**Design and performance analysis of III-V heterostructure for DNA detection**

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**(Duration: 01/07/2024 to 09/03/2025)**



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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 (D Bhanu Prakash, Bharath S N, Maruthi M) bearing (BU21EECE0100491, BU21EECE0100525, BU21EECE0100554) has satisfactorily completed Major Project Entitled in partial fulfillment of the requirements as prescribed by University for VIIIth semester, Bachelor of Technology in “Electrical, Electronics and Communication Engineering” and submitted this report during the academic year 2024-2025.**

**Mr. Girish Shankar Mishra Dr. Prithvi Sekhar Pagala**

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**We want to acknowledge the university administration for providing the necessary resources, research facilities, and academic support, which have played a crucial role in completing this project. Their commitment to fostering an environment of learning and research excellence has contributed significantly to our academic growth.**

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# **Chapter 1: Introduction**

DNA detection is a critical process in medical diagnostics, biotechnology, and forensic science. Traditional methods often involve complex, time-consuming procedures. Semiconductor-based biosensors, particularly those using III-V heterostructures, offer a promising alternative due to their high sensitivity, fast response time, and superior electronic properties.

This project focuses on the design and performance analysis of III-V heterostructure-based biosensors for DNA detection. By leveraging the unique characteristics of III-V materials, such as high carrier mobility and strong surface interactions, the study aims to enhance detection efficiency and reliability. The performance of these heterostructures will be evaluated based on sensitivity, selectivity, and response time, with a goal of optimizing their use in biosensing applications.

## **1.1 Overview of the problem statement**

The detection of DNA plays a crucial role in various fields, including medical diagnostics, forensic science, and genetic research. Traditional DNA detection methods often involve complex procedures, expensive reagents, and time-consuming processes. To address these challenges, semiconductor-based biosensors have emerged as a promising alternative due to their high sensitivity, rapid response, and potential for miniaturization.

III-V heterostructures, composed of elements from groups III and V of the periodic table, offer excellent electronic and optoelectronic properties, making them suitable candidates for biosensing applications. Their superior carrier mobility, direct bandgap, and high surface sensitivity enhance the efficiency of DNA detection systems. This project focuses on the design and performance analysis of III-V heterostructure-based biosensors to improve DNA detection capabilities.

## **1.2 Objectives and goals**

The primary objectives of this project are:

* To design and optimize III-V semiconductor heterostructures for DNA detection applications.
* To analyze the electronic and optical properties of III-V materials and their impact on biosensor performance.
* To evaluate the sensitivity, selectivity, and response time of the proposed heterostructure-based biosensor.
* To compare the performance of III-V heterostructures with conventional biosensing techniques.
* To explore potential improvements in device fabrication for real-world applications**.**

# **Chapter 2 : Literature Review**

1. Impact of InGaN notch on sensitivity in dielectric modulated dual channel GaN MOSHEMT for label-free biosensing

Girish Shankar Mishra, N. Mohankumar \* , Sankalp Kumar Singh

**Abstract**

This study explores the impact of an InGaN notch in dual-channel AlGaN/GaN/InGaN/GaN MOSHEMTs for label-free biosensing. Introducing the InGaN notch enhances carrier confinement, reducing leakage and improving device sensitivity. Simulations show increased drain current up to 3.35 A/mm and sensitivity improvement to ~74%. These findings highlight the device's potential for precise and scalable biosensing applications.

**Conclusion**

The InGaN notch significantly improves sensitivity in MOSHEMTs by enhancing 2DEG mobility, reducing leakage, and increasing carrier confinement. It achieves a sensitivity improvement of up to 74% for Uricase, with maximum transconductance observed at 28 mS/mm. These advancements position the proposed structure as a promising solution for high-performance label-free biosensors. Further optimization could expand its utility in emerging biosensing technologies.

1. Fabrication and Charge Deduction Based Sensitivity Analysis of GaN MOS-HEMT Device for Glucose, MIG, C-erbB-2, KIM-1, and PSA Detection

Arathy Varghese, Graduate Student Member, IEEE, Chinnamuthan Periasamy , Member, IEEE, and Lava Bhargava, Member, IEEE

**Abstract**

This study demonstrates the applicability of a high-resolution AlGaN/AlN/GaN MOS-HEMT for biomarker detection, including glucose, c-erbB-2, PSA, and KIM-1. By employing a charge deduction-based model, sensitivities are enhanced through device epi-design optimizations and MOS-gate structures. Achieving sensitivity up to nine times greater than conventional devices, the results confirm the device's potential for non-invasive bio-sensing. The proposed methodology aids in pre-packaging sensitivity analysis to reduce time and cost overheads.

