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Statistical Simulation for GaN HEMT Large Signal RF performance using a Physics-based Model

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***Abstract*—In this paper, we perform a Monte Carlo statistical simulation to see the impact of variability on large signal RF performance of a GaN HEMT using our physics-based compact model named the ASM HEMT model. Sensitivity analysis is performed to identify key parameters that significantly affect the harmonic balance power sweeps. Model parameters corresponding to trapping, sub-threshold slope, cut-off voltage and overlap capacitances were identified as the ones to which the large signal performance was highly sensitive. Monte Carlo simulation with these parameters as inputs was carried out and compared with multi-bias measured data for 10 GaN devices on a single wafer. Excellent agreement was obtained between the modeled and measured results.**

***Keywords*—GaN HEMTs; sensitivity analysis; Monte-Carlo; trapping**

I. INTRODUCTION

Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) have in the past decade emerged as strong candidates for high performance RF and high power applications primarily due to the excellent material properties of GaN such as high values of dielectric strength, carrier saturation velocity etc. This has led to the design and fabrication of GaN based devices with much higher breakdown voltages and lower ON-resistances in comparison to other material systems such as Silicon, GaAs etc [1], [2].

In order to harness these extremely promising properties of GaN HEMTs, RF circuit designers need a highly accurate, computationally efficient and robust device model. Due to variations in the performance of the active device, there is need of a model that replicates with high fidelity the statistical nature of the design so that production-level yield-oriented optimized RF circuit design is achieved. In the past, statistical models have been proposed which are based on empirical or table based models and as a result do not offer any interesting take-aways since the model parameters rarely bear any physical significance [3–5]. In this paper, we perform a Monte-Carlo simulation using our physics-based model named the Advanced SPICE Model for GaN High Electron Mobility Transistors (ASM-HEMT).

II. ASM-HEMT MODEL

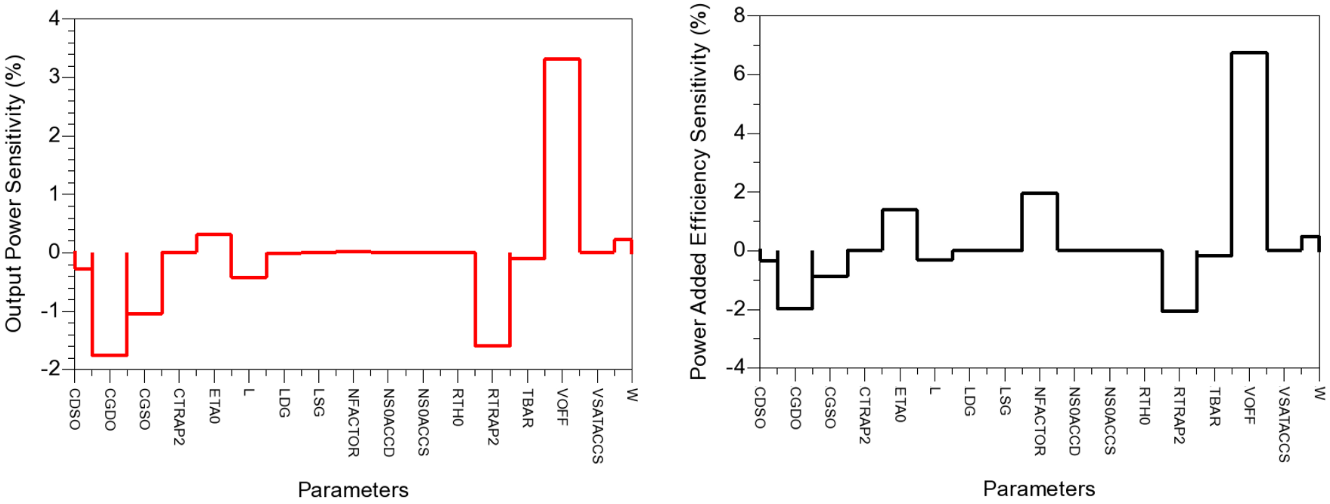
The ASM-HEMT Model is a physics-based model for GaN HEMTs in which closed form expressions for the drain current (I_d) and intrinsic charges ($Q_{g,s,d}$) are derived in terms of the surface-potential (ψ) [6–10]. Realistic device effects such as self-heating, trapping effects, access region resistances etc. are incorporated into the model to realise a more realistic device. The bias dependence of the device performance is handled by the model by a bias dependent value of ψ which in turn is an analytical function of the Quasi-Fermi level (E_F) [6]. The ASM-HEMT Model is currently under final phase of standardization at the Compact Model Coalition [11].

