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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 13, Issue 1 | Pages 50-54 | e-ISSN: 2347-470X

Impact on Breakdown Voltage for AlGaN Channel E-HEMT Device used with the DC Boost Converter Circuit

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ABSTRACT- In this paper, the impact on breakdown performance is demonstrated by the coupled operation of the E-mode AlGaN Channel HEMT for DC Boost Converter Circuit. CAD optimization of individual devices on the process and E-mode HEMT device level affects the circuit performance DC Boost Converter Circuit. The field plate length of Fp=2.7 µm results in the steady current at the voltage of VBV=790 V, whereas the field plate length of 3.6 µm results breakdown voltage of more than 1k volts. Circuit voltages at various nodes, Current in HEMT and SBD for switching cycle, and also the power dissipation is evaluated for two various doping concentrations 3E15(/cm3) and 9E15(/cm3). As a result, the dependency of power losses in the circuit on the physical parameters of the process stage is demonstrated.

Keywords: AlGaN Channel HEMT, DC Boost converter, Breakdown Voltage (VBV).

ARTICLE INFORMATION

Author(s): Godwinraj D, Godfrey D, P. Sundararaman, V. Nandagopal;

Received: 05/10/2024; **Accepted**: 14/01/2025; **Published**: 30/03/2025;
e-ISSN: 2347-470X;
Paper Id: IJEER 0510-05;
Citation: 10.37391/ijeer.130108
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-13/ijeer-130108.html

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1. INTRODUCTION

Gallium Nitride (GaN) and its related alloys, such as Aluminium Gallium Nitride (AlGaN), have emerged as promising materials for high-power, high-frequency electronic devices. The distinctive characteristics of these wide-bandgap semiconductors, including high electron mobility, high breakdown voltage, and excellent thermal conductivity, have facilitated the development of AlGaN channel E-HEMTs that excel in power and efficiency performance. Furthermore, the rapid progress in GaN-based device fabrication and the commercialization of GaN-based optoelectronics have accelerated the advancement of these high-power RF el The AlGaN channel in HEMT devices exhibits several advantages compared to traditional semiconductor materials. GaN-based HEMTs have achieved the highest operating frequencies among wide-bandgap semiconductor devices, a result of the exceptional transport characteristics of the two-dimensional electron gas formed at the AlGaN/GaN heterointerface and the substantial sheet carrier concentration in the device channel. Furthermore, Monte Carlo simulations have suggested that short-channel GaN devices can outperform even GaAs devices, further underscoring the potential of AlGaN-based channel structures. One of the key challenges in the development of AlGaN-based HEMTs has been optimizing the barrier layer thickness. Studies have shown that employing a thinner 3-nm-thick In0.18Al0.82N barrier layer can enable the achievement of an fmax of 287 GHz and a f_T of 228 GHz in a 45-nm-gate In0.18Al0.82N/AlN/GaN MESHI-HEMT fabricated on GaN substrates. This indicates that the thickness of the AlGaN barrier layer is a critical parameter in balancing the trade-off between high-frequency performance and device reliability [4-5].

Improving the performance of the HEMT device is achieved by enhancing the Breakdown voltage, it also contributes to an increase of power density in HEMTs. To enhance the breakdown voltage in HEMT, employing another wide bandgap semiconductor for the channel layer is an effective method instead of the conventional GaN channel layer [9]. The Breakdown characteristics make E-mode AlGaN Channel HEMTs good candidates for switching applications. The coupling with the DC boost converter circuit has been recently widely investigated utilizing power analysis for very high-power applications. However, DC boost converters were restricted to a 1-MHz switching frequency, which resulted in large sizes of passive components and a limited version for converter bandwidth. This coupled E-AlGaN Channel HEMT and DC converter boost circuit targeting radio frequency (RF) applications like dynamic drain bias power amplifiers. Higher the doping concentrations leads to the higher current conductivity with deeper 2-Dimensional Electron Gas which intern lead to the maximum distribution around the junction. In contrast, the lower doping concentration can lead to the better stability over high temperatures with current handling capability and improved transconductance. the doping concentration in the AlGaN barrier layer of AlGaN/GaN HEMT devices shows significant improvements in the formation and stability of the 2DEG, voltage distribution, breakdown voltage, current handling, and thermal stability [6-8].

