A NEW APPROACH OF THE LINEAR AND NON LINEAR STABILITY ANALYSIS OF PHEMT BASED ON A FINGER-DISTRIBUTED GENERIC NON LINEAR MODEL AND ELECTROMAGNETIC DEEMBEDDING

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Abstract - **Microwave transistor stability is a real preoccupation of MMICs designers. In this paper, it is shown that the classical electrical lumped model is inappropriate to the FET stability study. A non linear finger-distributed modeling technique, based on an electromagnetic deembedding, is presented. The derived model exhibits a very interesting capability to predict the electrical behavior of arbitrary shaped transistor. It also brings a real improvement in the FET analysis study.**

I. INTRODUCTION

For an MMICs designer, the choice of transistor used is a critical step of the whole design process. Many circuit's performances depend on it. Because any change in the manufactured circuit is no longer possible, the availability of accurate nonlinear model of these devices is of prime interest.

Unfortunately, the designers usually do not dispose of all the transistor models of the chosen process. Moreover, the knowledge of the stability properties of these components is essential. It appears that the stability behavior of power transistors, made up of several fingers, can not be predicted with the electrical classical lumped model.

To address these two kinds of problems, we present a new technique for non linear modeling of arbitrary shaped FETs. It is based on pulsed measurements and electromagnetic deembedding. The combination of an electromagnetic simulation of the metallization devices and multi bias pulsed I-V and S parameters measurements allow to derive a non linear finger-distributed model. This new topology brings a real improvement in the FETs stability study. In fact, for such analysis, device topology and finger mutual interactions must be taken into account.

In section 2, a new analytical deembedding methodology is described, in order to obtain the intrinsic S parameters of each fingers. Then, the generic non linear model extraction and its extrapolation properties [1] for other shaped transistors is presented. This technique was applied on a 0.25 μm Phemts power process.

In section 3, we propose the stability study of a ten fingers transistor (10 × 60 μm). It is shown that the association of a rigorous stability analysis method and a non linear finger-distributed model based on a electromagnetic simulation allows a real improvement in the FETs stability study.

II. THE FINGER-DISTRIBUTED GENERIC NON LINEAR MODEL

A. Electromagnetic deembedding of S parameter measurements

The method proposed here, relies on the only assumption that all the device fingers are identical. This measurement condition is met when S parameters are obtained under pulsed conditions, assuring any self heating of the transistor.

The aim of this methodology is to obtain the finger intrinsic S parameters. The geometry of the transistor is taken into account by the electromagnetic simulation [2] [3] which is used to model the metallic electrodes. This simulation provides a S parameters matrix which substitutes the lumped extrinsic elements. We use a S matrix given by the HP Momentum 2.5 D electromagnetic sotfware, including the classical inputs (gate, drain and source) and the internal ports placed on each gate drain and source electrodes. However 2.5D electromagnetic simulator does not allow an accurate description of the via hole behavior and some specific calculations must be performed to obtain source inductance value. This problem can be solved by using a full 3D simulator.

Let n be the number of elementary fingers of transistor. Then, we can redraw the scheme of the transistor as shown in figure 1. The n intrinsic identical transistor models corresponding to the n fingers of the device are wired with the electromagnetic S parameter matrix.

Let us define $[S_{EM}]$, the matrix coming from the electromagnetic simulation , $[S_m]$, the matrix of measured S parameters and [S], the finger matrix which is unknown.

The various matrices are defined as follows :

$$\begin{pmatrix} b_1 \\ \vdots \\ b_{2n+2} \end{pmatrix} = [S_{EM}].\begin{pmatrix} a_1 \\ \vdots \\ a_{2n+2} \end{pmatrix} \quad \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = [S_m].\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$$\begin{pmatrix} a_{2k+1} \\ a_{2k+2} \end{pmatrix} = [S].\begin{pmatrix} b_{2k+1} \\ b_{2k+2} \end{pmatrix}$$