III. SENSITIVITY ANALYSIS

In order to accomplish a reasonably meaningful statistical simulation, it is imperative to pinpoint the key parameters that are going to be varied to check for the statistical behaviour. We use our physics-based model to get a deeper insight by carrying out a sensitivity analysis using Keysight's ADS simulator to check for the most sensitive model parameters affecting output power ($\mathrm{P_{out}}$) and power added efficiency (PAE). The initial model parameter set is already extracted for a commercial GaN HEMT, with the model parameter description given in Table I [7]. Each of the parameters are individually varied within ±1% of the nominal value while keeping the values of the rest of the parameters fixed. Shown in Fig. 1 are the sensitivity histograms for $\mathrm{P_{out}}$ and PAE. As can be seen, parameters $\mathrm{V_{OFF}}$, $\mathrm{R_{TRAP2}}$, $\mathrm{C_{GSO}}$, $\mathrm{C_{GDO}}$, $\mathrm{N_{FACTOR}}$ and η_0 seem to be influencing $\mathrm{P_{out}}$ and PAE whereas parameters corresponding to access region resistance, thermal resistance, and more importantly the device geometrical parameters (L, $\mathrm{L_{SG}}$, $\mathrm{L_{DG}}$ and W) are relatively insignificant.

TABLE I: Model Parameter Description [7]

Model Element	Description
W	Width
L	Length
$\mathrm{L_{SG,DG}}$	Gate-Source, Gate-Drain Access Region Length
$\mathrm{T_{BAR}}$	AlGaN Barrier Thickness
$\mathrm{V_{OFF}}$	Cutoff Voltage
$\mathrm{U_0}$	Low field Mobility
$\mathrm{N_{FACTOR}}$	Subthreshold Slope Factor
η_0	DIBL
NS0ACCS/D	Access Region 2DEG Density
VSATACCS	Access Region Carrier Saturation Velocity
$\mathrm{R_{SC,DC}}$	Source, Drain Contact Resistances
$\mathrm{R_{TH}}$	Thermal Resistance
$\mathrm{R_{TRAP2}}$	Trap Resistance
$\mathrm{C_{TRAP2}}$	Trap Capacitance
$\mathrm{C_{GSO}}$	Gate-Source Overlap Capacitance
$\mathrm{C_{GDO}}$	Gate-Drain Overlap Capacitance
$\mathrm{C_{DSO}}$	Drain-Source Overlap Capacitance



(a) (b)

Fig. 1: Sensitivity histograms for (a) P_{OUT} and (b) PAE for individually varying parameters listed in Table I by 1% from the nominal value. The most sensitive parameters can be easily identified. An interesting observation to be made is the relatively less sensitivity of P_{OUT} and PAE towards fluctuations in geometrical parameters whereas V_{OFF}, R_{TRAP2}, C_{GSO} and C_{GDO} are highly significant.

Both P_{out} and PAE depend strongly on fluctuations in V_{OFF} since it limits the current excursions in the I-V plane. Fluctuations in V_{OFF} among different devices obtained after same process control parameters may arise due to different polarization charges induced at the edges of the AlGaN barrier or even due to the variation in the thickness of the AlGaN barrier itself. The overlap capacitances, particularly C_{GDO} and C_{GSO} determine the small signal behaviour of the model at RF which also reflects in the large signal simulations as suggested by the sensitivity histograms. This is the only significant manifestation of having structural variability among different devices. We note that PAE is sensitive as far as its relation with subthreshold parameters N_{FACTOR} and η_0 is concerned, which may primarily be due to the variation in the dissipated DC power within the device.