The DC converter boost circuit and connected E-AlGaN channel High Electron Mobility Transistor (HEMT) are primarily intended to improve radio frequency (RF) applications performance, particularly concerning dynamic drain bias power amplifiers. By using the E-AlGaN channel HEMT's enhanced electron mobility and high current capabilities, this integration ensures effective signal amplification at high frequencies. This combination is particularly beneficial in RF applications where maintaining signal integrity and power efficiency is crucial, such as in wireless communication systems and advanced radar technologies. The result is a robust and high-performance solution that addresses the demanding requirements of modern RF electronics [9-11].

This study investigates methods to enhance the performance of the integrated HEMT-based boost converter system. The breakdown voltage of the AlGaN E-mode HEMT device is improved through the implementation of multiple field plates. Furthermore, the device structure is optimized in conjunction with the boost converter circuit design. The power losses are analysed by varying the doping of the Schottky barrier diode, and the dependency of power losses on doping levels is evaluated. This multi-pronged approach aims to enhance the overall efficiency and operational capabilities of the integrated HEMT-based boost converter system electronics [1-3].

2. NOMENCLATURE AND DEVICE MODEL

The behaviour of the current in AlGaN channel high-electron-mobility transistors and Schottky barrier diodes can be understood by considering the interdependent relationships between their constituent components.

Table 1. Parameters used in the Simulation of AlGaN/GaN HEMT

f_{sw}	Switching Frequency
p_{sw}	Switching losses
C_{gs}	Gate-Source Capacitance
μ_n	Electron mobility
N_D	Doping Concentration
Eg	Band Gap
E_f	Fermi Energy Level
V_s	Surface Potential
V_c	Channel Potential
L_{FP}	Field plate length

The current is dependent on the electron mobility μ_n and doping concentration N_D, which are described by the Poisson equation and the transport equations governing the dynamics of electrons and holes. the HEMT drain current I_D is given as

$$I_D = \frac{W}{L} C_{gs} \mu_0 \frac{N_{ref}}{(N_D + N_{ref})} (V_{GS} - V_{TH})^2 \qquad (1)$$

the current I_S in Schottky Barrier Diode (SBD) is governed by thermionic emission as

$$I_S = I_0 \, e^{(\frac{V_D}{nV_T} - 1)} \qquad (2)$$

Whereas, $I_0 = A^* T^2 \, e^{(-\frac{\phi B}{KT})}$

The total current in the HEMT-SBD system can be expressed as the sum of the individual component currents during the switching cycle, where I_total= I_D + I_S. The power losses in this system can be calculated as the sum of the products of the voltage and current for each component, given by P_loss= V_D I_D+ V_S I_S, where V_D and V_S represent the voltages across the HEMT and SBD, respectively.

$$I_{total} = \frac{W}{L} C_{gs} \mu_0 \frac{N_{ref}}{(N_D + N_{ref})} (V_{GS} - V_{TH})^2 + I_0 \, e^{(\frac{V_D}{nV_T} - 1)} \qquad (3)$$

The parameters μ_0, A^*, W, L and V_GS will be involved in the calculation of the current I_S in the Schottky Barrier Diode (SBD) and also the HEMT drain current I_D [12]. The theoretical calculations conclude that the Higher doping concentrations will result in increase in the current I_S in the Schottky Barrier Diode (SBD) and also the HEMT drain current I_D.

3. DEVICE SIMULATION

The device structure of AlGaN Channel HEMT includes 2μm of Al0.07Ga0.93N buffer layer, 15 nm of AlGaN channel, 10 nm of Al0.15Ga0.85N first supply layer, 10 nm of Al0.07Ga0.93N piezo neutralization layer, 25 nm of Al0.15Ga0.85N second supply layer, the source–gate and gate-drain distance are 1μm and 15μm, respectively, and the gate length is set to 1μm. The structure of AlGaN/GaN Channel HEMT is depicted in *Figure 1*.

