# DESIGN AND SIMULATION OF AlGaN/GaN HIGH ELECTRON MOBILITY TRANSISTORS (HEMTS) USING SILVACO TCAD


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**Bachelor of Technology**

By


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## CERTIFICATE OF APPROVAL

The dissertation entitled "**DESIGN AND SIMULATION OF AlGaN/GaN HIGH ELECTRON MOBILITY TRANSISTOR USING SILVACO TCAD"** submitted by **Atul Kumar Singh (EC21B012), Rohit Kumar Verma (EC21B050), Deepak Baidya (EC21B023)** is presented in a satisfactory manner to warrant its acceptance as a prerequisite for the degree of Bachelor of Technology in Electronics & Communication Engineering of the National Institute of Technology, Arunachal Pradesh. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but only for the purpose for which it has been submitted.

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# CERTIFICATE FROM SUPERVISOR

This is to certify that the dissertation entitled "**DESIGN AND SIMULATION OF AlGaN/GaN HIGH ELECTRON MOBILITY TRANSISTOR USING SILVACO TCAD"** submitted by **Atul Kumar Singh (EC21B012), Rohit Kumar Verma (EC21B050), Deepak Baidya (EC21B023)** to the Department of Electronics & Communication Engineering of the National Institute of Technology, Arunachal Pradesh, as a partial fulfillment of their B. Tech Degree in Electronics & Communication Engineering of the Institute is absolutely based upon their own work, carried out during the period from January – May, 2025 under my supervision. Neither this dissertation nor any part of it has been submitted for the award of any other degree of this Institute or any other Institute/University.

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# ABSTRACT

The growing demand for high-performance, high-frequency electronic components has made wide bandgap materials, especially GaN-based HEMTs (High Electron Mobility Transistors), a topic of interest. AlGaN/GaN HEMTs are particularly appealing because of their excellent electron mobility, high breakdown voltage, and exceptional thermal stability. This thesis explores the design and simulation of AlGaN/GaN HEMT structures utilizing Silvaco TCAD tools, focusing on how changes in essential design parameters influence the device's I-V characteristics.

The thesis opens with a discussion on the operating principles of HEMTs, detailing the formation of the two-dimensional electron gas (2DEG) at the interface of AlGaN/GaN. It also examines the polarization effects that significantly enhance carrier mobility and boost device performance. Following this, an overview of Silvaco TCAD is presented, illustrating how this simulation platform effectively models semiconductor devices with high precision.

The main research concentrates on three key factors: the thickness of the AlGaN barrier layer, the aluminium mole fraction, and the doping concentration in the AlGaN layer. Initially, the thickness of the AlGaN layer is modified while keeping the other two factors unchanged. Simulation outcomes indicate that increasing the layer's thickness enhances the polarization effect at the interface, resulting in a higher 2DEG density and improved drain current. However, if the thickness exceeds a certain limit, excessive strain may compromise the material's integrity.

The second phase of the investigation assesses how varying the aluminium mole fraction affects the device. A greater mole fraction further amplifies polarization, boosting electron density and enhancing output current. However, excessively high mole fractions may lead to lattice mismatch, which increases defect density and decreases reliability. Finally, the doping concentration in the AlGaN layer is varied while maintaining constant thickness and mole fraction. Higher doping levels result in improved carrier injection and increased current output, although they might also contribute to elevated leakage currents and decreased control over the threshold voltage.

The I-V characteristics derived from the simulations affirm the vital influence of these parameters on device functionality. This research emphasizes the necessity of finding a balance among these factors to achieve optimal performance, particularly for high-frequency and high-power applications.

In summary, this study emphasizes that careful adjustment of the AlGaN layer parameters—thickness, composition, and doping—can greatly improve the performance of AlGaN/GaN HEMTs. The conclusions provide valuable insights for device engineers and researchers involved in the development of next-generation GaN-based semiconductor technologies

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# ACRONYMS

| | |
|---|---|
| WBG | Wide Bandgap |
| 2DEG | Two-Dimensional Electron Gas |
| HEMT | High Electron Mobility Transistor |
| DH | Double Heterojunction |
| TCAD | Technology Computer-Aided Design |
| AlGaN | Aluminium Gallium Nitride |
| GaN | Gallium Nitride |
| AlN | Aluminium Nitride |
| I-V | Current-Voltage |
| DH_HEMT | Double Heterojunction High Electron Mobility Transistor |
| SH_HEMT | Single Heterojunction High Electron Mobility Transistor |
| SiC | Silicon Carbide |
| RF | Radio Frequency |
| DC | Direct Current |
| $I_D$ | Drain Current |
| $V_D$ | Drain Voltage |
| $V_G$ | Gate Voltage |

# CHAPTER 1

# INTRODUCTION

Due to the increasing deployment of high-power and high-frequency electronic systems, especially in extreme environmental conditions, conventional silicon-based semiconductor technologies are reaching their operational limits. Silicon devices struggle to maintain performance under high voltage, high temperature, and fast switching conditions. As a result, there has been a growing interest in wide bandgap (WBG) semiconductors, which exhibit superior material properties suited for such demanding applications.

Among the most promising WBG materials is Gallium Nitride (GaN), which has garnered significant attention due to its large bandgap (~3.4 eV), high critical electric field, high thermal conductivity, and high electron mobility. These characteristics allow GaN devices to operate at higher voltages, higher frequencies, and elevated temperatures compared to traditional silicon devices. A key technology emerging from this material is the AlGaN/GaN High Electron Mobility Transistor (HEMT), which leverages the heterojunction interface to form a two-dimensional electron gas (2DEG) channel with exceptionally high carrier density and mobility, even without intentional doping.

AlGaN/GaN HEMTs are now extensively used in RF power amplifiers, power converters, and robust electronic units designed for aerospace, defence, automotive, and industrial applications. These devices are also integrated with modern user interfaces like touchscreens and digital control systems to enable intelligent and compact power electronics.

This project focuses on modeling and simulating an AlGaN/GaN HEMT using SILVACO TCAD tools, aiming to evaluate and optimize its electrical and thermal performance. The device structure includes a sapphire substrate, a GaN buffer layer, an AlGaN barrier layer, and metal contacts forming the source, gate, and drain. What is found in the simulation closely resembles the data from the experiments, indicating that the SILVACO models are reliable. The detail drawing of the HEMT provides a visible structure of Sapphire substrate, GaN buffer, AlN spacer, AlGaN barrier, compared to the gate metal contacts. It shows how each layer in the device works and what affects the optimization.

## 1.1 OBJECTIVE

- The objective is to design and simulate an AlGaN/GaN High Electron Mobility Transistor (HEMT) utilizing the SILVACO TCAD DeckBuild simulation platform.
- The device will be modeled with a multilayer structure that includes:
  - Sapphire substrate (region 1)
  - AlN nucleation layer (region 2)
  - GaN channel layer (region 3)

- AlGaN barrier layer (region 4).

- The study aims to examine how changes in the thickness of the AlGaN barrier influence the current-voltage (I–V) characteristics of the device.
- Additionally, the research will focus on the effects of varying the aluminium mole fraction in the AlGaN layer on the electrical behaviour and electron mobility of the transistor.
- An analysis will be conducted on how different doping levels in the GaN channel affect current flow and the overall performance of the device.
- Various gate voltages will be applied to record the I–V curves generated, allowing for a comparison of performance trends among the different structural configurations.
- The goal is to acquire valuable insights into how layer thickness, material composition, and doping levels collectively affect the behaviour and optimization of AlGaN/GaN HEMTs for potential future applications.

## 1.2 SCOPE OF IMPLEMENTATION

This project aims to simulate and comprehend the behaviour of AlGaN/GaN HEMTs through SILVACO TCAD. While it relies on simulations, the knowledge acquired holds substantial practical significance. GaN-based devices are revolutionizing various sectors by surpassing conventional silicon technology in challenging conditions.

### 1.2.1 Power Electronics

GaN HEMTs are becoming crucial components in high-efficiency power conversion systems such as DC-DC converters, inverters, and power supplies. Their capacity to manage high voltages and switch quickly makes them ideal for creating more compact and efficient power modules. These devices are extensively utilized in telecommunications, consumer electronics, and battery charging systems.

### 1.2.2 Electric Vehicles (EVs)

Within the realm of electric vehicles, GaN HEMTs are crucial for onboard chargers, motor drives, and battery management systems. Their rapid switching capabilities and minimal energy losses enhance the overall energy efficiency of the vehicle. By simulating these components, engineers can optimize their performance in response to different current and voltage conditions.

### 1.2.3 Radio Frequency (RF) and Microwave Systems

GaN HEMTs are chosen for many RF amplifiers, radar systems and communication base stations because of their high mobility. Stronger signals and less noise are possible because they can perform well at high frequencies. It provides engineers a way to perfect their devices to achieve greater reliability and better bandwidth.

### 1.2.4 Satellite and Aerospace Electronics

Because GaN devices operate well in extreme situations, they are ideal for space use. The chips are trusted during space missions thanks to their radiation resistance and toleration for high voltage. By simulating, engineers can estimate how the system will perform when used in space.

### 1.2.5 Defence and Radar Systems

GaN HEMTs are finding use in Défense, primarily in constructing radars and systems for electronic warfare. High-resolution and long-range detection systems rely on amplifiers for their excellent power-handling. Actually, testing the devices aids in strengthening them for the defence world.

### 1.2.6 Wireless Charging and Consumer Devices

Power transistors using GaN help make wireless chargers, smartphones and laptops less bulky and consume less energy. Designers can predict and improve the performance of a device by using accurate simulation models.

### 1.2.7 Research and Semiconductor Development

In research, both on the academic side and in industry, simulation is very important. With this technology, engineers can try out new choices for devices, review the properties of SiC or diamond and calculate predicted behaviour without spending on construction.

### 1.2.8 Renewable Energy Systems

The use of AlGaN/GaN HEMTs is enabling solar inverters and wind turbines to improve their energy conversion performance. Their ability to work swiftly helps in designing smaller and brighter systems. The simulation in this project makes it simpler to design parts for efficient and clean energy.

# CHAPTER 2
# LITERATURE REVIEW

The area of AlGaN/GaN High Electron Mobility Transistors (HEMTs) has been the subject of extensive investigation owing to their remarkable features, including a wide bandgap, high electron mobility, and strong breakdown strength. These attributes render them highly effective for RF, microwave, and power switching applications. Simulation work utilizing Silvaco TCAD is vital in optimizing devices prior to fabrication, yielding insights into carrier transport physics, field distribution, and quantum effects.

- Analysis of Drain Current Through Simulations **Kalita** and **Mukhopadhyay** [1] performed a comprehensive simulation study using Silvaco TCAD on AlGaN/GaN/AlGaN double heterojunction (DH) HEMTs, examining how doping concentrations, layer thicknesses, and Al mole fractions affect drain current. They found a peak saturation drain current of 3.61 mA for a 30 nm AlGaN thickness with a doping level of $3 \times 10^{18} cm^{-3}$ and a gate voltage of 1V. Their findings indicated that increased doping levels not only raised the drain current but also deepened the quantum well, thereby improving 2DEG confinement.