Trapping severely affects the large signal performance at RF as indicated by Fig. 1. In our model, trapping is captured by an RC network to mimic drain lag as shown in Fig. 2. The input to the RC is a function of the drain voltage (V_{d}) and the trap voltage (V_{trap}) developed across the RC is fed back into the model to update various quantities such as V_{OFF}, subthreshold slope, access region resistance parameters etc as suggested by pulsed IV measured data available in literature [12], [13]. It must be noted that the GaN devices for which the model parameters are extracted and used for this work, are passivated and therefore has minimal gate-lag effects. The variability in trap behaviour of the devices may come about due to randomness in trap densities, different trap-detrap time constants, trap locations in the buffer or due to time-degradation etc.

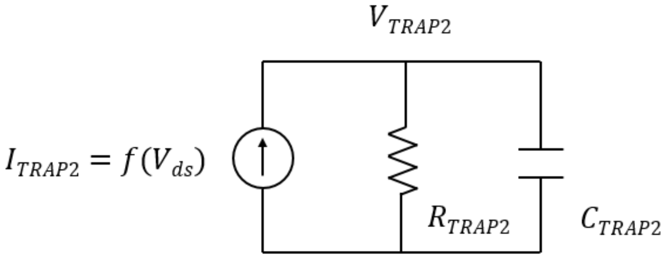


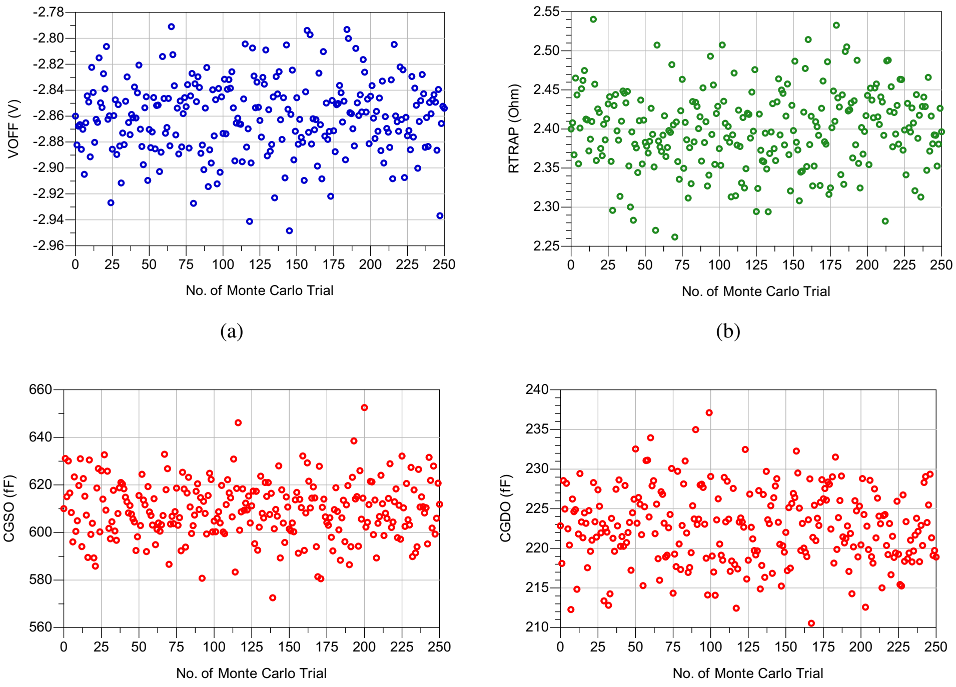
Fig. 2: A simplified RC network used to capture the trapping behaviour. $I_{\mathrm{TRAP2}}(V_{\mathrm{ds}})$ is fed to the network resulting into the development of voltage V_{TRAP2} which is used to update various quantities such as V_{OFF}, N_{FACTOR} etc. A second RC network can be used where input trap current is a function of V_{gs} in order to mimic gate-lag phenomenon, however in the devices used for this work, gate-lag is minimal due to passivation and a single RC network is sufficient to capture trapping behaviour.

