A Computational Modeling Method for Performance Optimization of GaN HEMT

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Abstract

This study presents a novel computational modeling method to optimize the microwave power performance of GaN HEMTs. Integrating commercial TCAD software with a physics-based compact model, the method utilizes Harmonic Balance simulations with an accurate trap description, establishing a direct correlation between physical mechanisms, technology designs, and RF large-signal performance. Calibration involves meticulous measurements and characterization techniques, facilitating small and large signal simulations to uncover the impact of buffer and surface traps. In the presented demonstration of this approach, results show that while the inclusion of both traps aligns well with measurements, surface traps alone cause a significant loss of power and efficiency, resulting in a 12% reduction in power-added efficiency and a 2.3 W/mm decrease in output power in the studied GaN HEMT.

Introduction

In recent years, the nitride semiconductor industry has been dedicated to enhancing the performance of GaN HEMT as the technology matures. Despite their remarkable advantages in high-power and high-frequency applications over Si-counterparts, the performance of GaN HEMTs is still hindered by adverse effects, notably electron trapping. The primary tool for physically modeling the intricate mechanisms of electron devices is Technology Computer-Aided Design (TCAD) software. However, TCAD falls short in providing an essential feature for optimizing power performance – accurate Radio Frequency (RF) large-signal simulations. Harmonic Balance (HB) emerges as the sole precise computational method for RF large-signal simulations. The inherent computational complexity within the 2D simulation environment of TCAD renders it incapable of utilizing HB calculations, particularly concerning traps. This results in a disparity between technology optimization and power performance under realistic conditions, such as high-power RF excitation.

This study presents a novel computational modeling approach aimed at optimizing the microwave power performance of GaN HEMTs. Our method integrates commercial TCAD software with a physics-based compact model that employs HB simulations featuring an accurate trap description. This innovative combination facilitates a direct correlation between any physical mechanism or technology design and RF large-signal performance, bridging the existing gap in understanding and enhancing the practical application of GaN HEMTs under high-power RF conditions.

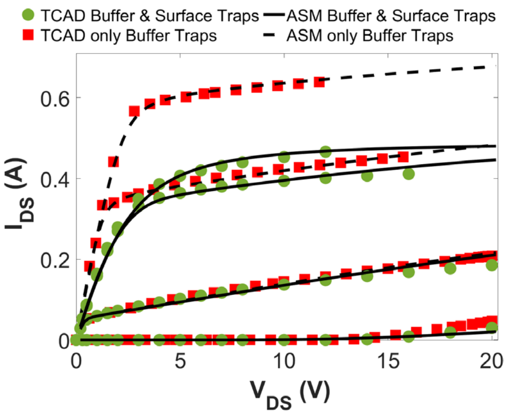

Figure 1 Pulsed output characteristics from TCAD and their simulations by ASM-HEMT for the calibration of the trap model. Two cases are examined, one with only buffer traps and another with buffer and surface traps. $V_{GSQ} = -2$ V, $V_{DSQ} = 20$ V, $V_{GS} = -2…1…1$ V.

Computational Details

Enhancing precision begins with the critical step of accurately calibrating TCAD. While our analysis employs Sentaurus Device, the methodology is universally applicable to any commercial TCAD. Calibration involves a comprehensive approach, utilizing various measurement and characterization techniques, including technology evaluation metrics such as Hall, TLM, DC I-V, and microwave measurements like static and pulsed S-parameters. To precisely calibrate trapping effects, a suitable trap characterization method, such as drain current transient spectroscopy, is imperative.

Subsequently, TCAD introduces variations in technology design and/or physical effects, with the primary objective of examining their impact on RF large-signal performance. At this stage, the compact model becomes instrumental. TCAD generates all essential data for compact model calibration, encompassing DC and pulsed output and transfer characteristics, as well as Y-parameters for intrinsic nonlinear capacitance calibration. Our analysis relies on the industry-standard physics-based compact model ASM-HEMT, equipped with an enhanced trap description covering the majority of trapping effects [2,3]. Upon completing ASM calibration, small and large signal simulations unveil the impact of the studied effects or designs on the RF performance of GaN HEMTs.

Fig. 1 illustrates a segment of the model calibration, showcasing pulsed output curves. TCAD analyzes two cases to create two compact model versions – one with only buffer traps and another with both buffer and surface traps. Pulsed measurements must be under iso-thermal and iso-trapping conditions, necessitating a short pulse width of 250 ns. Our trap model adeptly replicates the current collapse and knee walkout observed in TCAD-produced curves.

