# A LARGE SIGNAL PHYSICAL MESFET MODEL FOR CAD AND ITS APPLICATIONS

R. R. Pantoja, M. J. Howes, J. R. Richardson, C. M. Snowden

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

## ABSTRACT

A quasi-static, large-signal MESFET circuit model has been developed. It is based on a comprehensive quasi-two-dimensional semi-classical device physical simulation where its unique formulation and efficiency makes it suitable for the CAD of nonlinear MESFET subsystems. A single/two-tone harmonic balance analysis procedure which employs the describing frequency concept has also been developed and combined with the MESFET model. Numerical load-pull contours, as well as intermodulation distortion contours, have been simulated and comparing these with measured results substantiates the approach taken.

## INTRODUCTION

GaAs MESFETs are the fundamental building block for both discrete and Monolithic Microwave Integrated Circuits (MMICs). The requirements to minimise development costs and optimise device-circuit interaction have led to an increased interest in physical device models which intrinsically relate the basic material and geometrical parameters of a device to its DC and RF performance. Moreover, the trend towards higher frequency of operation (shorter gate length devices) requires models capable of describing non-equilibrium transport phenomena (hot-electron effects). The model presented here is based on a description of the carrier dynamics (transport equations) derived from the Boltzmann equation [1].

The validity of the model for both DC and small signal (S-parameter) conditions has been assessed previously [2,3] and the object of this paper is the application of the model to CAD of nonlinear microwave subsystems, when device-circuit interaction can be adressed and sensitivity analysis performed as a function of the basic device parameters. To this end a quasi-static, large-signal MESFET model has been derived from the simulation and combined with an efficient single/two-tone harmonic balance analysis procedure in order to simulate load-pull and intermodulation distortion contours.

## PHYSICAL SIMULATION AND QUASI-STATIC MODEL

The physical simulation is based on the four semi-classical semiconductor equations coupled with analytical expressions for the MESFET channel. These are solved over a one-dimensional mesh using a fast and accurate algorithm. The model accounts for process-related parameters (geometry, recess depth, material parameters, doping profile, etc.), surface depletion effects, substrate conduction, contact resistivities, avalanche breakdown and forward gate conduction. A more complete carrier transport model than in previous quasi-two-dimensional simulations [4,5] is employed and the Poisson and current continuity equations are solved together with the energy and momentum conservation equations. The solution of the latter allows for hot-electron effects (velocity overshoot) to be simulated, thus making the model also suitable for short gate-length MESFETs.

The basic simplifying assumptions for the MESFET channel, based on the results of full two-dimensional simulations, are:

(i) no current flows through the depleted region,

(ii) current density is one-dimensional and

(iii) potential contours in the undepleted part of the active channel and in the substrate are all parallel and are perpendicular to the active layer/substrate interface.

The model equations derived from these assumptions are discretised and solved along the channel using a forward/central difference scheme, the boundary conditions being the gate voltage and the drain (source) current. For each simulated point of the device characteristics ($I_{DS}$ vs $V_{DS}$), small perturbations of the gate voltage and/or drain current (the independent variables for the physical simulation) provide the MESFET's equivalent circuit element values $G_m$, $G_{DS}$, $C_{GS}$, $C_{DG}$ and $C_{DOM}$ shown in figure 1. The source and drain resistances ($R_S$ and $R_D$) as well as the drain-source capacitance ($C_{DS}$) are assumed to be bias independent and the gate, source and drain contact resistances ($R_{GC}$ , $R_{SC}$ and $R_{DC}$) are calculated within the simulation from information (resistivities, metallisation thicknesses and pad areas) supplied for the Schottky and Ohmic contacts. The gate charging resistance ($R_I$) is assumed to be inversely proportional to the gate-source capacitance and proportional to the electron transit time under the gate ($\tau$), which is also calculated by the simulation.

Figure 2 shows the bias dependent equivalent circuit element values for an NE9000 series 0.5 $\mu$m power GaAs MESFET. A set of results can be generated in less than 3 minutes on a VAX 8600. Data on the device structure, which was supplied by NEC, has been used for full two-dimensional simulations and for comparing simulated load-pull results with those obtained by measurements [6].