TABLE II: Parameters extracted for 10 GaN devices

Parameter	μ	$\sigma_{\%}$
V_{OFF}	-2.86 V	1
N_{FACTOR}	0.202	0.0
η_0	0.117	0.0
C_{GSO}	610 fF	2
C_{GDO}	225 fF	2
R_{TRAP2}	2.4 Ω	2

IV. MONTE CARLO SIMULATION

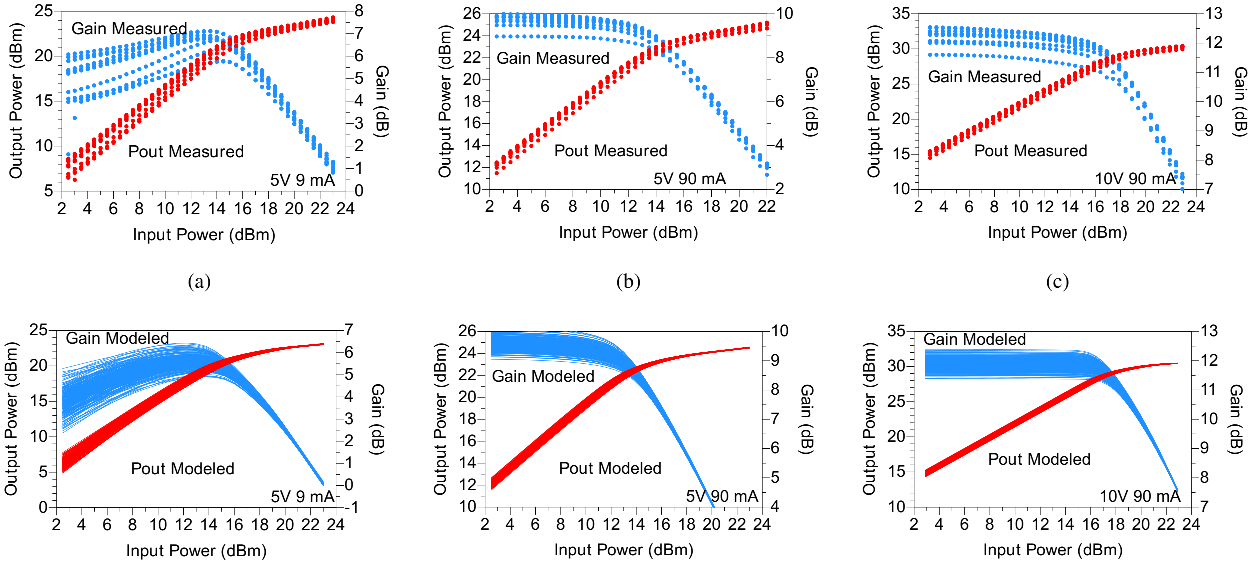
After having identified the model parameters to which P_{OUT} and PAE were sensitive, we use measured P_{OUT} and PAE data for a batch of 10 Qorvo GaN HEMTs on a single wafer and extract values for model parameters V_{OFF}, R_{TRAP2}, C_{GSO}, C_{GDO}, N_{FACTOR} and η_0. Their means (μ) and standard deviation percent ($\sigma_{\%}$) are given in Table II. It must be noted that the value of $\sigma_{\%}$ for N_{FACTOR} and η_0 are zero, since we kept their values fixed for all devices as they are core model parameters. Nevertheless, we proceed to Monte Carlo simulations in Keysight's ADS Simulator for 250 trials which is sufficient for achieving a decent confidence level. The inputs to the Monte Carlo controller are the above given 4 parameters with standard deviation percent the same as presented in Table II. The distribution followed by the input parameters around the nominal value is set to Gaussian.



(a) (b)

(c) (d)

Fig. 3: Values of parameters (a) V_{OFF} (b) R_{TRAP2} (c) C_{GSO} and (d) C_{GDO} for 250 Monte Carlo trials.



(a) (b) (c)

(d) (e) (f)

Fig. 4: Comparison of measured statistical data (a-c) for P_{OUT} and Gain with modeled statistical results (d-f). The modeled curves are for 250 trials whereas measured data is for a batch of 10 Qorvo GaN devices fabricated on a single wafer. Validation is done for 3 different bias conditions with $V_d = 5V\&10V$ and $I_{ds} = 9\&90mA$.

