MONTE CARLO SIMULATION OF SUBMICRON MESFETs

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A series of Monte Carlo results for GaAs MESFETs with submicron gate length are presented. The study is based on a self consistent simulation that couples the Monte Carlo procedure for charge transport in GaAs to a Poisson solver defined on a two dimensional grid. Channel electrons can reach velocities that largely exceed the saturation velocity (velocity overshoot). Such effect (enhanced by the reduction of gate length) guarantees very fast transit times in submicron structures. A comparison with the results obtained using a Drift-Diffusion algorithm are presented, which show the inadeguacy of tradition simulators in dealing with submicron structures.

1. Introduction

The trend towards the miniaturization of microelectronic components in order to achieve high speed and high integration has pushed the feature size of semiconductor devices well below the micron limit. Moving into the submicron scale, many new physical phenomena become important that require a sophisticated theoretical treatment. There exists, therefore, a new challenge towards the understanding of the principles of operation of those novel devices. Traditionally, device simulators have been based on drift diffusion (DD) or on balance equation (BE) models [1,2]. Both of them are fast and reliable as long as a local description of the physical phenomena in the device is possible. That is, when the carriers can be described by a distribution characteristic of the given field present in every region of the device. Such an assumption breaks down when the device dimensions are small (typically below one micron), and high fields are set up, leading to non-local phenomena. More specifically, when the field inside the device varies appreciably over lengths comparable with the electron mean free path, the electrons at a given position carry information about the field value at another position. The inclusion of the energy balance equation allows to incorporate some of these effects, at the cost of a much heavier computation [2]. The Monte Carlo technique, which is inherently non local, lends itself very well to the simulation of non stationary transport in devices [3-7].

In the following section we will briefly describe the MC algorithm. Section 3 will then present a discussion of the results obtained for submicron GaAs MESFETs, while a comparison with DD simulators will be given in Sect. 4.

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2. The Monte Carlo simulation of semiconductor devices

The simulation of a semiconductor device is performed for many particles in parallel and coupled to Poisson's equation in order to obtain the self-consistent potential consistent with the charge distribution given directly by the Monte Carlo procedure. Since no a-priori assumptions are needed on the form of the real and **k**-space carrier distributions, a Monte Carlo simulator is the only reliable tool for the investigation of those physical phenomena that critically depend on the shape of the distribution, or on the details of its tail (such as electron injection over potential barriers). Furthermore, the Monte Carlo technique allows us to focus on particular physical mechanisms that might be of importance on the device performance (for example, intercarrier scattering, impact ionization, generation-recombination, etc.). The prices one has to pay are a very time-consuming algorithm, and the requirement of a complete knowledge of the physical system under investigation.

The basic steps of a Monte Carlo simulation are :

i) Set up geometry and discretization scheme; two parameters that play an important role in the choice of the time step and the grid size are the plasma frequency and the debye length.

ii) Charge assignement. The charge of each particle is assigned to a particular mesh point. Since it is not possible to simulate all the electrons present in a real device, each simulated particle represents a cloud of electrons for the purpose of estimating currents, charge and field distributions. For all other purposes, each individual particle carries its elementary charge e. The doping charge is also added to the mesh according to its distribution.

iii) Potential solution. Poisson's equation is solved to determine the electrostatic potential at the mesh points. In connection to MC simulations, a finite difference scheme is generally used. The solution can be obtained in several ways, the most efficient being the direct matrix inversion, particularly effective on computers with vector processing. The electrostatic field is then obtained from the potential with a finite-difference algorithm.

iii) Flights. Each particle, now treated as an individual electron, undergoes the standard MC sequence of scatterings and free flights, subject to the local field previously determined from the solution of Poisson's equation. The MC sequence is stopped at fixed times, when the field is adjusted following the steps described above.

The description of the problem is completed by setting initial and boundary conditions. The initial conditions are not so important, since only the self-consistent steady-state result is usually retained. Boundary conditions are instead crucial, in particular in submicron devices, where contact properties drastically influence the whole behavior of the device.

