AMCAD Engineering

White Paper

Advanced Modeling for Computer-Aided Design

GaN HEMT Transistor Compact Modeling based on Pre-RF Pulse I-V Measurements

Nicolas Labrousse[1], Frederique Simbelie[1], Maxime Faure[1], Tony Gasseling[1]

[1]AMCAD Engineering

***Abstract* — We propose a new solution to characterize GaN HEMT transistors for RF applications, focusing on trapping phenomena. Traditional methods for I-V characterization are discussed, highlighting the limitations of single and double-pulse techniques. A new methodology using combined RF and DC pulses is introduced to better represent final application trapping conditions. The paper details the measurement technique and its implementation, emphasizing its advantages over existing methods. Thanks to this new measurement technique, combined with a new extraction process, compact modeling development time is reduced with good model performance.**
***Index Terms* — Pre-RF Pulse, Trapping Effect, I-V characterization, GaN, HEMT, Compact Model**

I. INTRODUCTION

GaN HEMT transistors are now a standard for RF applications. This technology exhibits good RF performances due to high cut-off frequency and high power density. Nevertheless, it still suffers from trapping phenomena, which degrades the overall performance. For the aim of first-pass circuit design, the transistor model must take into account trapping phenomena. Consequently, GaN HEMT transistor characterization and compact modeling have become tedious and time-consuming. The I-V characteristics are essential to model the output current source. Therefore, these measurements must be carried out under given conditions (pulse width, period, quiescent bias) in order to exhibit or mitigate successively the thermal effects and trap phenomena. In this paper, we present a new methodology based on the combination of RF and DC pulsed signals. This technique allows us to measure I-V characteristics, taking into account more realistic thermal and trapping conditions. In the first part, we discuss current solutions to measure I-V characteristics. We put in evidence the advantages and limitations of the so-called single and double pulse I-V measurement. In the second part, we detail our new measurement technique, which uses a standard VNA-based load-pull system to combine calibrated Pre-RF and DC pulses. In the third part, we present the measurement results obtained from a GaN HEMT. In the fourth part, we introduce the new compact modeling flow and present a comparison between the model and measurement results. In conclusion, we will emphasize the possible improvements.

II. I-V CHARACTERIZATION: TRAPPING EFFECT

Pulse I-V measurement consists of applying pulsed signals (voltages/currents) around a quiescent bias point for a relatively short duration (Pulse Width). The voltage-current characteristics (I-V) are measured during the pulse. Pulse width and period are chosen in order to perform so-called quasi-isothermal measurements.

A. Single-Pulse I-V Characteristic

In [1], it has been demonstrated that it is possible to quantify trapping effects by monitoring quiescent bias points. However, as stated in [2], the time constants associated with trap effects in GaN transistors show an asymmetry between capture (fast, on the order of a few ns) and emission (much slower than the typical pulse width). Thus, single-pulse I-V characteristics are not all obtained in the same conditions of charge traps.

B. Double-Pulse I-V Characteristic

One way to fix the traps' state of charge is to apply a pre-pulse before the measurement. The two-level pulse measurement system (single-pulse) has evolved into a three-level system (double-pulse). The third level corresponds to an additional pulse (pre-pulse) applied before the main one.

Therefore, this system has the advantage of minimizing the asymmetry of the traps' charge and emission time constants. In [2], it is demonstrated that the measurements made with the double-pulse system at two quiescent bias points give identical results because the traps' state of charge is fixed by the pre-pulse and not by the level of the main pulse.

C. RF-signal considerations

However, the real transistor excitation signals have a high PAPR characteristic for microwave applications. Thus, the envelope of the RF signal varies over time, causing a significant variation in the instantaneous power.

The trapping effects are transient phenomena, which, therefore, change over time as a function of the levels of the voltages applied to the transistor. Thus, the traps' state of charge is dynamically impacted by the instantaneous variation of the signals and, therefore, the RF signal's envelope [3].

In the case of current double-pulse measurements, the state of charge of the traps is fixed at a maximum and does not consider the variation of the envelope of the RF signal. Also, double-pulse measurements are made in a 50 Ω environment that does not reflect the load conditions seen by the component in the final application.

Therefore, one can wonder about using these measurement results to model the output current source.

III. PRE-RF PULSE I-V MEASUREMENT

In order to take into account RF signal impact, we propose a new measurement technique that combines DC pulse signals with a variable RF pre-pulse level to modify the state of charge of the traps dynamically [4].

