Full Wave Analysis of FET Fingers Using Various Semiconductor Physical Models

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Abstract **— We present a full wave simulation of FET fingers based on a global modeling approach. The electromagnetic fields inside the device are computed by a standard FDTD scheme and coupled to the semiconductor equations through the current density. Four different semiconductor models are used to characterize the active device. They are derived from the hydrodynamic model obtained by integration of Boltzmann's equations. The I-V Characteristics of the FET are obtained for the different models. The RF voltage gain and the S parameters can be compared. This is the first time that such an analysis is performed. The wave device interactions occurring in the FET can be modeled using various physical models. This allows us to determine which semiconductor model to use for a given gate length and a given frequency range when the electromagnetic interactions are simulated.**

I. INTRODUCTION

The progress in microwave technology over the past decade led to the development of smaller devices. This allowed higher operating frequencies and higher gain. As the frequency increases, electromagnetic effects occurring inside the FET cannot be neglected. Phenomena such as the phase velocity mismatch between gate and drain modes and reflection from electrodes open ends, affects the propagation of the wave along the gate width and therefore affects the performance. Distributed models usually used suffer from poor simulation of the EM wave propagation and questionable validity of the wave-device interactions taking place inside the FET.

Global modeling analysis of FET was first introduced by El-Ghazaly et al. [1]. It is based on the coupling of Maxwell's equations and the semiconductor equations used to characterize the dynamic of the electrons inside the device. The physical model used in [1] and [2] is the full-hydrodynamic model. It was used in [3] and [4] to perform a quasi-static analysis of sub-micrometer gate length transistor. The authors also demonstrated that this model was more accurate than the standard drift-diffusion model, which does not predict overshoot phenomena due to two-dimensional distribution of the energy.

Nowadays, power amplifiers used in base station for wireless telecommunications use very wide transistors. This creates the need for global modeling simulations of transistors at different frequency range.

In this paper, we propose to use several semiconductor physical models to characterize the dynamic of the carriers inside the FET. These models can then be implemented in a global modeling simulator to investigate the performance behavior of a FET finger depending on the gate length and the frequency.

II. SEMICONDUCTOR PHYSICAL MODELS

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 equations in order to get the quasi-static characteristics of the transistor. This system of coupled highly nonlinear partial differential equations is as follows: current continuity (1), energy conservation (2) and momentum conservation for the x-component (3).

$$\frac{\partial n}{\partial t} + \nabla.(n\bar{v}) = 0 \tag{1}$$

$$\frac{\partial(n\varepsilon)}{\partial t} + qn\bar{v}.\bar{E} + \nabla.(n\bar{v}(\varepsilon + k_b T)) = -\frac{n(\varepsilon - \varepsilon_0)}{\tau_\varepsilon(\varepsilon)} \tag{2}$$

$$\frac{\partial(nm^* v_x)}{\partial t} + qnE_x + \nabla.(nm^* v_x \bar{v}) + \frac{\partial(nk_b T)}{\partial x} = \frac{nm^* v_x}{\tau_m(\varepsilon)} \tag{3}$$

Where n is the carrier density, v the velocity, ε the energy, E the electric field, m^* the effective mass, k_b the Boltzmann's constant, T the temperature and τ_m , τ_ε the momentum and the energy relaxation time.

The solution of this system of partial differential equations represents the complete hydrodynamic model (CHM). Simplified models are obtained by neglecting time and/or space derivatives in the momentum equation (3). The simplified hydrodynamic model (SHM) is given by (4), which is equation (3) where the space derivatives have been neglected. The energy model (ENM) is given by (5), which is equation (3) where space and time derivatives have been neglected. Finally, a drift diffusion model (DDM) is derived by assuming that the mobility is a function of the electric field (6).

$$\frac{\partial(nm*v_x)}{\partial t}+qnE_x+\frac{\partial(nk_bT)}{\partial x}=\frac{nm^*v_x}{\tau_m(\varepsilon)} \tag{4}$$

$$qE_x+\frac{1}{n}\frac{\partial(nk_bT)}{\partial x}=\frac{m^*v_x}{\tau_m(\varepsilon)} \tag{5}$$

$$\mu(E)=\mu_0.\left(1+\frac{\mu_0|E|}{10^7}\right)^{-1} \tag{6}$$

These different models were used for quasi-static simulations in [3]-[4]. It was shown that CHM model predict a higher current compared to DDM due to overshoot phenomena taking place in the device. Deep level traps, surface charge and magnetic effects could be included.