A typical output of a MC simulation is presented in Fig.1, that shows the potential distribution (on a 40 x 12 uniform grid) for a submicron MESFET (gate length $L_g = 0.4\mu m$), with gate bias $V_{gs} = 0$ and drain bias $V_{ds} = 0.5V$. The total length of the

device is $2 \mu m$. The doping concentration of the epilayer is $10^{17} cm^{-3}$. A higher doping density ($3 \times 10^{17} cm^{-3}$) is used in the layers immediately below the source and drain electrodes, in order to simulate ohmic contacts. All the simulations for the present paper have been performed on CRAY-YMP using 100,000 particles.

3. Results

In submicron devices, very high electric fields can be found in the channel even at moderately low drain bias. Figures 2a and 2b show respectively the potential and field distribution in the channel of two MESFETs of 0.4 μm (continuous lines) and 0.2 μm (dashed lines) channel length. All other dimensions are kept constant (source and drain contact lengths are indicated by the thick marks on the figures). Typical of the submicron geometry is the fact that the electric field (in the longitudinal direction) peaks in the region under the gate, reaching values well above the threshold for negative differential resistance in the stationary case (around 3 kV/cm). The magnitude of this field is higher for the shorter device. The strong electric field in the channel leads to electron heating and velocity overshoot. The average energy of the channel electrons (Fig. 2c) exceeds the thermal value, following closely the electric field profile. At the

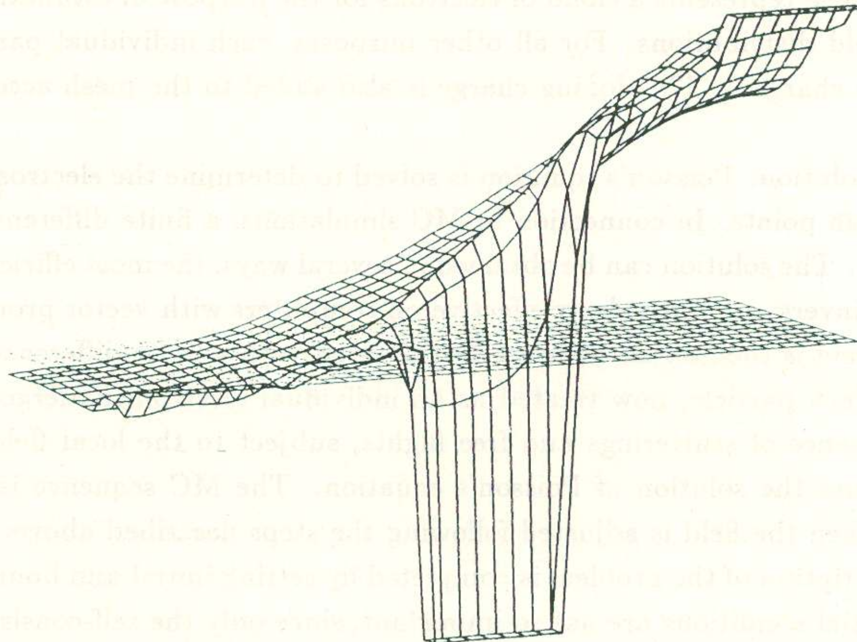

Fig. 1 Potential distribution for a quarter-micron gate length MESFET. The operating conditions are zero bias on the gate, and 1 V on the drain. The epilayer is doped at $10^{17} cm^{-3}$, the substrate at $10^{16} cm^{-3}$. The simulation has been performed using a 40 x 12 uniform grid with 100,000 electrons.

same time, the channel electrons reach longitudinal velocities (fig. 2d) that are much higher than the stationary ones at these fields. Due to the reduced dimensions, electrons do not transfer to the satelite valleys, keeping a high drift velocity for large part of the channel. At $V_{ds} = 0.5V$, only a few percent od the elctrons are founf in the L and X valleys, while at $V_{ds} = 1V$ such fraction grows to about 25 percent.

