A WAVELET-BASED APPROACH TO ANALYZE THE ELECTROMAGNETIC WAVE EFFECTS ON MICROWAVE TRANSISTORS

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Abstract – **A new wavelet-based simulation approach for the analysis and simulation of microwave/mm-wave transistors is presented. The Daubechies-base wavelet approach is applied to semiconductor equations to generate a nonuniform mesh. This allows forming fine and coarse grids in locations where variable solutions change rapidly and slowly, respectively. Also, some modifications for using the generated nonuniform mesh, which has been obtained based on the dc solution, in the ac analysis is presented.**

I. INTRODUCTION

With today's powerful computing capabilities, numerical simulation based on physical modeling can be used to predict and provide better understanding of device behavior. This approach becomes more desirable to understand the physical phenomena resulting from the ever-decreasing device dimensions. When semiconductor devices are operated at high frequencies, quasi-static semiconductor device models fail to accurately represent the effects of the physical phenomena where the carriers interact with the propagating electromagnetic wave along the device [1]. Therefore, circuit-based models, distributed and semi-distributed models, usually used suffer from poor simulation of the EM wave propagation and questionable validity of the wave device interaction taking place inside the transistor. The full-wave physical analysis of semiconductor devices that is based on the coupling of Maxwell's equations and the semiconductor equations used to characterize the dynamic of the electron inside the device can describe and simulate the electromagnetic wave effects on these semiconductor devices [1]. But, this full-wave analysis of microwave and millimeter-wave transistors is a tremendous task that requires involved advanced numerical techniques and different algorithms [2]. Therefore, there is an urgent need to present a new approach to reduce the simulation time, while maintaining the same degree of accuracy. A conventional numerical approach to solve the differential equations of semiconductor models [3] is Finite-Difference Time-Domain (FDTD) technique. In this method, the unknown parameters are calculated in discrete positions named mesh nodes. By implementation a technique for generation a nonuniform mesh, we would considerably reduce the number of unknowns and also decrease the time of simulation. In this nonuniform mesh, the density of nodes in domains where the unknown quantities vary rapidly is higher than the other regions. Such a technique corresponds to a multi-resolution of the problem. A very attractive way of implementing a multi-resolution analysis is to use wavelets [4]. Wavelets provide a natural mechanism for decomposing a solution into a set of coefficients which depend on scale and location. One can then work with the solution in a compressed form where one works only with the wavelet coefficients which are larger in magnitude than a given threshold.

In this paper, we propose to generate a nonuniform grid for simulating of microwave transistors using Daubechies-based wavelet method. The transistor first is biased and steady-state parameter solutions are obtained using FDTD and uniform grid. Then, the proposed wavelet scheme is applied and a nonuniform grid is generated. This mesh can be used in ac excitation state and decreases the time of full-wave simulation, significantly.

II. TRANSISTOR PHYSICAL MODEL

The semiconductor models used are based on the moments of Boltzmann's transport equations obtained by integration over the momentum space. Three equations need to be solved together with Poisson's equation in order to get the quasi-static characteristics of the transistor. This system of coupled highly nonlinear partial differential equations contains current continuity, energy conservation and momentum conservation equations [3]. The solution of this system of partial differential equations represents the complete hydrodynamic model. Simplified models are obtained neglecting some terms in momentum equation. One of these simplified models is

0-7803-8441-5/04/$20.00 © 2004 IEEE

drift-diffusion model (DDM) is derived by assuming that the mobility is a function of the electric field and doping. In this paper we simulate MESFET as microwave/mm transistor that is a unipolar device. For this device, the equations to be solved in the drift-diffusion model are [3]:

- Poisson's equations $$-\nabla^2\Phi = \frac{q}{\varepsilon}(N-n) \qquad (1)$$
- Continuity equation $$\frac{\partial n}{\partial t} = \nabla.\vec{J}_n \qquad (2)$$

with $$\vec{J}_n = \mu_n . n . \vec{E} + D_n . \vec{\nabla} n \qquad (3)$$

where Φ is potential, N is the doping profile, n is the electron (carrier) density, and μ_n and D_n are the mobility and the diffusion coefficient, respectively. In this work, electron mobility has been considered as a function of doping and electric field:

$$\mu_n(\vec{E}, N) = \frac{\mu_0(N) + (v_s(N)/E)(E/E_s(N))^4}{1+(E/E_s(N))^4} \qquad (4)$$

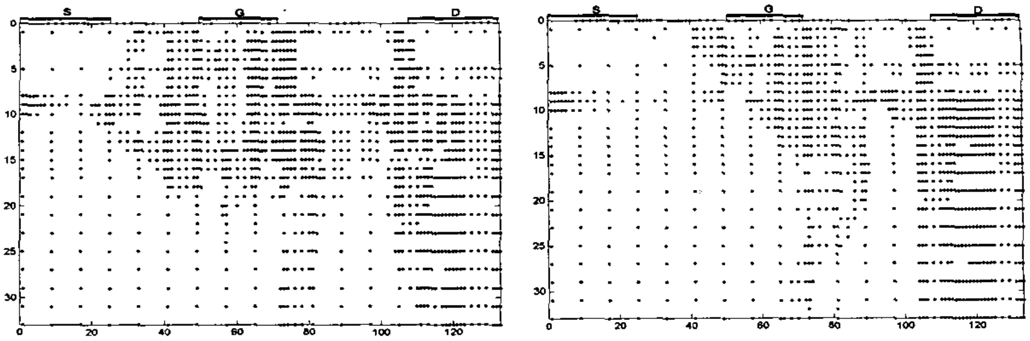
The parameters of this equation have been defined in [5]. The diffusivity is defined by the Einstein relation $D = (kT/q)\mu$. In order to characterize wave propagation-device interaction inside the transistor, the electromagnetic model that is described by the Maxwell's equations and the semiconductor model must be coupled. The full-wave simulation is started by obtaining the steady-state dc solution, using Poisson's equation and the semiconductor device model. The dc solution is used in the ac analysis as initial values. Then the ac excitation is applied and the Maxwell's equations are solved for obtaining the electric and magnetic field distributions. The new fields are used in the semiconductor model to find the current density. This process is repeated for each time interval [1]. We use FDTD technique to solve the equations and achieve stable and accurate solutions. At the first, a uniform mesh that covers the 2-D cross section of the MESFET is used. Initially, the device is biased and the dc parameter distributions (potential and carrier density) are obtained by solving the drift-diffusion model only. After calculating the distributions of these parameters, we apply wavelet scheme to the solutions and determine where quantities vary rapidly and slowly. In domains that the variation of parameters is low, the wavelet method can refine the mesh and reduce the nodes of initial uniform mesh. By this method, we can generate a nonuniform mesh that its density is low in dispensable places.

