FULLY INTEGRATED NONLINEAR MODELING AND CHARACTERIZATION SYSTEM OF MICROWAVE TRANSISTORS WITH ON-WAFER PULSED MEASUREMENTS

J.P. Teyssier, J.P. Viaud, J.J. Raoux, R. Quéré

IRCOM - CNRS - University of Limoges - IUT - 7 rue Jules Vallès - 19100 BRIVE (FRANCE)

Abstract : ***A novel approach for nonlinear characterization and modeling of microwave transistors has been developped. The whole process is organised as a set of methods contained in the transistor database. This implies that characterization and modeling are performed in an integrated manner. I(V) and S-parameters are measured on wafer under pulsed conditions, suitable for MESFETs, HEMTs or HBTs as illustrated by the proposed models.***

INTRODUCTION

Electrical simulation is an essential step in the design of MMICs, as the tuning of the circuit parameters is impossible after manufacturing. Thus, the accuracy of nonlinear transistor models is a decisive key point of the nonlinear simulation reliablity. Mainly two modeling methods are possible : device physics based and electrical equivalent circuit.

In case of electrical equivalent circuit modeling of transistors, small signal (S-parameters) and large signal [1] methods based on measurements are available. The well-known drawbacks of DC biased measurements are the non-equithermal status of the transistor, and, for some devices, the trapping effects. A pulsed set-up, performing consistent measurements of I(V) and S-parameters under pulsed conditions, permits to obtain RF characteristics at a fixed temperature [2][3]. The modeling is based on extensive characterization, the measurement and modeling results are stored in a device database.

This paper will describe the characterization performed with the pulsed test set-up as well as the model extraction. MESFET PMHFET and HBT nonlinear models will be demonstrated, and checked with small and large signal measurements.

I - INTEGRATED SYSTEM DESCRIPTION

The characterization and the modeling task are based on an open object-oriented database which contains all the device measurements and all the modeling results : figure n° 1.

I - 1 : Characterization set-up

In order to characterize the device, short pulses are simultaneously applied to both ports of the device. They arise from a DC bias level which can be varied. If the pulse duration is smaller than the thermal and trap time constants of the device and if this duration is larger than the electrical time constants, the temperature of the transistor is fully controlled by the DC bias level, and the traps are in the same state they would be for RF signals. Practically, pulse durations can be varied from 100 ns to several µs, depending on the devices.

Currents, voltages and RF S-parameters are acquired simultaneously during the pulses. The pulsed S-parameters solution is based on the Wiltron 36PS20A network analyser, synchronizing the pulse generators and the four-channel oscilloscope. Although there is an inherent dynamic loss in the RF pulsed measurement principle (20×log (duty cycle)), sufficiently accurate calibration can be achieved (figure n° 2) if we can maintain a constant RF power level at the device terminals. Moreover, a power level of −18 dBm to −15 dBm guaranties that the transistor is in a small signal (linear) state.

With pulsed bias associated with pulsed S-parameters, it is possible to measure the convective and RF characteristics of transistors for the whole operating regions, including conductive, breakdown, high power. In order to minimize the number of acquired points, a recursive dichotomy method (figure n° 3) automatically increases the number of points in the high curvature regions of the characteristics.

Various measures are performed without device disconnection :

- pulsed I(V) characteristics up to 100 V and 2 A ;
- DC I(V) characteristics up to 50 V and 1 A ;
- pulsed S-parameters with pulsed bias : 890 MHz to 20 GHz ;
- DC biased CW S-parameters : 100 MHz to 40 GHz.

I - 2 : Modeling methods

The device database handles modeling and optimization methods in order to produce nonlinear transistor models. Three kinds of modeling methods are implemented : S-parameter equivalent circuits ; nonlinear equations ; look-up tables.

When a suitable equivalent circuit topology has been chosen, the firt step is to obtain the extrinsic parasitic elements, it is done with the equivalent circuit using optimization for particular bias points [4]. The goal is to achieve flat values of the intrinsic elements versus frequency.