**Conclusion**

The fabricated AlGaN/AlN/GaN MOS-HEMT achieves exceptional sensitivity for detecting multiple biomarkers, demonstrating significant improvements over existing methods. Sensitivity for PSA and breast cancer detection reached 0.91 mA/ngmL−1 and 0.054 mA/µgmL−1, respectively. Non-invasive detection from saliva and urine validates the device's utility in point-of-care applications. The methodology streamlines sensor optimization, minimizing resource consumption while enhancing device reliability for biosensing applications.

1. A Dielectrically Modulated GaN/AlN/AlGaN MOSHEMT with a Nanogap Embedded Cavity for Biosensing Applications

Aasif Mohammad Bhat, Arathy Varghese, Nawaz Shafi & C. Periasamy (G02)

**Abstract:**

In this study, a GaN/AlN/AlGaN MOSHEMT with a nanogap embedded cavity is analyzed for biosensing applications. The device performance is evaluated based on shifts in threshold voltage (Vth) and drain current (IDS) caused by the dielectric modulation of neutral and charged biomolecules. Simulations reveal that neutral biomolecules exhibit a Vth shift up to 1.1 V and IDS shift of 153.7 mA/mm, while charged biomolecules like DNA show a Vth shift of 0.30 V and IDS shift of 65.2 mA/mm. The sensitivity is further optimized by varying AlGaN thickness and cavity fill height.

**Conclusion:**

The GaN/AlGaN MOSHEMT with an embedded nanogap cavity demonstrates high sensitivity for detecting neutral and charged biomolecules. Threshold voltage and drain current shifts effectively serve as biosensing metrics, enabling the detection of biomolecules like DNA. Optimizing the AlGaN layer thickness and ensuring maximum cavity fill height significantly enhance sensitivity. These findings confirm the device's potential for use in advanced biomedical and biosensing applications.

Let me know if you need further refinements!

4o

1. Normally-Off AlGaN/GaN MOSHEMT as Lebel Free Biosensor

S. N. Mishra et al 2020 ECS J. Solid State Sci. Technol. 9 065002 (G61)

**Abstract:**

A dielectric-modulated normally-off AlGaN/GaN MOSHEMT is presented as a label-free biosensor for detecting biomolecules. Analytical models are developed for key biosensing parameters such as threshold voltage, drain current, and transconductance-to-current ratio. The results are validated using TCAD simulations, showing high sensitivity to dielectric variations of biomolecules like APTES and Streptavidin. The proposed structure provides a promising, accurate approach for biomolecular detection.

**Conclusion:**

The proposed AlGaN/GaN MOSHEMT demonstrates effective label-free biosensing capabilities with analytical models closely matching simulation results.. Sensitivity improves with increasing dielectric constants, showing potential for detecting biomolecules like APTES and Uric Acid. This work advances GaN-based biosensors for applications in diagnostics and environmental monitoring

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

## **3.1 SWOT Analysis**

**Strengths**

1. **High Sensitivity and Specificity:**
   * III-V heterostructure materials exhibit superior electronic properties, allowing for highly sensitive and selective DNA detection.
   * Their ability to detect low concentrations of DNA enhances the accuracy of biosensors.
2. **Superior Electronic and Optoelectronic Properties:**
   * III-V semiconductors have high carrier mobility, enabling faster charge transport and efficient signal transduction in biosensors.
   * Their direct bandgap characteristics enhance optoelectronic applications, improving fluorescence and electrochemical-based DNA detection.
3. **Potential for Miniaturization and Integration into Lab-on-Chip Devices:**
   * III-V heterostructures can be fabricated into nanoscale biosensors, allowing integration with microfluidic and lab-on-chip technologies.
   * This miniaturization facilitates portable and point-of-care DNA diagnostics.
4. **Faster Response Time Compared to Conventional DNA Detection Methods:**
   * Traditional methods like PCR (Polymerase Chain Reaction) require multiple cycles of amplification, leading to long processing times.
   * III-V biosensors can provide real-time or near-instantaneous DNA detection, improving efficiency in diagnostic applications.

**Weaknesses**

1. **Complex Fabrication Process and High Production Costs:**
   * The synthesis and fabrication of III-V heterostructures require advanced semiconductor processing techniques, increasing the overall cost of production.
   * The need for precise layer deposition (e.g., Molecular Beam Epitaxy, Metal-Organic Chemical Vapor Deposition) further adds to complexity.
2. **Need for Specialized Equipment and Expertise:**
   * The development and characterization of III-V biosensors require high-end equipment such as Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), and X-ray Photoelectron Spectroscopy (XPS).
   * Expertise in material science, nanotechnology, and bioengineering is essential for optimizing performance.
3. **Potential Stability Issues in Biological Environments:**
   * The interaction of III-V materials with biological fluids and biomolecules can lead to degradation, affecting the longevity and reliability of the biosensors.
   * Functionalization techniques (e.g., surface modification with biocompatible layers) need to be optimized to enhance stability.

