Finite Element Monte Carlo Simulation of Recess Gate FETs

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Abstract

In this paper we report on a new Monte Carlo (MC) module incorporated in our Heterojunction 2D Finite element FET simulator H2F [1]. For the first time this module combines a precise description of the device geometry with realistic particle simulation of the non-equilibrium hot carrier transport in ultra-short recess gate compound FETs. The capabilities of the new finite element MC module are illustrated in example simulations of two compound FETs fabricated in the Nanoelectronics Research Centre of Glasgow University.

1. Introduction

The ensemble Monte Carlo approach plays an important role in the simulation of submicrometer compound FETs where both steady-state and transient device behaviour are dominated by velocity overshoot effects. A large variety of devices including MESFETs [2], HEMTs [3] and pseudomorphic HEMTs [4] have been extensively studied over the past decade using the MC approach, with emphasis placed on different aspects of the device operation and miniturisation. Almost all of those studies consider oversimplified planar or rectangular solution domains. This is usually dictated by the rectangular finite-difference grid used for the discretization of Poisson's equation. In addition, the surface potential pinning effects are usually neglected.

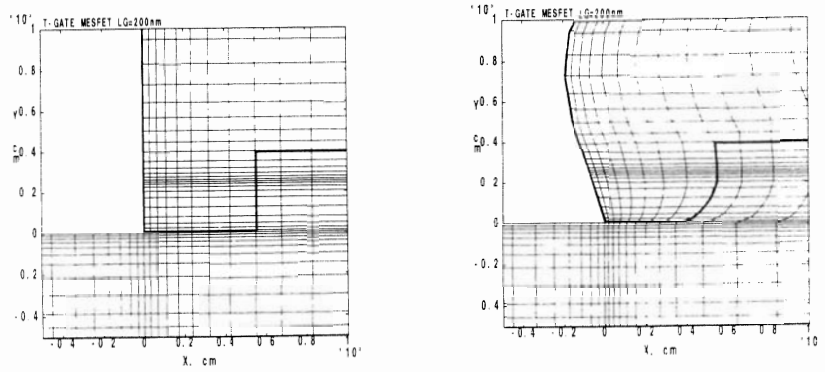
In contrast, almost all modern sub micrometer compound FETs are single or double recess devices [5] with complicated recess geometries. The length of the recess region is comparable to the length of the gate [5]. Device parasitics like access resistances and coupling capacitances are dependent on the shape and surface conditions of the recess [1]. These parasitics are critical to the device characteristics, limiting in many cases the device performance and restricting on the advantages of device miniturisation. Here we report on a new Monte Carlo simulation module suitable not only for qualitative research but for practical design of real sub micrometer FETs. It combines the extensive transport capabilities of the ansemble Monte Carlo with a precise description of the device geometry and proper handling of surface effects.

2. The Monte Carlo module

2. 1. Finite Element Grid Generation

Quadrilateral finite elements have been adopted to accurately model the device geometry; in particular the recess shape and gate profile. The triangulation includes not

only the semiconductor regions but also the air space in the recess region and above the cap layer. This provides proper modelling of the interaction between the charge on the surface states and the electrostatic potential and gives a realistic fringing field pattern.



(a) (b)

Figure 1: Generation of the quadrilateral grid in the recess region: (a) the initial rectangular grid (b) the quadrilateral grid after the transformation

The grid generation proceeds in two stages. In the first stage a rectangular non-uniform grid is generated such that it conforms to the vertical layer structure and to the simplified lateral pattern of the device. In the second stage the shapes of the recess region and the gate are introduced from a data file. These are usually obtained from SEM photographs of the device cross-section. By appropriate deformation the grid is adapted to the actual geometries, Figure 1(a,b).

2.2. Solution of the Poisson Equation

The Galerkin finite element approach has been adopted to solve Poisson's equation.

$$\frac{\partial}{\partial x}\varepsilon\frac{\partial}{\partial x}\psi+\frac{\partial}{\partial y}\varepsilon\frac{\partial}{\partial y}\psi+\rho_B+\rho_I=0 \tag{1}$$

where $\rho_B = q(p-n+N_D^+-N_A^-)$ is the bulk charge density and ρ_I is an interface and surface charge density, responsible for example for the surface potential pinning in recess gate FETs. The integration over quadrilateral elements during the discretization is carried out by a linear isoparametric mapping of each element into a unit square.

To provide a good initial approximation for the charge distribution in the device the nonlinear Poisson equation is solved, with electron and hole concentrations given by Boltzman or Fermi-Dirac statistics. This significantly reduces the amount of time necessary to obtain a steady-state solution.

2.3. Monte Carlo simulation in a Single Element

At the end of the finite-element triangulation process each finite element contains a single material with uniform doping concentration. Each finite element has a reference to a scattering table corresponding to the material type and doping level in the element.

A complete ensemble Monte Carlo procedure in a single quadrilateral element is the building block of the whole Monte Carlo module. During the motion of an individual particle its position with reference to the given quadrilateral finite element is tested using the linear isoparametric mapping used in the finite element formulation. If the

transformed co-ordinates of the particle both lie in the range (0,1) then the particle remains within the given quadrilateral element; otherwise, the particle has crossed one of the four boundaries and is now located outside the element. Hitting a grid boundary during a free-flight-time the particle will either be transferred to the neighbouring cell, reflected, absorbed etc. depending on the type of the given element boundary.

