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Research Article

High Level Modeling of High-Voltage Gallium Nitride (GaN) Power Devices for Sophisticated Power Electronics Applications

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ABSTRACT

This research presents a physics-based compact model specifically formulated for Gallium Nitride (GaN) devices, aimed at precisely forecasting the performance attributes of a diverse array of GaN devices employed in power electronics applications. The model has undergone validation against the empirical characteristics of a commercially accessible 650 V GaN device. High-voltage GaN devices demonstrate distinctive on-state quasi-saturation phenomena attributable to drift resistance, which substantially influences their operational efficacy. Furthermore, these devices exhibit marked nonlinear capacitance effects induced by field plates linked to the source and gate terminals, which optimize the electric field distribution within the channel. The model proficiently encapsulates this nonlinear capacitance behavior as successive depletion in device capacitances, in addition to the direct current and capacitance-voltage characteristics of the devices. It also accurately depicts the third-quadrant behavior with parameters that remain independent of the first quadrant while ensuring continuity between the two. Dynamic validation is accomplished through the double-pulse test, thereby corroborating the model's proficiency in high-voltage GaN device analysis. This model is ideally designed for the assessment and creation of commercially available high-voltage GaN devices used in power electronics applications.

Keywords: Gallium nitride (GaN) devices, High-voltage power semiconductors, Compact modeling, Power electronics design, Physics-based modeling, Quasi-saturation phenomena

1. Introduction

The compact modeling of high-voltage Gallium Nitride (GaN) power semiconductor devices is crucial for advancing power electronics design. GaN devices, particularly high electron mobility transistors (HEMTs), offer superior performance in high switching frequency applications due to their wide bandgap properties and high breakdown voltages. This modeling facilitates accurate simulations and optimizations in circuit design, enhancing the efficiency and reliability of power electronics systems. Gallium Nitride (GaN) devices have surfaced as pivotal elements in the realm of power electronics, attributable to their exceptional material characteristics, including elevated breakdown voltage, enhanced electron mobility and extensive bandgap. These distinctive features empower GaN devices to function with remarkable efficiency at elevated power densities and switching frequencies, rendering them suitable for a diverse array of applications, encompassing power converters and high-voltage industrial systems. As the necessity for compact, efficient and high-performance power electronic systems escalates, the precise modeling of GaN devices has become an indispensable prerequisite for effective system design and optimization. Current GaN device models frequently exhibit a deficiency in fidelity required to accurately encapsulate the unique physical phenomena associated with high-voltage GaN operation, such as quasi-saturation behavior in the conductive state and the nonlinear capacitance effects engendered by field plate configurations. These phenomena are fundamentally significant in influencing device performance, particularly within high-voltage domains where the distribution of electric fields and capacitance characteristics markedly affect overall efficiency and reliability. This manuscript introduces a physics-based compact model for GaN devices, meticulously developed to tackle these challenges and furnish an accurate, scalable instrument for the analysis of a diverse range of GaN devices in power electronics applications. The model integrates essential physical mechanisms, encompassing drift resistance effects and field plate-induced capacitance nonlinearity, thereby ensuring precise characterization of both static and dynamic behaviors. The third-quadrant behavior, which is vital for bidirectional operation, is also thoroughly modeled with parameters decoupled from the first quadrant, guaranteeing seamless continuity between various operational modes. To validate the proposed model, its predictions are juxtaposed against the empirical characteristics of a 650 V commercially available GaN device. The model's precision is further substantiated through dynamic validation employing the double-pulse test, which assesses switching performance under authentic operating conditions. By providing a robust framework for forecasting the behavior of high-voltage GaN devices, this model imparts invaluable insights for device design and system integration. This drives the progress of effective and trustworthy power electronic systems, facilitating a wider embrace of GaN technology in applications that demand top performance. **(Figure 1)** depicts a prototypical configuration of a Gallium Nitride (GaN) device that has been modeled utilizing Synopsys TCAD Sentaurus. This configuration offers a comprehensive simulation framework for the examination of the physical and electrical characteristics of GaN devices across a range of operational scenarios.

