PERFORMANCE COMPARISON OF MODFET AND MESFET USING COMBINED ELECTROMAGNETIC AND SOLID-STATE SIMULATOR

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ABSTRACT

A Combined Electromagnetic and Solid-State (CESS) simulation model for the analysis of electromagnetic wave effects on the behavior of the submicron semiconductor devices is presented. The CESS simulation model couples a 3D time-domain solution of Maxwell's equations to the semiconductor model. The performance comparison of two important high frequency devices, MODFET and MESFET, are discussed. The electromagnetic wave effects on the two devices are thoroughly analyzed. The simulation uses the electromagnetic wave concept to emphasize the better performance of MODFET over MESFET. The transfer of energy takes place between the electrons and the electromagnetic wave at high frequencies.

I. INTRODUCTION

The modeling and simulation of solid state devices were previously achieved by solving various combinations of Poisson's equation, continuity equation, and the momentum and energy balance equations, in many different forms [1]-[3]. In most cases, the dc and low frequency performances of solid state devices were analysed. They are modified later for high frequency simulation purposes. Moreover, these models are mostly in two dimensions, which does not include the electromagnetic wave propagation effects. When the device operates in the millimeter wave range, where the device width is comparable to the electromagnetic wavelength and the short wave period may be comparable to the electron relaxation times, the conducting electrons interactions with the electromagnetic wave cannot be neglected. In this work, Maxwell's equations are used in conjunction with a 3D hydrodynamic model to develop a Combined Electromagnetic and Solid State (CESS) simulator for high frequency devices, using the finite difference time domain (FDTD) method. When an ac signal is applied at the device input with appropriate dc bias, the CESS model predicts the correct device response and accounts for the energy transfer between the electrons and the EM wave. This novel approach has been utilized in millimeter-wave semiconductor modeling. It is a very powerful tool for analyzing the behavior of submicron gate MESFETs [4] - [5].

To demonstrate the potential of this simulator, it is used to analyze the millimeter wave performance of a Modulation Doped Field Effect Transistor (MODFET) as well as a Metal Semiconductor Field Effect Transistor (MESFET). Both dc and ac analyses are done for the two devices and are compared. The MODFETs and the MESFETs are field effect devices. The MODFET uses AlGaAs-GaAs heterostructure and have undoped GaAs as active layer but the MESFET uses heavily doped GaAs as active layer. Their very high speed, low power consumption, and relatively simple fabrication technology make them strong candidate for upper mm-wave frequencies [6]. They have excellent power-delay relationship and reduced short channel effects. However, overall MODFET performances are better than those of MESFET's [7].

II. THEORY

The CESS simulation model couples a 3D time-domain solution of Maxwell's equations to the semiconductor model. The semiconductor model is based on the moments of the Boltzmann's transport equation obtained by integration over the momentum space. The integration results in a strongly-coupled highly nonlinear set of partial differential equations called the conservation equations [8]-[9]. These equations provide a time dependent self-consistent solution for electron density, electron energy and electron momentum and are given for MODFET by:

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

$$\frac{\partial (n\varepsilon)}{\partial t} + \nabla .(nv\varepsilon) = qnv.\mathbf{E} - qnv.\nabla(\varphi+\chi) - \nabla .(nkTv) - \frac{n(\varepsilon-\varepsilon_0)}{\tau_\varepsilon} \tag{2}$$

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$$\frac{\partial(np_x)}{\partial t} + \nabla .(np_x v) = qnE_x - qn\nabla(\varphi+\chi) - \nabla\ (nkT) - \frac{np_x}{\tau_m} \quad (3)$$

For MESFET, in equations (2) and (3), the second terms on right hand side are absent. The electronic current density distribution J inside the active device at any time t is given by:

$$J(t) = -\, q\, n(t)\, v(t) \quad (4)$$

The evolution of current densities inside the active device gives rise to electric and magnetic fields. Maxwell's equations provide a time-domain evolution of these fields as:

$$\nabla \times \mathbf{H} = \varepsilon\frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} \quad (5)$$

$$\nabla \times \mathbf{E} = -\,\mu\frac{\partial \mathbf{H}}{\partial t} \quad (6)$$

The coupling between the two models is established by using the fields obtained from the solution of Maxwell's equation in the semiconductor model to calculate the current densities inside the device. These current densities are used to update the electric and the magnetic fields. The initialization is provided by solving the semiconductor model for the dc charges and currents in response to a specified dc operating point.

