AMCAD Engineering

White Paper

Advanced Modeling for Computer-Aided Design

Pre-RF Pulse IV measurements for enhanced transistor compact modeling work

Enhanced transistor compact modeling work with Pre-RF Pulse IV- Load Pull measurements

Chapter 1: Pulsed IV Measurements

The IV set of curves is an important figure of merit for estimating the power performance of RF transistors. The latter is subject to self-heating when characterized with continuous DC IV signals, especially when tested under high-power conditions. The self-heating phenomenon leads to a reduction in performance and can lead to the destruction of the component. Therefore, the characterization is carried out in pulsed mode to overcome this behaviour. The self-heating phenomenon is shown in Figure 1, where the IV characteristics measured in DC mode (in red) and pulse mode (in green) on a transistor in HEMT AlGaN/GaN technology are compared.

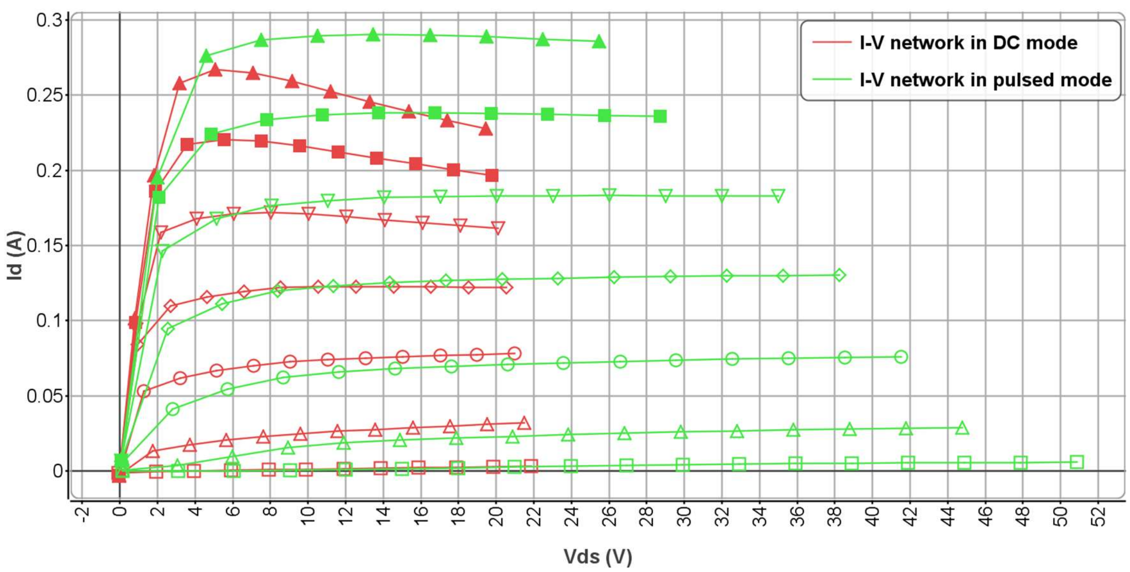

Figure 1: IV Characteristics measured in DC (red) and pulsed mode (green)

The principle of measurement in pulsed mode is presented in Figure 2. This one consists in applying pulsed signals (voltages/currents) around a quiescent bias point for a relatively short duration (Pulse Width). The voltage-current characteristics (IV) are then measured within the short pulse without being subject to significant sef heating that reduces the performance. In addition, higher voltage and/or current levels can be applied while mitigating the risk of device degradation or destruction of the transistor.

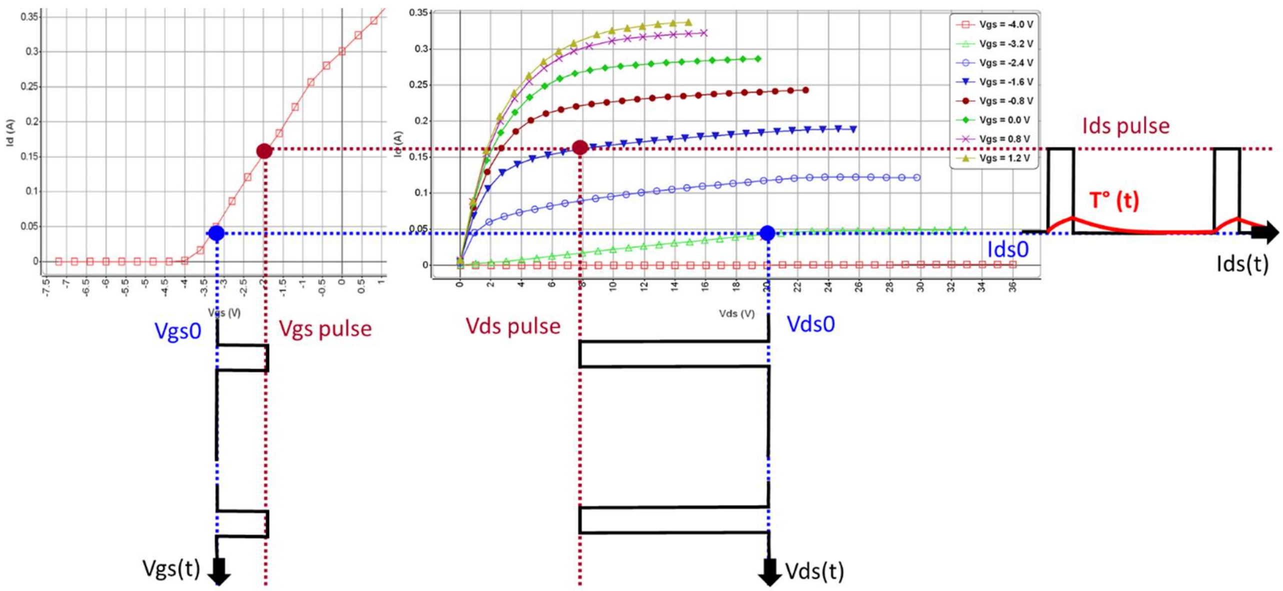

Figure 2: Pulsed IV measurements principle

The quiescent bias point (Vgs0; Vds0) sets the value of the mean power consumption and, as a consequence, the junction temperature. If the pulse width and the duty cycle of the pulsed bias are short enough, respectively 500ns and 10 µs as a rule of thumb, the mean temperature remains constant even if this one evolves slightly during the pulse. Thus, the shorter the pulse and the duty cycle are, the lower the self-heating is. Measurements are then so-called quasi-isothermal.

In this context, the pulse IV curves are essential to model the output current source at a given temperature.

Nevertheless, there are still some challenges to accelerating the compact modeling process of RF transistors. Indeed, pulse IV curve characteristic can also be impacted by trapping effects, which takes place in III-V transistor technologies.

Chapter 2: Problem observed when using pulse IV measurements

The process of extracting a compact model is sequential and incremental, as shown in Figure 3.