Decomposing $[S_{EM}]$ in four sub-matrices $[A_{EM}]$, $[B_{EM}]$, $[C_{EM}]$ and $[D_{EM}]$, the following linear equation system is obtained :

$$\left\{\begin{aligned} &[S_m]\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = [A_{EM}]\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + [B_{EM}]\begin{pmatrix} a_3 \\ \vdots \\ a_{2n+2} \end{pmatrix} \\ &[S']\begin{pmatrix} a_3 \\ \vdots \\ a_{2n+2} \end{pmatrix} = [C_{EM}]\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + [D_{EM}]\begin{pmatrix} a_3 \\ \vdots \\ a_{2n+2} \end{pmatrix} \end{aligned}\right. \qquad (1)$$

where [S'] is a n × n block diagonal matrix which each term of the diagonal is equal to :

$$[S]^{-1} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

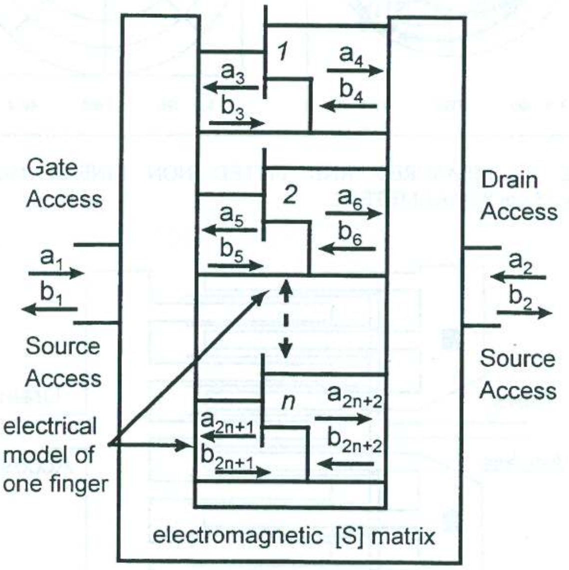

Fig. 1 TRANSISTOR WITH N IDENTICAL ELECTRICAL SCHEMES

System (1) can be written as an homogeneous equation :

$$([R]-[S'])\,(a_3 \cdots a_{2n+2})^t = 0 \qquad (2)$$

with

$$[R] = \left([C_{EM}]([S_m]-[A_{EM}])^{-1}[B_{EM}] + [D_{EM}]\right)$$

System (2) can be transformed by simple permutations of odd and even lines and columns giving the equivalent system.

$$\left[\begin{array}{c|c} R_{oo} & R_{oe} \\ \hline R_{eo} & R_{ee} \end{array}\right].\begin{bmatrix} a_3 \\ a_5 \\ \vdots \\ a_{2n+1} \\ \hline a_4 \\ a_6 \\ \vdots \\ a_{2n+2} \end{bmatrix}$$

$$-\left[\begin{array}{cccc|cccc} a & 0 & \cdots & 0 & b & 0 & \cdots & 0 \\ 0 & a & \ddots & \vdots & 0 & b & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 & \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & a & 0 & \cdots & 0 & b \\ \hline c & 0 & \cdots & 0 & d & 0 & \cdots & 0 \\ 0 & c & \ddots & \vdots & 0 & d & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 & \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & c & 0 & \cdots & 0 & d \end{array}\right].\begin{bmatrix} a_3 \\ a_5 \\ \vdots \\ a_{2n+1} \\ \hline a_4 \\ a_6 \\ \vdots \\ a_{2n+2} \end{bmatrix} = 0$$

Thus system can be split in four eigenvalue equations :

$$\begin{aligned} &(a.[I]-[R_{oo}])(a_o)=0 \qquad (b.[I]-[R_{oe}])(a_e)=0 \\ &(c.[I]-[R_{eo}])(a_o)=0 \qquad (d.[I]-[R_{ee}])(a_e)=0 \quad (3) \end{aligned}$$

Where $[I]$ is the identity matrix, $a_0 = (a_3, a_5 \ldots a_{2n+1})^t$ and $a_e = (a_4, a_6 \ldots a_{2n+2})^t$. $[R_{oo}]$, $[R_{oe}]$, $[R_{eo}]$ and $[R_{ee}]$ are n × n complex matrices. For each equation of system (3), n different eigenvalues are found. This defines n^4 combinations of eigenvalues a, b, c and d. Only one solution is physically correct. It is obtained when :