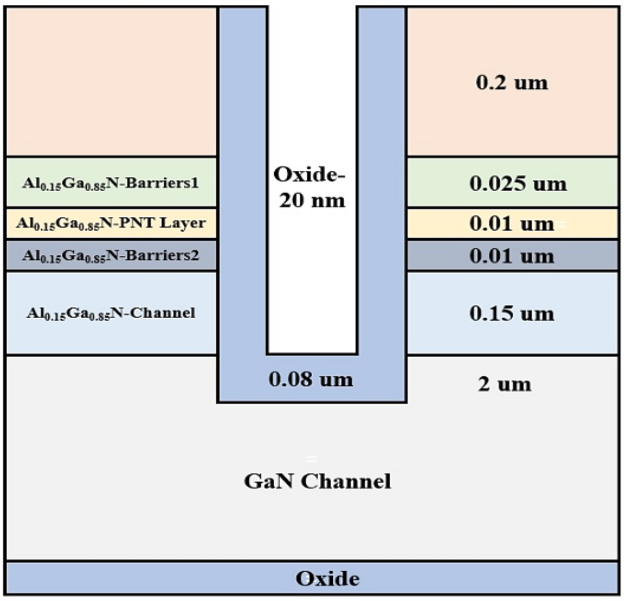

Figure 1. Structure of AlGaN/GaN channel HEMT with Oxide Thickness, 2 Barrier layers, and PNT Layer

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Research Article | Volume 13, Issue 1 | Pages 50-54 | e-ISSN: 2347-470X

The analysis considered two different doping concentrations: 3E15(/cm3) and 9E15(/cm3). The simulation results include the time-varying circuit voltages at various nodes, the currents flowing through the HEMT and the Schottky Barrier Diode during the switching cycle for the different doping concentrations, as well as the power dissipated in the HEMT over time for the varying doping levels.

Table 2. Schematic Structure Layers, thickness, Materials and its Length Details used in the Simulation

Layers	Thickness	Electrodes	Length
AlGaN barrier 1	10 nm	Gate Length (L_G)	1 µm
AlGaN buffer	2 µm	Field Plate Length (L_{FP})	0.9 µm – 3.6 µm
AlGaN barrier 2	10 nm	Source -Gate spacing (L_{SG})	1 µm
$Al_{0.07}Ga_{0.93}N$ PN	25 nm	Gate-Drain spacing (L_{GD})	15 µm
AlGaN channel	15 nm	-	-

performance capabilities. The 2 µm Al0.07Ga0.93N buffer layer facilitates the growth of subsequent layers with minimal defects. Furthermore, the 10 nm Al0.07Ga0.93N piezo neutralization layer is essential for mitigating the detrimental effects of piezoelectric polarization, which can otherwise compromise device reliability and performance. Lastly, the 15 nm AlGaN channel layer serves as the critical component that endows the HEMT with its high-electron mobility characteristics, a vital attribute for achieving the desired high-frequency and high-power operation.

4. RESULTS AND DISCUSSIONS

The normalized ID-VD curves of AlGaN Channel HEMT with different field plates demonstrate superior electron mobility and high current capability, essential for high-power applications as depicted in *Figure 2.*

