HIGH-FREQUENCY LARGE-SIGNAL PHYSICAL MODELING OF MICROWAVE SEMICONDUCTOR DEVICES

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Abstract
High frequency characterization of microwave semiconductor devices is presented based on physical modeling. The active device is simulated using a fast and accurate model based on the hydrodynamic equations which simulate the behavior of short gate field-effect transistors (FETs). The device response is analyzed as a function of the input signal frequency and its amplitude.

PHYSICAL MODELING OF FETs

Traditionally, the design and characterization procedures for microwave devices and circuits have relied on utilizing measurements. Measured small-signal S-parameters and DC data are frequently used in association with equivalent circuits. In these equivalent circuits, element values are obtained by fitting the model terminal characteristics to the measured data. This empirical approach requires extensive experimental data to establish a good basis for design. Moreover, when the active device is operating in non-linear circuits, such as power amplifiers and oscillators, measured data is required for a wide range of DC bias levels and frequencies to include the nonlinearities of the active device.

Detailed numerical modeling of today's typical devices is a powerful tool for a proper understanding of device behavior. This is achieved by using a set of equations that describe the physical behavior of the device. This approach is referred to as physical modeling. The development of two-dimensional physical models for DC and transient conditions have been reported in several papers [1]-[3]. To meet the demand for microwave and upper millimeter wave devices, FETs have been fabricated with submicrometer gate lengths; a situation developed where several new effects have to be incorporated in device modeling. These effects include nonstationary electron dynamics, nonisothermal electron transport and electron heating, carrier injection parasitic effects and high frequency effects. The improved efficiency of numerical schemes and the advent of supercomputers allow steady-state small and large-signal operations of FET microwave devices to be investigated over several tens of picoseconds.

In this paper, a fast and accurate two-dimensional physical model is used for the characterization of microwave devices over a wide range of frequencies. The model is based on the hydrodynamic equations obtained from the Boltzmann's Transport Equation (BTE). The numerical scheme is suitably realized and implemented on a parallel machine.

TRANSPORT EQUATIONS

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:

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

$$\frac{\partial (n\varepsilon)}{\partial t} + \nabla . (n v \varepsilon) = - qnv.E - \nabla . (nkTv) + \frac{n(\varepsilon - \varepsilon_o)}{\tau_\varepsilon} \qquad (2)$$

$$\frac{\partial (np_x)}{\partial t} + \nabla . (np_x v) = - qn E_x - \nabla . (nkT) - \frac{np_x}{\tau_m} \qquad (3)$$

where

- n: electron density
- ε: electron energy
- p_x: electron momentum in x-direction
- v: electron velocity
- T: electron temperature
- 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:

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

SOLUTION METHOD

Equations (1)-(3) are coupled highly nonlinear partial differential equations. Also, time and space variations of effective mass have to be accounted for, since variations in

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energy are not negligible and effective mass is a strong function of energy. To decouple these equations in time, a finite-difference (FD) based scheme is used. However, the velocity gradient terms, $(v.\nabla)v$, in the above equations make finite difference numerical schemes solving the above problem sensitive to small fluctuations and prone to instability. It is, therefore, expected that explicit schemes are highly unstable. Implicit schemes, on the other hand, produce nonlinear systems of equations making the problem computationally intensive. A variation of the direct explicit method, however, provides the required stability and efficiency. This scheme, called the Lax method [4], utilizes average values over two time and space steps to furnish stable solutions.

The behavior of the device is obtained in a self-consistent evaluation of the three equations, together with Poisson equation. All equations are discretized over a two-dimensional mesh that covers the entire simulated structure (Fig. 1). The space and time increments are adjusted to satisfy Debye length criteria. Because of these limitations on space and time increments and because of the inherent computational intensity in the 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, the scheme provides a reasonably fast method for obtaining device characteristics.