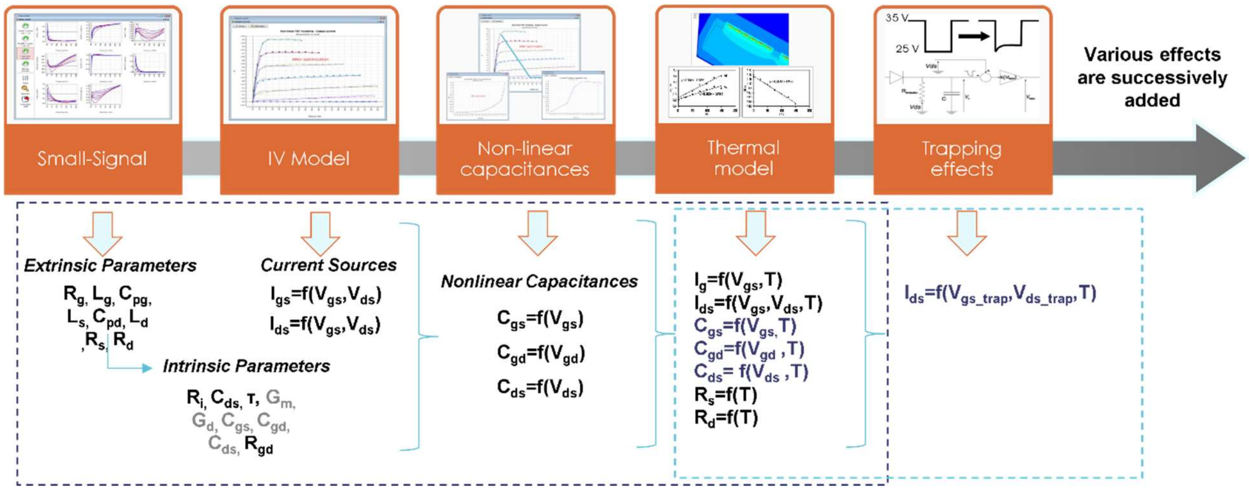

Figure 3: Compact model extraction process

The modeling work starts with the extraction of the linear model. This is then completed by describing nonlinear elements such as diodes, output current sources and nonlinear capacitances. These nonlinear behavior are extracted using synchronized pulsed S parameters and pulse IV measurements taken in the IV area where the RF load line takes place. The first pulse measurements are generally from a cold bias point (Vgs0=0V, Vds0=0V). Under these conditions, thermal effects and trapping phenomena are negligible.

The thermal and trap models [4] are both extracted using pulse IV pulse data plotted over time for a relatively long pulse IV duration to capture the thermal and trap time constants, as shown in Figure 4

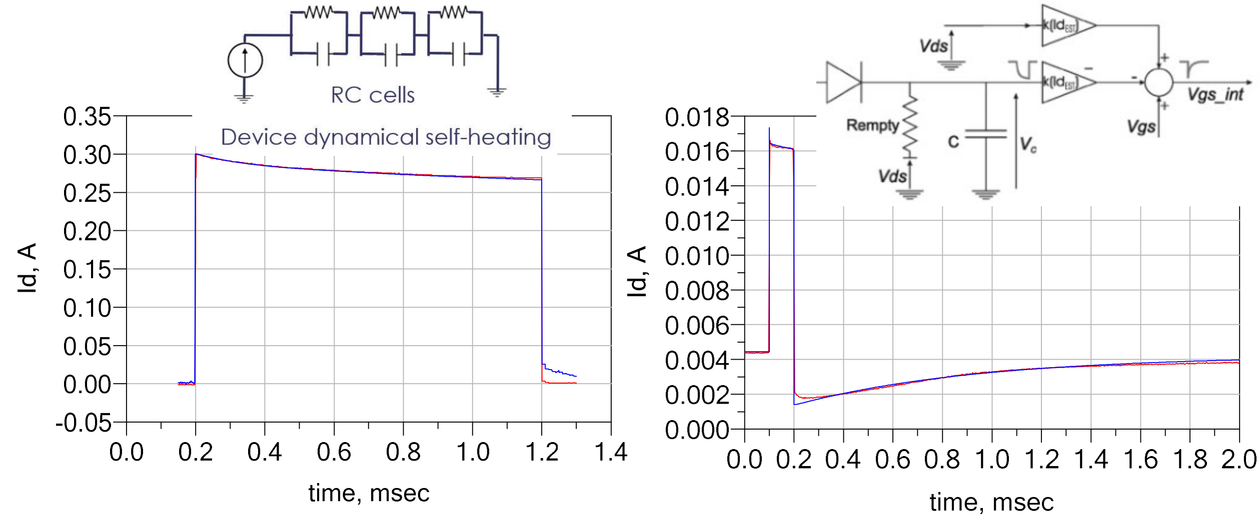

Figure 4: dynamic thermal effects (left) and trapping effects [4] (right) modeling examples

These models should fit the transient response of the current, whether the current drop is caused by self-heating or trapping effects. These descriptions complement the initial modeling work. Later, the complete model behavior must be validated against large-signal measurements, usually carried out in a load-pull environment and under conditions close to the final application.

Consequently, characterization and modeling work can be time-consuming for transistors in III-V technology. An example with measurements (red) versus model (blue) data are compared in

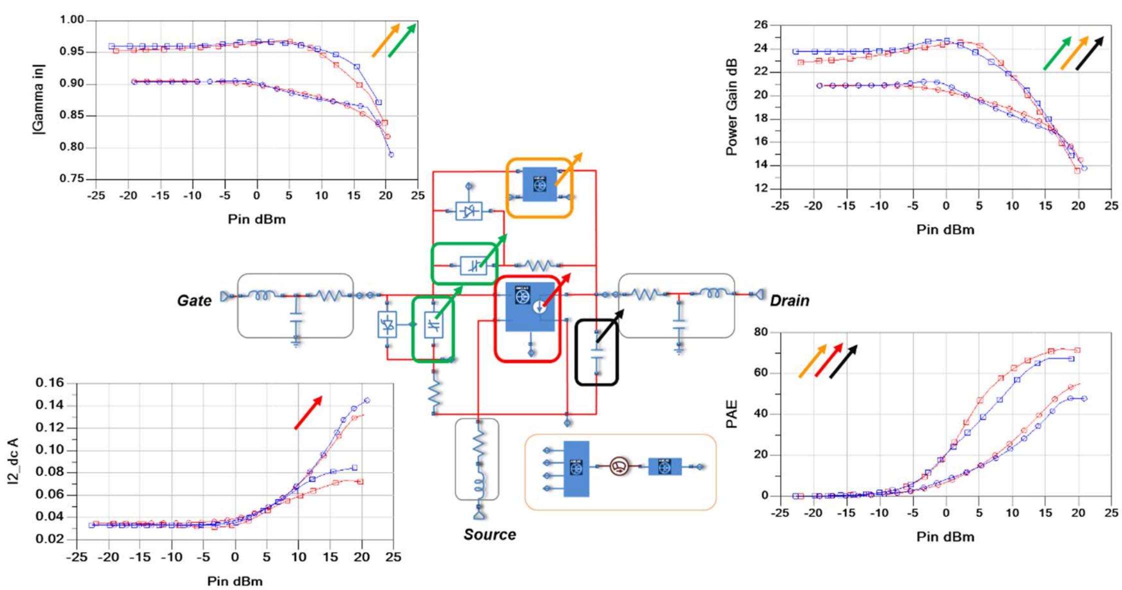

Figure 5. These graphs show RF performance such as output power (Pout), power gain (Gp), power-added efficiency (PAE), input impedances (Gamma In) and output current (I2) as a function of input power (Pin) for optimal load impedances defined to reach maximum output power (MXP) or maximum efficiency (MXE)

