# Electromagnetic-Wave Effects On Closely Packed Microwave Transistors Using A Fast Time-Domain Simulation Approach

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*Abstract*— **We present a new time-domain modeling technique to study the effect of electromagnetic-wave propagation on the performance of closely packed microwave transistors. The proposed approach solves the active device model that combines the transport physics, and Maxwell's Equations on nonuniform self-adaptive grids, obtained by applying Daubechies wavelet transforms followed by thresholding. This allows forming fine and coarse grids in locations where variable solutions change rapidly and slowly, respectively. The developed technique is applied to full-wave simulate two closely packed millimeter-wave transistors. Different numerical examples are presented; showing that accurate modeling of high-frequency devices should incorporate the effect of EM-wave propagation within and around the device. To our knowledge, this is the first time in literature to implement and report a wavelet-based technique for a fast full-wave physical simulation of more than one millimeter-wave transistor simultaneously.**

## I. Introduction

Modeling of high-frequency active devices needs a special attention. The wavelength of the propagating wave becomes comparable to the electron relaxation times. As a result, the electron transport physics is seriously affected by the propagating wave. Therefore, a global modeling approach needs to be developed to take that into account. Despite being the correct way to model high-frequency devices, global modeling techniques suffer from their extensive CPU-time requirement [1]. Therefore, there is an imperative need to present a new approach to reduce the simulation time, while maintaining the same degree of accuracy presented by the global modeling techniques. A possible approach is to use multiresolution nonuniform grids. Such technique can be categorized as a multiresolution time domain (MRTD), and the backbone to implement it is to use wavelets.

Therefore, a fast global modeling simulation approach for high-frequency active devices should involve a unified technique to simulate both passive structures and active devices efficiently, utilizing an MRTD technique.

In literature, different MRTD simulation approaches have been developed for passive structures and active devices independently. For instance, various MRTD approaches have been successfully applied to finite-difference time-domain (FDTD) simulations of passive structures [2]. However, for the active devices that are characterized by a set of coupled and highly nonlinear partial differential equations, applying the same approach would become quite time consuming. On the other hand, interpolating wavelets have been successfully applied to the simple drift diffusion active device model [3]. Being primarily developed for long-gate devices, the drift diffusion model leads to inaccurate estimations of device internal distributions and microwave characteristics for submicrometer devices. It is worth mentioning that in [3], the authors proposed a new technique to solve simple forms of Hyperbolic PDE's using an interpolating wavelet scheme. These PDE's can represent Maxwell's Equations or the simple drift-diffusion model, but not the complete hydrodynamic model. Thus, a new approach to apply wavelets to the hydrodynamic model is needed along with extending it to Maxwell's Equations for a fast global modeling simulation of high-frequency active devices.

In this paper, a unified approach to apply wavelets to the full hydrodynamic model and Maxwell's equations is developed. In addition, a full-wave global modeling simulator is developed to study the EM-wave propagation effect on closely packed millimeter-wave transistors.

## II. Methodology

The device model used is based on the moments of Boltzmanns Transport Equations obtained by integrating over the momentum space. The integration results in a strongly coupled highly nonlinear set of partial differential equations, which provide a time-dependent self-consistent solution for carrier density, energy, and momentum, respectively given by Equations (1)-(3).

$$\frac{\partial n}{\partial t} + \nabla \cdot (n v) = 0 \quad (1)$$

$$\frac{\partial (n\varepsilon)}{\partial t} + qnv \cdot \boldsymbol{E} + \nabla \cdot (nv(\varepsilon + k_B T)) = -\frac{n(\varepsilon - \varepsilon_o)}{\tau_\varepsilon(\varepsilon)} \quad (2)$$

$$\frac{\partial (np_x)}{\partial t} + qnE_x + \nabla \cdot (np_x v) + \frac{\partial (nk_B T)}{\partial x} = -\frac{n(p_x - p_o)}{\tau_m(\varepsilon)} \quad (3)$$



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$$J(t) = -q\,n(t)\,v(t) \tag{4}$$

The proposed wavelet-based algorithm for the active device is presented in [4]. In [4], the nonuniform grids are conceived by applying wavelet transform to the variable solution at any given time to obtain the coefficients of the details, which are then normalized to its maximum. Only grid points where the values of the normalized coefficients of the details larger than the threshold value are included for the next iterations.

Now, we turn our attention to Maxwell's Equations. The passive part of the FET represents a co-planar structure, in which a 3D FDTD is developed to solve for the electric and magnetic fields using Maxwell's Equations:

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{5}$$

$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J} \tag{6}$$

The current density estimated using Eq. (4) is used to update the fields in Maxwell's Equations. It is important to mention that the same approach developed to obtain the nonuniform grid for the variables in the conversation equations is applied to Maxwell's Equations as well. However, a different updating mechanism should be developed to keep track of the wave-propagation within the passive structure. The following is the algorithm developed for grid updating of FDTD simulations.

