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Nonlinear RF modeling of GaN HEMTs with Fermi kinetics transport and the ASM-HEMT compact model

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Preface

The IEEE MTT-S Young Professionals Workshop on Modeling and Optimization for Active Devices, first held on October 25th, 2022, is a virtual live event that is free of charge for all registrants. It serves as a platform for IEEE Young Professionals involved in RF active device modeling to showcase their research results and interact with the community. Co-sponsored by TC-2 and TC-3 of the MTT-S, it includes presentation sessions by Young Professionals and a panel discussion with senior experts.

While the second edition of this workshop took place on October 17th, 2023 under the new name *IEEE MTT-S Young Professionals Workshop on Modeling, Optimization, and Measurement Techniques for Active Devices (MOMA)*, here we recall the *Best Presentation* from last year's event, as voted by attendees live during the event. The article below is written by the recipients of that *Best Presentation Award* and is based on the research work described during their presentation last year.

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1 Introduction

Gallium nitride (GaN) high electron mobility transistors (HEMTs) are a key technological component in current and next generation radio frequency (RF) and millimeter-wave (mm-wave) integrated circuits and sub-systems. Applications where GaN has made considerable impact include radar, communications, satellite communications, and electronic warfare. A critical aspect of the RF design cycle is accurate modeling of the GaN HEMTs. Modeling of the transistors can take two significantly different forms: one referred to as technology computer aided design (TCAD), and the other called physics-based compact modeling. These subjects were the basis of the "best presentation" winning talk at the IEEE Microwave Theory and Techniques Design Automation Committee (TC-2) Modeling and Optimization workshop where the modeling research at the Air Force Research Laboratory (AFRL) was discussed. Namely, AFRL's custom TCAD solver called Fermi kinetics transport (FKT) [1] and physics-based compact modeling using the Advanced Spice Model for HEMTs (ASM-HEMT) [2] were presented. This article provides an overview of the physics-based modeling efforts at AFRL.

2 FKT Device Simulations

TCAD modeling has long been a staple of transistor research and development. In the world of Boltzmann solvers, there exist mainly two categories of methods which capture hot-electron effects in field effect transistors: the first are stochastic methods and the second are deterministic methods called energy-transport solvers [3]. The AFRL custom TCAD solver, FKT, is a type of energy-transport method which employs four moments of the Boltzmann transport equation to account for charge transport and hot-electron dynamics. A key distinguishing feature of the FKT solver is the choice of closure relation [3] for the system of nonlinear partial differential equations. FKT utilizes a thermodynamic heat flow for its closure relation [4] rather than the conventional approach of Fourier's law [3]. The result of a thermodynamic heat flow appears to be a robust and stable charge transport framework, and the favorable convergence properties have been benchmarked against a commercial hydrodynamics solver [5]. The excellent stability and convergence properties of the solver have also enabled large-signal RF simulations of GaN HEMTs as demonstrated in [6, 7]. Complete electronic bandstructure and scattering mechanisms are incorporated into the FKT device simulator through isosurface integral pre-processing routines. The calculated data is then fit with power laws in order to utilize general Fermi integral calculations in the transport solver [8, 9, 10]. The inclusion of these fundamental materials properties is critical for accurate device simulations [11]. Another key difference between FKT and conventional Boltzmann solvers is the use of an "energy-dependent mobility" for simulating electron transport [8, 9, 10]. The standard approach for deterministic solvers is choice of an electric field-dependent mobility model [12]. The FKT framework provides a self-consistent solution of the charge transport equations with Maxwell's equations. Discretization of Maxwell's equations are accomplished through a method called Delaunay-Voronoi surface integration [13]. The self-consistent solution of Maxwell's equations and charge transport enables simulations of hot-electron effects coupled to propagating-wave effects, which could be critical for simulation of next-generation millimeter-wave transistors [11]. Defect dynamics are an important topic for GaN HEMT DC and RF operation, and the FKT solver has been recently utilized to shed light on the fundamental physics of trapping effects. The well-known DC-IV kink effect was explored with FKT, and excellent simulation results reproduced this trapping effect in a particular GaN HEMT [14]. An interesting conclusion from this work was the role of field-assisted barrier defect ionization – a trapping mechanism less commonly considered in the literature [14]. The gate-lag response of GaN HEMTs was also explored using the FKT device simulator. This response is a signature of trapping effects in GaN HEMTs where the drain current transient is monitored while the gate supply voltage is pulsed from an off-state to an on-state with a constant drain supply voltage. FKT simulations of gate lag were experimentally validated with drain current transient measurements of AFRL's 140 nm GaN HEMT technology (GaN140) [15]. The main results of this work are illustrated in Figs. 1 and 2, which are reprinted from [15]. These results indicate the level of accuracy provided by the FKT device simulation framework compared to DC and drain current transient measurements of AFRL's GaN140 technology.