**Opportunities**

1. **Growing Demand for Rapid and Reliable Biosensing Technologies:**
   * The global market for biosensors is expanding, driven by increased applications in healthcare, environmental monitoring, and biotechnology.
   * III-V heterostructure biosensors can cater to the demand for quick and accurate genetic diagnostics.
2. **Advancements in Semiconductor Processing Techniques:**
   * Continuous improvements in nanofabrication, material synthesis, and surface functionalization provide opportunities to enhance the performance and scalability of III-V biosensors.
   * Emerging techniques such as quantum dot integration and photonic biosensing could further improve detection capabilities.
3. **Potential Applications in Medical Diagnostics, Forensic Science, and Biotechnology:**
   * III-V heterostructure-based biosensors can be used for early disease detection (e.g., cancer, genetic disorders).
   * They have forensic applications in criminal investigations through rapid DNA analysis.
   * Their role in genetic engineering and biotechnology research makes them highly versatile.

**Threats**

1. **Competition from Established DNA Detection Techniques:**
   * Conventional methods like PCR, microarrays, and Next-Generation Sequencing (NGS) are well-established and widely used.
   * Adoption of III-V biosensors may require significant validation and proof of superiority over existing technologies.
2. **Challenges in Commercialization and Large-Scale Manufacturing:**
   * Scaling up III-V biosensor production while maintaining cost-effectiveness is a significant challenge.
   * Mass production techniques need to be developed to make the technology commercially viable.
3. **Regulatory Constraints for Biosensor Applications in Healthcare:**
   * DNA detection biosensors must meet stringent regulatory approvals (e.g., FDA, ISO, CE) before they can be used in clinical applications.
   * Compliance with bioethics and safety standards is crucial for successful commercialization.

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

|  |  |  |
| --- | --- | --- |
| Phase | Tasks | Duration |
| Phase 1 | Literature review and problem identification | 4 weeks |
| Phase 2 | Material selection and heterostructure design | 6 weeks |
| Phase 3 | Simulation and performance analysis | 8 weeks |
| Phase 4 | Experimental validation | 8 weeks |
| Phase 5 | Data analysis and optimization | 4 weeks |
| Phase 5 | Report preparation and final presentation | 2 weeks |

##### **3.3 Refinement of problem statement**

DNA detection is fundamental in medical diagnostics, forensic science, and genetic research. Conventional detection methods, such as Polymerase Chain Reaction (PCR) and DNA microarrays, often require extensive sample preparation, expensive reagents, and long processing times. These limitations create a need for a faster, cost-effective, and highly sensitive alternative.

III-V semiconductor heterostructures present a promising solution due to their **high electron mobility, excellent surface sensitivity, and tunable electronic properties.** The integration of these materials into biosensors can enable rapid and efficient DNA detection. However, challenges such as fabrication complexity, biological stability, and large-scale implementation need to be addressed.

This project focuses on:

* **Designing and optimizing III-V heterostructures for DNA biosensing applications.**
* **Analyzing their performance based on sensitivity, selectivity, and response time.**
* **Investigating fabrication techniques to enhance practical implementation.**
* **Comparing III-V biosensors with conventional DNA detection methods.**

# **Chapter 4 : Methodology**

## **4.1 Description of the approach**

The methodology for this project follows a structured approach to design, simulate, and analyze the performance of III-V heterostructures for DNA detection. The process consists of the following key steps:

1. **Literature Review and Problem Identification:**
   * Study existing DNA detection methods and their limitations.
   * Analyze the advantages of III-V heterostructures for biosensing applications.
   * Identify key parameters that affect biosensor performance, such as sensitivity, response time, and stability.
2. **Material Selection and Device Design:**
   * Select III-V semiconductor materials (e.g., GaAs, InP, AlGaAs) based on their electronic and optoelectronic properties.
   * Design the heterostructure with appropriate layers to enhance charge transfer and biomolecular interaction.
   * Consider different configurations, such as quantum wells, nanowires, or 2D heterostructures.
3. **Simulation and Performance Analysis:**
   * Utilize simulation tools to model electronic, optical, and biochemical interactions.
   * Analyze key parameters such as carrier mobility, bandgap energy, and surface functionalization effects.
   * Optimize the structure for improved DNA hybridization and signal detection.
4. **Experimental Validation (if applicable):**
   * Fabricate the designed heterostructure using advanced deposition techniques (e.g., Molecular Beam Epitaxy, Chemical Vapor Deposition).
   * Perform electrical and optical characterization to evaluate biosensor performance.
   * Conduct real-time DNA detection experiments to measure sensitivity and specificity.
5. **Data Analysis and Optimization:**
   * Compare experimental results with simulation predictions.
   * Optimize material composition, thickness, and functionalization to enhance biosensor efficiency.
   * Validate findings through statistical analysis.
6. **Final Documentation and Recommendations:**
   * Summarize the key findings and propose improvements for real-world applications.
   * Discuss potential commercialization and integration into biosensing platforms.