$$[S_m] = [B_{EM}].\left([S'] - [D_{EM}]\right)^{-1}[C_{EM}] + [A_{EM}]$$

B. Extraction of the generic non linear model from measurements of one sample device

To apply the extraction methodology to a 4×75 µm Phemt (figure 2), an electromagnetic simulation of all the transistor metallic parts is performed. Pulsed I-V and pulsed S parameters measurements are realized on the 1-40 GHz frequency range. The topology of the finger model is given figure 3. Note that the model only have the drain and source resistances. Indeed, the others extrinsics elements are fully taken into account by the electromagnetic simulation. The whole model is composed by the embeeding network an the four identical electrical finger models. From pulsed I-V measurements performed on the transistor, the non linear current source and diode currents are modeled. For one finger, the scaling of the model is obtained in a very straight forward way :

$$Ids = \frac{Idss}{n} \times f(Vgs, Vds)$$

$$Id_{gs} = \frac{Id_0}{n} e^{\alpha \times Vgs}$$

$$Id_{gd} = \frac{Id_0}{n} e^{\alpha \times Vgd}$$

where n is the finger number and f() a non linear function [4] describing the drain current.

Applying the methodology of section 2, multi-bias S parameters of the device finger are obtained. From them, Ri, Rgd, Cds, Cgs and Cgd are extracted using the well-known direct extraction procedure. Table 1 gives the element values of the model found by direct extraction from S parameters for the point Vgs = -0.75V and Vds = 8V. Then, the non linear capacitances Cgs and Cds are fitted from this extraction. The finger non linear model is now fully defined. Using classical scaling rules, the gate length is introduced as a parameter. Figure 4 represents the measured and fitted non linear model 4 × 75 µm S parameters.

C. Extrapolation properties.

To show the extrapolation ability of our model, a 10 × 60 µm is chosen. It is presented figure 5. Note that its

Table 1 : ELEMENT VALUES OF THE MODEL

Rs	Rd	Cgs	Cgd	Cds
4.00 Ω	4.00 Ω	135 fF	3.36 fF	18.0 fF

Gm	Gd	Ri	Rgd	Tau
22.3 mS	0.401 mS	22.8 Ω	100 Ω	2.18 ps

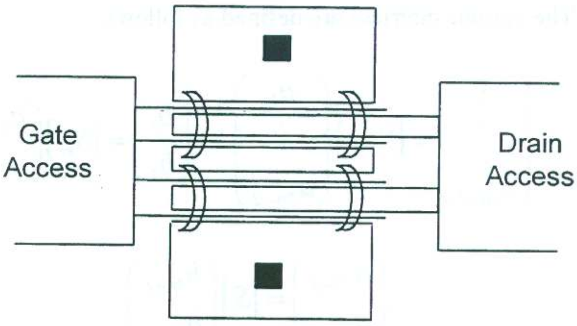

Fig 2 : 4 × 75 µm TRANSISTOR.

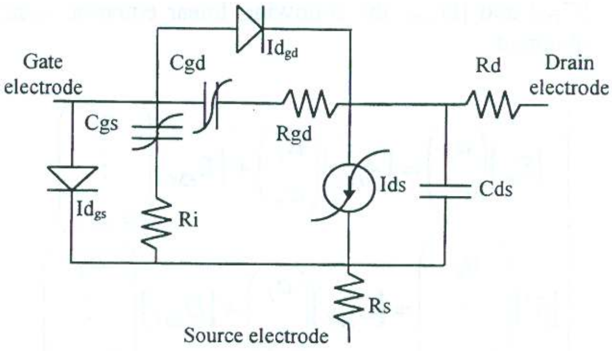

Fig 3 : DEVICE FINGER ELECTRICAL MODEL

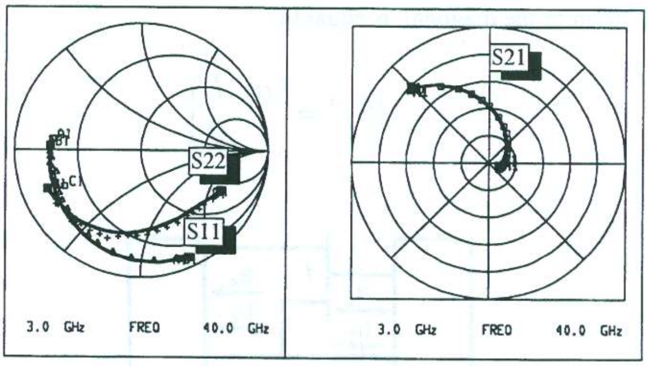

Fig. 4 : MEASURED AND FITTED NON LINEAR MODEL 4× 75 µm S PARAMETERS.