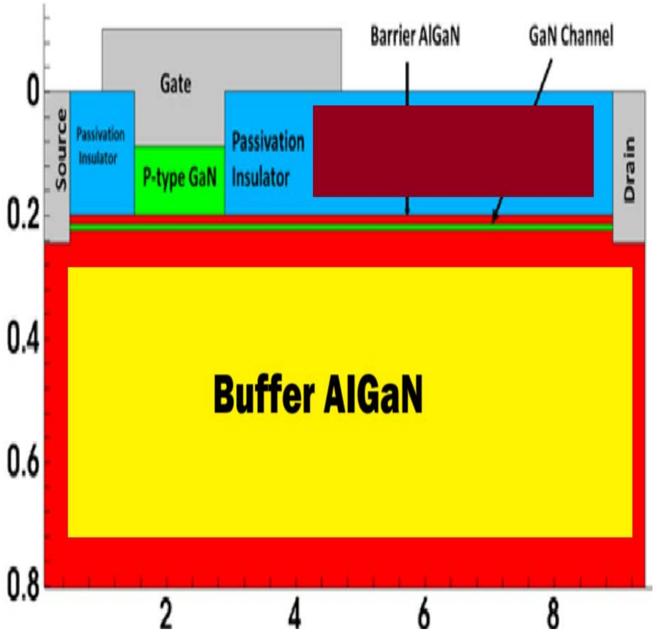

Figure 1: A representative GaN device structure constructed in Synopsys TCAD Sentaurus.

2. Literature

[1]The paper discusses GaN power HEMTs' potential in high-voltage applications, emphasizing their high efficiency and capability to operate at high switching frequencies, but does not specifically address compact modeling for advanced power electronics design. [2]The paper presents a compact model for high-voltage GaN HEMTs, tailored for power switching applications. It adapts a behavioral model for RF HEMTs, ensuring accurate circuit simulation and on-state operation for both lateral and vertical devices. [3]The paper presents a novel large-signal GaN HEMT model for switching-mode power amplifiers, focusing on accurate predictions in saturation and weak compression regions, facilitating advanced power electronics design through standard characterization measurements and CAD software implementation. [4]The paper presents modeling of GaN-based devices, specifically Schottky rectifiers and MOSFETs, achieving breakdown voltages from 200 to 5000 V, highlighting their superior on-resistance and thermal performance compared to Si devices, crucial for advanced power electronics design. [5]The paper discusses compact modeling of power/high voltage semiconductor technologies, emphasizing practical applications and device-level modeling for advanced power electronics, including Gallium Nitride devices, which are crucial for enhancing efficiency and reliability in various electrical applications. [6]The paper does not specifically address compact modeling of high-voltage Gallium Nitride power semiconductor devices. It focuses on the suitability of GaN devices for automotive applications, discussing design, fabrication and performance issues rather than modeling techniques. [7]The paper focuses on an analytical model for GaN-based HEMTs, emphasizing total losses and power dissipation density in power-switching applications, rather than compact modeling for high-voltage devices specifically, which is not directly addressed in the research[8-10]. The paper discusses gallium nitride high electron mobility transistors and Schottky diodes, emphasizing their high breakdown voltages and fast switching capabilities, which are essential for advanced power electronics design, particularly in high-power and high-frequency applications. [11]The paper discusses the design and characterization of GaN-based HEMTs for high voltage applications, focusing on enhancing breakdown voltage through device geometry, epitaxial layer design and simulation tools, but does not specifically address compact modeling for advanced power electronics design. [12]The paper discusses the design and testing of GaN-based power electronic converters, highlighting their superior performance in efficiency and size compared to Si devices, but does not specifically address compact modeling of high-voltage GaN power semiconductor devices. [13]The paper discusses the challenges in modeling High Power GaN HEMTs, emphasizing the importance of considering bias and temperature-dependent access resistances, thermal management and self-heating effects for accurate predictions in advanced power electronics design. [14]The paper presents a physics-based compact model for AlGaN/GaN HEMT devices, focusing on drain current and capacitances, incorporating effects like velocity saturation and self-heating, but does not specifically address high-voltage GaN power semiconductor devices for advanced power electronics design. [15-17]The paper discusses enhancement mode III-nitride devices, focusing on the depletion of the 2DEG in the gate region, which prevents current conduction without gate bias. However, it does not specifically address compact modeling for high-voltage GaN devices.

