A MEASUREMENT BASED MODEL OF HEMT TAKING INTO ACCOUNT THE NON LINEAR, NON UNIFORM TRANSMISSION LINE NATURE OF THE CHANNEL AND ITS ASSOCIATED LOW FREQUENCY NOISE SOURCES

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ABSTRACT

For the first time, a fully measurement based extraction procedure of non linear and non uniform transmission line model of FET devices is proposed. This model describes accurately the distributed nature under the device gate which allows a good distortion prediction (IM3) and promises good perspectives for simulation of noise characteristics in non linear circuits.

INTRODUCTION

With the increase of working frequencies toward millimeter waves, high volume commercially available MMICs including HEMTs operate yet at several ten GHz.
On the other hand, in FET based non linear circuits, inter-modulation frequencies are generated along the non linear channel from source to drain, and are directly responsible for many characteristics such as : the distortion in power amplifiers (IM3) or the PM noise in oscillators.
In order to optimize these features, the development of an accurate distributed model of HEMT is no longer an academic work [1]. In this communication we present a new non linear distributed model, fully extracted from pulsed I-V and S parameter measurements, which may be applied to all the field effect devices (MESFET, HEMT and MOSFET).
In this model, channel is considered from source to drain as a non uniform, non linear, active transmission line [2][3][4]. Figure 1 shows the proposed model. It includes N unit cells. Obviously the number of cells N depends on the gate length L. Practically, we found that for $L \leq 0.3$ µm, N = 10 is a good compromise between accuracy and complexity of this model.
Every unit cell includes :

- On one hand : a non linear gate channel capacitance $C = f_C (Vg_k)$, in parallel with a schottky diode $I = f_G (Vg_k)$. These elements are only function of their own port voltage Vg_k.
- On the other hand a non linear channel current controlled source $I = f_I (Vg_k, \Delta Vc_k)$ which depends on its own port voltage ΔVc_k, and on the controlling voltage of the cell : Vg_k.
- At last, two linear fringing capacitances are added at the source and drain end of the channel. The other extrinsic linear parasitic elements are described by lumped elements as usual [5].

It must be pointed out that the non linear functions f_C, f_G and f_I are identical for all the unit cells. Nevertheless, the unit cell voltages : Vg_k and ΔVc_k vary along the channel from source to drain, following the rank k of the cell under consideration : from 1 to N. It results an accurate non linear, non uniform, distributed model of the channel.
Moreover, while the model is non quasistatic by nature, it does not need the inclusion of any time-delay, nor a questionable charging resistor Ri [6].
In the first part of this paper, the model extraction procedure from pulsed I-V characteristic and S parameter measurements is described. As an example a 2 fingers of 100 µm wide PHEMT model is shown. The extracted model and the measurements are compared. The improvement on the non linear transistor modeling is shown in the third part. Finally, in the last part, low frequency noise sources are included into the model along the channel.

1. DISTRIBUTED MODEL EXTRACTION PROCEDURE

The extraction procedure is based on pulsed measurement of I-V characteristics and S parameters. The pulsed measurement allows to keep constant temperature and trap steady state during the characterization [5].
First, the extrinsic linear parasitic elements are obtained by the well known extraction methodology used for the classical lumped FET model.

The intrinsic part of the model is formed by a chain of N identical cells. Each cell represents the electrical behavior of a transistor slice. Then, it includes a schottky diode $I = f_G (Vg_k)$, in parallel with a non linear capacitance $C = f_C (Vg_k)$, and a non linear current controlled source $I = f_I (Vg_k, \Delta Vc_k)$. These elements only depend on the voltage Vg_k and ΔVc_k, which are present on the access of cell under consideration. In our model, every cell elements have both same equations and same parameter values along the channel. Only the controlled voltages Vg_k and ΔVc_k vary following the k rank of the cell number. Two edge capacitances are added at source side and drain end. They take into account the capacitive coupling effects between the metallic electrodes and the edge channel.

