A LARGE-SIGNAL PHYSICAL HEMT MODEL

Christopher G. Morton, John S. Atherton, Christopher M. Snowden, Roger D. Pollard and Michael J. Howes

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

Abstract

This paper reports a new, efficient physical HEMT model capable of accurately predicting DC, small- and large-signal performance. It has been interfaced to an industry standard simulator which allows for accurate, large-signal simulation to be integrated into the design process. Large-signal results demonstrate the model's suitability for MMIC CAD.

I Introduction

Physical models have advantages over circuit models due to their predictive nature and ability to relate manufacturing process variations to the electrical performance of devices. The implementation of a physical model for a HEMT, however, presents quite a challenge due to the complexity of the active layers and the small geometry of the device. Nevertheless, the use of HEMTs in MMICs is now widespread, providing significant motivation for the realisation of such an approach to aid in the design of microwave devices and circuits.

II Model Description

The quasi-two-dimensional (Q2D) model used here is based on the work of Snowden and Pantoja [1] but incorporates several new and important features which are essential for the simulation of HEMTs [2]. The Q2D approach is based on the assumption that the fundamental driving force for electron transport is the x-directed electric field. The potential drop from the source to drain can then be described in terms of the propagation of a Gaussian box as depicted in Figure 1. The charge within the Gaussian box is obtained

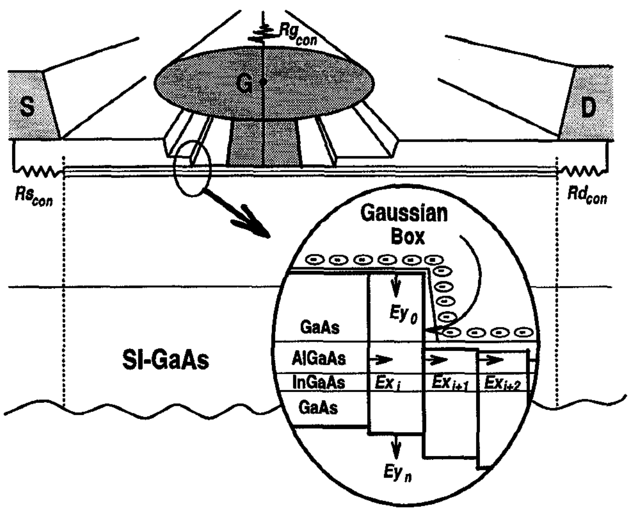

Figure 1: Schematic of Q2D approach

from a 'look-up table' which is generated using an accurate and efficient charge-control model [3]. Some of the Q2D model's important features have been reported previously [2] which enable the accurate prediction of pinch-off, breakdown and transconductance compression. The

TH
3F

0-7803-3246-6/96/$5.00 © IEEE

Q2D model preserves the conditions of conservation of momentum and charge which are both essential for accurate simulation of S-parameters. The efficiency of this new HEMT model is much

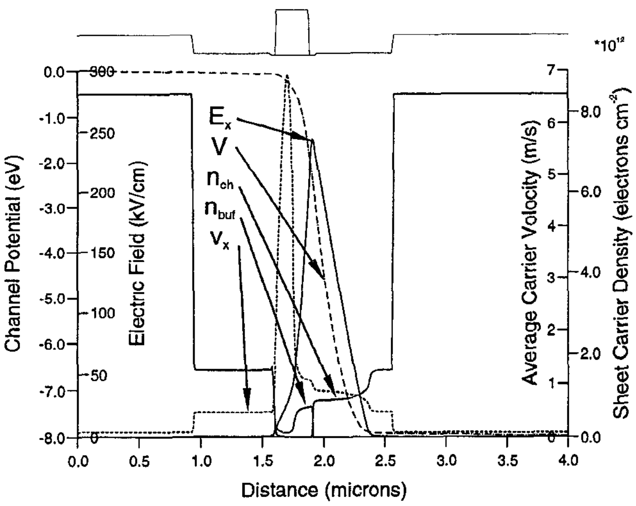

Figure 2: Example solution from quasi-two-dimensional model showing potential, electric field, carrier density and velocity profiles

improved over previous work and is such that DC I-V characteristics or S-parameters at one frequency and bias point are simulated in less than 12 seconds on a HP 735 workstation.

Figure 2 shows an example of a solution from the Q2D model, illustrating the sheet carrier density in the channel and the buffer, n_{ch} and n_{buf}, the x-directed electric field and carrier velocity, E_x and v_x, and the channel potential, V. The solution has been taken at a bias point close to device pinch-off to illustrate the case when the majority of carriers flow through the buffer and not through the device channel layer. The existence of buffer injection in the model arises from the negative polarity of dE_x/dx which is included self-consistently in the charge-control and transport simulations (y- and x- directions respectively) [2]. The Q2D model must be capable of modelling carrier injection into the buffer in order to accurately describe the time-variation of charge in the device channel during the rf simulation. The influence of the double recess is also shown in Figure 2 through the spreading of the electric field distribution on the drain side of the device. This type of information indicates the power of this Q2D model which provides significant insight into device operation and facilitates the optimization of transistor design.