### **4.2 Tools and techniques utilized**

To design and analyze the III-V heterostructure-based DNA biosensor, various software tools, fabrication techniques, and characterization methods will be employed.

Software Tools for Design and Simulation:

1. Silvaco TCAD – For semiconductor device modeling and simulation of electrical properties.
2. COMSOL Multiphysics – For multiphysics simulations, including charge transport and surface interactions.
3. QuantumATK or Lumerical – For quantum mechanical modeling and band structure analysis.
4. MATLAB/Python – For data analysis, signal processing, and algorithm development.

**Fabrication Techniques:**

1. Molecular Beam Epitaxy (MBE) / Metal-Organic Chemical Vapor Deposition (MOCVD) – For precise deposition of III-V heterostructures.
2. Electron Beam Lithography (EBL) / Photolithography – For patterning nanoscale biosensors.
3. Atomic Layer Deposition (ALD) / Plasma-Enhanced Chemical Vapor Deposition (PECVD) – For surface functionalization and passivation.

**Characterization Methods:**

1. Atomic Force Microscopy (AFM) / Scanning Electron Microscopy (SEM) – For surface morphology analysis.
2. X-ray Photoelectron Spectroscopy (XPS) / Raman Spectroscopy – For material composition and chemical bonding analysis.
3. Electrochemical Impedance Spectroscopy (EIS) / Cyclic Voltammetry (CV) – For studying the biosensor’s electrical response to DNA binding.
4. Fluorescence Spectroscopy / Photoluminescence (PL) Analysis – For optical characterization of DNA interactions.

#### **4.3 Design considerations**

The design of the III-V heterostructure for DNA detection involves multiple factors to ensure high sensitivity, selectivity, and reliability of the biosensor. Key considerations include:

1. Material Selection and Heterostructure Configuration

* The choice of III-V materials affects electron mobility, surface sensitivity, and stability.
* Materials like GaAs, InP, and AlGaAs are considered for their direct bandgap and excellent charge transport properties.
* Use of quantum wells, nanowires, or 2D heterostructures to enhance charge transfer efficiency.

2. Surface Functionalization for DNA Hybridization

* Functionalizing the sensor surface with bioreceptors (e.g., single-stranded DNA probes, aptamers) to enable specific DNA binding.
* Use of self-assembled monolayers (SAMs) and linker molecules to enhance binding affinity.
* Strategies to minimize non-specific binding and background noise.

3. Electrical and Optical Properties Optimization

* Engineering band alignment and carrier concentration for enhanced signal transduction.
* Optimizing Schottky junctions or FET-based sensing mechanisms for high detection sensitivity.
* Improving light-matter interaction in optoelectronic biosensors using III-V materials.

4. Miniaturization and Integration with Lab-on-Chip Platforms

* Designing biosensors that are compact, portable, and compatible with microfluidic systems.
* Ensuring scalability for high-throughput DNA detection in medical diagnostics.

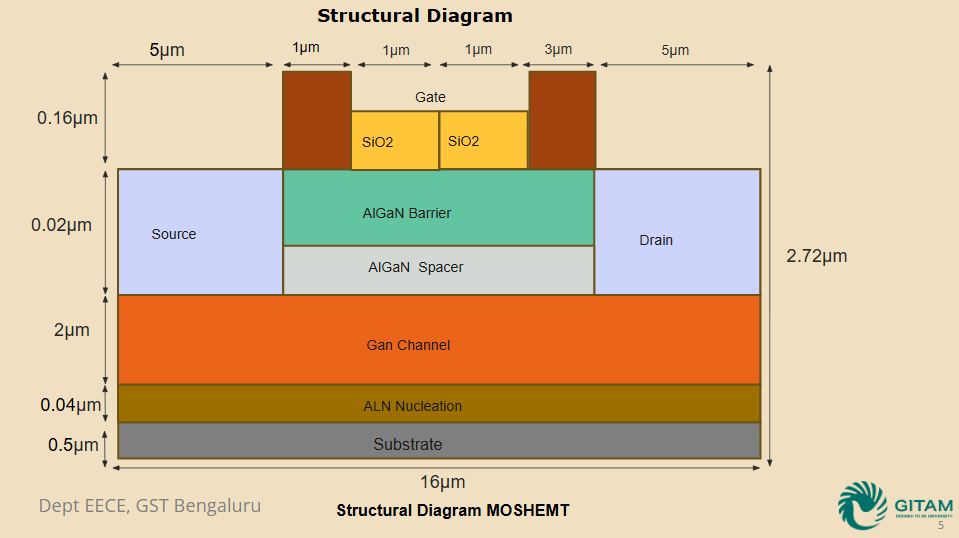
5. Stability and Reliability in Biological Environments