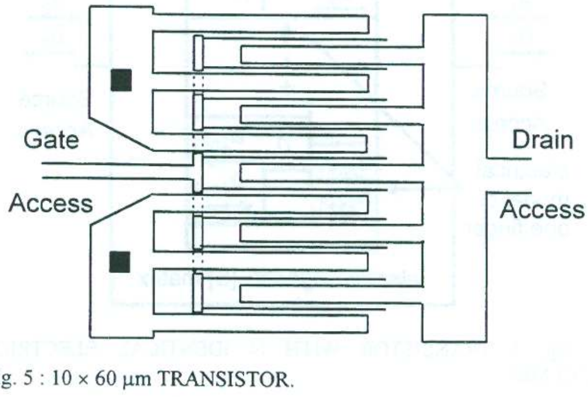

Fig. 5 : 10 × 60 µm TRANSISTOR.

topology is completely different from to the 4 × 75 µm one. An electromagnetic simulation of its metallic parts is performed. Using the generic finger model, we present figure 6 and 7 the measured and extrapolated non linear model 10 × 60 µm I-V characteristics and S parameters. They exhibit that the extrapolated model can accurately predict the transistor electrical behavior. In order to verify the whole coherence of the extrapolated model, the power characteristics under 50 Ω at 10 GHz of this new model and the classical lumped one are reported in figure 8.

III. PHEMT 10*60 µm STABILITY ANALYSIS

For a multi-fingers transistor, the instability causes are various : inappropriate loads, unbalance structure finger mutual interactions, electromagnetic couplings ... Most of them are due to the distributed nature of FETs. It is clear that a finger-distributed model based on a electromagnetic deembedding is very interesting for a stability study. Nevertheless, it is necessary to use a rigorous analysis method, able to take into account the whole active element contribution.

Platzker [5] introduced the Normalized Determinant Function (NDF) which is a generalization to the multi-transistors circuits of the Return Difference, first defined by Bode. The stability is ensured if the NDF polar plot does not have any origin counterclockwise encirclement. Its practical evaluation and the return ratio (RR) calculation are related in [5]. In [6], a method using a non linear model and permitting the NDF evaluation for all the desired bias, is presented. It is based on an ideal filter allowing simultaneously the transistor bias and the RR evaluation (figure 9).

The NDF analysis is applied on the 10 × 60 µm transistor. Because of each intrinsic finger is modeled like an intrinsic transistor, ten RR calculations are performed. In order to exhibit the improvement of our finger-distributed model over the lumped classical one, we represent figure 10 the NDF curves for these two models and for three different biases (table 2).

Note that for the classical model, NDF evaluation needs only one RR calculation. With this model and for the three biases, the stability is ensured with a great margin : the three plots are enclosed around (1;0). Moreover, no significant difference can be observed on the NDF with the bias variation. With the finger-distributed model, the stability is also ensured. Nevertheless, NDF analysis shows that the transistor is very closed to the instability, especially for point 3. In fact, for this one, the NDF plot cuts the real axis. We can notice that the three curves are different, showing a stability decrease with an increasing of Vgs. All these variations observed with the finger-distributed model correspond to a physical behavior. Moreover, it is interesting to add that individual

Table 2 : BIAS POINT

Point 1	Point 2	Point 3
Vgs=-0.75V Vds=8V	Vgs=-0.75V Vds=3V	Vgs=0 V Vds=8V

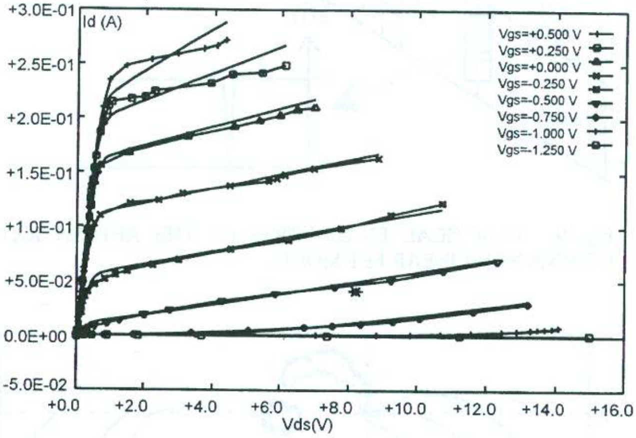

Fig. 6 : MEASURED AND EXTRAPOLATED NON LINEAR MODEL 10× 60 µm Id CURRENT.

