Technology CAD for microwaves: from devices to circuit performance

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I. Introduction

Physics-based device simulators have undergone significant advancement over the last decades [1]–[4]. In the past, Technology CAD (TCAD) simulation, i.e., the numerical analysis of electron devices through the device structure discretization and the numerical solution of physical equations [5]–[7], was generally assumed to be too demanding from the computational standpoint for the analysis of devices in the typical operating regime of microwave circuits, i.e., dynamic and nonlinear. Nowadays, leveraging on advances in computation resources, and new numerical techniques based on iterative solution of nonlinear models, all dynamic conditions can be efficiently addressed, including the Large-Signal (LS) periodic or quasi-periodic analysis [8]–[13] (Fig. 1). Typical applications include microwave circuits with multi-tone inputs, e.g., power amplifiers or mixers.

Technology CAD offers the advantage of a direct link to fabrication process parameters, including an accurate description of the device physics. On one side, TCAD allows to directly target microwave performance, e.g., power gain and intermodulation, when optimizing the device structure. It also allows to identify the main physical processes underlying specific features, e.g., long-term memory effects due to traps or temperature. Examples are in Secs. III-V. Finally, TCAD can be used to extract device models that can be directly exploited in circuit design. To this aim, the preferred choice is necessarily behavioral models, that are more accurate in reproducing physical simulations, fast and easily reconfigurable to include any additional technological or physical parameter that enhances the model accuracy. Compared to conventional compact device models, i.e., based on equivalent circuits, this procedure turns out to be more flexible. It also allows to merge device and electromagnetic (EM) physical simulations with available measured data in the model identification. An example is given in Sec. VI .

This paper presents several demonstrations of advanced TCAD capabilities, showing how physical simulation can seamlessly address the analysis of standalone devices and of entire microwave circuits, including both active devices and passive networks.

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II. TCAD implementation for microwave circuits

Among the commercial TCAD simulators available [1]–[4], none explicitly targets the device simulations in the nonlinear dynamic regime typical of microwave applications. In fact, TCAD time domain-analysis is generally available, but it suffers from the limitations typical of microwave circuit simulators: long simulation times are required to resolve both the fast and slow dynamics. As such, the applicability of this analysis is limited to the investigation of specific physical effects such as transients in presence of traps, but it is not suited for the global device analysis. Frequency domain analysis, e.g., through Harmonic Balance (HB), represents the ideal tool. To the best of our knowledge, the only commercial simulator implementing TCAD HB is Synopsys Sentaurus [1], limited to the large-signal working point, while Small-Signal Large-Signal analysis, required e.g., for the extraction of X-parameters [14] and the nonlinear noise analysis [10], is not available. In this paper, we exploit an in-house simulator to demonstrate the relevance of microwave TCAD, especially exploiting features which implementation in commercial tools we strongly support. Although the tool cannot be made public, we are available to cooperate with interested research groups to apply our simulator to other technologies. The TCAD environment we use is an in-house developed tool from Politecnico di Torino (POLITO), which is based on the drift-diffusion model that can be coupled to a set of additional equations according to the type of device simulation required. In particular: 1) a dynamic trap rate equation for each trap species present in the device; 2) a thermal circuit equation, coupling the device to an external thermal circuit, represented by equivalent thermal impedance; 3) the density gradient correction for the analysis of quantum confinement. A database of material systems including Si, AlGaN and AlGaAs compound semiconductor alloys is available, particularly suited to simulate microwave devices.

The simulator features full mixed-mode analysis, including multiple devices, such as in parallel, Doherty or stacked stages [15]–[17], and the embedding external passive network [18]. Multi-tone power or voltage external stimuli drive the device into periodic or quasi-periodic regime. The discretized physical equations are converted into the frequency domain and solved through the Harmonic Balance algorithm [10].