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## THE SINGLE / TWO-TONE HARMONIC BALANCE ANALYSIS PROCEDURE

The large signal equivalent circuit model is combined with a harmonic balance analysis routine capable of handling single frequency and two-tone excitations so that intermodulation distortion (IMD) contouring [7], as well as load-pull contouring, can be simulated. In the two-tone case, the describing frequency concept [8], whereby a bilinear transformation is employed to map the two-dimensional frequency grid onto a one-dimensional spectrum, is used; Discrete Fourier Transforms can then be employed efficiently. The crucial stage is the definition of the two-dimensional frequency grid where

$$\omega_{m,n} = m\omega_1 + n\omega_2 \quad (1)$$

$$|m| + |n| \leq p \quad (2)$$

With $p$ defined as the order of nonlinearity of the device this means that the Fourier coefficients corresponding to frequencies $\omega_{m,n}$, such that $|m| + |n| > p$, are negligible.

In order to improve efficiency in the DFT, the original frequency spectrum generated by commensurable basis frequencies $\omega_1$ and $\omega_2$ is transformed to an equivalent one using incommensurable basis frequencies $\omega_1{'}$ and $\omega_2{'}$. The transformed frequencies are called describing frequencies [8] and, as an important consequence, the corresponding DFT is frequency independent. Furthermore, by choosing

$$\omega_1{'} = p\,\omega_0 \quad (3)$$

$$\omega_2{'} = (p+1)\,\omega_0 \quad (4)$$

with $\omega_0$ an arbitrary frequency basis, it can be readily seen that the typical spectrum gaps present in modulation problems will not exist. This implies that the two-tone problem is reduced to an equivalent single-tone case and that the total number of frequencies considered is $p(p+1)$. The mapping is relatively simple and its inclusion in a conventional single-tone harmonic balance is straightforward.

The set of nonlinear equations generated in the harmonic balance procedure is solved using a secant solver scheme (similar to [9]), thus ensuring extremely fast convergence properties for a wide range of nonlinear problems such as power amplifiers. The solution requires less than 30 iterations when 6 harmonics are considered for the single-tone case and less than 40 iterations considering 30 frequencies ($p=5$) for the two-tone intermodulation distortion case.

## RESULTS

Load-pull contours for the NE9000 have been simulated over the 6 to 12 GHz range. The agreement with the measured results [6] is excellent as can be seen in figure 3 where load-pull contours of gain (figure 3a) and output power (figure 3b) corresponding to the 1dB compression point are shown.

Figure 4 shows the simulated results of the two-tone procedure with signals at 9.99 and 10.00 GHz with equal input powers (again for 1dB compression). It can be seen that both the gain and output power contours are similar in shape to those in figure 3, but a gain and output power compression effect can be clearly seen. Figures 4c and 4d show intermodulation distortion contours for both a low drive level (10dB below 1dB compression) and for the 1dB compression point. It is evident that there is a tendency for the optimum load termination for minimum IMD to move towards the center of the chart as the power is increased.

## CONCLUSIONS

A quasi-static large-signal MESFET model based on a quasi-two-dimensional device physical simulation has been developded and combined with a single/two-tone harmonic balance analysis procedure. Application of the describing frequency concept drastically reduced the complexity of the two-tone excitation problem by transforming it to an equivalent single-tone case. Numerical load-pull contours, as well as intermodulation distortion contours, have been simulated and excellent agreement with experimental results has been demonstrated.

**Acknowledgments**

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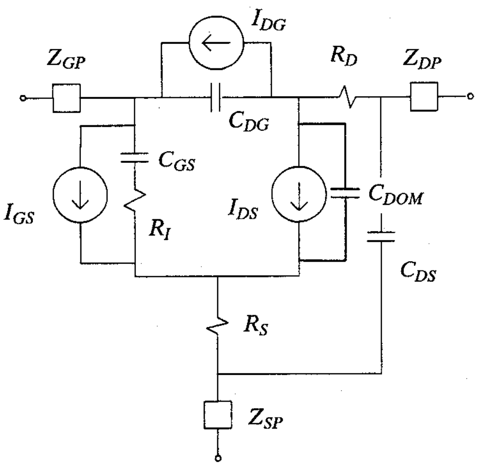
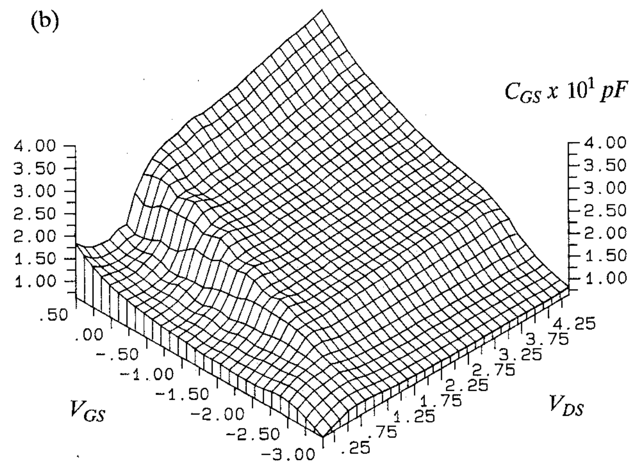
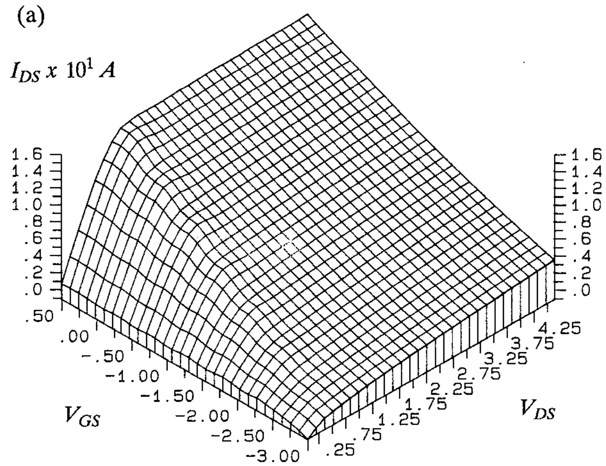



