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SB–PE drift-diffusion algorithm for FET devices global modeling

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ABSTRACT

We present an efficient numerical global modeling approach for the RF and microwave physic-based analysis of active devices that combines frequency-domain Fourier series expansion (Spectral Balance, SB) and space-domain polynomial expansion (PE) of the physical quantities inside the semiconductor. The proposed method (SB–PE), suited for the simulation of high-frequency Si, GaAs, and GaN FET devices, is based on the solution of the drift-diffusion transport equations, for the horizontal transport phenomena along the channel, coupled with a vertical self-consistent Schrödinger–Poisson solution for the vertical charge control. The frequency- and space-domain expansions drastically reduce the number of time and space sampling points where the equations are computed, greatly reducing the computational burden with respect to classical finite-difference approaches. Also the inclusion of frequency-dependent parameters of the semiconductor, important at very high frequencies (e.g. dielectric constant), and the coupling with an EM numerical solver, for a global modeling simulation, becomes straightforward, due to the frequency-domain approach, and to the reduced interconnection nodes between the physical simulator and the passive embedding network. A demonstrator for PC implementing a quasi-2D model with a drift-diffusion formulation has been implemented, and its results are compared with a standard finite-difference time-domain approach and with a standard Harmonic Balance formulation.

1. Introduction

Semiconductor device simulation has played a key role in the design and development of novel device structures and technologies. Although analog device designs have benefited greatly from physics-based device simulation, the important area of large signal steady-state analysis has been somewhat neglected by the device simulation community but, nowadays, the rapid growth of wireless communication systems has placed increasing demands on the design of semiconductor devices for analog applications [1–4]. In particular, large signal distortion effects are of critical importance in microwave and RF communication circuitry. Physics-based device-level simulation of these effects, especially in two dimensions [5,6], can be an important aid in the analog device design process. However, the transient analysis capability present in traditional semiconductor device simulators is inadequate for large signal distortion analysis. The most notable shortcomings of conventional transient analysis are its inability to directly capture the steady state response of systems driven by quasi-periodic inputs, along with its poor performance in the presence of widely separated spectral components. To address the aforementioned shortcomings of the traditional time domain methods, and to overcome the drawbacks of the finite-difference discretization in the time-domain, frequency-domain approaches have been proposed; in particular, Harmonic and Spectral Balance [7–13] algorithms have been demonstrated. In these approaches, the unknown physical quantities (e.g. electron density, velocity and energy, and electric potential) at each space point in the semiconductor are expanded in Fourier series with respect to time; the unknowns of the problem are now the coefficients of the Fourier series expansions, instead of the time samples of the physical quantities. The unknown coefficients are found by writing (two times) as many equations as the unknown (complex) coefficients; therefore, the time step is determined by Nyquist's sampling theorem, and is usually much larger than in the finite-different time-domain approach. The size of the problem is therefore reduced. Moreover, since the external passive part of the device is distributed but linear, it can be lumped into an equivalent representation in the frequency domain: for instance, a Norton equivalent network at the signal frequency and its harmonics. Its parameters (e.g. the complex admittance Y-parameters) are computed once and for all, and used in the iterations required for the numerical solution of the nonlinear transport equations. Additional advantages of the frequency-domain scheme include a more efficient handling of a two-tone excitation of the device, and frequency-dispersive behavior of the material. On the other hand, a disadvantage of this approach is the limitation to periodic and quasi-periodic excitations, a limitation usually not important for typical applications. A more serious disadvantage is the need to solve the problem simultaneously for

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all time instants, instead of the step-by-step procedure of the time-domain finite-difference approach. The consequent larger size of the problem partly reduces the benefit of the longer time step, while not offsetting the mentioned advantages.

For this reason the space-domain finite-difference discretization has been removed, by expanding the physical quantities in polynomials in the space variable [14,15]; the unknowns are now the coefficients of the polynomials. The equations are written in a number of space points equal to the degree of the polynomials (plus one), i.e. in a very limited number of points. This approach reduces the size of the problem within the semiconductor; moreover, it reduces the number of space points where the transport equations must be connected to the passive embedding structure. Each coefficient of the space-domain polynomial is then expanded in Fourier series, as in the previous case, with reduced number of time samples [14,15].

In this work the combined frequency- and space-domain series expansion approach, already demonstrated to be a viable method for hydrodynamic physics based analysis, is applied with a Quasi-2-Dimensional Drift-Diffusion formulation, for the global modeling analysis of a high-frequency FET device [1–4,12–15].

This scheme combines a reasonable accuracy and a relatively simple implementation with a drastically reduced simulation time if compared with a classical SB or HB technique especially when combined with an EM simulator.

For the verification of the feasibility of the approach, the DC and microwave characteristics of a FET device in both linear and nonlinear regime, already computed in [15] with an hydrodynamic approach, are reported with the proposed method. Moreover results have also been compared in terms of accuracy and PC computation time with respect to previous results.

