Global Modeling of Active Microwave Devices Incorporating a Novel Large-Signal Time-Domain Full-Hydrodynamic Physical Simulator Using Wavelet-Based Adaptive Grids

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Abstract **A novel large-signal time-domain simulation approach for full-hydrodynamic physical modeling of semiconductor devices using Wavelet-based adaptive grids is presented. The non-uniform grids of the main variables are conceived at a given time by applying biorthogonal Wavelet transforms to the current variable solutions followed by thresholding. A general criterion is mathematically defined for grid updating of each variable within the simulation. This criterion allows grid updating only when needed. In addition, few rules have been defined to take care of the fact that boundary conditions as well as discritization have to be handled differently for each new grid. Grids of the main variables are combined into one non-uniform grid whenever a new variable grid is conceived. The proposed technique is validated by simulating a submicrometer MESFET. The results of the proposed technique are compared with the results of a regular grid case showing more than 60% simulation time reduction while maintaining the same degree of accuracy. This is a first step toward applying Wavelets to global modeling of active microwave devices aiming to reduce the simulation time.**

I. INTRODUCTION

Modern high performance electronics are based on technologies such as monolithic microwave integrated circuits (MMIC's), with large number of closely packed passive and active structures, several levels of transmission lines and discontinuities, all operating at high speeds, frequencies, and sometimes over very broad bandwidths. It is thus perceptible that the design of MMIC's should involve robust design tools that simulate all the circuit elements simultaneously. The possibility of achieving this type of modeling is addressed by global circuit modeling that has been demonstrated in [1]-[4].

Global modeling is a tremendous task that involves advanced numerical techniques and different algorithms; as a result, it is computationally expensive [3]. Therefore, there is an urgent need to present a new approach to reduce the simulation time while maintaining the same degree of accuracy presented by the global modeling technique. One approach is to try to adaptively refine grids in locations where the unknown variables vary rapidly. Such technique is called multiresolution time domain (MRTD) and a very attractive way to implement it is to use Wavelets [5]-[6]. MRTD approach has been successfully applied to FDTD simulations of passive structures [7]-[10]. However, for the active devices that are characterized by a set of highly coupled and nonlinear differential equations, applying the same approach would become quite time consuming [11]. Several different approaches for solving PDE's using Wavelets have been considered and it has been noticed by several authors that nonlinear operators such as multiplication are too computationally expensive when done directly in a Wavelet basis. One of the approaches for solving PDE's is the interpolating Wavelets technique presented in [12]. In [12], the author deals with the nonlinearities using the so-called Sparse Point Representation (SPR). Interpolating Wavelets have been successfully applied to the simple drift diffusion active device model [13]-[14]. The simple drift diffusion, despite it is a good approximation for long-gate devices; it leads to inaccurate estimations of device internal distributions and microwave characteristics for sub-micrometer gate devices [15]. Thus, a new approach for applying Wavelets to the full hydrodynamic model of active devices is needed. Since global modeling requires solving the hydrodynamic model in conjunction with Maxwell's equations, this would be a first step heading for applying Wavelets to global modeling of active microwave devices in order to speed up the simulation.

II. PROBLEM DESCRIPTION

The MESFET model used in this work is a two dimensional quasi-static full-hydrodynamic physical model. The model solves Poisson's equation

$$\nabla^2 \phi = \frac{q}{\epsilon}(N_d - n) \qquad (1)$$

in conjunction with the full-hydrodynamic conservation equations for carrier density, carrier energy, and carrier momentum that are given by:

$$\frac{\partial n}{\partial t} + \nabla.(nv) = 0 \quad (2)$$

$$\frac{\partial}{\partial t}(n\,\varepsilon) + qnvE + \nabla.(n\ v(\varepsilon + k_B\ T)) = -n(\varepsilon - \varepsilon_0)/\tau_\varepsilon \quad (3)$$

$$\frac{\partial}{\partial t}(n\,p_x) + qnE_x + \frac{\partial}{\partial x}(n\,p_x\,v + nk_B T) = -n(p_x - p_o)/\tau_m \quad (4)$$

The total current density distribution J inside the active device at any time t is given by:

$$J(t) = -qn(t)v(t) + \epsilon\,\frac{\partial E}{\partial t} \quad (5)$$

Table I gives the parameters used in the simulation for the MESFET.

III. The Proposed Algorithm

Fig.1 shows the flow chart of the proposed technique. A uniform grid is defined at the beginning of the simulation. Equations (1)-(5) are then solved in the sequence shown by the flow chart to get the solution for the different variables at the new time. Relation (6) is the proposed criterion used to update the grids of the different variables within the simulation. The updating criterion simply checks if the solution of the variable x has changed by γ since last time Wavelet transform is performed.

$$\frac{\left|x^{l}_{max,min} - x^{c}_{max,min}\right|}{\left|x^{l}_{max,min}\right|} \geq \gamma \quad (6)$$

The notations *c* and *l* stand for the current time and the last time where Wavelet transform is performed respectively. While, *max,min* notation is to indicate that the maximum and the minimum of the variable x are checked if satisfying relation (6) at the same time. It worth noting here that points at boundaries are not included for the maximum or the minimum checking. The value of γ used in the simulation is 0.3. If relation (6) is satisfied, Wavelet transform is performed on the current solution followed by thresholding to obtain a new nonuniform grid for the variable x. Biorthogonal Wavelets are used with notation BIO3.1 to indicate three vanishing moments for the mother Wavelet and only one vanishing moment for the scaling function. The nonuniform grids of the different variables are then combined into only one nonuniform grid for the next iterations. The above steps are repeated until the stopping criterion is satisfied.