As soon as the parasitic elements are obtained, the intrinsic equivalent circuit elements are computed with a direct extraction procedure for each pulsed S-parameter point. For FET devices, it povides values of Cgs, Cgd, Gm, Gd, Ri, Tau, Cgd versus the pulsed command voltages, in addition to Ig and Id currents obtained from simultaneous pulsed I(V) measures.

A mathematical representation of these elements versus the commands is required. Two methods are available : the first is based on analytical equations versus the two commands. Analytical models require a high number of parameters to describe the whole working domain (up to 28 parameters for Id, Ig model of HEMTs [5]). Due to the difficulty to reach the best minimum, the use of optimization algorithms based on simulated annealing is required [6][7]. The second method provides a very fast and efficient link between the database and circuit simulators · look-up tables calculated with parametrized multidimensional splines have been implemented both in the database toolkit and in C.A D. simulators The parametrized spline representation is not constrained to pass exactly through the data points so it ensures good derivatives and thus good convergence properties without numerical oscillation.

II - RESULTS

II - 1 MESFET

I(V) results for a 4×75μm×0.5μm MESFET from HP05 processed at Thomson TCS are given on figure n° 4. The pulse duration of these measures is 100 ns, and the period is 100 μs. We have compared the same characterization performed with 400 ns pulses without any discrepancy. It shows that the duration assumptions presented in I-1 are verified The consistency between I(V) and RF measurements is illustrated in figure n°5 · it compares the transconductances from S-parameters and from the I(V) derivatives Cgs and Cgd capacitances versus Vgs,Vds commands are plotted on figures n° 6 and n° 7 from conductive to breakdown regions.

II - 2 PMHFET

An example of accurate fit obtained for a 8×75μm×0.25μm PMHFET from THOMSON is given on figure n°8 (the model is plotted in continuous lines). A 4×40μm×0.15μm PMHFET from THOMSON (designed for millimeter wave applications) has been characterized and modeled [5] with the pulsed equipment. In order to validate the model obtained from pulsed measurements up to 20 Ghz, CW S parameters up to 40 Ghz have been compared to the modeled ones with good accuracy as shown on figure n° 9

II - 3 HBT

Figures n° 10 and n° 11 demonstrate the critical thermal drift problem of HBTs [8], and its possible solution with the pulsed set-up . DC I(V) and pulsed I(V) collector current characteristics performed on a GaInP/GaAs HBT transistor, processed by the central research laboratory of Thomson CSF, are plotted together. It shows the large difference between DC measured and pulsed measured characteristics [9]. Then, a nonlinear model has been obtained for this transistor and the consitency between I(V) and RF measurements has been checked by ensuring the following equations (figure n°12) :

$$gm_0 Rbe = \beta \quad \text{with} \quad Rbe = \left(\frac{\partial\, Ib}{\partial\, \mathrm{Vbe}} \right)^{-1}$$

CONCLUSION

The I(V) and S-parameters pulse set-up, with pulses as short as 100 ns, offers an accurate characterization of on-wafer microwave transistors without thermal or trapping disturbance. It is shown that pulsed I(V) characteristics of transistors give the RF transconductances and output conductances. The deduced models are introduced in available C.A D. simulators ; they are suitable for accurate nonlinear simulations of circuits such as high power amplifiers, mixers, dividers based on MESFETs, HEMTs, HBTs.

The proposed set of characterization and modeling tools constitute an integrated framework built around a common transistor database. The database-integrated approach of the nonlinear measurement and modeling of transistors provides a fast and highly reliable way to obtain C.A.D models of microwave transistors. Our integrated framework is designed to be driven by an expert system, in order to fully control the whole measurement and modeling process by software.

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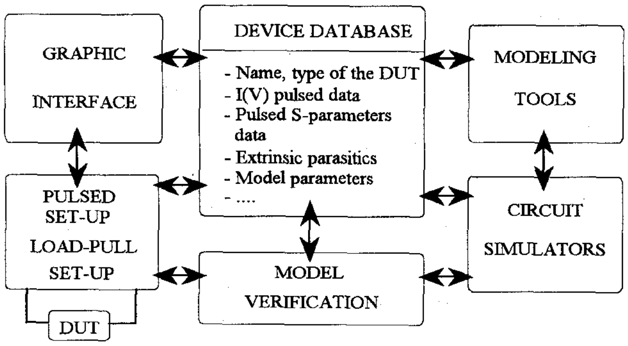


Figure n° 1 : Integrated database-oriented measurement and modeling system.

