

Physics-Informed Numerical Modeling and Performance Assessment of AlGa_N/Ga_N/BGa_N Double-Gate Dual-Channel High Electron Mobility Transistor Architectures

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Published Date: -

16 December 2025,

Page No.: - 33-40

KEYWORDS

AlGa_N/Ga_N HEMT, BGa_N buffer, double-gate architecture, dual-channel transistor, physics-informed modeling, 2DEG, current collapse, trapping effects, Ga_N power devices, numerical simulation.

ABSTRACT

The continuous scaling of high electron mobility transistor (HEMT) technologies based on wide-bandgap III–V semiconductors has enabled significant advancements in high-power, high-frequency, and high-temperature electronics. This study presents a physics-informed numerical modeling framework for analyzing the performance of AlGa_N/Ga_N/BGa_N double-gate dual-channel HEMT architectures. The proposed approach integrates semiconductor transport physics, polarization-induced charge formation, trapping phenomena, and mobility degradation models within a unified simulation environment. Special emphasis is placed on dual-channel conduction enhancement, electrostatic control improvement via double-gate engineering, and the role of BGa_N buffer layers in mitigating leakage and improving thermal stability.

The modeling strategy is grounded in polarization theory governing two-dimensional electron gas (2DEG) formation (Ambacher et al., 2000), while incorporating advanced device-level effects such as current collapse (Mizutani et al., 2003), trapping dynamics (Mitrofanov and Manfra, 2004), and surface-state-induced dispersion (Doverspike et al., 1995). Furthermore, thermal and phonon transport effects influenced by piezoelectric coupling are considered in alignment with Ga_N nanostructure behavior (Zhu and Luo, 2016). The study employs a physics-informed numerical framework consistent with device simulation methodologies described by Selberherr (1984) and SILVACO ATLAS tools (2010).

Simulation results demonstrate that the double-gate dual-channel architecture significantly enhances drain current density, suppresses short-channel effects, and improves breakdown voltage compared to conventional single-channel HEMTs. The introduction of BGa_N buffer layers further improves carrier confinement and reduces parasitic leakage pathways. The findings establish a robust foundation for next-generation Ga_N-based power and RF electronics optimized through physics-informed modeling.

1. Introduction

The evolution of wide-bandgap semiconductor devices has fundamentally transformed high-power and high-frequency electronics. Among these, AlGa_N/Ga_N-based high electron mobility transistors (HEMTs) are widely recognized for their superior electron transport properties, high breakdown field strength, and strong polarization-induced carrier confinement (Ambacher et al., 2000). These properties enable the formation of a high-density two-dimensional electron gas (2DEG) at the heterointerface, which serves as the primary conduction channel.

However, conventional single-channel HEMT architectures face critical limitations including current collapse, trapping-induced dispersion, thermal degradation, and restricted electrostatic control at nanoscale gate lengths (Mizutani et al., 2003; Doverspike et al., 1995). These challenges have motivated the exploration of advanced device architectures such as dual-channel structures, field-plate engineering, and buffer layer modifications.

The introduction of BGa_N-based buffer layers has emerged as a promising strategy to enhance carrier confinement and suppress leakage currents due to improved band engineering properties and reduced defect

density (Gautier et al., 2011; Ougazzaden et al., 2008). Additionally, double-gate architectures provide superior electrostatic control over the channel region, thereby mitigating short-channel effects and improving transconductance stability.

From a physics standpoint, GaN-based devices are strongly influenced by polarization fields, piezoelectric effects, and phonon interactions. These mechanisms directly impact electron mobility, thermal conductivity, and scattering processes (Zhu and Luo, 2016). Such effects must be rigorously incorporated into numerical models to achieve predictive accuracy.

The objective of this study is to develop a physics-informed numerical modeling framework for AlGaIn/GaN/BGaN double-gate dual-channel HEMT architectures. The model integrates carrier transport physics, polarization-induced charge formation, trapping dynamics, and thermal effects to evaluate device performance under realistic operating conditions.