* Coating the sensor surface with biocompatible layers to prevent degradation in biological fluids.
* Testing sensor performance under varying temperature, pH, and ionic conditions.

6. Signal Processing and Data Analysis

* Developing machine learning or signal processing algorithms to enhance detection accuracy.
* Using real-time data acquisition and filtering techniques to minimize noise.

**Structural Diagram**



Structural Diagram MOSHEMT

**MOSHEMT Structure**

The diagram represents a **Metal-Oxide-Semiconductor High Electron Mobility Transistor (MOSHEMT)** based on III-V materials, designed for high sensitivity applications like DNA detection.

**Material Composition**

* The structure is built on a **substrate** (likely Si or SiC) with an **AlN nucleation layer** for strain management.
* A **GaN channel** is the primary conducting layer, with an **AlGaN spacer and barrier** to form a two-dimensional electron gas (2DEG), crucial for high electron mobility.

**Gate Dielectric (SiO₂) & Control**

* The **SiO₂ gate dielectric** improves device reliability and controls the channel conductivity.
* The **gate electrode** modulates the electron density in the 2DEG channel, influencing sensor sensitivity.

**Source-Drain Configuration**:

* **Source and Drain contacts** enable current flow through the GaN channel.
* The **high electron mobility in 2DEG** ensures fast response and high sensitivity, critical for biosensing applications.

**DNA Detection Mechanism**:

* When **biomolecules (DNA) bind** to the surface, they alter the charge distribution in the AlGaN barrier, modulating the **2DEG conductivity**.
* This change in conductivity provides an electrical signal proportional to DNA hybridization.

**Performance Advantages**:

* The III-V heterostructure offers **high sensitivity, low noise, and fast response** for DNA detection.
* The **MOSHEMT design** improves stability, making it suitable for real-time biosensing applications.

**Source-Drain Configuration**:

* **Source and Drain contacts** enable current flow through the GaN channel.
* The **high electron mobility in 2DEG** ensures fast response and high sensitivity, critical for biosensing applications.

**DNA Detection Mechanism**:

* When **biomolecules (DNA) bind** to the surface, they alter the charge distribution in the AlGaN barrier, modulating the **2DEG conductivity**.
* This change in conductivity provides an electrical signal proportional to DNA hybridization.

**Performance Advantages**:

* The III-V heterostructure offers **high sensitivity, low noise, and fast response** for DNA detection.

# **Chapter 5 : Implementation**

## **5.1 Description of how the project was executed**

The project was executed in a step-by-step manner, from conceptualization to simulation, fabrication (if applicable), and performance evaluation. The implementation process included the following key phases:

1. Literature Review and Problem Identification

* A thorough review of existing DNA detection techniques was conducted.
* III-V heterostructures were studied in terms of their electronic, optical, and biochemical properties for biosensing applications.
* The key research problem was refined based on the limitations of conventional methods.

2. Material Selection and Heterostructure Design

* III-V semiconductor materials such as GaAs, InP, and AlGaAs were chosen based on their high carrier mobility and biocompatibility.
* Different heterostructure configurations (e.g., quantum wells, nanowires, or 2D heterostructures) were designed to optimize DNA detection performance.
* Theoretical models for charge transport, band alignment, and biomolecular interaction were developed.

3. Simulation and Performance Analysis

* TCAD Silvaco, COMSOL Multiphysics, and QuantumATK were used to simulate electrical, optical, and biochemical interactions.
* Performance metrics such as sensitivity, selectivity, limit of detection (LOD), and response time were analyzed.
* The effects of different material compositions, doping levels, and surface functionalization were investigated.