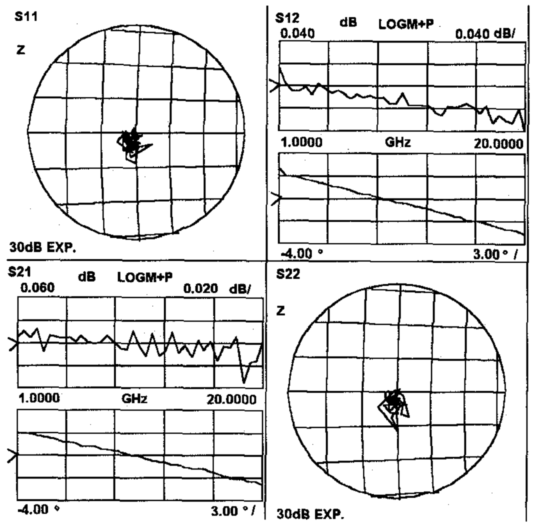


Figure n° 2 : Calibration result under pulsed conditions : with 28 dB dynamic losses : measure of an other line.

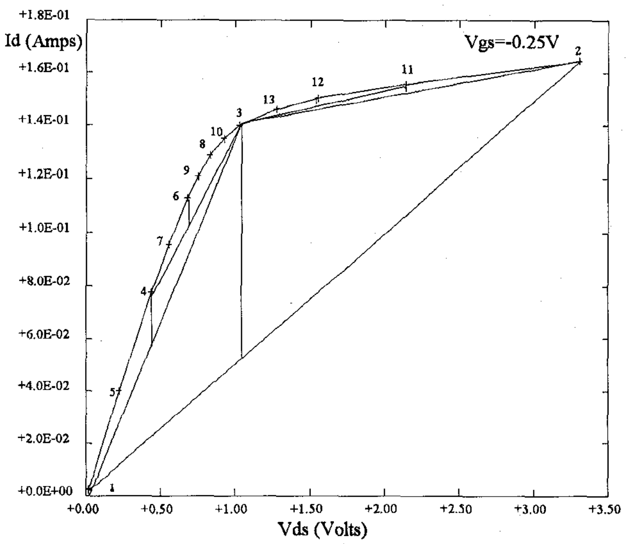


Figure n° 3 : Dichotomy algorithm : Vgs constant measure.

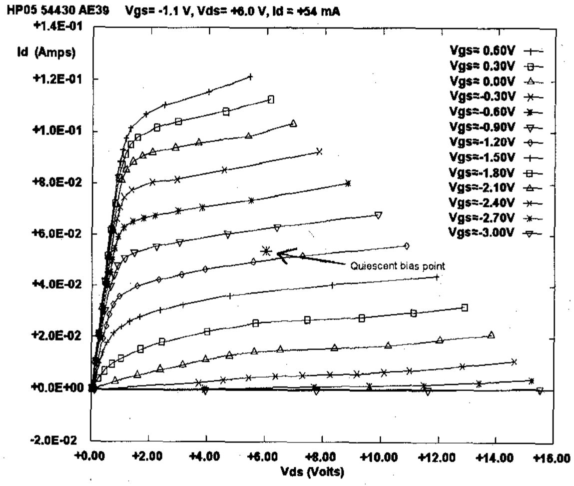


Figure n° 4 : I(V) output characteristics of a typical MESFET.

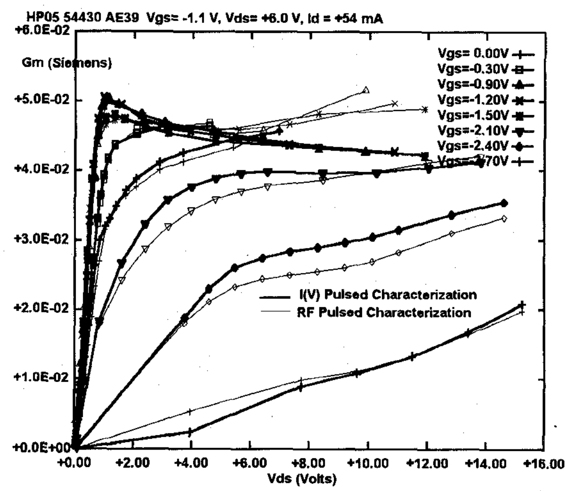


Figure n° 5 : Comparison of MESFET Gm extracted from pulsed I(V) and from pulsed S-parameters measurements.