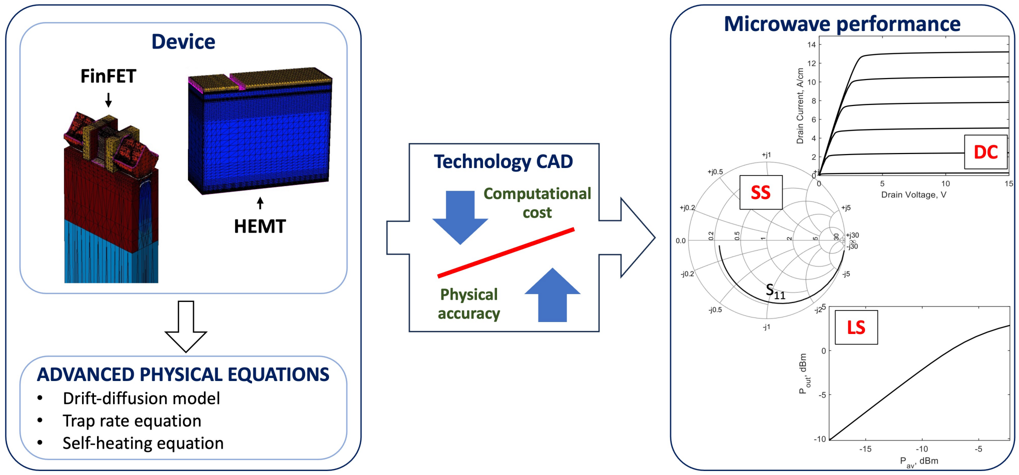

Fig. 1. TCAD allows for an accurate analysis of microwave devices in various operating conditions, including static (DC), small-signal (SS, Y or S-parameters) and large signal (LS). In particular, periodic LS analysis based on Harmonic Balance leads to the direct extraction of voltage, current or power harmonics vs. input power. The computational cost due to device discretization, can be overcome by an efficient numerical solution of the device equations and by the advances of computational resources even in ordinary desktop PCs.

The simulation outputs are the harmonic components of all voltages and currents at the device terminals plus the harmonics of all the internal quantities, e.g., electrostatic potential, carrier densities and carrier velocities. For small variations around an operating condition, the POLITO simulator also allows for a linearized analysis in the frequency domain, that further reduces the simulation time. Linearized simulations lead to the direct extraction of the SS scattering matrix, as well as the SS-LS conversion matrix and the SS and SS-LS conversion Green's Functions (GFs) [10]. GFs represent the kernel to compute the variation at the device terminals due to variations of internal quantities such as velocity fluctuations typical of diffusion noise and material physical variations due to technological spread. Hence, the GF approach is important e.g., for the linear and nonlinear noise analysis [10], and for efficient sensitivity and variability analyses [19], [20].

III. TCAD variability of microwave devices

Microwave circuit variability is heavily impacted by the active device technological spread. Unfortunately, both TCAD and compact models have only sparsely addressed the variability of LS performance [21]. TCAD analysis is especially powerful to seamlessly analyze the effect of process variability on all device performance, including DC, AC and LS. As an example of the simulator capabilities in terms of retaining the link with material and technological parameters, Fig. 2 shows a MonteCarlo analysis of a GaN HEMT, whose structure is reported in Fig. 3. The device is characterized by a Fe-induced trap concentration $N_{\mathrm{T}} = 10^{18}$ cm^{-3} with nominal energy $E_{\mathrm{T}} = E_{\mathrm{C}} - 0.45$ eV (with E_{C} corresponding to the energy at the bottom of the conduction band), and a net piezoelectric polarization charge at the AlGaN/GaN interface $\sigma_{\mathrm{pol}} = 1.34 \times 10^{13}$ cm^{-3} (see [22] for further details). The simulation results show how the technological spread of a material property (here the polarization charge of the HEMT channel) directly reflects into the spread of the DC characteristics and scattering parameters.

