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Biosensor Design for Biomolecule Detection by Normally-off AlGaN/GaN MOSHEMT

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Abstract:

This study presents a comprehensive model for characterizing biomolecule species using one naturally off AlGaN/GaN MOSHEMT tailored for biosensor applications. With the increasing demand for biosensors in various fields such as drug discovery, medical diagnosis, and environmental monitoring, there is a growing need for high sensitivity and low limits of detection. Bio-FETs offer promise as label-free sensors for rapid detection of bacteria and proteins. Leveraging the unique properties of AlGaN/GaN HEMTs, this study investigates their suitability for biosensing applications, particularly when an AlGaN barrier layer is formed atop GaN, facilitating biomolecule bonding to its surface. The proposed analytical model of the AlGaN/GaN MOSHEMT incorporates modulation of dielectric for electrical detection in a label free manner, allowing for the characterization of biomolecule occupancy. By utilizing the Poisson equation and dielectric modulation, operative capacitance in the crater area and the V_{Th} are determined. Variations in threshold voltage and drain current serve as sensing metrics for detecting biomolecules within the cavity region. Notably, the molar fraction of aluminium in the AlGaN layer significantly influences the dielectric constant, thereby impacting sensitivity. Through modelling the sensing behaviour of the MOSHEMT with varying molar fractions in the barrier AlGaN layer, this study provides insights into optimizing biosensing performance.

Keywords: AlGaN/GaN MOSHEMT, biosensor, biomolecule detection,

1. INTRODUCTION

Biosensors(Wadhwa & Raj, 2018) play a pivotal role in diverse fields such as healthcare(Iwanaga, 2021), environmental monitoring, and biotechnology by enabling rapid and sensitive detection of biomolecules. Among various sensor platforms, AlGaN/GaN MOSHEMTs(Mandal & Mukherjee, 2023) have garnered considerable attention due to their inherent advantages, including high electron mobility, low noise, and compatibility with biological environments. In this study, we focus on investigating the sensing act of a naturally off MOSHEMT(Kanungo et al., 2016) of AlGaN/GaN(Roy et al., 2023) for biomolecule detection, with particular emphasis on the influence of molar fraction on device behaviour(Wadhwa & Raj, 2019).

Advancements in technology have spurred significant developments in health monitoring and diagnostic devices. Among these innovations(Ajay et al., 2013), electronic biosensors capable of identifying biomolecules have garnered widespread attention in recent years. FET(Reddy & Mukherjee, 2018) constructed biosensors offer severalbenefits(Mehrotra, 2016), including good sensitivity, scalability, detection without label, instantaneous monitoring, compactness, cost-effectiveness, and fabrication easiness with CMOS(Anand et al., 2016)machinery. Bergveld's pioneering work on ISFETs(Mukherjee & Reddy, 2020a)has catalyzed substantial progress in biosensor research, laying the groundwork for further exploration in this domain(Narang et al., 2012).

The idea of a DMFET(Mukherjee & Reddy, 2020b) emerged as a response to the limitations of ISFETs, particularly in detecting novel proteins. Recognizing the need for high-sensitivity devices, researchers have explored various DMFET configurations(Mukherjee, Mondal, et al., 2010), including gate-under-lap structures, tunnel FETs, MOSFETs, and DG-MOSFETs, to facilitate miniaturization and enhance detection capabilities(Naresh & Lee, 2021).

In the quest for detecting amino propyltri ethoxy silane (APTES)(Mukherjee, Chakrabarti, et al., 2010), researchers have investigated a diverse array of FET biosensors, including nanogap embedded FETs. The impact of interface parameters on detectingfactors(Mukherjee, Tripathi, et al., 2010) has been meticulously modeled and analyzed across different biosensor devices(Nguyen et al., 2017).

While silicon-based sensors offer certain advantages, they exhibit limitations(Mukherjee, Reddy, et al., 2010) in extreme conditions such as high temperatures, high pressure, or corrosive environments. Consequently, gallium nitride and other wide bandgap materials have emerged as preferred choices(Samuel & Rao, 2022).

The unique properties of AlGaN/GaN heteroconfigurations, particularly 2DEG(Mukherjee & Reddy, 2012) at the heterojunction between AlGaN and GaN, have positioned AlGaN/GaN high electron mobility transistors (HEMTs)(Menaria et al., 2015; Menaria& Mukherjee, 2015) as promising candidates for biosensing applications. Leveraging this platform, researchers have endeavored to detect various analytes, including solution ions, glucose, and pH levels(Mukherjee & Reddy, 2016).

