Physical/Electromagnetic Quasi-Tridimensional Analysis of High-Frequency FET's

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ABSTRACT

This letter presents an effective technique for the analysis of microwave and millimetre-wave field-effect transistors, based on geometrical and material data only. The intrinsic (active) part of the device is described by quasi-2D hydrodynamic transport equations, coupled to a numerical electromagnetic field solver in three dimensions that takes into account the passive (extrinsic) part of the structure, including connections and distributed propagation effects. The analysis is performed entirely in the time domain, and includes linear and non-linear operations of the device.
Small-signal and large-signal results at microwave and millimetre-wave frequencies are presented for a 2×50μm HEMT device, and also for varying gate width, that demonstrate the capabilities of the technique. The feasibility of applications to the design and optimisation of high-frequency devices is demonstrated.

INTRODUCTION

In the last few years the increasing number of high-frequency MMIC applications has stimulated a considerable effort in the modelling of active devices (e.g. [1]), with the aim of predicting their behaviour and optimising their performances. However, the problem of relating the linear and non-linear transistor performance to the physical and geometrical parameters with a limited computational effort and reasonable accuracy is still open.

An FET model is basically divided in two parts: the *intrinsic* and the *extrinsic* one. The intrinsic part corresponds to the FET active region, where the charge control and transport phenomena take place. Physical or behavioural approaches can efficiently described this region. The extrinsic part on the other hand represents the passive effects of the interconnections between the external terminals and the active region of the transistor. The distributed nature of these effect is best represented by an electromagnetic field description.

This paper presents a technique for the analysis of high-frequency FETs through a coupled self-consistent solution of the electron control/transport equations and of the 3D electromagnetic problem, for the intrinsic and the extrinsic regions respectively. The method is implemented in the time domain by means of an FDTD technique for the electromagnetic part, and of a quasi-2D hydrodynamic method for the active part. This technique allows the simulation of the transistor performance on the basis of the geometrical, physical as well as material parameters only, giving an insight into the intrinsic/extrinsic parts interaction, and allowing a qualitative optimisation of the structure. The validity of the approach and its capabilities have been demonstrated for a 0.2μm HEMT with two 50-μm-wide gate fingers.

THE QUASI-TRIDIMENSIONAL FET MODEL

The model consists of a quasi-two-dimensional physical model of the intrinsic high-electron-mobility transistor coupled to a finite-difference time-domain electromagnetic simulator. The transistor active region, i.e. the region between source and drain, is subdivided in elementary sections along the gate finger width (fig.1b). Each section is associated to an elementary device, which is individually analysed; its non-stationary charge transport is treated as a quasi-two-dimensional problem [2, 3]. The implementation of a 3D non-stationary analysis of the transistor is obtained by coupling the individual sections and the passive structure by means of a finite-difference time-domain electromagnetic analysis of the transistor structure outside the active region, including pads and metallisations. The elementary transistors are introduced in the FDTD algorithm as non-linear controlled current sources (fig.1a); due to their non-linear nature, at each time-step a number of iterations is required in order to solve for the field. The structure is also coupled to an external generator, acting as the input signal of the transistor, and to a resistive load at the drain terminal. The DC analysis is performed only for the active device, while AC analysis is performed for the whole structure.

The flowchart describing the sequence of the operation is shown in Fig.2. The model of the elementary device takes into consideration the most important phenomena occurring in the active area of the electron device under analysis, while staying simple and fast enough to be used within the electromagnetic code. The basic transport equations for electrons, i.e. the moments of Boltzmann's transport equation, have been written in a simple form neglecting some less important terms (e.g. the diffusion term in the momentum and energy conservation equations). Moreover, the electron flow is assumed to take place essentially in the source-to-drain direction, neglecting the vertical components; a charge-control equation is added, together with Poisson's equation, to model the vertical structure of the device. The model has already been successfully employed for non-linear simulations in [3].

Given the much smaller dimensions of the region interested in transport phenomena w.r.t. the whole structure, the same cell size could not be used for both physical and electromagnetic analyses. All the effects related to the charge transport have therefore been included in a density current component flowing at the interface between the semiconductor and the air, as depicted in fig.1a. In this way only the surface field components interact with he charge flow in the channel, while the gate current has been modelled with a current wire perpendicular to the gate metallisation.