  This study is consistent with earlier theoretical models by **Charfeddine et al.** [2], who created a two-dimensional model that analyses the current-voltage characteristics and the kink effect in AlGaN/GaN HEMTs. They also underscored the influence of Al composition and barrier thickness on 2DEG sheet carrier concentration.

- Source Current Dynamics and Mole Fraction Tuning In a related study, **Kalita** and **Mukhopadhyay** [3] explored the behaviour of source current in DH-HEMTs. Their simulations indicated that as both drain voltage and gate voltage increase, the source current also rises, with further enhancements observed at higher aluminium mole fractions (up to 0.30). They recorded a maximum source current of 3.3 mA, underscoring the significance of optimizing mole fraction for current improvement. In a similar vein, **Juncai et al.** [4] have conducted modeling of AlGaN/GaN HEMTs aimed at high-speed applications, analysing how the structural design and doping profiles influence current flow and switching speeds. Their findings are in alignment with the previously noted mole fraction dependence and the device's overall performance.

- The research conducted by **Kalita** and **Mukhopadhyay** [5] expanded upon their simulations of single heterojunction AlGaN/GaN HEMTs featuring a thinner (10 nm) AlGaN barrier. Their findings indicated that the drain current remains minimal for Al mole fractions below 0.30 when subjected to a gate voltage of –2V, suggesting a threshold behaviour in 2DEG formation. The source and drain currents were shown to rise linearly with both gate voltage and mole fraction.

  These results are consistent with the experimental study by **Dabiran et al.** [6], who noted elevated channel conductivity in low-defect AlN/GaN single heterojunction HEMTs, underscoring the significance of material quality and interface engineering in achieving optimal current levels.

## 2.1 ADDITIONAL SIGNIFICANT CONTRIBUTIONS

- **Luo et al.** [7] proposed the use of double buried p-type layers within GaN buffers to improve device isolation and minimize leakage in AlGaN/GaN HEMTs.
- **Liu et al.** [8,9] offered sophisticated models for electron transport and gate design, which enhanced the predictability of performance in TCAD settings.
- **Simlinger et al**. [10] utilized 2D numerical device simulations to develop baseline models for the electric field and carrier dynamics in HEMTs.
- In addition, research by **Ghatak** and **Bhattacharya** [11–13] has established theoretical foundations regarding electron mass effects, photoemission, and the behaviour of nanostructures in compound semiconductors, all of which have a direct impact on HEMT modeling methodologies.

## 2.2 OUTCOME OF THE LITERATURE REVIEW

Analysing past simulation studies on AlGaN/GaN HEMTs, particularly those conducted using the Silvaco TCAD platform, uncovers several key elements that significantly influence device performance:

**Doping Concentration:** Increasing the doping concentration in the AlGaN layer results in a greater drain current and deeper quantum wells, which enhances 2DEG confinement and optimizes carrier transport.

**Aluminium Mole Fraction**: A mole fraction of aluminium exceeding 0.25—especially close to 0.30—has been repeatedly demonstrated to enhance current characteristics due to stronger polarization fields and 2DEG density at the heterointerface.

**Gate and Drain Voltages:** The gate and drain voltages are crucial in regulating current flow. Their interplay with material characteristics such as mole fraction and layer thickness directly influences the I–V characteristics and performance during switching.

**Structure Optimization:** A comparison between single and double heterojunction designs underscores the necessity of structural adjustments. While DH-HEMTs gain from improved confinement, SH-HEMTs experience restrictions in threshold behaviour at lower Al concentrations.

**TCAD as a Design Tool:** The Silvaco TCAD platform has proven to be a reliable tool for modeling electrical behaviour, examining physical effects, and forecasting performance trends in both traditional and innovative HEMT designs.

# CHAPTER 3
# HIGH ELECTRON MOBILITY TRANSISTOR (HEMT)

This chapter offers a thorough introduction to High Electron Mobility Transistors (HEMTs), exploring their basic principles, operational regions, bandgap engineering, and other relevant topics. HEMTs are sophisticated field-effect transistors that utilize heterojunctions—interfaces formed between two semiconductor materials with varying bandgaps—to create a two-dimensional electron gas (2DEG). This 2DEG allows electrons to travel with remarkable mobility, leading to enhanced performance in high-frequency and high-power applications. The chapter will investigate the different operational regions of HEMTs, including the linear, saturation, and cutoff regions, clarifying how these regions affect device behaviour. Furthermore, it will analyze the significance of bandgap engineering in improving HEMT performance, especially through the incorporation of wide bandgap materials like GaN and AlGaN, which enhance breakdown voltages and thermal stability. Additional discussions will include the various structural designs of HEMTs, such as enhancement-mode and depletion-mode devices, along with the influence of polarization effects on 2DEG formation. By integrating findings from recent research and technological progress, this chapter seeks to provide a solid understanding of the operational mechanisms and design factors related to HEMTs in modern electronic systems.

## 3.1 HEMT FUNDAMENTALS

A High Electron Mobility Transistor (HEMT) is an advanced semiconductor device that is essential in contemporary high-frequency and high-power electronic applications. In contrast to standard transistors that utilize a single type of semiconductor material, a HEMT is constructed using two distinct semiconductor materials with varying bandgaps. This combination establishes what is referred to as a heterojunction, which underpins the outstanding performance of the HEMT. The most frequently employed materials in HEMT designs are Aluminium Gallium Nitride (AlGaN) and Gallium Nitride (GaN). When these two materials are stacked together, they create a distinctive electronic environment at their junction, facilitating the development of a two-dimensional electron gas (2DEG). This 2DEG serves as a conduit for electrons to travel with exceptionally high mobility. Unlike traditional transistors, the electrons in a HEMT undergo minimal scattering, as they are not hindered by impurities or defects within the material. This results in accelerated operation and enhanced efficiency. HEMTs are especially recognized for their elevated electron mobility, which indicates the speed at which electrons can move through the transistor. This characteristic is essential in high-speed communication and signal processing scenarios, where minimizing delays and signal loss is crucial. Furthermore, HEMTs that utilize GaN take advantage of GaN's wide bandgap, enabling them to function at elevated voltages, high temperatures, and high frequencies without a decrease in performance. These attributes render HEMTs perfect for applications in 5G base stations, radar technology, satellite communications, and power electronics.

One significant benefit of HEMTs is their excellent noise performance, which is critical in applications such as satellite receivers and wireless communication, where minor electrical noise can impact signal quality. Thanks to their rapid response time and high-power density, HEMTs are also utilized in military applications, automotive radar, and aerospace electronics.

In terms of structure, a HEMT generally features a gate, source, and drain, similar to a standard field-effect transistor. Nonetheless, its internal layer architecture is significantly more intricate. The AlGaN layer serves as a barrier, while the GaN layer constitutes the channel. Electrons from the AlGaN layer gather at the junction with the GaN layer, creating the 2DEG, which facilitates rapid current flow. Typically, the transistor is fabricated on substrates such as sapphire, silicon carbide (SiC), or high-resistivity silicon, with selections made based on a balance of performance and cost.

In conclusion, HEMTs are highly effective, efficient, and incredibly fast electronic components that are paving the way for the upcoming generation of wireless and high-performance technologies. Their capability to function under extreme conditions while ensuring efficiency and reliability positions them as one of the most crucial technologies in contemporary electronics. With ongoing research, particularly utilizing simulation tools like Silvaco TCAD, the design and functionality of HEMTs are anticipated to progress further, leading to opportunities for even more challenging and innovative applications.

## 3.2 STRUCTURE OF HEMT

High Electron Mobility Transistors (HEMTs) are sophisticated semiconductor devices designed for applications requiring high speed and high power. Unlike traditional transistors, they utilize two semiconductor materials to create a heterojunction, which facilitates the formation of a highly conductive two-dimensional electron gas (2DEG). This channel promotes swift electron movement with minimal resistance. The HEMT structure comprises carefully arranged layers of materials, each fulfilling a distinct purpose. Below is a simplified cross-sectional illustration of the HEMT structure, accompanied by an in-depth discussion of each layer.

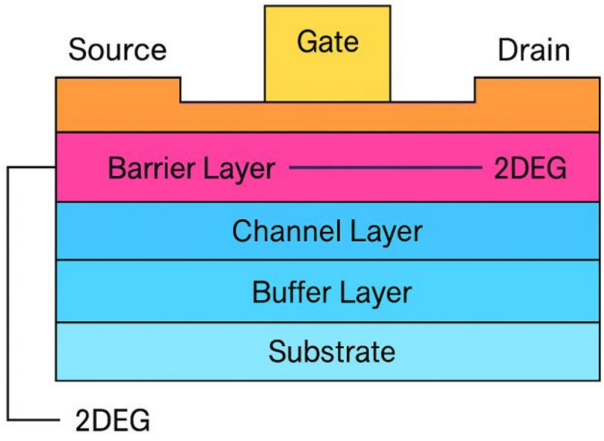


**Figure 3.1** HEMT Structure

The architecture of a High Electron Mobility Transistor (HEMT) consists of a stacked arrangement of semiconductor materials intended to enhance rapid electron transport through a two-dimensional electron gas (2DEG). A standard HEMT starts with a substrate at its foundation, typically made from materials like silicon (Si), sapphire, or silicon carbide (SiC). Positioned above the substrate is a buffer layer, generally formed of Gallium Nitride (GaN). This layer acts as a transitional medium that accommodates the lattice mismatch between the substrate and the upper active layers. It also plays a role in minimizing defect propagation into the channel layer, thus maintaining the device's electronic integrity. Additionally, the buffer may serve as an electrical isolation zone to prevent leakage currents from the substrate.

The undoped GaN channel layer is situated directly above the buffer layer. This layer is crucial for the operation of HEMTs, as it is where the two-dimensional electron gas (2DEG) forms. Unlike traditional semiconductors that need deliberate doping to establish conductive pathways, the HEMT's 2DEG emerges at the junction of the GaN channel and the barrier layer as a result of polarization effects. These effects consist of spontaneous polarization (which is intrinsic to the crystal structure) and piezoelectric polarization (caused by strain), which collectively generate a high-density electron sheet at the heterojunction.

The barrier layer, typically consisting of a thin film of Aluminium Gallium Nitride (AlGaN), is deposited over the GaN channel. This layer's primary role is to induce and confine the 2DEG at the GaN/AlGaN interface. An increase in the aluminium content in AlGaN results in a greater polarization difference, thereby enhancing the induced electron density in the 2DEG. Frequently, a very thin spacer layer made of undoped AlN or GaN is placed between the AlGaN and GaN layers to reduce scattering and enhance electron mobility.

On the surface of the AlGaN barrier layer, metallic contacts are established to create the transistor terminals: the source, drain, and gate. The source and drain are generally constructed from low-resistance ohmic contacts, often implemented with multi-layer metal configurations like Ti/Al/Ni/Au. These contacts facilitate the efficient flow of electrons into and out of the 2DEG channel. In contrast, the gate is commonly a Schottky metal contact (such as Ni/Au) that regulates the electron flow within the channel by managing the electrostatic field across the barrier layer. By applying various gate voltages, the 2DEG underneath the gate can be either depleted or accumulated, which allows the transistor to be switched on or off. A simplified diagram demonstrating this structure is presented in Figure 3.1.