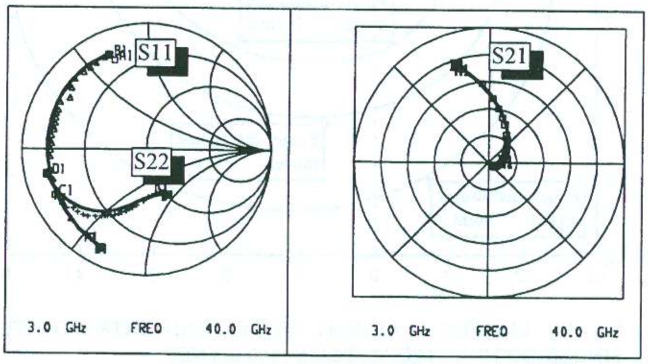

Fig. 7 : MEASURED AND EXTRAPOLATED NON LINEAR MODEL 4× 75 µm S PARAMETERS.

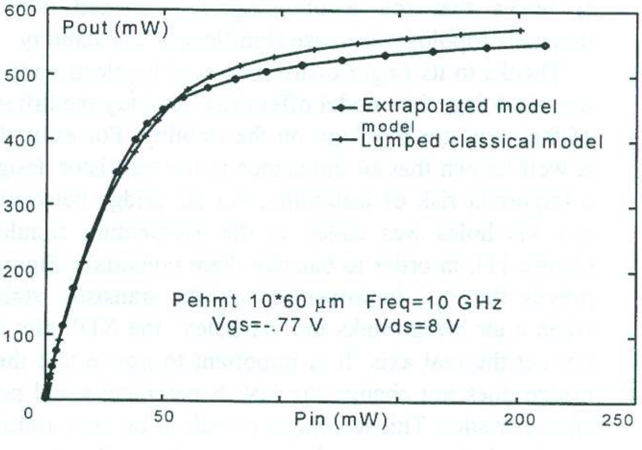

Fig. 8 :LUMPED CLASSICAL AND EXTRAPOLATED FINGER-DISTRIBUTED MODEL 6×100 µm POWER CHARACTERISTIC

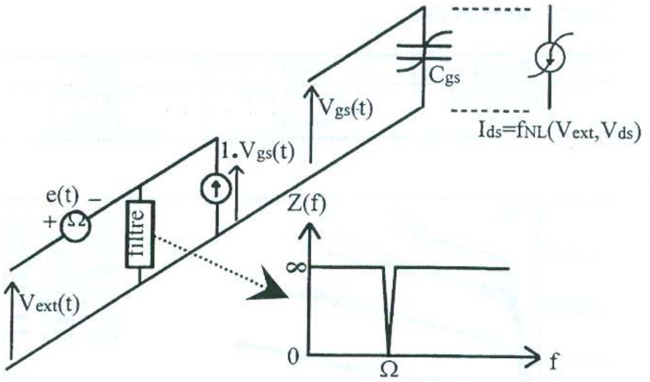

Fig. 9 : PRACTICAL EVALUATION OF THE RETURN RATIO USING A NON LINEAR FET MODEL

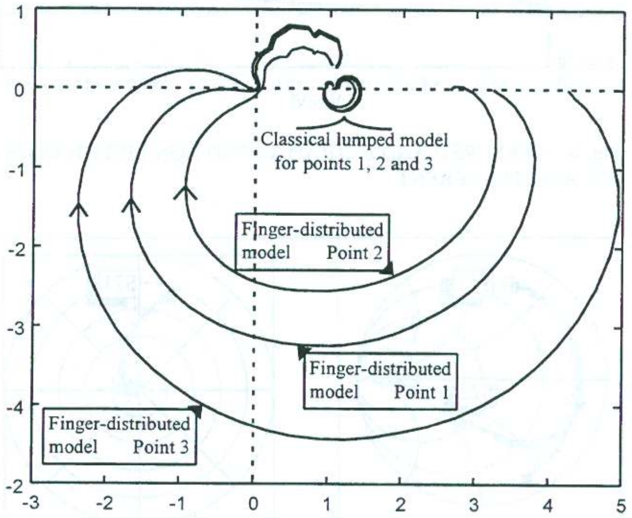

Fig. 10 : LUMPED CLASSICAL MODEL AND EXTRAPOLATED FINGER-DISTRIBUTED MODEL 6× 100 μm NDF.

RR (of each finger) does not predict a so closed instability. It seems that the whole fingers combined with the transistor topology decrease significantly the stability.

Thanks to its finger distribution and its electromagnetic deembedding, this model offers also to study the influence of the transistor topology on the stability. For example, it is well-known that an imbalance in the transistor design is a important risk of instability. An air bridge between the two via holes was added in the Momentum simulation (figure 11), in order to balance there potentials. Figure 11 proves the real improvement on the transistor stability when a air bridge links the via holes : the NDF plot does not cut the real axis. It is important to notice that the air