It is to be noted that these models have different computational cost. The CHM model is the most costly and the DDM model is the less costly. The CPU time spent to obtain the quasi-static characteristics of a two-dimensional FET can vary by 30% if one chooses to use the DDM or the CHM.

III. Global Modeling Implementation

The main methodology of the global modeling approach is presented in [1]-[2]. In order to characterize the wave-device interactions inside the FET, the electromagnetic and the semiconductor models must be coupled. The charge carriers are used as sources of electromagnetic fields inside Maxwell's equations. In turn, the fields are used as forcing functions inside the semiconductor models.

A two-dimensional quasi-static simulation is performed to determine the initialization values of the transport parameters, electronic densities and dc fields, due to a fixed bias point. This allows the full-wave simulation to be carried out at a well-defined bias point because direct solution of Maxwell's equations inherently rejects all dc quantities. This initialization process represents the correct approach to compute the total field inside the device. This total field is equal to the dc field computed from the quasi-static simulation plus the time varying field computed from Maxwell's equations plus the field computed from the ac sweep of the drain voltage along the load line of the amplifier (7).

$$\overline{E}^{Total}=\overline{E}^{dc}+\overline{E}^{Maxwell}+\overline{E}^{drain} \tag{7}$$

The electromagnetic fields E and H are computed using the FDTD method. The three-dimensional structure analyzed is presented in Fig. 1.

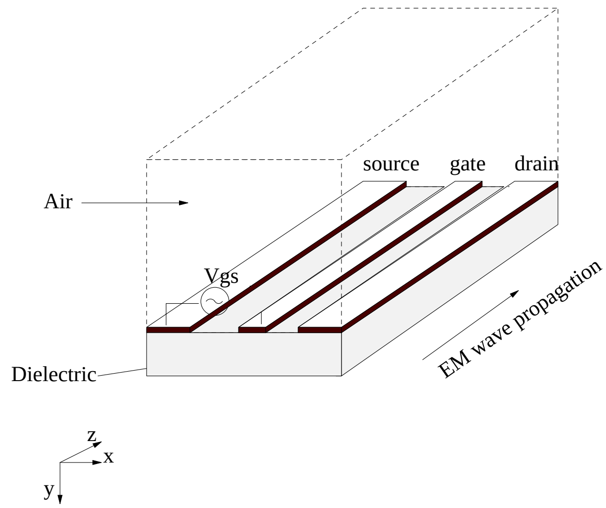

Fig. 1 Three dimensional FET finger

The total mesh size is 81*61*133 but the active device is inserted in a sub-mesh 61*31*81. Perfectly matched layers are used in the front and back-side while first order Mur boundary conditions are used on top, bottom, right and left side. This special arrangement of the absorbing boundary conditions was found to be crucial for numerical stability purposes. The two Maxwell's equations used in this model are the two curl equations given by (8) and (9).

$$\frac{\partial\overline{H}}{\partial t}=-\frac{1}{\mu}\nabla\times\overline{E} \tag{8}$$

$$\frac{\partial\overline{E}}{\partial t}=\frac{1}{\varepsilon}\left(\nabla\times\overline{H}-\left(\overline{J}^{Total}-\overline{J}^{dc}\right)\right) \tag{9}$$

Where J^{dc} is the dc current density computed from the quasi-static simulation and J^{Total} is the current density computed from the semiconductor model using $\overline{E}^{Total}$ as a forcing function on the electrons inside the FET.