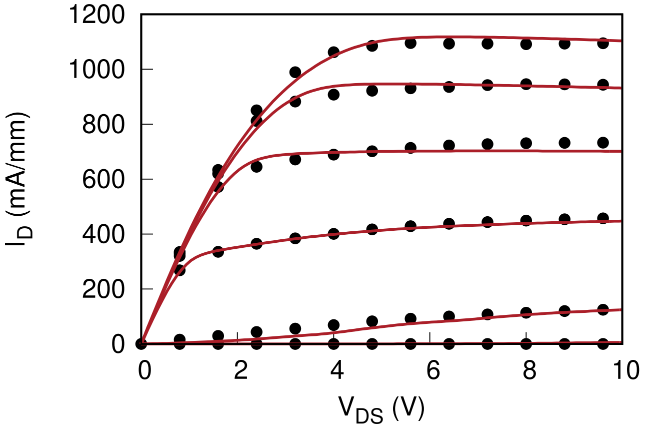

Figure 1: FKT simulated (red lines) and measured (black circles) DC drain currents for the AFRL GaN140 HEMT [15].

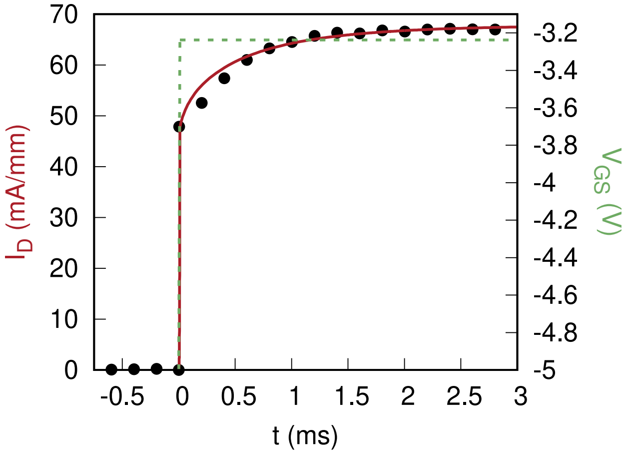

Figure 2: FKT simulated (red line) and measured (black circles) drain current transient response to a pulsed gate supply voltage for the AFRL GaN140 HEMT [15].

