ELECTRON-WAVE INTERACTION IN SUBMICROMETER GATE FIELD-EFFECT TRANSISTORS

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Abstract
The electromagnetic wave effects on the behavior of submicrometer gate Field-Effect Transistors is investigated by coupling a full wave solution of Maxwell's equations to the active device model. Three-dimensional simulations verify the expected device-wave interaction. According to simulation results, energy transfer between electrons and the EM wave takes place along the device width. This effect is represented by a build-up in the wave amplitude and an increase in the device gain.

INTRODUCTION

Detailed numerical modeling of today's typical devices is a powerful tool for a proper understanding of device behavior. Full account should be taken of at least two directions - that along the conducting channel and that normal to it. Recently, several two-dimensional computer models have been developed for this purpose (for example [1]-[3]). Conventionally, the models employ a solution of Poisson's equation to update the electric field inside the device which, in principle, presents no conceptual difficulty. However, interesting physical phenomena arise from the manner in which charge fluctuations and current responses are coupled to the fields. In the case of devices operating in the microwave range, the short wave period becomes comparable to the electron relaxation times, and electron-wave interaction takes place. A full wave solution is, thus, needed to take into account both magnetic and electric fields. The moving carriers inside the device become a source of electromagnetic (EM) fields. These EM fields, in turn, affect carrier transport. This coupling is believed to have a significant importance in simulating various electronic device [4].

Recently, a 3D finite-difference time domain model consisting of a solution of Maxwell's equations coupled to the hydrodynamic equations representing active device simulation has been developed [5]. The improved efficiency of numerical schemes and the advent of supercomputers allows steady-state small and large-signal operations of FET microwave devices to be investigated over several tens of picoseconds. In this work, the coupled model is used to investigate the effect of electron-wave interaction on the behavior of submicrometer gate FETs. The investigation includes energy transfer between the device and the propagating wave, EM wave build-up and device gain.

THE MODEL

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

$$\frac{\partial n}{\partial t} + \nabla . (n\mathbf{v}) = 0 \qquad (1)$$

$$\frac{\partial (n\varepsilon)}{\partial t} + \nabla . (n\mathbf{v}\varepsilon) = -qn\mathbf{v}.(\mathbf{E}+\mathbf{v}\times\mathbf{B}) - \nabla . (nkT\mathbf{v}) + \frac{n(\varepsilon-\varepsilon_o)}{\tau_\varepsilon} \qquad (2)$$

$$\frac{\partial (np_x)}{\partial t} + \nabla . (np_x\mathbf{v}) = -qn\,[E_x + (\mathbf{v}\times\mathbf{B})_x] - \nabla . (nkT) - \frac{np_x}{\tau_m} \qquad (3)$$

where

- q: electronic charge
- n: electron density
- ε: electron energy
- p_x: electron momentum in x-direction
- v: electron velocity
- **E**: electric field
- **B**: magnetic field
- T: electron temperature
- k: Boltzmann's constant
- τ_ε, τ_m : energy and momentum relaxation times
- ε_o: equilibrium thermal energy

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

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

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

TH
3C

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

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

The coupling between the two models is established by using fields obtained from the solution of Maxwell's equations in the active device model to calculate the current densities inside the device. These current densities are used to update the electric and magnetic fields. The initialization is provided by solving the active device model for the DC charges and currents in response to a specified DC operating point. The time-domain solution progresses as described in Fig. 1. More details about the coupled model can be found in [5].

The 3D structure of the simulation region is shown in Fig. 2. To simulate the infinite space surrounding the structure, absorbing boundaries are used. For the back side, where the propagating wave hits and absorption of the wave is most important, second order absorbing boundaries [6] are implemented. The variables of the second order conditions are set for optimum absorption. First order absorbing boundaries are used for all other faces. At the front face (z=0) a plane source is applied. The plane corresponds to the solution of Laplace's equation for the applied excitation.

NUMERICAL SCHEME

Equations (1)-(3) are coupled highly nonlinear partial differential equations. To decouple these equations in time, a finite-differnece (FD) based scheme is used. The solution is obtained in a self-consistent evaluation of the three equations in conjunction with Maxwell's equations. The equations are discretized over a three-dimensional mesh that covers the entire simulated structure (Fig. 2). The space and time increments are adjusted to satisfy Debye length criteria for semiconductor simulation and wavelength criteria for EM simulation for a stable solution. Because of these limitations on space and time increments and because of the inherent computational intensity in the coupled model, parallel implementation of the numerical scheme is necessary. In this work the simulation is performed on a Massively Parallel machine (MasPar). With proper mapping of the variables arrays on the machine processing elements and efficient Fortran 90 coding, it is possible to investigate device behavior over tens of picoseconds within a 24 hour period.