## 3.3 OPERATION OF AlGaN/GaN HEMT

The functioning of an AlGaN/GaN High Electron Mobility Transistor (HEMT) relies on the management of current through a high-mobility electron channel that is established at the interface between Aluminium Gallium Nitride (AlGaN) and Gallium Nitride (GaN). Unlike conventional MOSFETs, which depend on doped areas for conduction, the AlGaN/GaN HEMT uses spontaneous and piezoelectric polarization to create a two-dimensional electron gas (2DEG) at the heterojunction without the need for intentional doping. This 2DEG serves as the primary pathway for current flow and offers enhanced electron mobility by minimizing impurity scattering. The device features three main terminals: source, drain, and gate. Current moves from the source to the drain, while the gate voltage ($V_{GS}$) regulates this flow by altering the 2DEG density below the gate.

### 3.3.1 Off-State Operation

In the off-state, a sufficiently negative gate voltage is applied, which reduces the 2DEG channel underneath the gate area. The electric field produced by the negative $V_{GS}$ causes electrons to be repelled, thereby lowering or significantly diminishing carrier concentration in the channel. Consequently, the drain current ($I_D$) nearly approaches zero, effectively switching the transistor off. This represents the device's non-conductive state. The threshold voltage ($V_T$) is critical in this context—it indicates the minimum gate voltage necessary to initiate the formation of a conductive channel. When $V_{GS}$ is below this threshold, the 2DEG is depleted, preventing current flow.

### 3.3.2 Linear Region

As $V_{GS}$ rises and surpasses the threshold, the device enters the linear region. During this state, a partial 2DEG channel develops, and a small drain-source voltage ($V_{DS}$) enables current to flow from the source to the drain. In this region, $I_D$ increases nearly linearly with $V_{DS}$, causing the transistor to act like a voltage-controlled resistor. The current in this phase is affected by both the gate voltage, which regulates channel conductivity, and the drain voltage, which propels the current. The linear region is crucial for analog applications that require signal amplification. Since the channel has not completely closed off, electrons travel through a low-resistance pathway, allowing the device to operate effectively with minimal power loss.

### 3.3.3 Saturation Region

As $V_{DS}$ is further increased and surpasses the overdrive voltage ($V_{DS} > V_{GS} - V_T$), the device shifts into the saturation region. At this stage, the electric field near the drain becomes sufficiently strong to locally deplete the 2DEG, resulting in a pinch-off condition. The current no longer rises linearly with $V_{DS}$ and instead stabilizes, reaching a nearly constant maximum level. In this region, $I_D$ is primarily influenced by $V_{GS}$, with changes in $V_{DS}$ having minimal impact on the output current. This characteristic is highly advantageous for digital and RF switching applications, where a stable and high output current is essential. The saturation region underscores the benefits of the AlGaN/GaN system, which provides high breakdown voltages, low on-resistance, and thermal robustness.

## 3.4 KEY PARAMETERS AND EQUATIONS OF AlGaN/GaN HEMT

To gain a comprehensive understanding of the AlGaN/GaN High Electron Mobility Transistor (HEMT), it is crucial to examine several key physical parameters and the equations that dictate their functionality. These parameters not only characterize the electrical performance of the device but also assist in its design, optimization, and simulation. Specifically, elements such as charge concentration, threshold voltage, drain current, and transconductance provide valuable insights into how a HEMT operates under different conditions.

### 3.4.1 Two-Dimensional Electron Gas (2DEG) Sheet Density ($n_s$)

The foundation of HEMT technology lies in the creation of a high-mobility 2DEG at the AlGaN/GaN heterointerface. This charge layer arises from polarization effects instead of intentional doping, which leads to enhanced mobility and lower scattering. The sheet carrier concentration $\mathbf{n_s}$, is influenced by the gate voltage and can be expressed as

$$n_s = \frac{\varepsilon_i}{q \cdot d_i}\left(V_g - V_T + \Delta\phi\right) \tag{3.1}$$

In this equation,
$\varepsilon_i$ denotes the dielectric constant of the AlGaN barrier, $d_i$ indicates its thickness, $V_g$ refers to the applied gate voltage, and **Δϕ** represents the conduction band bending as a result of polarization. This relationship demonstrates that as $V_g$ becomes increasingly positive, the 2DEG density rises, which improves conductivity in the channel. The ability to control $n_s$ in this manner enables precise gate regulation over the channel.

### 3.4.2 Threshold Voltage ($V_T$)

The threshold voltage (**$V_T$**) is the gate voltage at which the 2DEG channel starts to conduct a significant amount of current. This parameter is essential for understanding the switching characteristics and the behaviour of the HEMT in normally-on/off configurations.
The formula for **$V_T$** includes various physical properties of the device

$$V_T = \phi_B - \frac{\Delta E_C}{q} - \frac{qN_D d^2}{2\varepsilon} \tag{3.2}$$

In this equation, $\phi_B$ represents the Schottky barrier height at the interface between the gate metal and the AlGaN layer, **$\Delta E_C$** denotes the conduction band discontinuity at the heterojunction, $N_D$ indicates the background doping level in GaN, while $d$ and **ε** signify the barrier's thickness and permittivity, respectively. A more negative $V_T$ suggests a depletion-mode (normally-on) device, while making $V_T$ approach zero allows for enhancement-mode (normally-off) functionality, which is considered safer and favoured in power electronics.

### 3.4.3 Drain Current in the Linear Region

When the HEMT operates in its linear or ohmic region, the drain current (**$I_D$**) rises in direct proportion to **$V_{DS}$**, causing the device to function as a voltage-controlled resistor. This behaviour is represented by:

$$I_D = \mu C_g \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] \tag{3.3}$$

In this context, **μ** represents the electron mobility in the 2DEG. The term $C_g$ denotes the gate capacitance per unit area, while $W$ and $L$ refer to the width and length of the gate, respectively. This equation is particularly important for analog amplification applications where maintaining linearity is vital.

### 3.4.4 Drain Current in the Saturation Region

When the $V_{DS}$ exceeds the saturation threshold (which means $V_{DS} > V_{GS} - V_T$), the channel gets pinched off close to the drain, and $I_D$ reaches a saturation level. The current in this region is expressed as:

$$I_{D(\mathrm{sat})} = \frac{1}{2}\mu C_g \frac{W}{L}(V_{GS} - V_T)^2 \tag{3.4}$$

This equation presumes that the device operates under a square-law relationship akin to that of MOSFETs in the long-channel operation. The saturation region plays a crucial role in digital switching and RF power amplification, where a consistent and high output current is necessary despite variations in **$V_{DS}$**.

### 3.4.5 Transconductance ($g_m$)

Transconductance, represented as $g_m$, is an important metric for evaluating the amplification ability of a transistor. It quantifies how much $I_D$ varies when there is a change in $VGS$ and is given by the following expression:

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu C_g \frac{W}{L}(V_{GS} - V_T) \quad (3.5)$$

Higher $g_m$ values indicate stronger control of the gate over the channel, which translates into better gain in RF circuits and amplifiers.

### 3.4.6 Output Conductance ($g_{ds}$)

Output conductance, denoted as $g_{ds}$, indicates the extent to which the drain current varies in relation to $V_{DS}$ within the saturation region.

$$g_{ds} = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_{V_{GS}=\text{const.}} \quad (3.6)$$

An optimal HEMT would display a zero value for $g_{ds}$, which signifies ideal current saturation; however, actual devices show a small yet non-zero output conductance. Reducing $g_{ds}$ enhances signal stability and efficiency in high-frequency applications.

## 3.5 ENERGY BAND AND 2DEG FORMATION IN AlGaN/GaN HEMTs

Comprehending the functionality of AlGaN/GaN high-electron-mobility transistors (HEMTs) starts with analysing the energy band alignment at the interface of the heterojunction. A standout characteristic of this device is the generation of a high-density two-dimensional electron gas (2DEG), which is a result of the intrinsic variations in the material properties of Aluminium Gallium Nitride (AlGaN) and Gallium Nitride (GaN). The theoretical framework of this effect is represented in the energy band diagram depicted in Figure 3.2.

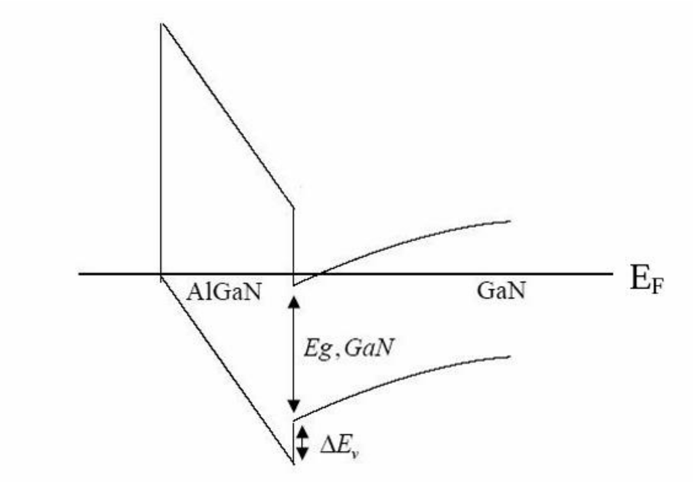


**Figure 3.2** Bandgap diagram of AlGaN/GaN HEMT

At the core of the AlGaN/GaN HEMT lies a heterojunction configuration, where a thin AlGaN layer is layered atop a GaN channel layer. These materials exhibit significantly different bandgap energies—AlGaN has a larger bandgap when compared to GaN. This discrepancy results in sudden alterations, or offsets, in both the conduction and valence bands at the junction. In particular, the conduction band discontinuity ($\Delta E_C$) is crucial in capturing free electrons at the interface, facilitating the creation of a confined electron layer, the 2DEG, in the GaN.

The band alignment illustrated in Figure 3.2 shows how electrons are energetically inclined to pile up in the lower conduction band of GaN, situated just beneath the AlGaN barrier. This accumulation results in the establishment of a quantum well, wherein electrons are confined to a narrow, planar region with restricted vertical movement. Importantly, this gathering of electrons occurs without the need for intentional doping, which is beneficial as it reduces impurity scattering and optimizes carrier mobility.

A significant factor in forming the 2DEG is the polarization effect intrinsic to the wurtzite crystal structure found in both GaN and AlGaN. When AlGaN is epitaxially grown onto GaN, the resulting strain produces piezoelectric polarization. This is further enhanced by spontaneous polarization, which is characteristic of both materials. The overall polarization at the interface generates a sheet of bound positive charge at the base of the AlGaN layer. Consequently, free electrons are attracted into the potential well located in the GaN layer, leading to the formation of the 2DEG.

The position of the Fermi level (EF) in the band diagram validates the existence of a conductive channel, even without an applied gate bias. The Fermi level sits above the conduction band edge in the GaN layer, signifying that the channel is inherently occupied by electrons under equilibrium conditions.