Figure 1 - Large-signal MESFET model

(b)




(a)




(c)

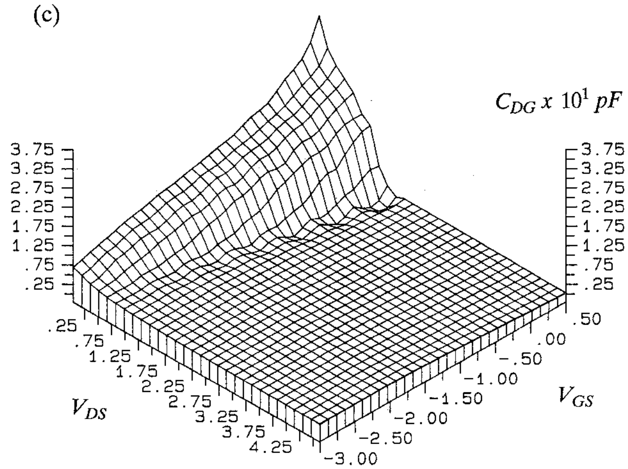



Figure 2 - Bias dependent equivalent circuit element values; $I_{DS}$ (a), $C_{GS}$ (b) and $C_{DG}$ (c)

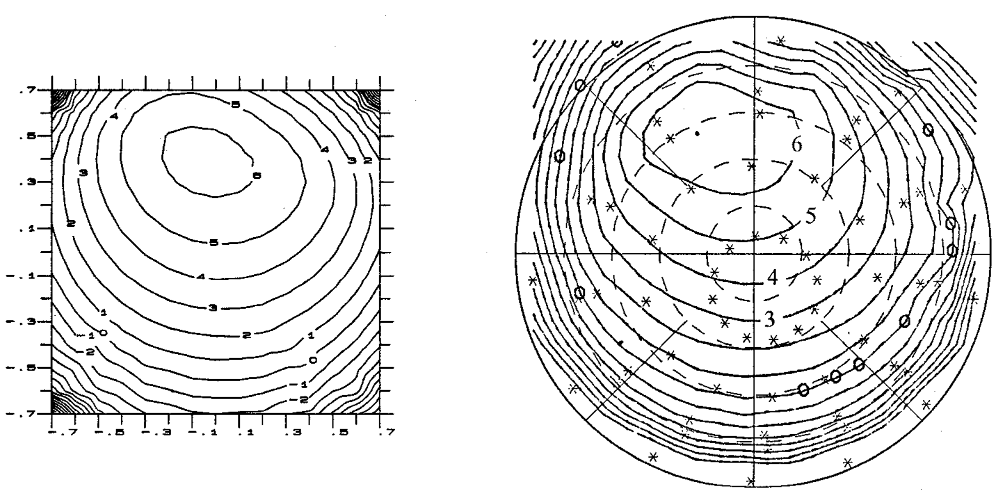



Figure 3a - Simulated and measured gain contours at 1 dB compression for a 10 GHz signal

