Non-linear RF Modeling of GaN HEMTs with Industry Standard ASM GaN Model (Invited)

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***Abstract* — In this paper, we present nonlinear radio-frequency (RF) modeling of Gallium Nitride based high electron mobility transistors (GaN HEMTs) using recently selected industry standard surface-potential-based Advance SPICE Model (ASM) for GaN HEMTs. We describe the key features of ASM GaN model from user perspective. Non-linear RF modeling flow from DC to small-signal to large-signal characteristics is presented for GaN HEMTs.**

***Index Terms* —ASM GaN, GaN HEMTs, Non-linear models, GaN RF models, GaN simulations**

I. INTRODUCTION

Owing to their highly favorable properties of high sheet-charge density, high carrier mobility, wide band-gap, and high saturation velocity, Gallium Nitride based high electron mobility transistors (GaN HEMTs) have emerged as excellent devices for high frequency and high power applications [1]. As this device technology is progressing the need for accurate, fast, robust and predictive circuit simulations is becoming increasingly important. These simulations enable circuit designers to extract the best performance out of these devices in a time- and cost-effective manner. Compact models are at the heart of circuit simulations and are of paramount importance for optimal and efficient circuit design with GaN HEMTs. Indeed, development of compact models for GaN HEMTs is a very active research area with several types of modeling approaches proposed. These range from empirical [2], to neural network based [3], to threshold voltage based [4], to behavioral [5] to surface-potential-based [6], [7] models.

Compact Model Coalition (CMC) [8] under the umbrella of Si2 is an international consortium which standardizes compact models for promising semiconductor devices. CMC initiated the process to standardize a compact model for GaN devices in 2013 [9], [10]. After several rounds of meticulous industry standardization process at the CMC ASM GaN model has been selected to be an industry standard compact model for GaN RF and power devices.

Over the years we have presented several aspects of modeling GaN HEMTs with surface-potential-based ASM GaN model. Here we briefly describe the key fundamentals of this model, especially for the benefit of new model users. We also present new results on non-linear modeling of GaN HEMTs for DC, S parameters, and large signal RF characteristics. Model extraction flow of ASM GaN model is discussed. The paper is arranged as follows. In section II we describe the ASM GaN model. In section III we present the DC, S parameters, and large signal RF results with discussions on key aspects of extraction flow. In section IV we conclude the paper.

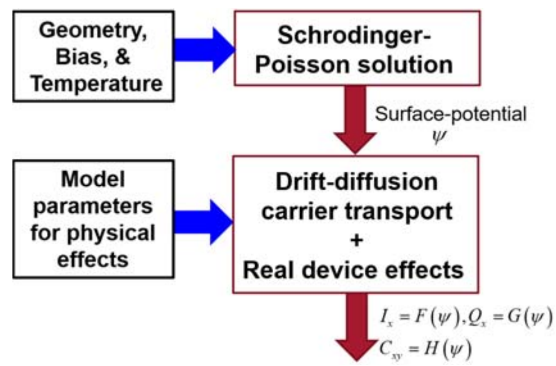

Fig. 1. ASM GaN model overview. Surface-potential (SP) is calculated with bias, temperature, and device geometry as inputs. All terminal currents (I_x), charges (Q_x), and capacitances between any two terminals (C_{xy}) are physically derived functions of SP.

II. MODEL DESCRIPTION

Compact model is a concise mathematical description of terminal characteristics of a device as function of the input conditions. For ASM GaN model this mathematical relationship is developed from device physics and can be visualized with Fig. 1. The surface-potential (ψ) is function of input bias, device geometry, and temperature. The terminal device characteristics are functions of the surface-potential. The functional forms are derived based on relevant device physics.