RESULTS AND DISCUSSION

Numerical results are generated for a 0.2 μm gate MESFET. The device has the design parameters as in Table 1. The sinusoidal excitation is applied at the gate electrode at z=0 (Fig. 2), and the total gate voltage becomes:

$$Vgs(t) = Vgso + \Delta vgs \sin(\omega t) \quad (7)$$

where ω is the operating frequency.

A. Wave Propagation

Fig. 3 shows the temporal variation in wave amplitude at device widths of 2.5, 5.0, 7.5 and 10.0 μm. The transient duration is consistent with the device switching time. The following observations can be made. First, the power gain increases along the device width. This is explained as more and more energy is transfered from the electrons to the propagating wave. Second, the wave amplitude is very small up to the first 6 picoseconds of simulation. Then the wave starts to build up and follow the sinusoidal input until it eventually reaches steady state amplitude. This time delay in the development of the wave is attributed to the electron transit time from the source side to the drain side of the device. A simple time-distance calculation verifies this observation. Near the front end of the device (z=2.5 μm) the amplification is small. The wave gets more amplified at points deeper in the device width (z=10.0 μm). In all cases the wave takes a finite time to reach steady state.

B. Device characteristics

Fig. 4 illustrates a significant device behavior. In the figure, the peak values - at steady state - of gate voltage, drain voltage and output current are drawn versus distance along the device width. The quantities are normalized with respect to the values at the center of the device width. The results indicate a nonlinear energy build-up along the device width at the drain side and a linear drop in wave amplitude at the source side. The explanation is related to that given in wave propagation case. For wider transistors or higher input levels, the nonlinear energy build-up is expected to become more pronounced along the device width.

C. Gain and phase velocities

Fourier analysis is performed to obtain the gain-frequency and phase-frequency dependence. Fig. 5(a) shows the device gain at several points in the device width. The curves have global maxima at the fundamental frequency (f_0=80 GHz) and relative peaks at multiples of f_0. The DC component is also shown for each case. The phase velocity of the wave can be calculated using the phase information given in Fig. 5(b). The value thus obtained at the fundamental frequency gives information about the effect of electron wave interaction on wave propagation characteristics. The calculations give a reduced value of phase velocity at the output side ($v_p=1.01 \times 10^{10}$ cm/s). It can also be noted from the curved-up phase line of Fig. 5(b) that wave dispersion takes place at higher frequencies.

CONCLUSIONS

The work described in this paper presents electron-wave interaction in a typical microwave device structure. It has been shown that a model consisting of a full wave time-domain solution of Maxwell's equations coupled to the active device model is capable of evaluating the effect of the propagating wave on device behavior. The results illustrate a build up in the device gain along the device width. This effect is attributed to the energy exchange between the electrons and the electromagnetic wave.

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Table I. Simulation paremeters

Drain and source contacts	0.5 µm
Gate-source separation	0.4 µm
Gate-drain separation	0.5 µm
Device thickness	0.4 µm
Device width, W	10 µm
Device length, L	2.1 µm
Gate length, Lg	0.2 µm
Active layer thickness, a	0.1 µm
Active layer doping	2×10^{17} cm^{-3}
Schottky barrier height	0.8 v
DC Gate-source voltage, Vgso	-0.5 v
AC Gate-source voltage, Δvgs	0.1 v