In a first step, the parameters of the diode and the controlled non linear current source are extracted. To do this, a software based on fast simulated diffusion algorithm, allowing to minimize a non linear error function, is used [7]. From the characteristic measurement Ids (Vgs, Vds), the 13 parameters of the controlled current generator equations, fI (Vgk, ΔVck) are determined. And from characteristic measurement Igs (Vgd, Vds), the two diode parameters are obtained. The non linear element equations are fully described in [8].

Finally, the N non linear capacitances, $C = f_C (Vg_k)$ and the two edge capacitances Cbs and Cbd are determined from the S parameter measurements. The direct extraction procedure can not be used, here, due to the high element number. Then another software, based on the fast simulated diffusion algorithm is used to obtain the 6 parameter values of the non linear capacitances and the two edge capacitance values. The error function is computed with the intrinsic Y parameters of the model and those calculated from the S parameter measurements. Obviously, this optimization must be performed with several measurement points chosen on the I-V characteristic load-line zone.

2. COMPARISON BETWEEN MODEL AND MEASUREMENTS.

As an example, we show the results obtained on a PHEMT of 2 fingers of 100 μm wide. The pulsed I-V and S parameter measurements are performed on the 1 to 20 GHz frequency range. The bias point is Vgs = 0.21 V, Vds = 2.8 V and Ids = 41.7 mA.
A 10 cell distributed model seems to be a good compromise between accuracy and model complexity. The table 1 gives the extrinsic linear parasitic elements. Note that the linear capacitance Cds is considered as an extrinsic element.
The non linear function $f_I (Vg_k, \Delta Vc_k)$ of one controlled current source is reported on figure 2. The extraction procedure leads to the edge capacitance values : Cbs = 247 fF and Cbd = 34 fF.
The figure 3 shows a good agreement between whole model and measured transistor I-V characteristics. The figure 4 presents the modeled and measured S parameters for a pulsed point nearby the bias point. These figures demonstrate that the extracted distributed model can accurately fit the measured data.
To show that the distributed model have physical behavior, the channel voltage Vc_k is plotted on the figure 5 for this intrinsic bias condition $Vgs_i = 0.2$ V and $Vds_i = 3$V. It shows that the voltage Vc_k is a non linear function along the channel.

3. APPLICATION TO THE THIRD ORDER INTER-MODULATION SIMULATION

In order to show the model ability to take into account the distributed nature of the field effect transistor, two tone measurement is performed on the device The chosen bias point is Vgs = 0.2 V and Vds = 2.8 V and the generator frequencies are f1 = 10.0 GHz and f2 = 10.02 GHz. The load value is 50 Ω.The figure 6 shows a good agreement between the simulated and measured output power at f1 and 2f1-f2 frequencies.

4. DISTRIBUTED NON LINEAR LOW FREQUENCY NOISE SOURCES

In order to model the low frequency noise sources of the channel, the measurements of the drain noise spectral density for different bias points (Vgs_0, Vds_0) are performed from 1 Hz to 1 MHz frequency range. In each unit cell, an elementary noise source is added, calculated from short circuit noise current extracted from previous measurement. These elementary Norton current sources are presumed uncorrelated. At a given noise frequency and bias point, the measured noise spectral density $Si_{drain} (Vgs_0 ,Vds_0)$ can be related to the local noise sources $\langle ic_k^2 \rangle$ as:

$$Si_{drain}(Vgs_0, Vds_0) = \sum_{k=1}^{N} \langle ic_k^2 \rangle \, |h_k(Vgs_0, Vds_0)|^2$$

Where the $h_k(Vgs_0,Vds_0)$ are transfer functions, calculated from the linearized non linear model and N is number of the cells. To extract the value of every local power spectral density $\langle ic_k^2 \rangle$, a physically based expression of $\langle ic_k^2 \rangle$ function of the applied local voltages Vg_k and ΔVc_k, must be defined. In a first simplified approach $\langle ic_k^2 \rangle$ are taken identical for all cells by writing :

$$\left\langle ic_k^2 \right\rangle = \sum_{k=1}^{N} \frac{Si_{drain}(Vgs_0, Vds_0)}{\left|h_k(Vgs_0, Vds_0)\right|^2}$$

As an example, the figure 7 gives the local low frequency noise source density of a cell, versus the local voltages Vg_k and ΔVc_k. A more accurate expression may be obtained by taking into account the non-linear expression of the carrier velocity in function of the local electric field.

