# INTRINSIC AND EXTRINSIC PARAMETERS OF GALIUM - NITRIDE TRANSISTORS

**Erik Herceg**

Doctoral Degree Programme (3), FEEC BUT

E-mail: herceg@feec.vutbr.cz

**Abstract**: This article deals with the extrinsic and intrinsic parameters of the Galium-Nitride RF transistor. These parameters are essential in any design of large-signal analysis of RF amplifiers. Package parasitics are the biggest problem of integrated circuits (ICs), especially at high frequencies. Each IC package gives unwanted parasitics to the primary function of the IC. The analysis of these package parasitics can be performed by the transistor manufacturer, which provides a non-linear model of the transistor, where parasitics elements are separated from the transistor. With these separated package parasitics, the highest efficiency, power output, and accurate harmonic termination can be achieved. The main purpose of this article is to describe these problems.

**Keywords**: GaN Transistor, Waveforms, Extrinsic, Intrinsic, Load-Pull, Source-Pull, Radio-Frequency, Transistor Parasitics

## 1 INTRODUCTION

Wireless and RF technology is closely connected to our everyday lives, so the development of wireless technologies is important. Every gateway, transceiver, jammer, radars, and most of the wireless electronic devices have their RF power amplifier. Nowadays, achieving of high efficiency belongs between priorities. The most used amplifiers classes for telecommunications are class-A and class-AB. These amplifiers are inefficient but have the best distortion results. These amplifiers are usually operating under the P1dB region to avoid higher harmonics. Other high-efficiency amplifiers are overdriven to saturation region because higher harmonics are used to shape the waveforms, and with the help of these harmonics, the efficiency increase. On the other hand, the harmonics are higher, and distortion reaches really high levels. This can be minimized by the use of Digital PreDistorters (DPD), but they consume a lot of energy when applied to the final device. The DPD technique is useful when applied to high-power RF amplifiers, where the power consumption of FPGA is neglectable.

With the expansion of GaN transistors and the accuracy of non-linear models, the development of high-efficiency amplifiers become more effective and more accessible. For high-efficiency amplifier design, the non-linear model is necessary. Without this model and separate parasitics elements of the package, the amplifier with the required parameters would be really difficult to design. For S-parameters, efficiency can not be affected. Amplifiers such as class-E, class-F, and for example, class-J are important to design, with this non-linear model, because the waveform engineering, can not be applied. Waveform engineering is a process where the designer compares the shape of the intrinsic waveforms. The correct function of the defined class can be determined from these current and voltage waveforms. Every class of amplifier has its defined ideal waveforms, and with the proper output impedance matching, these intrinsic waveforms can be verified. Not only waveforms but also the IV curves and the load-line must be simulated inside the package. The difference between intrinsic and extrinsic parameters is fundamental in the design of high efficiency and high power amplifiers.

Problems of parasitic transistor elements is a well-known thing. In radio-frequency, the separated parasitics from the core of the transistor is the issue of last years. These parameters are usually provided by the manufacturer, but there is also a way how these parasitics can be extracted [1]. Extracting these parameters is time-consuming, but it is certain that there is a way to find out. However, the only problem is the need for advanced Y or X parameters. One of the biggest issues is a walkaway of a knee voltage. This is the specific parameter of GaN transistors, and this should be taken into account [2]. The thermal profile of GaN was presented in [3] and its influence to drain current and was compared on-die transistor. Different types of heatsink materials and heat conductors were measured. The behaviour of this issue with GaN rises with the temperature and working time of the GaN. An example of waveform engineering and its problems was presented in [4].

## 2 INTRINSIC AND EXTRINSIC I-V CURVES

The first measurement, where intrinsic and extrinsic parameters must be separated, is the I-V curves and its load-line. In ideal measurements, the load-line is the line between two points, in which the first point is addressed by knee voltage and the maximum drain current, and the second is defined by the user. The second point is always defined at zero drain current, but the drain voltage can be set at different spots – breakdown or usually the maximum drain voltage.