RESULTS

In order to demonstrate the capabilities of the model, a set of simulations for a 0.2 μm gate lenght, AlGaAs/GaAs HEMT has been carried out. The device has 2 gate fingers, 50 μm wide, in a T shape (fig.1b). The drain metallisation has been terminated by a 100 Ω load resistor, while the source metallisation has been shorted to ground; the input signal is applied to the gate metallisation. DC bias is also applied to gate and drain. A small-signal test has been first performed, with a 50 GHz sine-wave input; the gate bias voltage has been varied in the range [-0.9V ÷ -0.3V] to test the small-signal gain dependence on gate bias, while the drain voltage has been fixed at 1V. The results are shown in fig.3, where the changes in output voltage reflect the changes in transconductance. The same analysis is shown in Fig.4 for a wider span of the bias voltage. A large-signal test has also been performed, at two gate bias voltages; in fig.5 the output waveforms are plotted, showing the appearance of distortion due to nonlinearities. The proposed method therefore proves to be suitable for investigating the linear and non-linear characteristics of high-frequency devices.

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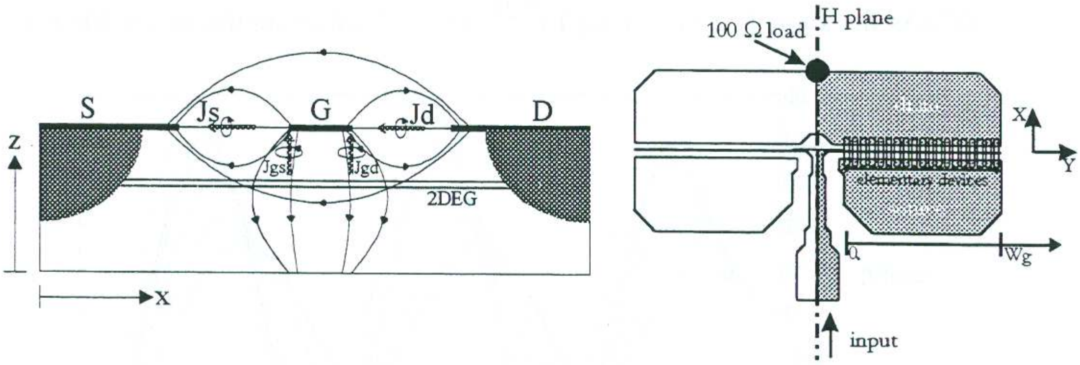


a) b)

Fig. 1: Modellisation of the interaction between field and charge transport a) in the plane [*x*,*z*], b)in the plane [*x*,*y*].

