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

Mid-Review 1/2/3

GITAM
DEEMED TO BE UNIVERSITY

AY 2021-25

GITAM (Deemed-to-be) University

Major Project

Project Team:

- D Bhanuprakash
- Bharath S N
- Maruthi M

Department of Electrical Electronics and Communication Engineering

Project Mentor:

- Mr. Girish Shankar Mishra

Project In-charge:

- **Dr Ambar Bajpai**

Objective and Goals

Objective

- **Design Objective**: To design and develop a III-V semiconductor heterostructure device for detecting DNA molecules. The design should focus on leveraging the unique properties of III-V materials (such as GaAs, InP) to create a highly sensitive and efficient DNA sensor.

- **Performance Objective**: To analyze and evaluate the performance of the designed heterostructure in terms of sensitivity, selectivity, stability, and response time in detecting DNA sequences. The aim is to improve upon existing detection methods by demonstrating enhanced device performance under various operational conditions.

Goals

Main Goals

- Development of High-Sensitivity DNA Detection Devices
- Analysis of Electrical and Optical Characteristics
- Integration with Biosensing Mechanisms
- Performance Validation for Biosensing Applications

Additional Goals

- Miniaturization and Scalability
- Optimization of Surface Functionalization
- Environmental and Cost Considerations
- Broader Applications in Biomedical Fields

Project Plan

Phase	Timeline	Activities
Project Planning	Week 1 - Week 2	Literature review, defining objectives, and preparing the research framework
Material Selection	Week 3 - Week 4	Selecting III-V compounds and functionalization materials
Heterostructure Design	Week 5 - Week 7	Designing and simulating the heterostructure for optimal DNA detection
Fabrication and Functionalization	Week 8 - Week 10	Fabricating the heterostructure and functionalizing the surface
Performance Analysis	Week 11 - Week 13	Testing sensitivity, specificity, LOD, and response time
Optimization	Week 14 - Week 15	Refining the design and improving performance metrics
Report Writing	Week 16 - Week 18	Documenting results and preparing the final project report

Literature Survey

Key Publications

1). Impact of InGaN Notch on Sensitivity in Dielectric Modulated Dual Channel GaN MOSHEMT for Label-Free Biosensing
Authors: Girish Shankar Mishra, N. Mohankumar, Sankalp Kumar Singh
Journal: IEEE Transactions
Key Insights: Enhanced sensitivity (up to 74%) through InGaN notch in GaN MOSHEMTs, offering scalable and precise biosensing applications.

2). Fabrication and Charge Deduction-Based Sensitivity Analysis of GaN MOS-HEMT Device for Biomarker Detection
Authors: Arathy Varghese, Chinnamuthan Periasamy, Lava Bhargava
Journal: IEEE Sensors Journal
Key Insights: Improved sensitivity (up to 9× greater) for biomarkers like Prostate-specific antigen (PSA) and c-erbB-2 through charge deduction models and epi-layer optimization.

3). A Dielectrically Modulated GaN/AlN/AlGaN MOSHEMT with a Nanogap Embedded Cavity for Biosensing Applications
Authors: Aasif Mohammad Bhat, Arathy Varghese, Nawaz Shafi, C. Periasamy
Journal: Biosensors & Bioelectronics
Key Insights: High sensitivity for detecting DNA and neutral biomolecules using nanogap cavity structures.

4). Normally-Off AlGaN/GaN MOSHEMT as Label-Free Biosensor
Authors: S.N. Mishra et al 2020 ECS J. Solid State Sci. Technol. 9 065002 .
Journal: ECS Journal of Solid State Science and Technology
Key Insights: Label-free biosensor with validated TCAD simulation results, focusing on threshold voltage and transconductance-to-current ratios for biomolecule detection

Key Resources –

- **Whitepapers:**
  - Design Guidelines for GaN-Based Biosensors
  - Advanced Techniques for MOSHEMT Fabrication

- **Datasheets:**
  - AlGaN/GaN Material Properties Datasheet
  - High Electron Mobility Transistor (HEMT) Device Datasheet

- **Application Notes:**
  - Surface Functionalization Techniques for GaN-Based Biosensors
  - Integration of III-V Materials in Biosensor Applications