bridge does not change the I-V, S parameters and power characteristics. This technique reveals to be very useful for circuit designers as they can adjust the transistor metallizations to increase the FET stability.

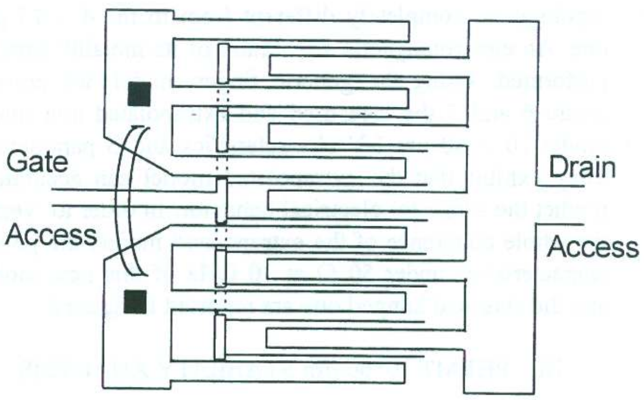

Fig. 11 : INTRODUCTION OF AN AIR BRIDGE IN THE HP-MOMENTUM SIMULATION.

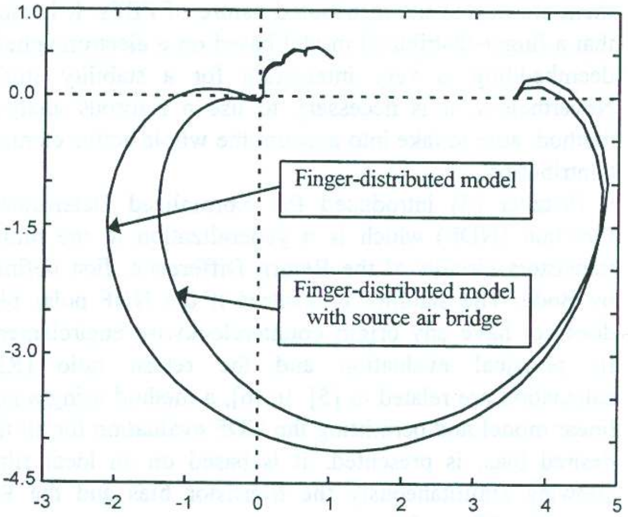

Fig. 12 : INFLUENCE OF A SOURCE AIR BRIDGE ON THE 6× 100 μm STABILITY FOR VGS=0 V AND VDS=3 V

IV. CONCLUSION

A new approach of the FET stability is presented. It is based on a non linear finger-distributed model. In this equivalent circuit, the metallic parts of the transistor are taken into account with an electromagnetic simulation. Each finger is modeled as an intrinsic transistor. For the first time, a new analytical method allowing the determination of the S matrices of the intrinsic fingers is presented. This model has shown a great capability to predict the electrical behavior of any arbitrary shaped transistor. Applying the NDF method to this model, many physical phenomena have been reproduced , proving the improvement of our model to predict the FET stability.

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V. REFERENCES

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