The development of surface-potential formulations for ASM GaN model originates with fundamental device physics governed by Schrödinger's and Poisson's equation in the quantum well of GaN HEMTs. This physics is distilled in form of an analytical surface-potential (SP) model in ASM GaN model [11], [12]. The developed analytical solution is highly accurate and has excellent mathematical smoothness or continuity. The later property is particularly important for good convergence in circuit

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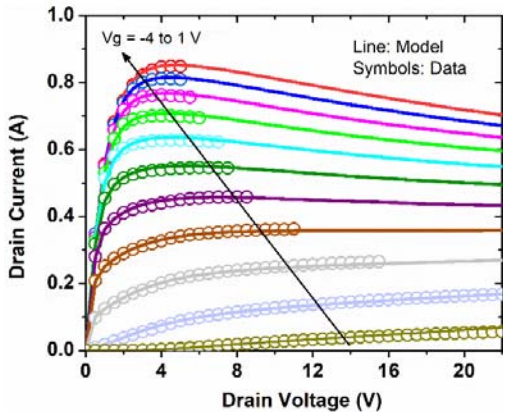
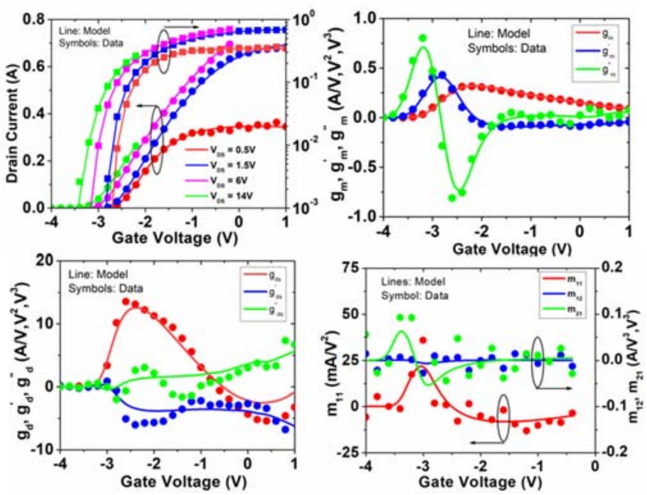
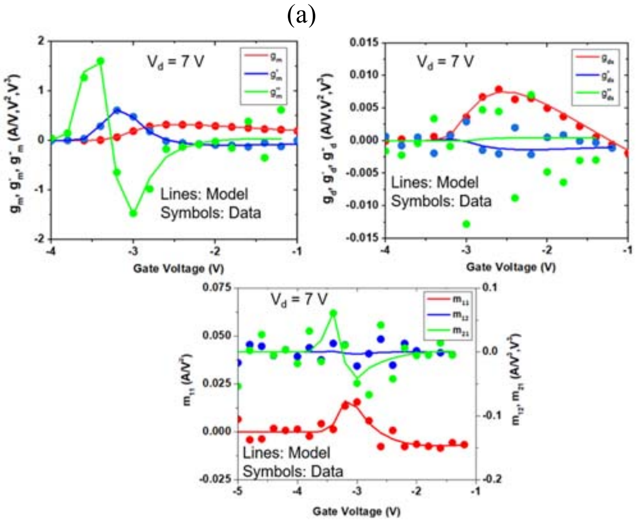


Fig. 2. Output characteristics of GaN HEMT modeled with ASM GaN model.



(a)



(b)

Fig. 3. Accurate modeling of transfer curves and higher order derivatives of I_d w.r.t V_g and V_d. Accurate model for all key derivatives responsible for nonlinear behaviour including g_m, g_m\`, $g_m$\`\`, $g_d$, $g_d$\`, g_d\`\` and the cross-terms m_{11}, m_{12}, m_{21} has been achieved with ASM GaN model shown here for (a) V_d = 5 V, and (b) V_d = 7 V.

simulations, especially for transient and harmonic balance simulations.

Surface-potential (SP) describes the two-dimensional electron gas (2-DEG) charge and its variation with input voltages. Drift-diffusion carrier transport physics is applied to derive the drain-current. ASM GaN model uses physical Ward-Dutton [13] charge partitioning scheme to divide the charges between the terminals. This partitioning scheme also ensures charge conservation in the model. Charge conservation is important for good convergence in circuit simulations. Furthermore, with accurate physical models for terminal charges, capacitances between any two terminals of the device can be calculated by,

$$C_{ij} = k\frac{\partial Q_i}{\partial V_j} \quad (1)$$

where sub-scripts i, j corresponds to terminals gate, source, and drain terminals, Q_i and V_i being the charge and the voltage associated with i-th terminal, and $k = 1$ if $i = j$ and $k = -1$ when $i \neq j$. All capacitances are thus physically-derived multi-input functions of bias voltages.