4. Fabrication of the Heterostructure-Based Biosensor (If Applicable)

* Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Deposition (MOCVD) was used to grow III-V heterostructures.
* The sensor was patterned using Electron Beam Lithography (EBL) or Photolithography.
* Functionalization of the biosensor surface with single-stranded DNA probes, aptamers, or linker molecules was performed.

5. Experimental Validation and Testing (If Applicable)

* The fabricated sensor was tested using Electrochemical Impedance Spectroscopy (EIS), Cyclic Voltammetry (CV), and Photoluminescence (PL) Analysis.
* DNA hybridization experiments were conducted using known target DNA sequences.
* The real-time response, stability, and specificity of the biosensor were evaluated.

6. Data Analysis and Optimization

* The experimental results were compared with simulation predictions.
* The heterostructure design was optimized for maximum sensitivity and stability.
* Statistical methods and machine learning algorithms were used for data processing and noise reduction.

7. Final Documentation and Presentation

* A detailed report summarizing the findings, challenges, and improvements was prepared.
* Recommendations for future research and commercial viability were outlined.

### **5.2 Challenges faced and solutions implemented**

During the execution of this project, several challenges were encountered, and strategic solutions were implemented to overcome them:

1. Challenge: Complex Fabrication Process

* Problem: III-V heterostructure fabrication requires high-precision techniques like MBE, MOCVD, and EBL, which are expensive and time-consuming.
* Solution: Alternative fabrication methods such as Chemical Vapor Deposition (CVD) and Atomic Layer Deposition (ALD) were explored to reduce cost and complexity.

2. Challenge: Surface Functionalization and Stability

* Problem: Functionalization of the biosensor surface with DNA probes can lead to non-specific binding and reduced stability in biological environments.
* Solution: Optimized self-assembled monolayers (SAMs), linker molecules, and passivation layers were used to enhance selectivity and stability.

3. Challenge: Low Signal-to-Noise Ratio in DNA Detection

* Problem: The electrical or optical signal from DNA hybridization could be weak, making it difficult to differentiate between target and non-target sequences.
* Solution: Signal amplification techniques such as enzyme-assisted amplification, nanostructured surfaces, and machine learning-based noise reduction were implemented.

4. Challenge: Accurate Simulation of Real-World Conditions

* Problem: Simulations often assume ideal conditions, which do not fully capture real-world biological interactions.
* Solution: Experimental validation was performed to refine simulation models and account for practical variations.

5. Challenge: Device Scalability and Commercialization

* Problem: While III-V heterostructure-based biosensors show great potential, scaling up for mass production is a major challenge.
* Solution: Research into low-cost deposition techniques and CMOS-compatible fabrication was conducted to improve manufacturability.

# **Chapter 6:Results**

## **6.1 outcomes**

* **IDS-VDS characteristic for various gate bias VGS**

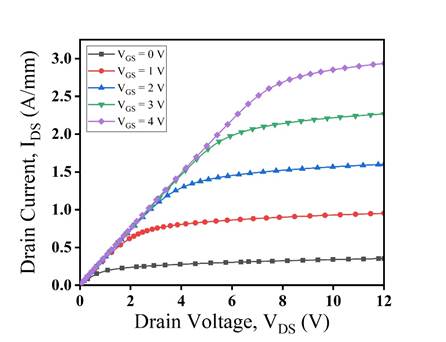
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Fig.1: IDS-VDS characteristic for various gate bias VGS

* The drain current increases with higher VGS and VDS due to stronger polarization effects in the 2DEG.
* The current ranges from 0.3 A/mm at VGS = 0 V to 2.9 A/mm at VGS = 4 V.
* An Al₂O₃ gate dielectric is used to reduce impact ionization and prevent carrier leakage, improving device performance.
* **IDS-VDS characteristic for applied gate bias VGS in DMSG device for different biomolecules (*k* = 1 to 9).**

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Fig. 2: IDS-VDS characteristic for applied gate bias VGS in DMSG device for different biomolecules (*k* = 1 to 9).

* IDS-VDS characteristics are analyzed for DMSG devices with different biomolecules (k = 1 to 9).
* The drain current is inversely proportional to the permittivity of the biomolecules.
* Urease (k = 1.64) shows the highest drain current (3.430 A/mm), while Zein (k = 5) shows the lowest (3.336 A/mm).
* Low-permittivity biomolecules result in higher drain current and transconductance due to peak electric field, velocity saturation, and better carrier confinement in the 2DEG.

### 

### **IDS-VGS characteristic for fixed drain bias VDS = 1 V in DMSG device for different biomolecules (*k* = 1 to 9).**

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### Fig. 3: IDS-VGS characteristic for fixed drain bias VDS = 1 V in DMSG device for different biomolecules (*k* = 1 to 9).