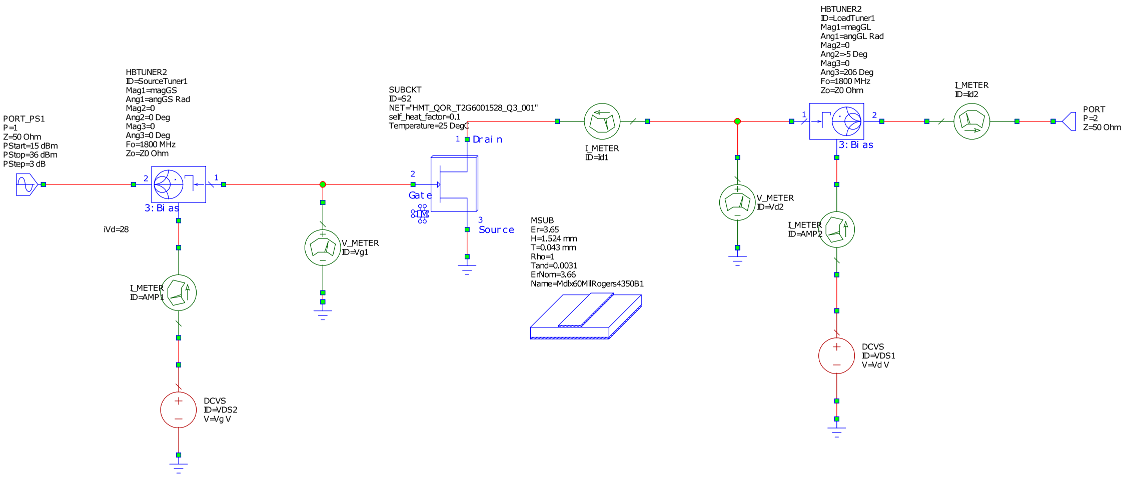

**Figure 1:** Simulation set-up for I-V curve simulations.

Figure 1 shows the simulation set-up of the load-line. Impedance tuners are connected to the input and output, where the source and load impedance can be set. These values are measured in source and load-pull simulations. From the shape of the load-line, the correct impedances can be set. In the figure, the non-linear device is connected between two tuners. In this situation, the optimum $V_{DS}$ was 28 V, and the bias point set by quiescent drain current was 2 mA, at a gate voltage of approximately -3.38 V. As quiescent point, the quiescent point of class-B was chosen, where the conduction angle was at 180°, what is a fundamental condition for this class of operation.

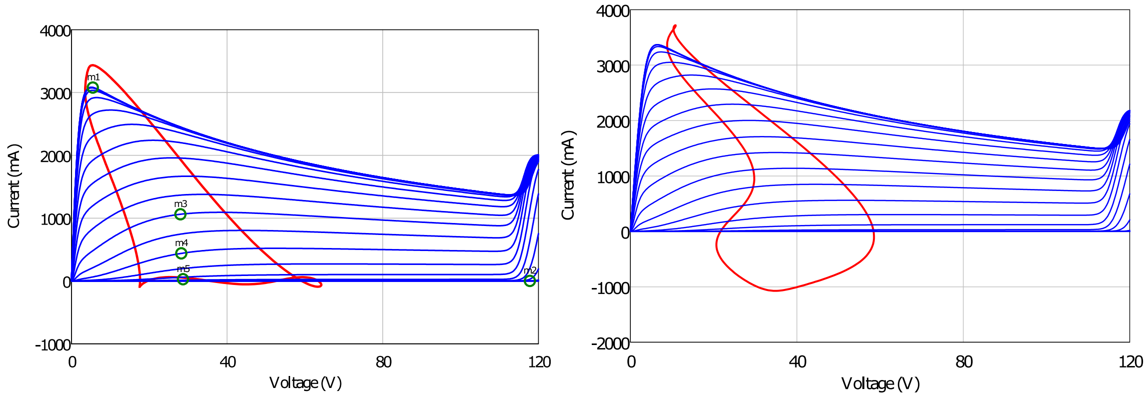


**Figure 2:** The comparison of intrinsic (left) and extrinsic (right) I-V curves (blue) and its load-line (red) for the class-B amplifier.

Figure 2 shows the difference between extrinsic and intrinsic I-V curves of the transistor. The left picture shows intrinsic I-V curves for 27 dBm at the input of 18W T2G6001528 GaN transistor from Qorvo. Marker m1 shows the knee voltage of the I-V curve; marker m2 specifies the break-down voltage of the transistor. Other markers show the basic classes of the amplifier. Both pictures show the unoptimized load and source impedance, so the lines are not ideal. The main difference is the negative swing of extrinsic load-line due to the effects of the parasitic of the package, which can also be observed on the voltage and current waveforms.