3 ASM-HEMT Compact Modeling

Physics-based compact modeling of GaN HEMTs continues to be an important component in the RF integrated circuit design cycle. Two prominent physics-based nonlinear models for GaN HEMTs are the MIT virtual source GaN RF model (MVSG) [16] and the ASM-HEMT [2]. The compact nonlinear modeling research at AFRL has focused on the ASM-HEMT, however, the MVSG could be used in a similar fashion for research projects. At AFRL, the ASM-HEMT was first validated for the AFRL GaN140 HEMT across a broad range of fundamental frequencies from X- to Ka-band using a single model [17], and the nonlinear harmonic modeling of the GaN140 process was validated in [18]. These first results provided confidence in the accuracy of nonlinear models extracted from the internal GaN process at AFRL. Several research projects were initiated after successful demonstration of accurate ASM-HEMT modeling. First, nonlinear embedding modeling of GaN HEMTs was explored in collaboration with The Ohio State University [19, 20]. This type of nonlinear modeling could enable circuit designers to instantly prescribe the harmonic impedances for specific amplifier classes without the need for tedious harmonic active load-pull [21]. Statistical nonlinear modeling [22] and deep learning-based nonlinear modeling [23] of GaN HEMTs are other active research topics which have the goals of analyzing process variations and enabling fast and accurate extraction of GaN HEMTs, respectively. Finally, a recent thrust has been devoted to temperature-dependent nonlinear modeling of GaN HEMTs using the ASM-HEMT [24]. This technique could provide the framework for extrapolation beyond measured ambient temperatures and integrated circuit designs for high-temperature applications. Two results from this work are illustrated in Figs. 3 and 4 which demonstrate the DC and large-signal RF validation of the ASM-HEMT versus ambient temperature, which are reprinted from [24].

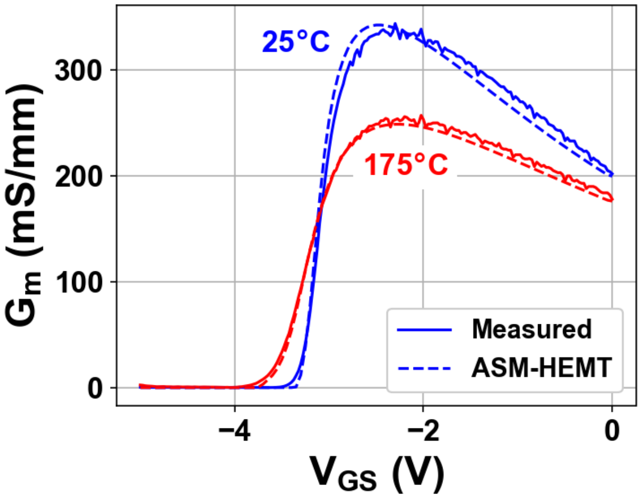

Figure 3: ASM-HEMT simulated (dashed lines) and measured (solid lines) DC transconductance of the AFRL GaN140 HEMT [24].

4 Conclusion

The combination of custom TCAD simulations using FKT and accurate physics-based nonlinear compact modeling provides an excellent framework for understanding the fundamental physics of GaN HEMTs. Future research with the FKT device simulator could explore various state-of-the-art III-nitride transistor technologies, their DC and RF response in extreme environments, and could predict the thermal and trapping signatures of the transistors. For ASM-HEMT modeling, future research could include model extraction from FKT device simulations and nonlinear RF modeling for extreme environment applications.

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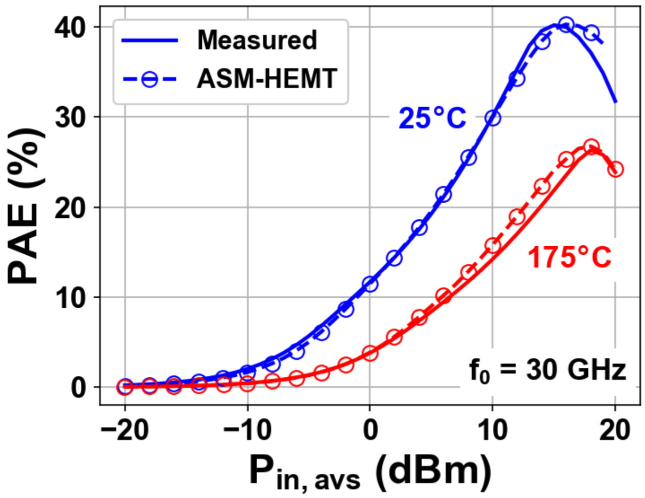

Figure 4: ASM-HEMT simulated (dashed lines) and measured (solid lines) power added efficiency (PAE) of the AFRL GaN140 HEMT [24].

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