Comprehensive Characterization and Modelling of Micro-wave Power HEMTs for Large-Signal Power Amplifier Design

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Abstract — **A comprehensive modelling approach is applied to the study of power pHEMT devices for high efficiency microwave and millimetre-wave power amplifier applications. The association of electromagnetic, physical and non-linear simulations has been applied for the first time to the design of high power microwave amplifiers. This research has provided insight into the operation of large transistors, allowing the contribution of individual FET fingers and cells to be investigated. This work has already demonstrated how the transistor structure contributes to the RF performance and enables the design of the transistor and embedding circuit to be optimised.**

I. Introduction

Increasing demand for high efficiency solid-state power amplifiers for both commercial and defence applications has led to increased research focused on increasing power output and power added efficiency. Particular areas of focus are for mobile communications (up to 2.2 GHz), radar (up to 10 GHz), point to point communications (7 to 56 GHz) and satellite communications (mainly up to 30 GHz). In addition to the focus on developing better power transistors (Fig. 1), considerable effort has been devoted to examining high efficiency circuit configurations such as Class E and Class F. The non-linear design of both the circuit and device remain a challenge for this type of application. The work described in this paper is aimed at addressing some of these issues. At the present time there is very little research published for millimetre-wave power amplifier designs of this type.

This paper describes the application of a combined self-consistent simulation, incorporating electrical, electromagnetic and non-linear models of a pHEMT power transistor and its embedding amplifier circuit [1-7]. This paper describes how this approach has been applied for the first time to the design of microwave and millimetre-wave power amplifiers, where the modelling work has been applied in conjunction with active load-pull measurements. Several power pHEMT structures and geometries have been analysed using this approach.

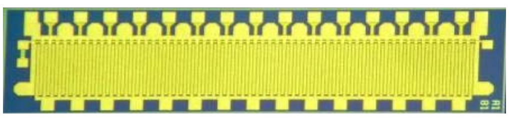

Fig. 1. Filtronic 150 mm power pHEMT

Our study combines an electromagnetic analysis with a physical analysis to predict the response of an entire power pHEMT device. It is based on its actual structure and fabrication parameters. Thus the modelling scheme adopted is an extrinsic - intrinsic (passive – active) division. This procedure has allowed the investigation of the role of geometrical dependencies and the internal operation of multifinger pHEMTs on the RF performances of the amplifier. The electromagnetic simulation coupled to the physical device model (carrier transport equation based) [8] is used to predict the behaviour of the device for various gate widths [2-4], and identify the relative contributions of individual gate finger cells. Finally, this model is applied to the large-signal design of discrete and MMIC high power amplifiers, by coupling the electromagnetic-physical model with non-linear circuit simulators. Most published work on electromagnetic simulation of FETs has been limited to very few cells (source-gate-drain finger combinations). The work described in this paper can be extended to address very large devices. A comparison with large-signal measurements is made, demonstrating the effectiveness of this approach.

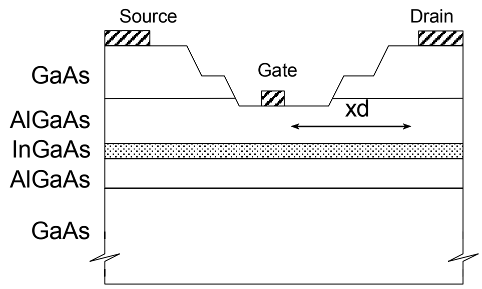

Fig. 2. Channel geometry

II. Electromagnetic And Physical Simulation Of Multi-Finger Power FETs

The complete simulation of the device metallization using electromagnetic simulation has been previously used to predict the values of the parasitics with the total gate width of the device [2-4]. Coupled with the physical simulation based on a quasi-two-dimensional transport model, this approach permits an extension of the investigation to the channel geometry : the "active region" (described Fig. 2) and overall FET layout (finger width, spacings and manifolds). The benefits of electromagnetic simulation are that it not only permits the prediction of the behaviour of devices with various gate widths but also takes into account the influence of elements located near the active device and notably the source vias [2]. This method allows the extrinsic elements of the device model to be predicted and also gives the opportunity to investigate the behaviour of extrinsic parasitics using an extraction process similar to the cold FET technique [11]. The Momentum simulator from Agilent has been mainly used in this work. As an example of what can be achieved, Fig. 3 presents the values of some parasitics as a function of the number of fingers, and Fig. 4 as a function of the gate-drain spacing. The use of the data obtained directly from the electromagnetic simulation provides more information than is currently available using the equivalent circuit approach. In particular, the immediate environment of the device such as the source vias and the lateral coupling between fingers are accounted for as well as the distributed nature of the device, which are not easily taken into account using equivalent circuit models at higher frequencies.