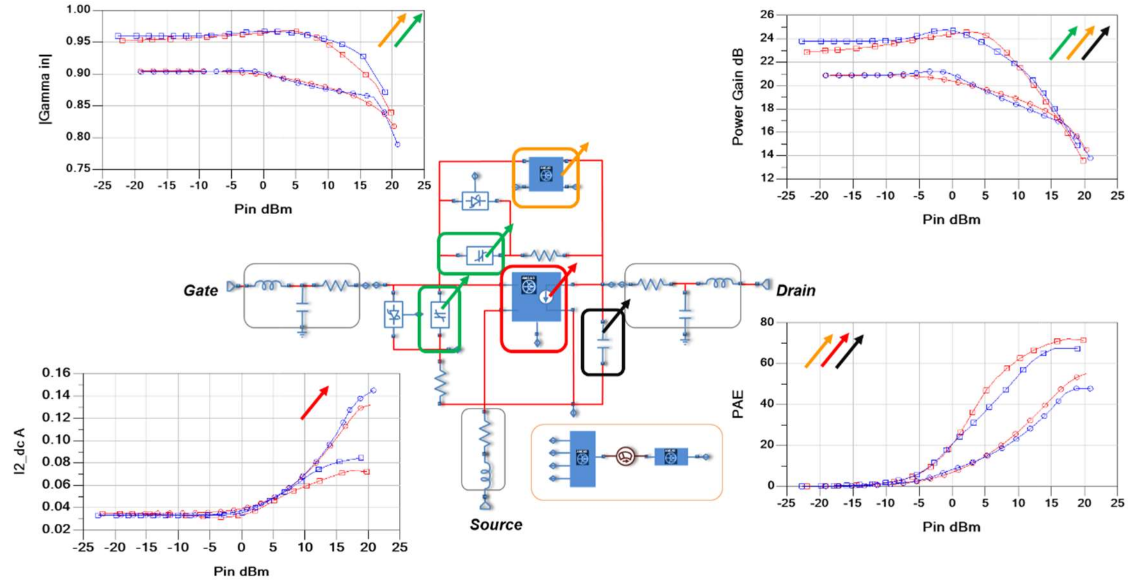

Figure 5: Comparison of measurement (red) versus model (blue) for large signal RF performance and model parameters which influence the fit

As shown in this example, all parameters have been optimized to predict performances for MXE and MXP load conditions.

To obtain such results, each stage of the model development must be treated rigorously, whether during the measurement phase or the extraction of the model parameters phase.

Despite all these efforts, a final model refinement phase is always necessary. It consists of modifying certain model parameters to find a good compromise of the model's performance in both small and large-signal operating conditions.

This optimization process consists of a pragmatic approach that identifies which part of the model most influences a given characteristic. Thus, different model parameters should be optimized depending on the characteristics that need improvement. As part of the optimization process of a compact model, the relationships given in Table 1 and illustrated in Figure 5 have been identified.

Characteristics to enhance	**Model parts to optimize**
Gamma In	Cgs, Cgd
Id	Output current source
Gain, Pout, PAE	Cgd, Cds

Table 1: Model optimization

Modeling errors put apart, to explain the differences observed between the model extracted from pulsed IV and pulsed S parameter measurements and the model refined against load-pull measurements, two hypotheses are put forward :

- The operating conditions seen by the transistor during the measurements needed for the model extraction (IV & S parameters) differ substantially from those used for the model validation (VNA-based Load-Pull). For the latter case, the load impedance conditions, the power level, the bias conditions (DC versus pulsed) and the junction temperature are quite different. For all these reasons, despite the great care taken during the model extraction work, it is not always easy to easily align the large signal performances in simulation using only a model extracted from small signal measurements with pulsed IV and S parameter data.
- As stated in [1], the time constants associated with trap effects in GaN transistors show an asymmetry between capture time (fast, on the order of a few ns) and emission time (much slower than the typical pulse width). Thus, the pulse IV curves obtained from basic pulse IV measurements do not always represent charge traps provided by RF large signals.

This last point is illustrated in Figure 6. The IV characteristic is measured in class AB conditions (Vgs0 = -2.35V, Vds0 = 40V in this example). Intrinsic load lines simulated under the same bias condition for the 2 load impedances MXP and MXE are superimposed. In blue, the zone of fixed trap level (Vds < Vds0) has been delimited. In red, the zone of the variable trap level is highlighted (Vds > Vds0).

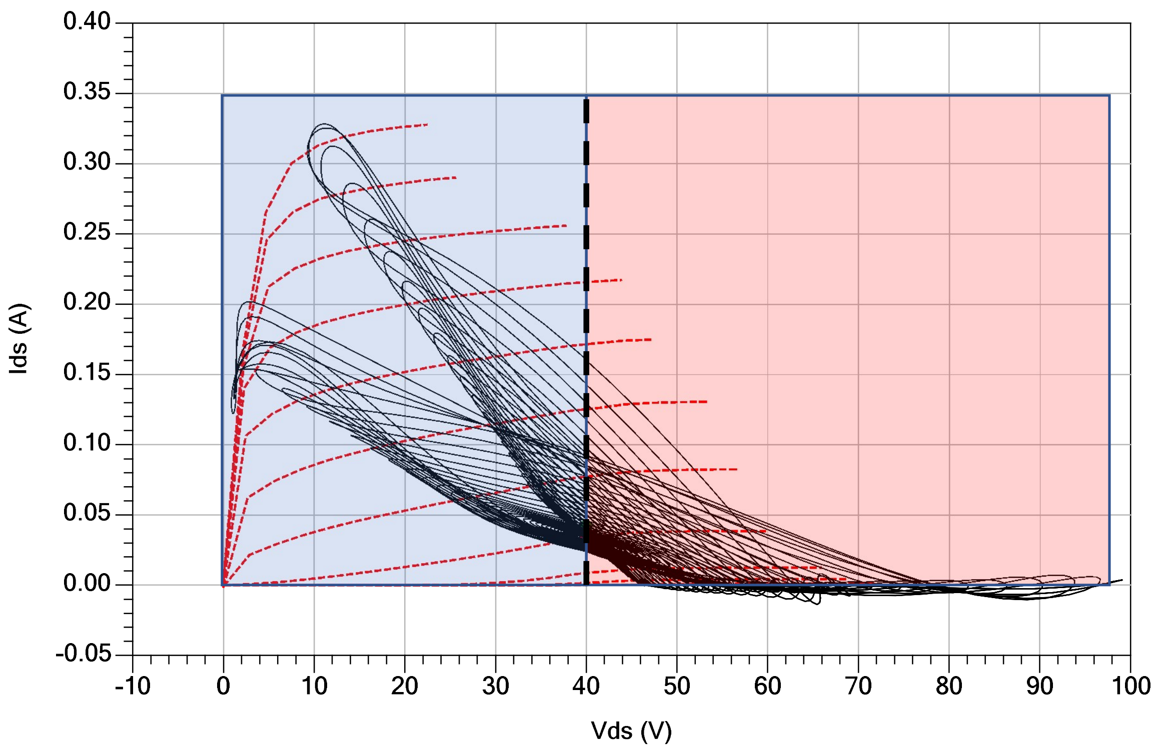

Figure 6: IV characteristic measured for (Vgs0 = -2.35V, Vds0 = 40V), identification of areas with constant (blue) and variable (red) state of charge.

As depicted, for the 2 load impedances (MXP and MXE), from the quiescent bias point, the load-lines swing in the 2 zones of the IV characteristic. Consequently, to facilitate the modeling work, it would be required to use a measurement bench which would consider the actual state of charge throughout the IV characteristic related to these RF swings.

Chapter 3: Existing Solution to Address the Problem

One way to fix the traps' state of charge is to apply a pre-pulse to trigger the traps before the actual pulsed IV is used for curve plots. Therefore, a two-level pulse IV (quiescent and pulse) system has evolved into a three-level system (quiescent, pulse, and pre-pulse). The third level corresponds to an additional stimulus before the main pulse. Figure 7 illustrates the measurement principle of a three-level system representing the time signals (left) and the resulting IV network of curves (right).