2. The model

In our model we have adopted a general FET device schematization as depicted in Fig. 1. For a global analysis, the device is first divided into an embedding, passive linear region (substrate, passivation dielectric, access pads, etc.), and an active nonlinear region, in our case the channel. The active is subdivided in several slices parallel to the source–drain direction, connected by the long gate fingers. Each slice is connected to the embedding region at a suitable number of points along the source–drain direction, e.g. at the gate, drain and source metallization, and at the surface between gate and source and gate and drain; the embedding region is also connected to the external excitation, i.e. the input signal at the gate side, and to the external load at the drain side.

In Fig. 2 a high level view of a global modeling possible scheme for circuit simulation is shown. The embedding region is analyzed by means of a numerical electromagnetic field solver in the frequency domain, at DC, fundamental frequency, and harmonic frequencies of the input signal. Any standard algorithm or commercial CAD tool can be used for the analysis. As a result, the embedding region is lumped into an equivalent representation; for instance, a Thévenin equivalent, formed by a complex N-port impedance matrix and N equivalent voltage sources, where N is the number of connection points between the embedding and the active regions. A Thévenin equivalent is computed for each frequency of analysis and results used for the physic simulator.

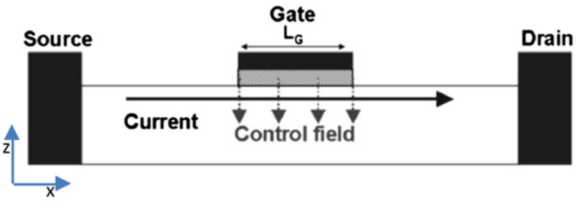

Fig. 1. Adopted scheme for a Quasi 2-Dimensional formulation approach.

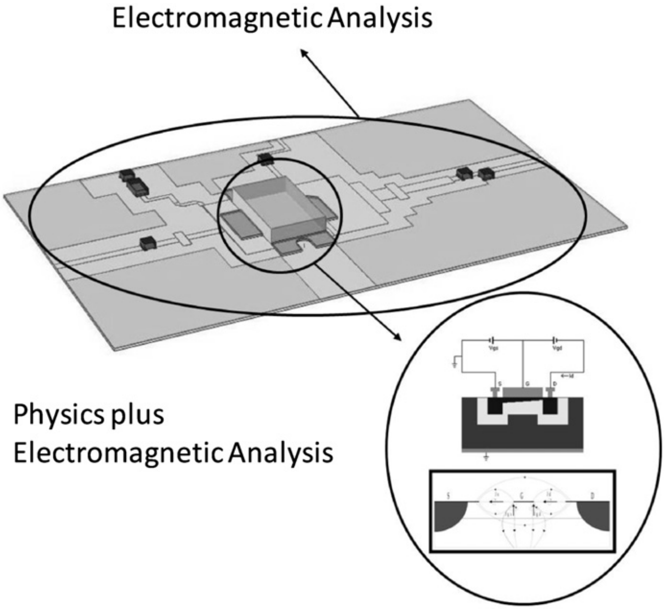

Fig. 2. High level view of a global modeling possible scheme for circuit simulation.

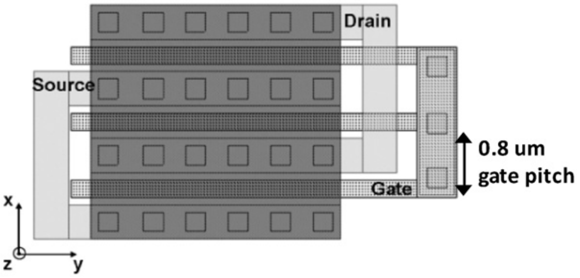

Fig. 3. MOSFET multifinger structure.

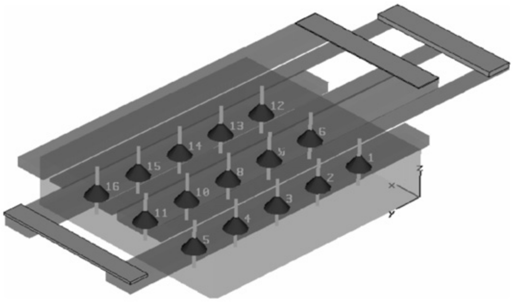

Fig. 4. Connecting ports between channel region and the embedding structure for physic/electromagnetic analysis.

In this case the transport phenomena are considered to be one-dimensional from source to drain. The considered device (an AMS 0.35 μm Multifinger MOSFET with three finger and 10 μm gate periphery, see Fig. 3), is first divided into an external, passive linear region, the access pads, and an active, nonlinear region, in our case the multifinger channel. Any extension to embedded regions, such as substrate, passivation dielectric, etc., are included in the analysis by means of an electromagnetic solver (see Fig. 4) as demonstrated in [14,15]. The device channel horizontal electron transport is