IV. TCAD-based thermal analysis

Besides technological parameters, physics-based simulations allow for reliable device analysis vs. temperature. Temperature-dependent modeling is essential to describe self-heating, typically occurring in power devices and in aggressively scaled nanostructures, e.g FinFETs, due to the difficult heat sinking. FinFETs are a promising emerging technology for microwave applications, both for wireless communications and quantum sensing [23]. As an example, we report the temperature-dependent LS analysis of a class A Power Amplifier (PA) for small cells applications based on FinFET technology. Fig. 4 shows the 2D cross section of the individual fin used for TCAD simulations, while the full PA is a multi-finger, multi-fin structure (10 fingers with 30 fins each) with a fin height of 25 nm, yielding a total gate periphery of 15 μm (see [24] for further details). Fig. 5 shows how temperature affects the PA dynamic load lines in compression, while Fig. 6 reports the power gain as a function of input power, showing a clearly nonlinear temperature variation straightforwardly captured by the physical approach. Moreover, our TCAD simulations also allow to seamlessly combine temperature dependent and process variability analyses with negligible numerical overhead [25].

V. TCAD analysis of low-frequency dispersion

Dynamic thermal and trap phenomena are the main physical effects underlying the low-frequency dispersion found in microwave devices. Trap related effects are especially relevant in GaN HEMTs, mainly due to the relative immaturity of the technology. Their characterization is difficult since the internal trap spatial and energy distributions are not directly observable. TCAD analysis plays a key role in assessing the signature of traps on DC, AC and LS performance. DC gate and drain lag through time-domain measurements [26]–[28] are relevant research topics, however recently also the SS and noise low-frequency behaviors have attracted significant interest [29]–[31]. In the POLITO TCAD implementation,

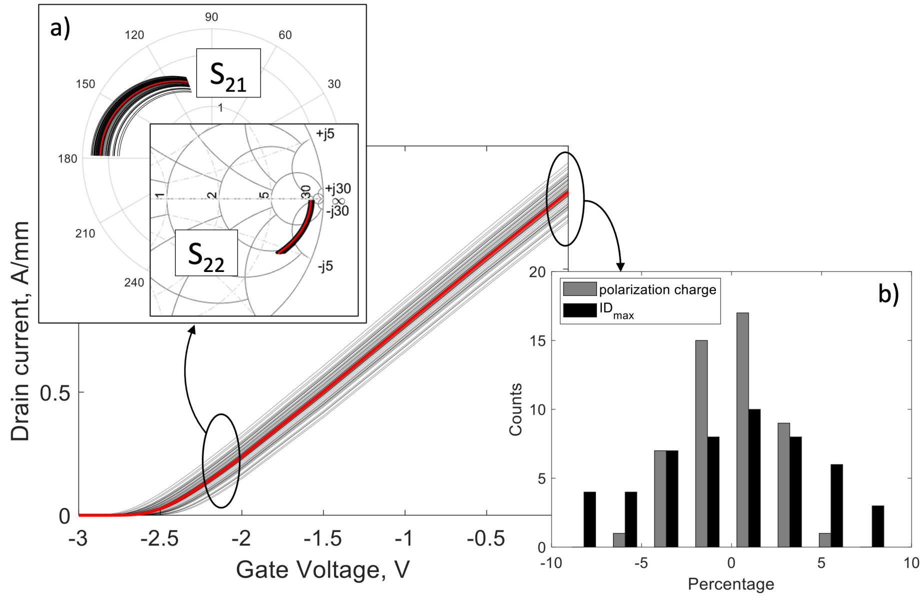

Fig. 2. Harmonic Balance-based physical simulations allow a seamless analysis of device variability, including DC, SS and output power, without the need of an intermediate compact model extraction. In this MonteCarlo analysis of a GaN HEMT, the polarization charge undergoes random variations with a normal distribution characterized by 5% variance. The DC transcharacteristics are shown at $V_{\rm D} = 10$ V. The insets, show a) the S_{21} and S_{22} spread in the frequency range [1-70] GHz at $V_{\rm G} = -2.22$ V, and b) the distribution of $I_{\rm Dmax}$ at $V_{\rm G} = 0$ V, showing a spread up to 10% with respect to the nominal value.