CONCLUSION

For the first time to our knowledge, a non linear, non uniform transmission line model of HEMT, fully extracted from measurements, is presented. Due to the robustness of the extraction procedure, it may be applied without any significant modification to other field effect devices. This extraction robustness is due to the accurate representation of the distributed nature of the channel from source to drain, which reproduces naturally the non-quasistatic behavior of the transistor.

This distributed model from source to drain may be included in a whole model which takes also into account both the wave propagation along the width of the transistor fingers, and the distributed nature of the metallization [9].

Finally, local non linear noise sources, measurement based, are integrated to every unit-cell. This model should accurately simulate the PM and AM noise in oscillators, or more generally the conversion noise in non linear circuits.

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Rg (Ω)	Rd (Ω)	Rs (Ω)	Lg (pH)	Ld (pH)	Ls (pH)	Cpg (fF)	Cpd (fF)	Cds (fF)
1.0	1.5	1.5	251	213.4	67.4	22.9	46.7	21.4

Table 1 : extrinsic linear parasitic elements

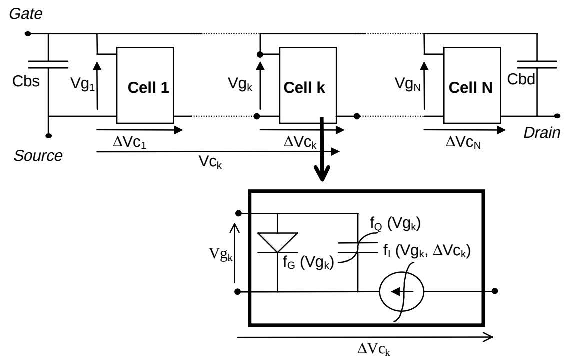

Figure 1 : topology of the intrinsic distributed model along the gate.

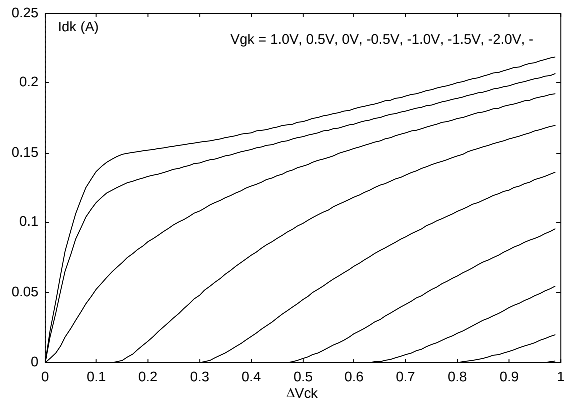

Figure 2 : $Id_k = f_I (Vg_k, \Delta Vc_k)$.

