Single function drain current model for MESFET/HEMT devices including pulsed dynamic behavior

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***Abstract* — A new approach to modeling the dynamic behavior of microwave devices based on pulsed measurements, is presented. Both DC and pulsed I/V characteristics of these devices are modeled using a single function derived from an existing and well-established MESFET/HEMT nonlinear static current model. The robust methodology in this work can be applied to other current models and subsequently implemented into a new large-signal circuit as a single current source, capable of accurately predicting both static and small-signal performance of FET devices.**

***Index Terms* — Circuit modeling, FETs, microwave devices, pulsed measurements, scattering parameters.**

I. INTRODUCTION

One of the techniques developed in the characterization of the dynamic behavior of GaAs MESFET/HEMT devices for microwave applications is the use of pulsed measurements. The differences between static (DC) and dynamic I/V characteristics, observed with these techniques, are attributed mainly to self-heating, impact ionization, and trapping effects [1]. In general, following DC parameter extraction, previous characterization approaches involved correcting these differences with either an additional current source [2], or with passive elements [3].

However, in this work, both the static and dynamic currents have been modeled together with one equation only, using pulsed measurements. Consequently, a single function for the drain source current, Ids, based on an existing current model, was obtained, from which it was possible to analytically extract the values of Ids DC, Ids pulsed and its derivatives, under multi-bias conditions.

Thus, this work demonstrates that, by extracting one set of parameters from pulsed measurements, it is possible to accurately predict the intrinsic small-signal RF behavior of FET devices in the GHz range. The proposed equation and the method of its implementation in nonlinear circuit simulators agree with previous works and techniques reported on self-backgating effects [4], nested transformations [1], multi-terminal models [5]-[6], and low frequency dispersion phenomena [7]. From a mathematical point of view the proposed Ids function is easy to implement and existing models can inherit its benefits. To evaluate the performance of the proposed model, DC, scattering and pulsed measurements were carried out on various devices and results show good agreement for low and high power transistors.

II. PROPOSED MODEL

This work has employed the pulsed measurement system provided by Accent Technologies: DIVA 265 [8]. Taking into account the existing techniques mentioned in the previous section we propose a new nonlinear drain current equation as:

$$\text{Ids} = F\left(\text{Vdi}_p\,,\ \text{Vgi}_p\,,\ \text{Vdi}_{DC}\,,\ \text{Vgi}_{DC}\right) \qquad (1)$$

where Vdi_p, Vgi_p are the pulsed-intrinsic drain/gate voltage, respectively; and Vdi_{DC}, Vgi_{DC} are the DC-intrinsic drain/gate voltage, respectively.

To predict the pulsed behavior, a combinational function is used to include the relation between pulsed and DC voltages in the argument of the original DC equation, but which maintains the parameters already obtained from a purely DC fit. Incorporating this technique into the Ids model presented in [9], a new model, called "COBRA-PERU", has been developed with the capability to predict large-signal multi-bias pulsed measurements:

$$\text{Ids} = \beta \cdot V_{eff}^{\frac{\lambda}{1+\mu\cdot vds_e^2+\varepsilon\cdot V_{eff}}} \cdot \tanh\left(\alpha \cdot vds_e \cdot \left(1+\zeta \cdot V_{eff}\right)\right) \qquad (2.a)$$

$$V_{eff} = \left(1/2\right)\cdot\left(\text{Vgst} + \sqrt{\text{Vgst}^2+\delta^2}\right) \qquad (2.b)$$

$$\text{Vgst} = \left(vgs_e - \left(1+\beta^2\right)\cdot V_T + \gamma \cdot vds_e\right) \qquad (2.c)$$

$$vds_e = d_{vd}\cdot\left(k_1 - k_2\cdot d_{vd}\right) + d_{vg}\cdot\left(k_3 - k_4\cdot d_{vg}\right) + \text{Vdi}_{DC} \qquad (2.d)$$

$$vgs_e = d_{vg}\cdot\left(k_5 - k_6\cdot d_{vg}\right) + d_{vd}\cdot\left(k_7 - k_8\cdot d_{vd}\right) + \text{Vgi}_{DC} \qquad (2.e)$$

where vds_e, vgs_e are the gate/drain equivalent-voltages respectively; d_{vg}, d_{vd} are the difference between pulsed and DC voltages in gate and drain side respectively; and k_1 to k_8 are fitting parameters.

