

# From T-CAD simulations to large signal model for GaN RF device

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**Abstract**— The large-signal RF power performance of an AlGaIn/GaN High Electron Mobility Transistor (HEMT) is studied starting from technology computer-aided design (TCAD) simulations in terms of DC characteristic and S parameters. A clear procedure of physical parameters calibration is described. Trapping effects and GaN mobility model are included. Good agreement between simulations and measurements is reported, giving a meaningful starting point for the large signal model with the aim to optimize the efficiency of GaN HEMTs. The large signal model extracted is crucial to predict the device performance and give an essential contribution for the device maturity at industrial level.

**Keywords**— Gallium nitride (GaN), heterojunction field-effect transistor (HFET), high electron-mobility transistor (HEMT), parameter extraction, large-signal modeling, T-CAD, simulations

## I. INTRODUCTION

GaN-BASED based devices have huge field of application for power amplifiers, millimeter-wave integrated circuits (MMIC) [1], next generation information communication systems [2] and power switching. The excitement arises from GaN's basic materials properties of high breakdown field, good mobility, high carrier density, and good thermal conductivity. GaN technologies are attractive for base station equipment to power device industry and automotive.

The circuits need an accurate description of the High-Electron-Mobility-Transistor (HEMT) in the form of a reliable and accurate large signal model. Currently, GaN devices large-signal models useful for power efficiency prediction are typically based on parameters obtained from measurements and device physics [3-4]. It is an added value to predict efficiency using technology computer-aided design (TCAD) simulations, which reproduce not only the morphology of the device, but also the physical phenomena involved. Device optimization using TCAD simulations is an invaluable instrument for GaN technology development, as 0 on power performance can be evaluated by TCAD to further improve available mature technologies. Unfortunately, the circuit and physical models for GaN-based devices are not well defined or calibrated. So, in this work we started suggesting a methodology that takes into account the GaN physical phenomena thanks to T-CAD simulations and then a Large signal model (LSM) will be extracted thanks to a full characterization of device under test (DUT). This is possible because we performed an accurate calibration of TCAD

physical models based on experimental measurements. The main target is to develop a circuit model for GaN-HEMT, in order to give useful contribution for the maturity of GaN technologies.

## II. DC CALIBRATION AND AC PARAMETERS EXTRACTION—TCAD ANALYSIS

### A. Device under test description

The device under examination is an AlGaIn/GaN HEMT on Silicon with a gate length (LG) of 0.5  $\mu\text{m}$ . The structure and device geometry are reproduced by TCAD simulation, the process flow was performed with ATHENA [6]. A two-dimensional scheme is reported in Fig. 1.

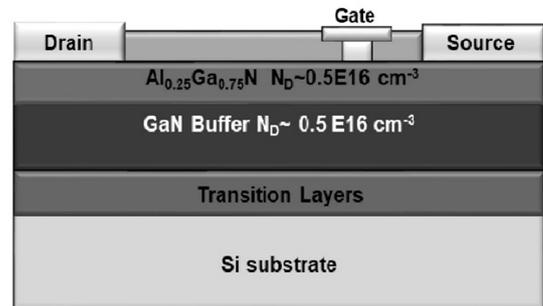


Figure 1. Two-dimensional scheme of AlGaIn/GaN HEMT under examination

### B. TCAD Simulation Setup

The two-dimensional device simulator used in this work was ATLAS by Silvaco Inc. [7]. Poisson's equation and continuity equations for electrons and holes are solved, and a drift-diffusion model is used to solve transport equations. Low mobility model is taken according to Albrecht model [8], while for high field condition we applied the Farahmand's theory [9]. As the gate is a Schottky contact, a barrier Schottky of 1.1 eV is considered. The spontaneous polarization and strain (piezoelectric effect) model are turned-on following the Ambacher model [10], so the two-dimensional electron gas (2DEG) has a density of  $1.08 \times 10^{13} \text{ cm}^{-2}$ . Surface states are included through a fixed charge density  $\sigma_{\text{int}} = 0.5 \times 10^{12} \text{ cm}^{-2}$ , uniformly distributed on the un-gated source-gate region and gate-drain regions within 1 nm from the AlGaIn surface and