Moreover, the aluminium concentration in the AlGaN barrier has a significant impact on the band structure. Increasing the aluminium content amplifies the conduction band offset and polarization effects, thus augmenting the 2DEG sheet density. However, this must be finely balanced, as too much aluminium can result in elevated gate leakage currents and diminished device reliability.

The gate terminal within the HEMT architecture, typically a Schottky contact, regulates the 2DEG density. By applying a negative voltage across the gate, the conduction band is elevated, ultimately depleting the 2DEG below. This gate control mechanism enables the device to efficiently alternate between on and off states, which is a fundamental aspect of HEMT performance.

In summary, the band diagram in Figure 3.2 not only emphasizes the fundamental physics of the AlGaN/GaN heterojunction but also demonstrates how the 2DEG is inherently formed and regulated within the device. The pronounced polarization effects and advantageous band offsets are key to the enhanced high-frequency and high-power capabilities of these devices.

# CHAPTER 4
# DEVICE MODELING OF AlGaN/GaN HEMT IN SILVACO

This chapter presents Silvaco TCAD (Technology Computer-Aided Design), a popular tool for simulating semiconductor devices that enables researchers to model, simulate, and analyse the electrical properties of sophisticated semiconductor structures. It begins by outlining the capabilities of Silvaco TCAD and its significance in contemporary device engineering. Following that, it describes the specific AlGaN/GaN HEMT structure developed and simulated with the software, including the materials, layers, and parameters incorporated into the modeling.
The simulation yields critical output characteristics such as the drain current–voltage (I-V) relationship, which offers insights into the operational performance of the device. These findings not only confirm the theoretical comprehension of HEMT behaviour but also assist in the further enhancement of device design. The chapter connects theoretical concepts with practical application, emphasizing how simulation tools can expedite advancements in semiconductor research.

## 4.1 INTODUCTION TO SILVACO

The model for the AlGaN/GaN HEMT created in this study was designed and simulated using the Silvaco TCAD software suite. This platform provides an extensive array of tools specifically formulated for simulating complex semiconductor devices, particularly those that involve compound materials such as group III-V semiconductors. The modeling process commenced in **DeckBuild**, which is both a graphical and command-line interface that allows users to create and manage simulation input files. These files encompass all the physical specifications of the device, including its geometry, material layers, doping profiles, and electrical contacts.

Simulations were carried out utilizing **ATLAS**, which is the primary device simulator from Silvaco. ATLAS addresses fundamental semiconductor equations on a two- or three-dimensional mesh that is applied to the established device structure. It incorporates drift-diffusion and continuity equations, which facilitate a precise prediction of charge carrier behaviour under various biasing conditions. For the analysis of the graphical output and the extraction of key parameters from the simulation outcomes, **TonyPlot** Silvaco's visualization tool, was employed.

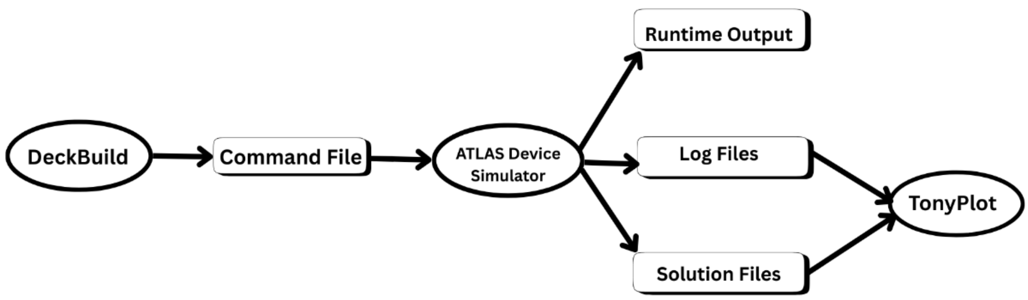


**Figure 4.1** Silvaco Simulation Flowchart

## 4.2 SIMULATION WORKFLOW IN ATLAS

Establishing a device simulation in ATLAS requires adhering to a clearly defined sequence of commands. Through several iterations, we recognized the significance of following this order diligently. Even a slight misplacement of a **solve** command or missing a boundary condition could result in errors or produce outcomes that do not accurately represent the device's behaviour.

### 4.2.1 Structure Definition

We started by defining the physical structure of the device. By utilizing essential commands such as **mesh**, **region**, **electrode**, and **doping**, we illustrated the geometric grid, designated materials, and appropriately positioned electrodes. Numerous adjustments were necessary to create a mesh that was sufficiently dense to capture key gradients without putting too much strain on computational resources.

### 4.2.2 Material and Model Configuration

After establishing the physical layout, we moved on to assign material characteristics and activate the necessary physical models. Commands like **material**, **models,** and interface were vital in this step. For an AlGaN/GaN HEMT, it was particularly important to include polarization effects and high-field mobility models. We observed early on that the absence of even one model could result in unrealistic I-V curves or unforeseen leakage paths.

### 4.2.3 Numerical Method Selection

At this stage, we configured the settings for the numerical solver using the method command. While the default settings sufficed for less complex scenarios, more sophisticated simulations needed meticulous adjustments. Modifying parameters such as convergence criteria and damping factors became essential to stabilize the solution process, particularly under high-bias conditions.

### 4.2.4 Simulation Execution

With the structure and models established, we set the operating conditions and commenced the simulations. This required commands like **log**, **solve**, **load**, and **save**. Depending on our analysis goals—whether they involved output characteristics, transfer curves, or thermal responses—we conducted various bias sweeps and stored intermediate states for additional examination.

### 4.2.5 Data Extraction and Visualization

In the final step, we evaluated the results using the extract command to collect parameters like threshold voltage, saturation current, and transconductance. For graphical interpretation, we utilized **TonyPlot**, which proved useful for reviewing band diagrams, carrier densities, and field distributions. Though the plots needed some manual adjustments for better clarity, they greatly assisted in confirming the physical accuracy of the simulation outcomes.

## 4.3 DESIGN AND SIMULATION OF AlGaN/GaN HEMT STRUCTURE USING SILVACO ATLAS

In this research, we created a high electron mobility transistor (HEMT) utilizing an AlGaN/GaN heterostructure, which was modeled and simulated within the Silvaco ATLAS environment. The structure was meticulously designed with a vertical multi-layer stack on a sapphire substrate. The simulation parameters, including geometry, material specifications, doping levels, and electrode arrangements, were implemented using ATLAS command syntax.

The device consists of four primary layers. At the bottom, a sapphire layer with a thickness of 1000 nm acts as the insulating substrate (Region 1). On top of this, there is a 20 nm thick AlN layer (Region 2), serving typically as a buffer or nucleation layer to manage lattice mismatch and enable high-quality GaN epitaxy.

The GaN layer, which is 1948 nm thick (Region 3), constitutes the main channel of the device where the two-dimensional electron gas (2DEG) is anticipated to develop. Above this channel is a 32 nm AlGaN barrier layer (Region 4) with an aluminium mole fraction of 33%, which enhances polarization effects essential for 2DEG formation without intentional doping of the channel.

The device's lateral configuration includes three terminals: the source and drain electrodes each measure 500 nm in width and are positioned at the device's edges, while the gate electrode is 2000 nm wide and centrally located in between them. All electrodes are defined on the top surface and connected to the AlGaN layer, following the mesh and electrode commands.

The AlGaN region (Region 4) is uniformly doped with n-type carriers at a concentration of $1.5 \times 10^{18}$ cm$^{-3}$, guaranteeing a sufficient carrier supply for conduction. The electrical contacts are modeled with specific work functions: 3.93 eV for both the source and drain, and 5.0 eV for the gate, to accurately reflect the barrier behaviour and electron injection characteristics.

The mesh is finely detailed, particularly in the vertical direction near the surface, to ensure precise resolution of both the thin AlGaN layer and the critical AlGaN/GaN interface. Horizontal and vertical mesh points are meticulously defined to capture the gradient effects across varying regions.

This simulation also incorporates models such as Shockley-Read-Hall recombination, polarization effects (with strain-induced polarization scaling set to 0.8), and field-dependent mobility employing the Albrecht model. These models account for significant physical mechanisms influencing carrier transport in III-nitride HEMTs.

A sequence of DC simulations was conducted, varying both gate and drain voltages across different biasing conditions to extract output characteristics. The resulting data were recorded in structured log files and visualized using TonyPlot for additional analysis of the device's electrical performance.

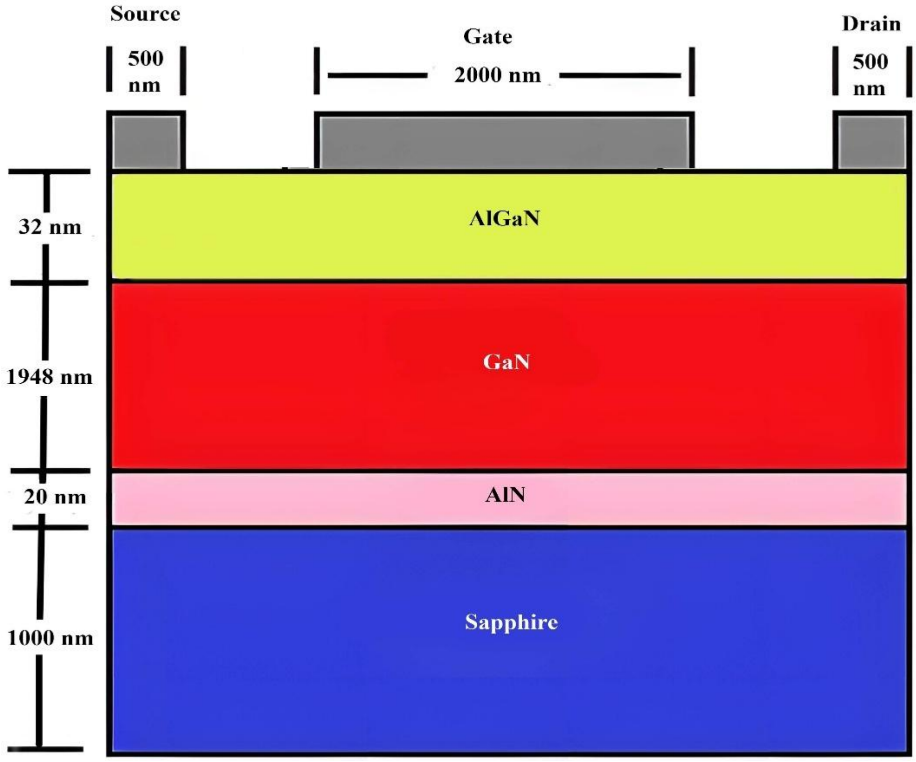


**Figure 4.2** Schematic Representation of an AlGaN/GaN Double-Heterojunction HEMT Structure Featuring a 32 nm AlGaN Barrier and a Fixed Gate Length of 2000 nm

## 4.4 VARIATION OF HEMT OUTPUT CHARACTERISTICS WITH DESIGN PARAMETERS

The V–I characteristics of AlGaN/GaN HEMTs are significantly influenced by variables such as AlGaN thickness, aluminium mole fraction, and doping levels. Increasing the thickness of AlGaN boosts the polarization-induced electric field at the heterojunction, which increases the 2DEG density and enhances the drain current and transconductance. However, if the thickness becomes too great, it can lead to an unfavourable shift in the threshold voltage and exacerbate short-channel effects. A higher aluminium mole fraction also elevates the 2DEG density by strengthening polarization; however, excessive aluminium content can compromise interface quality and reliability. Doping levels play a crucial role as well moderate doping enhances carrier control, while excessive doping can lead to increased leakage and diminished performance. In summary, precise adjustment of these parameters is vital for optimizing current drive, threshold control, and device stability.