A. Measurement Bench System

The Pulsed I-V characteristics are obtained in a non-50 Ω environment presented in Fig. 1. The pulsed RF source provides a controlled Pre-RF pulse at the frequency of interest f_0, while the pulsed I-V system aims to generate and measure voltage and current signals.

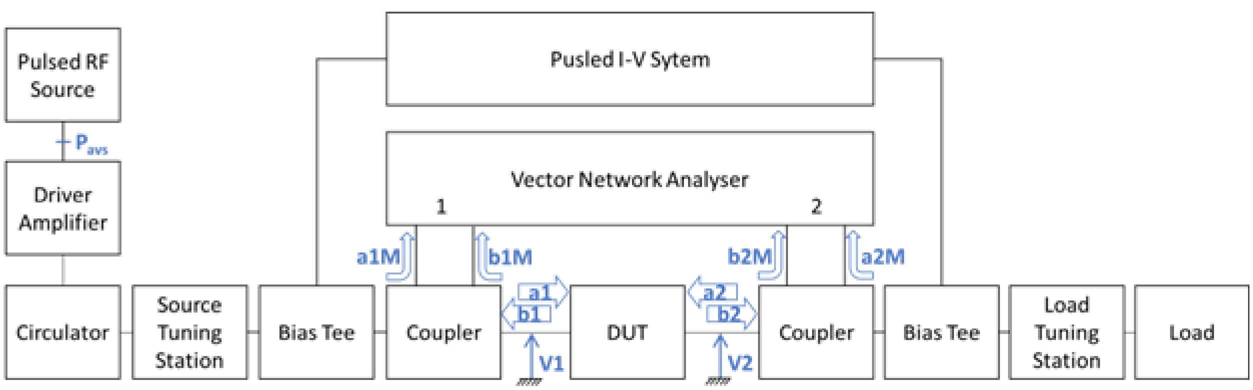

Fig. 1 Load-Pull measurement system schematic

Input and output bias tees combine Pre-RF and DC pulses to the Device Under Test (DUT) accesses. Vector Network Analyzer is mandatory to acquire preliminary large-signal measurements. These measurements are used for calibrating input Pre-RF pulse level as well as for model validation. The load tuning station controlled the output load impedance conditions. Thus, the output Pre-RF pulse is naturally generated thanks to the DUT voltage gain.

Within this system, the measurement conditions used for the model extraction and validation are perfectly aligned.

B. Main Principle

The measurement principle is illustrated in Fig. 2. The pulsed I-V characteristics are measured along various load cycles (cross symbols). Prior to each DC pulse, the Pre-RF pulse is applied to the device accesses.