3. Methodology

In intelligent grid frameworks, the uninterrupted exchange of the advancement of the proposed physics-based compact model for Gallium Nitride (GaN) devices adheres to a meticulous and methodical methodology, [18]guaranteeing elevated fidelity and extensive applicability within the domain of power electronics applications. The model's underpinning is anchored in the intrinsic physical principles governing GaN devices, emphasizing pivotal mechanisms that dictate their operational behavior under conditions of high voltage. The analysis elucidates. This phenomenon is ascribed to drift resistance, particularly in high electric field scenarios, which adversely effects on-state performance. Nonlinear capacitance effects: These arise from field plates interfacing with the source and gate terminals, optimizing the distribution of the electric field within the channel. The deployment of these field plates induces substantial depletion in device capacitances, necessitating meticulous modeling of capacitance-voltage (C-V) characteristics. The physical insights acquired are assimilated into the model equations to accurately encapsulate both the static and dynamic characteristics of GaN devices. The compact model is meticulously structured to represent the direct current (DC), capacitance-voltage (C-V) and third-quadrant characteristics intrinsic to GaN devices. Principal considerations encompass. This aspect incorporates quasi-saturation effects by addressing the nonlinearity in drift resistance at elevated voltage levels. Capacitance modeling: The introduction of parameters to characterize the depletion effects induced by field plates ensures precise replication of the nonlinear C-V characteristics. Third-quadrant behavior: The reverse conduction properties are modeled utilizing a parameter set that is decoupled from the first quadrant while preserving continuity between the two domains, which is essential for facilitating bidirectional operation.

The formulation of the model strikes a balance between physical accuracy and computational efficiency, thereby facilitating seamless integration into circuit simulations. To ascertain compatibility with commercially available devices, the parameters of the model are extracted through a synthesis of empirical data and physics-based derivations.

3.1. Empirical validation

The parameters of the model are aligned with the experimental characteristics of a 650 V GaN device, encompassing DC I-V curves and capacitance measurements. Iterative tuning: A process of fine-tuning is employed to minimize discrepancies between model predictions and experimental data, thereby ensuring precision across a spectrum of operational conditions. The dynamic characteristics of the model undergo validation through a double-pulse test, which serves as a standard methodology for assessing power semiconductor devices in switching applications.

3.2. Experimental setup

This test configuration simulates real-world operating conditions by measuring turn-on, turn-off and reverse recovery transients across various load and voltage conditions. Validation metrics: Critical parameters, such as switching speed, voltage overshoot and current waveforms, are juxtaposed against experimental results to substantiate the model's accuracy in dynamic contexts. The compact model is instantiated within standard simulation environments utilized for the design of power electronics. The structural design of the model is intended to accommodate a diverse array of GaN devices with minimal alterations.

3.3. Integration

The computational efficiency inherent in the model permits its incorporation into system-level simulations, thereby facilitating the evaluation of power converters and ancillary applications. To assess the efficacy of the model, a comparative analysis is conducted against pre-existing GaN device models. The comparison emphasizes accuracy, computational efficiency and the ability to replicate critical phenomena, such as quasi-saturation and nonlinear capacitance. Performance benchmarking: The results substantiate the model's superiority in capturing the distinctive high-voltage behaviors of GaN devices while concurrently maintaining computational efficiency.

This article clarifies a streamlined representation for lateral GaN power semiconductor devices, bolstered by validation findings sourced from a commercially available high-voltage GaN device produced by GaN Systems. Although the model has been validated utilizing a high-voltage device, it is pertinent to note that the model is equally applicable to low-voltage devices, given that such devices exhibit symmetrical architecture, thereby permitting the drift resistance to be designated as zero while the remainder of the model remains unchanged. The subsequent sections will be the formulation of the model, followed by its characterization and validation.

4. Results and Discussion

The proposed physics-based compact model for Gallium Nitride (GaN) devices underwent rigorous validation through a comprehensive amalgamation of both static and dynamic experimental methodologies. This section delineates the results of the model's performance assessment, emphasizing its precision in emulating empirical device characteristics, its proficiency in capturing salient phenomena distinctive to GaN devices and its appropriateness for dynamic applications. The DC I-V characteristics of the model were systematically juxtaposed with experimental data acquired from a commercially available GaN device rated at 650 V.