The HP-EEsof Root Model [4] is a measurement based, technology and process independent FET model. It has shown excellent agreement between predicted and measured large-signal characteristics for a number of devices and conditions, based upon measured bias dependent S-parameters. Alternatively, the model can be generated using simulated S-parameters from a physical model [5]. This approach for large-signal modelling using a physical model has a number of advantages: (i) it is efficient compared to the conventional type of large-signal time-domain simulation; (ii) multiple large-signal simulations can be carried out for a particular device structure from the simulation of a single Root Model; (iii) the physical model can be linked to commercial simulators for small-, large-signal and statistical simulation.

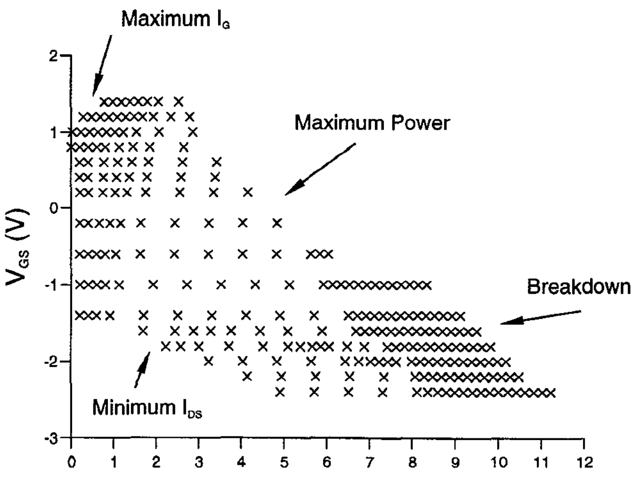

Figure 3: Simulation plane for HP pseudomporphic HEMT

S-parameters are generated over the simulation plane ($V_D - V_G$) with the bias points chosen so that more points are calculated in regions of high nonlinearity. The algorithm used is similar to that used for the measurement of S-parameters [4].

This reduces the simulation time and storage requirements and ensures accurate interpolation of the model parameters - this mimics the measurement plane used for the measurement-based Root Model. Figure 3 shows the bias points used for the S-parameter simulation. The device is simulated well into pinch-off, breakdown and forward bias regions. The contour integration routines [4] produce a 'look-up table' compatible with commercial simulators in which non-linear simulation can be performed - HP EEsof's Microwave Design System (MDS). Generation of a complete simulated Root Model data file for a single device over the full range of operation takes approximately 15 minutes on a HP 735 workstation.

III Analysis

The device used in this study is a 0.25×240 μm gate InGaAs channel pseudomporphic HEMT with doping above and below the channel [6], fabricated by Hewlett-Packard Microwave Technology Division. Figure 4 shows a comparison with the measured and simulated DC I-V characteristics. The measured characteristics correspond

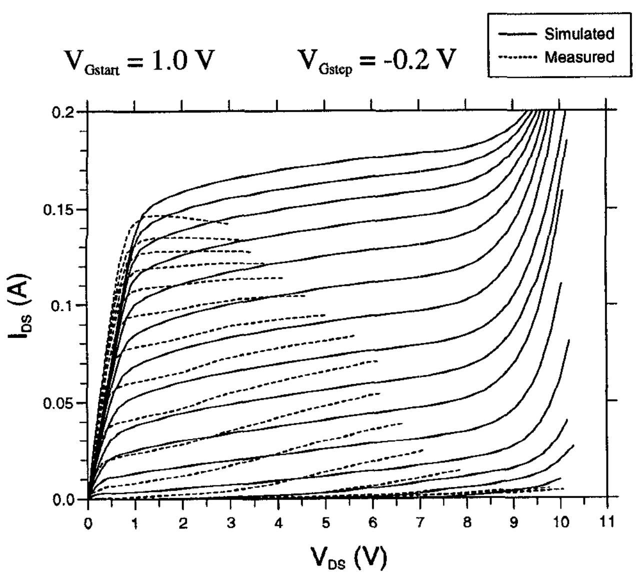

Figure 4: Comparison of simulated and measured DC I-V characteristics

to the Root Model S-parameter bias points and their range is limited by the onset of device breakdown and the maximum power dissipation locus. It should be noted that the measured and simulated I_{dss}, pinch-off and breakdown voltage agree very well. At higher values of gate voltage there is significant self-heating which reduces the measured output conductance.