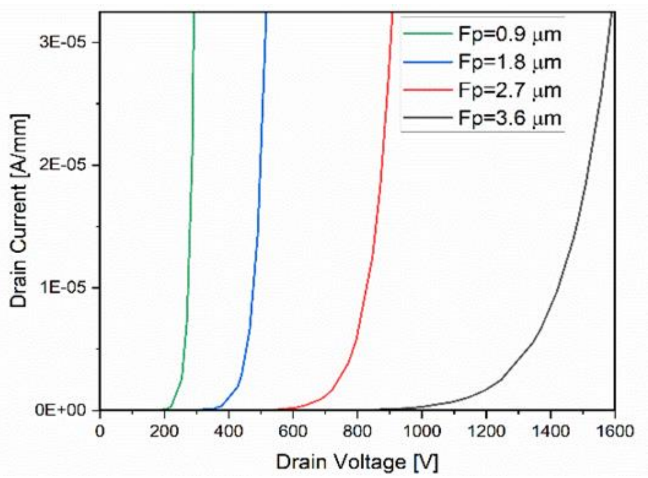

Figure 2. Normalized ID-VG curves to the different field plate lengths

Field plate highly enhances the electron mobility in AlGaN/GaN HEMTs by lowering the electric field distribution around the gate. Improved electron mobility is an important aspect for enhancing the mobility and efficiency of the HEMT, allowing it to function at high frequencies with low power loss. Analyzing the circuit voltages at various nodes in AlGaN/GaN high electron mobility transistors as a function of time is crucial for understanding the device's electrical properties and performance [13]. The Field Plate will distribute the current, by reducing the high electric peak with uniform distribution leads to the maximum breakdown voltage.

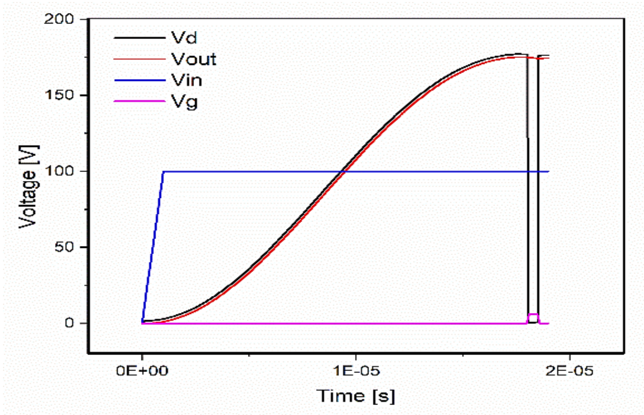

Figure 3. Circuit voltages at various nodes depending on time for doping concentration 3E15 (/cm3)

Still, it has some of the challenges because of its device length and parasitic capacitance and fabrication possibilities. The trade-off between the design has been to effectively managed for breakdown, high current capability and high-power switching. The doping concentration in the AlGaN barrier layer significantly influences the formation of the two-dimensional electron gas and the resulting voltage distribution within the device. *Figure 3*, shows the extracted Circuit voltages at various nodes depending on time for doping concentration 3E15(/cm3), and Circuit voltages at various nodes depending on time for doping concentration 9E15(/cm3) are depicted in Figure 4. It could be observed that the AlGaN channel is formed below the oxide region. Current in HEMT and SBD during the switching cycle for doping concentration 3E15(/cm3) and Current in HEMT and SBD during the switching cycle for doping concentration 9E15(/cm3) are mentioned in *figures 5 and 6.*

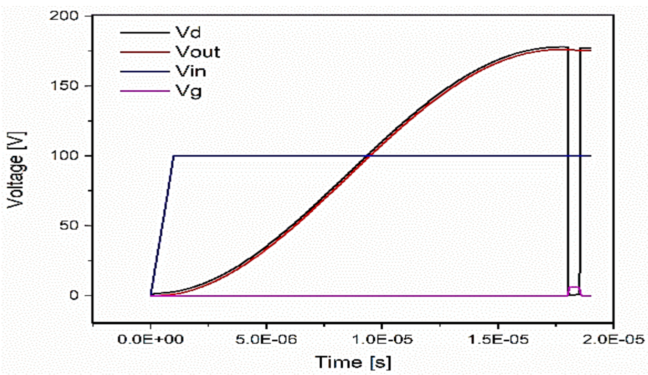

Figure 4. Circuit voltages at various nodes depending on time for doping concentration $9E^{15}$ (/cm^3)

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The variation in the doping concentration in the AlGaN barrier layer of AlGaN/GaN HEMT devices shows significant improvements in the formation and stability of the 2DEG, voltage distribution, breakdown voltage, current handling, and thermal stability.

