CHARACTERIZATION AND MODELLING OF MICROWAVE AND MILLIMETER-WAVE LARGE-SIGNAL DEVICE-CIRCUIT INTERACTION BASED ON ELECTRO-THERMAL PHYSICAL MODELS

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ABSTRACT

This paper describes a comprehensive approach to modelling the large-signal behaviour of microwave and millimeter-wave transistor circuits based on electro-thermal physical device models with harmonic-balance or time-domain simulators. MESFET oscillator and pHEMT MMIC power amplifier designs have been used to validate the method, achieving excellent agreement between simulated and measured data.

INTRODUCTION

The demand for accurate and flexible models for CAD applications which meet the requirements for process-oriented design has led to increasing interest in physical models. Furthermore, the non-linear interaction between the active device and the embedding circuit is readily characterized by this type of model. Traditionally, physical models have been regarded as the domain of device physicists and researchers, requiring extensive computational resources. However, the dramatic improvements in computer technology coupled with equally significant advances in model development have led to the use of physical models within true interactive CAD environments [1].

The highly competitive nature of the current microwave industry has led the need to achieve optimal performance from device and circuit designs with the minimum of development time and costs. This can be readily achieved for small-signal designs, but is particularly challenging for large-signal circuits where self-heating and non-linear device-circuit interactions occur. It is further exacerbated for mm-wave circuits where the impact of parasitics and the distributed nature of both the device and circuit components become more acute.

This paper will describe the application of MESFET, HEMT and HBT physical models to microwave and millimeter-wave circuit design. The significance of self-heating and the consequent use of electro-thermal models will be discussed. The impact of thermal effects on the large-signal performance of circuits will be demonstrated. Millimeter-wave HEMT simulations designed to investigate the device-circuit interaction of mm-wave power amplifiers and oscillators will be illustrated. The significance of correctly modelling parasitics in these applications will be highlighted.

ACTIVE DEVICE MODELS

A key factor in developing the physical models presented in this paper was the requirement that they would execute rapidly enough to allow their use in interactive CAD. This precluded the use of existing two-dimensional models and instead a range of quasi-two-dimensional FET models and physics-based HBT models have been developed. The FET models are illustrated in Figure 1.

The HEMT and MESFET models utilise a quasi-two-dimensional (q2D) carrier transport description, which has been previously reported [1,2,3,4]. The models have been extended to include self-heating and improved parasitic capacitance models. The HEMT utilizes a quantum mechanical charge-control model which is coupled to the transport model. A particularly important aspect of this model is that despite of its highly efficient q2D

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formulation it retains the x and y electric field dependency and yet remains over 1000 times faster than full two-dimensional models.

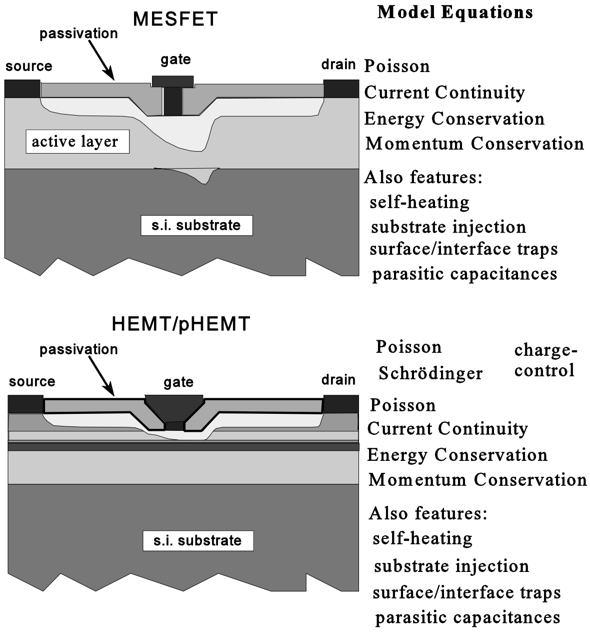


Figure 1 MESFET and HEMT Models

The transistor models have been extended to encompass multi-cell power transistors and utilize the hierarchy illustrated in Figure 2. A key feature of this approach is that each cell of the transistor is solved as a self-consistent electro-thermal model - this is particularly important for large FETs, with many cells (combinations of gate, source and drain contacts) and for HBTs which experience current collapse. The electro-thermal HBT physics-based model is based on the description recently reported in [5]. This HBT model has been applied to the design of large-signal power amplifiers operating in the frequency range 800 MHz to 12 GHz.