passivation layer. Additional sources of charge, inside GaN-bulk, have been included. An acceptor-type trap can be either negative or neutral: it is neutral when empty and negatively charged (ionized) when filled (with an electron). In this work, we considered Carbon acceptor bulk traps distributed on all GaN-buffer layer, with an energy level of 0.9 eV above the valence [11]. The dynamic traps are modeled by a Shockley–Read–Hall recombination term, included in the continuity equations. Electron and hole capture cross sections of  $1 \times 10^{-15}$  cm<sup>2</sup> are used for all trap levels, which are consistent with other reported numerical simulations [12-13].

The paragraph *C* describes the calibration of TCAD models taking into account the measurements in DC conditions. While in paragraph *D* we report the GaN device AC behavior based with this new set of models' parameters.

### C. DC calibration

A good starting point for the TCAD simulation calibration parameters is the comparison with Transmission Line Method (TLM) measurements. These experimental approach on simplified structures gives the possibility to investigate the channel sheet resistance at AlGaIn/GaN interface and to study the 2DEG behavior. TLM emulates the regions outside the gate and allow to set the polarization charge in the source-gate and gate-drain regions. Therefore, the comparison between simulations and the experimental data of the TLM current curves for different contact distances allows to set the polarization model parameters. On the GaN HEMT device the experimental transfer characteristics report the drain current ( $I_d$ ) depending on gate voltage ( $V_g$ ) for a fixed drain bias ( $V_d$ ). The curves here reported are at  $V_d=1$  V and  $V_d=10$  V, respectively. From picture Fig. 2 a very good fitting in terms of drain current is obtained. This is mainly due to a proper calibration of the Albrecht's model. Also, the simulated conductance at  $V_d=10$  V (Fig. 3) is in strong agreement with the experimental one and this point is crucial to have a good prediction in terms of AC performance.

Finally, the DC outputs characteristics for different gate bias are reproduced. The experimental data are from pulsed  $I_d/V_d$  curve in order to avoid the self-heating effect, so from a simulation point of view no thermal model has been considered and all the results here reported are obtained in isothermal conditions (temperature  $T=300$  K). A direct comparison with the experimental DC curve is here reported at two different gate bias ( $V_g=0$  V and  $V_g=2$  V), see Fig. 4. The good match also for these DC conditions validate the mobility model setting and the physical phenomena considered in terms of traps and fixed charges at AlGaIn surface.

### D. AC parameter extraction

The GaN HEMT performances for RF applications are a crucial point for this technology, so TCAD simulations help to foresee the device behavior and further improve available mature technologies under particular electrical bias points, i.e. depending on frequency, different applied bias for gate and drain. So, it will possible to predict the physical limit of the device under test and, on the other hand, underline the best working conditions.

For these reasons we performed the AC simulations in terms of current gain,  $G_{MAX}$ , S parameters. This approach validate our models and we are more confident on the TCAD simulation outputs. In Fig. 5 and Fig. 6 we compared  $h_{21}$  and  $G_{MAX}$  parameters at  $I_d=20$  mA/mm and  $V_d=50$  V with

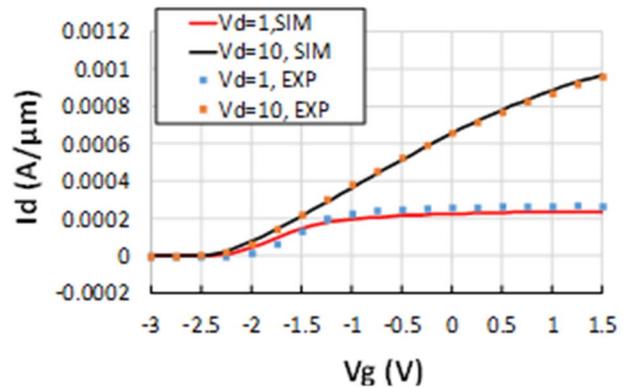


Figure 2. Experimental (symbols) and simulated (line)  $I_d/V_g$  curve for  $V_d=1$  V and  $V_d=10$  V.