The MC results indicate that overshoot and heating effects are emphasized by the reduction of gate length, clearly suggesting that the improvement in the cutoff frequency (inversely proportional to the channel transit time) detected experimentally when the device shrinks are attributable to the overshoot phenomenon. Correspondingly, the output current calculated in the simulation increases from 241 mA/mm up to 291 mA/mm moving from $L_g = 0.4\mu m$ down to $L_g = 0.2\mu m$.

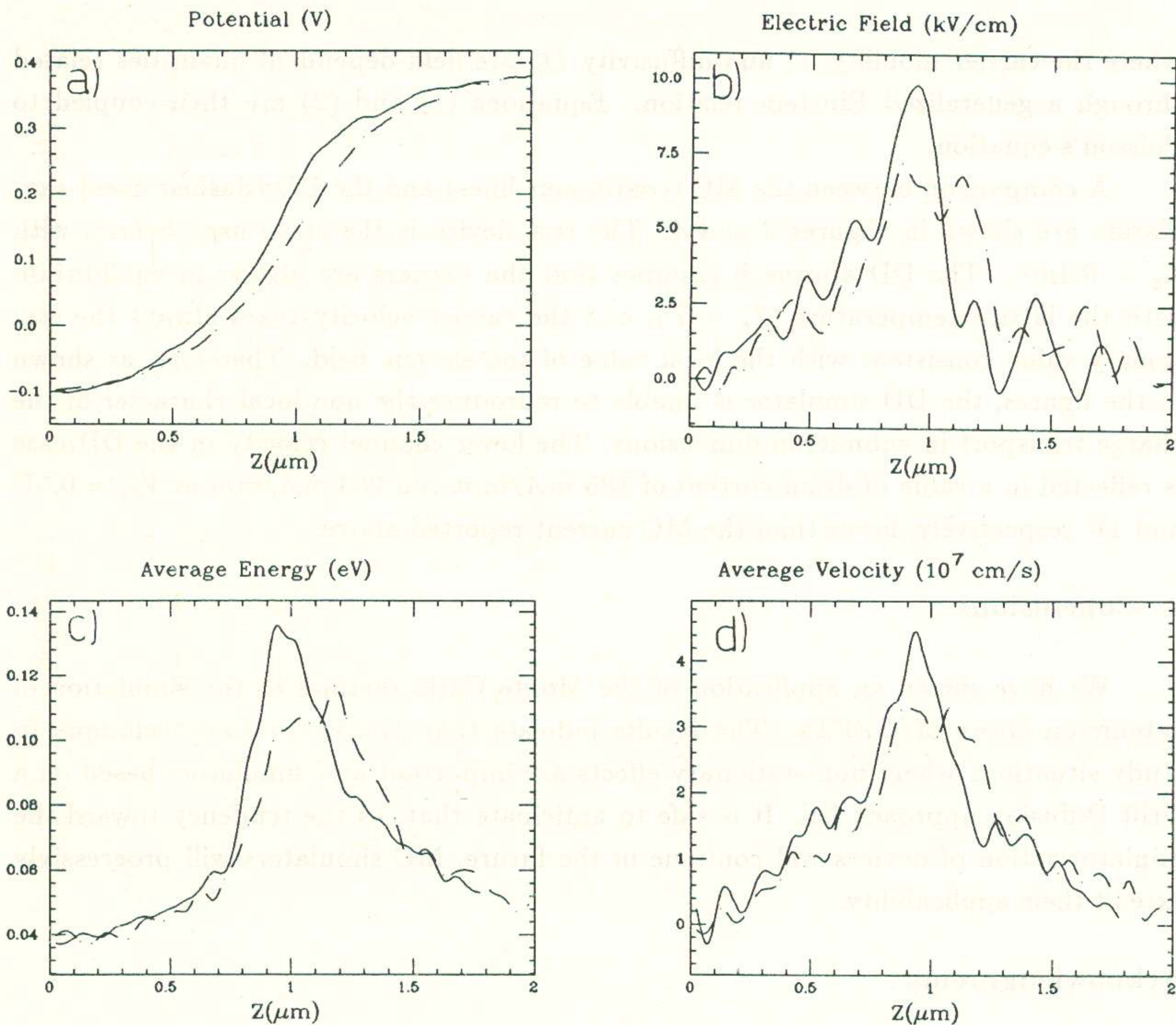

Fig. 2 Potential (a), longitudinal electric field (b), average electron energy (c) and average electron longitudinal velocity (d) in the channel as a function of the distance from the source. $V_{ds} = 0.5V$ and $V_{gs} = 0V$. The continuous lines refers to $L_g = 0.2\mu m$, the dashed lines to $L_g = 0.4\mu m$.

4. Comparison with Drift-Diffusion simulator

As pointed out earlier, the Monte Carlo technique is a fairly new tool in the area of semiconductor device modeling. Traditional simulators are based on the drift-diffusion (DD) model, which is particularly appealing because of its intrinsic speed. The DD algorithm uses the continuity equation:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot (\mathbf{J_n}) \, , \tag{1}$$

with the following definition of the current density:

$$\mathbf{J_n} = qn\mu_n \mathbf{E} + qD_n \nabla n \, , \tag{2}$$

where the carrier mobility μ_n and diffusivity D_n are field-dependent quantities related through a generalized Einstein relation. Equations (1) and (2) are then coupled to Poisson's equation.