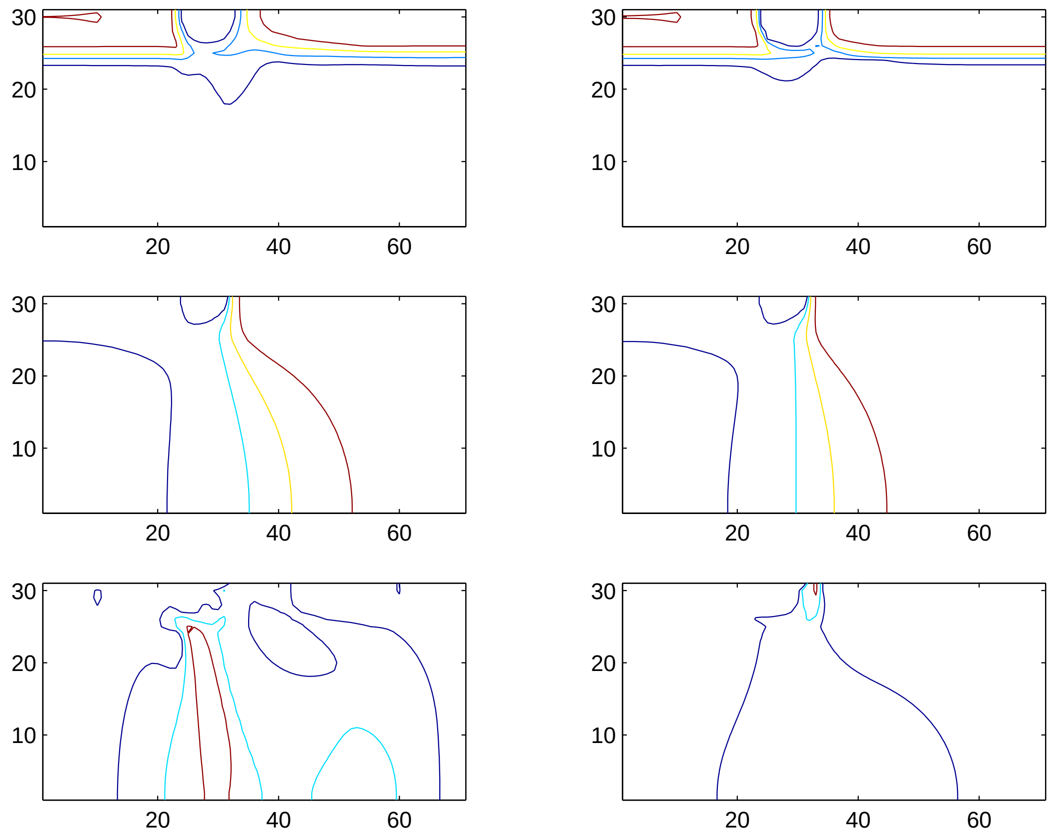

Fig. 2. Cross sections of the carrier density, potential, and velocity (x component). First column is for CHM and second column is for DDM. First row is the carrier density, second row is the potential and final row is the velocity.

IV. SIMULATION RESULTS

The quasi-static characteristics are obtained by solving (1), (2) and (3) together with Poisson's equation on a two-dimensional domain. The FET under analysis is a conventional MESFET of gate length *0.3 µm* with a *0.1 µm* active channel doped at 2.10^{17} A/cm^3 and a buffer layer of *0.4 µm* doped at 1.10^{14} A/cm^3. The source to gate separation is *0.5 µm* and the gate to drain separation is *1.0 µm*. The transistor is biased at a gate voltage V_{gs}= *-0.5 V* and at a drain voltage of V_{ds}= *3 V* with a *0.8 V* diffusion voltage.

Fig. 2. Shows the carrier density, potential and velocity (x-component) obtained using the CHM and DDM models. It demonstrates that the hydrodynamic model predicts that more electrons move into the buffer layer and that overshoot phenomena takes place with the velocity exceeding the saturation velocity.

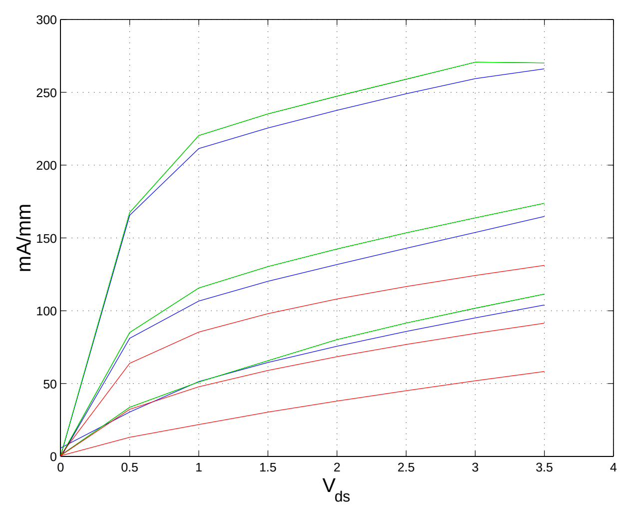

Fig. 3. I-V Characteristics of the MESFET. CHM in blue, SHM in black, ENM in green and DDM in red. For three gate voltages: 0 V, -0.5 V and –1 Volts.

