ON THE EFFICIENT SIMULATION OF ELECTRON-ELECTRON INTERACTIONS IN NANOSCALE MOSFETS

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The ongoing scaling of MOSFET devices requires new models and simulation techniques for particle based Monte Carlo simulations of devices in the nanoscale regime. Electron-electron interactions must be considered because of two reasons. First, the Coulomb force is a long range force implying that both the short and the long range interactions have to be considered. Second, the hot-carrier and short-channel effects will have a significant impact on device performance due to the small number of carriers and impurities in the active region of nanoscale devices. There are two techniques that have been used in the past for solving the problem of properly including the short and the long range electron-electron and electron-ion interactions in particle based simulations: the P^3M approach [1] and the corrected Coulomb approach [2].

Most Ensemble MC simulators however do not include the full Coulomb interactions due to the necessary computational time and resources. In order to simulate the full Coulomb interactions in MC particle based simulators, P^3M methods (particle-particle particle-mesh methods [3]), adapted to the boundary conditions necessary for semiconductor devices, were used recently [2, 4].

However when this method is applied to simulations of semiconductor devices, the drawbacks are twofold. First DFT cannot be used to solve the Poisson equation since the boundary conditions are non-periodic. Second the inverse of the Laplace operator must be calculated for each particle in order to prevent counting nearby particles twice which is, of course, very time-consuming. In order to alleviate this problem, the inverse can be pre-computed (which takes several hours) and stored (which requires lots of memory), but this must be repeated for any new device structure.

To overcome these problems, we propose to use a FMM (fast multi-pole method [5]) instead. The FMM is based on the idea of condensing the information of the potential generated by point sources in several truncated series expansions. After calculating suitable expansions, the long-range part of the potential is obtained by evaluating the truncated series at the point in question and the short-range part is calculated by direct summation. Its computational effort is only $O(n)$ where n is the number of particles.

In order to verify that this approach is advantageous for particle based MC simulations, we used it to study the effects mentioned above in a MOSFET with a gate length of 15 nm using our MC simulator. The device used for the simulations is shown in Figure 1(a). The electric field due to the long-range electron-ion interaction and the applied boundary biases was calculated once in the beginning by solving the Poisson equation. Figure 2 shows the carrier distribution obtained by the PM (particle-mesh) and FMM approaches and in Figure 3 the average electron energy and velocity are plotted for both the PM and FMM cases.

Since this method is independent of the device grid, it is well-suited for inclusion into existing MC device simulation codes. In summary this approach is highly efficient concerning simulation time, avoids the drawbacks inherent in the P^3M approach, and enables to take into account all kinds of short-range and long-range electron-electron and electron-ion interactions in a rigorous manner.

References

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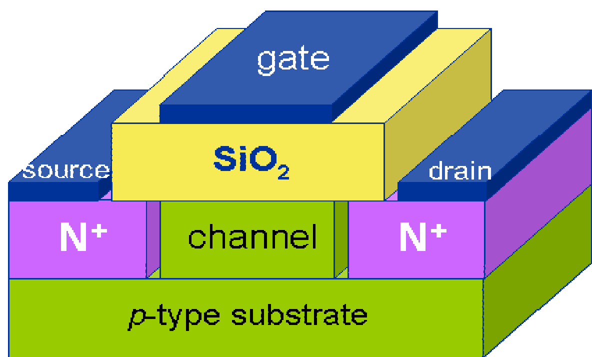
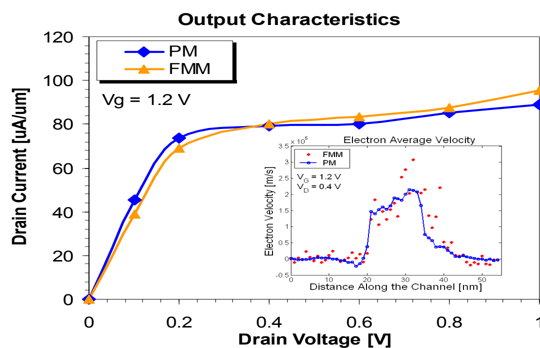
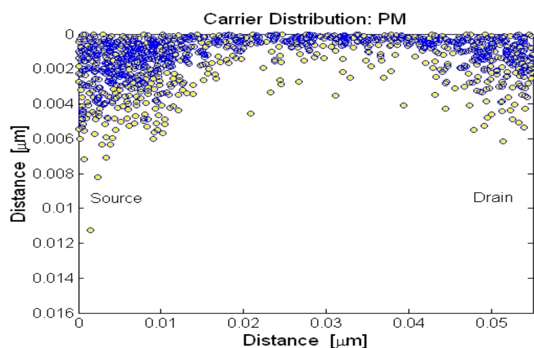