Research Objectives

1. To develop a physics-based numerical model for dual-channel AlGaIn/GaN/BGaN HEMT structures.
2. To analyze the impact of double-gate architecture on electrostatic control and current density.
3. To investigate trapping and current collapse mechanisms affecting device performance.
4. To evaluate the role of BGaN buffer layers in improving carrier confinement and thermal stability.
5. To provide a comparative performance assessment against conventional HEMT structures.

Scope and Significance

This research is significant for next-generation power electronics, RF amplifiers, and high-temperature systems. The integration of physics-informed modeling enables improved predictive accuracy over empirical approaches, facilitating optimized device design before fabrication.

Literature Review

The foundational principle of AlGaIn/GaN HEMT operation lies in polarization-induced charge formation at heterojunction interfaces. Ambacher et al. (2000)

established that spontaneous and piezoelectric polarization fields generate a high-density 2DEG without intentional doping, which forms the basis of high-conductivity channels in GaN-based devices. This phenomenon is critical for achieving high current density and mobility.

However, device reliability issues arise due to trapping effects and surface states. Binari et al. (2001) demonstrated that trapping phenomena significantly degrade microwave power performance, while Doverspike et al. (1995) highlighted low-frequency dispersion effects in GaN HFETs caused by deep-level traps. These studies collectively indicate that carrier trapping remains a fundamental limitation in GaN-based electronics.

Current collapse mechanisms have been extensively studied. Mizutani et al. (2003) showed that bias stress induces severe degradation in drain current due to charge trapping in buffer and surface states. Similarly, Khan et al. (1994) reported early observations of current/voltage collapse in heterostructure insulated gate field-effect transistors under high drain bias conditions.

Trap-related conduction mechanisms such as Poole-Frenkel emission have also been identified as significant contributors to leakage current modulation (Mitrofanov and Manfra, 2004). These effects must be included in physics-based modeling frameworks to accurately capture transient device behavior.

Advanced device architectures have been proposed to overcome these limitations. Dual-channel HEMTs and AlN/GaN-based architectures have demonstrated improved suppression of gate lag and enhanced current conduction (Deen et al., 2016). Additionally, field-plate and enhancement-mode designs improve breakdown voltage and switching performance (Lee et al., 2018; Greco et al., 2018).

The role of BGaN materials has gained attention due to their tunable bandgap properties and improved heterostructure engineering potential. Gautier et al. (2011) and Ougazzaden et al. (2008) investigated bandgap bowing and structural characteristics of BGaN layers, demonstrating their applicability in buffer engineering and leakage suppression.

From a simulation perspective, device modeling frameworks such as SILVACO ATLAS (2010) and

theoretical approaches outlined by Selberherr (1984) provide the computational foundation for semiconductor device analysis. Additionally, band structure parameters for III–V materials have been systematically compiled by Vurgaftman et al. (2001), enabling accurate numerical modeling.

Thermal and phonon transport effects also play a crucial role in GaN devices. Zhu and Luo (2016) demonstrated that piezoelectric coupling significantly influences phonon properties and thermal conductivity in GaN nanofilms. This directly impacts self-heating effects in high-power HEMT structures and must be considered in physics-informed simulation frameworks.

Despite extensive research, there remains a gap in integrated modeling approaches that simultaneously incorporate polarization physics, trapping mechanisms, dual-channel transport, and BGaN buffer effects within a unified double-gate architecture. This study addresses this gap by proposing a comprehensive physics-informed numerical modeling framework.

Methodology

Physics-Informed Modeling Framework

The proposed work develops a physics-informed numerical modeling framework for AlGaIn/GaN/BGaN double-gate dual-channel HEMT architectures by integrating semiconductor transport physics, electrostatic field distribution, polarization-induced charge formation, and defect/trapping dynamics into a unified simulation environment. The methodology is grounded in established GaN device physics, where the formation of a two-dimensional electron gas (2DEG) is primarily governed by spontaneous and piezoelectric polarization effects at heterointerfaces (Ambacher et al., 2000).

Unlike purely empirical device modeling approaches, the present framework incorporates physics constraints directly into the numerical solver structure. This ensures that carrier density, mobility, and electrostatic potential distributions evolve consistently with material-level physical laws. The modeling strategy is compatible with established device simulation platforms such as SILVACO ATLAS (2010) and follows the governing semiconductor equations outlined by Selberherr (1984).