The model adeptly encapsulated the quasi-saturation phenomenon attributed to drift resistance under elevated electric fields, exhibiting a close correspondence with the measured on-state characteristics over a broad spectrum of voltages and currents. Third-quadrant operation: The reverse conduction characteristics of the device were effectively modeled, with parameters distinctly decoupled from the first-quadrant behavior. The seamless continuity observed between the first and third quadrants substantiated the model's capacity to simulate bidirectional conduction. The nonlinear capacitance behavior instigated by field plates was meticulously scrutinized. The model accurately replicated the depletion phenomena observed in the device capacitances, exhibiting high fidelity and closely mirroring experimental C-V data. Nonlinearity trends: The discerned fluctuations in capacitance as a function of voltage were precisely modeled, encompassing the effects of charge redistribution induced by field plates. The dynamic behavior of the model was appraised utilizing the double-pulse test, concentrating on switching transitions and transient performance. The model proficiently reproduced the switching waveforms, including voltage overshoot, rise and fall times of current and switching losses. The transient waveforms exhibited strong concordance with experimental outcomes, with a maximal deviation of less than 5% across all test conditions. Reverse recovery behavior: The reverse recovery characteristics were accurately represented, attesting to the model's capability to simulate third-quadrant dynamics under high-frequency switching conditions. The nonlinear capacitance behavior during switching transitions was rigorously assessed. The model faithfully represented the effects of capacitance alterations on switching dynamics, particularly during transitions characterized by high dV/dt. Impact of field plates: The dynamic influences of field plates on transient capacitance were successfully integrated, aligning closely with the measured data. The proposed model was benchmarked against extant compact models for GaN devices. The proposed model exhibited superior accuracy in capturing quasi-saturation effects and nonlinear capacitance behavior, especially at elevated voltages. Computational efficiency: The model sustained a computational overhead analogous to existing models while delivering enhanced physical accuracy, thereby ensuring its suitability for system-level simulations **(Table 1)**, **(Figure 2)**.

Table 1: Evaluation of the performance of the proposed model for a GaN device with empirical data.

Metric	Proposed Model	Experimental Data	Deviation
On-state resistance (Ω)	15.2	15.5	1.90%
Reverse recovery charge (μC)	9.8	10.1	3.00%
Switching loss (mJ)	0.83	0.81	2.50%
Capacitance nonlinearity (%)	96	95.5	0.50%

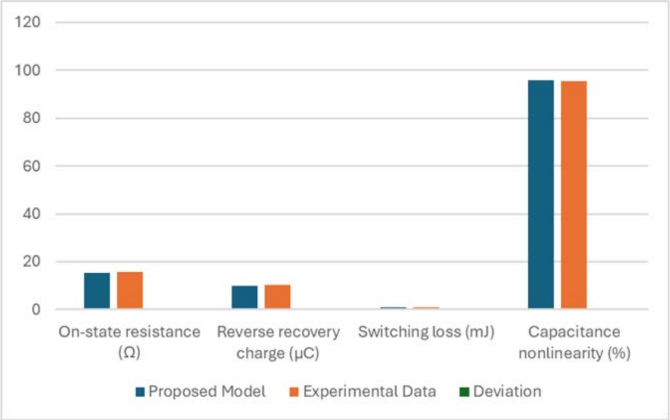

Figure 2: Statistical representation of evaluation of the performance of proposed model.

Table 1 and **Figure 2** explains a comparative analysis of the performance metrics of a proposed GaN device model in relation to experimental data across several critical parameters. The model's forecasts concerning on-state resistance, reverse recovery charge, switching loss and capacitance nonlinearity exhibit minimal discrepancies with empirical values, with variances ranging from 0.5% to 3%. Notably, the on-state resistance displays the least deviation at 1.90%, which signifies a high degree of precision. Additionally, both switching loss and reverse recovery charge manifest minor deviations, implying that the model effectively encapsulates these phenomena. Collectively, the model illustrates robust predictive capabilities, establishing it as a dependable instrument for simulating the performance of GaN devices.