Apart from its finite element implementation our Monte Carlo procedure is standard [6]. The time of free-flight and subsequent scattering mechanisms are chosen using the usual self-scattering scheme. The potential distribution is recalculated and the electric fields updated approximately every 5 fs depending on the minimum element size and the doping concentration in the heavily doped cap layers of our devices. The step size ensures that the carriers will transit no more than one element before the field is updated. The scattering mechanisms implemented include: ionised impurity, acoustic phonon, piezo-electric, optical phonon and polar optic scattering modes. A non-parabolic three valley (Γ,L,X) conduction band model was used for the III-V materials.

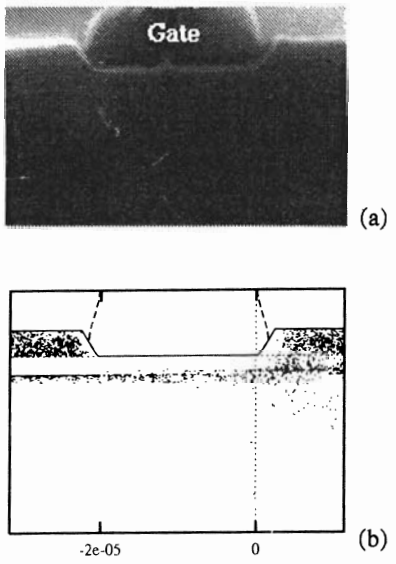


Figure 3: (a) SEM cross-section of a pseudomorphic HEMT (b) The corresponding H2F MC simulation domain

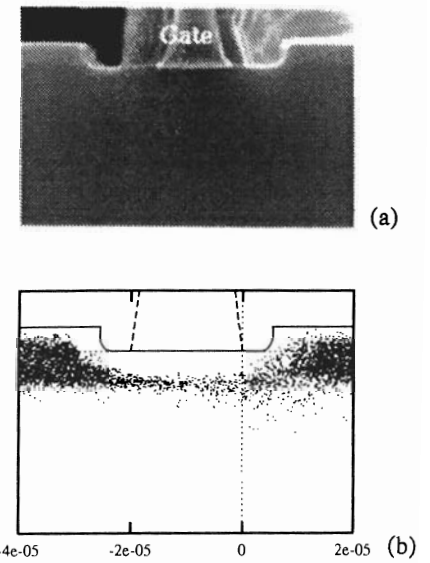
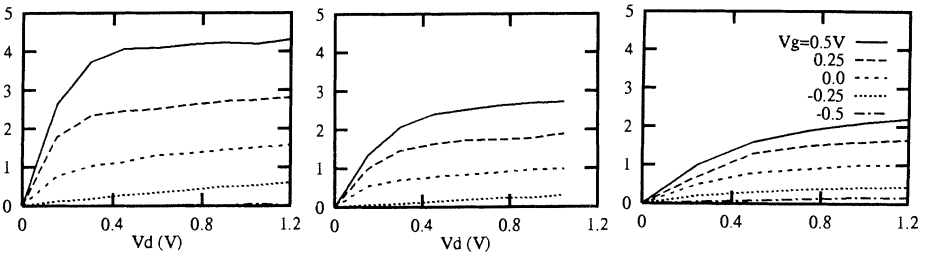


Figure 2: (a) SEM cross-sectional view of a 200 nm gate MESFET (b) The corresponding H2F MC simulation domain

3. Examples:

The ability of the quadrilateral finite element approach to precisely describe the shape of the recess region is illustrated for two short gate compound FETs with different recess shapes. Figure 2 (a) represents the SEM cross sectional view and the H2F simulation domain of a 200 nm gate length pseudomorphic HEMT fabricated virtually without offset between the gate and the recess edges. Figure 3 (a) represents the SEM cross sectional view and the H2F simulation domain of a 200 nm MESFET with 55 nm offset between the gate and recess edge. The distribution of superparticles at gate voltage $V_G = 0$ V and drain voltage $V_D = 1.5$ V are also given for both devices in Figure 2 (b) and 3 (b) respectively. In this example study we concentrate on the MESFET

from Figure 3 because the effect of the recess is more pronounced in this device as a result of the relatively large gate offset. Monte Carlo simulation results regarding pseudomorphic HEMTs will be published elsewhere.



(a) (b) (c)

Figure 4: Calculated and measured I_D-V_D characteristics of a 200 nm MESFET. (a) MC simulation without surface charge (b) MC simulation with surface charge Ns=2.5x10^{12} cm-2, (c) Measured characteristics

The surface conditions in the recess region critically affect the output device characteristics. The calculated and measured I_D-V_G characteristics are given in Figure 4 (a-c). The negligence of the surface potential pinning in the recess region (Figure 4 (a)) leads to unacceptable error in the calculate I_D-V_G curves. The introduction of surface charge in the recess region leads to a much better agreement between the simulations and the experiment (Figure 4 (b, c)).

4. Conclusions

In this paper we have described a new Monte Carlo module that is capable of modelling recess gate MESFETs and HEMTs. The novel feature of this module is the use of a Finite-Element discretization scheme to represent the device geometry in the best possible way. The the importance of the proper handling of the recess shape and the surface effects is demonstrated in example simulations of short MESFET and HEMTs.

References

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