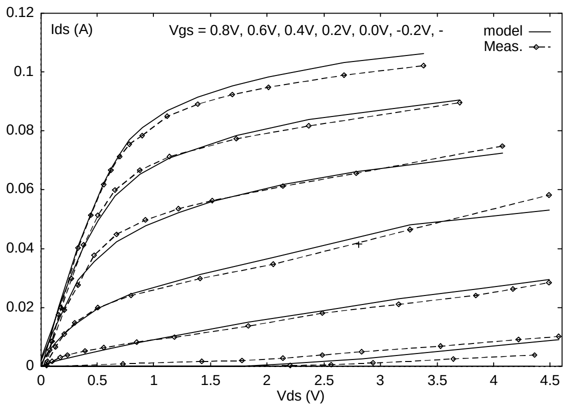

Figure 3 : Modeled and measured I-V Characteristics of the whole transistor

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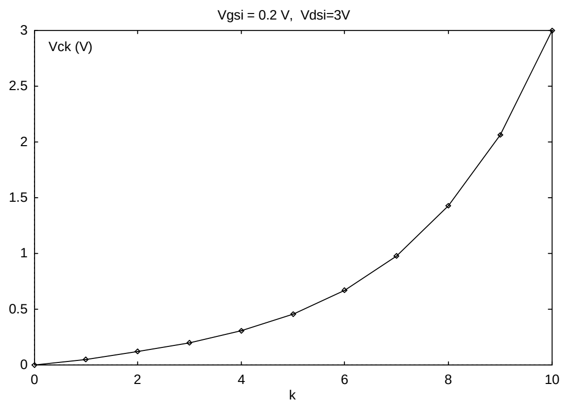

Figure 5 : Vc_k voltage for $Vgs_i = 0.2$ V and $Vds_i = 3$V.

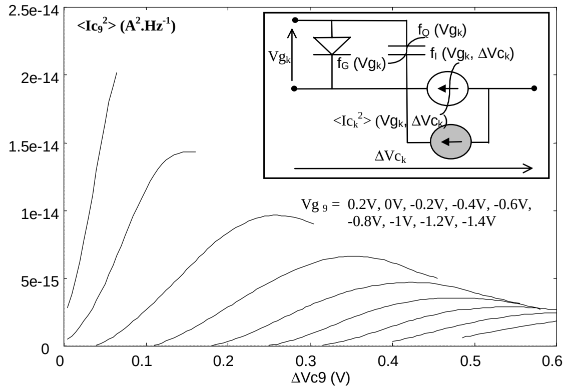

Figure 7 : Local noise source $<Ic_9^2> = f(Vg_9, \Delta Vc_9)$ at 10 kHz of the cell number 9.

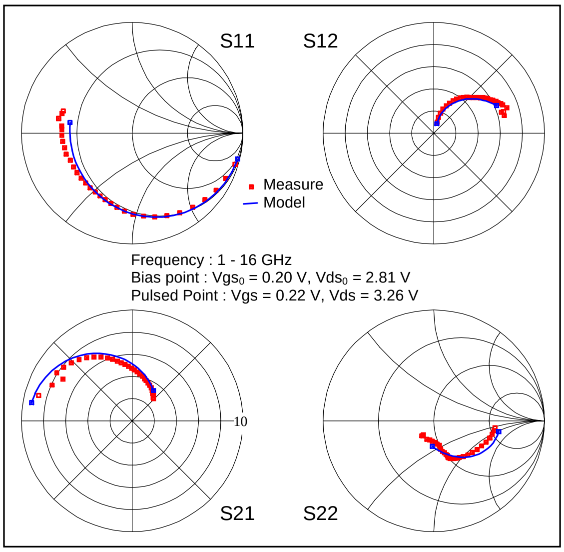

Figure 4 : modeled and measured S parameters.

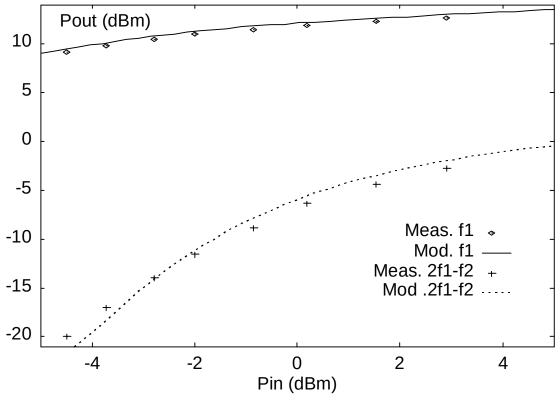

Figure 6 : Comparison between two tone simulation and measurement.