***Step 1:*** Construct a 3D matrix M that has only 0's and 1's, based whether or not a non-zero solution of the field exits at this location.

***Step 2:*** Estimate the value of ρ (FDTD grid-updating factor) as:

$$\rho = \frac{\sum_{i,j,k} (M_{new} \oplus M_{old})_{i,j,k}}{N_{xd} \cdot N_{yd} \cdot N_{zd}} \tag{7}$$

where $M_{new}$ and $M_{old}$ are the matrices constructed using step one for the current and old solutions of the fields, respectively. $N_{xd}$, $N_{yd}$, and $N_{zd}$ are the number of grid points in $x$, $y$, and $z$ directions, respectively.

***Step 3:*** Check ρ's value against a predefined value, for example 5%.

***Step 4***: If satisfied, move the grid to $z = z + dz$, and $dz$ is proportional to ρ.

***Step 5:*** $t = t + dt$

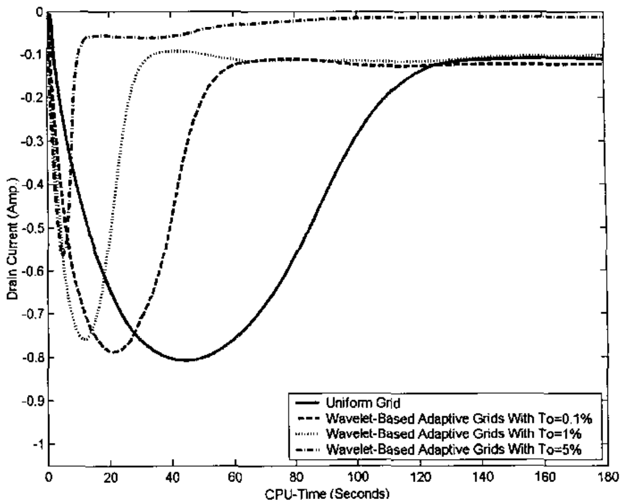


Fig. 1. DC drain current convergence curves for the uniform grid case and the proposed algorithm with different threshold values.

## III. Technique Validation

### A. *Hydrodynamic Model Simulations*

The approach presented in this paper is general and it can be applied to any unipolar transistor. To demonstrate the potential of this approach, it is applied to an idealized MESFET structure, which is discretized by a mesh of 64 $\Delta x$ by 64 $\Delta y$ with $\Delta t = 0.001ps$. Forward Euler is adopted as an explicit finite-difference method. In addition, upwinding is employed to have a stable finite-difference scheme. The space step sizes are adjusted to satisfy Debye length, while the time step value $\Delta t$ is chosen to satisfy the Courant-Friedrichs-Levy (CFL) condition.

Considering Fig. 1, it can be observed that using the proposed approach has reduced the CPU-time dramatically. For instance, there is a reduction of about 75% in CPU-time over the uniform grid case, using an initial threshold value of 1%. While, the DC drain current error is within 1%. Furthermore, using different initial threshold values affects the accuracy of the solution despite the CPU-time reduction. Fig. 1 suggests that using an initial threshold value equals to 1% is the right choice in terms of both accuracy and CPU-time

### B. *FDTD Simulations*

A 3-D Yee-based FDTD code is developed, with the proposed algorithm employed. In addition, a Gaussian excitation pulse is employed to evaluate the algorithm over a wide range of frequencies. Table I depicts the results, where it is observed as the threshold value increases, CPU-time and error introduced decreases as well. It is worth mentioning here that using an initial threshold value equals to 10% seems to reduce error along with the CPU-time. However, when the potential curves are considered, it is found that using an initial threshold value equals to 10% introduces dispersion, which is a serious type of error. Accordingly, an initial threshold value of 5% is recommended in terms of both CPU-time and error. It is significant to note that the passive and active parts of the problem have different optimal threshold values. This is expected since the variables in the conservations equations are highly nonlinear compared to the fields obtained when solving Maxwell's Equations.

