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Time-Domain Electromagnetic-Physics-Based Modeling of Complex Microwave Structures

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***Abstract*—We present results and analysis of electromagnetic physical modeling of multifinger transistors, based on a newly developed time-domain numerical technique. Different examples are presented showing that accurate modeling of high-frequency devices should incorporate the effect of EM-wave propagation and electron-wave interactions within and around the device. Moreover, high-frequency advantages of multifinger transistors over single-finger transistors are underlined. The objective of this paper is to report an enhanced version of a previously developed multiresolution time-domain technique and also apply it for electromagnetic-physical modeling of multifinger transistors. Work is being done now to obtain S-parameters using the proposed technique and compare it with measurements.**

***Index Terms*— Full hydrodynamic model, global modeling, Maxwell's Equations, multifinger transistors, MRTD, semiconductor simulation, wavelets.**

I. Introduction

Multifinger transistors have proven better performance over conventional transistors, especially at very high frequency [1]-[3]. However, till now, modeling of such devices did not account for EM-wave propagation effects as well as electron-wave interactions using a fully numerical simulator. Accordingly, it is indispensable to present analysis of multifinger transistors based on a coupled electromagnetic-physics-based simulator. The possibility of achieving this type of modeling is addressed by global circuit modeling that has been demonstrated in [4]-[7].

II. Problem Description

The transistor model used in this work is a three dimensional (3-D) large-signal electromagnetic-physical model. The active device model is based on the moments of the Boltzmann's transport equation (BTE) obtained by integrating over the momentum space. The integration results in a strongly coupled highly nonlinear set of partial differential equations, called the conservation equations:

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

$$\frac{\partial (n\varepsilon)}{\partial t} + qn\boldsymbol{\upsilon}.\boldsymbol{E} + \nabla.(n\upsilon(\varepsilon + K_B T)) = -\frac{n(\varepsilon - \varepsilon_0)}{\tau_\varepsilon(\varepsilon)} \tag{2}$$

$$\frac{\partial (np_x)}{\partial t} + qnE_x + \frac{\partial}{\partial x}(np_x\upsilon_x + nK_B T) = -\frac{n(p_x - p_0)}{\tau_m(\varepsilon)} \tag{3}$$

In the above equations, n is the electron concentration, υ is the electron velocity, $\boldsymbol{E}$ is the electric field, ε is the electron energy, ε_0 is the equilibrium thermal energy, and p is the electron momentum. The energy and momentum relaxation times are given by τ_ε and τ_m, respectively. Similar expression can be obtained for the *y*-direction momentum. The three conservation equations are solved in conjunction with Maxwell's equations:

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{4}$$

$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J} \tag{5}$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{H}$ is the magnetic field, $\boldsymbol{D}$ is the electric flux density, and $\boldsymbol{B}$ is the magnetic flux density. The fields in Maxwell's equations are updated using the current density $\boldsymbol{J}$ estimated by (6).

$$\boldsymbol{J}(t) = -qn\upsilon(t). \tag{6}$$

The above model accurately describes all the non-stationary transport effects by incorporating energy dependence into all the transport parameters such as effective mass and relaxation times, along with including EM-wave propagation effects.

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III. PROPOSED ALGORITHM

Recently a unified multiresolution numerical approach to apply wavelets to the full hydrodynamic model and Maxwell's equations has been developed [8]. The main idea of the technique is to take snapshots of the solution during the simulation, and apply wavelet transform to the current solution to obtain the coefficients of the details. The coefficients of the details are then normalized, and a threshold is applied to obtain a nonuniform grid. Two independent grid-updating criteria are developed for the active and passive parts of the problem. Moreover, a threshold formula that is dependent on the variable solution at any given time has been developed and verified. Details of implementing this new time-domain technique are presented in [8].

IV. MICROWAVE CHARACTERISTICS OF HIGH-FREQUENCY TRANSISTORS

To study the characteristics of transistors at high frequency, a time-domain Guassian signal is applied between the source and gate electrodes for a field effect transistor (FET). The input and output time-domain signals are observed at different points along the width of the device. The characteristics of the device are then estimated. For example, the propagation constant γ can be evaluated as:

$$\gamma = \frac{1}{l}\log_e\left\{\frac{F(\omega,z+l)}{F(\omega,z)}\right\}. \qquad (7)$$

Where $F(\omega,z)$ is the Fourier transform of the time-domain signal. The attenuation and propagation constants are evaluated as the real and imaginary parts of γ, respectively. Figure 1 shows the attenuation constant as a function of frequency at different points along the device width for a typical FET. One notices that the attenuation constant increases with frequency as well as from point to point along the device width. The phase velocity υ_{ph} and effective dielectric constant ϵ_r can be estimated using Eqs. 8 and 9, respectively.

$$\upsilon_{ph} = \frac{\omega}{\beta} \qquad (8)$$

$$\varepsilon_r = \frac{\beta^2 c^2}{\left(2\pi f\right)^2} \qquad (9)$$

Where β is the propagation constant, c is the free-space wave velocity, and ω is the frequency in rad./sec. Figure 2 shows the phase velocity versus frequency at different