### 4.4.1 Effect of AlGaN Thickness On I-V Characteristics

The thickness of the AlGaN barrier layer in a HEMT structure is vital in influencing it's I-V characteristics, especially in region 4 of the device. As the thickness of the AlGaN layer increases, the polarization effects at the AlGaN/GaN interface become more pronounced, leading to a stronger electric field and an increased density of the two-dimensional electron gas (2DEG). This growth in 2DEG density enhances channel conductivity, resulting in a noticeable rise in the drain current for a given gate-source voltage. Consequently, the output characteristics exhibit steeper slopes and higher current levels. Additionally, the threshold voltage generally shifts negatively with an increase in AlGaN thickness, suggesting a move towards normally-on behaviour. While this can be advantageous for high-frequency performance due to improved transconductance, excessive thickness may lead to increased short-channel effects and potential degradation in material quality as a result of strain relaxation. Therefore, it is crucial to optimize the thickness of the AlGaN layer to find a balance between high current output and device stability, especially in high-power and high-frequency applications.

#### 4.4.1.1 Effect of Thickness on Drain Characteristics ($I_D$ - $V_{DS}$)

As the thickness of the AlGaN layer in a High Electron Mobility Transistor (HEMT) increase, the drain characteristics tend to enhance because of increased polarization-induced charge at the AlGaN/GaN interface. This results in a higher density of the two-dimensional electron gas (2DEG), which boosts the channel conductivity and the ability to carry current. Nonetheless, after reaching a specific thickness, the strain within the AlGaN layer may relieve, leading to defects that can impair device performance, reduce electron mobility, and contribute to leakage currents. Therefore, while moderate increases in AlGaN thickness can enhance output current and transconductance, excessive thickness may adversely affect the reliability and efficiency of the device.

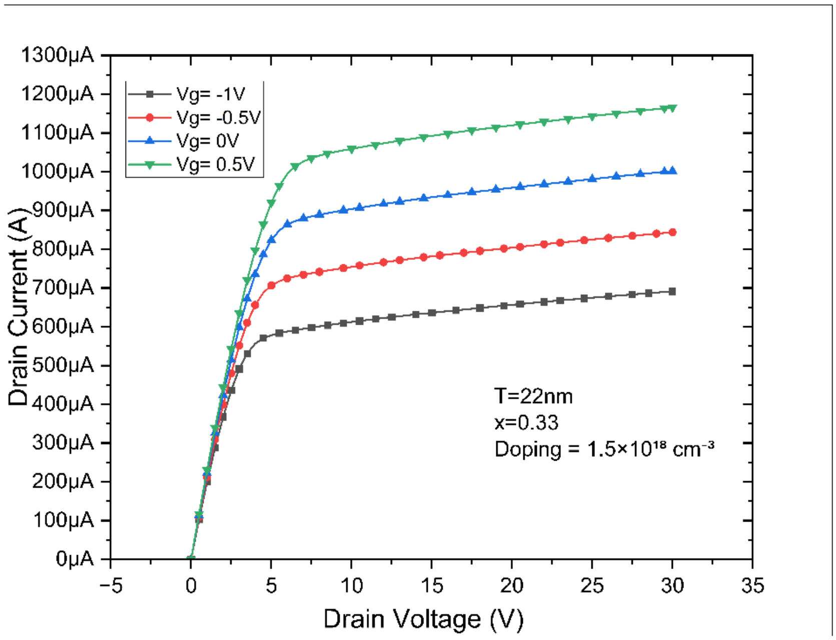


**Figure 4.3** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 22 nm, Al mole fraction x=0.33, and doping concentration $1.5\times10^{18}$ cm$^{-3}$.

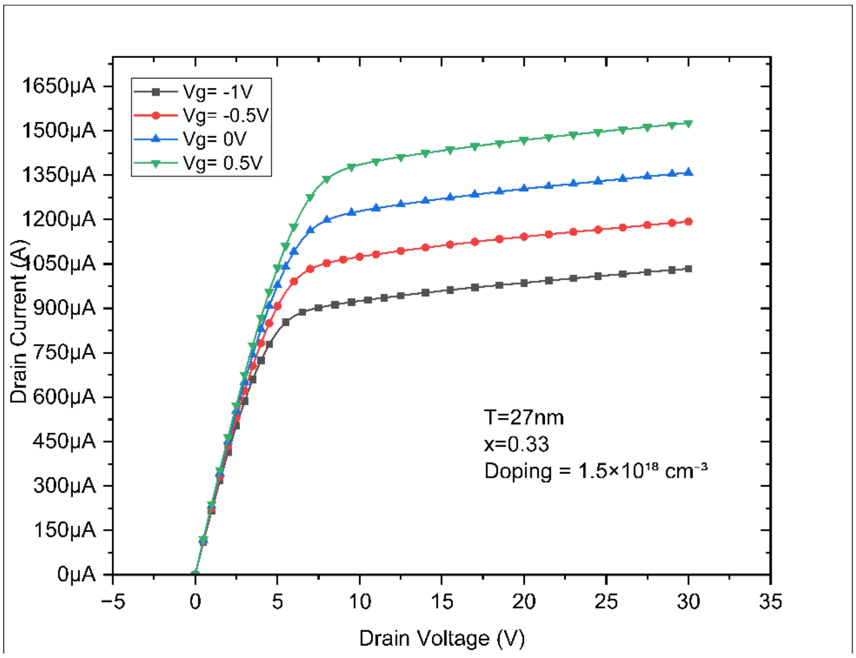


**Figure 4.4** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 27 nm, Al mole fraction x=0.33, and doping concentration $1.5{\times}10^{18}$ cm$^{-3}$.

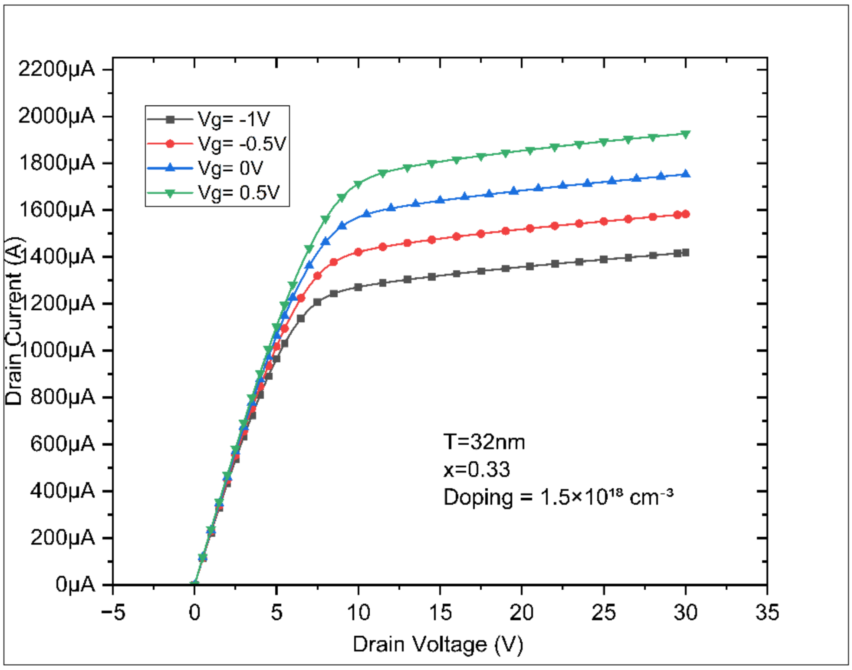


**Figure 4.5** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 32 nm, Al mole fraction x=0.33, and doping concentration $1.5{\times}10^{18}$ cm$^{-3}$.

The drain characteristics of the HEMT vary noticeably with the thickness of the AlGaN layer. As the thickness increases from 22 nm to 32 nm, the drain current ($I_D$) rises significantly due to the increased 2DEG density at the interface, enhancing channel conductivity. The device with 32 nm thickness shows the highest current levels, indicating better electron confinement and improved transconductance. Overall, thicker AlGaN layers improve output performance up to a point, as demonstrated by the higher currents in the 32 nm sample compared to thinner layers.

#### 4.4.1.2 Effect of Thickness on Output Characteristic ($I_{DS}$ - $V_{DS}$)

The relationship between source current and drain voltage at varying gate voltages offers valuable insights into the output characteristics of AlGaN/GaN HEMTs. Investigating this relationship with different AlGaN barrier thicknesses, while maintaining a constant aluminium mole fraction and doping concentration, reveals distinct performance patterns. As the thickness of the AlGaN increases, enhanced polarization effects at the AlGaN/GaN interface contribute to a higher density of the two-dimensional electron gas (2DEG). This leads to an increase in source current for the same drain voltage, signifying improved channel conductivity and current driving capability. Furthermore, the device demonstrates stronger modulation by the gate with thicker AlGaN layers, suggesting better control over channel formation.

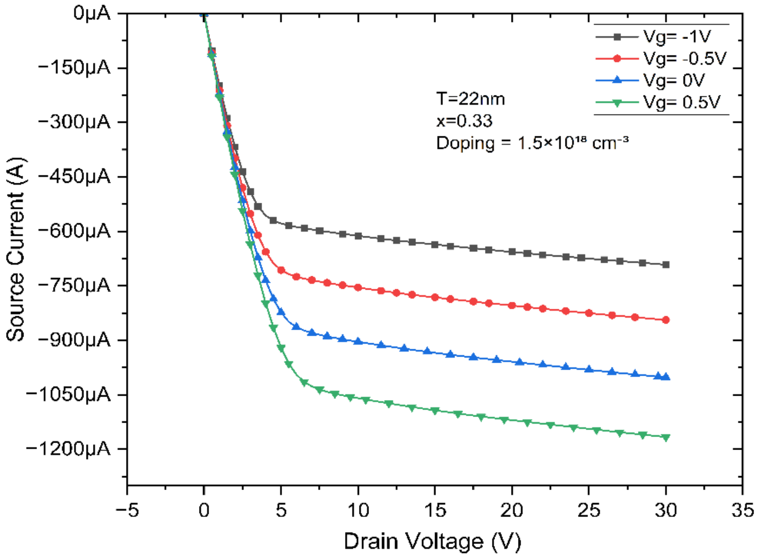


**Figure 4.6** Variation of Source Current with Drain Voltage at Different $V_G$ for Thickness 22 nm and Al Mole Fraction of 0.33, with Doping Concentration of $1.5\times10^{18}$ $cm^{-3}$.

