FAST AND ACCURATE PROCESS-ORIENTED MODEL FOR CAD OF MODFETS

R. K. Veresegyhazy and C. M. Snowden

Department of Electronic and Electrical Engineering
University of Leeds, Leeds, LS2 9JT, UK

Abstract

A fast, quasi-two-dimensional physical MODFET model, capable of accurately simulating single-, multi-channel and pseudomorphic MODFETs has been developed. This has been used to predict DC, small- and large-signal microwave performance, and has been applied to microwave and millimeter wave device and circuit CAD.

Introduction

This paper describes a new physical model for MODFETs, based on a quasi-two-dimensional description of the device and a self-consistent quantum mechanical model.

Until recently, physics-based FET modelling have been too slow to be considered practical tools for device and circuit design engineers. The relatively new technique of quasi-two-dimensional (Q2D) modelling of FETs provides an excellent tool and can simulate devices up to 1000 times faster than full-two-dimensional models, whilst retaining a desirable process-oriented description [1, 2]. A new MODFET simulator based on a Q2D method has been developed for use in microwave CAD. This model is particularly suited to represent the non-linear operation of FETs in large-signal applications.

Single-, multi-channel and pseudomorphic (Figure 1) MODFETs can be simulated with the modelling programme.

Model

A key part of the new Q2D simulation is the charge control model which determines the free charge carrier concentration at any point in the conducting channel as a function of the potential. Our model is based on the self-consistent solution of Poisson's and Schrödinger equations, allowing up to nine Eigen energies to be evaluated. When the quantum well is not very deep, as it is often the case, it is possible to by-pass the quantum mechanical calculations which makes the simulation even faster.

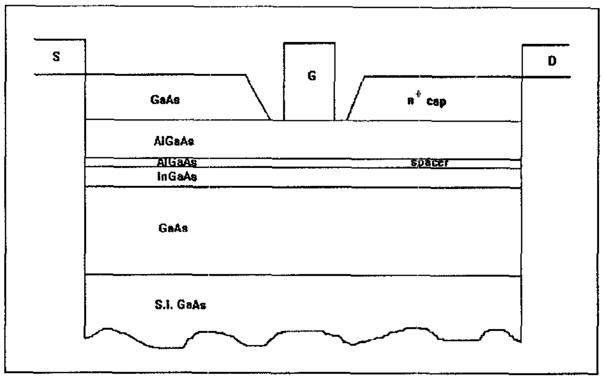

Figure 1. Structure of a typical pseudomorphic MODFET.

The conduction band edge in an AlGaAs/InGaAs/GaAs pseudomorphic MODFET (Table 1), for a cross-section below the gate is shown in Figure 2, and the free electron concentration can be seen in Figure 3.

The simulation produces a look-up table primarily for the sheet electron concentration in each different layer, as a function of the channel-to-gate voltage and the channel-to-surface voltage. The unique feature of the model is its capability to describe recessed as well as planar structures. Unlike other recently published models, our model can simulate parasitic MESFET conduction, allowing a more accurate representation of device operation. In fact, devices with an arbitrary number of different layers can be simulated. The charge control law constitutes the sheet electron concentration curves (Figure 4) and the capacitance curves (Figure 5).

OF2

gate width: 1 mm
gate length: 0.2 μm
source gate distance: 1.3 μm
gate drain distance: 1.3 μm
layer structure:
AlGaAs(electron supplying layer): 20 nm, Al conent: 20%, donor concentration: $2x10^{24}m^{-3}$
AlGaAs (spacer): 3 nm, Al content: 20%, donor concentration: $1x10^{20}m^{-3}$
InGaAs (active layer): 20 nm, In content: 15%, donor concentration: $1x10^{20}m^{-3}$
GaAs (buffer layer): 200 nm, donor concentration: $1x10^{20}m^{-3}$

Table 1: The structure and properties of the simulated pHEMT device.

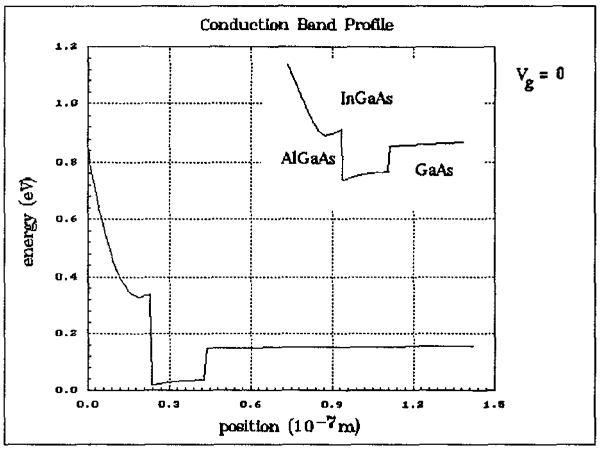

Figure 2. Energy-band diagram of a vertical section below the gate of a pseudomorphic MODFET.