III. WAVELET SCHEME

In the numerical simulation of equations it is common that small scale structure will exist in only a small percentage of the domain. If one chooses a uniform numerical grid fine enough to resolve the small scale features in the majority of the domain the solution to the equations will be over resolved. One would like, ideally, to have a dense grid where small scale structure exists and a sparse grid where the solution is composed only of large scale features. Now we consider a Daubechies-based wavelet system. Wavelets provide a natural mechanism for decomposing a solution into a set of coefficients which depend on scale and location. One can then work with the solution in a compressed form where one works only with the wavelet coefficients which are larger in magnitude than a given threshold. Wavelets, therefore, sound ideal for solving the type of problem mentioned previously. The idea of using wavelets to generate numerical grids began with the observation in [6] that the essence of an adaptive wavelet-Galerkin method is nothing more than a finite difference method with grid refinement. Jameson demonstrated in [6] that Daubechies wavelet expansion represents a localized mesh refinement. In this paper we will follow his wavelet based grid generation algorithm explained in [7].

IV. SIMULATION RESULTS

As be mentioned, for generating the nonuniform mesh, first the device is biased and analyzed by solving one of the semiconductor hydrodynamic models using a uniform mesh and then the proposed wavelet scheme is applied to obtained dc parameters. Because the dc solution is used in ac analysis as initial values and also the level of ac excitation is lower than the dc level at most times, therefore one can conclude hat after applying ac excitation to the structure, the distributions of parameters will fix approximately. For this reason, we can use the nonuniform mesh generated from dc solution in ac analysis. But, when the signal is propagated along the third dimension of the transistor, it is amplified and the level of the ac signal is increased, so the generated nonuniform can be invalid at the end of transistor structure. Therefore in this simulation we investigate this situation and validate the generated nonuniform mesh. The structure and physical parameters of MESFET transistor simulated in this paper is similar to the transistor analyzed in [8]. The details of generation of nonuniform mesh have been described in [8]. Fig. 1 shows the generated mashes in two different bias points. As be seen, for different bias points only the meshes in region between source and gate in active layer are different. So the use of a nonuniform mesh that is denser in this region, will be more accurate for the ac analysis.



(a) (b)

Fig.1 The generated nonuniform meshes in two bias points (a)V_{gs}=-1V, V_{ds}=2V (b)V_{gs}=-0.5V, V_{ds}=3V

V. CONCLUSION

A wavelet approach based on the Daubechies wavelet scheme has been used to generate a nonuniform mesh toward full-wave analysis of microwave/mm-wave transistors. The transistor first is biased and steady-state parameter solutions are obtained. Then, the proposed wavelet scheme is applied to the solutions and a nonuniform grid is generated. The simulation results showed that this nonuniform mesh with some modifications, such as considering the denser mesh between source and gate in active layer, can be used in ac excitation state and decreases the time of full-wave simulation, significantly.

ACKNOWLEDGEMENT

This work was supported in part by Iran Telecommunication Research Center (ITRC).

REFERENCES

[1] M. A. Alsunaidi, S. M. S. Imtiaz, and S. M. El-Ghazaly, "Electro-magnetic wave effects on microwave transistors using a full-wave high-frequency time-domain model," *IEEE Trans. Microwave Theory Tech*, vol. 44, pp. 799–808, June1996.

[2] R. O. Grondin, S. M. El-Ghazaly, and S. Goodnick, "A review of global modeling of charge transport in semiconductors and full-wave electromagnetics," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 817–829, 1999.

[3] Y. K. Feng and A. Hintz, "Simulation of submicrometer GaAs MESFET using a full dynamic transport model," *IEEE Trans. Electron Devices*, vol. 35, pp. 1419–1431, Sept. 1988.

[4] S. G. Mallat, "A theory for multiresolution signal decomposition: The wavelet representation," *IEEE Trans. Patt. Anal. Machine Intell.* vol. 11, pp. 674–693, July 1989.

[5] X. Zhou and H. S. Tan, "Monte Carlo formulation of field-dependent mobility for $Al_xGa_{1-x}As$," *Solid-State Electronics*, vol. 38, pp. 567-569, 1994..

[6] L. Jameson, "On the wavelet optimized Finite Difference method," *ICASE Report, No. 94-9*, NASA Langley Research Center, Hampton, 1994.

[7] L. Jameson, "Wavelet-based grid generation," *ICASE Report, No. 96-31*, NASA Langley Research Center, Hampton, 1996.

[8] M. Movahhedi, and A. Abdipour, "Wavelet-based grid generation toward full-wave physical analysis of microwave/mm-wave transistors," *Accepted to appear in 4th Int. Conf. Microwave and Millimeter wave tech. (ICMMT2004),* China, Aug. 2004