DEVICE-CIRCUIT INTERACTION

A key advantage of physical models is that they are intrinsically capable of representing DC, small- and large-signal behaviour, without any modification to the model and unlike equivalent circuit and black-box models there is no requirement for an extensive series of measurements, since all data is provided from the process and physical structure. Several methods of integrating the physical models into embedding circuits have been investigated in this work. The most straightforward method of interfacing physical models to existing commercial CAD software is through an intermediate look-up table or equivalent circuit (for example the Root Model). In this respect the physical model is utilized in the same way that experimental measurements would be used to characterize the device, with the added advantages of speed and unambiguous relationships between equivalent circuit model elements and physical dependence [2]. This approach has been used extensively to model and design non-linear circuits. An example of an W-band HEMT power amplifier harmonic-balance simulation is shown in Figure 3. This utilizes the HP-EEsof MDS environment and the Root model is utilized as an intermediate stage. The Root model is extracted from the physical simulation and allows a very rapid execution of non-linear harmonic-balance simulators. It is necessary to utilize an electro-thermal version of the Root model to represent power devices and this is a challenging aspect of this approach.

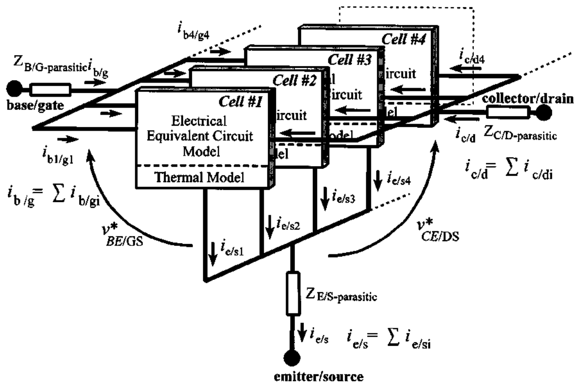


Figure 2. Multi-Cell electro-thermal model for power transistors (used for HBT and FET devices).

The above approach suffers from the same constraints as equivalent circuit and black-box models and for this reason it is preferable to directly embed the physical device model in the circuit model. This usually requires a time-domain solution for at least the active part of the circuit and has the advantage that transient effects can be investigated (although steady-state operation requires a longer simulation time).

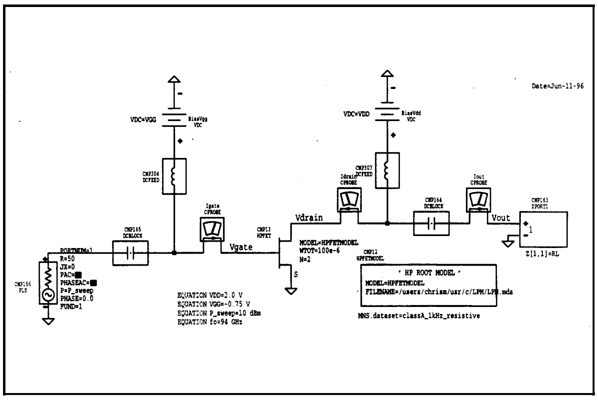


Figure 3 94 GHz HEMT Power amplifier simulation layout, linking physical models through the Root Model, using a commercial simulator.

The device-circuit model integration for time-domain implementations requires a knowledge of the terminal current and voltages, and their derivatives. This has been achieved in this work for both MESFET and HEMT q2D device models with interfaces to customized time-domain circuit models and commercial versions of SPICE. The main disadvantage of this technique is the reduction in speed of solution, although steady-state solutions are extracted in relatively short time periods using an adaptive time-step algorithm (usually less than 10 cpu seconds). A distinct advantage is that all non-linear interactions in terms of amplitude, frequency and impedance-dependence between the circuit and device are fully accounted for, together with thermal transients (which may require several μs of simulation).

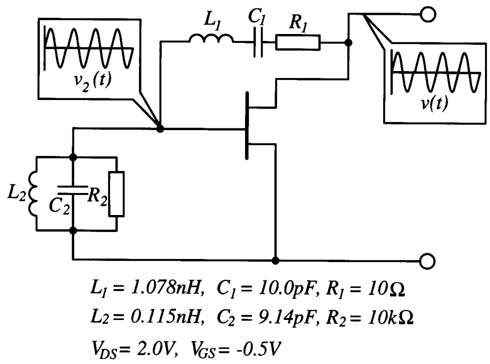


Figure 4. 5 GHz MESFET Oscillator design based on two-terminal device-circuit model, analysed in terms of the admittance $G+jB$ presented at the output.

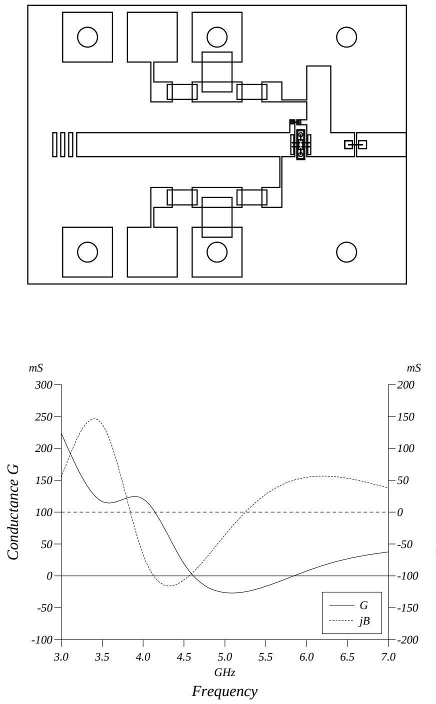


Figure 5. 5 GHz MESFET Oscillator design circuit layout and simulated two-terminal admittance $G+jB$ as a function of frequency.