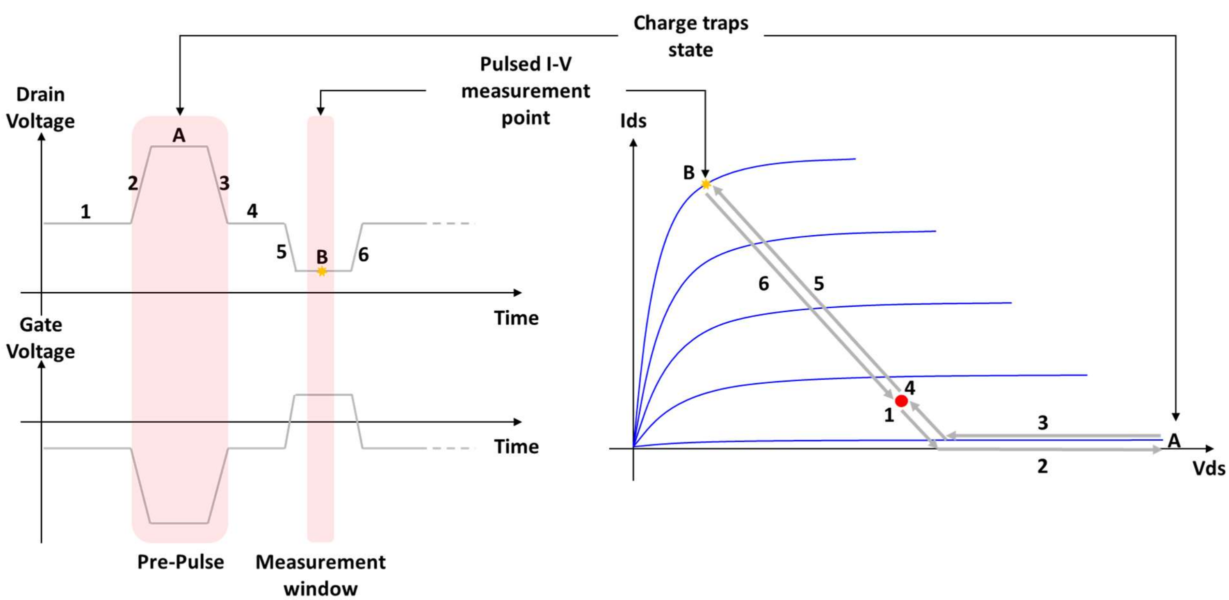

Figure 7: General principle of three-level IV stimulus to measure point B

The quiescent bias point (1) fixes the mean temperature condition. The pre-pulse (A) makes it possible to fix the traps' state of charge of whatever explored zone of the IV network. The pre-pulse is generally fixed to represent the line of maximum charge (peak Vds voltage usually reached by the RF load line), i.e. for a very negative gate voltage and a drain voltage much higher than the quiescent voltage. Under these conditions, the traps' state of charge is maximum.

Therefore, this system has the advantage of fixing the traps' state of charge over the entire IV network and thus minimizing the asymmetry of the traps' charge and emission time constants. As shown in Figure 8, the top chart is obtained with a two-level pulse IV system. On the bottom chart, a three-level IV system is used. Measurements are made for two bias points, I (red) and II (blue), providing the same mean self-heating conditions. As shown, the measurements made with the three-level IV system are identical regardless of the bias point because the traps' state of charge is fixed by the pre-pulse and not by the level of the main pulse.

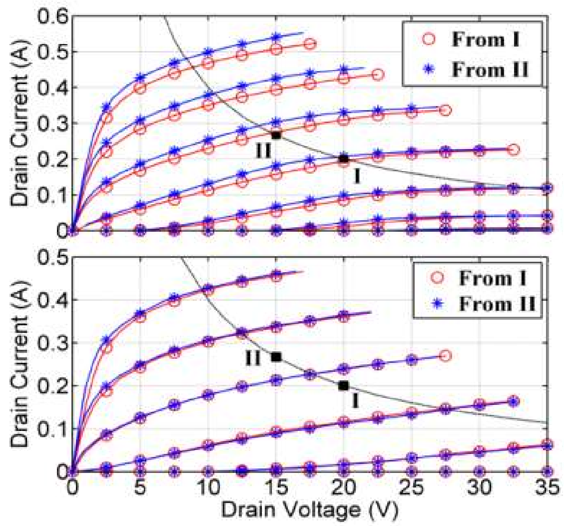

Figure 8: Top chart: Pulse IV measurements were made with a two-level system. Bottom chart: curves measured with a three-level system. Measurements are made for two different bias points, I (red) and II (blue)[1]

However, while three-level systems improve the knowledge of the trapping effect influence on IV curves, real RF excitation signals may influence this characteristic differently. Indeed, when using RF signals, the envelope of the RF signal may impact the traps differently, leading to another IV curve description.

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.

The impact of the RF signal envelope on the traps' state of charge has been shown in [2] and [3]. For these studies, a pulsed RF signal is applied to the component, and the response to this signal is studied by analyzing the evolution of the average current. Figure 9 illustrates the impact of the RF signal level on the average output current (Ids0).

[1] A. Santarelli *et al*., « A Double-Pulse Technique for the Dynamic I/V Characterization of GaN FETs, » in *IEEE Microwave and Wireless Components Letters*, vol. 24, no. 2, pp. 132-134, Feb. 2014, doi: 10.1109/LMWC.2013.2290216.

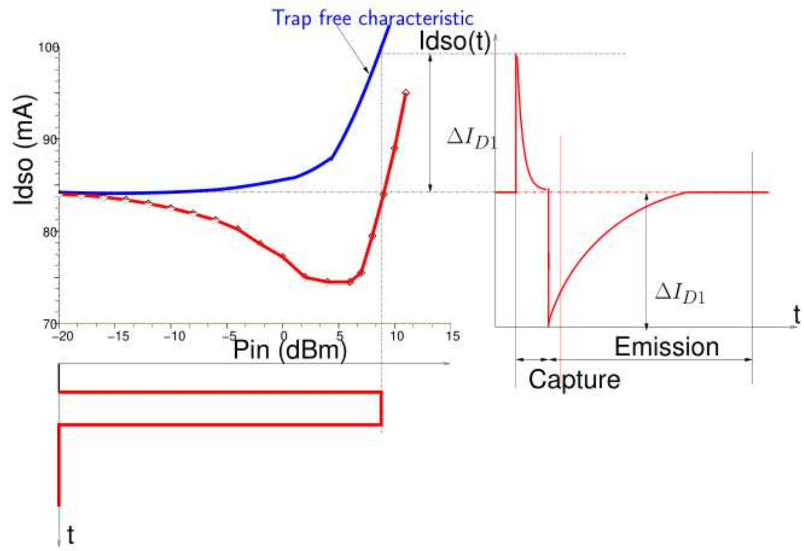

Figure 9: illustration of current decrease caused by trapping effects when increasing the magnitude of the pulsed RF signal [2]

These curves show the evolution of the real average current measured (in red) and the ideal simulated current (in blue) when the traping circuit is deactivated. The pulse shape of the output current (Ids0(t)) is also plotted as a function of time when a pulsed RF signal drives the transistor. As expected, the average current measured is lower because the RF signal envelope's magnitude modifies the trap's state of charge.

However, in the case of three-level pulse measurements, the state of charge of the traps does not consider the dynamic variation of the envelope of the RF signal. In addition, a three-level pulse system does not stimulate the transistor as in real conditions where the load impedance changes the slope of the RF load line, which changes the peak RF voltage, which influences charge levels in return.

Therefore, this measurement concept can be questioned when the target is to help the modeling engineer to accelerate the work to define the output current source parameters for different load impedance conditions.

Chapter 4: Proposed Solution

To address these challenges, a new measurement technique is proposed to combine double-level pulse IV with a pre-RF pulse signal to modify the state of charge of the traps dynamically **(patent notice n° WO2023062452).** The principle is illustrated in Figure 10. The IV network is then divided into several areas (green, blue and red in the figure), all centred around the bias point of the final application. For each area, the pre-RF pulse magnitude is constant, thus fixing the state of charge of the traps.

[2] O. Jardel, «Modeling of Trap Induced Dispersion of Large Signal Dynamic Characteristics of GaN HEMTs,» IEEE MTT-S International Microwave Symposium Digest (MTT), pp. 1-4, doi: 10.1109/MWSYM.2013.6697576, 2013.

