Monte Carlo Device Modeling of a Self-Aligned n-MOSFET

Introduction

As MOS field-effect transistors are scaled down to a nanometer regime, non-equilibrium and ballistic effects can play a major role in determining device characteristics. In order to address this issue, SILVACO has developed a new module for Monte Carlo device modeling called MC Device. The new MC Device module is based on the MOCA simulator from the University of Illinois [1]. The model includes quantum corrections using an integrated 1-D Schrödinger solver, treats strained silicon including its spatial dependence, and provides statistical enhancement based on the comb and splitting-gathering methods. The model does not assume quasi-equilibrium of each carrier type as normally done in moment-based transport models like drift diffusion. Instead, the Monte Carlo transport model obtains the distribution function by solving the Boltzmann transport equation for each carrier type and by using full band structure and physical carrier scattering models. The MC Device module has been integrated into ATLAS for bulk and 2-D simulations.

Simulations

This article describes the simulation of a 40-nm silicon self-aligned n-MOSFET using the new Monte Carlo transport model. The structure of the self-aligned n-MOSFET is generated by 2-D process modeling using ATHENA [2]. The process simulation obtains the structure and mesh shown in Figure 1. The gate and channel lengths are 40 nm. The gate oxide thickness is 1 nm. The device has n-type source and drain regions doped to 1E20 cm⁻³. The channel is p-type at approximately 1E18 cm⁻³. The device uses a polysilicon gate.

The device simulation is performed with ATLAS using the MC Device module [3]. In this simulation, full band structure is employed for relaxed silicon using two conduction bands. The short channel length and relatively low channel doping indicates that quasi-ballistic transport will occur in the channel. The standard set of carrier scattering models for acoustic and optical phonons, impurities, and impact ionization were used [3]. In this case, the quantum correction was not activated although the model is provided as part of the MC Device module. We plan to show results for the quantum correction model in a future article.

The structure generated by ATHENA is imported and used to generate a similar structure for use with MC Device. MC Device requires rectangular regions, so the non-rectangular regions in the ATHENA structure (see Figure 1) are automatically converted to rectangular regions in the MC Device structure (see Figure 2). Since MC Device also requires a rectangular tensor-product mesh and a higher resolution mesh than the mesh used by ATHENA, the MC Device mesh (not shown) has been regenerated as a rectangular tensor project mesh using meshing statements in the input file. Alternatively, you can import the triangular mesh from ATHENA and automatically construct a rectangular tensor-product mesh based on the imported triangular mesh. The contacts for the source and drain are added to the structure to control the particle and potential boundary conditions on these boundaries. The gate contact controls the potential boundary condition on its boundary.

Monte Carlo device simulators like MC Device, which use an ensemble of electrons or holes, can perform a realistic transient simulation based on a good initial solution or a pseudo transient simulation based on an approximate initial guess. In our case of the self-aligned n-MOSFET, the later approach is used where the goal is to obtain the steady-state solution of the electron Boltzmann equation and the Poisson equation. For self-aligned n-MOSFET, MC Device performs a transient simulation for 25,000 iterations using a time step of dt=0.1 fs. The time-average electric potential and average electric fields for Vg=Vd=1 V and Vs=Vsub=0 V are shown in Figure 2. The time-average electron concentration and the time-average velocity vector direction are shown in Figure 3 for the same bias conditions.

Figure 1. A 40-nm self-aligned n-MOSFET generated using ATHENA.
The time-averaged kinetic energies of electrons are shown in Figure 4 for the same bias conditions. The results show the highest average energies occur near the edge of drain. The transient simulation yields three converging estimates for the steady-state source or drain current for the same bias conditions. The three estimates for the source or drain current are based on three integrations of the current density from the center, left, and right of this structure. The three estimates are shown as functions of the simulation time in Figure 5.

The average distribution function of the source well, channel, drain edge, and drain well are shown in Figure 6 for the same bias conditions. The curves show the heating of electrons as they traverse the channel. The diversion of the distribution function from a drifted Maxwellian distribution function shows why Monte Carlo modeling of this device is helpful.
Conclusion

This article presents the device Monte Carlo modeling of 40-nm self-aligned n-MOSFET using the new MC Device module in ATLAS. The model predicts the non-equilibrium and quasi-ballistic transport behavior in nano-scale transistors and allows you to analyze behavior that depends on accurate modeling of hot carrier tails of the carrier distribution functions.

References
1. The MOCA software was developed by the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign.