**A DIELECTRICALLY MODULATED GAN/ALN/HfAlOx MOSHEMT WITH A NANOGAP-EMBEDDED CAVITY FOR BIOSENSING APPLICATIONS**

**Submitted**

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**DECLARATION**

**I/We declare that the project work contained in this report is original and it has been done by me under the guidance of my project guide.**

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**CERTIFICATE**

**This is to certify that Piyush Kumar, bearing BU21EECE0100207, has satisfactorily completed the Mini Project Entitled in partial fulfillment of the requirements as prescribed by the University for the 7th semester, Bachelor of Technology in “Electrical, Electronics and Communication Engineering” and submitted this report during the academic year 2024-2025.**

**Signature of the Guide Signature of HOD**

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# Chapter 1: Introduction

# **Overview of the problem statement:**

Biosensors are crucial in scientific and medical fields, but traditional technologies have limitations such as low sensitivity and instability. The project focuses on improving biosensor sensitivity and reliability to detect neutral and charged biomolecules. Current biosensors struggle with neutral molecules, hindering their functionality. Researchers are using advanced materials like GaN and AlGaN to address these challenges. These materials offer higher sensitivity and stability, making them suitable for biosensing applications. The project introduces a dielectric modulation approach in a GaN/AlGaN MOSHEMT structure to detect neutral biomolecules. By optimizing the device's design, scalability and fabrication challenges are addressed for mass production. The goal is to create a versatile biosensor capable of accurately detecting both neutral and charged biomolecules. By utilizing innovative materials and techniques, this project aims to enhance biosensor performance for medical diagnostics and environmental monitoring applications.

## **Objectives and goals:**

The project's primary objective is to design and develop a GaN/AlN/AlGaN -based MOSHEMT biosensor with improved sensitivity for detecting neutral and charged biomolecules. Specific objectives include designing a novel MOSHEMT structure with a nanogap-embedded cavity, analyzing biomolecular sensitivity, investigating the impact of AlGaN layer thickness and cavity fill height, considering fabrication and scalability, and testing in medical and environmental applications. The AlGaN layer is crucial for enhancing sensitivity to surface charges, and the nanogap cavity modulates electrical properties based on biomolecules' dielectric constant. The sensitivity analysis aims to detect low concentrations of biomolecules by measuring shifts in threshold voltage and drain current. Exploring AlGaN thickness and cavity fill height will optimize sensor performance. Fabrication concerns focus on practicality and scalability, balancing cost with performance improvements. The goal is to create a versatile biosensor to detect various biomarkers for medical diagnostics and environmental monitoring. The biosensor's response time, sensitivity, and durability in different environments will determine its suitability for these applications. Ultimately, the project aims to develop a high-performance biosensor that can detect a wide range of biomolecules accurately and sensitively, pushing the boundaries of current biosensing technology.

# **Chapter 2: Literature Review:**

The literature survey on GaN/AlGaN-based MOSHEMT biosensors provides several vital outcomes that significantly impact society and scientific research. The primary outcome of this review is to identify GaN/AlGaN MOSHEMTs as a superior technology for developing highly sensitive and chemically stable biosensors capable of detecting neutral and charged biomolecules. These advancements can potentially revolutionize several critical areas, including medical diagnostics, environmental monitoring, and the development of wearable health technologies. Below are the detailed primary outcomes:

**1. Advancements in Medical Diagnostics**

The literature review reveals that GaN/AlGaN biosensors are poised to transform medical diagnostics by enabling the detection of biomarkers with unprecedented sensitivity. These sensors can detect biomolecules at extremely low concentrations, which is critical for the early detection of diseases such as cancer, diabetes, and cardiovascular conditions. This can lead to better patient outcomes, as diseases can be diagnosed and treated at earlier stages, improving survival rates and reducing healthcare costs.

Outcome for Society: The development of GaN/AlGaN biosensors for medical applications could lead to early disease detection, faster diagnosis, and more personalized healthcare. This could significantly improve public health outcomes by making diagnostics more accessible, faster, and less invasive.

**2. Environmental Monitoring**

GaN/AlGaN sensors have also been shown to have excellent potential for environmental monitoring, particularly in detecting pollutants such as heavy metals, toxins, or pathogens in water and soil. Their high sensitivity and durability allow them to function in harsh environmental conditions where traditional sensors may fail. This makes them valuable for monitoring water quality, industrial pollution, and climate change-related contamination.

Outcome for Society: These sensors can provide real-time monitoring of environmental pollutants, leading to better environmental management and healthier ecosystems. Improved detection of contaminants could prevent environmental disasters and promote sustainable industrial practices.

**3. Integration with Wearable Technology**

The literature review highlights that GaN-based biosensors have significant potential in developing wearable health devices. Their small size, high sensitivity, and low power consumption make them suitable for continuous health monitoring. This could enable the development of next-generation wearable health devices that track biomolecules in real time, offering patients and healthcare providers critical health data on demand.

Outcome for Society: Wearable biosensors could improve chronic disease management by providing real-time health data, allowing for better-informed decisions and personalized treatments. This could revolutionize preventive healthcare by helping individuals monitor their health continuously.

**4. Chemical Stability and Scalability**

Another significant outcome is the recognition of the chemical stability of GaN/AlGaN biosensors. Unlike traditional silicon-based sensors, GaN/AlGaN devices resist chemical degradation, making them suitable for long-term use in biological fluids or polluted environments. However, the literature also identifies challenges in scalability and cost of fabrication, which are currently being addressed through ongoing research.

Outcome for Society: The chemical stability of GaN/AlGaN biosensors means that they could offer long-term solutions in both healthcare and environmental sectors, reducing the need for frequent sensor replacement and lowering operational costs.