Governing Equations and Transport Physics

The device operation is modeled using self-consistent solutions of Poisson's equation and the carrier continuity equations:

Poisson's equation governs electrostatic potential distribution:

$$\nabla \cdot (\epsilon \nabla \phi) = -q(p - n + ND^+ - NA^- + \rho_{pol})$$

where ρ_{pol} represents polarization charge density induced at AlGaIn/GaN and GaN/BGaN interfaces.

Electron and hole transport is described using drift-diffusion formalism:

$$J_n = qn\mu_n E + qD_n \nabla n$$

$$J_p = qp\mu_p E - qD_p \nabla p$$

Continuity equations:

$$\partial n / \partial t = (1/q) \nabla \cdot J_n + G_n - R_n$$

$$\partial p / \partial t = -(1/q) \nabla \cdot J_p + G_p - R_p$$

Carrier mobility is modeled using field- and doping-dependent expressions inspired by Caughey–Thomas formalism (Caughey and Thomas, 1967), modified for GaN wide-bandgap behavior.

Polarization and 2DEG Formation Model

The formation of 2DEG at AlGaIn/GaN interfaces is modeled using polarization discontinuity:

$$\sigma_{pol} = \sigma_{sp} + \sigma_{pz}$$

where σ_{sp} represents spontaneous polarization and σ_{pz} represents strain-induced piezoelectric polarization. This polarization sheet charge is the primary mechanism responsible for high electron density confinement (Ambacher et al., 2000).

In dual-channel architectures, an additional conduction channel is introduced at the GaN/BGaN interface, where band engineering modifies the conduction band offset and enhances carrier confinement efficiency.

Double-Gate Electrostatic Control Model

The double-gate configuration introduces enhanced electrostatic control over channel charge density. The

gate potential influences both upper and lower channels through coupled boundary conditions:

$$\phi_{top} = V_{g1} - V_{th1}$$

$$\phi_{bottom} = V_{g2} - V_{th2}$$

This dual modulation reduces short-channel effects and improves transconductance linearity.

Electrostatic scaling improves gate control factor γ :

$$\gamma = C_g / (C_g + C_{dep} + C_{parasitic})$$

where dual-gate architecture increases effective gate capacitance coupling.

5.5 Trapping and Current Collapse Modeling

Trap states are incorporated using SRH recombination-trapping formalism with additional dynamic capture/emission rates. Current collapse behavior is modeled based on deep-level trapping mechanisms described in GaN HEMTs (Mizutani et al., 2003; Mitrofanov and Manfra, 2004).

Trap occupancy dynamics:

$$\partial N_t / \partial t = C_n(1 - f)n - E_n f$$

where C_n is capture coefficient and E_n is emission rate.

These traps contribute to transient degradation in drain current and RF dispersion effects (Doverspike et al., 1995).

Thermal and Phonon Interaction Effects

Thermal transport is modeled using heat diffusion equations coupled with self-heating effects:

$$\nabla \cdot (k \nabla T) + Q = 0$$

where Q represents Joule heating. Phonon scattering and thermal conductivity variations are incorporated based on piezoelectric coupling effects in GaN nanostructures, which significantly influence heat dissipation efficiency (Zhu and Luo, 2016).

Device Structure and Simulation Setup

The simulated device consists of:

- AlGaN barrier layer
- GaN primary channel
- GaN/BGaN secondary channel
- BGaN buffer layer
- Double-gate electrodes (top and bottom gate control)

Key simulation parameters include:

- Gate length: nanoscale regime (short-channel)
- Dual-channel carrier confinement layers
- Polarization charge boundary conditions
- Trap density distribution in buffer and interface regions

Numerical discretization is performed using finite difference methods with adaptive meshing in high-field regions.

Results and Findings

The physics-informed numerical simulations of the AlGaN/GaN/BGaN double-gate dual-channel HEMT architecture reveal substantial improvements in both DC and high-frequency performance compared to conventional single-channel HEMT structures. The results are interpreted through electrostatic control efficiency, carrier transport enhancement, and suppression of degradation mechanisms such as trapping and current collapse.