SIMULATION RESULTS

Numerical results are generated for a 0.25 µm gate MESFET. The device has the design parameters as in Table I. The excitation is applied at the gate electrode as in Fig. 1 such that

$$Vgs(t) = Vgso + \Delta vgs \sin(\omega t) \tag{5}$$

where ω is the frequency of the applied signal. The configuration in Fig. 1 allows the voltage at the drain to vary in response to variations in the current. At each Δt, the value of v_{ds} is updated. The load resistance is determined according to the DC operating point of the circuit. A typical input-output response of the transistor is shown in Fig. 2. The output waveform is inverted with respect to the input signal. The figure shows that the device takes about 4 picoseconds to respond to the variations in the gate voltage. This time delay corresponds to the transit time that electrons take to travel across the gate.

A. Frequency Response

A small signal is applied at the gate electrode to obtain the frequency response of the device. The peak value of the signal, Δvgs is 10 mV at frequencies of 0-200 GHz. Using Fourier analysis, the gain of the device is calculated and shown in Fig. 3. The cutoff frequency is obtained at the -3 dB point and the maximum frequency of oscillation at the unity gain point. For the simulated structure specified in Table I, the cutoff frequency is around 90 GHz and the maximum frequency of oscillation is around 170 GHz. To validate this result, the gate capacitance and the output transconductance of the device were calculated and found to be 0.31 pF/mm and 172.5 mS/mm respectively. These values correspond to a cutoff frequency of 88 GHz. This value is in a good agreement with that obtained in this simulation which is believed to be more accurate than the widely used analytical value given by:

$$f_o = \frac{1}{2\pi} \frac{v_p}{L_g} \tag{6}$$

where v_p is the peak electron velocity.

B. Nonlinear Response

The non-linear response of the device is studied by applying a sinusoidal input signal with a varying input level. For a small signal of 10 mV, as in Fig. 2, the output is a smooth replica of the input signal. As the input level increases, the peak value drops and harmonics start to build up in the output signal as illustrated in Figs. 4 and 5 which show the AC drain voltage obtained by applying AC voltage at the gate of 200 and 300 mV peak, respectively, at a frequency of 90 GHz. In Fig. 4, the output signal is distorted in the positive half and harmonics are generated at the peak of the signal. This effect becomes more pronounced when the input level increases to 300 mV. The output waveform in this case gets broader as more harmonics are produced. The distortion in the output signal takes place as the device approaches pinch-off. The evaluation of the magnitude of the harmonics can be obtained by Fourier analysis.

C. Computational Aspects

The simulation problem in this work is very suitable to be implemented on a SIMD machine. Parallel implementation utilizes the properties of the FD scheme. The parallel scheme is capable of performing 1 psicosecond of simulation in less than one minute of MasPar CPU time. This simulation speed is very adequate for routine characterization procedures of microwave devices.

CONCLUSIONS

A physical model for submicron gate transistors was utilized to analyze the frequency dependence of the device gain and the nonlinear effects in a microwave FET. The presented results suggest that this technique can be used to analyze the nonlinear effects of the intrinsic semiconductor device. Once the nonlinearities are well understood and fully characterized at the frequency band of interest, the parasitic elements effects can be taken into account by either comparing the simulation results for the intrinsic device with measured data or by supplementing the intrinsic device simulator with another model to predict the values of such parasitic elements.

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Table I. Simulation parameters.

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 length, L	2.15 µm
Gate length, Lg	0.25 µm
Active layer thickness, a	0.1 µm
Active layer doping	$2x10^{17}$ cm^{-3}
Schottky barrier height	0.8 v
DC Gate-source voltage, Vgso	-0.5 v
DC Drain-source voltage, Vdso	3.0 v

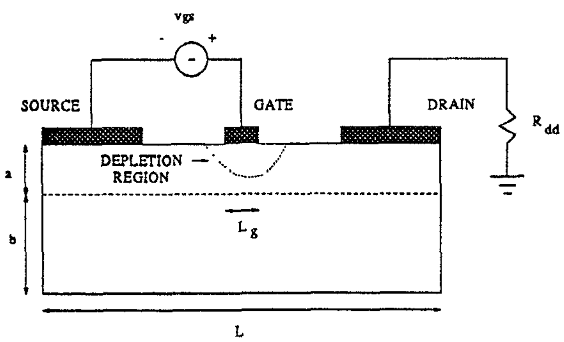

Fig. 1. Circuit used in Ac analysis.