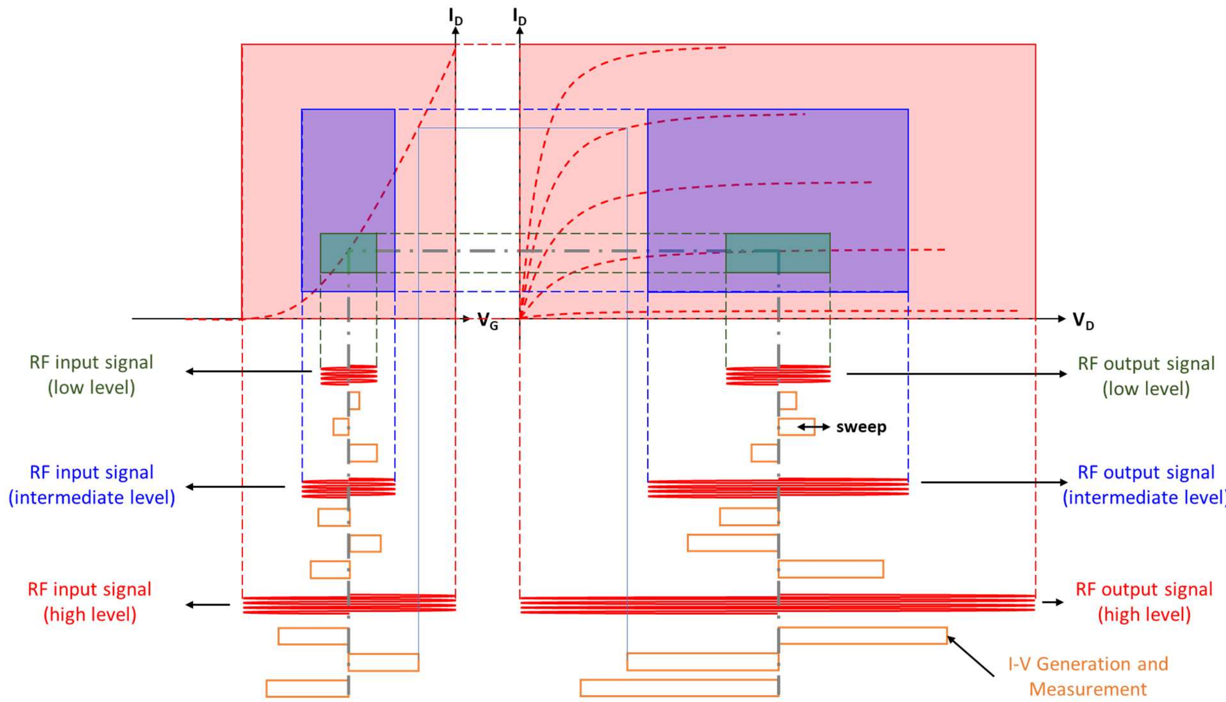

Figure 10: General principle of pre-RF pulse measurements

This technique is associated with a specific measurement algorithm allowing the modification of the state of charge of the traps in a similar way to the dynamic variation of the envelope of the RF signal. After each pre-RF pulse, a pulse IV value is measured and generated from the DC quiescent bias points. The levels of these pulses are defined not to exceed the region delimited by the pre-RF pulse.

Preliminary large-signal measurements allow calibrating the power amplitude of the pre-RF pulse for the load impedance and IV area of interest. With this measurement technique, it is possible to determine a realistic IV characteristic of a component under load and bias conditions identical to those of the final application. It considers the dynamic variation of the state of charge of the traps induced by the variation of the RF envelope of the signal.

To illustrate the advantage of this measurement technique, a comparative study was performed between different measurement techniques: three-level pulse DC-IV and pre-RF pulse combined with double-level pulse IV. The measurements were performed on an AlGaN/GaN on SiC HEMT transistor with a total periphery of 0.4 mm (8 gate fingers for a width of 50 µm). The bias point is fixed at (Vgsq = -3.2V, Vdsq = 20V), corresponding to a class AB bias.

The results obtained by the different measurement systems are presented in Figure 11.

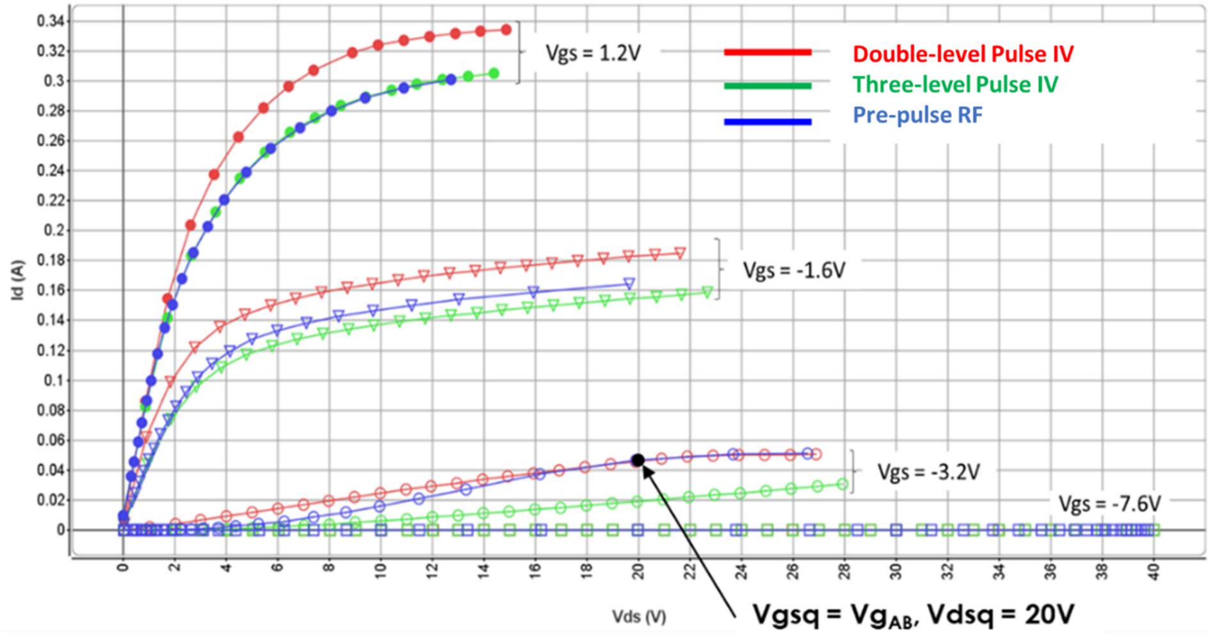

Figure 11: Comparison of IV plots using 3 different measurement systems.

It is noticeable that :

- Using the double-pulse level system (in red), for the top curves, the current is generally higher than for the other IV curves because the charge state of the traps is underestimated, as this one is only driven by the quiescent bias point.
- Using the three-level pulse IV system (in green), for the top curves, the state of charge of the traps is well taken into account for open channel conditions. The current is not overestimated. Nevertheless, the current level is underestimated for the bottom curves because the level of traps can be too high as the magnitude of the three-level pulse is too high.
- The pre-RF pulse measurement allows us to gather the benefits of both measurement methodologies. Using a dynamic magnitude of a variable pre-RF pulse, the state of charge of the traps is well considered for every curve. At low current (low RF power), the state of charge is mainly fixed by the bias point (the red and blue curves overlaps). At high currents (saturated power), the state of charge is mainly fixed by the pre-RF pulse (the blue and green curves overlap).

: Ideally, a double-level pulse system with a dynamic variation of the magnitude of the pre-pulse would address the issue of current under/overestimation. Nevertheless, there is no obvious rules to reproduce similar trapping effects when using either pulsed IV or pulsed RF signals. The advantage of using pre-pulse RF is the following. As explained in the following section of this whitepaper, the magnitude of the pre-pulse RF signal can be calibrated for different load impedances, to make sure IV curves and RF load lines are consistent when measuring IV curves for a certain level of charge state of the traps. This is the key to minimize model refinement between pulsed IV and load pull data latter on.