Drain Current Enhancement and Dual-Channel Contribution

The introduction of a dual-channel configuration significantly increases the overall drain current density due to the formation of two spatially separated conduction channels. The upper AlGaN/GaN interface contributes a high-mobility 2DEG, while the lower GaN/BGaN interface introduces an additional conduction pathway with improved carrier confinement. This dual conduction mechanism reduces current saturation effects and enhances linearity under high bias conditions.

The polarization-induced charge density at both

interfaces strengthens carrier accumulation, consistent with polarization theory (Ambacher et al., 2000). The simulation indicates that the second channel contributes to improved current distribution uniformity, reducing localized current crowding effects and enhancing thermal stability.

Electrostatic Control and Short-Channel Effects

The double-gate architecture demonstrates a marked improvement in electrostatic control compared to conventional single-gate designs. The presence of top and bottom gate coupling reduces electrostatic potential fluctuations in the channel region. As a result, the device exhibits reduced drain-induced barrier lowering (DIBL) and improved threshold voltage stability.

The enhanced gate control factor leads to improved subthreshold slope characteristics and reduced leakage current. This improvement is particularly significant in nanoscale geometries where short-channel effects typically dominate device behavior. The findings are consistent with advanced GaN architectures that utilize field-plate and multi-gate strategies for performance optimization (Lee et al., 2018).

Current Collapse and Trapping Suppression

A key observation from the simulation is the significant reduction in current collapse phenomena due to improved charge redistribution and reduced trap activation. In conventional HEMTs, surface and buffer traps capture carriers under high drain bias, leading to transient degradation of drain current (Mizutani et al., 2003). In the proposed structure, the dual-channel design reduces the electric field intensity at critical trap-prone regions.

Additionally, the BGeN buffer layer reduces defect density and suppresses deep-level trap formation. This results in improved transient response and reduced hysteresis during switching operations. The modeling of trap dynamics aligns with previously reported mechanisms of Poole–Frenkel emission and trap-assisted conduction (Mitrofanov and Manfra, 2004).

Thermal Stability and Self-Heating Effects

Thermal simulations indicate that the BGeN buffer layer contributes significantly to improved heat dissipation pathways. The reduced phonon scattering and modified thermal conductivity behavior enhance heat spreading

across the substrate. This effect is critical for high-power operation, where self-heating can severely degrade mobility and reliability.

The coupling between piezoelectric effects and thermal transport, as described in GaN nanostructures, plays a key role in determining temperature distribution within the device (Zhu and Luo, 2016). The double-gate configuration further helps distribute power dissipation more evenly across the channel region.

Breakdown Voltage and High-Bias Performance

The simulated device demonstrates improved breakdown voltage characteristics due to reduced peak electric field concentration. The dual-channel architecture distributes electric field lines more uniformly, preventing localized field spikes that typically lead to premature breakdown. The BGeN buffer layer also contributes to enhanced dielectric strength and reduced leakage pathways.

RF Performance Implications

The enhanced carrier transport and reduced trapping effects result in improved high-frequency performance. The reduction in low-frequency dispersion and gate lag improves signal integrity in microwave and RF applications. The dual-channel architecture enables higher transconductance stability across a broader frequency range, making it suitable for power amplification applications.

Discussion

The simulation outcomes of the AlGaIn/GaN/BGeN double-gate dual-channel HEMT architecture highlight the effectiveness of integrating multi-physics mechanisms into device-level design. The observed improvements in drain current density, electrostatic stability, and breakdown voltage are fundamentally rooted in polarization-driven charge modulation and advanced structural engineering of the heterojunction system (Ambacher et al., 2000).

A key theoretical implication of this study is the validation of dual-channel conduction as a viable strategy to overcome intrinsic limitations of single-channel GaN HEMTs. In conventional architectures, electron transport is primarily confined to a single 2DEG layer, making the device highly sensitive to interface traps and surface states. In contrast, the dual-channel configuration

redistributes carrier density across two spatially separated conduction planes, thereby reducing localized field stress and improving carrier transport uniformity. This aligns with prior findings where multi-channel GaN structures demonstrated enhanced current density and breakdown robustness (Y. Zhang et al., 2020).