TABLE I

| $T_0$ | *CPU-time* | *Error on Potential* | |
|---|---|---|---|
| | | *2-norm* | *Infinity-norm* |
| (Uniform Grid) | 744.90 s | | |
| 0.1% | 300.17 s | 0.0873% | 8.80% |
| 1.0% | 205.92 s | 0.0871% | 8.75% |
| 5.0% | 155.10 s | 0.0778% | 7.69% |
| 10.0% | 111.05 s | 0.0473% | 3.66% |

## VI. RESULTS AND DISCUSSIONS

In this section, a full-wave physical simulator is developed to model two closely packed millimeter-wave transistors. Fig. 2 gives a 3D view of the simulated transistors. The simulated devices are biased to $V_{ds}$ =3.0 and $V_{gs}$ =-0.1V. The DC distributions are obtained by solving the active device model only. A sinusoidal signal is employed in the AC simulations with peak value of 100mVand frequency of 80 GHz, respectively. The two transistors shown in Fig. 2 are identical. First, full-wave simulations are performed for one transistor only, and the results are depicted in Fig. 3. Considering this figure, one can observe the variations of the output voltage with the distance along the device width. The reasons are due to the nonlinear energy build-up along the device width, and due to the phase velocity mismatch between the EM-waves at the gate and drain electrodes. Fig. 3 demonstrates the importance of coupling the EM-waves with the semiconductor transport physics for accurate modeling of millimeter-wave transistors.

Now, we turn our attention to the full-wave simulations of the two transistors shown in Fig. 2. First, we assume that one of the transistors is operating, while the other transistor is not. Fig. 4 depicts the simulation results, which emphasize the significance to include the EM-wave propagation effects around the device. Ideally, the non-operating transistor should have a zero drain potential, however due to the proximity of an operating transistor, an induced voltage that varies along the device width is introduced.

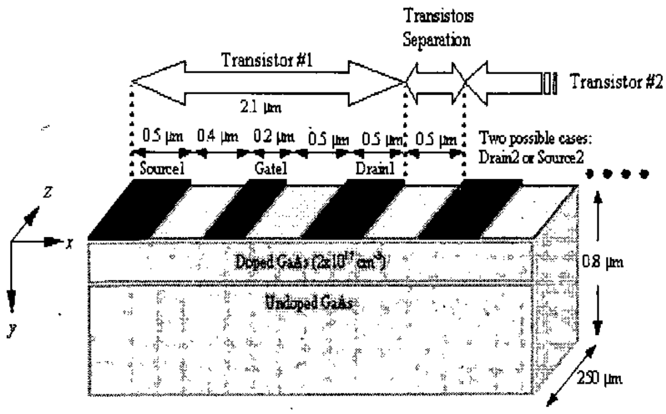


Fig. 2. 3D view of the simulated transistors (not to scale).

Next, the two transistors in the configuration shown in Fig. 2 are simulated, assuming that both transistors are now operating. There may be two cases to consider. The first case is to assume the drains of the two transistors are adjacent to each other. While, the other case is to consider the drain of one of the transistors is adjacent to the source of the other transistor. Figures 5 and 6 show the simulation results. The first conclusion that can be drawn out of the two figures is that the proximity of an operating transistor affects the output voltage due to the EM-wave propagations. Furthermore, the EM-wave effects for the case of two adjacent drain electrodes is much larger than the other case. This is expected, since the drain electrode has the amplified output signal. The gains of the simulated transistors are less than unity due to the high operating frequency.

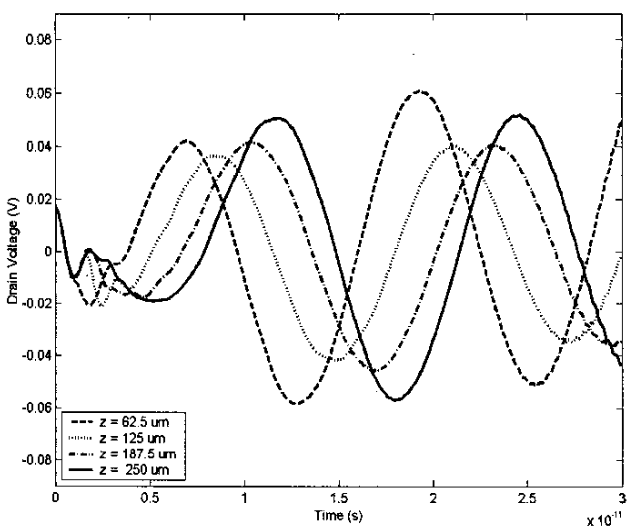


Fig. 3. Drain voltage of the simulated transistor when EM-wave propagation is considered at different points in the z-direction.