Note that these expressions (which indeed may be applied to any Ids model), evaluate to the DC voltages when the excursion of the pulses are the same as the DC level, thus mathematically reducing the new current model to the original equations on which it was based.

III. PULSED I/V AND DC VALIDATION

As a first step, the model proposed in [9] is fitted to the DC measured data for a depletion-mode GaAs MESFET to extract the DC parameters. The behavior of that static model compared to the measured data is shown in Fig. 1.

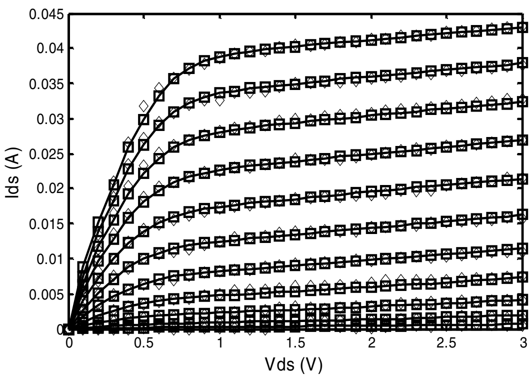

Fig. 1. Measured (diamonds) and modeled (squares) Ids in static conditions (DC) for NE76038. Vgs range: 0V to -1V (0.1V step).

As a second step, only the k-parameters of (2) are optimized in pulsed conditions. Note that only one set of k-parameters is required to fit the pulsed model under all bias conditions. The convergence is assured because good initial values for each parameter have been extracted from experimental data. Some results are shown in Fig. 2.

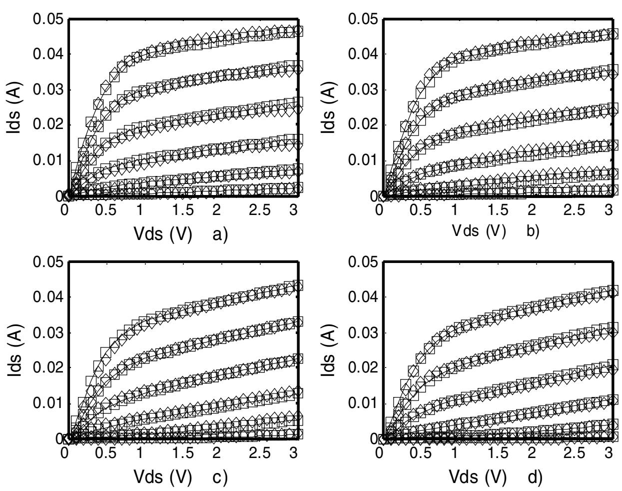

Fig. 2. Measured (diamonds) and modeled (squares) Ids obtained for the NE76038 with the proposed technique. Pulse-width: 0.2µsec; Duty cycle: 0.02%. Extrinsic applied voltages: a) Vgs_{DC}=0V, Vds_{DC}=0.5V; b) Vgs_{DC}=-1V, Vds_{DC}=0.5V; c) Vgs_{DC}=0V, Vds_{DC}=3V; d) Vgs_{DC}=-1V, Vds_{DC}=3V. Vgs range: 0V to -1V (0.2V step). Similar accuracy was obtained in multi-bias conditions.

In Fig. 2, it is possible to see that despite relatively small differences inherent to the natural limitations of the original model, the modeled pulsed Ids follows the measured pulsed current in multi-bias conditions with good accuracy. Similar results were obtained implementing this technique to another model [10], for a PHEMT device. To verify the validity of the proposed technique, the same procedure was performed with a high-power device. Some results are presented in Fig. 3.