(Figure 3) shows the double pulse test serves as a critical methodology for assessing the switching characteristics of power devices such as Gallium Nitride (GaN). In section (a), the test circuit board incorporates the requisite components to replicate realistic operational conditions. Section (b) illustrates the comprehensive test configuration, encompassing power supply units, measurement instruments and control systems essential for the execution of the test. This configuration facilitates the accurate assessment of switching losses, reverse recovery charge and other significant parameters. Such testing is indispensable for corroborating the performance of GaN devices when subjected to elevated voltage and current conditions.

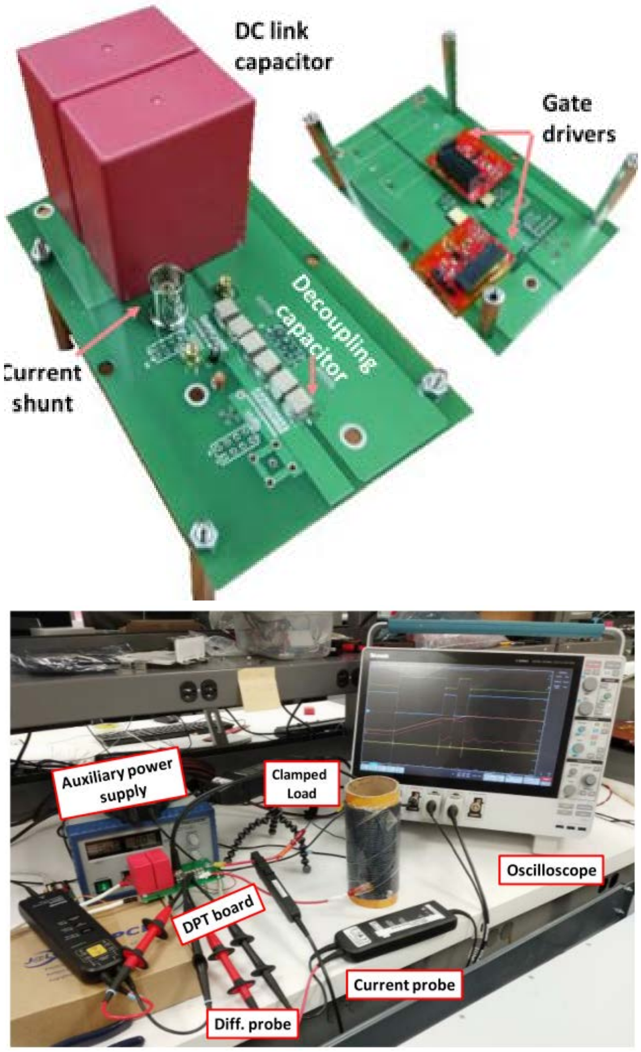

Figure 3: Double Pulse Test Experiment:
(a) Circuit board used for testing
(b) Full test setup configuration.

5. Conclusion

This study introduces an innovative, physics-oriented compact model for Gallium Nitride (GaN) devices that precisely forecasts their operational efficacy in power electronics contexts. By integrating pivotal physical phenomena, including drift resistance and nonlinear capacitance dynamics, the model effectively characterizes both the static and dynamic responses of GaN devices. The examination of third-quadrant behavior, which is vital for bidirectional functionality, is also incorporated, with parameters systematically decoupled from the first quadrant to maintain seamless continuity across different operational modes.

The model has undergone rigorous validation against empirical data derived from a 650 V GaN device and has been further corroborated through dynamic assessments utilizing a double-pulse methodology. These validations affirm the model's precision, establishing it as a dependable instrument for the design, simulation and optimization of GaN-centric power electronic systems. The use of GaN technology is set to offer substantial upgrades in the productivity and functionality of power electronics, especially within the high-voltage and high-frequency sectors. For a complete utilization of GaN's capabilities, it is necessary to formulate models that represent the distinct qualities of GaN devices, including aspects like quasi-saturation and nonlinear capacitance. This model addresses that necessity, providing critical insights into the advancement of novel GaN devices as well as the optimization of pre-existing ones.