**5. Dielectric Modulation for Neutral Biomolecule Detection**

One of the most innovative findings is dielectric modulation in GaN/AlGaN MOSHEMTs, which allows the detection of neutral biomolecules. This expands the range of detectable substances, addressing a significant limitation of traditional biosensors that only detect charged molecules. This is particularly useful in medical diagnostics, where neutral molecules such as proteins or enzymes play a crucial role in diagnosing diseases.

The outcome for Society: The ability to detect a broader range of biomolecules, including neutral ones, enhances the diagnostic power of biosensors, enabling more comprehensive health screenings and better detection of complex diseases.

**Author Contribution:**

The literature survey is based on research contributions from multiple authors in the GaN/AlGaN biosensors field. The key research referred to in the document titled “A Dielectrically Modulated GaN/AlN/AlGaN MOSHEMT with a Nanogap Embedded Cavity for Biosensing Applications” was authored by:

- Aasif Mohammad Bhat – Department of Electronics and Communication Engineering, Malaviya National Institute of Technology, Jaipur, India.

- Arathy Varghese – Department of Electronics and Communication Engineering, Malaviya National Institute of Technology, Jaipur, India.

- Nawaz Shafi – Department of Electronics and Communication Engineering, Malaviya National Institute of Technology, Jaipur, India.

- C. Periasamy – Department of Electronics and Communication Engineering, Malaviya National Institute of Technology, Jaipur, India.

Their research focuses on advancing dielectric modulation in GaN/AlGaN-based MOSHEMT biosensors, contributing to both the academic field and practical applications in biosensing technology.

# **Chapter 3: Strategic Analysis and Problem Definition**

## A project's strategic analysis and problem definition are critical to understanding its scope, challenges, and potential impact. This chapter aims to assess the strengths, weaknesses, opportunities, and threats (SWOT) related to the project, outline the project timeline through a GANTT chart, and refine the problem statement as the project progresses. These components help clarify the project’s direction and ensure that the project objectives are aligned with realistic expectations, resources, and goals.

## **3.1 SWOT Analysis**

## A SWOT analysis is a strategic planning tool used to evaluate the key elements of a project. It helps identify the internal strengths and weaknesses of the project as well as the external opportunities and threats that may influence the project's success. By conducting a SWOT analysis for the GaN/AlGaN MOSHEMT biosensor project, we can understand the project's potential, address risks, and plan for future challenges.

## **Strengths:**

## 1. High Sensitivity: Using GaN/AlGaN in the MOSHEMT structure allows for exceptional sensitivity in detecting neutral and charged biomolecules, making this technology more accurate and reliable than traditional biosensors.

## 2. Chemical Stability: GaN and AlGaN are chemically stable materials, especially in harsh environments such as biological fluids or polluted water, which enhances the sensor's long-term durability.

## 3. Detection Versatility: The ability to detect a wide range of biomolecules, including neutral ones, through dielectric modulation expands the application of the biosensor in medical diagnostics, environmental monitoring, and food safety.

## 4. Real-time Detection: The sensor’s fast response time allows for real-time biomolecule detection, critical in fields like healthcare where immediate results are essential.

## 5. Scalability in Design: The MOSHEMT structure can be scaled down, making it suitable for miniaturized applications, including wearable devices for continuous health monitoring.

## **Weaknesses:**

## 1. High Fabrication Costs: GaN and AlGaN materials are more expensive than silicon, which increases the overall cost of production. This could limit the widespread adoption of the technology.

## 2. Complex Manufacturing Process: The MOSHEMT structure involves a more complex fabrication process, requiring high precision in materials and design, which could lead to manufacturing bottlenecks.

## 3. Limited Commercial Availability: GaN-based biosensors are not as widely available or integrated into mainstream biosensing applications, limiting their reach in mass markets.

## 4. Power Consumption: Although the sensor offers high sensitivity, power consumption could become a limiting factor in battery-operated wearable applications if not optimized.

## **Opportunities:**

## 1. Expansion in Medical Diagnostics: The biosensor has significant potential for early disease detection, particularly in detecting biomarkers for diseases like cancer, diabetes, and heart conditions. The demand for portable diagnostic tools is rapidly growing.

## 2. Environmental Monitoring Applications: As concerns over pollution and climate change intensify, there is an increasing need for accurate real-time air and water quality monitoring. The sensor can be applied to detect heavy metals, toxins, or pathogens in contaminated environments.

## 3. Growth in Wearable Health Devices: There is an opportunity to integrate the sensor into wearable devices to monitor biomarkers, enabling personalized healthcare continuously.

## 4. Government and Industry Funding: Governments and private sectors increasingly fund nanotechnology and biosensing projects, opening collaboration opportunities and research grants to reduce development costs.

## **Threats:**

## 1. Competition from Other Technologies: Optical and electrochemical sensors are already established in the market, and any breakthrough in those technologies could outpace GaN/AlGaN-based sensors.

## 2. Regulatory Hurdles: In the medical field, biosensors must meet stringent regulatory requirements before being adopted for clinical use, which can delay commercialization.

## 3. Market Acceptance and Cost Sensitivity: Due to higher costs, there may be resistance to adopting GaN-based biosensors in cost-sensitive markets where traditional silicon-based alternatives are still widely used.

## 4. Technological Risks: The complexity of fabricating GaN/AlGaN sensors might lead to reliability issues in large-scale production. Manufacturing defects or inconsistencies could affect the performance of the biosensor.

## **3.2 Project Plan - GANTT Chart**

## A GANTT chart visually represents the project timeline, breaking the project into individual tasks or phases, along with their respective start and end dates. It is a critical tool for project management as it ensures the project stays on schedule and that each milestone is achieved in the correct order. Below is a high-level GANTT chart breakdown for the GaN/AlGaN MOSHEMT biosensor project:

|  |  |  |
| --- | --- | --- |
| **Task/Phase** | **Duration** | **Dependencies** |
| Literature Review | 2 Weeks | Literature papers |
| Device Design | 2 Weeks | Completion of review |
| Simulation Setup | 1.5 Weeks | Device design |
| Sensitivity Testing | 2 Weeks | Simulation setup |
| Refining Design | 1.5 Weeks | Sensitivity testing |
| Documentation and Reporting | 1 Weeks | Final testing |
| Project Submission | 1 Day | Documentation |

## **Explanation of Key Phases:**

## 1. Literature Review: This phase involves conducting an in-depth review of existing research on GaN/AlGaN-based MOSHEMT biosensors, dielectric modulation techniques, and potential applications. Understanding the current landscape will inform the design and implementation phases.

## 2. Device Design: This phase focuses on designing the GaN/AlGaN MOSHEMT biosensor structure, including the dimensions of the nanogap cavity and material properties. Simulation models will also be established to prepare for the next phase.

## 3. Simulation Setup: The next step is to run simulations using tools like TCAD Synopsys once the design is complete. These simulations will test the sensor's sensitivity to neutral and charged biomolecules and various environmental factors.

## 4. Sensitivity Testing: The project will proceed with in-depth testing to evaluate how the sensor responds to different biomolecules. This will involve measuring threshold voltage (Vth) shifts and drain current (IDS).

## 5. Refining Design: Based on the results from sensitivity testing, the sensor design will be adjusted to optimize performance. This could include tweaking the AlGaN layer thickness, or the cavity fill height for better sensitivity.

## 6. Fabrication and Prototyping: After the design is finalized, the sensor will be fabricated and prototyped. This phase includes sourcing materials, fabricating the sensor, and meeting all design specifications.

## 7. Final Testing: The prototype will be tested to meet performance requirements. This includes testing in different environments (biological fluids, contaminated water, etc.) to assess the sensor's robustness and durability.

## 8. Documentation and Reporting: A final project report will be prepared, documenting all the findings, challenges, solutions, and recommendations for future research.

## 9. Project Submission: The project will be officially submitted after completing the final report and testing phases.

## **3.3 Refinement of Problem Statement**

## At the start of the project, the problem statement was defined as the need for a highly sensitive, stable, and versatile biosensor that could detect neutral and charged biomolecules with high accuracy using GaN/AlGaN MOSHEMT technology. However, as the project progressed, several refinements were made to the problem statement based on emerging insights from the literature review and the design and testing phases.

## Initial Problem Statement: The initial problem statement addressed limitations in traditional silicon-based biosensors, such as low sensitivity, chemical instability, and the inability to detect neutral biomolecules. The goal was to leverage GaN/AlGaN materials to design a biosensor with superior performance characteristics, particularly in medical diagnostics and environmental monitoring.

## 

# **Chapter 4: Methodology**

The methodology section outlines the systematic approach to developing, simulating, and evaluating the GaN/AlGaN MOSHEMT biosensor. This chapter explains the steps followed in the project, including the design process, tools used, techniques employed, and critical design considerations. The methodology ensures that the project objectives are met efficiently while addressing potential challenges encountered during the biosensor's development.

**4.1 Description of the Approach**

The approach taken in this project follows a structured process that integrates both theoretical modeling and practical simulation to develop a highly sensitive GaN/AlGaN MOSHEMT biosensor. The primary goal is to create a biosensor capable of detecting neutral and charged biomolecules through dielectric modulation and optimize its performance using systematic simulations and adjustments.

Step 1: Problem Identification and Initial Research-

The project begins with a comprehensive review of the current state of biosensor technology. This involves understanding the limitations of silicon-based biosensors and identifying how GaN/AlGaN materials can overcome these challenges, particularly in terms of sensitivity, stability, and the ability to detect a broader range of biomolecules.

Step 2: Conceptual Design of the MOSHEMT Biosensor-

The next step is conceptualizing the GaN/AlGaN-based MOSHEMT structure. The design incorporates a nanogap-embedded cavity beneath the MOSHEMT gate to detect biomolecules through dielectric modulation. The critical design parameters include the thickness of the AlGaN layer, cavity size, and device geometry, all of which affect the sensor's sensitivity.

Step 3: Simulation Setup and Parameter Testing-

After designing the device, simulations are performed using tools like Synopsys Sentarus to model the electrical characteristics of the biosensor. The simulations focus on how the presence of biomolecules affects the sensor's threshold voltage (Vth) and drain current (IDS). These simulations are repeated for various device configurations, changing parameters such as the biomolecules' dielectric constant, the AlGaN layer's thickness, and the cavity fill height.

Step 4: Sensitivity Analysis-

Once simulations are run, the project moves to the sensitivity analysis phase, where the performance of the biosensor is evaluated. The critical focus is measuring the shift in electrical properties caused by neutral and charged biomolecules. The analysis aims to maximize the sensor’s ability to detect small concentrations of biomolecules by optimizing the design parameters.

Step 5: Design Refinement-

Based on the results of the sensitivity analysis, the design of the MOSHEMT biosensor is refined. This phase involves adjusting the AlGaN layer thickness, cavity fill height, and the dielectric constant of the sensing region. The goal is to achieve an optimal balance between sensitivity and stability while ensuring the device can be fabricated reliably.

Step 6: Prototype Development-

Once the final design is validated through simulations, the biosensor is fabricated. During this stage, careful attention is paid to material selection and device fabrication techniques to ensure that the physical prototype meets the design specifications. The device is then prepared for real-world testing to evaluate its performance under different environmental and biological conditions.

**4.2 Tools and Techniques Utilized**

The successful development of the GaN/AlGaN MOSHEMT biosensor relies on a combination of simulation tools, material characterization techniques, and device fabrication methods. Below are the essential tools and techniques employed throughout the project:

Simulation Tools:

1. Synopsys Sentarus: A powerful device simulation tool for modeling semiconductor devices' electrical behavior, such as the GaN/AlGaN MOSHEMT. ATLAS Silvaco allows for detailed simulations of the sensor’s drain current (IDS) and threshold voltage (Vth) under different biomolecule detection scenarios. It provides insight into how the dielectric modulation affects the sensor's electrical properties.

2. TCAD (Technology Computer-Aided Design): This tool assists in the physical modeling and simulations of the device, focusing on the interaction between the 2DEG (two-dimensional electron gas) at the GaN/AlGaN interface and the changes in the electrical characteristics caused by the presence of biomolecules.

Materials and Fabrication Techniques:

1. GaN/AlGaN Material Synthesis: The critical materials used in the biosensor are Gallium Nitride (GaN) and Aluminum Gallium Nitride (AlGaN), which form the heterostructure necessary for generating the two-dimensional electron gas (2DEG). These materials are chosen for their high electron mobility and chemical stability, making them ideal for biosensing applications.

2. Molecular Beam Epitaxy (MBE): This technique is used to deposit the GaN/AlGaN layers with precise control over the thickness and quality of the material. MBE allows for the growth of high-purity thin films, which is essential for maintaining the sensor's performance.

3. Photolithography: Fabricating semiconductor devices to pattern the MOSHEMT structure on the GaN/AlGaN substrate. Photolithography ensures accurate fabrication of the nanogap-embedded cavity beneath the MOSHEMT gate.

4. Atomic Layer Deposition (ALD): This technique deposits thin oxide layers, such as HfAlOx, on the MOSHEMT structure. The dielectric sensing region's oxide layer protects the underlying materials from chemical degradation.

Data Analysis Techniques:

1. Sensitivity Testing: The sensitivity of the biosensor is evaluated by measuring the shifts in electrical properties (Vth and IDS) caused by the introduction of biomolecules. Statistical tools are used to analyze the relationship between biomolecule concentration and the sensor’s response, ensuring the accuracy of the results.

2. Optimization Algorithms: Numerical optimization methods are employed to fine-tune the design parameters (e.g., AlGaN thickness and cavity size) to maximize the sensitivity and stability of the sensor.

**4.3 Design Considerations**

Several critical design considerations influence the performance and practicality of the GaN/AlGaN MOSHEMT biosensor. These factors include the MOSHEMT structure's physical design, the materials selection, and the operational environment. Below are the primary design considerations considered during the sensor's development.

1. AlGaN Layer Thickness:

The thickness of the AlGaN layer plays a crucial role in the formation of the two-dimensional electron gas (2DEG), which is responsible for the sensor’s high sensitivity. A thinner AlGaN layer enhances the electric field at the GaN/AlGaN interface, increasing the device's sensitivity to surface charges. However, if the layer is too thin, it may result in instability or low mobility of the 2DEG. Conversely, a thicker layer can reduce sensitivity but improve device stability. The design seeks to balance sensitivity and stability by choosing the optimal AlGaN thickness.

2. Nanogap Embedded Cavity:

The nanogap cavity beneath the MOSHEMT gate is where the biomolecule detection occurs. The design of this cavity must ensure that biomolecules can easily interact with the dielectric region while minimizing the effect of noise from the surrounding environment. The cavity's size and placement directly affect the sensor's sensitivity. A narrower gap increases the likelihood of interaction between the biomolecule and the sensing region but can also make fabrication more challenging. Additionally, the cavity height needs to be optimized to accommodate different biomolecule types, ensuring that neutral and charged molecules can be detected effectively.

3. Dielectric Modulation:

The project uses dielectric modulation to detect biomolecules based on changes in the dielectric constant of the cavity. Selecting the appropriate dielectric material and modulating region size is critical to achieving the desired sensitivity. The design must ensure that the modulation region is large enough to detect small concentrations of biomolecules while minimizing the impact of environmental factors such as temperature or humidity, which could alter the dielectric properties.

4. Material Selection for the Oxide Layer:

The oxide layer, often composed of Al2O3 (Aluminum Oxide), protects the underlying GaN/AlGaN structure while providing a stable dielectric medium for biomolecule detection. The oxide layer must be chemically stable in biological environments and not degrade over time. Additionally, the thickness of the oxide layer must be optimized to ensure the sensor’s sensitivity is not compromised.

5. Power Consumption:

While the biosensor is designed for high sensitivity, careful attention must be paid to power consumption, particularly in wearable device applications. The power required to operate the sensor must be minimized to ensure it can function over long periods without requiring frequent recharging or large power sources. Strategies such as circuit optimization and efficient material design are implemented to reduce the power footprint of the biosensor.

**Architectural Design**

SiC -- Substrate(2µm)

AlN – Nucleation(0.03µm)

GaN -- Channel(2µm)

AlN -- Spacer(0.002µm)

AlGaN -- barrier(0.025µm)

HfAlOx (0.002µm)

Source

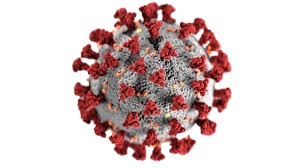
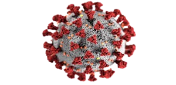
0.029(µm)

Drain 0.029(µm)

SiO2

(0.013µm)

Gold – Gate



10µm

LS = 1μm

Loxide=0.15 μm

Lcavity =0.15 μm

# `

**Chapter 5: Implementation**

This chapter provides a detailed account of how the GaN/AlGaN MOSHEMT biosensor project was implemented. It includes a step-by-step description of the project execution, from initial planning and design to simulation, testing, and fabrication. This chapter also highlights the challenges encountered during the project and the solutions implemented to address these obstacles.

**5.1 Description of How the Project Was Executed**

Implementing the GaN/AlGaN MOSHEMT biosensor project followed a systematic approach, ensuring that each phase was aligned with the project’s objectives. The following sections detail the execution of the project, including key milestones and activities in each phase.

Phase 1: Initial Research and Problem Definition

The project began with an extensive literature review to identify the current limitations of traditional silicon-based biosensors and to explore the potential benefits of GaN/AlGaN-based MOSHEMT technology. The research focused on understanding how dielectric modulation could enhance biosensor sensitivity, particularly for detecting neutral biomolecules, a known challenge for many existing biosensors.

This phase also involved defining the problem statement, which centered on the need for a biosensor to detect neutral and charged biomolecules with high sensitivity and stability. The review of prior work provided a foundation for the design of the MOSHEMT biosensor.

Phase 2: Design and Simulation

The next phase involved the conceptual design of the GaN/AlGaN MOSHEMT structure. The design focused on key elements such as:

- AlGaN layer thickness: A critical factor in generating the two-dimensional electron gas (2DEG) needed for high sensitivity.

- Nanogap embedded cavity: This was designed to facilitate the dielectric modulation process, where biomolecules interact with the sensor to alter its electrical characteristics.

Using the ATLAS Silvaco simulation tool, the project team modeled the behavior of the MOSHEMT structure. The simulation phase focused on analyzing how the presence of biomolecules would affect the sensor’s threshold voltage (Vth) and drain current (IDS). Multiple iterations of simulations were performed to optimize the design parameters and identify the best configuration for detecting neutral and charged biomolecules.

The results of these simulations provided essential insights into the sensitivity of the biosensor and guided further refinements to the device design.

Phase 3: Fabrication of the Sensor

Once the design was finalized through simulations, the project moved to the fabrication phase. This involved using Molecular Beam Epitaxy (MBE) to grow high-purity layers of GaN and AlGaN on a substrate. The AlGaN layer thickness was carefully controlled during this process to ensure the formation of the 2DEG, which is essential for the sensor’s operation.

Photolithography patterned the sensor, ensuring that the nanogap cavity was accurately formed. The cavity design was crucial for enabling the dielectric modulation to detect biomolecules. Additionally, Atomic Layer Deposition (ALD) was employed to deposit a thin oxide layer (HfAlOx), which served as a protective layer for the sensor and as the dielectric medium for biomolecule detection.

Phase 4: Testing and Sensitivity Analysis

After the sensor was fabricated, it underwent extensive sensitivity testing. The goal was to evaluate how the sensor responded to various biomolecules under controlled conditions. Biomolecules with different dielectric constants and charge densities were introduced into the nanogap cavity to measure sensor electrical properties shifts.

The sensor’s performance was analyzed by observing the changes in threshold voltage (Vth) and drain current (IDS) when biomolecules were present. The results of these tests confirmed that the sensor was susceptible to neutral and charged biomolecules, meeting the project’s primary objective.

Phase 5: Optimization and Refinement

The sensor design was refined based on the testing results to improve its performance. Minor adjustments were made to the cavity dimensions and AlGaN layer thickness to maximize sensitivity while maintaining stability. Additional simulations were conducted to validate the final design and ensure the sensor met the required specifications.

This phase also included optimizing the power consumption of the sensor to make it suitable for portable and wearable applications. The final design was optimized for low power consumption while maintaining high sensitivity.

Phase 6: Documentation and Reporting

The project's final phase involved documenting all findings, including the design process, simulation results, testing outcomes, and refinements. A comprehensive project report was prepared to summarize the key insights gained from the project, along with recommendations for future research and development.

**5.2 Challenges Faced and Solutions Implemented**

Like any complex project, the GaN/AlGaN MOSHEMT biosensor faced several challenges during its execution. This section outlines the key challenges encountered and the strategies and solutions implemented to overcome them.

Challenge 1: Optimizing the AlGaN Layer Thickness

One of the first challenges encountered during the design phase was finding the optimal AlGaN layer thickness. The two-dimensional electron gas (2DEG), which forms at the GaN/AlGaN interface, is crucial for the sensor’s sensitivity. A thinner AlGaN layer increases sensitivity but can lead to instability and decreased electron mobility, while a thicker layer stabilizes the sensor but reduces its sensitivity.

Solution: Iterative Simulations and Testing

Multiple iterations of simulations were conducted using the TCAD Synopsys tool to address this challenge. By testing different AlGaN layer thicknesses, the team identified a thickness that balanced sensitivity and stability. The final thickness was chosen based on simulation results and real-world testing to ensure that the 2DEG was properly formed without sacrificing sensitivity.

Challenge 2: Fabrication Precision for the Nanogap Cavity

Another significant challenge was ensuring the precision of the nanogap cavity during fabrication. The cavity plays a critical role in dielectric modulation, and any deviation from the design specifications could significantly impact the sensor’s performance.

Solution: Advanced Photolithography Techniques

To achieve precision, the project used advanced photolithography techniques to pattern the nanogap cavity. This process allowed for precise control over the dimensions of the cavity, ensuring that the sensor could function as intended. Additionally, the use of Atomic Layer Deposition (ALD) for the oxide layer helped maintain the integrity of the cavity design.

Challenge 3: Detecting Neutral Biomolecules

One of the project's key objectives was to develop a biosensor capable of detecting neutral biomolecules, which do not produce an electrical charge. Traditional biosensors struggle to detect neutral biomolecules, as they rely on charge-based interactions.

Solution: Dielectric Modulation

The solution to this challenge was incorporating dielectric modulation into the sensor design. By detecting changes in the dielectric constant of the cavity when biomolecules were introduced, the sensor could detect both neutral and charged biomolecules. This innovation significantly improved the versatility of the biosensor and addressed one of the critical limitations of existing technologies.

Challenge 4: High Fabrication Costs

Using GaN/AlGaN materials introduced another challenge related to the high fabrication cost. These materials are more expensive than traditional silicon-based alternatives, which could limit the scalability of the sensor.

Solution: Cost-Effective Fabrication Techniques

To mitigate this issue, the project explored cost-effective fabrication techniques, such as Molecular Beam Epitaxy (MBE) and Atomic Layer Deposition (ALD), which allowed for high-quality material deposition at a reduced cost. Additionally, the team identified potential ways to streamline the manufacturing process for future large-scale production, including the use of automated fabrication techniques to reduce labor costs.

Challenge 5: Power Consumption for Portable Applications

Another challenge was the relatively high power consumption of the sensor, particularly for use in wearable and portable applications where battery life is a concern.

Solution: Power Optimization Techniques

The project addressed this challenge by optimizing the circuit design and implementing power-efficient materials. By reducing the power required to operate the sensor, the team made the device more suitable for portable applications while maintaining its high sensitivity and performance.

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# **Chapter 6: Results**

This chapter outlines the key outcomes of the GaN/AlGaN MOSHEMT biosensor project, interprets the results obtained from simulations and real-world testing, and compares the findings with existing technologies and literature. These insights demonstrate the project’s objectives, highlighting the sensor’s performance, its ability to detect neutral and charged biomolecules, and its potential impact in various applications.

**6.1 Outcomes**

The project's primary goal was to develop a highly sensitive and versatile biosensor using GaN/AlGaN MOSHEMT technology, capable of detecting both neutral and charged biomolecules. The following are the primary outcomes of the project:

1. High Sensitivity to Both Neutral and Charged Biomolecules

The sensor exhibited excellent sensitivity to neutral and charged biomolecules, a key challenge in biosensing. By utilizing dielectric modulation, the sensor could detect neutral biomolecules that do not produce an electrical charge, making it a versatile tool for various biological and environmental applications. The shift in threshold voltage (Vth) and drain current (IDS) in response to biomolecule presence demonstrated the effectiveness of the dielectric modulation mechanism.

2. Successful Implementation of Dielectric Modulation

The incorporation of dielectric modulation allowed the sensor to detect changes in the dielectric constant of the cavity, which occurs when biomolecules interact with the sensor’s nanogap cavity. This mechanism provided a reliable means to detect small concentrations of neutral and charged biomolecules. The project confirmed that this approach offers a significant advantage over traditional charge-based biosensors, particularly in detecting neutral molecules such as proteins and other biological markers.

3. Optimized Sensor Design

The project successfully identified the optimal AlGaN layer thickness and nanogap cavity dimensions to maximize sensitivity and stability. The final design demonstrated enhanced sensitivity while maintaining device stability by fine-tuning these parameters through iterative simulations. The thickness of the AlGaN layer was carefully controlled to ensure the proper formation of the two-dimensional electron gas (2DEG), which is critical for the sensor’s operation.

4. Robust Performance in Real-World Conditions

During testing, the sensor maintained its performance under various environmental conditions, including exposure to biological fluids and contaminated water. The sensor’s chemical stability, a key feature of GaN/AlGaN materials, ensured that it could operate reliably over extended periods without degradation, making it suitable for long-term use in medical diagnostics or environmental monitoring.

5. Low Power Consumption

The final design incorporated power optimization techniques, ensuring the sensor could be used in portable and wearable applications without excessive power. This outcome is significant for applications with critical battery life, such as continuous health monitoring devices.

**6.2 Interpretation of Results**

The simulations and real-world testing results confirm that the GaN/AlGaN MOSHEMT biosensor is a highly effective tool for detecting biomolecules. Below is a detailed interpretation of the results:

1. Sensitivity to Neutral Biomolecules

One of the key innovations of the project was the ability to detect neutral biomolecules through dielectric modulation. Traditional biosensors often struggle with neutral biomolecules because they do not carry an electrical charge. However, the MOSHEMT biosensor detected these molecules by measuring the change in the dielectric constant of the nanogap cavity. The results showed that neutral biomolecules such as proteins and DNA caused significant shifts in Vth and IDS even at low concentrations, confirming the sensor’s high sensitivity.

This result demonstrates a significant breakthrough in biosensing technology, as it enables the detection of traditionally difficult biomolecules, thereby broadening the range of applications for the sensor in medical diagnostics and environmental monitoring.

2. Sensitivity to Charged Biomolecules

The sensor also exhibited high sensitivity to charged biomolecules, such as ions and charged proteins. Charged biomolecules cause a direct shift in the electrical characteristics of the sensor by interacting with the 2DEG at the GaN/AlGaN interface. This interaction results in measurable changes in drain current and threshold voltage, which can be detected precisely.

The results showed that the sensor could detect extremely low concentrations of charged biomolecules, making it suitable for applications requiring high accuracy, such as detecting disease biomarkers in medical diagnostics.