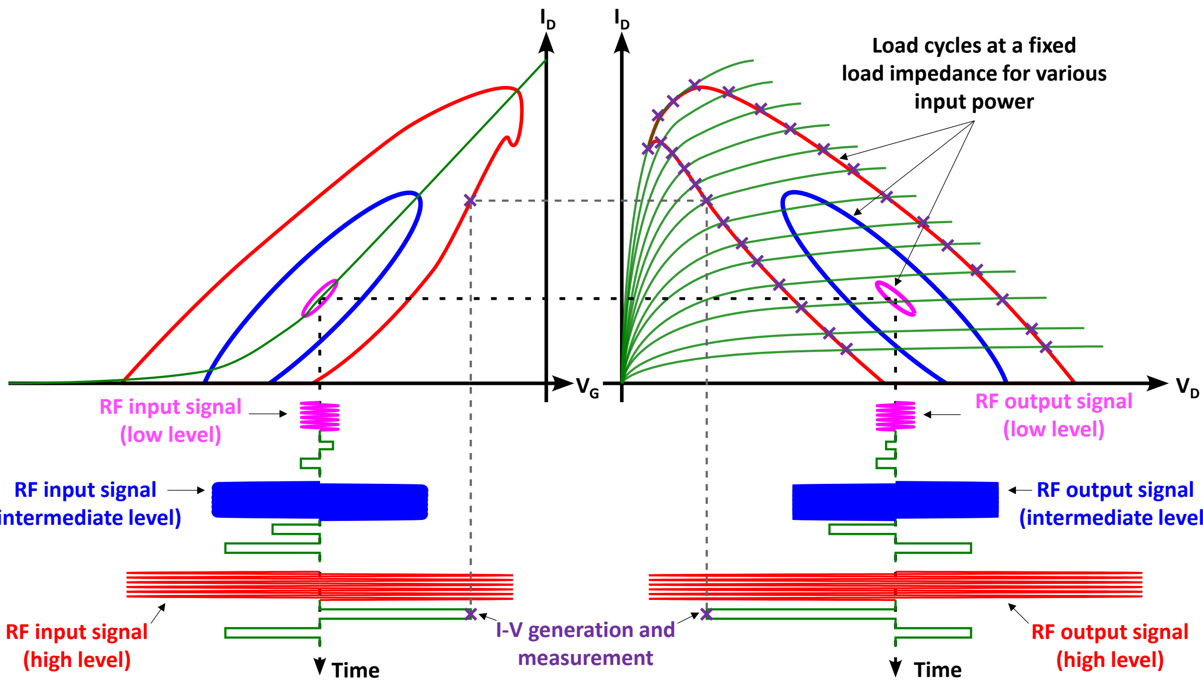

Fig. 2 General principle of pulsed measurement DC+RF

For each load cycle, the Pre-RF pulse level is fixed. Then, the Pre-RF pulse varies according to the envelope of the RF signal determined from the preliminary large-signal measurements. The DC pulse sequence is obtained from the following algorithm:

C. Measurement Algorithm

Thanks to the vectorial calibration, the incident (a1, b1) and reflective (a2, b2) waves are acquired in the DUT access plans. Then, the instantaneous input and output RF signals $V1_{RF}$ and $V2_{RF}$ are calculated from the following equation (1).

$$\boldsymbol{Vi_{RF}} = (\boldsymbol{a_i} + \boldsymbol{b_i}) \cdot \sqrt{\boldsymbol{50}} \quad (1)$$

Where Vi_{RF} are the complex voltages at the fundamental (f_0) and harmonics. The index i designates the port number (1,2). It is noticed that Vi_{RF} are varying within the load condition and the instantaneous RF source level, noted as Pavs in Fig. 1. For a given Pre-RF pulse level, the input and output DC voltages (during the DC pulses) are evaluated based on the input and output cycles, at f_0, as illustrated on Fig. 3

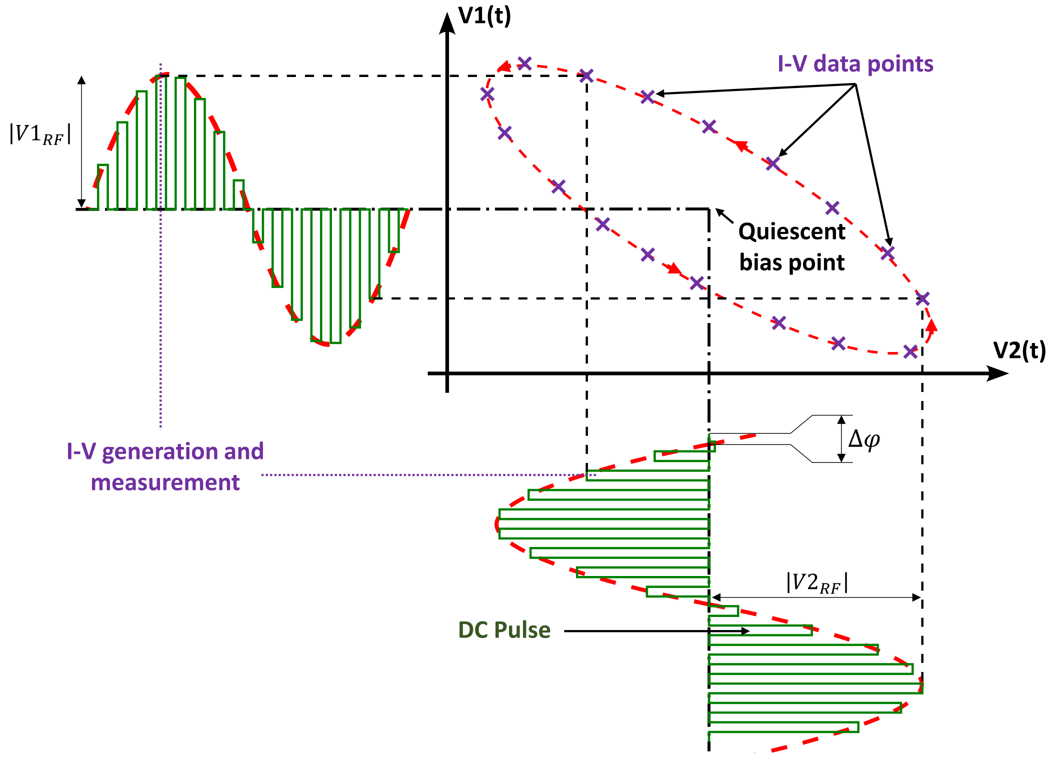

Fig. 3 Pulsed DC evaluation based on input and output cycles at f_0 for a given Pre-RF pulse level.