TABLE I
MESFET PARAMETERS USED IN SIMULATION

Drain and source contacts	0.5 μm
Gate-source separation	0.5 μm
Gate-drain separation	1.0 μm
Device thickness	0.4 μm
Device length	2.8 μm
Gate length	0.3 μm
Device Width	200 μm
Active layer thickness	0.1 μm
Active layer doping	$2x10^{17}$ cm^{-3}
Schottky barrier height	0.8 V
DC gate-source voltage	-1.0 V
DC drain-source voltage	3.0 V

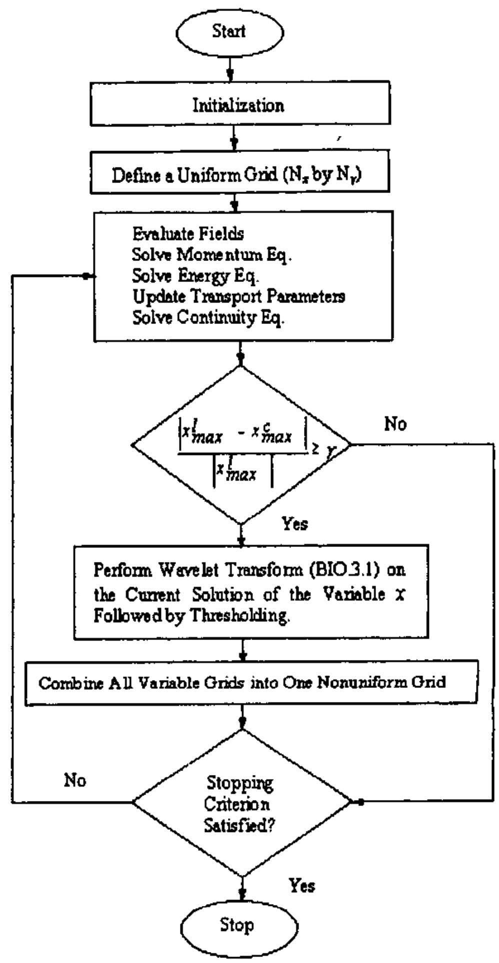

Fig. 1. Generic Flow Chart of the Proposed Algorithm

It is found that the grids of the different variables do not get updated by the same rate. The grids used in the simulation are for potential, carrier density, energy, x-momentum, and y-momentum. Fig. 2 shows the DC drain current versus the simulation time for both the uniform and the proposed Wavelet-based adaptive grids. It can be seen that proposed algorithm converges faster than the uniform grid case. Moreover, we may conclude that the accuracy of the proposed algorithm is in the same order of the uniform grid case since we have almost the same drain current value at steady state.

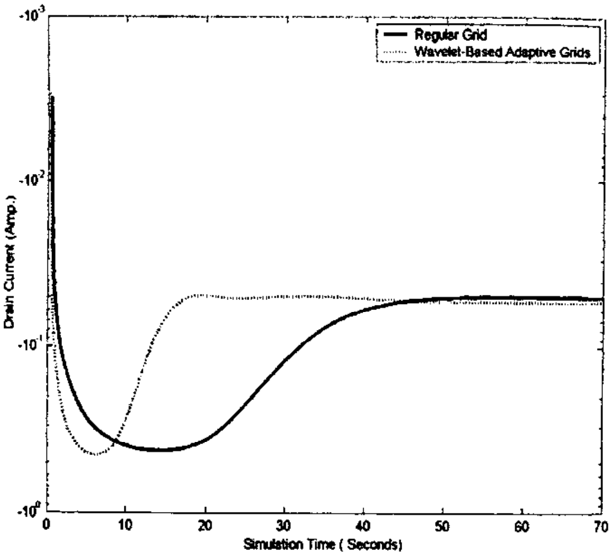

Fig. 2. DC Drain Current Convergence curves for the Regular and the Proposed Wavelet-Based Grids.

IV. DC Results

IV characteristics obtained by the proposed technique is given in fig. 4. The curves are obtained by following the flow chart given by fig. 1 for different values of Vds and Vgs. The current density is calculated using equation (5) and using only the first term, which represents the conduction current. For example, the grid of the potential obtained at the end of the simulation is shown in fig. 3.

V. AC Large Signal Results

The AC excitation applied to the gate electrode is given by:

$$v_{gs} = v_{gso} + \upsilon_{gs} \sin(\omega t) \qquad (7)$$

Where v_{gso} is the D.C bias applied to the gate electrode, υ_{gs} is the peak value of the AC signal (0.2 volts), and ω is the frequency of the applied signal in rad. per sec. The frequency used in the simulation is 60 GHz.