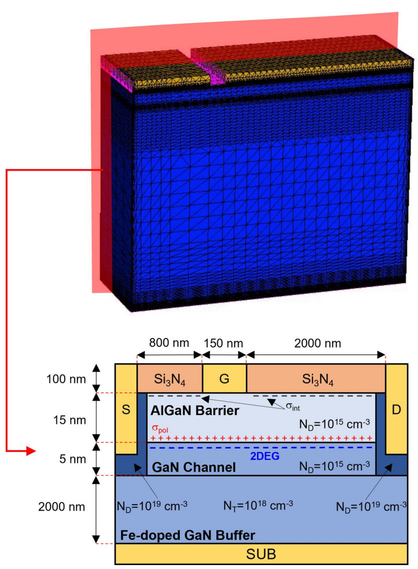

Fig. 3. HEMT structure and 2D cross-section exploited in the numerical TCAD simulation.

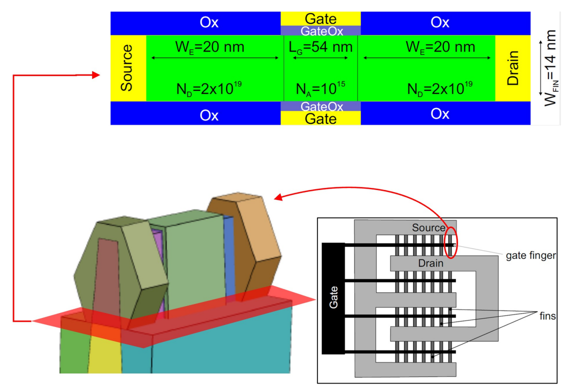

Fig. 4. FinFET structure and 2D cross-section exploited in the numerical TCAD simulation.

trap dynamics are implemented directly through trap rate equations coupled to the drift-diffusion model and solved in the frequency domain [22]. Only this approach allows for a seamless simulation of traps across all dynamic regimes, including small- and large-signal. As an example, Figures 7 and 8 show the real and imaginary parts of the low-frequency output admittance for the same device of Fig. 3, highlighting the dispersion as a function of the trap energy. The real part is characterized by a reduction of the output resistance at high frequency, in agreement with the experimental characterization of microwave devices. Globally, Y_{22} is characterized by a transition frequency depending on the trap energy, as also demonstrated by the presence of a peak in the imaginary part. This peak frequency is especially important to identify the trap signature from experimental characterization.

VI. TCAD-based Behavioral Model for Multi-Physics Circuit Analysis

TCAD analysis represents the ideal platform to extract parametric device behavioral models, i.e., including a dependency on the main technological parameters, e.g., doping, temperature, trap concentrations etc. Compared to compact models, in the behavioral approach adding more model parameters can be implemented in a seamless way, e.g., increasing the dimensionality of a look-up-table (LUT) based model or adding more neurons in a Neural Network implementation [32]. Among nonlinear dynamic behavioral models, X-parameters (Xpars) [33] are well suited for microwave nonlinear applications as they are based on a frequency domain characterization. In

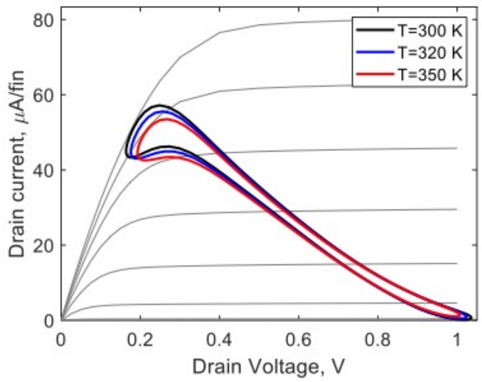

Fig. 5. Class A 70 GHz amplifier based on a multifinger 54 nm gate length FinFET technology (overall periphery 15 μm, maximum output power 3 dBm). Dynamic load lines on optimum load at $P_{\rm av} = -3$ dBm show power compression due to knee voltage walk-out with increasing lattice temperature. DC characteristics are reported at 300 K.