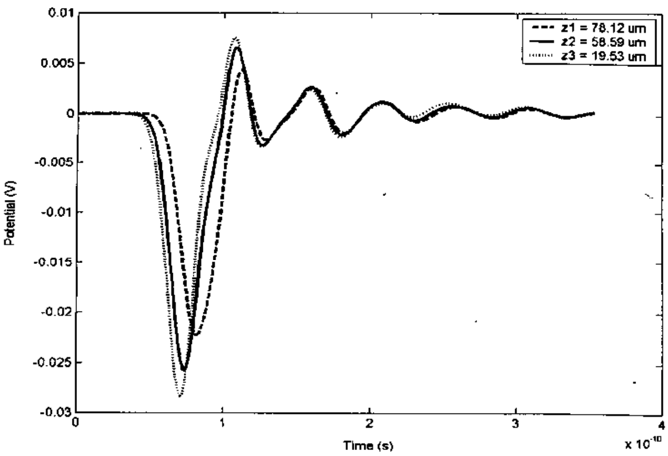


Fig. 4. Potential of a passive electrode at different points in z-direction induced due to the proximity of an operating transistor. excited by a Gaussian signal.

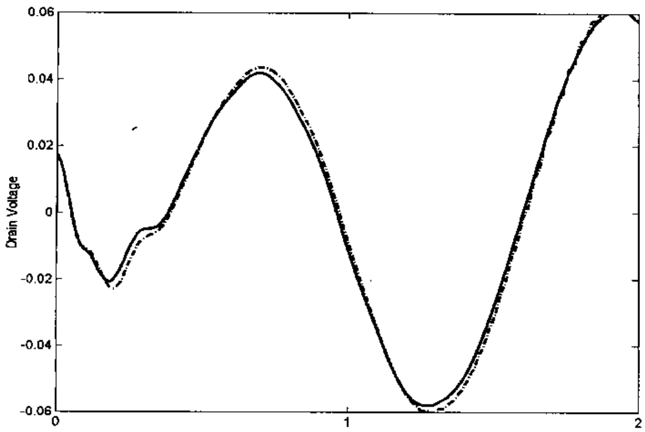


Fig. 5. Drain voltage at $z = 62.5\mu m$ when EM-wave propagation is considered. Solid line: transistor is simulated alone. Dashed line: Source electrode of a second operating transistor is $0.5\mu m$ apart from the drain of the simulated transistor.

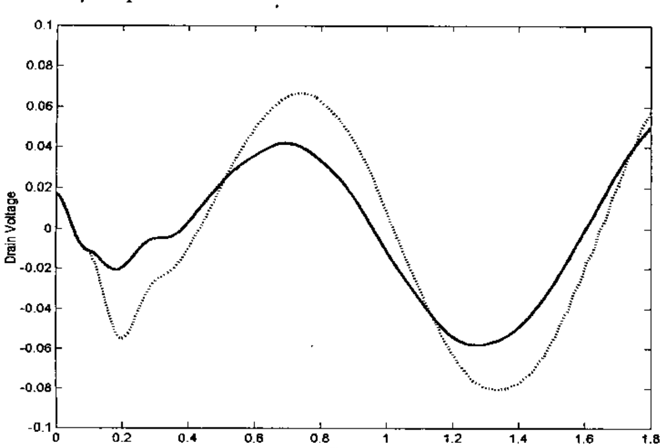


Fig. 6. Drain voltage at $z = 62.5\mu m$ when EM-wave propagation is considered. Solid line: transistor is simulated alone. Dotted line: Drain electrode of a second operating transistor is $0.5\mu m$ apart from the drain of the simulated transistor.

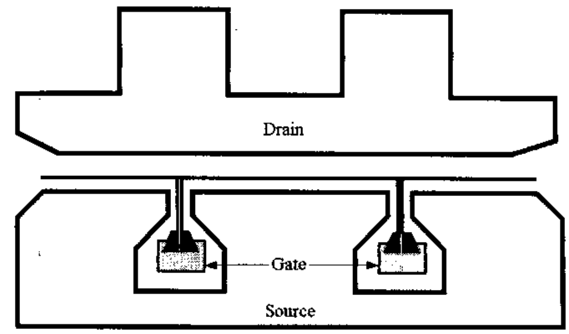


Fig. 7. Generic structure of a four-finger transistor: A full-wave simulator for it is currently under development.

## V. CONCLUSIONS

A new wavelet-based full-wave physical simulation approach has been developed to simulate two closely packed millimeter-wave transistors. A reduction of 75% in CPU-time is achieved compared to a uniform grid case with the same order of accuracy. The results show that the performances of the simulated transistors have been changed when the effect of EM-wave propagation, inside and around the device, is taken into consideration. This paper represents a fundamental step toward accurate simulation of a large number of closely packed microwave components, with considerably less CPU-time.

This work also represents the preliminary research necessary for full-wave physical simulations of multi-finger transistors, which are currently under development.

## ACKNOWLEDGEMENT

This work was supported by the US army research office under contract # *DAAD-19-99-1-0194.*

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