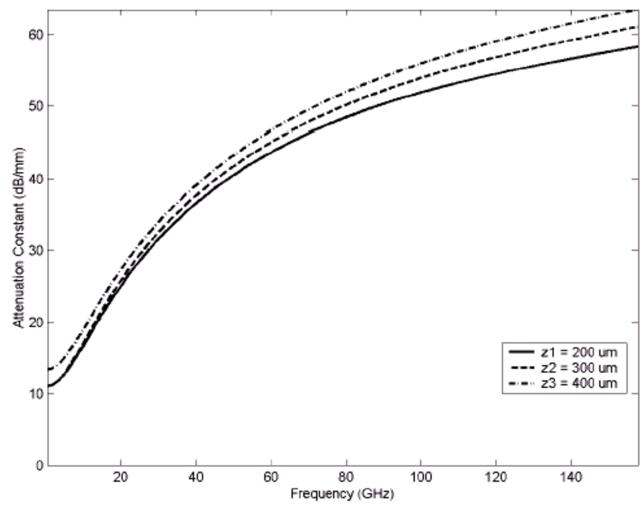

Fig. 1. Attenuation constant as a function of frequency at different points along the device width for the gate electrode (single finger).

points along the device width, respectively. The results shown in Figs. 1- 2 are mainly due to the change of the distribution of the electric field as a function of frequency and distance. These results are distinctive to high frequency devices only, which could be exploited by employing optimized microwave structures such as multifinger transistors. It is worth mentioning that these results are contrary to those obtained for passive structures, where the phase velocity should decrease with frequency. Considering Figs. 1-2, one calculates the attenuation and phase velocity at 60GHz (wireless LAN standard), to be 40 db/mm and 0.55c, respectively.

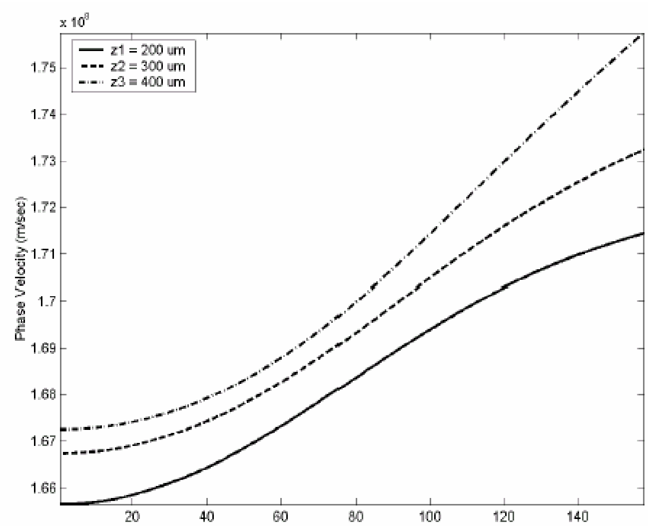

Fig. 2. Phase velocity as a function of frequency at different points along the device width for the gate electrode (single finger).

V. Electromagnetic-Physics-Based Modeling of Multifinger Transistors

It is clear from the previous results that EM-wave propagation and electron-wave interactions change the device characteristics at high frequency. Accordingly, different structure shapes and configurations need to be employed to minimize these effects, aiming to improve the device performance, especially at high operating power and frequency. A possible solution is to use multiple gate-fingers of shorter lengths. In this manner, EM-wave propagation effects along the device width are minimized. Moreover, attenuation is reduced as a result of reducing the gate metallic resistance. Thus large number of fingers is better in terms of reducing attenuation and wave-propagation effects along the device width. However, large number of fingers means that attenuation and EM-wave propagation effects are increased along the feeding line. Moreover, more fingers results in more EM-waves interference. Thus, EM-wave synchronization for the multiple fingers is crucial for maximum power and minimum interference. It is noteworthy to state that the EM-wave phase-velocity mismatches is due to the different applied voltages to the electrodes and also due to the unsymmetrical shape of the structure. Therefore, the number of fingers and distance between gate-fingers should be optimized simultaneously.

Also, for the case of the four-finger transistor, the shape and size of the air-bridge connecting the different fingers affect the high-frequency characteristics of the transistor. Considering Fig. 3(c), one notices that new capacitances between the air-bridge and transistor electrodes C_{air_bridge} are created. This would definitely change the EM-wave phase velocities and as a result change the device behavior. Thus an optimal air-bridge structure and size should be employed as well. Further, the air-bridge should not be fragile in order not to break easily, which represents an extra constraint that needs to be included in our optimization problem. The feeding line shape also represents a parameter that needs to be considered for circuit-matching issues.

In this paper, ad-hoc optimization is performed to obtain near-optimal transistor parameters based on the above criteria. Table I shows the new parameters for the optimized multifinger transistors, and Fig. 3 gives a generic 3D view of the simulated multifinger transistors.

Output voltages for the simulated multifinger transistors are shown in Fig. 4. Considering this figure, one observes that the voltage-gain increases when using four-finger transistors. In addition, the shape of the output signal for the four-finger transistor case appears to be much better, which means less number of harmonics. Work is being done now to extract S-parameters for the structures shown in Fig. (3).