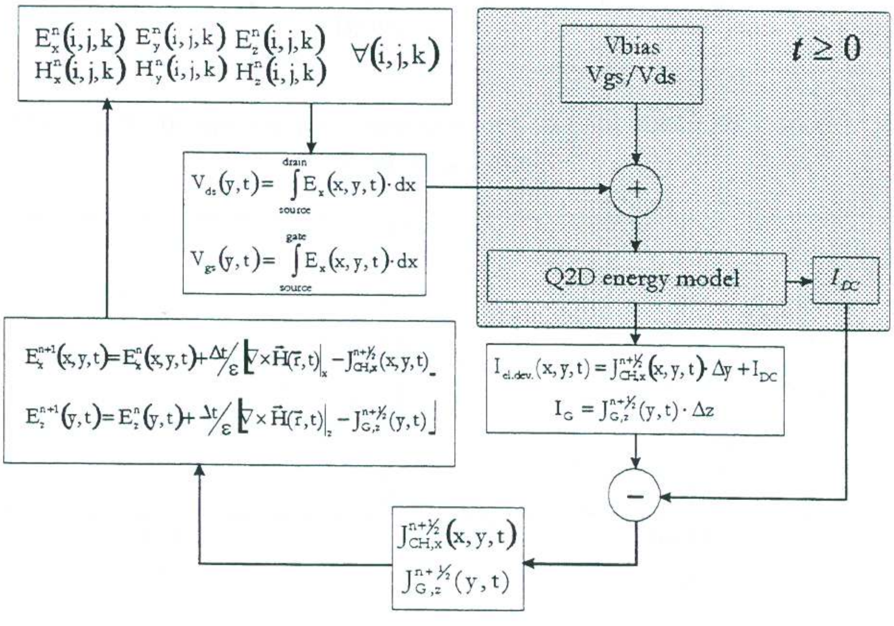


Fig. 2: Flowchart of the proposed technique

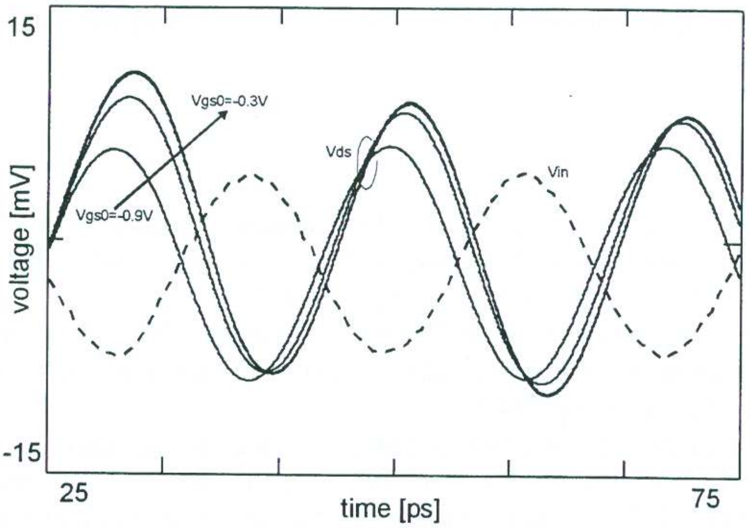


Fig. 3: Calculated input (dashed) and output voltages (continuos curves) for different gate bias voltages from -0.9V and –0.3V. Simulation data: gate length=0.2μm; source- and drain-to-gate distance=1.2 μm; AlGaAs thickness 61 nm, doping 10^{+24} At./m^{-3}; substrate thickness: 100 μm

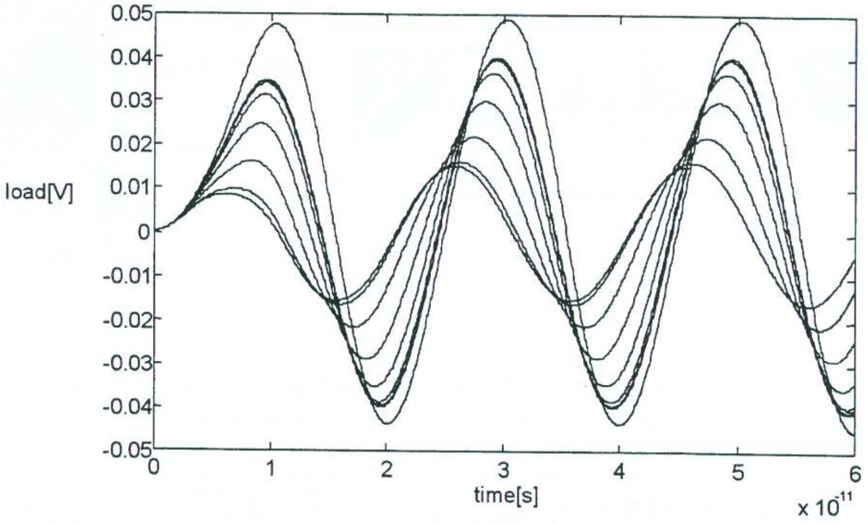
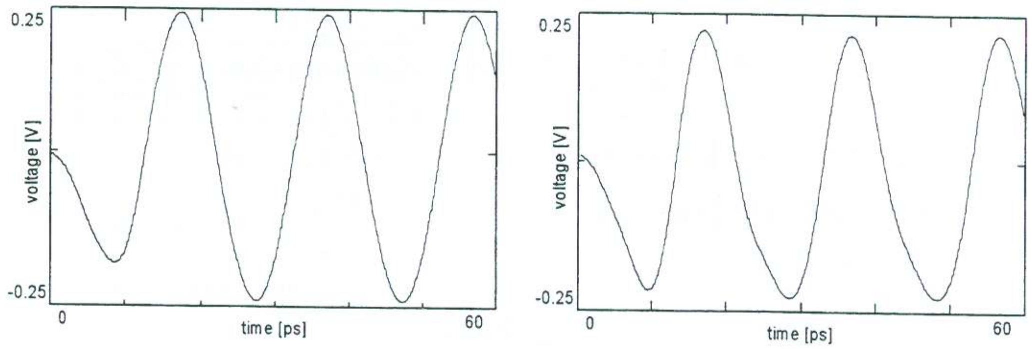


Fig. 4: Output voltage waveforms for gate bias voltages ranging from -0.9V to –0.3V for the same device as in fig.3



a)

b)

Fig. 5: Computed output voltages for a large-signal input and for: a) Vgs,bias=-0.8V, b) Vgs,bias=-0.9.