The basic calculations of the load-line can be calculated with classical DC calculations. The optimum load resistance [5]:

$$R_{L\_OPT} = \frac{2 \text{ x } V_{OPT}}{I_{MAX}} \; [\Omega] \tag{1}$$

, where $R_{L\_OPT}$ is optimum load resistance, $V_{OPT}$ is optimum voltage – drain voltage of quiescent point, and $I_{MAX}$ is maximum drain current. The value of the optimal resistance can also be calculated with the help of the desired output power [5]:

$$R_{L\_OPT} = \frac{1}{2}\left(\frac{V_R}{V_{CC}}\right)^2 \frac{V_{OPT}^2}{P_{OUT}} \; [\Omega] \tag{2}$$

, where $V_R$ is the value of voltage amplitude across the load resistance, and $P_{OUT}$ is the required value of RF output power, and $V_{CC}$ is optimum drain voltage.

## 3 LOAD PULL SIMULATIONS

As indicated above, load-pull curves also have a significant influence, when simulating intrinsic or extrinsic curves. The principle of load-pull is to iteratively change source and load impedance at the input, respectively, at the output of the transistor. While changing the impedances, the curves are changing its positions on the Smith Chart, and the correct result is, when the output power, PAE or other simulated parameter achieves similar values. With stabilization circuits, the position of the final curves is changing, so it's better to do it after the stabilization of the amplifier.

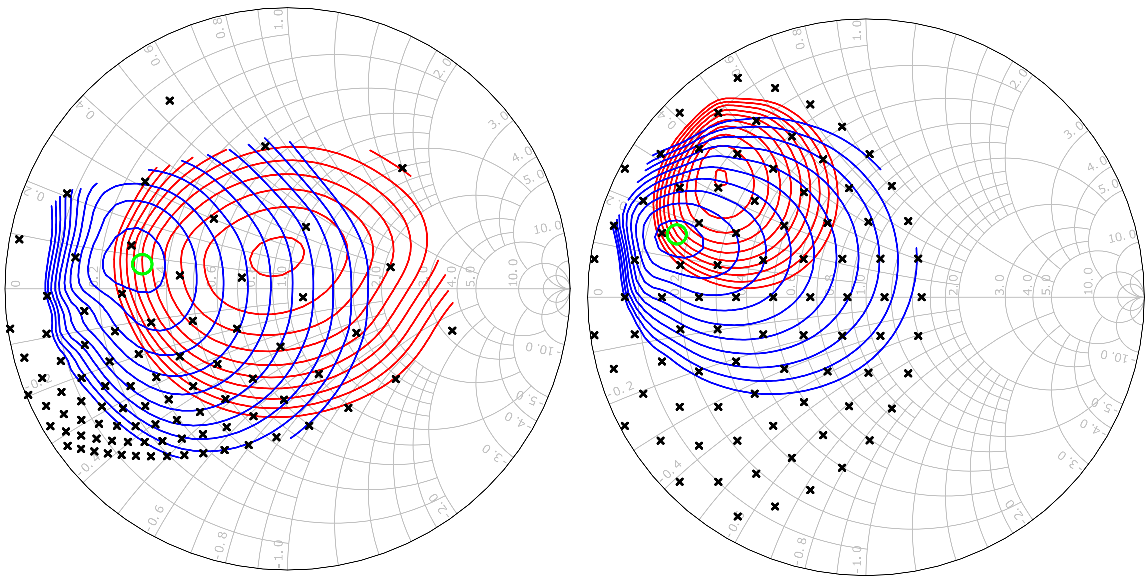

**Figure 3:** The comparison of intrinsic (left) and extrinsic (right) load-pull simulations. The red curves represent PAE and blue the output power $P_{OUT}$.

Again as in the first example with I-V curves, the load-pull measurements are also different from the change of impedance measurement points. Load – Pull simulations are shown in Figure 3. For comparison of actual achieved values, the intrinsic maximum power-added efficiency (PAE) achieved 76 %, and the maximum PAE achieved this value at load impedance equaled to 42.5 + j*0.12 Ω, instead of the extrinsic maximum PAE was at 14 + j*11 Ω and was about 70 %. The simulated frequency was 1800 MHz at Rogers 4035b.