III. DEVICE SIMULATION

The finite-difference scheme was used in semiconductor device simulations. This scheme lends itself naturally to the simple rectangular geometry generally considered for semiconductor device simulations. In this work, several finite-difference techniques, such as the upwind and the Lax methods, are used in conjunction with the basic finite-difference formulation to achieve stable and accurate solutions [10]. Equations (1)-(3) are coupled highly nonlinear partial differential equations. The finite difference scheme decouples these equations. The solution is obtained in a self-consistent evaluation of the three equations in conjunction with Maxwell's equations. The time-domain solution of Maxwell's equations is obtained using a three-dimensional mesh where field components are arranged following Yee's method [11]. Using a first order differencing, equations (5) and (6) can be decoupled over a small time interval Δt. Higdon's second order boundary conditions are used to prevent the reflections from the sides [12]. Both explicit and semi-implicit schemes have been incorporated to develop the model. The semi-implicit scheme offers a more stable simulation model. As this technique is computationally intensive, the simulation is performed on a Massively Parallel machine (MasPar). The details of the simulation technique can be found in [5].

IV. RESULTS AND DISCUSSIONS

In order to validate the CESS simulation model, a MODFET structure similar to Shawki et al. [13] is taken to compare the performances. The transfer characteristics are compared for different gate lengths. They exhibit reasonable agreement with each other in Fig.1.

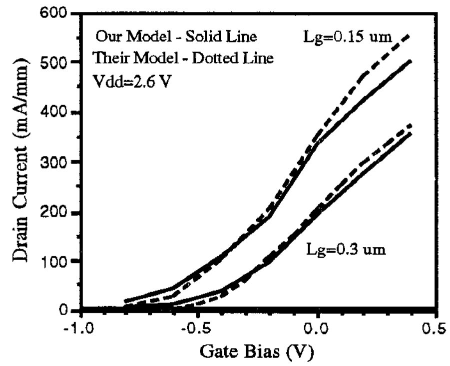

Fig. 1 Comparison of transfer curves of MODFET with those of T. Shawki et al. [13] for different gate lengths.

The MODFET (Fig. 2) and the MESFET (Fig. 3) used in this work have the following parameters. Gate-source spacing=0.37 μm, gate-drain spacing=0.7 μm, gate length=0.24 μm, spacer thickness=60 A, and undoped GaAs thickness=0.3 μm, AlGaAs layer thickness (heavily doped GaAs for MESFET) = 0.1 μm, gate width=250 μm. At first, the dc analysis is done for both of them. The variation of transconductance and cut-off frequency with gate bias for both MODFET and MESFET are shown and compared in Figures 4 and 5, respectively. The transconductance and the cut-off frequency are higher for MODFET which supports its potential for high speed operation. The maximum transconductance and the maximum cut-off frequency occur for MODFET at higher reverse gate voltage than MESFET which is expected.

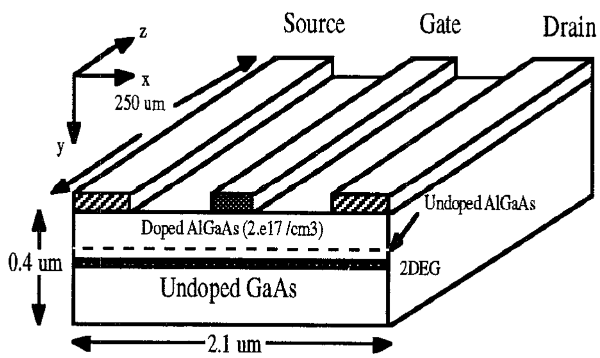

Fig. 2 The simulated MODFET structure.

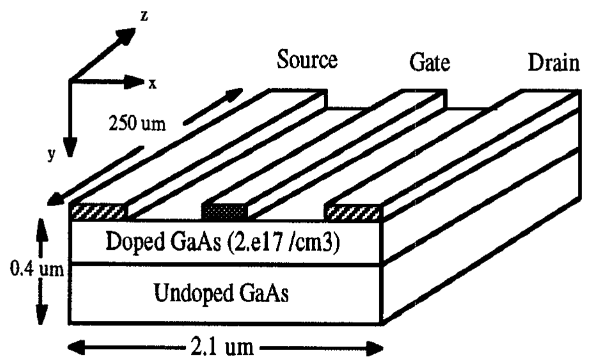

Fig.3 The simulated MESFET structure.

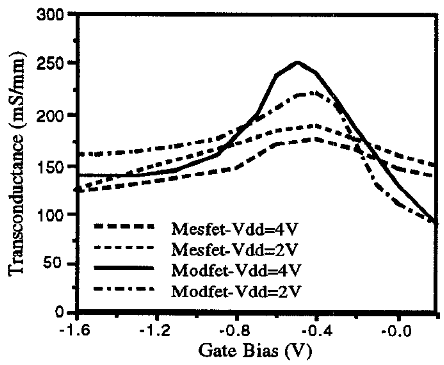

Fig. 4 Comparison of transconductances of MODFET and MESFET structures for two drain biases.