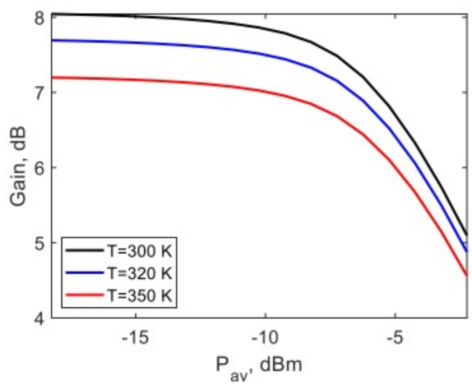

Fig. 6. FinFET class A amplifier power gain at different lattice temperatures. The gain variation with temperature is decreasing from back-off to compression showing nonlinear T-sensitivity.

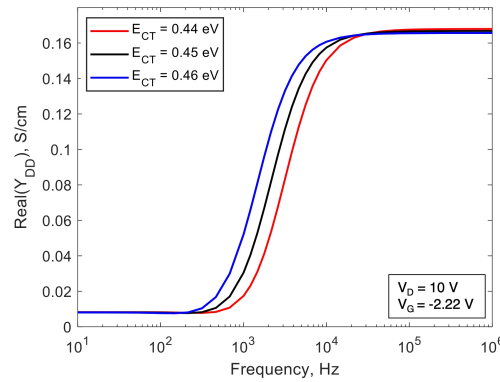

Fig. 7. Real part of the low-frequency output admittance of a 150 nm gate length GaN HEMT with substrate Fe-doping. Three trap energies are considered, showing a low-frequency dispersion mainly affecting the transition frequency. This parameter reflects the output resistance, which is lower at higher frequency, a degradation effect often observed in microwave GaN HEMTs.

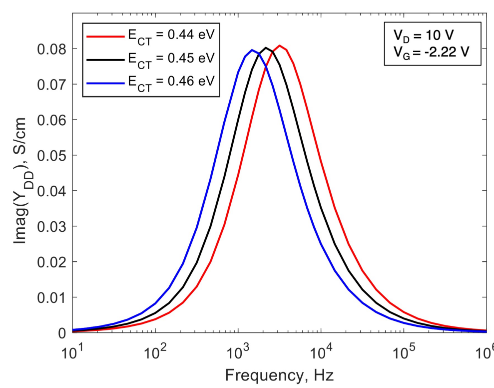

Fig. 8. Imaginary part of the low-frequency output admittance for the same GaN HEMT of Fig. 7. The peak frequency variation with trap energy can be used to assist trap signature identification from characterization.

POLITO simulator, Xpars are extracted directly from Harmonic Balance simulations, as shown in [14]. Xpars are easily imported into CAD tools and the dependency on physical or technological parameters is implemented by adding virtual ports to the electrical model [34]–[36].

When designing a microwave stage, e.g., a power amplifier (PA), physics-based analysis of the passive networks through Electromagnetic (EM) simulations is often required to accurately simulate the layout, including the coupling of transmission lines and other distributed effects. Such simulations need to be repeated many times for the layout optimization, making the design process extremely time consuming. Moreover, even passive networks are affected by significant process variability, which require parametric MonteCarlo analysis. Here as well, behavioral models of the passive structures retaining the link to process parameters, can replace EM simulations, significantly alleviating the computational burden. In particular, an MDIF model allows to import such behavioral description into circuit CAD tools as a multiport block [18], [34]. Behavioral multiport models for both the active and passive structures are then coupled at the circuit level enforcing continuity of port waves at each harmonic leading to the efficient simulation of the entire microwave stage, as shown in Fig. **??**.

Statistical microwave analysis can be efficiently carried out at the circuit level exploiting the parametric behavioral models extracted from physical analysis. As an example, we consider the MonteCarlo (MC) analysis of a deep class-AB tuned-load power amplifier at 12 GHz based on a GaAs MMIC technology [16]. The layout of the PA is shown in Fig. 10. Process induced variability (PIV) is dominated by the spread of SiN insulator layer used in MIM capacitors, and of the active device doping. A MC analysis was carried out with an ensemble of 250 randomized PA circuits sweeping the available input power over 50 points from back-off to compression for each MC iteration. Fig. 11 shows the spread of the Pin-Pout curves with the two concurrent variations, along with the separate effects of MIM layer and doping variations. The analysis shows that the optimization of passive networks at high power can be hindered by the spread induced by the active device variability, which cannot be eliminated at the design level.