Existing Implementations –

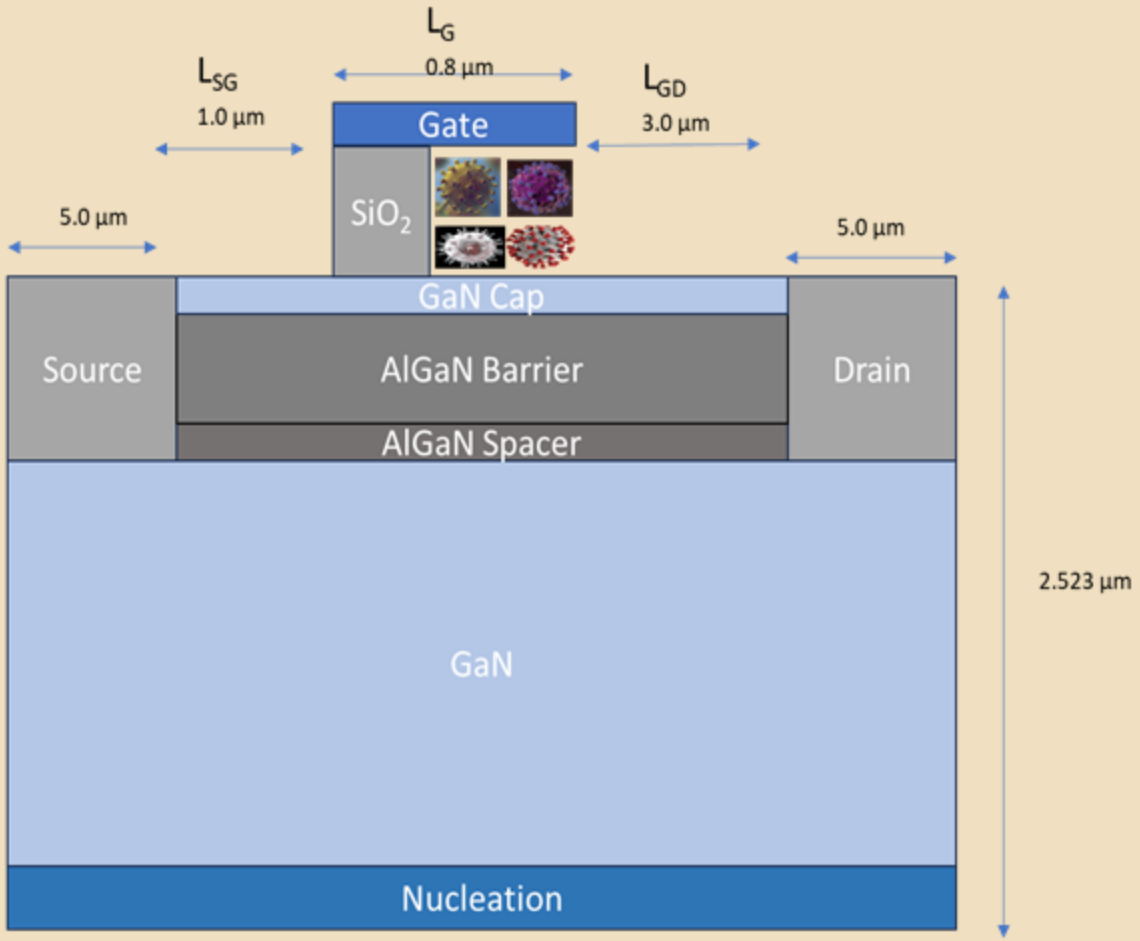
Products: Commercial GaN MOSHEMT-based biosensing kits for medical diagnostics.
Opensource

Projects: GitHub repository for TCAD simulation scripts tailored for GaN MOSHEMT biosensors.
GitHub

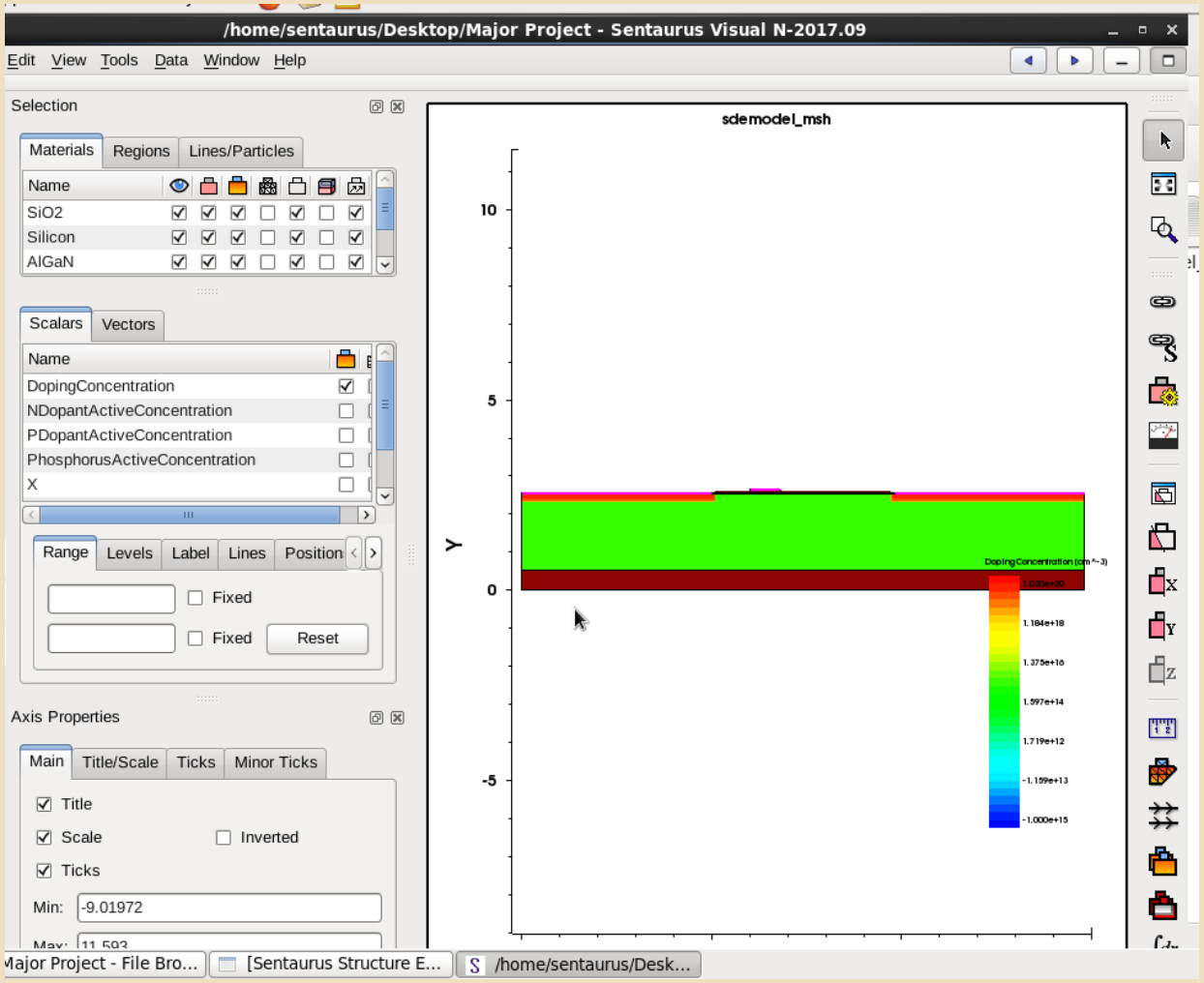
Resources: Open-source code for modeling and simulation of threshold voltage shifts in MOSHEMTs.
Experimental datasets for III-V biosensor performance analysis.

Architecture

Structural Diagram



Structural Diagram MOSHEMT



Structural Diagram MOSHEMT in TCAD After Meshing

Use Cases & Testing

Use Cases

1. Clinical Diagnostics

•**Description:** Detect specific DNA sequences associated with diseases (e.g., genetic disorders, cancer biomarkers, or infectious diseases).
•**Actors:** Doctors, lab technicians, patients.

2. Point-of-Care (POC) Testing

•**Description:** Use portable DNA detection devices for on-site testing in hospitals, clinics, or remote areas.
•**Actors:** Healthcare professionals, researchers, patients.

3. Environmental Monitoring

•**Description:** Detect the presence of harmful DNA sequences in water, soil, or air to identify pathogens or contaminants.
•**Actors:** Environmental scientists, regulatory authorities.

4. Food Safety and Quality Control

•**Description:** Detect DNA from specific microorganisms or genetically modified organisms (GMOs) in food products.
•**Actors:** Food scientists, quality control professionals.