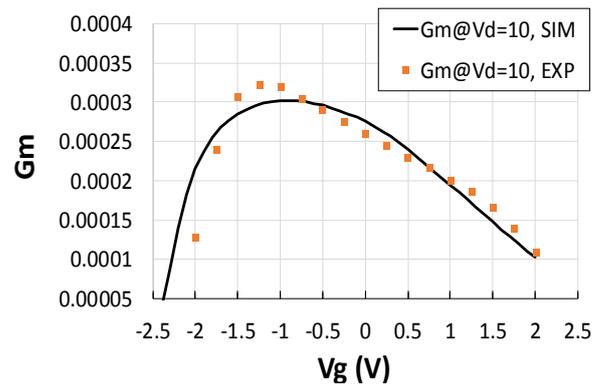


Figure 3. Experimental (symbols) and simulated (line)  $g_m$  curve at  $V_d=10$  V.

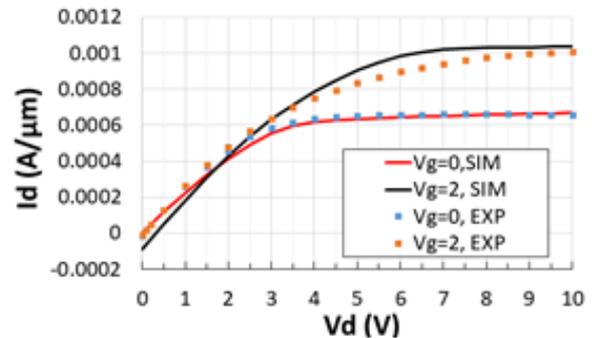


Figure 4. Experimental (symbols) and simulated (line)  $I_d/V_d$  output characteristics at different gate voltages  $V_g=0$ V (red) and  $V_g=2$  V (black).

experimental data measured on DUT. In this case we noticed a reasonable agreement and this represent a good starting point for the large signal model extraction.

A project with Virtual Wafer Fab by SILVACO was set [14]. It allows to run more simulations simultaneously, for different gate voltages, so as to have the S parameters varying either the frequency and drain current. We selected the  $V_g$  range from -3 V to 3 V with a step of 1 V, and at each gate bias point the AC simulation was performed for  $V_d$  from 0 V to 100 V and frequency from 1 MHz up to 20 GHz for a total number of 61 different running simulations. VWF is designed for a convenient use of process and device simulation tools and to perform large, simulation-based design studies [14].

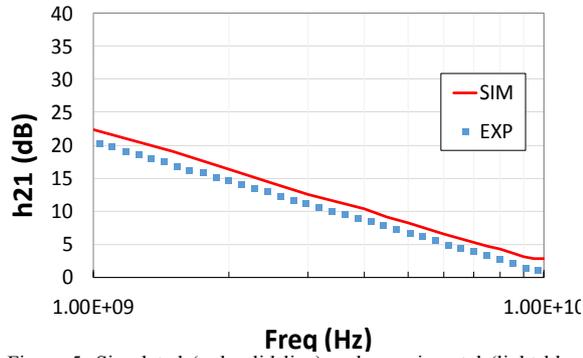


Figure 5. Simulated (red solid line) and experimental (light blue symbols) current gain  $h_{21}$  depending on frequency at  $I_d=20$  mA/mm and  $V_d=50$  V

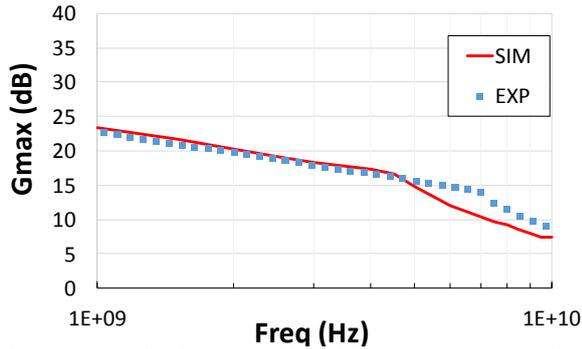


Figure 6. Simulated (blue solid line) and experimental (yellow symbols)  $G_{MAX}$  parameters depending on frequency at  $I_d=20$  mA/mm and  $V_d=50$  V.