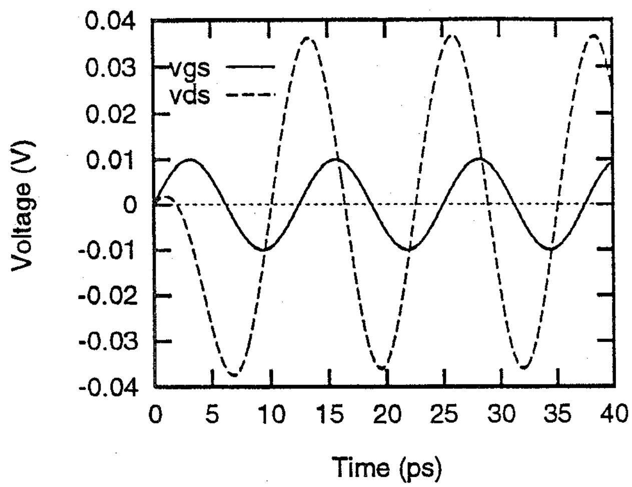

Fig. 2. Typical input-output signals with the following parameters: L_g=.25 μm, Δvgs=10 mV, and f=80 GHz.

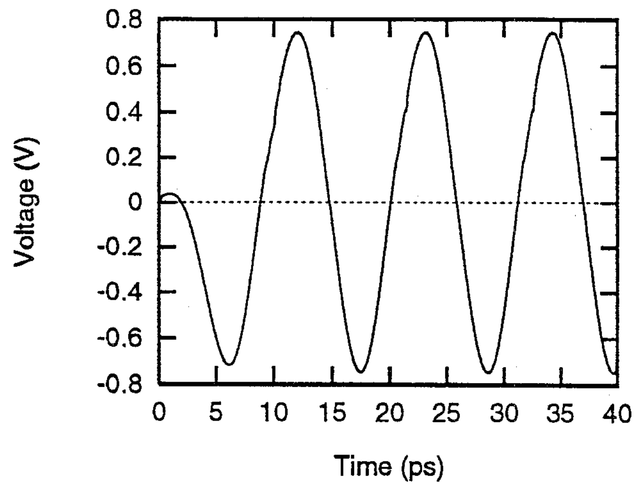

Fig. 4. Output signal corresponding to a 200 mV input.

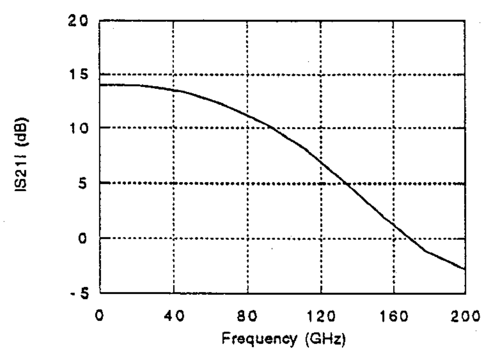

Fig. 3. S_{21} parameter vs. frequency.

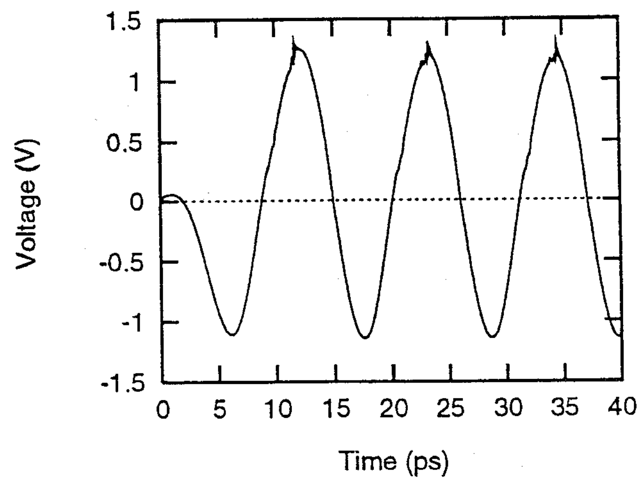

Fig. 5. Output signal corresponding to a 300 mV input.