Monte Carlo Simulation of a Submicron MOSFET Including Inversion Layer Quantization

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A Monte Carlo simulator of the electron dynamics in the channel, coupled with a solution of the two-dimensional Poisson equation including inversion-layer quantization and drift-diffusion equations has been developed. This simulator has been applied to the study of electron transport in normal operation conditions for different submicron channel length devices. Some interesting non-local effects such as electron velocity overshoot can be observed.

I. INTRODUCTION

Non-local effects are becoming more and more prominent as MOSFET dimensions shrink to deep-submicrometer regimes. In order to study these effects, non-local models must be used to accurately describe electron transport in MOSFETs. The Monte Carlo method is held to contain a more rigorous description of device physics than models based on the solution of fundamental balance equations [1-2]. A quantum description of the confined inversion layer should also be included [3-4]. Knowledge of electron mobility dependence on variables such as the transverse and longitudinal electric fields is important for simulation and modelling of MOSFETs. Monte Carlo simulations are essential to study these electron mobility dependencies needed for circuit simulators of state-of-the-art MOSFETs.

II. DEVICE SIMULATION

We have simplified the solution of all the equations involved in the description of electron transport in a

submicron MOSFET with the procedure described below. To have a departure point we took the following steps: The quasifermi levels as well as their separation were assumed to be constant in the transverse direction but were allowed to vary along the longitudinal direction. The total variation of the quasifermi levels along the channel is given by the drain-to-source bias voltage and is broken down into a sequence of steps spread out among several still undefined spatial locations along the channel. According to this hypothesis, the device is divided (by setting $N-1$ points inside the channel) into an appropriate number N of smaller channels (subchannels) of unknown length L_i , where $\sum L_i = L$, L is the effective channel length. The one-dimensional Schroedinger and Poisson equations are then selfconsistently solved at both ends of each subchannel, taking into account the pseudofermi level separation at each point. Each subchannel is then described as a sheet layer of charge located inside the semiconductor bulk at a distance z_1 from the silicon-oxide interface. This position z_1 is the mean transverse position of the inversion electron dis-

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tribution. The current in the subchannel is obtained by adding drift and diffusion contributions. If the voltage drop across the subchannel is very small, the following expression for the drain current (I_{DS}) is obtained:

$$I_{DS} = \frac{qW\mu_t(E_{||}, E_{\perp})}{L_i} [-\bar{N}_I(\Psi_{\text{drain}}^* - \Psi_{\text{source}}^*) + \phi_t(N_{I,\text{drain}} - N_{I,\text{source}})] \quad (1)$$

where Ψ^* is the electrostatic potential in z_I , N_I the electron density in the subchannel ends, N_I the average density of electrons in the subchannel, and ϕ_t the thermal voltage. The electron mobility depends on both the longitudinal ($E_{||}$) and transverse ($E_{\perp}$) electric fields. An approximated dependence on $E_{||}$ is assumed for the first time, while an accurate expression obtained by one-electron Monte Carlo simulation is used for the low-field mobility and its dependencies with the transverse-electric field and the temperature, which is crucial for reproducing with accuracy experimental results. The length of each subchannel is obtained by applying Expression 1 according to an iterative procedure. The two-dimensional Poisson equation is solved using the solution obtained previously as a starting point :

$$\frac{\partial^2 \phi(x, y)}{\partial x^2} + \frac{\partial^2 \phi(x, y)}{\partial y^2} = -\frac{\rho(x, y)}{\epsilon_s} \quad (2)$$

where “x” is the parallel and “y” the perpendicular co-ordinates to the channel. An adaptive grid has been set in the whole structure. The two-dimensional problem considered in (2) has been decomposed into N one-dimensional problems :

$$\frac{d^2 \phi_i(y)}{dy^2} = -\frac{\tilde{\rho}_i(y)}{\epsilon_s} \quad (3)$$

where

$$\tilde{\rho}_i(y) = \rho(x_i, y) + \epsilon_s \left. \frac{\partial^2 \phi_0(x, y)}{\partial x^2} \right|_{x=x_i} \quad (4)$$

$\Phi_0(x, y)$ is the solution obtained previously, and x_i is a grid column in the channel. With this effective charge density $\tilde{\rho}_i(y)$, we can use the procedure explained above to solve the Poisson and Schroedinger equations, repeated until a convergence criterium is reached.