(a) Device structure.

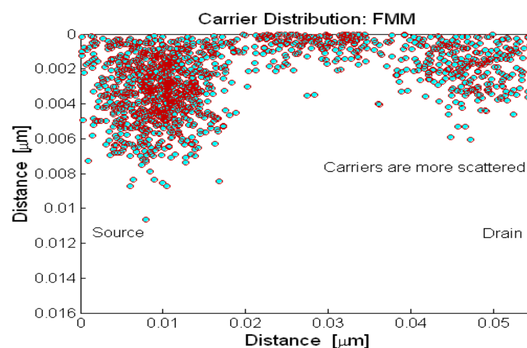


(b) Output characteristics.

Figure 1: **(a)** The simulated device has an oxide thickness of 1.0 nm, a channel length of 15 nm, a channel width of 0.5 ¯m, a source-drain junction depth of 15 nm, and the substrate doping is $N_A = 3 \cdot 10^{19}\,\text{cm}^{-3}$ and the doping of the source-drain regions is $N_D = 10^{19}\,\text{cm}^{-3}$. **(b)** The output characteristics of the device for $V_G = 1.2\,\text{V}$. The inset shows the average electron velocity along the channel for $V_G = 1.2\,\text{V}$ and $V_D = 0.4\,\text{V}$. The current increase in the FMM case can be attributed to the increase in carrier velocities in the channel region.

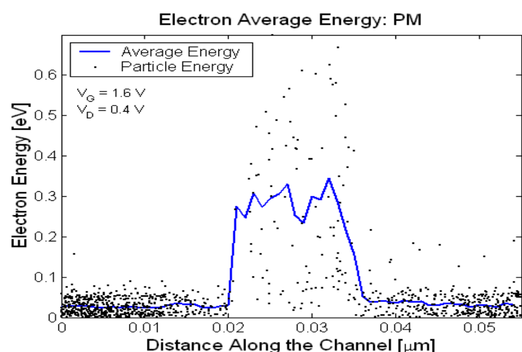


(a) Electron distribution (PM).

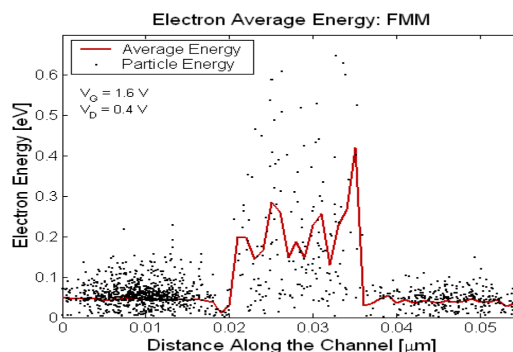


(b) Electron distribution (FMM).

Figure 2: The electron distribution as obtained **(a)** by the PM method and **(b)** using the FMM approach. The inclusion of the short-range electron-electron interaction by the FMM results in more scattered electrons with higher energy.



(a) Average electron energy (PM).



(b) Average electron energy (FMM).

Figure 3: The average electron energy along the channel for the **(a)** PM and **(b)** FMM case for $V_G = 1.6\,\text{V}$ and $V_D = 0.4\,\text{V}$.