For the aim of the above comparison, the load line was chosen to maximize the RF voltage swings at the input and the output of the component accesses to fully cover the IV characteristic at the high input power level. In these conditions, the gain compression is as high as 7 dBc.

However, more realistic conditions of gain compression can be used. These are determined using load-pull measurement on the device of interest. Figure 12 shows the PAE (red) and Pout (green) contours obtained at a 4 dB gain compression level. The maximum PAE and output power are achieved for the following impedances: 13.14+32.03i Ohms (MXE) and 22.65+24.03i Ohms (MXP).

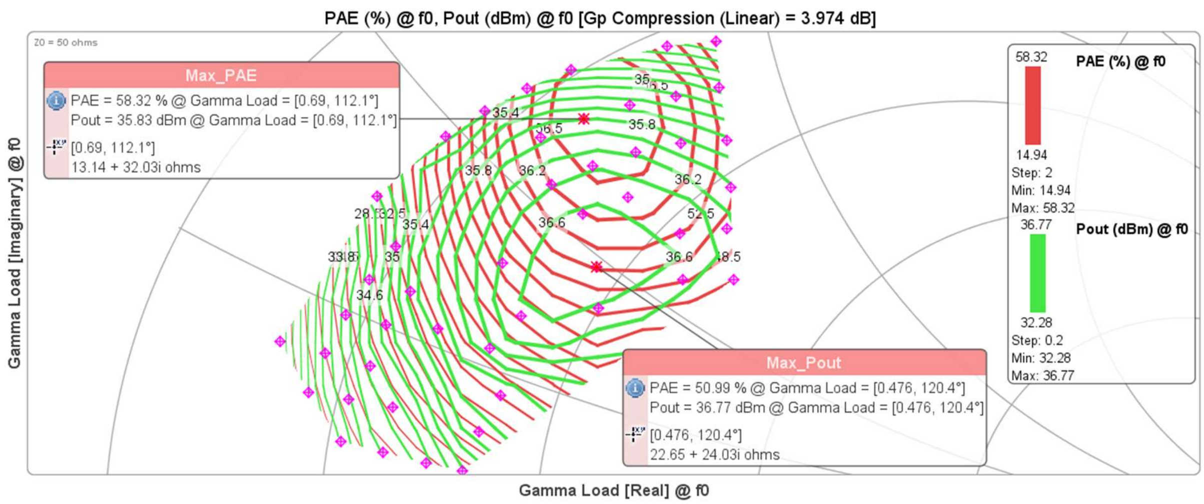

Figure 12: Load-Pull measurement results: PAE (red) and Pout (green) contours @ 4 dBc and f0 = 10 GHz.

For each load impedance, a unique variation law is determined to link the pre-RF pulse magnitude and the magnitude of the pulse IV signal used to plot the curves.

First of all, absolute input and output RF signal magnitudes are calibrated at the component reference planes using a VNA-based load pull solution. Figure 13 sketches the load-pull system architecture

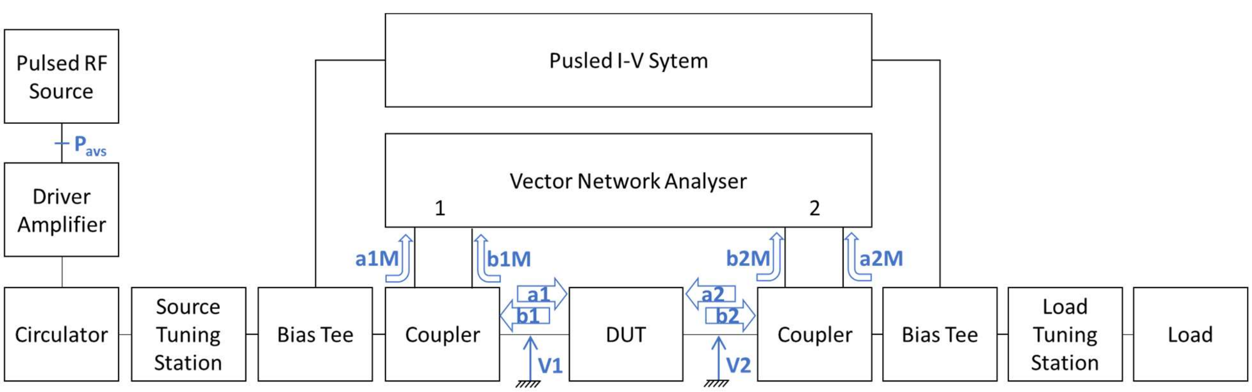

Figure 13: Load-Pull measurement system schematic

Thanks to the vectorial calibration, incident and reflective waves (a1, b1) and (a2, b2) can be measured at the input and output accesses of the Device Under Test (DUT). The instantaneous input and output RF magnitudes V1 and V2 can then be calculated using the following formulations in Eq.1 and Eq.2.

$$V1 = (a1 + b1) * \sqrt{50} \qquad \text{Eq.1}$$

and

$$V2 = (a2 + b2) * \sqrt{50} \qquad \text{Eq.2}$$

During the preliminary load-pull measurements, V1 and V2 are a function of the load condition (Zload) and the instantaneous RF source power level, as noted by Pavs in Figure 13. For a given load impedance, the 2 variation laws noted $f1$ and $f2$ are respectively determined by Eq.3 and Eq.4.

$$V1 = f1(Pavs, Zload) \qquad \text{Eq.3}$$

and

$$V2 = f2(Pavs, Zload) \qquad \text{Eq.4}$$

Figure 14 shows the 2 variation laws obtained for MXE at the top, and MXP, at the bottom. The graphs on the left show the input RF magnitude (at the input access of the DUT – V1) as a function of the raw input power (at the RF source level). The blue dots are the different pre-RF pulse levels chosen for MXE load impedance. As we can see, there are 4 levels noted from P_{RF1} to P_{RF4}. On the right, the input RF magnitude (V1) is plotted as a function of the output RF magnitude (at the output access of the DUT – V2).

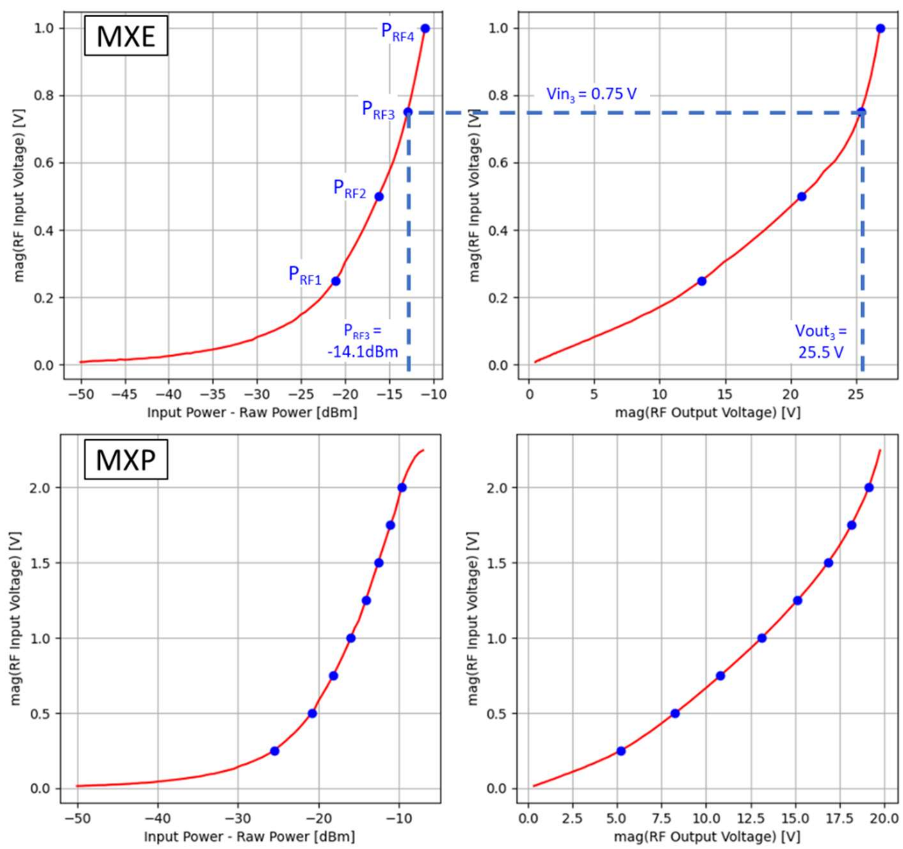

Figure 14 : Variation laws for determining the pre-RF pulse levels for MXE (top) and MXP (bottom) load impedances.