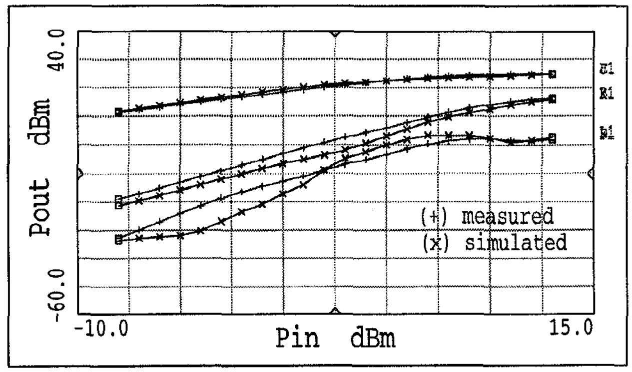

Figure 5: Fundamental, first and second harmonics into 100Ω in class A operation

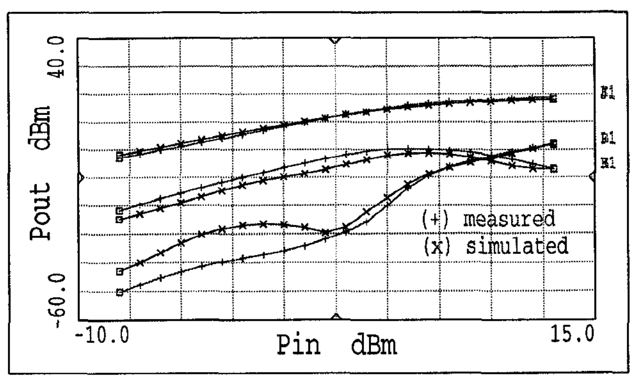

Figure 6: Fundamental, first and second harmonics into 100Ω in class AB operation

Comparing the large-signal performance of the measured and simulated Root Models provides quantitative validation of the physical model. The agreement achieved when comparing a Root Model (based on measurements) and actual large-signal measurements is excellent [4]. Figures 5, 6 and 7 show comparisons between power transfer characteristics produced using measured (+) and simulated (×) Root Models within HP-EEsof's MDS. All simulations were performed at 5GHz.

Two different bias points and loads were used for the comparisons. In Figure 5 the bias is $V_{DS} = 4.5V$, $I_{DS} = 85mA$ (a typical Class A amplifier bias point) with a load of 100 Ohms. Figures 6 and 7 show power transfer characteristics at a bias of $V_{DS} = 4.5V$ and $I_{DS} = 10mA$ (a typical Class AB amplifier bias point) using loads of 100Ω and 50Ω respectively. In all three figures, the agreement between the 'measured' and simulated performance is excellent. Typically, the fundamentals agree to within 1dB well into compression. The agreement between the measured and simulated harmonics is also very good, demonstrating the success of the approach taken.

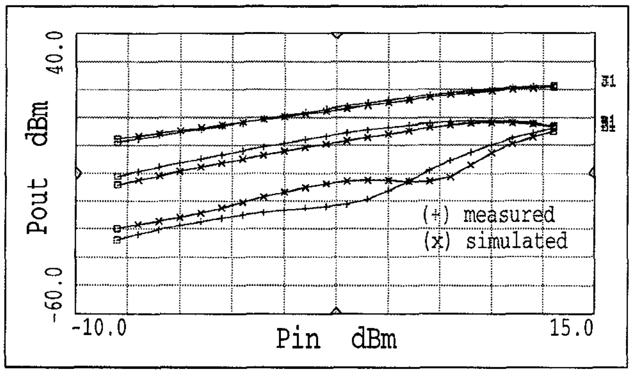

Figure 7: Fundamental, first and second harmonics into 50Ω in class AB operation

IV Conclusion

The use of a physical model for large-signal HEMT performance prediction has been described for the first time to the authors' knowledge. The interfacing of an efficient physical simulator to a 'table-based model' has allowed the simulation to be performed within industry-standard non-linear CAD tools. The efficiency of the model and the quality of the agreement between measured and simulated results illustrates the power of this approach and demonstrates its suitability as an integral part of the design process for MMICs.

References

[1] C. M. Snowden and R. R. Pantoja. "Quasi-two-dimensional MESFET simulations for CAD." *IEEE Trans. Elec. Dev.*, 36(9):1564–1574, September 1989.

[2] C.G. Morton, C. M. Snowden, and M. J. Howes. "HEMT physical model for MMMIC CAD." *Proceedings of the 25th European Microwave Conference*, September 1995.

[3] C.G. Morton. "The epitaxial layer design of HEMTs." *D.Phil Thesis, University of York*, November 1994.

[4] D. Root, S. Fan, and J. Meyer. "Technology independent large-signal non Quasi-Static FET models by direct construction from automatically characterized device data." *21st European Microwave Conference Proceedings*, pages 1017–1022, September 1991.

[5] J.S. Atherton, C.M. Snowden, and R.D. Pollard. "Design of experiments using a physical model." *Proceedings of the 25th European Microwave Conference*, pages 1017–1022, September 1995.

[6] G. Zhou, K. Chan, B. Hughes, M. Mierzwinski, and H. Kondoh. "A pseudomorphic MODFET structure with excellent linear power performance at millimeter-wave range." *Proceedings of IEEE IEDM*, pages 109–112, 1989.

Acknowledgements

The authors acknowledge funding from HP-EEsof, Santa Rosa and EPSRC (UK). The authors also thank staff at Hewlett-Packard, Santa Rosa including David Root, Siqi Fan and Jeffrey Meyer for help with the Root Model interface, Kevin Kerwin for provision of physical data and Don McGinty for supplying the measured Root Model.