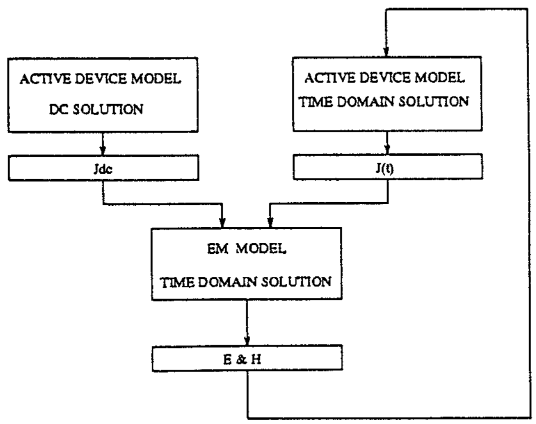


Fig. 1. Flowchart describing the sequence of operations in the coupled model

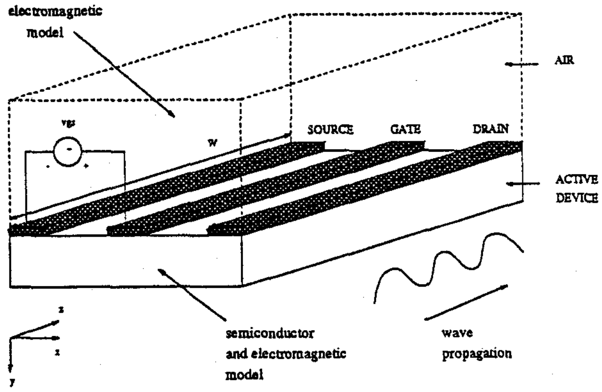


Fig. 2. 3D structure used for simulation.

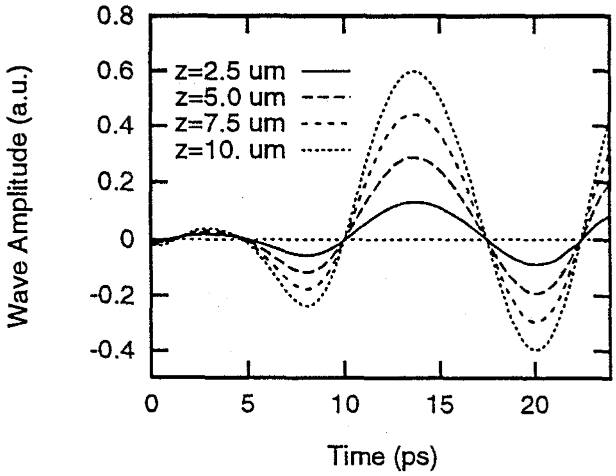


Fig. 3. Time variation of the output wave at several points in the z-direction.

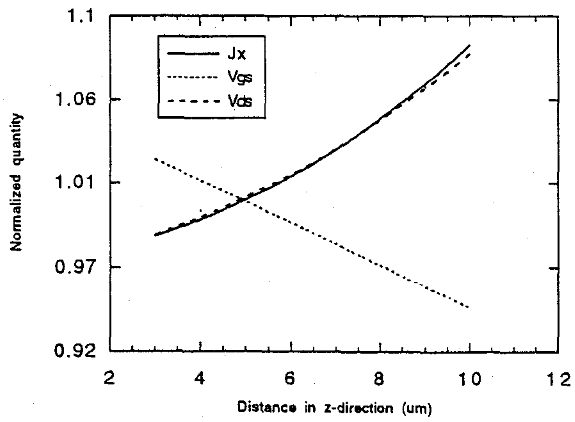
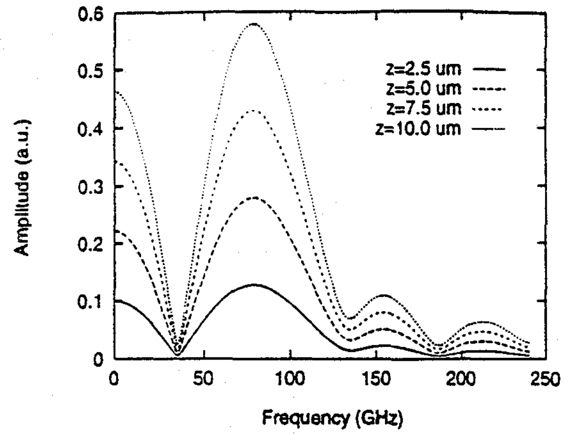
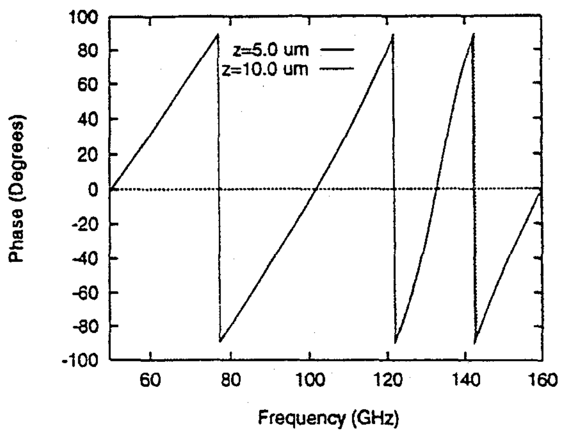


Fig. 4. Space variations of the peak values of gate voltage, drain voltage, and output current.



(a)



(b)

Fig. 5. Fourier analysis of the output wave at several points in the z-direction. (a) amplitude (b) phase