A comparison between the MC (continuous lines) and the DD (dashed lines) simulators are shown in Figures 3 and 4. The test device is the same used before, with $L_g = 0.4\mu m$. The DD approach assumes that the carriers are always in equilibrium with the lattice temperature ($T_e = T$), and the carrier velocity takes always the stationary value consistent with the local value of the electric field. Therefore, as shown in the figures, the DD simulator is unable to reproduce the non local character of the charge transport in submicron dimensions. The lower channel velocity in the DD case is reflected in a value of drain current of 186 mA/mm and 263 mA/mm at $V_{ds} = 0.5V$ and $1V$ respectively, lower than the MC current reported above.

5. Conclusions

We have shown an application of the Monte Carlo method to the simulation of submicron GaAs MESFETs. The results indicate that MC is the best technique to study situations where non-stationary effects are important and simulators based on a Drift-Diffusion approach fail. It is safe to anticipate that, as the tendency toward the miniaturization of devices will continue in the future, MC simulators will progressivly extend their applicability.

Acknowledgments

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References

1. S. Selberherr, " Analysis and Simulation of Semiconductor Devices", Springer Verlag, Wien (1984).
2. G. Baccarani, M. Rudan, R. Guerrieri, and P. Ciampolini, in "Process and Device Modeling", Ed. W.L. Engl, p. 107, North Holland, Amsterdam (1986).
3. C. Jacoboni, and L. Reggiani, Rev. Mod. Phys. **55**, 645 (1983).
4. A. Yoshii, M. Tomizawa, and K. Yokoyama, IEEE Trans. Electron Dev. **ED30**, 1376 (1983).
5. C. Moglestue, IEEE Trans. Computer-Aided Design, **CAD-4**, 536 (1985)
6. M. V. Fischetti and S. E. Laux, Phys. Rev. **B38**, 9721 (1988).
7. C. Jacoboni, and P. Lugli, " The Monte Carlo Method for Semiconductor Device Simulation", Springer Verlag, Wien (1989).