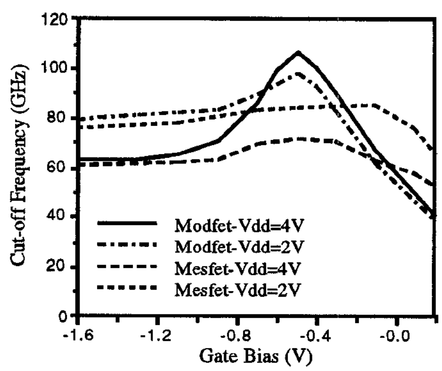

Fig. 5 Comparison of cut-off frequencies of MODFET and MESFET structures for two drain biases.

The ac analysis is also performed for MODFET and MESFET. A sinusoidal voltage of peak 0.1 V and frequency 80 GHz is applied across the gate and the source. The output is obtained across the drain and the source at several points along the device width in the z-direction. The effect of the electron-wave interaction on both the devices can be described by the input and the output waveforms. The input voltage wave for both the devices decreases in magnitude at the beginning as it moves along the device electrodes as shown in Figures 6 and 7. This is due to the EM energy loss to the conducting electrons. As the output voltage wave develops, the coupling between the input and the output waves, enhances the input voltage wave. The output voltage wave, as shown in Figures 8 and 9, takes a finite time to respond to the input voltage wave. This is the delay which is due to the finite device-switching time. Early in the simulation, the electronic effect is not present and the wave amplitude decreases along the device width. Later, as more and more electromagnetic energy is propagated along the device, the wave energy builds up, and the wave amplitude increases. The higher amplitude of the output voltage is observed for MODFET than MESFET which supports the dc results.

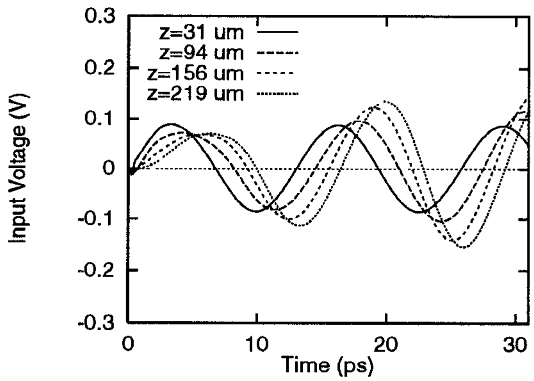

Fig. 6 The input voltage of MODFET for different device widths.

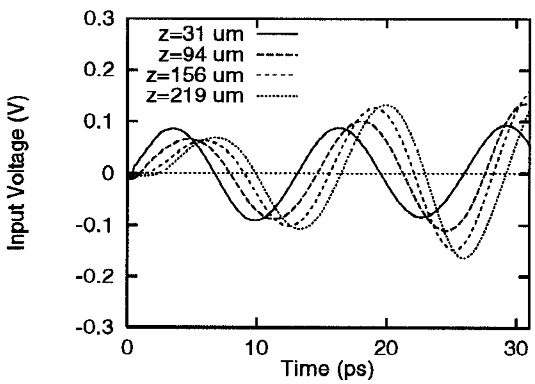

Fig. 7 The input voltage of MESFET for different device widths.

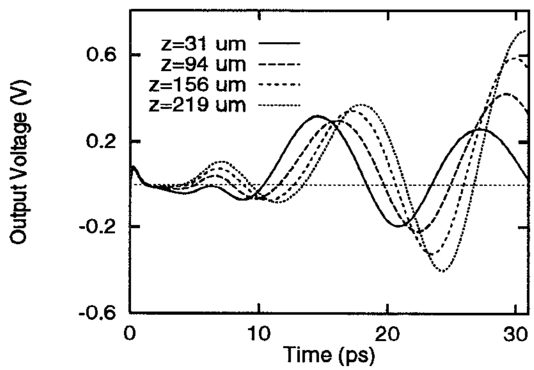

Fig. 8 The output voltage of MODFET for different device widths.

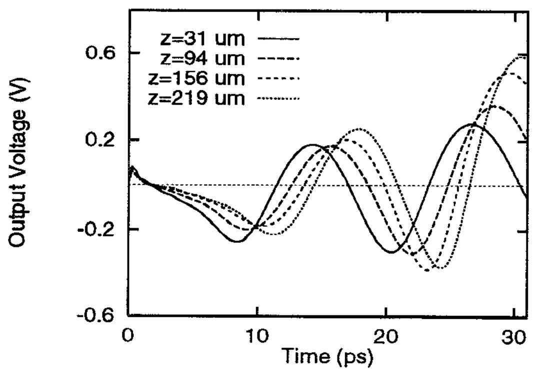

Fig. 9 The output voltage of MESFET for different device widths.

V. CONCLUSION

A Combined Electromagnetic and Solid-State (CESS) simulation model for the analysis of electromagnetic wave effects on the behavior of the submicron semiconductor devices is presented. The performance comparison of two important high frequency devices, MODFET and MESFET, are discussed. The electromagnetic wave effects on the two devices are thoroughly analyzed. It is concluded from the simulation that there are significant effects of EM waves on semiconductor device operations at high frequencies.

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