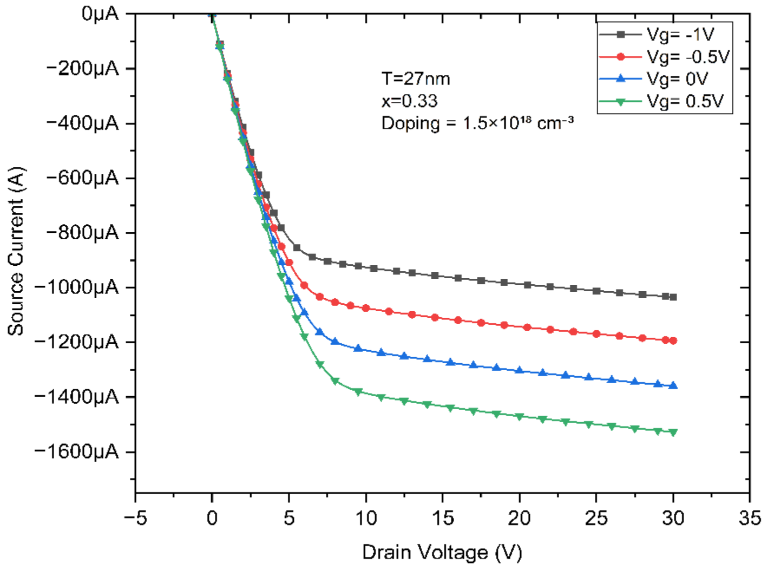


**Figure 4.7** Variation of Source Current with Drain Voltage at Different $V_G$ for Thickness 27 nm and Al Mole Fraction of 0.33, with Doping Concentration of $1.5\times10^{18}$ $cm^{-3}$.

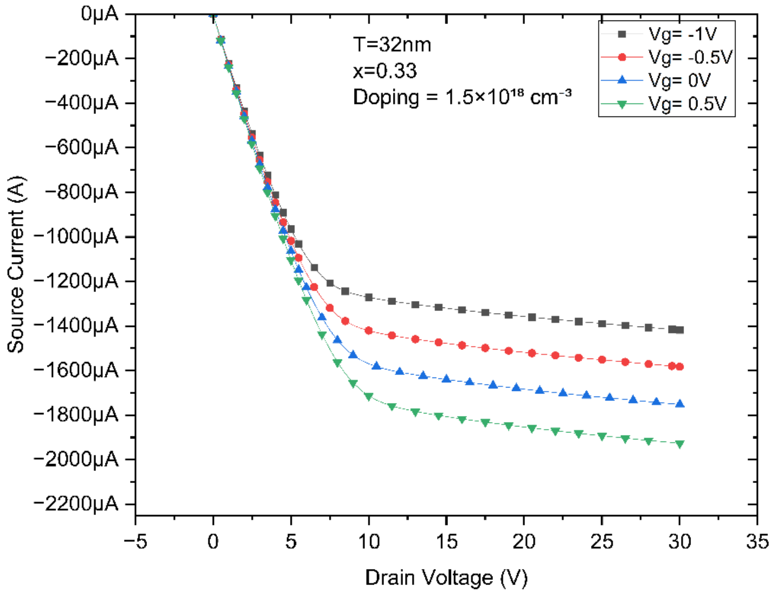


**Figure 4.8** Variation of Source Current with Drain Voltage at Different $V_G$ for Thickness 32 nm and Al Mole Fraction of 0.33, with Doping Concentration of $1.5\times10^{18}$ $cm^{-3}$.

The source current varies with drain voltage in AlGaN/GaN HEMTs at different gate voltages for various AlGaN barrier thicknesses. The findings clearly indicate that the thickness of AlGaN significantly affects the device's output characteristics. As the thickness increases, the polarization effects at the AlGaN/GaN interface become more pronounced, resulting in a higher density of two-dimensional electron gas (2DEG). This rise in carrier concentration boosts channel conductivity, leading to increased source current for the same drain voltage across all gate voltages. Additionally, thicker AlGaN layers show enhanced gate modulation, reflecting better electrostatic control. However, beyond a certain thickness, further increases can introduce issues such as threshold voltage shifts and possible material strain. In conclusion, this chapter emphasizes the necessity of optimizing AlGaN thickness in HEMT design, particularly for achieving a favourable balance between high current output and stable device performance under varying gate and drain bias conditions.

### 4.4.2 EFFECT OF MOLE FRACTION VARIATION ON I-V CHARACTERISTICS

The aluminium mole fraction within the AlGaN layer is crucial for shaping the I–V characteristics of AlGaN/GaN HEMTs. An increase in mole fraction boosts the polarization-induced electric field at the AlGaN/GaN interface, subsequently raising the density of the two-dimensional electron gas (2DEG). A higher density of 2DEG enhances channel conductivity, leading to a significant rise in drain current for a given gate and drain voltage. This improvement translates into increased transconductance and overall better performance of the device, especially in high-frequency settings. However, an excessive amount of aluminium can result in a larger lattice mismatch between AlGaN and GaN, which might introduce interface defects and reduce the quality of the material. These complications can adversely impact reliability, surface roughness, and carrier mobility. Thus, while elevating the aluminium mole fraction can greatly enhance output characteristics, careful optimization is necessary to prevent compromising device stability and long-term performance. Adequate control of the mole fraction is vital for achieving high-efficiency operation of HEMTs.

#### 4.4.2.1 Effect of Mole fraction on Drain Characteristics ($I_D$ - $V_{DS}$)

The amount of aluminium in the AlGaN layer significantly affects the drain characteristics ($I_D$-$V_{DS}$) of AlGaN/GaN HEMTs. An increase in mole fraction boosts polarization at the AlGaN/GaN interface, resulting in a higher density of two-dimensional electron gas (2DEG). This leads to enhanced channel conductivity and increased drain current for a specific $V_{DS}$. However, a high aluminium concentration can lead to lattice mismatch, compromising interface quality and diminishing mobility. It can also alter the threshold voltage and impact device stability. Thus, finding an optimal mole fraction is crucial for balancing performance, reliability, and output efficiency in high-power and high-frequency HEMT applications.

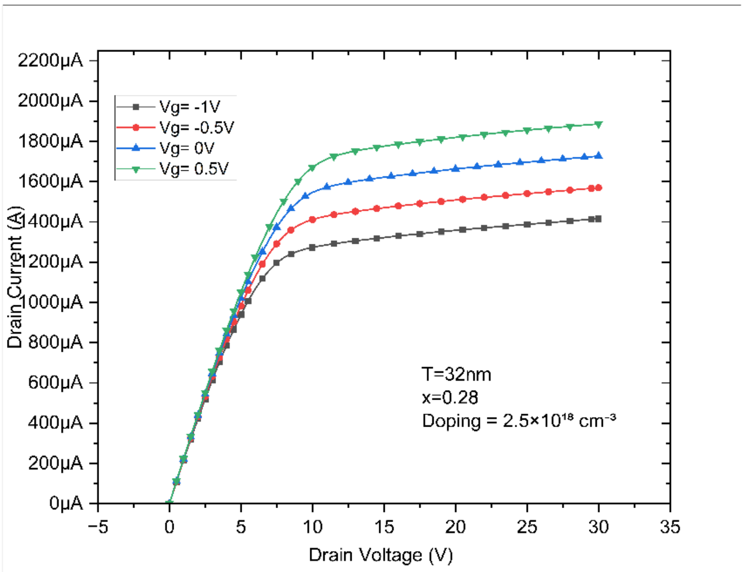


**Figure 4.9** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 32 nm, Al mole fraction x=0.28, and doping concentration $2.5\times10^{18}$ cm$^{-3}$.

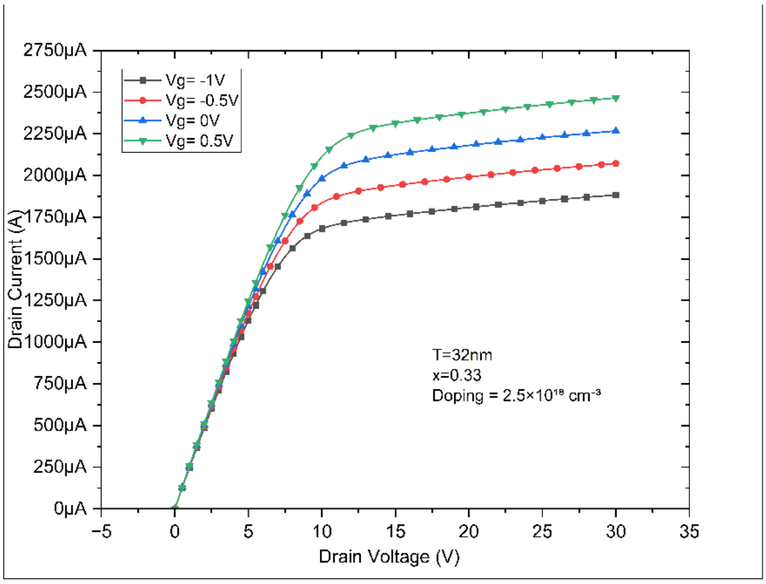


**Figure 4.10** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 32 nm, Al mole fraction x=0.33, and doping concentration $2.5\times10^{18}$ cm$^{-3}$.

By maintaining the AlGaN thickness at 32 nm and a doping concentration of $2.5\times10^{18}$ cm$^{-3}$, an increase in the aluminium mole fraction from 0.28 to 0.33 led to a significant rise in the drain current observed in the $I_D$-$V_{DS}$ characteristics. This enhancement is due to the stronger polarization effects at elevated mole fractions, which boost the density of the two-dimensional electron gas (2DEG) at the AlGaN/GaN interface. Consequently, the channel conductivity improves, resulting in sharper output curves and enhanced current drive. This trend indicates that higher aluminium content improves device performance but needs to be optimized to prevent interface degradation.

### 4.4.2.2 Effect of Mole fraction on Output Characteristic ($I_{DS}$ - $V_{DS}$)

The aluminium mole fraction in the AlGaN layer has a significant impact on the output characteristics ($I_{DS}$-$V_{DS}$) of AlGaN/GaN HEMTs. As the mole fraction increases, the polarization charge at the AlGaN/GaN interface becomes stronger, which enhances the formation of the two-dimensional electron gas (2DEG). A higher 2DEG density reduces channel resistance, allowing more electrons to flow from source to drain under the same bias conditions. This leads to an increase in drain current and a steeper slope in the output characteristics, indicating better current drive capability. However, beyond a certain mole fraction, excessive lattice mismatch can degrade interface quality, affecting carrier mobility and reliability.