The power is dissipated during the switching cycle on/off phases. The reverse current of the SBD during the on-switching contributes to more power dissipated in the transistor during this phase. Reducing the reverse current recovery of the SBD, therefore, leads to a reduction of power losses in the transistor. Reducing reverse current recovery leads low current flows in the reverse direction while switching, directly the reason to a lowering in power loss while the on-switching phase. The power dissipation in High Electron Mobility Transistors is heavily influenced by the doping concentration of the device. Higher doping concentrations generally lead to increased power dissipation over time due to the elevated carrier densities, which result in more pronounced thermal effects within the devices.

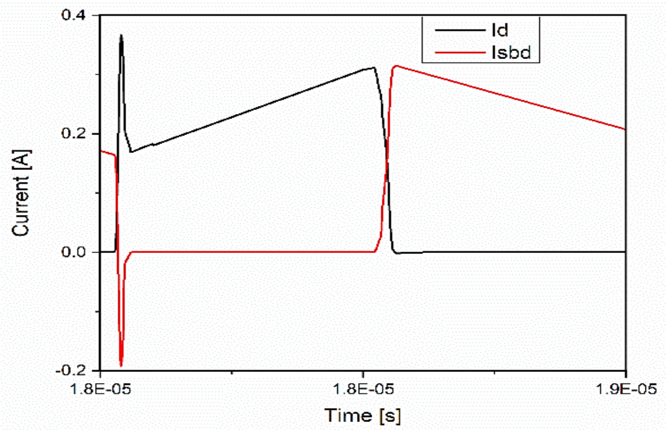

Figure 5. Current in HEMT and SBD during the switching cycle for doping concentration 3E15 (/cm3)

This elevated power dissipation can contribute to higher operating temperatures and potentially reduced device reliability. Conversely, lower doping concentrations can help mitigate the overall power dissipation, but this approach may compromise the device's performance characteristics, such as reduced current handling capability and transconductance.

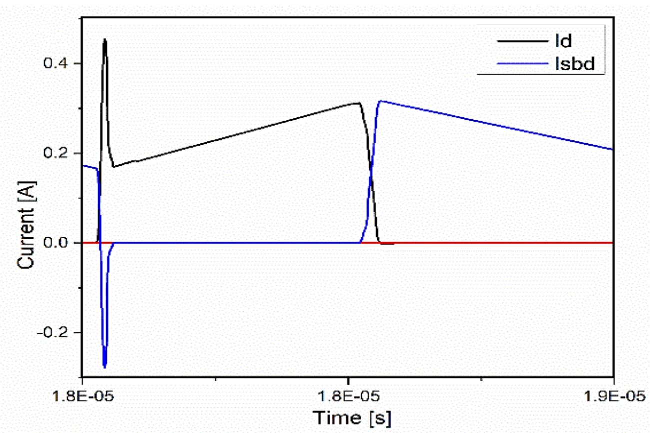

Figure 6. Current in HEMT and SBD during the switching cycle for doping concentration 9E15 (/cm3)

Optimizing the balance between power dissipation and doping concentration is crucial to achieve the most favorable tradeoff among efficiency, performance, and reliability.

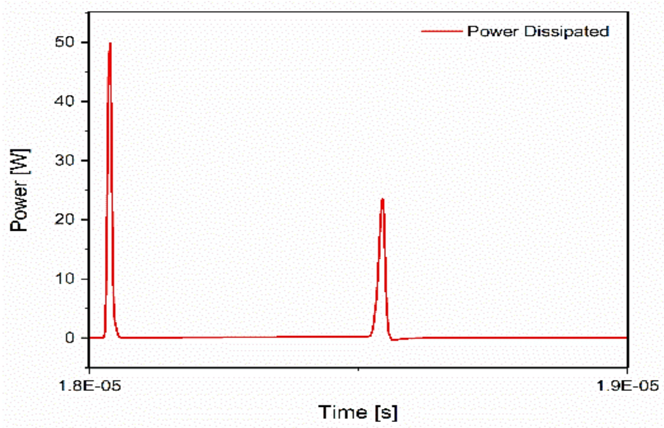

Figure 7. Power dissipated in HEMT versus time for doping concentration 3E15 (/cm3)