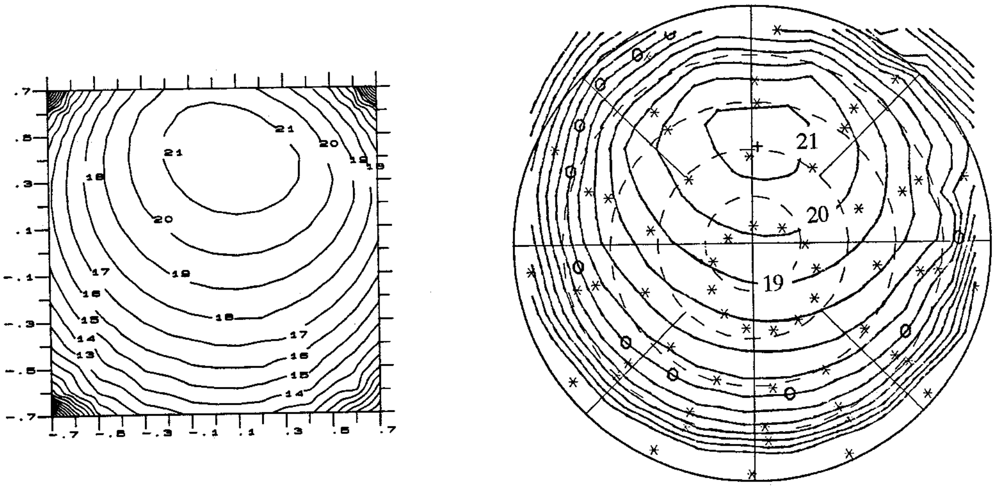



Figure 3b - Simulated and measured output power contours at 1 dB compression for a 10 GHz signal

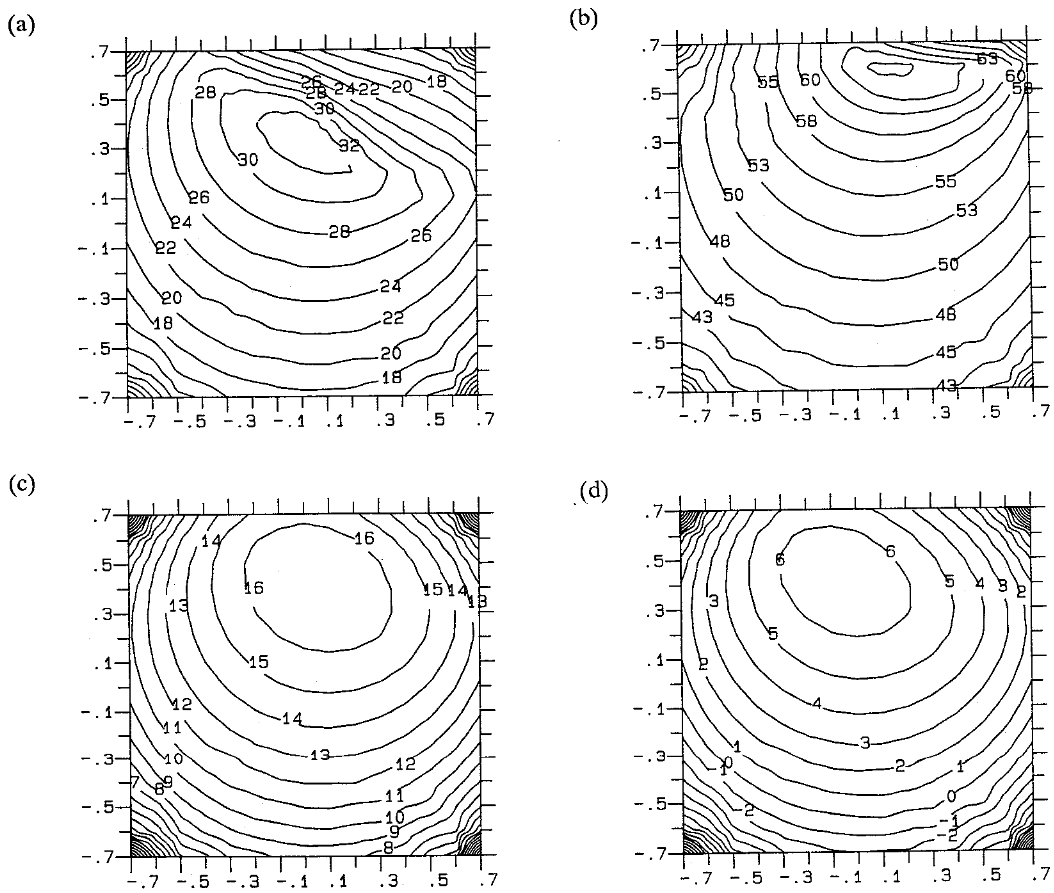



Figure 4 - IMD analysis results; IMD contours (a), output power (c) and gain (d) at 1 dB compression and IMD contours (b) at 10 dB below the 1 dB compression point