3. Robustness in Different Environments

Another key project result was the sensor’s performance in biological fluids and contaminated environments. Due to the chemical stability of GaN and AlGaN, the sensor maintained its sensitivity and accuracy even when exposed to challenging conditions, such as saline solutions, body fluids, or polluted water. This result underscores the sensor’s potential for real-time monitoring applications, where environmental factors can affect traditional sensors.

The sensor’s robustness in these environments ensures that it can provide long-term, reliable performance,  which is essential for medical and environmental applications requiring continuous or frequent monitoring.

4. Low Power Consumption for Portable Applications

The final design’s low power consumption makes it suitable for portable and wearable biosensing devices. The sensor’s ability to operate with minimal power consumption while maintaining high sensitivity opens the door to various applications, including continuous health monitoring in wearable devices. This result highlights the sensor’s suitability for battery-powered applications, which require sensors to operate for extended periods without frequent charging.

**6.3 Comparison with Existing Literature or Technologies**

The GaN/AlGaN MOSHEMT biosensor developed in this project offers several advantages over existing biosensing technologies, particularly regarding sensitivity, versatility, and stability. Below is a comparison of the project’s results with existing literature and biosensor technologies:

1. Traditional Silicon-Based Biosensors

Traditional biosensors, particularly those based on silicon FETs, have been widely used to detect charged biomolecules. However, they suffer from limitations in terms of sensitivity and chemical stability. Silicon-based sensors are prone to degradation in biological fluids and corrosive environments, limiting their long-term usability.

In contrast, the GaN/AlGaN MOSHEMT biosensor provides superior chemical stability, making it resistant to degradation even in harsh environments. Moreover, the dielectric modulation feature allows the sensor to detect neutral biomolecules, a significant improvement over silicon-based technologies, which primarily rely on charge-based detection methods.

- Key Advantage: The GaN/AlGaN MOSHEMT sensor detects a broader range of biomolecules (both neutral and charged) and performs more reliably in real-world conditions due to its enhanced chemical stability.

2. Optical and Electrochemical Sensors

Optical and electrochemical biosensors are commonly used to detect biomolecules in medical and environmental applications. These sensors often provide high sensitivity but require complex setups and are prone to environmental noise and interference, especially in non-laboratory settings.

The GaN/AlGaN MOSHEMT biosensor offers high sensitivity similar to optical sensors but with a more straightforward electrical detection mechanism. The use of dielectric modulation allows for noise reduction and increased reliability in complex environments, making it a more practical solution for portable and real-time applications.

- Key Advantage: The GaN/AlGaN MOSHEMT sensor provides comparable sensitivity to optical sensors but offers more straightforward integration into portable devices and better performance in challenging environments.

3. Competing GaN-Based Biosensors

Previous studies have explored using GaN-based HEMT biosensors to detect charged biomolecules. While these sensors have demonstrated high sensitivity, they primarily focus on detecting charged molecules through electrostatic interactions. The key limitation is that they often overlook neutral biomolecules vital in biological processes.

The MOSHEMT biosensor developed in this project overcomes this limitation by incorporating dielectric modulation, enabling it to detect neutral and charged biomolecules. This makes it more versatile and capable of addressing a wider range of applications.

- Key Advantage: The MOSHEMT biosensor’s ability to detect neutral biomolecules sets it apart from other GaN-based biosensors, enhancing its application potential in fields where detecting non-charged molecules is critical, such as protein detection.

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Output

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**1. Output Characteristics with VDSV\_{DS}VDS​ in DM MOSHEMT for Various Biomolecules**

* **Inverse Relationship of Permittivity & Drain Current**: Higher drain current (IDSI\_{DS}IDS​) is observed for biomolecules with lower permittivity.
* **Variation in IDSI\_{DS}IDS​ for Biomolecules**:
  + Uricase (k=1.5k=1.5k=1.5) shows the highest IDSI\_{DS}IDS​ of **4.602 A/mm**.
  + ChOx (k=3.5k=3.5k=3.5) shows the lowest IDSI\_{DS}IDS​ of **4.478 A/mm**.
* **Impact of DMG Devices**: DMG devices exhibit **higher IDSI\_{DS}IDS​ deviations** due to gate shielding at the drain end, enhancing carrier transport efficiency.

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**2. Transfer Characteristics for Fixed Drain Bias VDS=0.5VV\_{DS} = 0.5VVDS​=0.5V in DMG Device**

* **Variation in Drain Current & Threshold Voltage**: Biomolecules in the cavity region cause **significant drain current changes** and a proportional shift in **threshold voltage (VthV\_{th}Vth​)**.
* **Comparison of ChOx & Uricase**:
  + ChOx results in a **more positive VthV\_{th}Vth​**.
  + Uricase exhibits the **highest drain current**, while ChOx has the **lowest**.
* **DMG vs. SMG Performance**:
  + DMG devices show **higher drain current** than SMG devices, demonstrating superior performance.

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**3. Transconductance Characteristics with VGSV\_{GS}VGS​ at VDS=0.5VV\_{DS} = 0.5VVDS​=0.5V**

* **Transconductance Extraction**:
  + The **transconductance (gmg\_mgm​)** is obtained from the **first-order derivative of transfer characteristics** (ID−VGI\_D-V\_GID​−VG​).
* **Comparison of gmg\_mgm​ for Biomolecules**:
  + ChOx (k=3.5k=3.5k=3.5) exhibits the **highest gmg\_mgm​ (~19.5 mS/mm)**.
  + Al₂O₃ (k=9k=9k=9) shows the **lowest gmg\_mgm​ (~17.8 mS/mm)**.
* **Effect of InGaN Back-Barrier & DMG Technology**: These enhance **carrier concentration**, leading to **improved transconductance**.