Furthermore, variations in the material properties, such as alloy composition, and operating conditions of the HEMT, including bias voltages and ambient temperature, are also reflected in the time-dependent changes of the power dissipation characteristics. The power dissipated in HEMT versus time for doping concentration 3E15 (/cm3) and Power dissipated in HEMT versus time for doping concentration 9E15 (/cm3) were respectively shown in *Fig. 7* and 8. This leads to the corresponding reduction of the instantaneous dissipated power of the transistor.

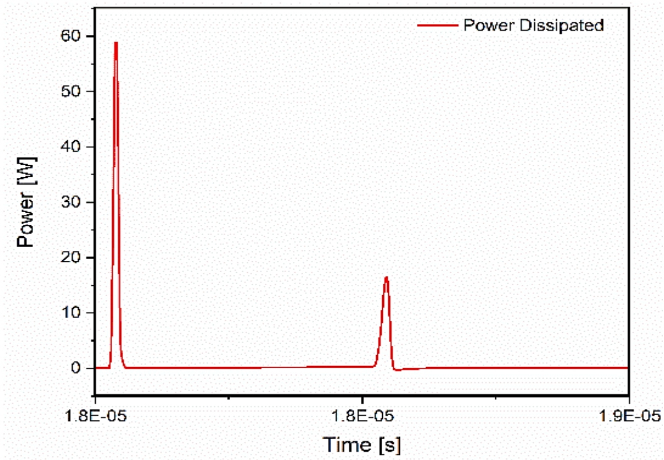

Figure 8. Power dissipated in HEMT versus time for doping concentration 9E15 (/cm3)

This mixed-mode approach unlocks new possibilities in power electronics by harnessing the complementary strengths of GaN and SiC, leading to enhanced system-level performance, efficiency, and reliability for a wide range of high-power, high-frequency, and mission-critical power conversion needs. The hybridization of AlGaN/GaN HEMT and SiC semiconductor technologies, referred to as the mixed-mode approach, leverages the unique strengths of each material to optimize power conversion and reduce overall power dissipation and energy losses. This seamless integration of the two wide-

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bandgap semiconductors is particularly beneficial for high-frequency and high-power electronic applications.

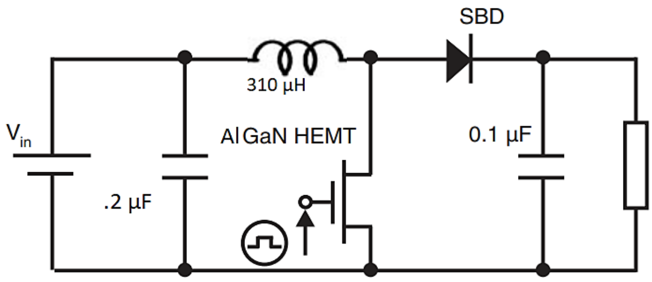

Figure 9. Schematic of DC boost converter circuit

Figure 9 depicts the Schematic of the DC boost converter circuit used for the analysis. As a result, the coupled GaN and SiC SBD devices are simulated in a boost converter circuit using mixed mode. The Doping of the SBD diode is varied and the dependency of the power losses is calculated for various Doping levels.

5. CONCLUSIONS

In this work, the device breakdown voltage is enhanced with AlGaN E-mode HEMT, and optimization of structure with the Boost converter circuit is carried out. Increased doping concentrations within the Schottky barrier diode led to higher saturation current (I_S) in the diode, as well as elevated drain current (I_D) in the HEMT device. The doping of the SBD diode is varied and the dependency of the circuit voltage concerning time, Current in HEMT and SBD for different switching cycles, and power dissipation is calculated for 3E15 (/cm3) and 9E15 (/cm3) Doping levels.

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