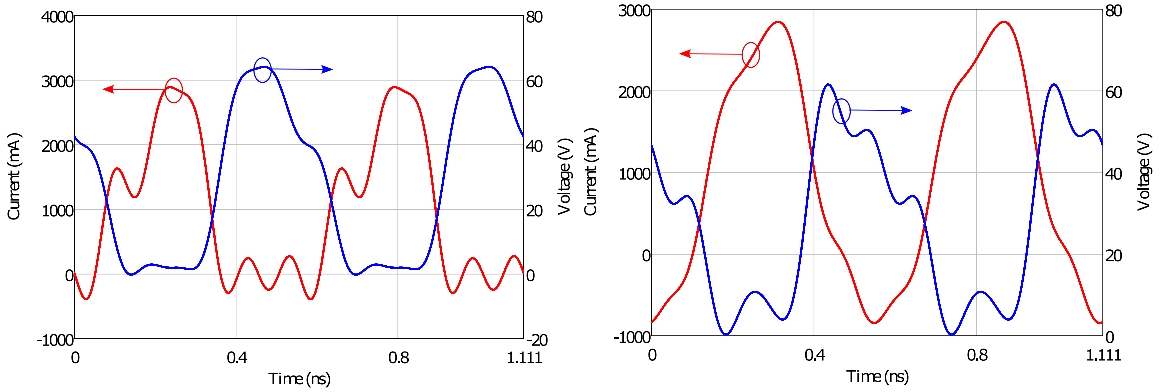


**Figure 4:** The comparison of intrinsic (left) and extrinsic (right) waveforms simulations. Drain $I_D$ waveforms are represented by red color, drain voltage by blue.

The last comparison is devoted to intrinsic and extrinsic waveforms. Figure 4 shows the main difference. While in the left graph, the obvious class-F amplifier waveforms can be spotted, in the right picture is distorted with parasitics of the package. The class-F waveforms are shaped, by reflected higher, mostly third harmonic, which is terminated to high impedance. The reflected wave has to be set-up correctly to achieve an increase of the PAE. For the waveform engineering processes, the many iterations of choosing, the right impedance for fundamental, second, and third harmonic. Without the intrinsic waveforms, where the bond wires and other parasitics elements are excluded, the amplifier design could not be correctly finished. Knowledge of ideal waveforms of all high-efficiency classes and behavior of the transistor can be applied to the correct function of the amplifier.

All package parasitics can be described with reactance and resistive components. Every part of the transistor has its package parasitics. At the input, the transistors parasitics are the parallel package capacitance $C_{PG}$, series gate inductance $L_G$ and series gate resistance $R_G$. The source also has its series $R_S$ and $L_S$ parasitics. The drain has the same as the gate ($C_{PD}$, $L_{D,}$ and $R_D$), but the values are different due to the width of the gate at the wafer level.

## 4 CONCLUSION

This article brought a basic comparison between extrinsic and intrinsic parameters of transistor. The impact of parasitics on fundamental parameters of the transistor was presented. Fundamentals of waveform engineering were also presented. Basic and main simulations, where these parasitics have the most significant influence on functionality, were simulated and described. Between these simulations, all non-linear simulation can be covered as are: harmonic balance, load-line, load, and source pull simulations. Without the intrinsic parameters, this novel design process could not be applied to RF power amplifiers design.

## ACKNOWLEDGMENT

The presented research was supported by the Internal Grant Agency of Brno University of Technology project no. FEKT-S-20-6526.

**REFERENCES**


[1] Reynoso-Hernandez, J. A., Jaqueline Estrada-Mendoza, M.C. Maya-Sanchez, M. A. Pulido-Gaytan, J. R. Loo-Yau, J. E. Zuniga-Juarez a Juan Luis Del Valle-Padilla.: A new method for extracting Ri and Rgd of the intrinsic transistor model of GaN HEMT based on extrema points of intrinsic Y-parameters. 2015 IEEE MTT-S International Microwave Symposium. IEEE, 2015, p. 1-3, ISBN 978-1-4799-8275-2

[2] Alim, Mohammad A., Ali A Rezazadeh, Norshakila Haris a Christophe Gaquiere.: Anomaly and intrinsic capacitance behaviour over temperature of AlGaN/GaN/SiC and AlGaAs/GaAs HEMTs for microwave application. 2016 11th European Microwave Integrated Circuits Conference (EuMIC), 2016, p.149-152, ISBN 978-2-87487-044-6

[3] Yazawa Kazuaki, Dustin Kendig, Justin Reiter a Ali Shakouri.: Intrinsic transient thermal response of GaN HEMT. IEEE MTT-S International Microwave Symposium (IMS), 2016, p 1 – 3, ISBN 978-1-5090-0698-4

[4] Mashad Nemati, Hossein, Alan L. Clarke, Steve C. Cripps, Johannes Benedikt, Paul J. Tasker, Christian Fager, Jan Grahn a Herbert Zirath.: Evaluation of a GaN HEMT transistor for load- and supply-modulation applications using intrinsic waveform measurements. IEEE MTT-S International Microwave Symposium, 2010, p. 509-512, ISBN 978-1-4244-6056-4

[5] Cripps, Steve C.: RF power amplifiers for wireless communications. 2nd ed. Boston: Artech House, 2006, ISBN 1596930187