Based on these graphs, the three-level pulse measurement sequence drives the relationship between each pre-RF pulse level (P_{RFX}), the maximum input (Vin_X) and output ($Vout_X$) pulse DC level excursions around the application quiescent bias point.

For example, at a given bias point (Vgs0, Vds0), at MXE load impedance, for a pre-RF pulse level of -14.1 dBm (P_{RF3}), the input DC excursions will be Vgs0 +/- 0.75 V (Vin_3) and the output DC excursions will be Vds0 +/- 25.5 V ($Vout_3$).

Interestingly, the variation laws are different for MXE and MXP load impedances. As shown in Figure 14, three IV networks are measured using the same quiescent bias point Vgsq = Id-AB (100 mA), Vdsq = 30 V. The IV curves in blue are obtained without a pre-RF pulse. The IV curves in red and purple colors are obtained with the pre-RF pulse, respectively, at MXE and MXP load impedances. For clarity, some intermediate curves (Vgs) are not shown.

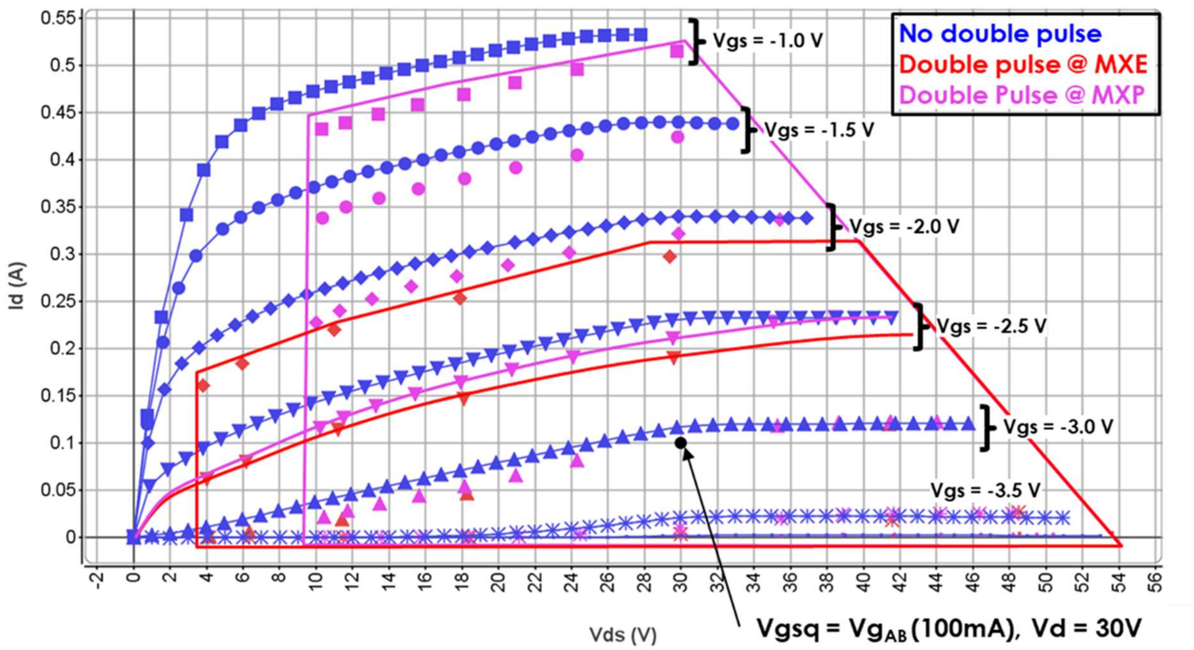

Figure 15: Comparison of pre-RF pulse measurements for different load impedances.

As observed, for the same Vgs curve, the output current at MXE is lower than the one measured for MXP. This is related to the trap level being higher when the transistor is loaded at MXE. This can be explained by the fact that the RF load line's swing at MXE goes in a higher Vds peak voltage area, which triggers the drain lag phenomena more significantly. This comparison put into evidence the importance of the load conditions chosen for the IV measurements and their impact on the traps' state of charge.

The technique presented in this document makes it possible to obtain a realistic IV measurement by considering the effects of traps in conditions close to those of the final application.

Therefore, it allows better expertise of traps' impact on a particular application's final performance.

Also, these measurements can be used to model the component's output current source without adding a trap model, provided that the model is only used for a similar quiescent bias point and load impedance.

To highlight the benefit of this new measurement methodology, a benchmark of the time spent to extract and refine compact models against load pull measurements has been done. Two sets of data have been used. The first one comprises basic pulsed IV measurements provided by a double-level pulse IV system. A pre-RF pulse measurement system used on top of a VNA load pull bench provides the second set of measurements.

The time needed to refine the model in both conditions is illustrated in Figure 12.