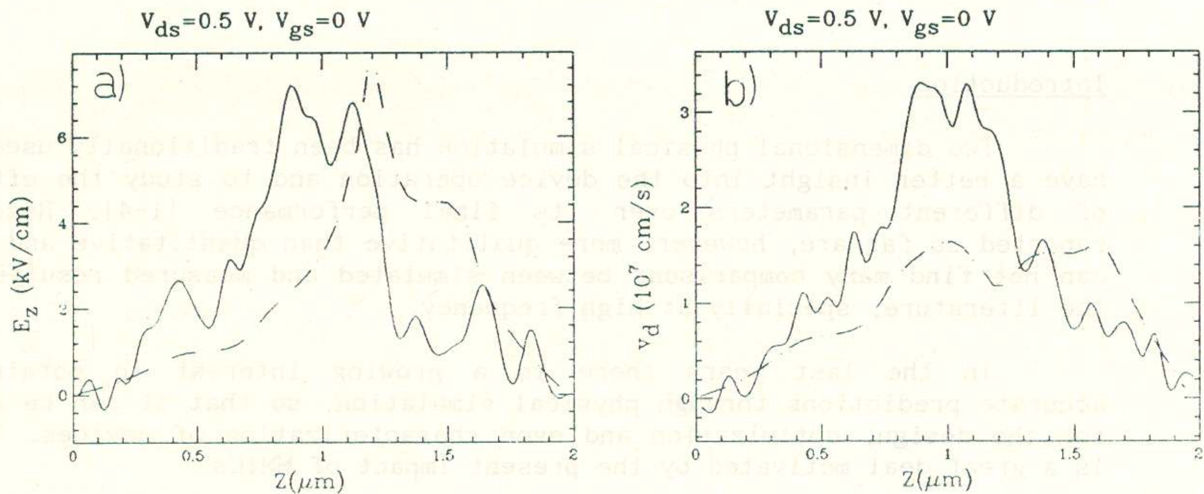

Fig. 3 Longitudinal electric field (a) and longitudinal average velocity (b) distributions in the channel of a $0.4 \mu m$ MESFET as obtained by MC (continous curves) and DD (dashed curves) simulators. The bias conditions are indicated.

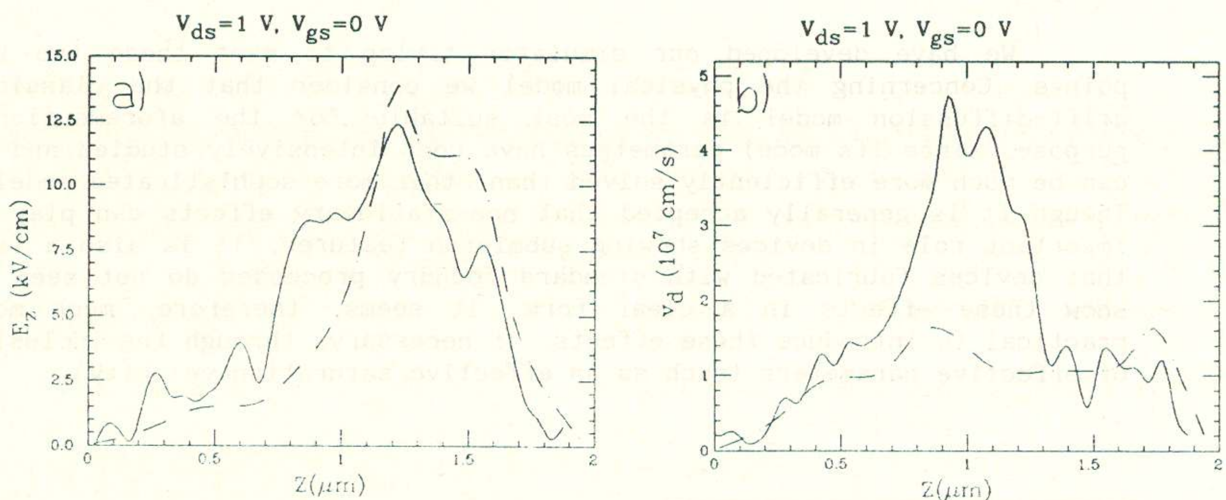

Fig. 4 Longitudinal electric field (a) and longitudinal average velocity (b) distributions in the channel of a $0.4 \mu m$ MESFET as obtained by MC (continous curves) and DD (dashed curves) simulators. The bias conditions are indicated.