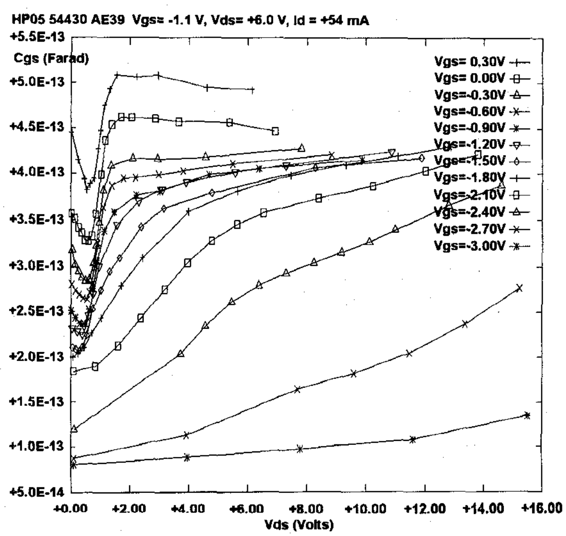


Figure n° 6 : Cgs capacitance extracted from pulsed S-parameters.

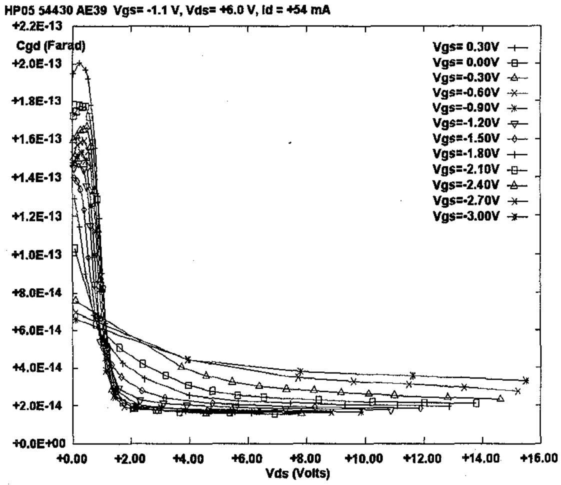


Figure n° 7 : Cgd capacitance extracted from pulsed S-parameters.

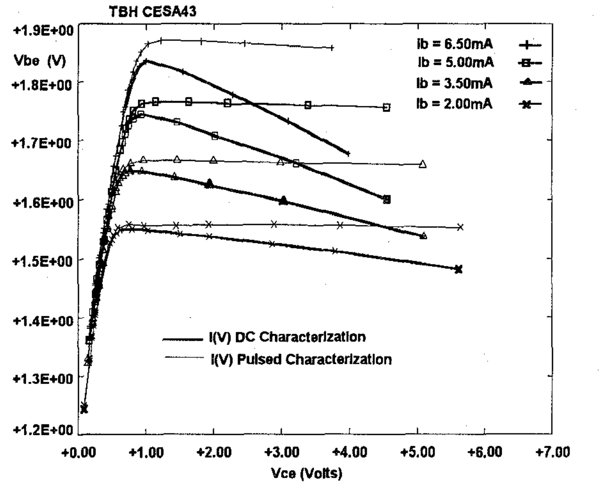


Figure n° 10 : Input characateristics of a 4x2x30 µm² GaInP/ GaAs HBT : Comparison between DC and pulsed measures.