In the case of pseudomorphic structures the effects of strain on the band gap, conduction band edge discontinuity, dielectric constant and effective mass are calculated based on the data in [3] and [4].
The charge control model is integrated into an efficient channel simulator which is based on an energy transport model similar to the model in [1] and is therefore suitable for the simulation of submicrometer gate MODFETs. Under normal operating conditions the gate largely depletes the active channel as the electron concentration from the charge-control law is small (see Figure 4). However, the current continuity is maintained due to the contribution of electrons injected into the substrate.

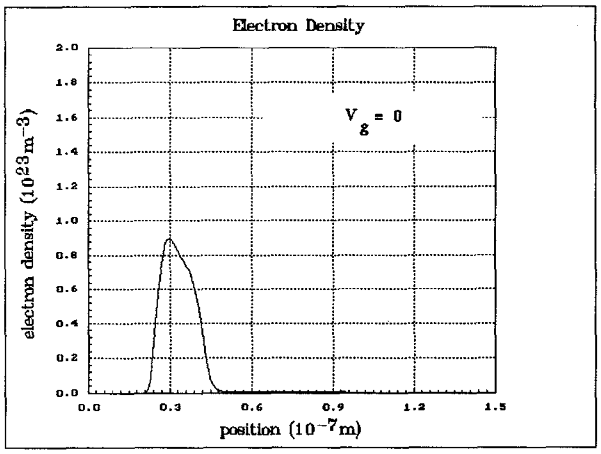

Figure 3. Electron density for the cross-section of a pseudomorphic MODFET corresponding to the conditions shown in Figure 2.

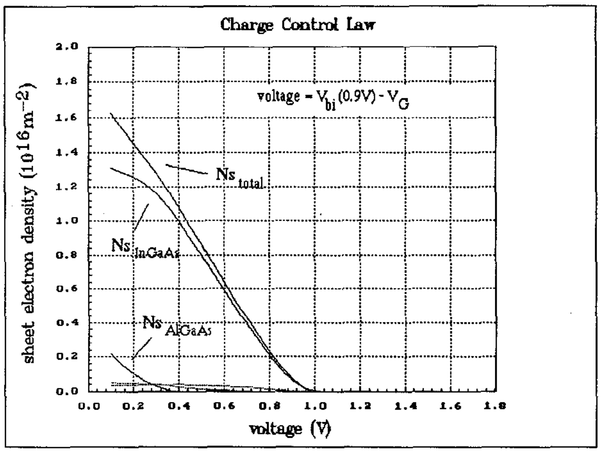

Figure 4. Charge control law: sheet electron concentration in each layer

This model, like most other quasi-two-dimensional models, is basically a current driven one. For a given I_{DS} (and V_G) V_{DS} is calculated by integrating the electric field along the channel from the source to the drain. The electric field itself is calculated solving a quadratic equation which is a combination of Poisson's equation and the electron transport equations.
It is particularly difficult to model with a current driven model situations when the device exhibits negative output conductance, as can be the case for positive gate biases in power devices. To overcome this difficulty the I-V characteristics are calculated in a simulated voltage driven way: the drain current is found for any given drain-source

voltages using an efficient sectioning algorithm which varies the imposed source current until the supplied and calculated drain-source voltages coincide.

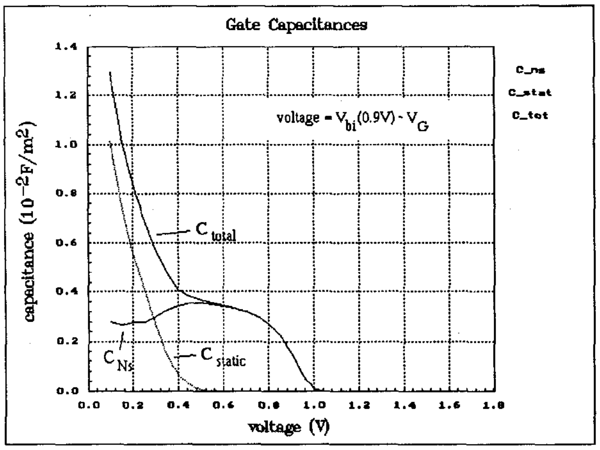

Figure 5. Charge control law: capacitances.

I-V characteristics and microwave S-parameters are obtained in a few minutes on a personal computer with a 80486 processor. Simultaneously, the program can determine the elements of non-linear quasi-static equivalent circuit model (Figure 6). S-parameters are calculated using a time-domain version of the physical model.