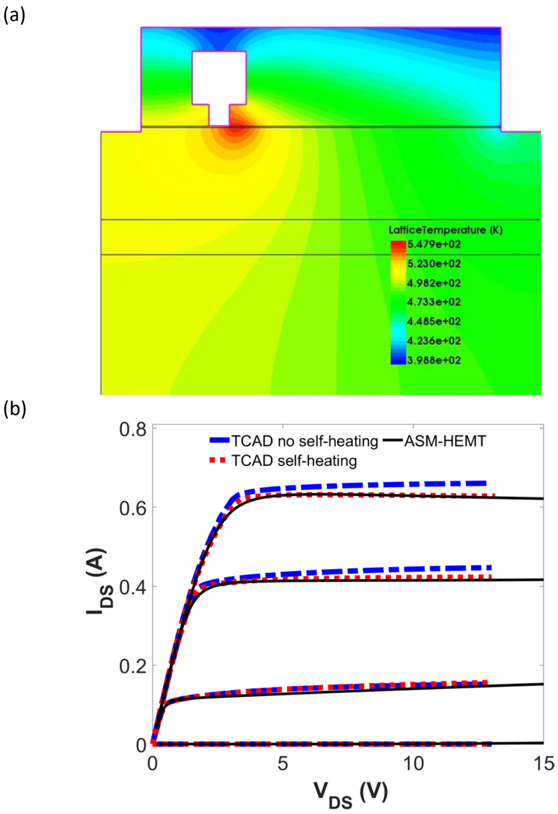

Figure 2 (a) Simulations of lattice temperature during calibration of TCAD for the thermal effects. (b) TCAD-produced DC output characteristics with and without self-heating effect for calibrating the thermal parameters of the compact model ASM-HEMT.

Fig. 2 delves into thermal model calibration, adopting the thermodynamic model of TCAD to explore self-heating. As an example, Fig. 2a depicts the lattice temperature map showing the peak at the gate edge of the drain side. TCAD provides ASM with DC output curves, inclusive of self-heating (Fig. 2b), facilitating the extraction of thermal parameters for the compact model.

Results and discussion

In this phase, we systematically explore the influence of buffer and surface traps on the microwave power performance of the investigated GaN HEMT. To achieve this, we utilize RF power sweep measurements within a load-pull measurement system. Fig. 3 presents measurements at 20 GHz, comparing three versions of the compact model. The first incorporates both buffer and surface traps, the second only integrates buffer traps, and the third excludes traps entirely.

Initially, we observe a remarkable alignment between measurements and simulations when both traps are considered. However, a discernible reduction in power and efficiency becomes evident solely due to the presence of surface traps when we compare the two respective TCAD-based compact models (ASM with both buffer and surface traps and ASM with only buffer traps). The examined device exhibits a notable loss of nearly 12% in power-added efficiency (PAE) and an approximate 2.3 W/mm reduction in output power. This outcome underscores the significant impact of surface traps on the overall microwave power performance of the GaN HEMT, emphasizing the critical need for effective mitigation strategies in practical applications.

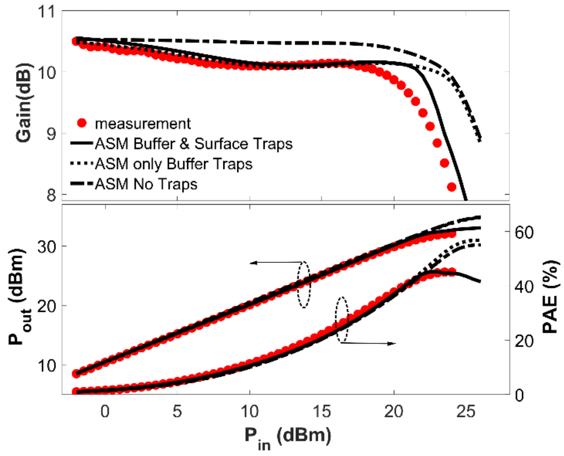

Figure 3 Simulations of RF-power sweep measurements by the TCAD-based compact trap model implemented in ASM-HEMT. Gain, P_{out}, and PAE are shown for three different cases, one with buffer and surface traps, another with only buffer traps, and one with no traps in the model. The fundamental frequency is 20 GHz, $V_{DS} = 20$ V, and $I_{DSQ} \approx 0.05 \cdot I_{DSS}$.

Conclusion

Our computational modeling method, integrating TCAD software with a physics-based compact model, provides valuable insights into optimizing the microwave power performance of GaN HEMTs. By addressing the limitations of TCAD in RF large-signal simulations, we bridge a crucial gap in understanding, enabling a direct correlation between design parameters and performance outcomes. The study's results underscore the significant impact of surface traps on power and efficiency, emphasizing the importance of precise modeling methods toward the total maturity of GaN HEMTs in high-power microwave applications.

Acknowledgments

Financial support by Deutsche Forschungsgemeinschaft (DFG) under grant no. 440549658, and by the German Ministry of Education and Research (BMBF) under the project reference 16FMD02 (Forschungsfabrik Mikroelektronik Deutschland), is gratefully acknowledged. The authors would also like to thank Jens Schmidt for the load-pull measurements.

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