The introduction of a double-gate configuration further enhances device electrostatics. The coupling between top and bottom gates effectively reduces potential fluctuations within the channel region, thereby suppressing short-channel effects such as DIBL and threshold voltage roll-off. This behavior is consistent with earlier enhancement-mode and field-plate GaN HEMT designs, which demonstrated that improved gate control directly correlates with reduced leakage and improved switching performance (Lee et al., 2018). However, unlike conventional field-plate approaches, the double-gate system provides symmetrical electrostatic confinement, which results in more uniform carrier modulation.

Trap-related phenomena remain a critical limiting factor in GaN-based devices. The present modeling framework incorporates trapping dynamics and demonstrates that current collapse is significantly mitigated in the proposed architecture. This improvement is attributed to reduced peak electric fields and modified carrier distribution near defect-prone regions. Experimental studies have shown that trapping effects are strongly linked to surface band bending and bias-induced charge redistribution (Izpura, 2002; Mizutani et al., 2003). The reduction in trap activation observed in the simulation is therefore consistent with the theoretical understanding of trap-limited transport mechanisms and Poole–Frenkel emission processes (Mitrofanov and Manfra, 2004).

Thermal management is another critical factor influencing GaN device reliability. The inclusion of BGaN buffer layers improves thermal conductivity distribution and reduces phonon scattering-induced hot spots. This observation is strongly supported by phonon transport theory, where piezoelectric coupling plays a significant role in thermal resistance modulation (Zhu and Luo, 2016). The improved thermal profile directly enhances mobility retention under high-bias operation, thereby increasing device lifetime and operational stability.

Despite these advantages, the proposed architecture

introduces fabrication complexity. Double-gate alignment precision and dual-channel interface quality are critical factors that may limit large-scale manufacturability. Additionally, BGaN material integration requires precise control over boron composition and epitaxial growth conditions, as variations can significantly affect bandgap uniformity and carrier confinement (Ougazzaden et al., 2008). These constraints highlight a trade-off between performance enhancement and fabrication feasibility.

From a modeling perspective, while the physics-informed framework captures key transport and thermal phenomena, it still relies on drift-diffusion assumptions, which may not fully describe ballistic transport effects at extremely scaled dimensions. Future extensions incorporating Monte Carlo or quantum transport models would further enhance predictive accuracy.

Overall, the results confirm that combining dual-channel conduction with double-gate electrostatic control and BGaN buffer engineering provides a synergistic pathway for next-generation GaN HEMT optimization. The study reinforces the importance of physics-informed simulation approaches in bridging the gap between theoretical device design and practical semiconductor fabrication.

Conclusion

This study presented a comprehensive physics-informed numerical modeling framework for analyzing AlGaN/GaN/BGaN double-gate dual-channel HEMT architectures. By integrating polarization physics, carrier transport equations, trapping dynamics, and thermal effects, the model successfully captured the complex interplay of mechanisms governing wide-bandgap transistor performance.

The results demonstrate that dual-channel conduction significantly enhances drain current density and improves current distribution uniformity. The double-gate architecture provides superior electrostatic control, reducing short-channel effects and improving threshold stability. Furthermore, the incorporation of BGaN buffer layers effectively suppresses leakage currents and enhances thermal stability through improved phonon transport characteristics.

A key contribution of this work is the demonstration that physics-informed modeling can accurately predict performance improvements arising from advanced

heterostructure engineering. The inclusion of trapping and polarization effects ensures realistic simulation of current collapse behavior and RF dispersion phenomena, thereby improving the reliability of design predictions.

However, challenges remain in terms of fabrication complexity and the need for more advanced transport models at nanoscale dimensions. Future research should focus on quantum-corrected simulations, experimental validation of BGaN-based dual-channel structures, and optimization of double-gate fabrication techniques.

Overall, the proposed architecture represents a promising direction for high-power, high-frequency, and high-temperature electronics, with significant potential for RF amplification, power conversion, and next-generation communication systems.

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