The physically derived core quantities are augmented with models of several real device phenomena occurring in the GaN device. These include: mobility-field, velocity saturation, non-linear access region resistance, models for field-plates, drain-induced barrier lowering, output conductance model, temperature dependence, self-heating, and trapping effects. These phenomena are accounted for in the final terminal current and charge formulations in a consistent manner as the current and the charge calculations use the same surface-potential.

III. RESULTS AND DISCUSSIONS

ASM GaN model in Verilog-AMS form is freely available to download from [14], [15]. This code has been successfully tested in multiple commercial circuit simulators. In this section we present and discuss model results and extraction flow for nonlinear RF modeling.

First step in developing nonlinear large signal RF model for GaN HEMTs with ASM GaN model is to model the DC characteristics of the device. In Fig. 2 and Fig. 3 we show DC model results for a commercial GaN HEMT. Equivalent results have been achieved for GaN HEMTs of varying sizes and from various sources. DC parameter extraction flow for ASM GaN model is similar to physics-based models used for silicon transistors such as BSIM-BULK [16] or PSP [17]. The flow starts with modeling of linear condition (V_{ds} ~ 0.1 V) transfer curve (I_d-V_g). First, the region near and below the threshold or the cut-off voltage (V_{off}) is modeled and then the high gate-voltage region. Parameters associated with carrier mobility, its electric field dependence, sub-V_{off} region current slope, and low-current access region resistance model are extracted from linear I_d-V_g characteristics. Next, saturation or high drain-voltage transfer curve is modeled. At high V_{ds}, V_{off} reduces due to the drain-induced barrier lowering effects and ASM GaN model has a model parameter for this effect. After near V_{off} modeling, the full saturation I_d-V_g transfer characteristics can be modeled using the parameters associated with velocity saturation effect, high-current non-linear access region resistance parameters, and thermal resistance. Thermal resistance can be obtained from three-dimensional thermal simulations or from specific measurements and the value can be directly put into the model. Next, the output characteristics can be modeled, and will need only fine adjustments with output conductance parameter, thermal resistance, and velocity saturation

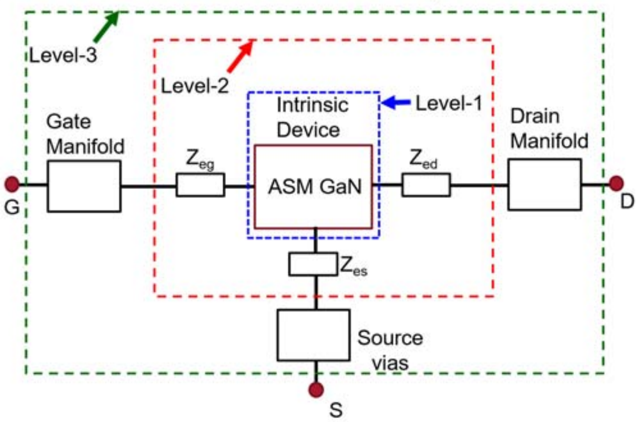


Fig. 4. Full RF non-linear model consists of three levels. Level-1 is ASM GaN model for intrinsic device, Level-2 are parasitic elements associated with electrode metal lines, and Level-3 is for manifolds and via.