Once the actual potential distribution, longitudinal and transverse fields, and inversion and depletion charge concentrations along the channel have been calculated, the electron dynamics are simulated by the Monte Carlo method. The grid is chosen to be thin enough that a constant value of the different transport magnitudes can be assumed in each grid interval (i.e. each grid interval was characterised by a constant value of the longitudinal- and transverse-electric fields, surface potential, inversion and depletion-charges, electronic subband minima, etc.). Taking into account these values, the scattering rates are evaluated in each grid zone. Phonon, surface-roughness, and Coulomb scattering have been considered, following the procedure in a previous work [4-6]. To continue in Monte Carlo simulation, a great number of electrons are introduced, one by one, into the channel from the source. The longitudinal electric field in each grid zone modifies the electron wavevector according to the semiclassical model during a free flight whose length is calculated according to a standard Monte Carlo procedure by generating a random number and using the maximum of the total scattering rate along the whole channel. The time an electron spends in each grid zone, the electron mean-velocity and mean-energy in each interval are recorded. The electron velocity distribution along the channel can thus be evaluated. Taking into account expression $\mathbf{v}_{\text{drift}} = \mu(\mathbf{x})\mathbf{E}_{||}$ we can define a local electron mobility in the channel to be used in Expression 1 to calculate the new drain current and subchannel lengths. The whole procedure is solved again until a convergence criterium is reached.

III. RESULTS

0.1 μm , 0.2 μm , 0.25 μm , 0.5 μm , and 1 μm channel length MOSFETs have been simulated. The bulk doping concentration was $N_A = 4 \times 10^{17} \text{ cm}^{-3}$, the gate-oxide thickness $t_{\text{ox}} = 5.6 \text{ nm}$ and the source junction depth $x_j = 0.1 \mu\text{m}$. Figures 1 and 2 show the 2D electrostatic potential distribution and the 3D electron concentration for the 0.2 μm channel MOSFET simulated for $V_{GS} = 2.4 \text{ V}$ and $V_{DS} = 1 \text{ V}$. The short-chan-

FIGURE 1 2D electrostatic potential plot for the MOSFET simulated. $V_{GS} = 2.4$ V, $V_{DS} = 1$ V, $x_j = 0.1$ μm , $N_A = 4 \times 10^{17} \text{ cm}^{-3}$, $t_{ox} = 5.6$ nm, $L_{eff} = 0.2$ μm

FIGURE 2 3D electron density distribution plot for the MOSFET simulated. $V_{GS} = 2.4$ V, $V_{DS} = 1$ V, $x_j = 0.1$ μm , $N_A = 4 \times 10^{17} \text{ cm}^{-3}$, $t_{ox} = 5.6$ nm, $L_{eff} = 0.2$ μm

nel effects are quite evident even for this bias; however, we have seen that the two-dimensional current corrections to the one-dimensional model are not important due to the high bulk-doping concentration. The average kinetic-energy distribution for electrons along the channel is always below 0.5 eV, in the range of external voltages covered in this work. Therefore, according to Laux and Fischetti [1], a simplified description of the silicon band structure is justified. Nevertheless, we have also represented the effects of non-parabolicity on the electron dynamics in the channel. The inversion charge distribution along the channel is shown in Figure 4, Monte Carlo results (symbols) and drift-diffusion results (solid line) are compared. Both curves are in good agreement along the channel, and the same agreement was observed for the rest of transistors simulated. Figure 3 shows

FIGURE 3 Electron velocity versus channel position. Electron velocity overshoot can be observed near the drain. $V_{GS} = 2.4$ V, $V_{DS} = 1$ V, $x_j = 0.1$ μm , $N_A = 4 \times 10^{17} \text{ cm}^{-3}$, $t_{ox} = 5.6$ nm, $L_{eff} = 0.2$ μm

FIGURE 4 Electron density along channel obtained by Monte Carlo method (symbols) and by drift-diffusion method (solid line). $V_{GS} = 2.4$ V, $V_{DS} = 1$ V, $x_j = 0.1$ μm , $N_A = 4 \times 10^{17} \text{ cm}^{-3}$, $t_{ox} = 5.6$ nm, $L_{eff} = 0.2$ μm

the electron drift velocity along the channel obtained by the MC method. Noticeable velocity overshoot can be observed near the drain. Fig 5 shows the electron mobility along the channel for the same MOSFET. Making use of the Monte Carlo results obtained we are able to model electron mobility accounting for electron velocity overshoot and other effects observed in very short channel length MOSFETs and use them in simple drift-diffusion simulators.

FIGURE 5 Electron mobility versus channel position. $V_{GS} = 2.4$ V, $V_{DS} = 1$ V, $x_j = 0.1$ μm , $N_A = 4 \times 10^{17}$ cm^{-3} , $t_{ox} = 5.6$ nm, $L_{eff} = 0.2$ μm

IV. CONCLUSION

The study of non-local effects such as velocity overshoot, as well as modelling of the dependence of electron mobility and other magnitudes needed to describe electron transport in a MOSFET channel on the transverse and longitudinal electric fields along the channel, has been made possible using a Monte Carlo simulator of the electron dynamics in the channel, coupled with a solution of the two-dimensional Poisson equation including inversion-layer quantization and drift-diffusion equations.

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Biographies

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