### III. LARGE SIGNAL MODEL

Within simulations, in order to evaluate the RF performances of devices, the extraction of electrical nonlinear model that work in large signal conditions too is mandatory. Starting from TCAD Simulations in terms of DC characteristic and S parameters a large signal electrical model was extracted and load-pull simulations have been performed. Thanks to that we can extract RF performances in terms of gain, power and efficiency.

#### A. Model extraction

In this section we describe briefly the large signal model extraction starting from TCAD simulations. The picture Fig. 7 represents the electrical scheme used.

As first step the TCAD simulations S-parameter, for a huge number of bias points, were used to extract the small signal models. Each parameter belongs to model, the nonlinear  $I_{ds}$ , gate-source ( $C_{gs}$ ), gate-drain ( $C_{gd}$ ) and drain-

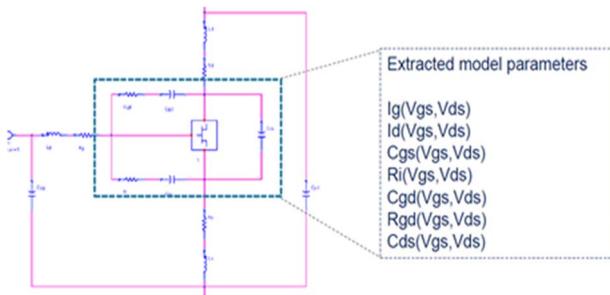


Figure 7. Large signal model scheme

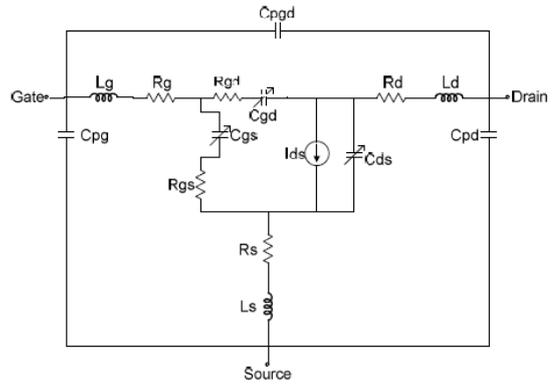


Figure 8. Small signal model scheme

source ( $C_{ds}$ ) capacitances, gate-source ( $R_{gs}$ ) and gate-drain ( $R_{gd}$ ) nonlinear resistances depend from gate and drain voltage instead parasitic package resistances, inductances and capacitances are constant. The Fig. 8 represents the small signal model used to extract large signal model.

At the end of procedure, we obtain small signal model one for each considered bias point. Using the interpolating function implemented in the electrical simulator, a look-up table non-linear model able to realize small and large signal simulations is realized.

#### B. DC and S parameter comparison

In order to evaluate the accuracy of the extracted nonlinear GaN model, a comparison between TCAD simulation and simulation realized with the electrical GaN model has been done. A comparison in terms of DC characteristic and S parameter considering a huge number of bias points has been done, as well illustrated in Fig. 9 and Fig.10.

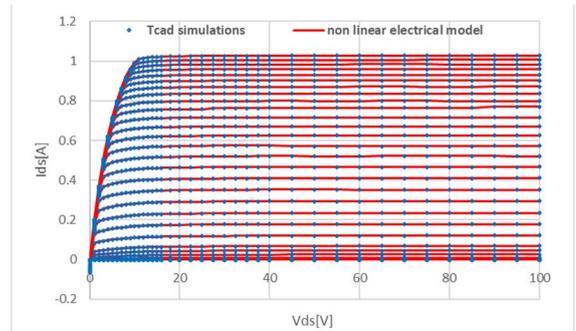


Figure 9. DC comparison: T-CAD simulations (blue symbols) and non-linear electrical model (red line).