The input and output cycles consist of associating the input voltage variation, V1(t), to the output voltage one, V2(t). Instantaneous voltage variation can be expressed as in the expression (2).

$$\boldsymbol{Vi(t) = Vi_{DC} + |Vi_{RF}| \cdot \sin(2\pi f_0 \cdot t + \varphi_i)} \quad (2)$$

Where, Vi_{DC} is the DC component induced by the quiescent bias polarization, $|Vi_{RF}|$ is the amplitude of the RF component at f_0, and φ_i the associated phase. $|Vi_{RF}|$ and φ_i are obtained from equation (1). In practice, only the phase difference $\Delta\varphi = \varphi_2 - \varphi_1$ is considered, as shown in Fig. 3 while φ_1 is fixed to 0.

Finally, the input and output voltage sequence is obtained by discretizing the time over a period ($T = 1/f_0$).

IV. Measurement results

The method described in the previous section is applied to carry out the measurement on a GaN on SiC device. The device under test has a total periphery of 1 mm for 8 gate fingers. After de-embedding the input and output fixtures, the measurement results are included in the active device plan.

Experimentations allow the observation of the results in Fig. 4. The three load impedances are chosen using the preliminary load pull measurements at 5 dB compression. A, B and C impedances are selected for the following conditions: maximum output power (A), maximum drop in the average output current (B) and maximum efficiency (C). The pulsed IV networks are plotted for each load condition. Mainly, it is possible to discern that the cycle inclination varies due to the impedance.

Each point of this measurement has a different couple of terminal voltage V_{gs} and V_{ds}. IV results are cut out using gradient color in the function of the Pre-RF pulse power level. It is worth noting that the collapse in the output current shape is in the range of 5 to 10 dBm of the delivered input power.

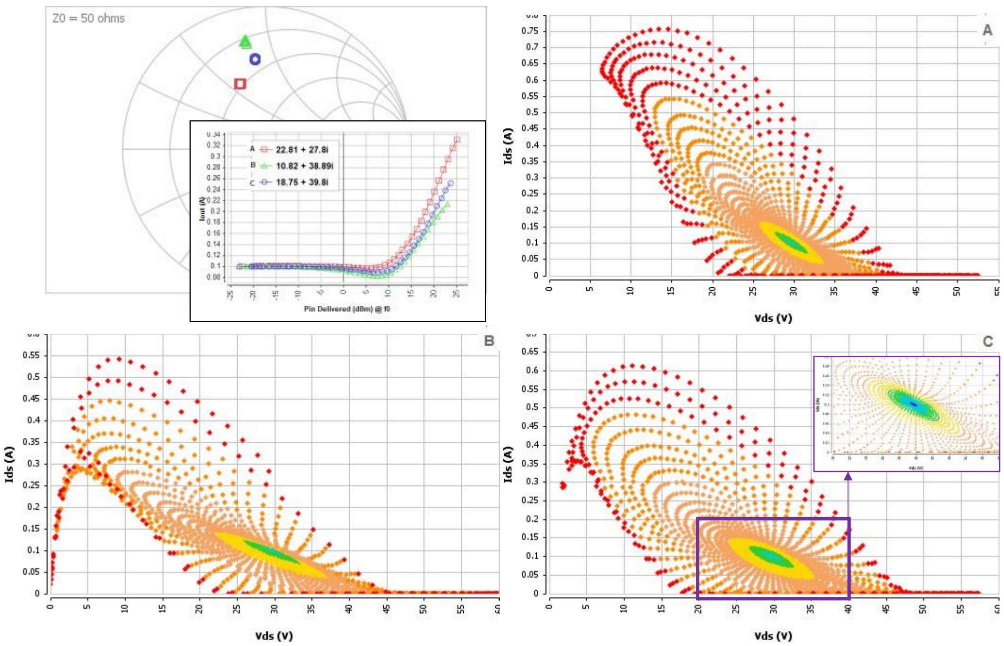

Fig. 4 Pre-RF pulse measurement results for 3 Load impedances (A, B & C) – Gradient color defined the delivered input power range in dBm ([-25 ; -15] blue, [-15 ; -5] blue-green, [-5;0] lime green, [0;5] gold, [5 ; 15] sandy brown, [15, 20] dark orange and [20;25] red)

V. MODEL DEVELOPMENT ACCORDING TO THE PRE-RF PULSE MEASUREMENTS