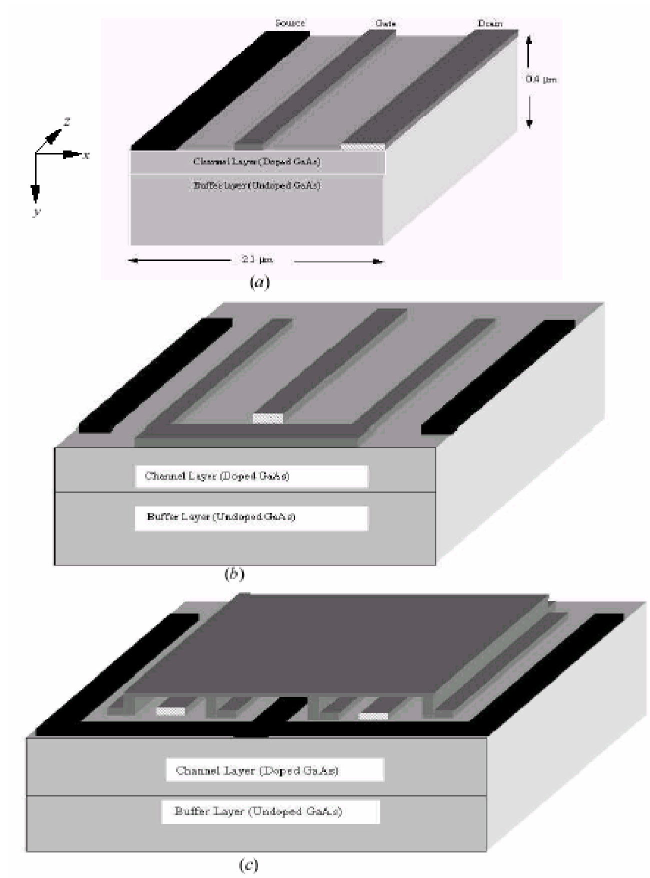

Fig. 3. Generic 3D view of the simulated multifinger transistors (not to scale). (a) Single-finger transistor (1x 450μm). (b) Two-finger transistor (2x 225μm). (c) Four-finger transistor (4x112.5μm).

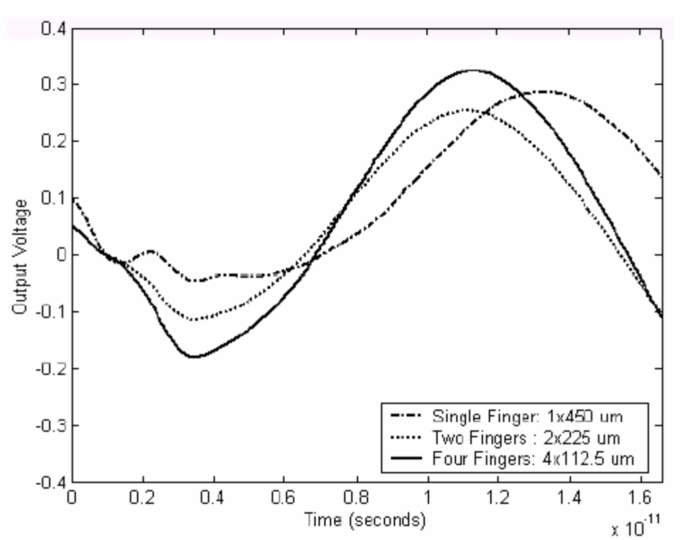

Fig. 4. Output voltage for the simulated multifinger transistors when EM-wave propagation and electron-wave interactions are considered.

TABLE I
TRANSISTOR'S OPTIMIZED PARAMETERS

Drain and source contacts	0.5 μm
Gate-source separation	0.5 μm
Gate-drain separation	0.4 μm
Device thickness	0.4 μm
Device length	2.1 μm
Gate length	0.2 μm
Device Width	1x450, 2x225, 4x112.5 μm
Active layer thickness	0.1 μm
Active layer doping	$2x10^{17}$ cm^{-3}
DC gate-source voltage	-0.2 V
DC drain-source voltage	3.0 V
Operating frequency	60 GHz

VI. CONCLUSION

The preliminary results of this paper show that at very high frequency, several phenomena with strong impact on the device behavior start to emerge, such as phase velocity mismatches, electron-wave interaction, and attenuation. The results suggest that contemporary microwave devices should be optimized to minimize these effects or possibly take advantage of in favor of an improved device characteristics. The results also recommend multifinger transistors as potential alternatives to conventional transistors. This is achieved by using multiple-finger gates of less width instead of a single-gate device. Furthermore, this paper underlines the enhanced microwave characteristics of multifinger transistors attributable to reducing attenuation and EM-wave propagation effects along the device width. The future research work will involve employing rigorous optimization techniques to obtain the optimal multifinger transistor structure based on the electromagnetic-physical model presented in this paper. Moreover, S-parameters measurements will be carried out and compared to the results achieved by this model.

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