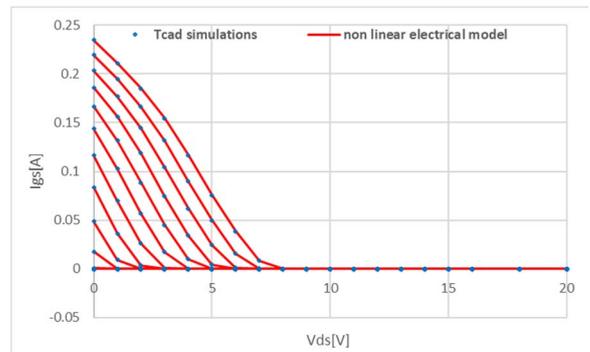


Figure 10.  $I_d/V_g$  comparison T-CAD simulations (blue symbols) and non-linear electrical model (red line).

Regarding the S parameters comparison, we consider the points reported in Fig. 11. Markers represent the bias points that we consider for the S-parameters comparisons. S parameter has been simulated from 100 MHz to 10 GHz. As shown in Fig. 12 and Fig 13 a good agreement between TCAD simulations and nonlinear electrical model has been obtained.

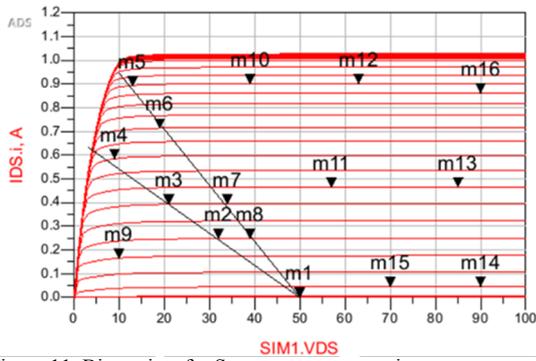


Figure 11. Bias points for S parameters comparison.

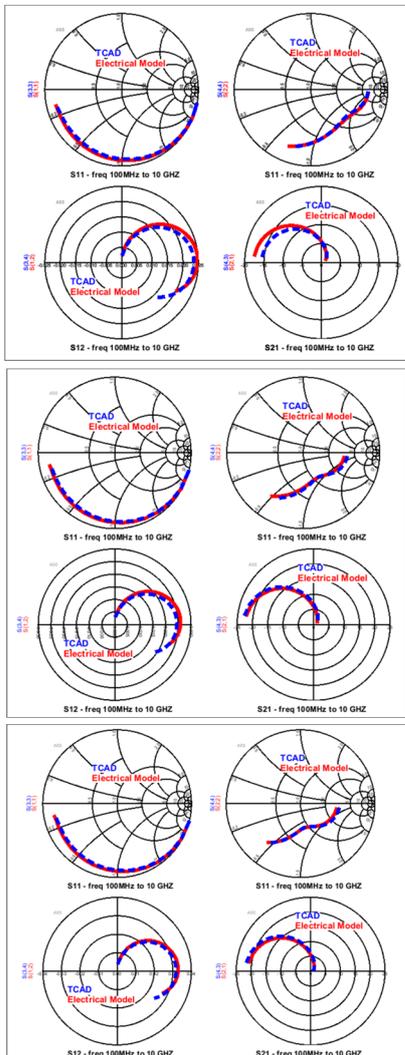


Figure 12. S parameters comparison: blue TCAD simulations, red non-linear electrical model – from m1 to m3 markers.