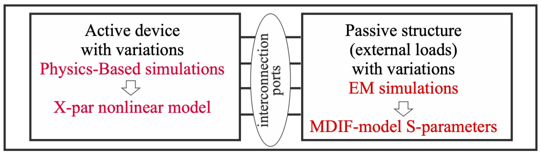

Fig. 9. Multiport behavioral modeling of the device through Xpars and of the passive networks through Measurement Data Interchange Format (MDIF) model allow for the efficient microwave stage analysis in circuit CAD tools (from [18]).

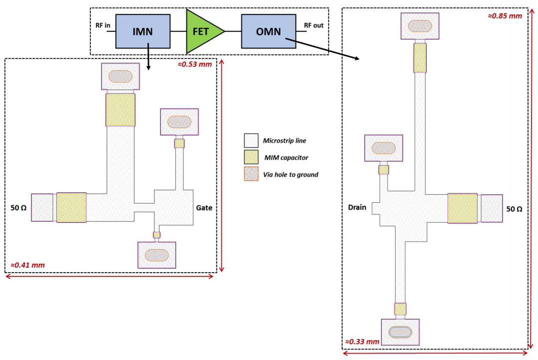

Fig. 10. Simulated MESFET PA (from [16]) showing the layout of the IMN (Input Matching Network) and OMN (Output Matching Network). All MIM capacitors are assumed to be affected by PIV.

VII. Conlusions

The added value of physics-based analysis for microwave circuit design has been discussed. Thanks to the combination of numerically efficient TCAD and ad-hoc behavioral models, the link between the Large-Signal performance and the underlying technological process can be fully retained and can be exploited to perform advanced circuit analyses, such as statistical and self-heating.

References

[1] "Synopsys Sentaurus." [Online]. Available: https://www.synopsys.com/silicon/tcad/device-simulation/sentaurus-device.html

[2] "Silvaco TCAD." [Online]. Available: https://silvaco.com/tcad/

[3] Global TCAD Solutions. [Online]. Available: https://www.globaltcad.com/

[4] "Ginestra simulationsoftware platform." [Online]. Available: https://www.appliedmaterials.com/us/en/semiconductor/solutions-and-software/software-solutions/ginestra-simulation-platform.html

[5] M. R. Pinto, "Comprehensive semiconductor device simulation for silicon ULSI," Ph.D. dissertation, Stanford University, 1990.

[6] S. Selberherr, *Analysis and Simulation of Semiconductor Devices*. Springer Vienna, 2011.

[7] R. Dutton and A. Strojwas, "Perspectives on technology and technology-driven CAD," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 19, no. 12, pp. 1544–1560, 2000.

[8] J. Roychowdhury, D. Long, and P. Feldmann, "Cyclostationary noise analysis of large RF circuits with multitone excitations," *IEEE Journal of Solid-State Circuits*, vol. 33, no. 3, pp. 324–336, Mar. 1998.

[9] Y. Saad, *Iterative methods for sparse linear systems*, 2nd ed. Philadelphia, PA: SIAM, Society for Industrial and Applied Mathematics, 2007.

[10] F. Bonani, S. Donati Guerrieri, G. Ghione, and M. Pirola, "A TCAD approach to the physics-based modeling of frequency conversion and noise in semiconductor devices under large-signal forced operation," *IEEE Transactions on Electron Devices*, vol. 48, no. 5, pp. 966–977, may 2001.

[11] B. Troyanowky, "Frequency domain algorithms for simulating large signal distortion in semiconductor devices," Ph.D. dissertation, Stanford University, 1997.