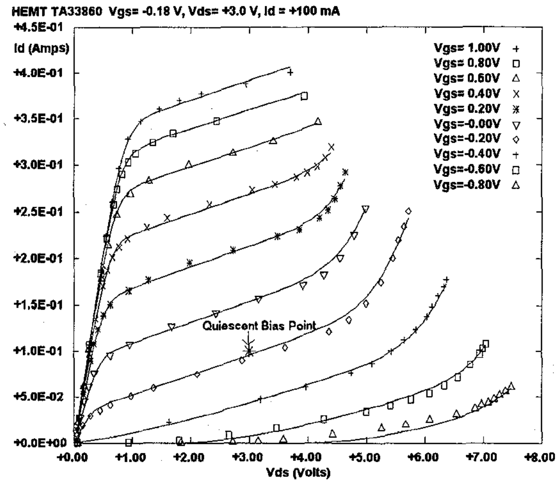


Figure n° 8 : output characteristics of a 8 x 75 x 0.25µm PMHFET : comparison between mesure and model.

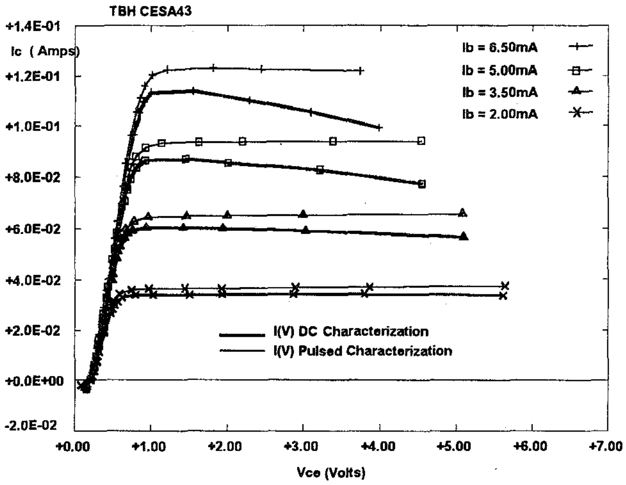
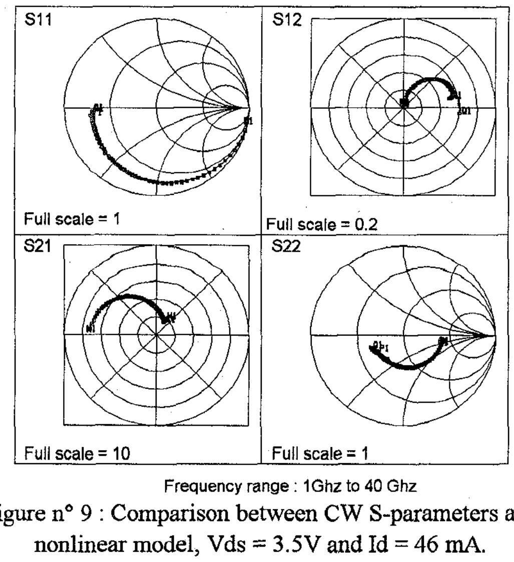


Figure n° 11 : Output characteristics of a 4x2x30 µm² GaInP/ GaAs HBT : Comparison between DC and pulsed measures.



Frequency range : 1Ghz to 40 Ghz

Figure n° 9 : Comparison between CW S-parameters and nonlinear model, Vds = 3.5V and Id = 46 mA.

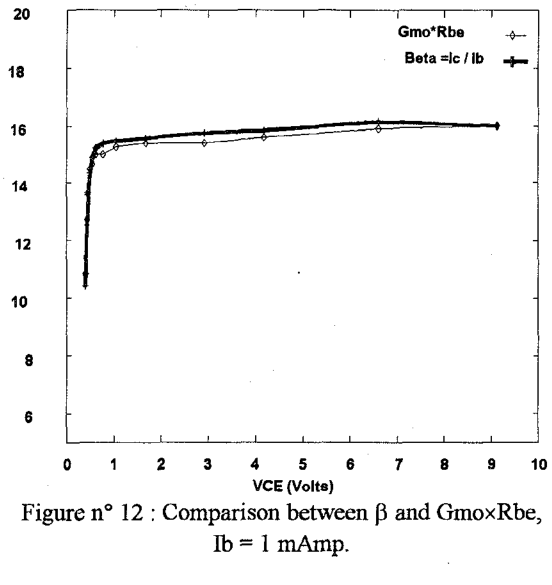


Figure n° 12 : Comparison between β and Gmo×Rbe, Ib = 1 mAmp.