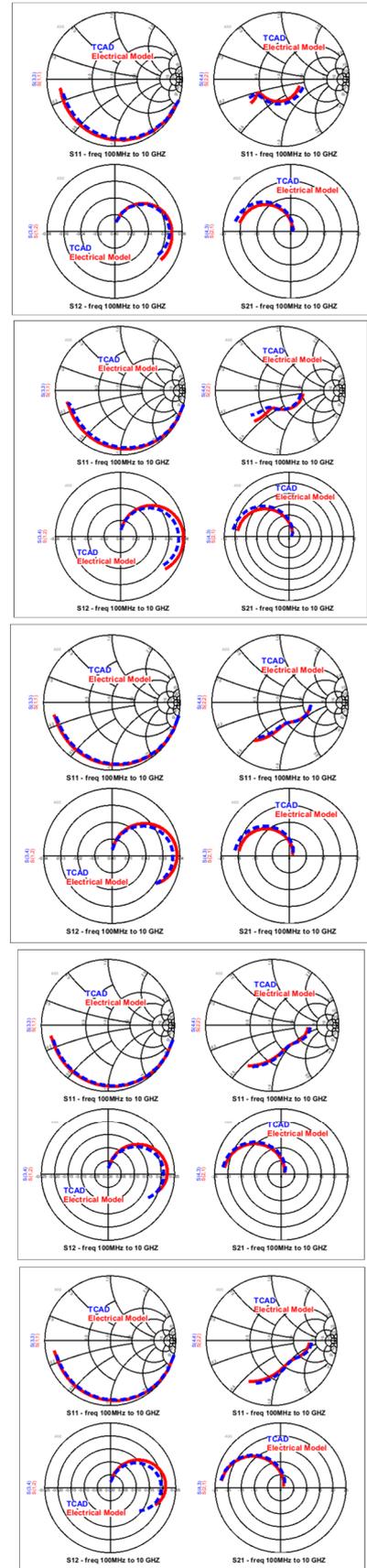


Figure 13. S parameters comparison: blue TCAD simulation, red non-linear electrical model – from m4 to m8 markers.

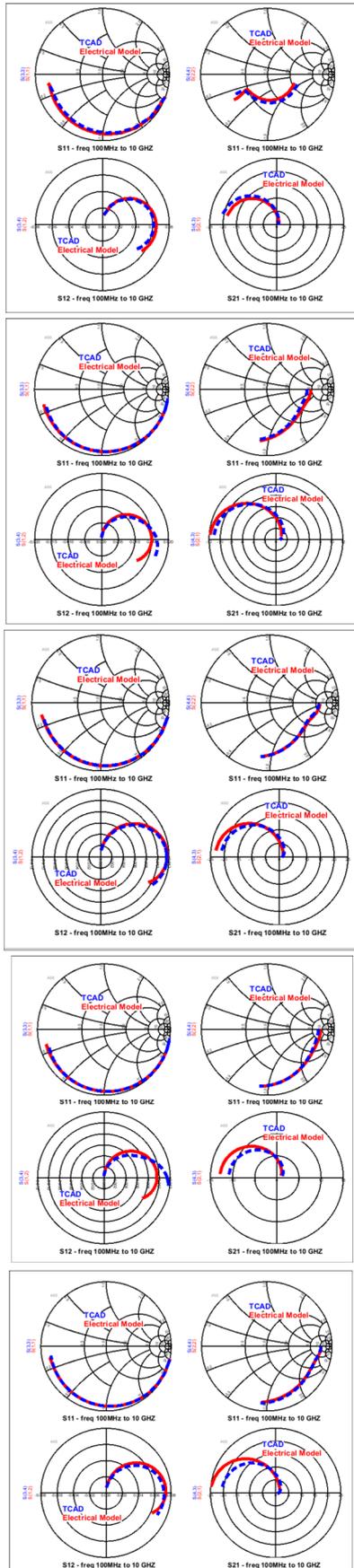


Figure 14. S parameters comparison : blue TCAD simulation, red non-linear electrical model – from m9 to m13 makers.