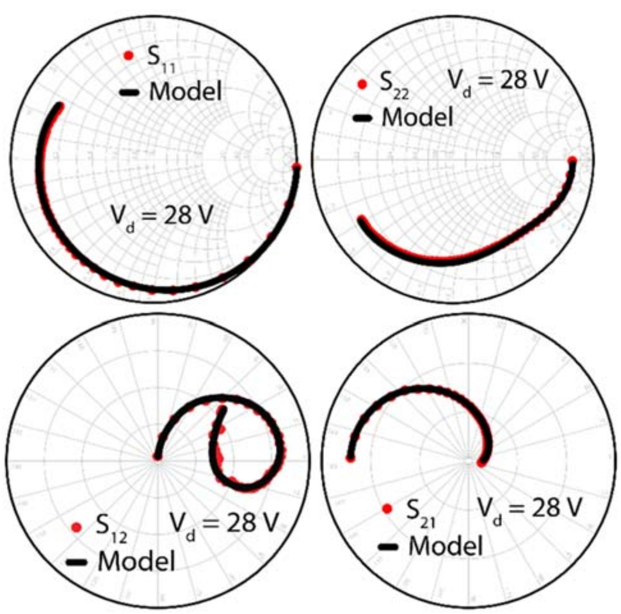


Fig. 5. Modeling S-parameters of GaN HEMT device from 0.5 to 25 GHz with ASM GaN model. Line: Model and Data: Symbols.

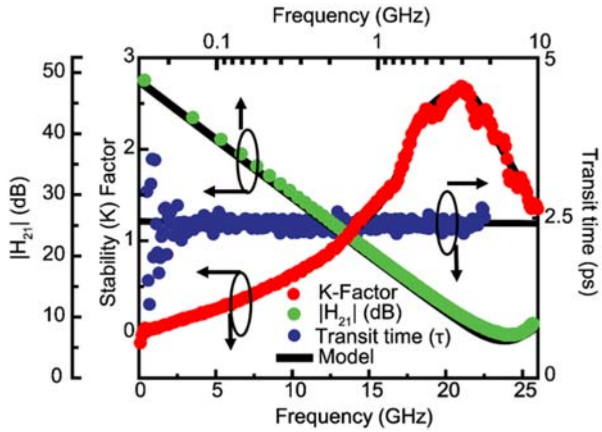


Fig. 6. Modeled stability factor (K), transit time (τ), and $|H_{21}|$ versus frequency for 2x200 μm GaN HEMT at 19.4 mA bias current and drain-voltage V_d = 28 V. $|H_{21}|$ uses logarithmic X-axis as the top of the chart.

parameters. In Fig. 2 and Fig. 3(a) and (b) we show that an accurate model of I_d and its derivatives w.r.t V_g and V_d in all the regions of device operation has been obtained. ASM GaN model also accurately models the region below the cut-off voltage. This region becomes important for high RF input drive conditions. In addition to I_d, its higher order derivatives w.r.t V_g and V_d i.e. g_m, g_m\`, $g_m$\`\`, $g_d$, $g_d$\`, g_d\`\` and the cross-dependences given by,

$$m_{11} = \frac{\partial^2 I_d}{\partial V_g \partial V_d}, m_{12} = \frac{\partial^3 I_d}{\partial V_g \partial V_d^2}, m_{21} = \frac{\partial^3 I_d}{\partial V_g^2 \partial V_d} \quad (2)$$

can be accurately modeled with ASM GaN model. The modeling of higher order derivatives is critically required for capturing the nonlinear behavior of the transistor [18].

After DC, high frequency behavior of the device or S parameters can be modeled. The parasitic elements associated with the actual layout and the position of the measurement reference planes needs to be included with the intrinsic ASM GaN model. The complete model can be visualized as shown in Fig. 4, consisting of three levels: level-1 is the intrinsic ASM GaN model, level-2 is the model of electrode inductances, resistances, and capacitances associated with metal lines of the electrodes represented by Z_{ex} with x = g, d, or s, and level-3 are the parasitic elements for the source via, gate- and drain-manifolds. Note that inter-electrode fringing capacitances are included in the intrinsic model via the model parameters CGSO, CGDO, and CDSO. Level-3 parasitic effect can be either modeled with a lumped element network, or the S2P files from EM simulations can be directly used for modeling this region. Level-2 parasitic elements can be extracted from the standard extraction procedure [19].