[12] B. Troyanovsky, Z. Yu, and R. W. Dutton, "Physics-based simulation of nonlinear distortion in semiconductor devices using the harmonic balance method," *Computer Methods in Applied Mechanics and Engineering*, vol. 181, no. 4, pp. 467–482, Jan. 2000.

[13] J. Sanchez, G. Bosman, and M. Law, "Two-dimensional semiconductor device simulation of trap-assisted generation-recombination noise under periodic large-signal conditions and its use for developing cyclostationary circuit simulation models," *IEEE Transactions on Electron Devices*, vol. 50, no. 5, pp. 1353–1362, May 2003.

[14] S. Donati Guerrieri, F. Bonani, and G. Ghione, "Linking X parameters to physical simulations for design-oriented large-signal device variability modeling," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*. IEEE, jun 2019.

[15] S. Donati Guerrieri, E. Catoggio, and F. Bonani, "Analysis of Doherty power amplifier matching assisted by physics-based device modelling," *Electronics*, vol. 9, no. 12, p. 2101, apr 2023.

[16] S. Donati Guerrieri, C. Ramella, E. Catoggio, and F. Bonani, "Bridging the gap between physical and circuit analysis for variability-aware microwave design: Power amplifier design," *Electronics*, vol. 18, no. 11, p. 2832, sep 2022.

[17] C. Ramella, S. Donati Guerrieri, and M. Pirola, "TCAD-based Pseudo-Common-Gate X-PAR model for GaAs stacked power amplifier design," in *2023 International Workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits (INMMIC)*. IEEE, nov 2023.

[18] S. Donati Guerrieri, C. Ramella, F. Bonani, and G. Ghione, "Efficient sensitivity and variability analysis of nonlinear microwave stages through concurrent TCAD and EM modeling," *IEEE Journal on Multiscale and Multiphysics Computational Techniques*, vol. 4, pp. 356–363, 2019.

[19] S. Donati Guerrieri, F. Bonani, F. Bertazzi, and G. Ghione, "A unified approach to the sensitivity and variability physics-based modeling of semiconductor devices operated in dynamic conditions—Part I: Large-signal sensitivity," *IEEE Transactions on Electron Devices*, vol. 63, no. 3, pp. 1195–1201, mar 2016.

[20] ——, "A unified approach to the sensitivity and variability physics-based modeling of semiconductor devices operated in dynamic conditions.—Part II: Small-signal and conversion matrix sensitivity," *IEEE Transactions on Electron Devices*, vol. 63, no. 3, pp. 1202–1208, mar 2016.

[21] Z. Chen, Y. Xu, C. Wang, Z. Wen, C. Rong, and R. Xu, "A novel nonlinear large-signal statistical model of GaN HEMT used in S-band power amplifier design and yield estimation," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 30, no. 1, Mar. 2016.

[22] E. Catoggio, S. Donati Guerrieri, and F. Bonani, "TCAD modeling of GaN HEMT output admittance dispersion through trap rate equation Green's functions," *Electronics*, vol. 11, no. 12, p. 2457, may 2023.

[23] G. Crupi, D. M.-P. Schreurs, J.-P. Raskin, and A. Caddemi, "A comprehensive review on microwave finfet modeling for progressing beyond the state of art," *Solid-State Electronics*, vol. 80, pp. 81–95, Feb. 2013.

[24] E. Catoggio, S. Donati Guerrieri, and F. Bonani, "Efficient TCAD thermal analysis of semiconductor devices," *IEEE Transactions on Electron Devices*, 2021.

[25] A. M. Bughio, S. Donati Guerrieri, F. Bonani, and G. Ghione, "Physics-based modeling of FinFET RF variability," in *2016 11th European Microwave Integrated Circuits Conference (EuMIC)*. IEEE, oct 2016.

[26] A. M. Angelotti, G. P. Gibiino, A. Santarelli, and C. Florian, "Experimental characterization of charge trapping dynamics in 100-nm AlN/GaN/AlGaN-on-si HEMTs by wideband transient measurements," *IEEE Transactions on Electron Devices*, vol. 67, no. 8, pp. 3069–3074, aug 2020.