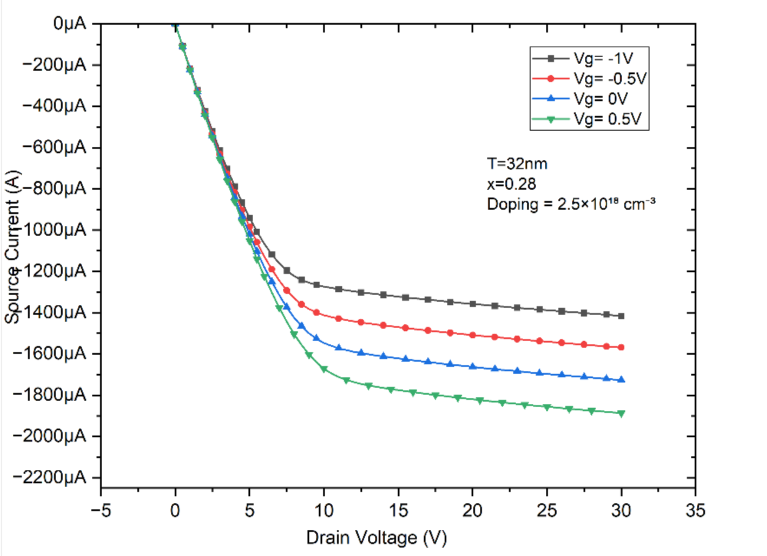


**Figure 4.11** Variation of Source Current with Drain Voltage at Different $V_G$ for T = 32 nm and Al Mole Fraction of 0.28, with Doping Concentration of $2.5\times10^{18}$ $cm^{-3}$.

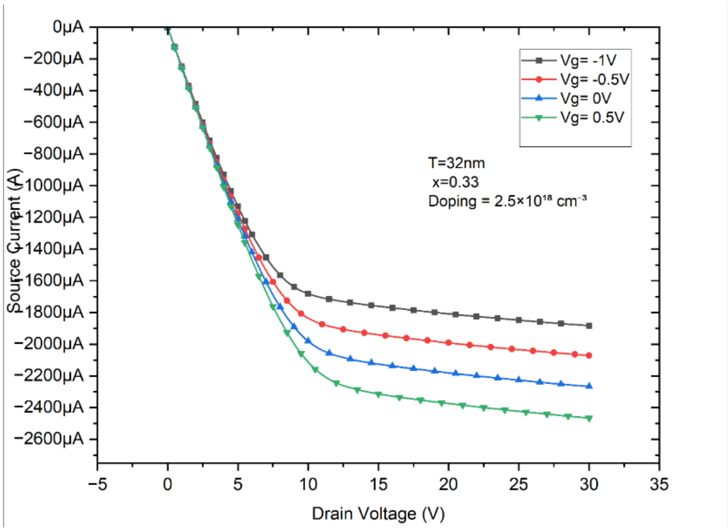


**Figure 4.12** Variation of Source Current with Drain Voltage at Different $V_G$ for T = 32 nm and Al Mole Fraction of 0.33, with Doping Concentration of $2.5\times10^{18}$ $cm^{-3}$.

With the AlGaN barrier thickness fixed at 32 nm and a doping concentration of $2.5\times10^{18}$ $cm^{-3}$, the aluminium mole fraction was varied from 0.28 to 0.33 to observe its impact on the output characteristics ($I_{DS}$–$V_{DS}$) of the HEMT. The plotted results show a clear increase in drain current as the mole fraction increases. This enhancement is due to stronger spontaneous and piezoelectric polarization at higher aluminium content, which increases the density of the two-dimensional electron gas (2DEG) at the AlGaN/GaN interface. The increased 2DEG density improves channel conductivity, resulting in higher current output and steeper $I_{DS}$–$V_{DS}$ curves. This indicates improved current handling and transconductance with higher mole fractions. However, while performance improves within this range, excessive aluminium may lead to increased lattice strain and interface defects. Thus, the observed results suggest that careful tuning of the mole fraction is essential for optimizing device performance while maintaining structural integrity.

### 4.4.3 EFFECT OF DOPING CONCENTRATION VARIATION ON I-V CHARACTERISTICS

The doping concentration within the AlGaN/GaN HEMT structure significantly influences it's I–V characteristics. By modifying the doping level—especially in the barrier or buffer layer—the device's carrier concentration and electrostatic control can be precisely adjusted. An increase in doping concentration results in a greater availability of free carriers, which boosts the density of the two-dimensional electron gas (2DEG) at the AlGaN/GaN interface. This enhancement leads to improved channel conductivity and increased drain current for a specific gate and drain bias. However, if the doping level becomes too high, it can increase impurity scattering, lower carrier mobility, and introduce leakage currents, which may ultimately compromise device reliability and thermal stability. Furthermore, elevated doping levels can alter the threshold voltage, which may change the switching behaviour of the device. Typically, the resulting I–V curves exhibit steeper slopes and increased saturation currents with moderate increases in doping. Consequently, optimizing the doping concentration is essential for achieving a balance between performance, efficiency, and long-term stability in HEMT operation.

#### 4.4.3.1 Effect of Doping Concentration on Drain Characteristics ($I_D$ - $V_{DS}$)

The doping concentration in AlGaN/GaN HEMTs has a direct impact on the drain characteristics (**$I_D$ - $V_{DS}$** )by altering the carrier density and the distribution of the electric field within the device. Raising the doping level, particularly in the barrier or buffer layer, promotes the formation of a two-dimensional electron gas (2DEG) at the heterojunction, which decreases channel resistance and increases drain current. This leads to steeper **$I_D$ - $V_{DS}$** curves and enhanced output performance. However, excessively high doping levels can cause increased impurity scattering and leakage currents, which can adversely affect mobility and reliability. Therefore, finding an optimal doping level is crucial for balancing current drive, efficiency, and the stability of the device.

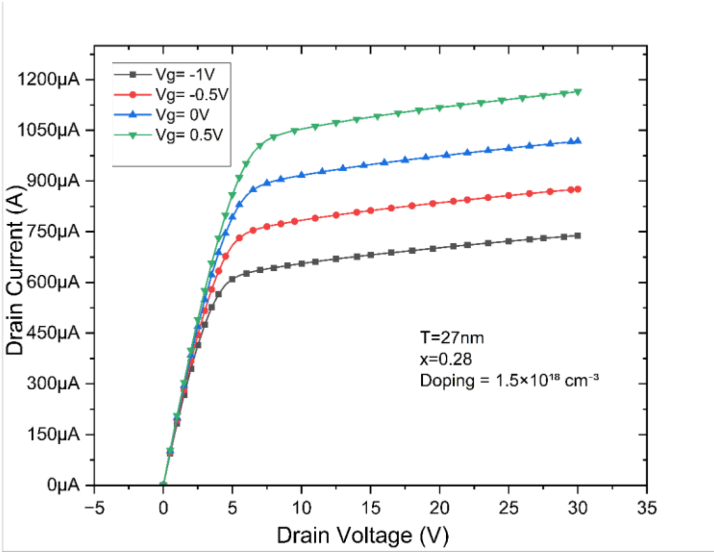


**Figure 4.13** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 27 nm, Al mole fraction x=0.28, and doping concentration $1.5\times10^{18}$ cm$^{-3}$.

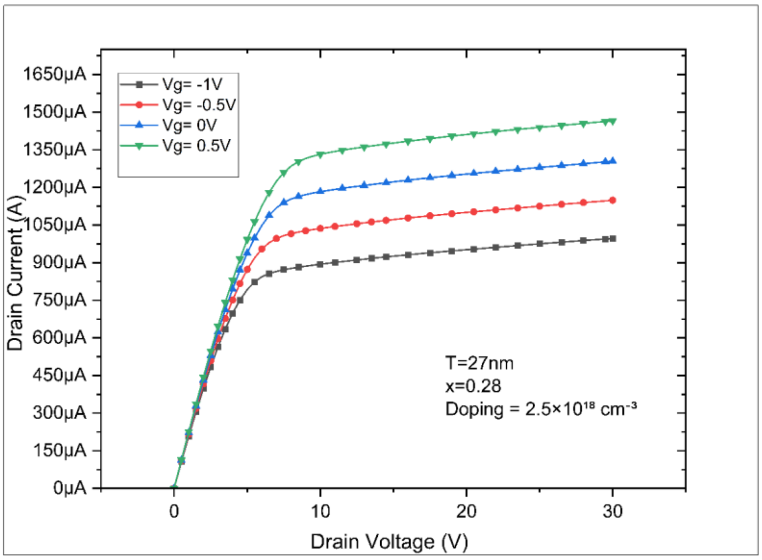


**Figure 4.14** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 27 nm, Al mole fraction x=0.28, and doping concentration $2.5\times10^{18}$ cm$^{-3}$.

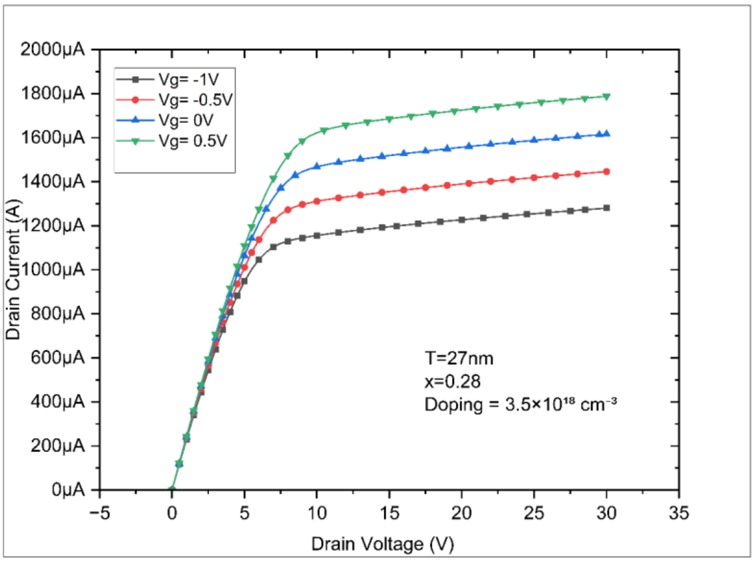


**Figure 4.15** Drain characteristics of AlGaN/GaN HEMT with AlGaN barrier thickness of 27 nm, Al mole fraction x=0.28, and doping concentration $3.5\times10^{18}$ $cm^{-3}$.

With the AlGaN barrier thickness fixed at 27 nm and aluminium mole fraction held constant at 0.28, the doping concentration was varied from $1.5\times10^{18}$ $cm^{-3}$ to $3.5\times10^{18}$ $cm^{-3}$ to evaluate its effect on the drain characteristics (**$I_D$ - $V_{DS}$** ) of the HEMT. The plotted results show a clear trend of increasing drain current with higher doping concentrations. This occurs due to the enhanced formation of the two-dimensional electron gas (2DEG) at the AlGaN/GaN interface, resulting from increased ionized donor concentration. A higher 2DEG density improves channel conductivity and lowers sheet resistance, leading to improved current conduction under the same bias conditions. The **$I_D$ - $V_{DS}$** curves become steeper with increasing doping, indicating enhanced output performance. However, very high doping levels may increase impurity scattering, leakage currents, and affect thermal stability. Therefore, optimizing the doping level is essential to maximize performance while ensuring device reliability and minimizing degradation effects.