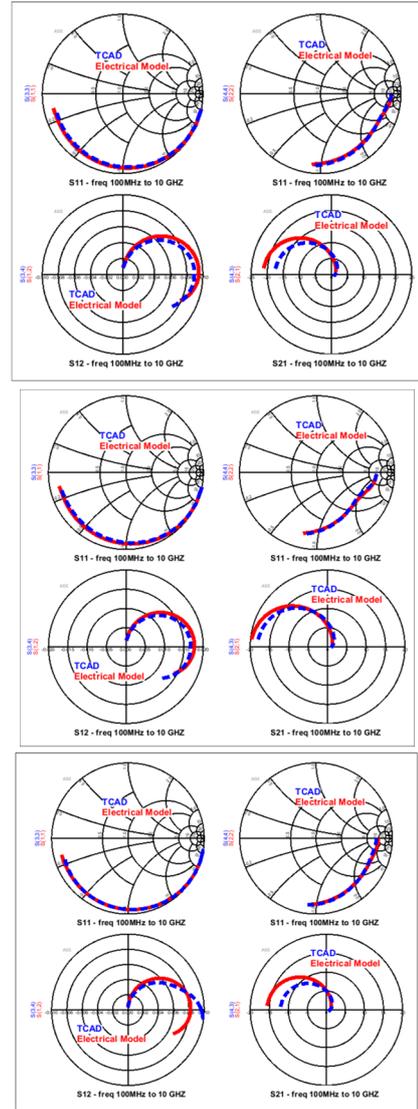


Figure 15. S parameters comparison: blue TCAD simulations, red non-linear electrical model) –from m14 to m16 makers

### C. Large Signal Simulations

In this section we show large signal simulations based on nonlinear electrical model. To evaluate the RF performances of devices, in terms of transducer gain, drain efficiency and output power, load-pull simulations has been performed (Fig. 16).

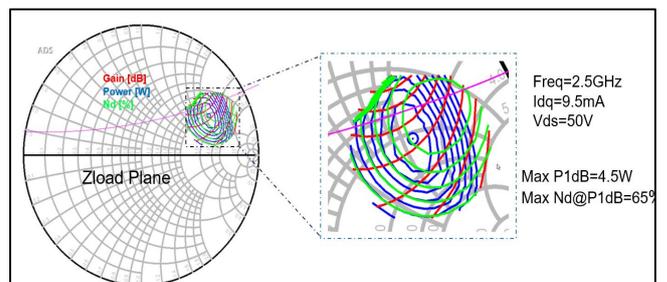


Figure 16. Load pull simulation at drain voltage  $V_d = 50$  V and frequency 2.5 GHz.

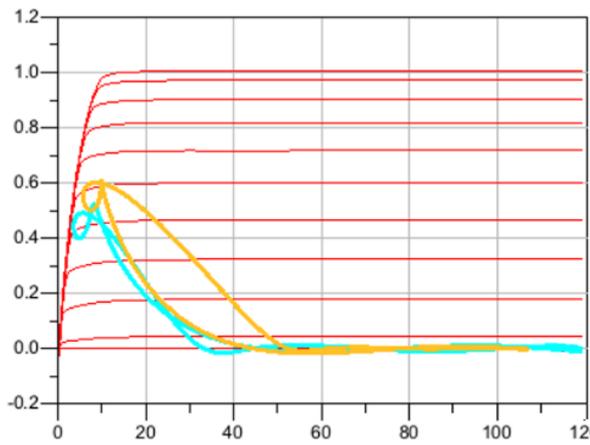


Figure 17. Load lines for max Power (orange) and max efficiency (light blue) tuning.

The best tuning for max P1dB and max efficiency for P1dB was found, and load line curve was observed too. We can evaluate the load line curves for all considered load impedances, in order to predict which load impedance provide a load-line dangerous for drift phenomena (Fig. 17).

#### IV. CONCLUSIONS

An accurate and reliable T-CAD and large signal models are crucial for device optimization and to evaluate the device performance. We have demonstrated that TCAD is an precious instrument for predicting the RF power performance of GaN HEMTs, with some further investigation for future development. A robust and simple parameter extraction procedure offers confidence that the performance of transistors having different layouts, geometries or process variation can be well foreseen before fabrication.

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