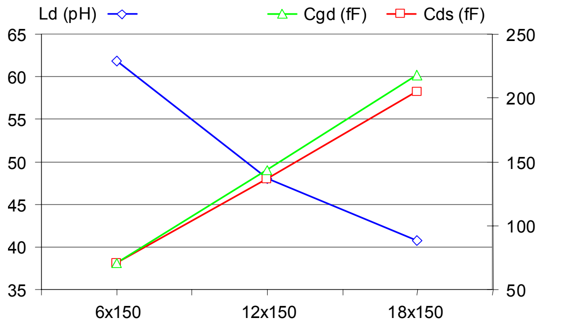

Fig. 3. Device extrinsic parasitics evolution with the number of fingers

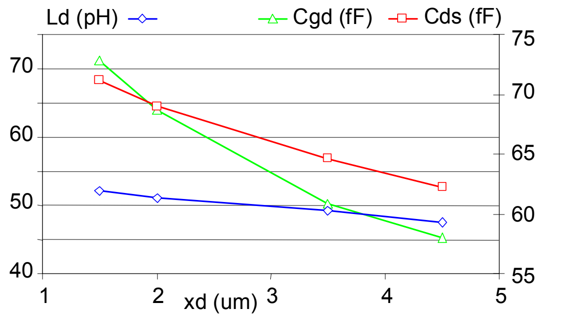

Fig. 4. 6x150 um device extrinsic parasitics evolution with gate-drain spacing (xd)

The active regions of the device (Fig. 2) are simulated using the Leeds Physical Model [8-10], which is based on a hot electron quasi-two-dimensional pHEMT model. This physical model utilizes a quasi-two dimensional carrier transport description and includes thermal effects [12]. The input data is provided both from the process epitaxial wafer structure, cross-sectional geometry and allows single and double-recessed gates with delta and bulk doping. The model self-consistently solves the Poisson, current continuity, energy conservation and two-dimensional Schrödinger equations for the device cross-section. The simulation is extremely fast and relatively compact for application on personal computers. In the same way that the electromagnetic simulation is used to investigate the planar geometry of the device, the physical simulation is used to study the channel region. An example of the application of the physical model is given Fig. 5, where the evolution of some small-signal equivalent circuit parameters is shown for variations in the gate-drain spacing of the power FET. The physical simulation is particularly valuable in characterising the non-linear behaviour of the active region when the device is operated in a large-signal mode.

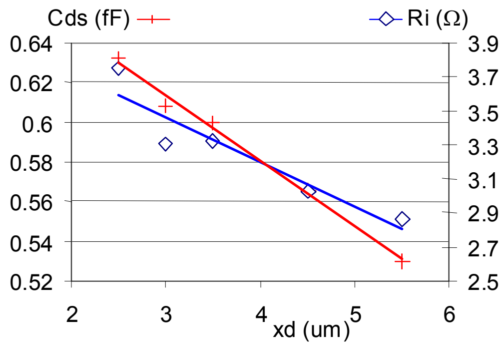

Fig. 5. 150 um active cell small signal equivalent parameter evolution with drain-gate spacing (Vgs=-0.3, Vds=6 V)

III. Characterisation And Design

The small signal parameters obtained for a 6x150 um (0.5 um gate width) pHEMT power FET are shown in Fig. 6. The physical model is used in the same way that experimental measurements would be used to characterize the device for the non-linear simulations, with the added advantage of speed. This allows a straight-forward method of integration with CAD software. The whole modelling approach is currently applied to investigate the design of power amplifiers for microwave and millimetre-wave applications, with specific interest in the scalability of the designs with increasing gate periphery to achieve higher power levels in a compact fashion.

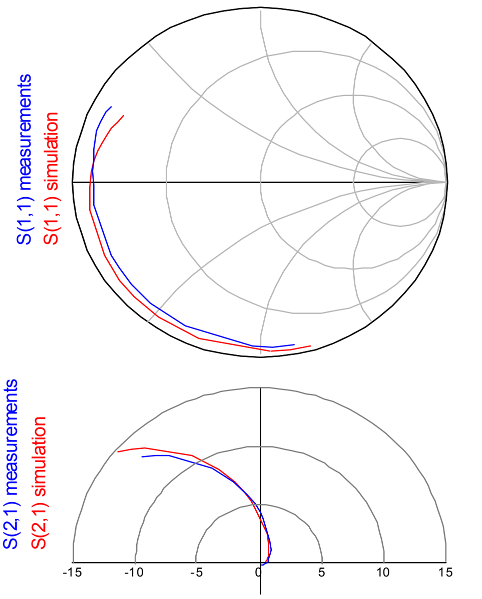

Fig. 6. Measured and simulated S parameters 6x150 um device (0.8 to 40 GHz, Vgs=-0.3 V, Vds=6 V)