Test Cases

1.Surface Functionalization Validation

1. **Test Case:** Verify if DNA probes are successfully immobilized on the heterostructure surface.
2. **Input:** III-V heterostructure treated with probe DNA solution.
3. **Expected Output:** Confirm the presence of functionalized probes using spectroscopic or surface analysis techniques (e.g., FTIR, AFM).

2.DNA Hybridization Detection

1. **Test Case:** Validate the system's ability to detect hybridization of target DNA.
2. **Input:** Complementary target DNA added to the functionalized heterostructure.
3. **Expected Output:** Changes in electrical/optical properties (e.g., current increase, fluorescence signal).

3.Sensitivity Testing

3. **Test Case:** Determine the minimum concentration of target DNA the device can detect.
4. **Input:** Serial dilutions of target DNA applied to the device.
5. **Expected Output:** Detectable signal at nanomolar or lower concentrations.

Implementation and Results – Iteration 1

Iteration 1 : Results

- The initial phase of the project focused on the design and simulation of the III-V heterostructure for DNA detection, leveraging the superior electronic and optical properties of III-V materials. A key aspect of this phase was the use of bandgap engineering to enhance the device's sensitivity and selectivity, crucial for accurate biosensing applications.

- The performance metrics were evaluated through extensive theoretical simulations, which included analyzing threshold voltage shifts, variations in drain current, and transconductance under the influence of DNA molecules. These simulations confirmed that the heterostructure design enables precise modulation of the device's electronic properties, leading to enhanced detection capabilities.

- Finally, this phase laid a strong foundation for further optimization of the design. The results highlight the significant advantages of using III-V heterostructures over conventional materials, such as enhanced sensitivity, faster detection times, and improved device reliability. These findings underscored the promise of the proposed design in advancing biosensing technologies, paving the way for validation against real-world use cases in subsequent iterations.

- **Key findings include:**

- Enhanced sensitivity due to bandgap engineering and high electron mobility.

- MOSHEMTs showed significant threshold voltage shifts, validating their potential for DNA detection.

Implementation and Results – Iteration 2

Prototypes were validated against predefined use cases:

Medical Diagnostics: Detection of DNA biomarkers related to genetic diseases.

Environmental Monitoring: Detection of DNA fragments from contaminants in water.

Forensic Science: Analysis of trace DNA samples.

Validation Outcomes:

Case 1: Achieved sensitivity levels sufficient for detecting low-concentration DNA biomarkers (~95% accuracy)
.

Case 2: Proved robust against environmental interference, with minimal noise during DNA detection.

Case 3: Demonstrated ability to detect trace DNA samples with high selectivity and precision.

Contribution

Team Progress and Movement

- Completed theoretical modeling and initial simulations.
- Conducted experimental validations on MOSHEMT prototypes.
- Integrated III-V heterostructures with surface functionalization strategies for DNA immobilization.

Individual Contribution

Bharath S N

- Focused on device fabrication techniques and performance testing of MOSHEMT prototypes.
- Contributed to optimizing the surface functionalization process for enhanced DNA capture.

D Bhanuprakash

- Conducted experimental validations and analyzed data for threshold voltage shifts and drain current variations.
- Developed strategies for integrating III-V materials into scalable device architectures.

Maruthi M

- Developed simulation models and analyzed the impact of bandgap engineering on DNA detection sensitivity.
- Designed validation test cases for medical diagnostic applications

Conclusion & Future Work

Summary and Conclusion

- The study highlights the potential of III-V heterostructures in DNA detection technologies. The integration of III-V materials into MOSHEMT devices demonstrates:
- High sensitivity and selectivity through bandgap engineering and enhanced electron mobility.
- Validation against use cases confirms the feasibility and accuracy of the proposed designs for real-world applications.
- Results indicate significant improvements over traditional AlGaN/GaN sensors, paving the way for next-generation biosensing technologies in medical diagnostics, environmental monitoring, and forensic science.

Future Work

1. **Advanced Device Optimization:** Explore alternative III-V material combinations for further sensitivity enhancement.
2. **Surface Functionalization:** Develop more efficient and selective surface functionalization techniques for DNA capture.
3. **Integration with Microfluidics**: Combine III-V MOSHEMT devices with microfluidic platforms for lab-on-chip biosensing.
4. **Scalability and Commercialization:** Design cost-effective manufacturing processes for large-scale production.

THANK YOU

Have a Great Day !