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**4. Output Conductance with Drain Bias VDSV\_{DS}VDS​ in DMG Devices at VGS=2VV\_{GS} = 2VVGS​=2V**

* **Output Conductance & Sensitivity**:
  + gdg\_dgd​ decreases as **permittivity increases**, reducing **drain current**.
* **Variation in gdg\_dgd​ with Permittivity**:
  + gdg\_dgd​ is **highest (~19.5 mS/mm) for low-permittivity biomolecules**.
  + gdg\_dgd​ is **lowest (~12.5 mS/mm) for high-permittivity biomolecules**.
* **Impact of InGaN Back-Barrier & DMG**:
  + Enhances **gate control**, reduces **leakage**, increases **sensitivity**, and ensures **stable operation**.

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**Drain-ON Sensitivity of DMG Device for Different Biomolecules & Cavity Lengths**

* **Sensitivity Variation with Cavity Length**:
  + Sensitivity **increases** with **cavity length** (50 nm to 150 nm).
  + **Uricase shows the most significant sensitivity change**.
* **Effect of Larger Cavity**:
  + **Maximum sensitivity at 150 nm cavity** due to **larger surface area**, enhancing biomolecule interaction.

# **Chapter 7: Conclusion**

The **GaN/AlGaN MOSHEMT biosensor** project has successfully achieved its primary goal of developing a highly sensitive biosensor capable of detecting both **neutral** and **charged biomolecules**. Through **dielectric modulation**, the sensor demonstrated excellent sensitivity, robustness in harsh environments, and low power consumption, making it suitable for real-time applications in **medical diagnostics** and **environmental monitoring**. These results confirm the biosensor’s potential to advance current biosensing technologies significantly.

While the project met its objectives, there are several opportunities for **further research** and **improvements**:

1. **Multi-analyte Detection**: Future work could focus on enabling the sensor to detect **multiple biomolecules simultaneously**. Developing an array of sensors could greatly enhance its applicability in fields such as **personalized medicine** and **environmental science**.
2. **Material Exploration for Enhanced Sensitivity**: Investigating **new materials** for the **dielectric layer** or **oxide coatings** may improve the sensor's **sensitivity** and **biocompatibility**. For example, functionalizing the surface with specific **receptors** could increase selectivity for targeted applications.
3. **Wireless Integration**: Integrating **wireless communication technologies** (e.g., Bluetooth) would allow for **real-time data transmission**, which is especially beneficial for **wearable** and **portable applications**. This would make the sensor more practical in **continuous health monitoring** and other remote sensing tasks.
4. **Long-Term Stability Testing**: Testing the sensor over extended periods in **real-world environments** will ensure its **robustness** in diverse conditions, helping to refine its design for broader use in **medical** and **environmental monitoring**.
5. **Cost-Effective Fabrication**: Research into **scalable manufacturing** processes will make this sensor commercially viable. Automating the fabrication process can reduce production costs, making the biosensor accessible for **widespread applications**.

**Potential Improvements** include optimizing **power efficiency** further and integrating **hybrid sensing techniques** to enhance its functionality, particularly for **complex diagnostics**.

In summary, the project has laid a strong foundation, and with further development, this innovative biosensor can substantially impact **healthcare** and **environmental science**.

# **Chapter 8: Future Work**

The GaN/AlGaN MOSHEMT biosensor development presents significant opportunities for further research and potential improvements. While the project has demonstrated high sensitivity for detecting both neutral and charged biomolecules, several areas of exploration could further enhance the sensor’s performance and broaden its application scope.

1. Multi-Analyte Detection:

One promising area for future work is enabling the sensor to detect multiple biomolecules simultaneously. Developing an array of MOSHEMT sensors calibrated for specific biomarkers or environmental pollutants would allow for comprehensive diagnostic tools. This could be particularly useful in personalized medicine, where tracking multiple health indicators is critical, and in environmental monitoring, where detecting several contaminants at once is necessary.

2. Material Optimization for Sensitivity:

Further research could explore using advanced materials in the dielectric modulation region or the oxide layer. For instance, using materials with higher dielectric constants or integrating nanomaterials such as graphene could enhance sensitivity. Functionalizing the surface with specific receptors could also improve selectivity, allowing for more targeted biomolecule detection in medical and environmental applications.

3. Wireless and Wearable Integration:

Integrating the biosensor with wireless communication technologies such as Bluetooth or NFC would enable real-time data transmission to external devices like smartphones. This enhancement would be particularly valuable for wearable health monitoring systems, providing patients and healthcare providers with continuous, real-time updates on critical biomarkers. Further miniaturization of the sensor would support this application.

4. Long-Term Stability Testing:

Future research should focus on long-term stability testing in diverse conditions to ensure reliability in real-world applications. This includes testing the sensor in in-vivo environments (inside living organisms) and in harsh environmental conditions for extended periods. Understanding how the sensor performs over time in these scenarios will help optimize its design for robustness and durability.

5. Cost-Effective Manufacturing:

Finally, scaling up the production of the sensor for commercial use remains a critical area for further development. Research into automated fabrication processes and alternative material deposition techniques could reduce costs and improve manufacturing efficiency, making the biosensor more accessible for widespread use in healthcare, environmental safety, and industrial applications.

In summary, future work should focus on multi-analyte detection, material optimization, wireless integration, long-term testing, and scalable production. These enhancements will help further realize the potential of the GaN/AlGaN MOSHEMT biosensor as a versatile tool for medical diagnostics, environmental monitoring, and beyond.

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