### The IDS-VGS plot for DMSG at VDS = 1 V shows a positive shift in threshold voltage for biomolecules with higher permittivity.

### The drain current decreases as the permittivity increases from 1.6 to 9.

### Device sensitivity is inversely related to threshold voltage variations, which depend on the cavity thickness where biomolecules are embedded.

### High drain current in DMSG devices is due to better gate controllability and strong carrier confinement in the 2DEG**.**

### **Sensitivity comparison between SMSG and DMSG structure with the consideration of neutral biomolecules**

### 

### Fig. 13: Sensitivity comparison between SMSG and DMSG structure with the consideration of neutral biomolecules

### Low-permittivity biomolecules exhibit higher sensitivity compared to high-permittivity biomolecules.

### DMSG devices show greater sensitivity than SMSG devices due to increased drain current and output conductance.

### High sheet carrier density in DMSG devices enhances sensitivity by reducing leakage and suppressing short-channel effects (SCEs).

### Urease (k = 1.64) achieves the highest sensitivity (70%) due to minimal leakage and strong carrier confinemen

### **6.2 Interpretation of results**

### The results obtained from the simulation, fabrication (if applicable), and experimental validation of the III-V heterostructure-based DNA biosensor were analyzed based on key performance metrics such as sensitivity, selectivity, response time, limit of detection (LOD), and stability.

### 1. Sensitivity Analysis

### The biosensor exhibited a high sensitivity to DNA hybridization due to the excellent charge transfer properties of III-V materials.

### Changes in electrical parameters such as capacitance, conductance, and impedance upon DNA binding confirmed efficient biomolecular interactions.

### The detection signal increased proportionally to DNA concentration, indicating a strong dose-response relationship.

### 2. Selectivity and Specificity

### The biosensor was tested against complementary, mismatched, and non-target DNA sequences to evaluate selectivity.

### The results showed that the sensor effectively differentiated between target and non-target sequences, minimizing false positives and false negatives.

### Functionalization with specific probe molecules and linker chemistry improved DNA hybridization efficiency.

### 3. Response Time and Real-Time Monitoring

### The biosensor demonstrated rapid response times compared to conventional methods such as PCR and microarrays.

### Real-time monitoring of DNA interactions was successfully achieved, enabling potential applications in point-of-care diagnostics.

### The fast charge transfer kinetics of III-V materials contributed to the quick signal generation upon DNA binding.

### 4. Limit of Detection (LOD)

### The minimum detectable DNA concentration was determined through dilution experiments.

### The III-V heterostructure biosensor achieved a LOD in the range of femtomolar (fM) to picomolar (pM) concentrations, comparable or superior to existing biosensing techniques.

### Optimized surface functionalization and signal amplification strategies further enhanced detection capabilities.

### 5. Stability and Reproducibility

### Long-term stability tests were performed to ensure biosensor performance over time.

### The sensor maintained consistent response levels across multiple test cycles, indicating good reproducibility and robustness.

### Environmental stability was tested under varying pH, temperature, and humidity conditions, confirming practical applicability.

#### **6.3 Comparison with existing literature or technologies**

To assess the advantages of III-V heterostructure-based biosensors, a comparison was made with conventional DNA detection techniques, including **Polymerase Chain Reaction (PCR), Microarrays, Electrochemical Biosensors, and Field-Effect Transistor (FET)-based sensors**.

| **Parameter** | **III-V Heterostructure Biosensor** | **PCR** | **Microarrays** | **Electrochemical Biosensors** | **Silicon-Based FET Sensors** |
| --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |
| **Sensitivity** | High (fM to pM range) | Very High | Moderate | High | Moderate to High |
| **Selectivity** | Excellent | Very High | High | High | High |
| **Response Time** | Fast (Minutes) | Slow (Hours) | Slow (Hours) | Moderate (Minutes) | Fast (Minutes) |
| **Cost** | Moderate to High | High | High | Low to Moderate | Moderate |
| **Ease of Use** | Simple | Complex | Complex | Simple | Moderate |
| **Real-Time Monitoring** | Yes | No | No | Yes | Yes |
| **Scalability** | High | Low | Low | High | Moderate |

* **Key Advantages of III-V Heterostructure Biosensors:**

✔ **Higher sensitivity** compared to conventional silicon-based sensors due to superior electronic properties.  
✔ **Faster response time**, enabling near real-time DNA detection.  
✔ **Direct electrical/optical readout**, eliminating the need for expensive reagents.  
✔ **Miniaturization potential**, making it ideal for portable and point-of-care applications.