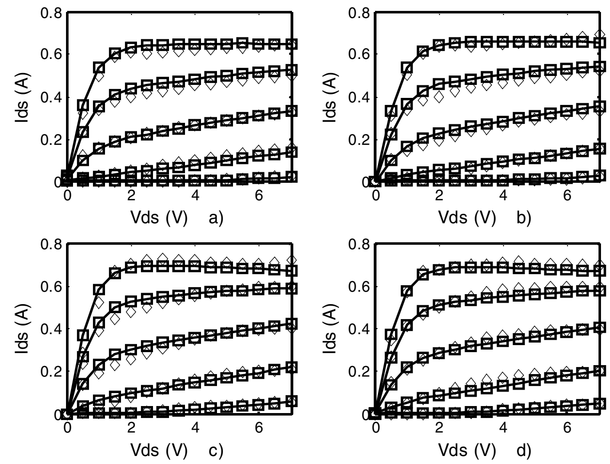

Fig. 3. Measured (diamonds) and modeled (squares) pulsed Ids for FLL177 GaAs MESFET with the proposed technique. Pulse-width: 0.2µsec; Duty cycle: 0.02%. Extrinsic applied voltages: a) Vgs_{DC}=0V, Vds_{DC}=6V; b) Vgs_{DC}=-2V, Vds_{DC}=7V; c) Vgs_{DC}=-2V, Vds_{DC}=2V; d) Vgs_{DC}=0V, Vds_{DC}=1V. Vgs range: 0V to -2V (0.5V step). Similar results were obtained in multi-bias conditions.

IV. RF VALIDATION

We now extend the model to study the performance of the proposed technique in RF-small-signal applications. Firstly the parasitic elements are extracted from scattering parameters using the Agilent PNA E8361A vector network analyzer. The technique used was that proposed in [9],[11]-[12]. For the extraction of the intrinsic elements, the classical method proposed by [13] is implemented. Those results are used as a reference for comparison purposes with our proposed model.

Secondly, we sought to verify that the dispersion of the intrinsic output conductance and transconductance, (g_m , g_d), are in the kHz range. Following analysis of the Ids characteristic under various pulse-width conditions, no dispersion for frequency ranges greater than a few kHz was observed. This was further verified from extraction of these intrinsic parameters from pulsed measurements (MHz) and from scattering parameters (GHz) under multi-bias conditions. Again, the behavior of the extracted values was largely non-dispersive. Consequently the voltage differentials: $Vgi_{RF} = d_{vg}$; $Vdi_{RF} = d_{vd}$, and (2) can now be used to model not only the DC and large-signal pulsed currents, but also the small-signal RF behavior in the following way:

$$\frac{\partial Ids}{\partial Vgi_{RF}} = g_{mRF};\frac{\partial Ids}{\partial Vgi_{DC}} = g_{mDC};\frac{\partial Ids}{\partial Vdi_{RF}} = g_{dRF};\frac{\partial Ids}{\partial Vdi_{DC}} = g_{dDC} .\quad(3)$$

The first two terms in (3) represent the RF/DC transconductance, and the last two represent the RF/DC output conductance respectively.

For large-signal conditions (2) was implemented in a multi-terminal nonlinear equivalent circuit as it is shown in Fig 4. For simplicity we consider only negative gate voltage bias conditions.

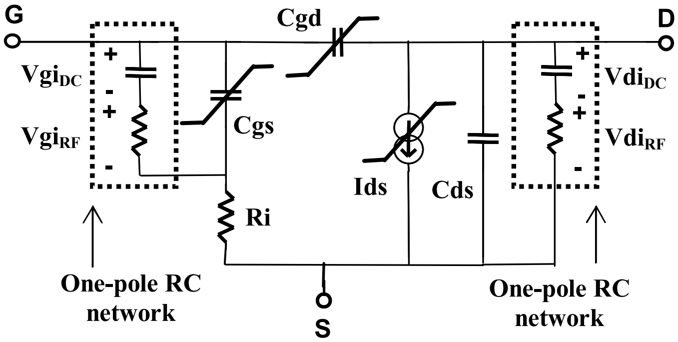

Fig. 4. Proposed intrinsic-large-signal equivalent circuit, showing the main nonlinearities.