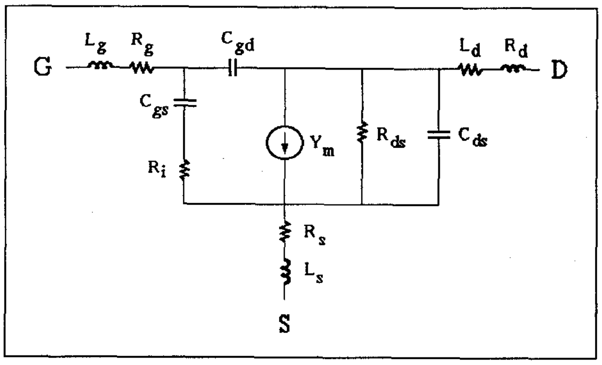

Figure 6. Quasi-static equivalent circuit with extrinsic elements.

Application

The applicability of the model is widespread. Device and circuit designers can investigate new structures, such as pseudomorphic MODFETs, and optimize their design prior to fabrication for given microwave circuit requirements. Single-recess low-noise millimeter wave MODFETs as well as double-recessed power FETs can be modelled and third-order intercepts and 1 dB compression points predicted. S-parameters are extracted over a wide frequency range using time domain simulation with this model. Large signal operation of MODFET circuits is obtained using a modified harmonic-balance method [5].
The large signal performance of the pHEMT in Table 1 is shown in Figure 7, for 1mm gate width. The pHEMT was operated in a Class A configuration, biased at V_{DS} = 5V, I_D = $I_{DSS}/2$.

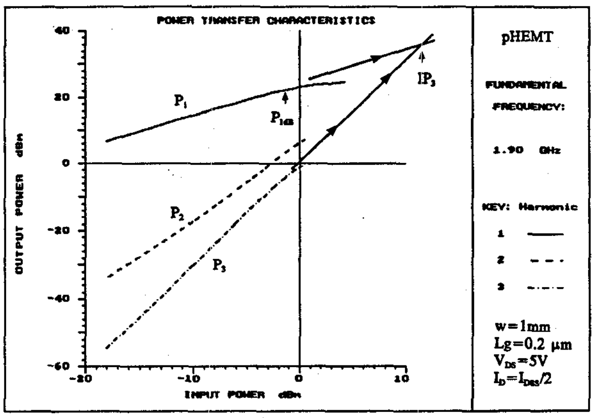

Figure 7. Large signal operation.

The simulated pHEMT was found to have a Class A power output of 22 dBm at the 1dB compression point (P_1dB), a third-order intercept output power (TOI) of 36dBm, and a small-signal gain of 24dB at 1.94GHz. At 12 GHz the gain reduced to 9.8dB with a P_1dB of 22dBm and TOI of 34dBm. These large-signal simulations required only 2 minutes for 25 data points on a 50MHz 486 personal computer, using the modified harmonic balance technique described in [5]. No convergence problems were experienced (up to 6 dB gain compression).

The DC characteristics of a multi-channel AlGaAs/GaAs/AlGaAs/GaAs power HEMT are shown in Figure 8, for a 0.3 μm gate length device with a gate width of 1 mm. The simulated small-signal gain was determined as 14.5dB compared with a measured value of 15dB. The large-signal simulation predicts a power output of 25dBm in Class A operation, biased at V_{DS} = 6V, I_D=390mA.

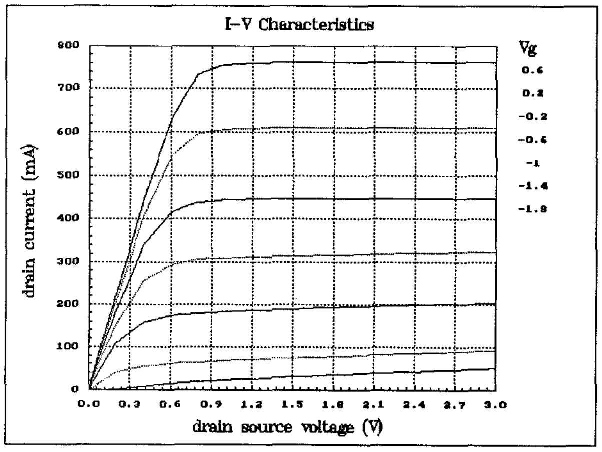

Figure 8. DC characteristics.

The model is suitable for building into a reverse modelling scheme which automatically optimizes the device structure to match certain pre-defined microwave parameters or to extract device structure data from the measured DC- [6] RF- or microwave behaviour.

Conclusions

This highly efficient physical device model allows the DC small- and large-signal microwave characteristics of planar and recessed gate HEMTs to be obtained based on device geometry and process data. It is easily applied to a wide variety of HEMT structures including pHEMT, AlGaAs/GaAs and multichannel structures. This model is particularly useful for optimizing HEMT designs and for use in non-linear circuit design.

Acknowledgement

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