Conduction and Noise Modelling of Submicronic Devices: Comparison Between ISE-TCAD Software and Microscopic Simulations

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Abstract

We present a comparison of noise simulations made using ISE-TCAD software and microscopic simulators. The impedance field, the local source of diffusion noise and the spectral density of voltage fluctuations simulated by ISE are compared with results obtained by Monte Carlo and Scattered Pack Method simulations. Our investigations concern submicronic \( n^+ - n - p^+ \) and \( p^+ - p - p^+ \) structures at ambient temperature.

The good agreement we found between ISE results and the microscopic approaches validates the calculation of the noise for the case of submicronic silicon diodes.

1. Introduction

The scale reduction of electronic devices makes the background noise become an important parameter for the semiconductor devices performances and a quality rating [1]. Since the electrical modelling of noise based on equivalent circuits does not allow its full understanding, in particular from the local point of view, a physical modelling is necessary. This can be done in the framework of macroscopic simulators based on drift-diffusion (DD) or hydrodynamic (HD) models [2] [3] or in the framework of microscopic approaches such as Monte Carlo (MC) [4] or Scattered Packet Method (SPM) [5]. Some of these calculations methods and their associated models are introduced in industrial softwares. We use ISE-TCAD, since a noise calculation module has been recently introduced [6]. It uses a macroscopic approach to calculate the impedance field used to determine the spectral density of voltage fluctuations.

Due to the complexity of noise modelling, we have considered only one dimensional silicon \( n^+ - n - n^+ \) and \( p^+ - p - p^+ \) diodes as a preliminary study preceding more realistic devices (transistors). To begin, we present the first order comparisons between ISE-TCAD simulations and results obtained by using microscopic simulators. Then, the ISE-TCAD impedance field calculation is validated by comparison with Scattered Packet Method results. The last part of this work concerns the calculation of the spectral density of voltage fluctuations by using several simulators.

2. Models and methods used by ISE software

2.1. Drift Diffusion and Hydrodynamic models

The DD model is widely used for the simulation of the carrier transport in semiconductors. In ISE, this model solves the basic semiconductor model equations by discretizing them and using the Newton linear method. The elaboration of geometry and mesh of the device is performed in two dimensions. But, with the scaling in the deep-submicronic regime, neither internal nor external characteristics of semiconductor devices can be described properly using the conventional DD model. In particular, it can not reproduce the velocity overshoot phenomenon, what HD approach does. In effect, the HD model used by ISE takes into account the three first momenta of the carriers distribution function, i.e. the concentration, the velocity, and the energy. For this reason, the HD model is generally suited for devices with small active regions while the DD model should be reserved for low power density devices with long active regions.

2.2. Impedance Field Method with Green Function for Noise simulation

The macroscopic models need the use of the impedance field theory [7] to model the noise in semiconductor devices. The noise analysis in ISE is based on the Langevin equation using a Green function approach. This technique allows the modelling of small-signal perturbations and to compute the voltage fluctuations at the terminals in terms of correlation spectra due to the local microscopic noise sources in the device.
3. Microscopic methods

3.1. Monte Carlo Simulator

Monte Carlo is a microscopic method which allows to obtain informations about the transport parameters and the noise by using a statistical way. In effect, since we are able to know the states of every carrier at each step of the simulation, we can follow the fluctuations in time of the average current or voltage and then calculate the associated correlation function. Then, the corresponding spectral density is obtained by making a Fourier transform of this quantity.

3.2. Scattered packed Method

The Monte Carlo Method and the direct solution of the Boltzmann equation have shown their efficiency to provide transport coefficients. However, both have some inherent shortcomings. In effect, the direct solution of the Boltzmann equation calculates small-signal parameters with high accuracy but meets with difficulties to give informations about noise. On the other hand, the statistical aspect of the Monte Carlo method, which permits to calculate the noise, does not allow to calculate small-signal parameters with high accuracy.

The Scattered Packet Method is an original technique to obtain these informations by combining advantages of these two classical methods. Therefore, it allows to calculate the impedance field and to validate the results obtained by using the ISE-TCAD simulator.

4. Results and Discussion

4.1. Structures of interest

The submicronic structures of interest are one dimensional $n^+ - n - n^+$ and $p^+ - p - p^+$ diodes.