In the implementation of the proposed large-signal equivalent circuit (Fig 4.), for this study, use is made of a one-pole RC network in the gate and drain side of the device with |R| >> |1/(*j.w*.C)| to properly separate the RF and DC voltages, and with a time constant in the order of milliseconds to model dispersive phenomena in the kHz range. The order of magnitude of the values used in these networks also agrees with those proposed by [7] to explain other kinds of phenomena such as low-frequency input-capacitance dispersion.

For small variations of voltages, the first-order Taylor series approximation of (2) is:

$$\nabla Ids_{(DC+RF)} = g_{mDC} \cdot \nabla Vgi_{DC} + g_{dDC} \cdot \nabla Vdi_{DC} + g_{mRF} \cdot \nabla Vgi_{RF} + g_{dRF} \cdot \nabla Vdi_{RF} \quad (4)$$

In other words, from an equivalent circuit point of view, the global behavior (small-signal, including RF+DC) of the DUT can be represented by four voltage controlled current sources. In consequence, the proposed large-signal equivalent circuit can be reduced to its equivalent for small variations of voltages as shown in Fig. 5.

In Figs. 4 and 5, the RC networks do not influence the scattering parameters in the GHz range as they have high impedance at these frequencies. In that sense, considering only RF small-signal conditions, the proposed model reduces exactly to a conventional model (e.g. as in [13]). (The DC parameters are null.) From a physical point of view, the high values of the R's could be related to the GaAs resistivity [7].

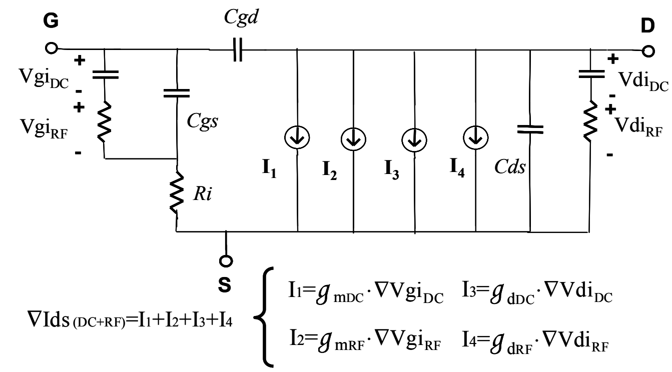

Fig. 5. Proposed intrinsic small-signal (including RF+DC) equivalent circuit obtained from the circuit given in Fig 4.

Simulations in ADS, using the extracted parasitics and a SDD, verify this general analysis. In effect, (2) with the k-parameters extracted from pulsed measurements, was implemented in ADS, using the proposed nonlinear large-signal equivalent circuit. Some results are shown in Fig. 6.

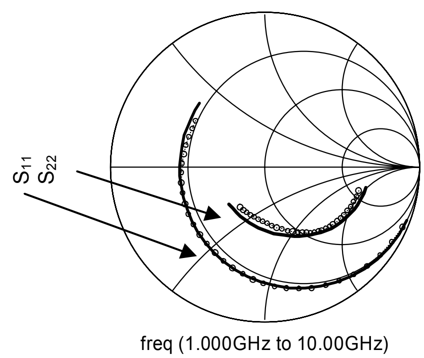

Fig. 6. Measured (circles) and modeled (lines) scattering parameters for the NE76038 using the proposed method. Extrinsic applied voltages: Vds_{DC}=3V; Vgs_{DC}=0V (in which low-frequency dispersion of g_d is significant). Similar agreement was obtained in multi-bias conditions and for other s-parameters.

In Fig. 6 it is possible to see that the results of scattering parameters in multi-bias conditions agree very well with those obtained from the measured data. Furthermore these values are very similar to the data obtained with the conventional method [13]. It demonstrates that effectively the nonlinear model is reduced to the conventional form [13] in RF small-signal conditions. Similar good agreement was obtained in multi-bias conditions.

V. Conclusion

In this work, we have presented a new technique for large-signal characterization that can be implemented with different drain current models. Using the proposed technique it is possible to perform the direct extraction of the transconductance and output conductance in low and high frequency, under multi-bias conditions, and also to obtain the pulsed response of MESFET/HEMT devices. It has been demonstrated that good results can be obtained using the model with different kinds of devices.

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