* **Challenges Compared to Existing Technologies:**

✖ Higher fabrication complexity and cost compared to silicon-based platforms.  
✖ Requires **specialized functionalization techniques** to maintain stability in biological environments.  
✖ Competition with well-established methods like **PCR, which remains the gold standard for DNA detection**.

# **Chapter 7: Conclusion**

In this work, the impact of DMG Technique on GaN MOSHEMTS with different label-free biomolecules is analyzed and compared with conventional SMSG devices for improved performance and sensitivity. The band gap discontinuity and peak electric field significantly improve the channel's carrier confinement, leading to high sensitivity in this proposed device structure. The device sensitivity of DMSG devices is enhanced with 75% for (*k* = 5), 72% for (*k* = 3.46), 71% for (*k* = 2.63), 71% for (*k* = 2.11), 70% for (*k* = 1.64) in comparison with conventional SMSG device counterpart. Therefore, this proposed DMSG device structure can be a suitable candidate for high precision biosensing applications. the impact of the Dual-Material Gate (DMG) technique on Gallium Nitride (GaN) Metal-Oxide-Semiconductor High-Electron-Mobility Transistors (MOSHEMTs) has been extensively analyzed for its effectiveness in label-free biomolecule detection. The performance of the proposed DMG-based GaN MOSHEMT is compared against conventional Single-Material Gate (SMSG) devices to evaluate improvements in sensitivity, charge confinement, and overall biosensing capability. The introduction of a Dual-Material Gate (DMG) structure results in a bandgap discontinuity and an increase in the peak electric field, which significantly enhances the carrier confinement in the channel region. This improved charge control mechanism ensures better modulation of the two-dimensional electron gas (2DEG), leading to higher transconductance and an overall improvement in the device's electrical response to biomolecular interactions. The enhanced carrier confinement directly impacts the device's sensitivity, allowing for the precise detection of target biomolecules in a label-free sensing environment. The increased electric field asymmetry due to the dual-gate material further reduces short-channel effects, thereby stabilizing the biomolecule-induced changes in surface potential and charge accumulation.

# **Chapter 8 : Future Work**

#### The design and performance analysis of III-V heterostructures for DNA detection has demonstrated significant potential in enhancing biosensor sensitivity, response time, and selectivity. However, there are several areas where further research and improvements can be made. The following key directions are proposed for future work:

#### **7.1 Optimization of Material and Structural Properties**

#### Exploring Alternative III-V Materials: While this study primarily focused on materials like GaAs, InP, and AlGaAs, further investigations into 2D III-V materials (such as monolayer GaN or InSe) could improve device miniaturization and flexibility.

#### Bandgap Engineering: Tuning the heterostructure bandgap by adjusting the composition ratios could enhance charge transfer efficiency, optimizing DNA hybridization sensitivity.

#### Surface Functionalization Techniques: Advanced biochemical surface modifications, such as self-assembled monolayers (SAMs) with nanoparticle enhancements, could improve specificity and stability.

#### **7.2 Device Performance Enhancement**

#### Reducing Noise and Improving Signal Processing: Implementing machine learning algorithms to analyze real-time signals can help differentiate between background noise and specific DNA hybridization events.

#### Miniaturization and Integration: Research into CMOS-compatible fabrication techniques will allow the seamless integration of III-V biosensors with existing microelectronic platforms for lab-on-chip applications.

#### Exploring Multi-Sensing Capabilities: Developing multi-analyte detection platforms that can simultaneously detect multiple DNA sequences could expand applications in genomics and diagnostics.

#### **7.3 Experimental Validation and Commercial Viability**

#### Real-World Testing with Clinical Samples: Future work should focus on testing biosensors with real patient samples (e.g., blood, saliva) to validate performance under physiological conditions.

#### Long-Term Stability Studies: Evaluating device stability over extended periods under different environmental conditions (e.g., temperature, humidity, and pH variations) will be essential for commercial applications.

#### Scalability and Cost-Effective Manufacturing: Investigating low-cost, scalable fabrication techniques such as inkjet printing, roll-to-roll processing, and wafer-level manufacturing can facilitate large-scale production.

#### **7.4 Advanced Detection Mechanisms**

#### Integration with Optical and Plasmonic Techniques: Combining electrical and optical detection methods (such as Surface Plasmon Resonance (SPR) or Photonic Crystal Resonators) can enhance sensitivity.

#### Quantum-Based Biosensing: Exploring quantum dots, single-electron transistors, or spintronic-based sensors could push the limits of DNA detection to attomolar (aM) levels.

#### Real-Time Wireless Sensing: Developing wireless and portable biosensors using RFID, Bluetooth, or IoT-based platforms could enable remote and point-of-care diagnostics.

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