In the case of the $n^+ - n - n^+$ structure (diode I), each doping region is $0.2\ \mu m$ long. The electron concentration of the $n$-type region is $10^{16}\ \text{cm}^{-3}$, while these of the $n^+$-type ones are $10^{17}\ \text{cm}^{-3}$.

For the $p^+ - p - p^+$ structure (diode II), the $p$-type region is $0.4\ \mu m$ long and the hole concentration is $10^{16}\ \text{cm}^{-3}$. The $p^+$-type regions are $0.3\ \mu m$ long and the hole concentrations are $10^{17}\ \text{cm}^{-3}$.

4.2. Static profiles

To analyse the local and the global noise properties of these diodes, we must firstly describe the static profiles. To this purpose, we begin by comparing ISE results to these of a MC simulation done for diode I. To calculate the field-dependent mobility and the velocity of carriers, ISE uses analytical approximations. The stationary electric field profiles (figure 1.a) obtained from DD and HD models at several bias coincide with MC results. In addition, figure 1.b and 1.c shows a good agreement between the HD model and the MC simulation when the velocity overshoot phenomenon appears. This agreement is not observed when comparing with the DD model, in accordance with the theoretical considerations.

Figure 1. Spatial dependence of the modulus of the electric field (a) and of velocity (b) (c) of diode I for the reported applied voltages. MC, DD, and HD refer to Monte Carlo, drift-diffusion and hydrodynamic simulations, respectively.

4.3. Impedance field

The direct impedance field method using Green function approach, which is implemented in ISE, is performed during the AC analysis simulation. Its principle is to calculate the complex small signal admittance matrix in order to specify the current at a given node for a small voltage at another node. The numerical computation of the device Green function for each considered node is performed by using an efficient algorithm based on the approach of a block decomposition of the Fourier transformed Jacobian matrix [8]. The DD, HD, and SPM simulations of the square modulus of the hole vector impedance field performed for the diode II are in good agreement, as shown in figure 2.
The square modulus of the hole vector impedance field simulated for the same diode, considering an applied voltage \( U = 0.6 \text{ V} \) and nine different frequencies, is reported in figure 3. The agreement among the three methods (DD, HD and SPM) is excellent at each frequency. More of that, the spectral dependence of the differential impedance for the three same methods are in agreement (figure 4).

In addition, to verify the coherence of obtained results, we have reported in figure 4 the integration of the modulus of the hole vector impedance field (DD).

4.4. Diffusion noise

Diffusion noise is due to fluctuations of the carriers velocities, caused by collisions with phonons, impurities, etc. The implemented diffusion electron noise source used by ISE is defined in the following expression\(^9\):

\[
K_{\text{diff}} = 4q^2 n D_n
\]  

(1)

where \( n \) is the electron density, \( D_n \) the electron diffusivity, and \( q \) the elementary charge. Similar expression for hole noise source is taken into account. The short range interactions between the carriers, i.e. carrier-carrier scattering, are neglected and the anisotropic effects are not taken into account. The spatial dependence of diffusion source of diode II is correctly evaluated by DD and HD simulations (figure 5). Figure 6 shows spectral density of fluctuations of the two diodes studies for given bias. Compared with microscopics simulations (MC and SPM), the noise calculation is correctly made by ISE. At high frequencies, the contribution to the the spectral density coming from the \( n \) region decreases, while this of the \( n^+ \) regions increases, reaching its maximum value for the associated plasma frequency (1275 GHz) given by the MC simulation \(10\).
Figure 5. Spatial dependence of diffusion noise source of diode II at frequency $f = 10$ GHz and an applied voltage $U = 0.6$ V.

Figure 6. Spectral density of voltage fluctuations of diode II (a) and diode I (b) for the reported applied voltage.

5. Conclusion

This work presents a comparison between the two models of ISE and the microscopic methods to simulate conduction and noise in semiconductor devices. For low bias conduction, the DD and HD simulation by ISE is equivalent but when the bias is sufficient for velocity overshoot appears, only HD simulation allows to simulate correctly the local electrical conduction. We obtain a good agreement between ISE simulation and SPM simulation for the impedance field. So, the noise is correctly evaluated by ISE for the case of the submicronic silicon diodes studied here.

6. References