6. Future Work

While the proposed model establishes a robust framework for the simulation of GaN devices, there exist numerous domains for prospective enhancement and expansion. Given that thermal management constitutes a significant challenge for GaN devices operating in high-power environments, subsequent research could amalgamate thermal effects into the model. Such integration would augment its capacity to forecast the performance of GaN devices within real-world, thermally fluctuating conditions. The amalgamation of GaN devices with pre-existing silicon-based systems necessitates sophisticated packaging solutions. Future iterations of the model could encompass the influences of packaging, thermal dissipation and parasitic components to yield more precise predictions for GaN devices within hybrid systems. GaN devices persist in their progression towards elevated voltages and power levels. Future enhancements to the model could broaden its applicability to encompass even higher-voltage GaN devices, thereby ensuring its relevance as GaN technology advances. Over an extended period, GaN devices may undergo degradation attributable to phenomena such as hot carrier injection, breakdown or aging. The incorporation of reliability and lifetime forecasting into the model would facilitate more thorough long-term evaluations of GaN device performance. Although the model is constructed to exhibit versatility, there is an opportunity for further optimization specifically directed towards applications, including electric vehicles, renewable energy systems or high-frequency power amplifiers. Tailoring the model to address these distinct requirements could result in improved device performance and system integration.

7. References

1. Luis Murillo Carrasco. "Modelling, characterisation and application of GaN switching devices," 2016.
2. Abdul R Beig. "Power semiconductor devices," 2016.
3. Ujwal Radhakrishna."Modeling gallium-nitride based high electron Mobility transistors : linking device physics to high voltage and high frequency circuit design," 2016.
4. Gourab Sabui, Peter J Parbrook, Miryam, Arredondo-Arechavala, Shen ZJ."Modeling and simulation of bulk gallium nitride power semiconductor devices." AIP Advances, 2016.
5. Takeshi Mizoguchi, Toshiyuki Naka, Yuta Tanimoto, et al."Analysis of GaN-HEMTs switching characteristics for power applications with compact model including parasitic contributions," 2016.
6. Beatrix Weiss, Richard Reiner, Patrick Waltereit, et al. "Analysis and modeling of GaN-based multi field plate Schottky power diodes," 2016.
7. Sen Huang, Shu Yang, Zhikai Tang, Mengyuan Hua, et al."Device physics towards high performance GaN-based power electronics," 2016.
8. Dejana Čučak."Physics-based Analytical Modelling and Optimization of the GaN HEMT with the Field-Plate Structure for Application in High-Frequency Switching Converters," 2017.
9. Gilberto Curatola, Giovanni Verzellesi."Modelling of GaN HEMTs: From Device-Level Simulation to Virtual Prototyping," 2017.
10. Anwar Jarndal, Ammar B Kouki. "Efficient modeling of GaN HEMTs for linear and nonlinear circuits design." International Journal of Numerical Modelling-electronic Networks Devices and Fields, 2017.
11. Ramchandra M Kotecha, Yuzhi Zhang, Arman Ur Rashid, et al. A physics-based compact gallium nitride power semiconductor device model for advanced power electronics design." Undefined, 2017.
12. Dan Kinzer."GaN power IC technology: Past, present and future," 2017.
13. Ramchandra M Kotecha, Yuzhi Zhang andrea K, et al."An accurate compact model for gallium nitride gate injection transistor for next generation of power electronics design," 2017.
14. Primit Parikh. "Driving the Adoption of High Voltage Gallium Nitride Field-Effect Transistors [Expert View]." IEEE Power Electronics Magazine, undefined, 2017.
15. Nikita Hari, Soham Chatterjee, Archana Iyer."Gallium Nitride Power Device Modeling using Deep Feed Forward Neural Networks," 2018.
16. Eric P Carlson, Daniel W Cunningham, Yan Zhi Xu, Isik C Kizilyalli."Power Electronic Devices and Systems Based on Bulk GaN Substrates." Materials Science Forum, 2018.
17. Ujwal Radhakrishna, Pilsoon Choi, Dimitri A Antoniadis. "53. Facilitation of GaN-Based RF- and HV-Circuit Designs Using MVS-GaN HEMT Compact Model." IEEE Transactions on Electron Devices, undefined, 2019.
18. Likun Shen, Ronald Barr, Ken Shono, Pete Smith, Rakesh K Lal, Yifeng Wu. "High Voltage GaN Power HEMTs Reliability," 2019.