Fig. 3 shows the IV characteristics obtained by steady state simulations. As predicted, the energy models give a much higher current than the DDM. The difference between SHM and ENM is indistinguishable on the graph. Simulations of different gate length transistor will be performed to determine when the SHM and ENM differ.

A global modeling simulation of the structure depicted in Fig. 1 was performed. Fig. 4 shows the velocity mismatch of the gate and drain modes.

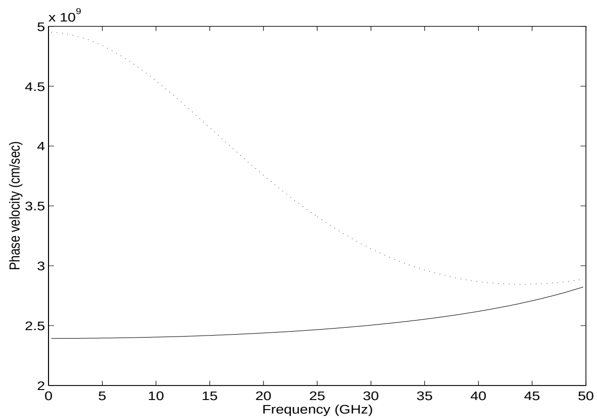

Fig. 4 Phase velocity as a function of frequency; gate mode (solid line), drain mode (dotted line).

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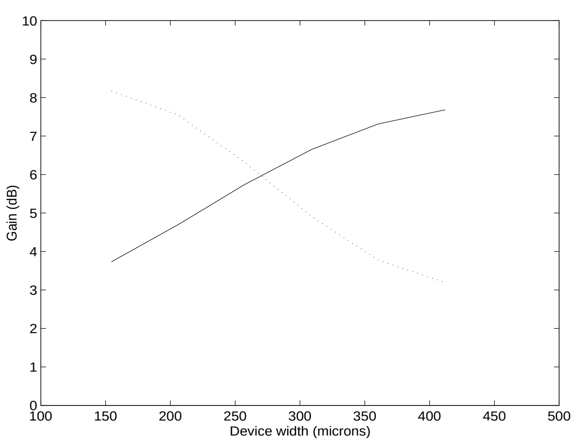

Fig. 5. RF Gain of the MESFET as a function of device width; frequency=10GHz (solid line), 100GHz (dotted line).

In Fig. 5, we present the RF voltage gain obtained for a *10GHz* input voltage and a *100GHz* input voltage versus gate width. Due to extensive computational time necessary to obtain the time domain results, simulation of the SHM, ENM and DDM full wave models will be presented in a later version of this work

V. Conclusions

Full-wave simulation of an active FET finger is investigated using different semiconductor models. These semiconductor models have different range of validity as some time and space derivatives are neglected from one to the other. Therefore different types of wave-device interactions are studied. RF voltage gain is obtained for different gate width at two different frequencies. This shows the importance of appropriate semiconductor models when trying to model high frequency active devices using a global modeling technique.

Acknowledgement

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References

[1] S. M. Imtiaz and S. M. El-Ghazaly, ”Global modeling of millimeter-wave circuits: Electromagnetic simulation of amplifiers” *IEEE Trans. Microwave Theory and Tech*., vol. MTT-45, pp. 2208-2216, December 1997.

[2] S. M. Hammadi and S. M. El-Ghazaly, ”Air-Bridged gate MESFET: A new structure to reduce Wave propagation effects in high-frequency transistors” *IEEE Trans. Microwave Theory and Tech*., vol. MTT-47, pp. 890-899, June 1999.

[3] Y.K Feng and A. Hintz “Simulation of Submicrometer GaAs MESFET’s Using a Full Dynamic Transport Model” *IEEE Transactions on Electron Devices*, Vol. 35, No. 9, pp. 1419-1431, September 1988.

[4] C. M. Snowden. and D Loret “Two-Dimensional Hot Electron Models for Short Gate-Lengthl GaAs MESFET’s ” *IEEE Transactions on Electron Devices*, Vol. 34, No. 2, pp. 212-223, August 1987.