First, The DC solution is obtained by solving Poisson's equation in conjunction with the three hydrodynamic conservation equations. Then, a new value of v_{gs} is obtained using equation (7).

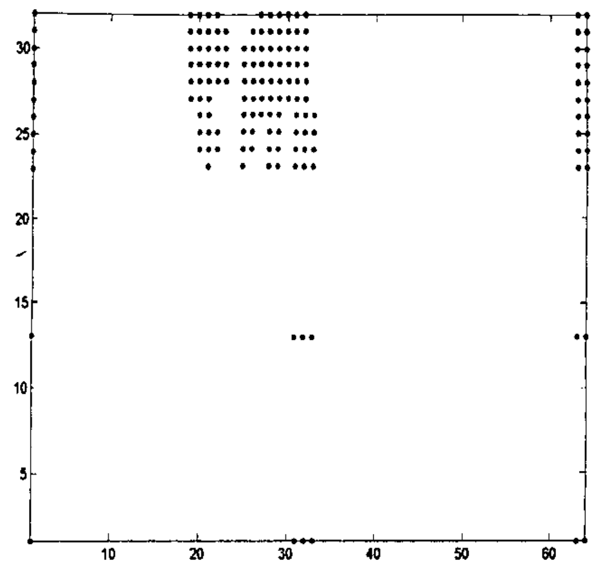

Fig. 3. Potential Grid obtained at the end of simulation

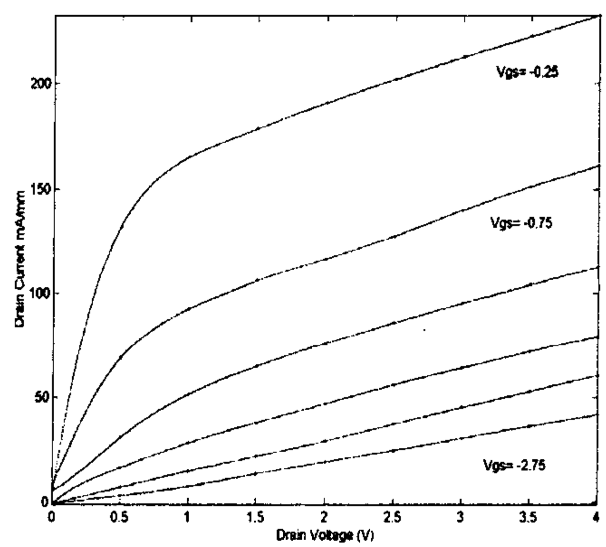

Fig .4. IV Characteristics Obtained by the Proposed Algorithm

The new value of vgs is used to update Poisson's equation and to get the new voltage distribution and consequently the new electric field. The electric field is then used to update the variables in the conservation equations. This process is repeated every Δt following the proposed algorithm shown in fig. 1 until $t=t_{max}$. The current density is obtained using equation (5). The current density is calculated on the plan located midway between the drain and the gate. Output voltage is calculated by multiplying the total current by the resistance that defines the DC operating point (Q point) of the MESFET.

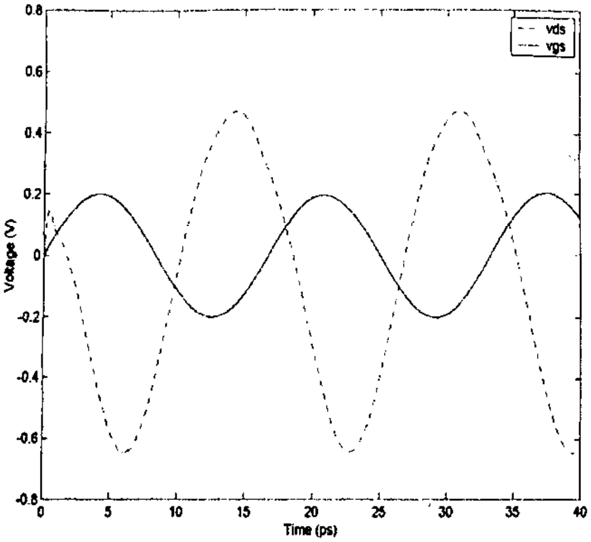

Fig. 5. Large Signal Results Obtained by the Proposed Algorithm

VI. Conclusion

A novel Wavelet approach has been developed and successfully applied to the full hydrodynamic model. The proposed algorithm solves the highly coupled nonlinear partial differential equations that characterize the semiconductor device behavior on nonuniform grids. The nonuniform grids are conceived at a given time by applying Wavelet transforms to the current variable solutions followed by thresholding. It is found that each variable has its own grid at any given time. In addition, grids of the different variables do not get updated by the same rate. A 60% reduction in the simulation time is obtained while maintaining the same degree of accuracy compared to a compact-size uniform grid case. The proposed algorithm efficiently solves both the DC and the large signal AC problems.

Acknowledgment

This work was supported by the U.S Army Research Office under contract DAAD19-99-1-0194.

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