V. RESULTS AND DISCUSSION

Comparison between modeled and measured statistical results for P_{OUT} & Gain (Fig. 4) and PAE & I_{dd} (Fig. 5) is shown for 3 different bias conditions - $V_d = 5V\&10V$ and $I_{ds} = 9\&90mA$. The input RF power at a frequency of 10 GHz is swept from $2.5 - 22.5$ dBm and the load terminations are extracted from loadpull measurements for optimum P_{OUT} and PAE. The measured traces are seen to fall well within the bounds defined by the curves simulated using the model thereby depicting a high accuracy of the model. It is also seen that in certain cases, the modeled traces are more dispersed i.e having a greater standard deviation than the measured traces, which indicates a relatively modest sample size of measured data and therefore more constricted than the modeled traces. The accuracy of the statistical simulation obtained highlights the sensitivity analysis performed to narrow down and identify parameters that impact statistical performance under large signal RF conditions.

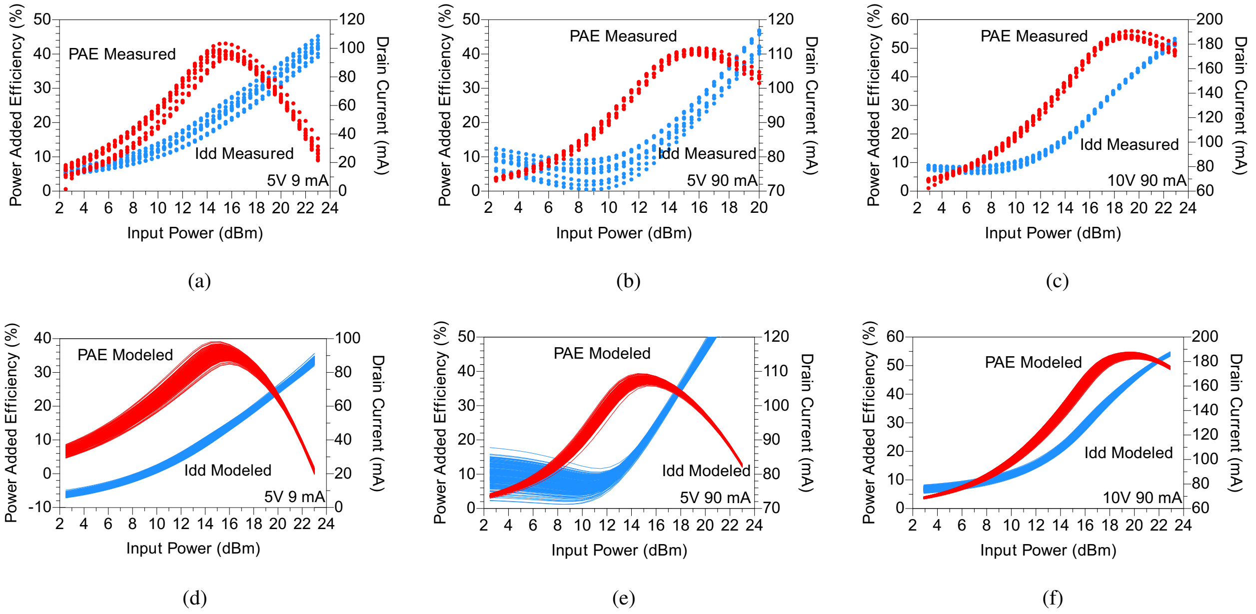


Fig. 5: Comparison of measured statistical data (a-c) for PAE and $\mathrm{I_{dd}}$ with modeled statistical results (d-f). Validation is done for 3 different bias conditions with $\mathrm{V_d} = 5\mathrm{V}\&10\mathrm{V}$ and $\mathrm{I_{ds}} = 9\&90\mathrm{mA}$.

VI. CONCLUSION

We demonstrated a statistical simulation for large signal RF performance of GaN HEMTs using a physics-based model to analyse the impact of variability. A sensitivity analysis was performed to identify key model parameters that determine the statistical nature of harmonic balance power sweeps. It was seen that the effect of fluctuations in geometrical dimensions was minimal and could therefore be ignored. However, the impact of trapping, which is severe in GaN HEMTs as well as stochastic in nature, was identified and included in the Monte Carlo simulation. In addition, variations in overlap capacitances were also seen to be critical in determining the statistical results. Excellent results were obtained upon comparison with measured data for commercial GaN HEMTs.

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