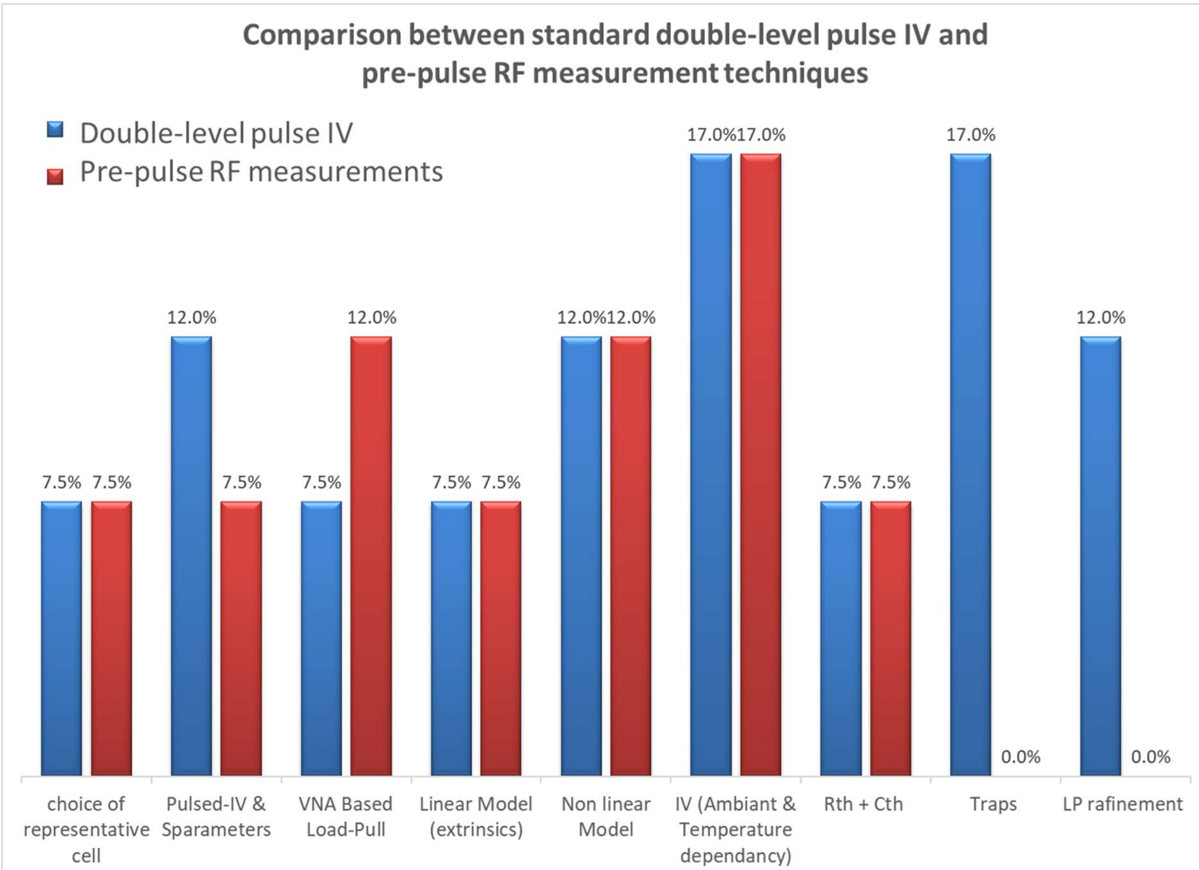

Figure 16: Benefits provided by the Pre-RF pulse measurement for compact model extraction

This graph provides the completion times of each step of the measurement and extraction process of a standard compact model in blue and based on the new double-pulse measurement technique in red. In both cases, the standard process is used as a reference, thus making it possible to calculate the estimated gain brought by the new method.

Initially, this graph makes it possible to realize the critical stages of the standard process. These steps are:

- IV measurements and S parameters (12%)
- Extraction of the nonlinear model (12%)
- Extraction of the parameters of the output current source and the diodes at room temperature and their dependencies according to the temperature (17%)
- Extraction of the trap model(s) (17%)
- Optimization of the model to fit large-signal measurements (12%).

These steps represent the majority of the development process of a compact model, with a total of 70% of the efforts in measurement and modeling.

With the new measurement and extraction method, the measurement time remains essentially the same because the IV measurements necessary for the extraction of the output current source, usually done in a 50 Ohm environment, are now done using the pre-RF pulse measurement method using a “VNA Based Load-Pull” system.

If the model is intended to be used at a single bias point, developing the trap model(s) is no longer mandatory. Similarly, optimizing the model on large-signal data is drastically reduced, given the perfect alignment of the IV and large-signal measurements.

Consequently, the pre-RF pulse measurement method proposed in this work may allow a significant reduction in the development time of a compact model by around 30%.

Suppose the model needs to be validated for different bias points. In that case, this measurement technique can be repeated to minimize the time spent to extract a trap model that impacts the IV curves' behavior.

To illustrate the interest in the proposed measurement technique, another application note will present a benchmark of the two methodologies. The study will show the RF performances of 2 models: one extracted using the usual set of measurement data and the standard extraction process. The second one uses pre-RF pulse IV measurement. These 2 models will be compared against large-signal measurements obtained from a “VNA-based load-pull” system.

Chapter 5 : Architecture of the measurement bench

The architecture of the pre-RF pulse measurement system is shown in Figure 13.

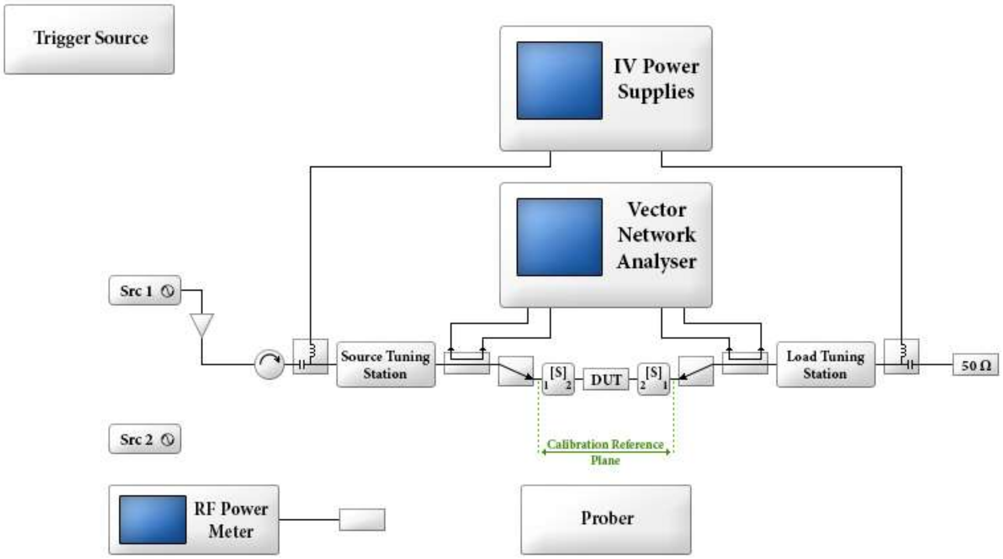

Figure 17: Measurement bench architecture

A “VNA-based load-pull” measurement setup combines the pulse IV and the pre-RF pulse. The bench consists of an AMCAD AM3200 system for generating and measuring pulsed DC signals (IV Power Supplies) and a pulsed RF source (Src 1) to generate the pre-RF pulse. The source (optional) and load impedances are controlled using tuners. Also, a Vector Network Analyzer (VNA) measures the incident and reflected waves to determine the pre-RF pulse variation law.

It should be noted that this bench can be used to perform small and large-signal measurements, achieving almost all the measurements necessary for the extraction and validation of the model. Finally, the measurement conditions presented in this document are identical to the large-signal measurements used to validate the model, thus guaranteeing good consistency of the data used for both the extraction and validation steps of the model.

From a software resource point of view, the bench is controlled using the IVCAD software platform and its various modules, as detailed in Table 2.

IVCAD Module	Nom	Description
MT930B1	BASIC VISUALIZATION	Visualization IV, SPAR, Load-Pull
MT930B2	ADVANCED VISUALIZATION	Advanced visualization IV (time domain), SPAR (stability), Load-Pull (Extended viewer, time domain, magic source pull)
MT930C	VNA LOAD-PULL	“VNA-Based Load-Pull” measurement provides access to amplitude and phase information of the incident and reflected waves. This information is essential for validating the compact model under conditions close to the final application.
MT930C2	Double Pulse Meas. Add-On	Configuration tool for Double Pulse measurement
MT930J	PULSED IV	Pulsed IV characteristics measurement
MT930K	PULSED S-PARAMETERS	Pulsed S-Parameters measurement
MT930L	SCRIPTING LANGUAGE	Enable the automation between pulse IV and Pre RF pulse Load Pull measurements.
MT930P	MEASUREMENT TOOLBOX	Toolbox for measurement data processing

Table 2: IVCAD modules necessary to perform pre-RF pulse IV measurement.

Conclusion

In conclusion, this new measurement methodology uses a variable power-calibrated pre-RF pulse associated with a sequence of pulsed IV measurements following the evolution of the RF envelope signal. The pre-RF pulse dynamically controls the trapping state of charge to obtain more accurate IV characteristics of the transistor under realistic operating conditions.

This patented technology uses a "VNA-based Load-Pull" measurement system. Therefore, the measurement conditions used for model extraction and validation are perfectly aligned, reducing the number of iterations to fit the model on small- and large-signal measurements.

Such IV characteristics provide invaluable information to extract a better model of the transistor output current source and thus might save time during compact model extraction and validation phases.

Finally, no additional trap model is required (for a given application bias point and load impedance). This technique can be used within the framework of modeling transistors used in high-efficiency power amplifiers like the Doherty amplifiers. In this case, the measurement process can be done for the Main and Peaking stages under the appropriate bias and load conditions, respectively (Class AB, MXP) and (Class C, MXE).

References

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