Once the parasitic elements are properly included in the model, the extraction flow starts with modeling of the imaginary parts of Y_{12}, and Y_{22}. These can be modeled by adjusting the model parameters CGDO and CDSO respectively. Next, the imaginary part of Y_{11} can be modeled by adjusting the CGSO parameter. Note that the bias dependence of capacitances is accounted for in the model via the physical charge expressions. The real parts of Y-parameters from the model should be close to the measurements at this point as the trans-conductance G_M and output conductance G_{DS} has already been accurately modeled during the DC extraction. The dispersion in G_{DS} due to the self-heating effects can be modeled with the thermal capacitance CTH0 parameter. For some devices adding series RC network to model the losses in substrate has also been found to be necessary. However, this is device/technology dependent. G_M dispersion can be modeled by invoking the model for trapping effects. Fig. 5 shows the S parameter fits from 0.5 to 26 GHz for a 2x200 μm commercial GaN HEMT device with ASM GaN model with S_{11} and S_{22} on smith-chart and S_{12} and S_{21} on polar plots. These results translate into accurate model for key figure of merits such as $|H_{21}|$, stability factor (K) and transit-time (τ) shown in Fig. 6.

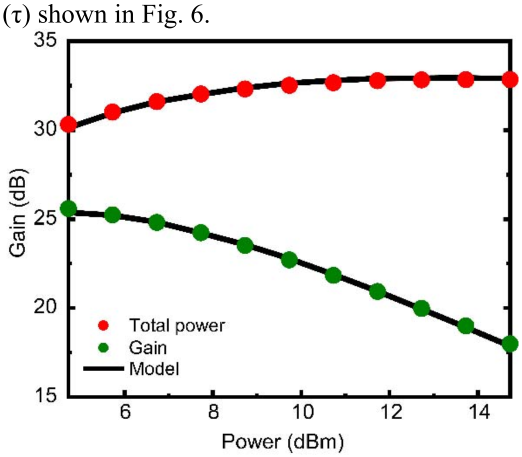


Fig. 7. RF drive-up characteristics modeled with ASM GaN model for 2x200 μm GaN HEMT.

After S parameters, the large signal characteristics can be modeled. We have found that with the parameters extracted so far in the extraction flow, typically reasonable large signal model results are obtained, and only small adjustments are required to get accurate large signal model. For large signal RF model fitting the change in the cut-off voltage dispersion and the series resistance dispersion need to be accounted for. However, for devices from different sources this is required to a varying degree. This is possibly due to variability of the degree to which devices (from different sources) suffer from trapping effects. For the device in Fig.6, the large signal model is shown in Fig. 7 which demonstrates accurate large signal RF model. In Fig. 8 we show large signal model results for another device with size of 8x40 μm for a bias point of 3.2 mA/mm and

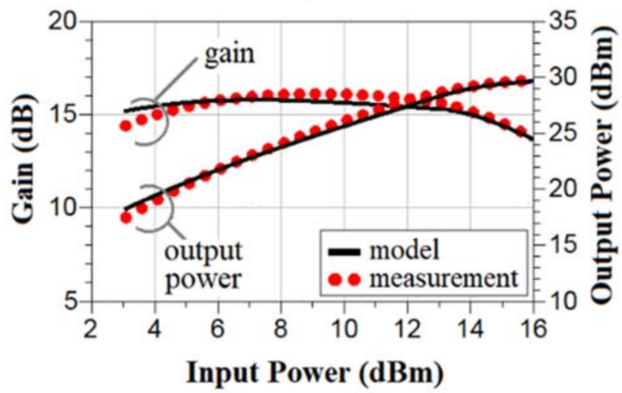


Fig. 8. Large signal RF characteristics modeled with ASM GaN model for 8x40 μm device,

Vd = 20 V which demonstrates a reasonable model accuracy for a different bias point.

IV. CONCLUSIONS

We present results and discussions on extraction flow for non-linear large signal RF modeling of GaN HEMTs with new industry standard ASM GaN model. Excellent non-linear modeling results have been obtained with this physics-based model for devices from multiple sources and of varying sizes following the extraction flow discussed in this paper. As an industry standard this model is soon going to appear in all major commercial simulators and the nonlinear RF extraction flow can help model users.

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