[27] N. Zagni, G. Verzellesi, and A. Chini, "Temperature-independent current dispersion in 0.15 μm AlGaN/GaN HEMTs for 5g applications," *Micromachines*, vol. 13, no. 12, p. 2244, dec 2022.

[28] C. De Santi, M. Buffolo, G. Meneghesso, E. Zanoni, and M. Meneghini, "Dynamic performance characterization techniques in gallium nitride-based electronic devices," *Crystals*, vol. 11, no. 9, p. 1037, Aug. 2021.

[29] P. V. Raja, N. K. Subramani, F. Gaillard, M. Bouslama, R. Sommet, and J.-C. Nallatamby, "Identification of buffer and surface traps in fe-doped AlGaN/GaN HEMTs using Y21 frequency dispersion properties," *Electronics*, vol. 10, no. 24, p. 3096, dec 2021.

[30] P. Beleniotis, F. Schnieder, S. Chevtchenko, and M. Rudolph, "Localization of trapping effects in GaN HEMTs with pulsed s-parameters and compact models," in *2022 17th European Microwave Integrated Circuits Conference (EuMIC)*. IEEE, sep 2022.

[31] E. Catoggio, S. D. Guerrieri, and F. Bonani, "Gan hemt trap-induced variability through concurrent noise and ac tcad modelling," in *2023*

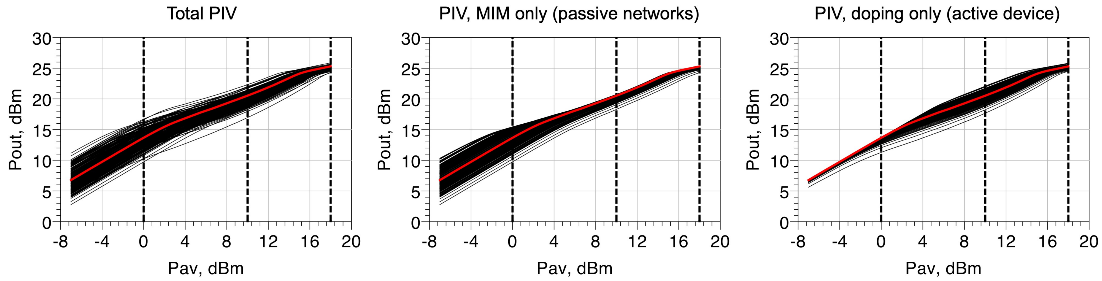

Fig. 11. Statistical analysis of a GaAs MMIC PA carried at the circuit level with behavioral models extracted from physical analysis [16].

International Conference on Noise and Fluctuations (ICNF). IEEE, Oct. 2023.

[32] L. Kouhalvandi, E. Catoggio, and S. Donati Guerrieri, "Synergic exploitation of TCAD and Deep Neural Networks for nonlinear FinFET modeling," in *20th International Conference on Smart Technologies-EUROCON 2023*. IEEE, jul 2023.

[33] D. Root, J. Horn, J. Verspecht, and M. Marcu, *X-Parameters*. Cambridge University Press, 2013.

[34] S. Donati Guerrieri, C. Ramella, E. Catoggio, and F. Bonani, "Bridging the gap between physical and circuit analysis for variability-aware microwave design: Modeling approaches," *Electronics*, vol. 11, no. 6, p. 860, mar 2022.

[35] S. J. Gillespie, D. E. Root, M. Marcu, and P. H. Aaen, "Electrothermal X-Parameters for dynamic modeling of RF and microwave power transistors," in *2018 13th European Microwave Integrated Circuits Conference (EuMIC)*. IEEE, sep 2018.

[36] E. Catoggio, S. Donati Guerrieri, C. Ramella, and F. Bonani, "Thermal modeling of RF FinFET PAs through temperature-dependent X-parameters extracted from physics-based simulations," in *2022 International Workshop on Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMiC)*. IEEE, Apr. 2022.