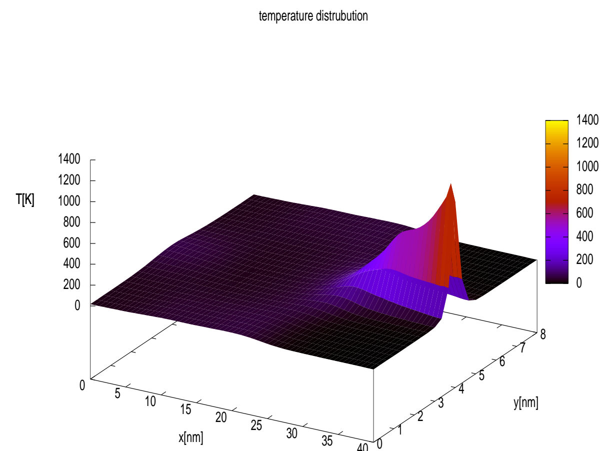

Fig. 4. Electrostatic energy when the applied potential between sorce and drain is V_{SD} = 0.1 V and sorce and gate are equipotential

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