### 4.4.3.2 Effect of doping concentration on Output Characteristic ($I_{DS}$ - $V_{DS}$)

The output characteristics (**$I_{DS}$ - $V_{DS}$**)of AlGaN/GaN HEMTs are significantly influenced by the doping concentration in the barrier or buffer layer. As the doping concentration increases, the availability of ionized donors enhances the formation of the two-dimensional electron gas (2DEG) at the AlGaN/GaN interface. This increase in 2DEG density leads to improved conductivity in the channel, resulting in higher drain current and steeper **$I_{DS}$ - $V_{DS}$** curves. Consequently, the device shows better output performance and current handling capability. However, excessive doping may introduce increased impurity scattering and gate leakage, which can degrade carrier mobility and overall device reliability. Thus, while moderate doping improves output characteristics, careful optimization is needed to avoid performance trade-offs. The observed variation in **$I_{DS}$** with **- $V_{DS}$** confirms the critical role of doping in determining the HEMT's output behaviour.

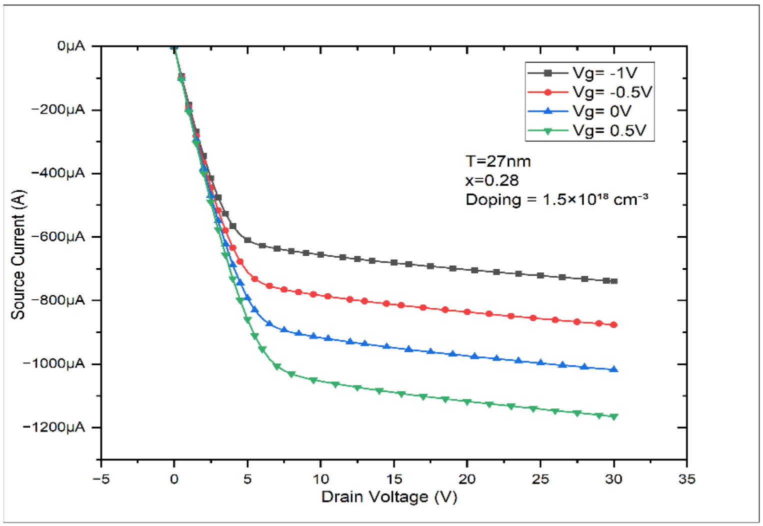


**Figure 4.16** Variation of Source Current with Drain Voltage at Different $V_G$ for Thickness 27 nm and Al Mole Fraction of 0.28, with Doping Concentration of $1.5\times10^{18}$ $cm^{-3}$.

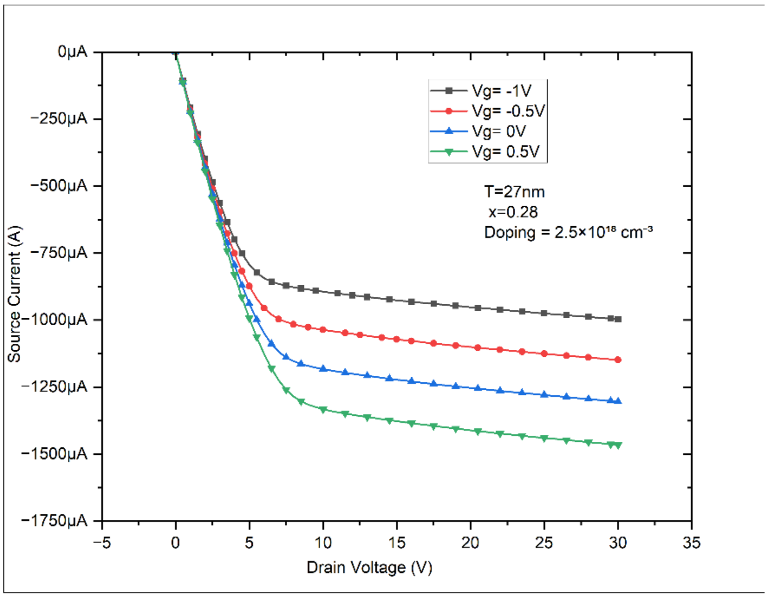


**Figure 4.17** Variation of Source Current with Drain Voltage at Different $V_G$ for Thickness 27 nm and Al Mole Fraction of 0.28, with Doping Concentration of $2.5\times10^{18}$ $cm^{-3}$.

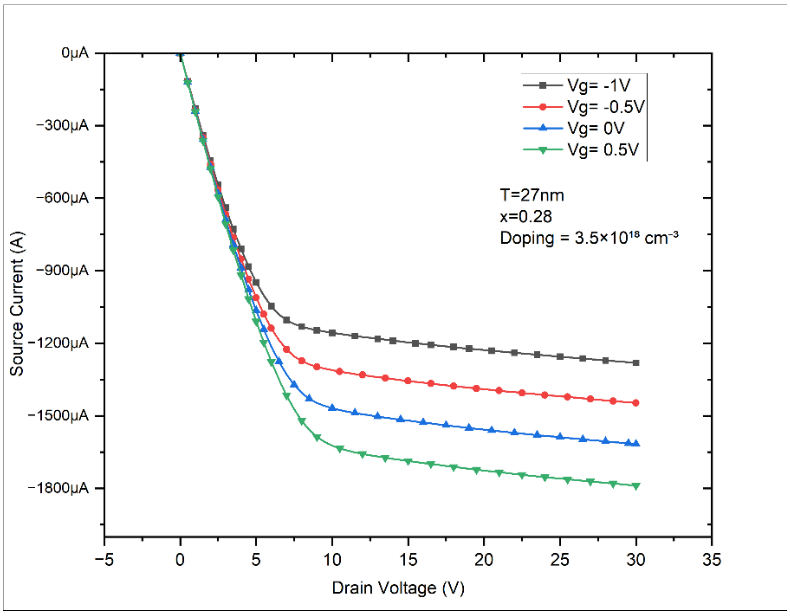


**Figure 4.18** Variation of Source Current with Drain Voltage at Different $V_G$ for Thickness 27 nm and Al Mole Fraction of 0.28, with Doping Concentration of $3.5\times10^{18}$ $cm^{-3}$.

This section investigates the effect of aluminium mole fraction variation on the output characteristics **($I_{DS}$-$V_{DS}$** )of an AlGaN/GaN HEMT, keeping the AlGaN barrier thickness constant at 27 nm and the doping concentration fixed at $3.5\times10^{18}$ $cm^{-3}$. The aluminium mole fraction was varied from 0.28 to 0.33, and the resulting output curves were analysed across different gate voltages. As the mole fraction increases, the drain current rises significantly for a given **$V_{DS}$**. This trend is due to enhanced polarization effects at higher aluminium content, which lead to increased two-dimensional electron gas (2DEG) density at the heterointerface. A stronger 2DEG improves channel conductivity, resulting in better current drive and steeper **($I_{DS}$-$V_{DS}$)** characteristics. However, very high aluminium content may lead to increased lattice strain, potentially affecting reliability and interface quality. The results indicate that mole fraction is a key design parameter, and its optimization is essential for achieving high performance without compromising device stability.

# CHAPTER 5
# CONCLUSION AND FUTURE WORK

This chapter offers final insights derived from the comprehensive examination of the device features previously discussed. It also suggests possible pathways for subsequent research and development. The conclusion encapsulates the major findings, while the future work section emphasizes aspects that need further exploration to improve the performance and scalability of AlGaN/GaN HEMT devices.

## 5.1 CONCLUSION

This thesis investigated the impact of essential structural parameters—specifically, the thickness of the AlGaN barrier layer, the aluminium mole fraction, and the doping concentration—on the electrical characteristics of AlGaN/GaN High Electron Mobility Transistors (HEMTs). Through a range of simulations and graphical evaluations, the research assessed how each parameter influences the behaviour of drain and source currents, particularly the $I_{DS}$ - $V_{DS}$ characteristics across different gate voltage levels.

The analysis of AlGaN barrier thickness showed that increasing the thickness enhances polarization effects at the AlGaN/GaN interface, resulting in a higher density of two-dimensional electron gas (2DEG) and improved channel conductivity. Consequently, devices demonstrate increased drain current levels and steeper output characteristics. However, beyond a specific optimal thickness, material degradation due to strain relaxation and heightened short-channel effects can adversely affect device performance, underscoring the importance of precise control over thickness.

The adjustment of the aluminium mole fraction indicated that a higher aluminium content fortifies the polarization field, which further elevates the density of 2DEG and current conduction. As the mole fraction increases from 0.28 to 0.33, the output characteristics clearly reveal enhanced current driving capability and improved transconductance. Nevertheless, high aluminium incorporation may introduce lattice strain and compromise interface quality, presenting challenges for long-term reliability.

Doping concentration, another significant parameter, directly influences carrier density and threshold voltage. As doping levels rise from $1.5\times10^{18}$ to $3.5\times10^{18}$ $cm^{-3}$, a marked enhancement in drain current and the slope of the $I_{DS}$ - $V_{DS}$ curves is noted, attributed to improved formation of 2DEG. Yet, increased doping can also result in greater impurity scattering and leakage currents, which might restrict thermal stability and efficiency.

In conclusion, achieving optimal performance in AlGaN/GaN HEMTs depends on a delicately balanced interplay of barrier thickness, aluminium mole fraction, and doping concentration. Each parameter uniquely influences the formation and management of 2DEG, and their interaction must be meticulously calibrated to attain high-speed, high-power, and thermally robust device performance. The knowledge acquired from this study lays a significant groundwork for further enhancements and innovations in the design of next-generation HEMTs.

## 5.2 FUTURE WORK

This study has generated important insights regarding how AlGaN barrier thickness, aluminium mole fraction, and doping concentration affect the output characteristics of AlGaN/GaN HEMTs, yet several paths remain available for additional investigation and improvement.

To begin with, future research could broaden the current analysis by including temperature-dependent evaluations. Given that GaN-based HEMTs are frequently utilized in high-power and high-temperature settings, investigating the thermal stability and performance of the 2DEG at elevated temperatures would provide valuable information concerning device durability and long-term dependability. This might involve examining how changes in the investigated parameters influence thermal resistance and breakdown voltage.

Moreover, integrating trap and surface states into the simulations would enhance the accuracy of the model. Surface traps, especially at the AlGaN/GaN interface or within passivation layers, have a significant effect on current collapse and dynamic on-resistance. Including these factors would lead to a more precise depiction of actual device performance and assist in devising techniques for mitigation.

In addition, the effects of either graded or step AlGaN barrier configurations could be investigated. Rather than utilizing a uniform Al composition, a graded barrier could improve carrier confinement and decrease lattice mismatch, potentially resulting in better 2DEG mobility and reduced interface trap densities.

Examining new gate designs, such as recessed gates, T-gates, or hybrid configurations, could also be beneficial. These designs might be assessed for their influence on threshold voltage regulation, current saturation, and high-frequency capabilities, particularly when coupled with the optimized structural parameters determined in this research.

Furthermore, exploring various substrate materials, such as SiC or diamond, could be worthwhile. These substrates have superior thermal conductivity compared to silicon and could greatly enhance heat dissipation, facilitating higher power operation and further refinement of electrical performance.

Lastly, moving from simulation to experimental validation is a logical subsequent step. Producing and characterizing devices with the identified optimal parameter sets would validate the simulated trends and allow for adjustments to the models employed.

In closing, the foundational knowledge acquired through this thesis provides a robust basis for enhancing the performance and reliability of AlGaN/GaN HEMTs, offering numerous avenues for further development and practical implementation.

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