Examples of time-domain circuit simulations incorporating q2D physical active device models are shown in Figures 4 to 7. The MESFET oscillator shown in Figures 4 and 5 operated within 3% of the design frequency *and* output power, with harmonics better than -30 dBc. Results from the large-signal microwave simulation of a HEMT amplifier are shown in Figure 6, showing excellent agreement between measured and simulated data .

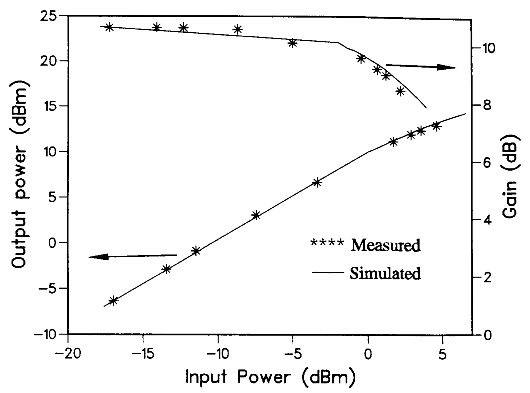
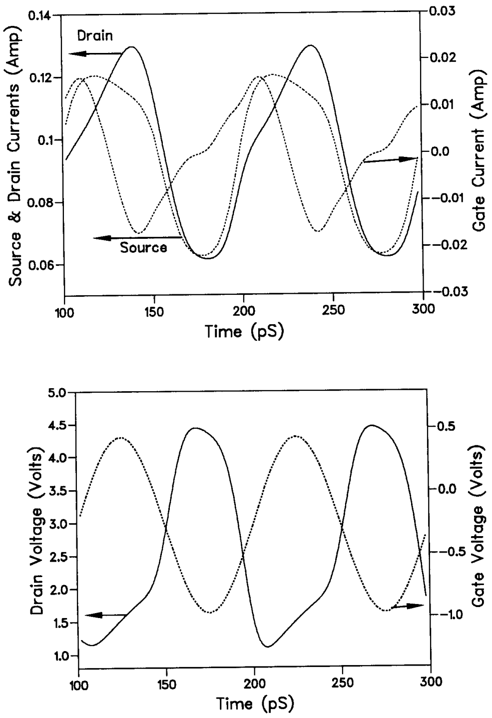


Figure 6. Large-signal simulated and measured



performance of the 10 GHz HEMT amplifier (50□).

Figure 7 Time-domain 10 GHz HEMT amplifier simulation showing large-signal voltage and current waveforms (50□ load).

The steady-state 10 GHz large-signal time-domain waveforms of the HEMT amplifier are shown in Figure 7. This simulator also allows the transient performance to be assessed.

The impact of thermal effects on the performance of microwave and millimeter-wave circuits has been investigated using the above integrated electro-thermal approach and allows a self-consistent solution to be obtained, fully taking into account the non-linear interaction of the device with the circuit. Furthermore, in the case of MMICs the thermal contribution of adjacent components can be taken into account within the simulation - simple cases have been verified using a three-dimensional thermal simulator (HeatWave) in association with infra-red measurements. An example of this type of analysis is shown in Figure 8 for a power pHEMT die. The thermal analysis is also used to determine the thermal resistance matrix for the die [5].

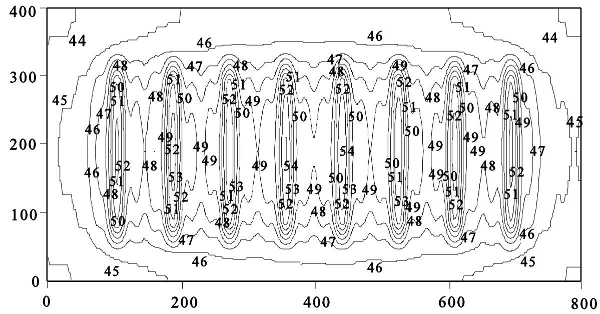


Figure 8 Surface temperature contours for a 0.25×8×200 µm pHEMT power transistor die, obtained using the 3D thermal simulator.

4. CONCLUSIONS

A fully integrated technique for investigating device-circuit interaction and including thermal modelling has been described. The application of this technique to commercial simulators has been explored. The method has been validated for several HEMT, MESFET and HBT circuits.

5. ACKNOWLEDGEMENTS

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