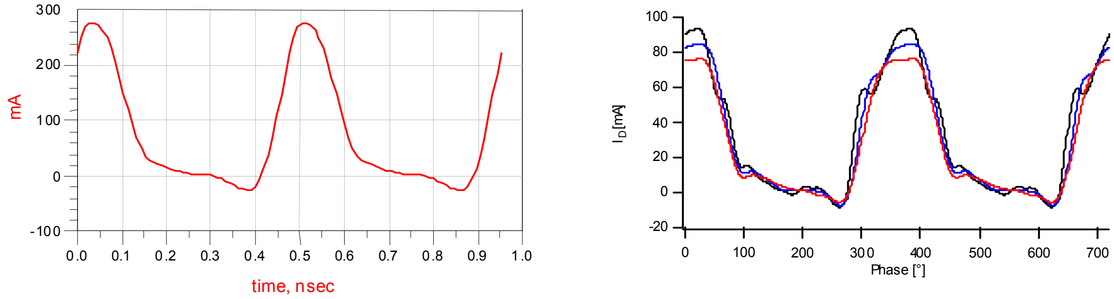

Fig. 7. Class F simulation and measurements : simulated active cell current at 2.1 GHz and load-pull measurements at 840 MHz

The results have been compared with non-linear active load-pull measurements performed at Cardiff University for the same type of device (Fig. 7). Careful examination of these load-pull measurements has confirmed the origin of the low-level slope and ripples seen on the current waveform of a class F amplifier, and the significant interaction between the source vias (equivalent inductance and resistance) and the multi-cell FET structure. This work has also revealed the non-uniform distribution of power handling between the cells of the power FET and provides a much greater insight into the internal operation of the power devices. The power distribution between each finger is simulated both for the input power consumption and the individual contributions to the output power of each finger (Fig. 8). The individual dynamic load lines for each cell and the voltage distribution between fingers have been investigated. This enables optimum output load to be explored as the number of fingers/cells is increased. In this way the design of the power amplifier and the design of the power FET interact to obtain the optimal output power and efficiency.

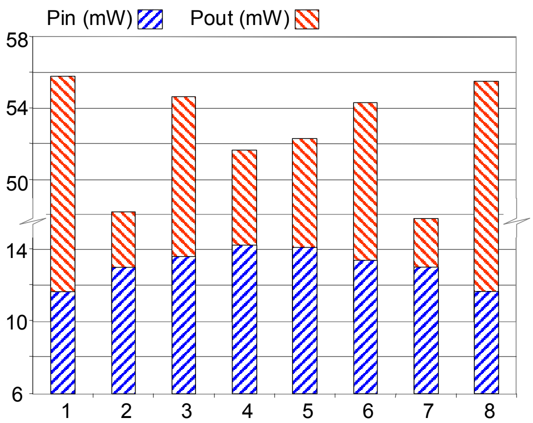

Fig. 8. Simulated power distribution in a 8 finger pHEMT

These investigations are now extended to larger devices. Starting from an initial 6x150 um device with lateral vias, the gate width is increased by adding more fingers/cells. The Fig. 9 & 10 present the normalised output power and power added effciency at different frequencies. The only parameter altered between each maximum power added efficiency design, is the number of fingers/cells.

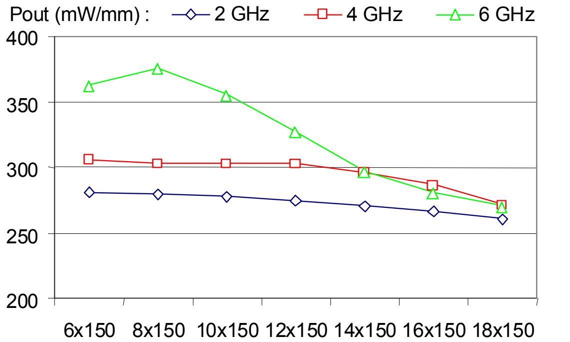

Fig. 9. Normalized output power for devices with increased fingers/cells at different frequencies at PAE max

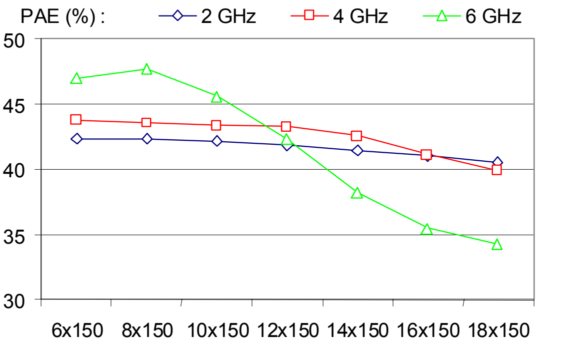

Fig. 10. Maximum power added efficiency for devices with increased fingers/cells at different frequencies

The results shows a decrease in performance as the number of fingers/cells increases. The degradation is more pronounced as the frequency is increased too. As a result, it appears that the lateral vias structure is not the best suited to achieve higher power at higher frequencies. Closer investigations are currently being conducted to explore the cause of this behavior (intrinsic drain, gate and source voltages, non-linear interraction between fingers or device geometry).

VI. Conclusion

A comprehensive approach, combining electromagnetic and physical device modelling with non-linear measurements that provides the freedom to fully investigate power pHEMT devices has been presented. Both the passive parasitics and the active region are characterized with geometrical and process parameters and the behaviour of the full device predicted. This comprehensive investigation permits a better understanding of the inner operation of the power devices. These results are particularly useful when the various couplings and distributed effects become significant in large power devices and at millimetre-wave frequencies.

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