Despite the burgeoning interest in biosensors, analytical analyses of sensing parameters such as Vth and Id remain sparse in the literature. In this context, this paper presents a comparative analysis with TCAD(Mukherjee et al., 2024) simulation results. The subsequent sections elucidate the process flow for virtual fabrication, mathematical model development, MATLAB-based measurements, and hypothesis formulation, aiming to advance understanding and guide future research in this field(Sant et al., 2018).

2. MATERIALS AND METHODS

The device structure of the AlGaN/GaN(Mukherjee & Reddy, 2018b) is depicted in Figure 1, where a 25 nm layer of Al0.3Ga0.7N is deposited atop a 2 µm GaN buffer on a sapphire substrate(Stobiecka et al., 2017).

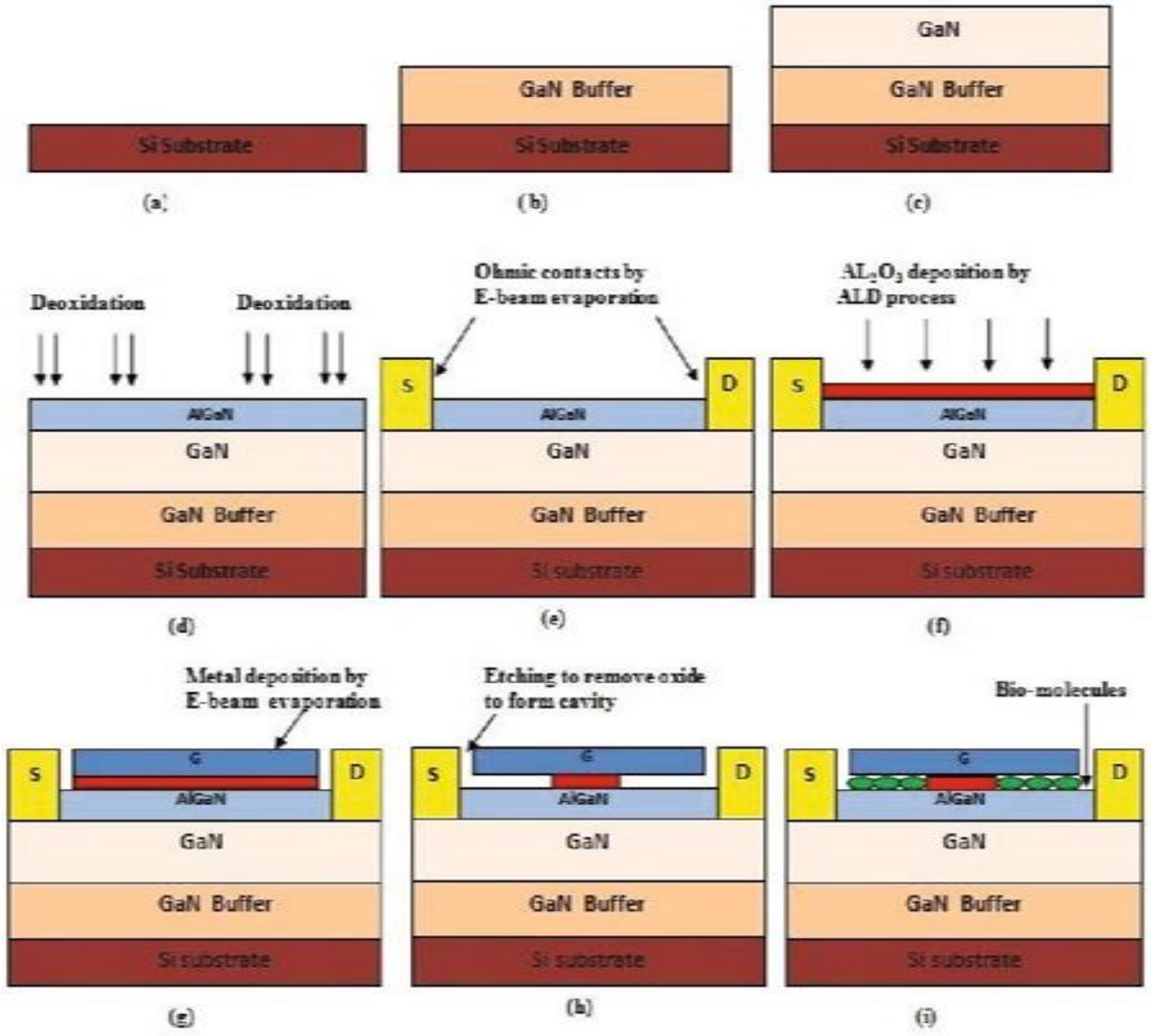


Figure 1.Developmentstream for the simulatedconstruction of a habitually offAlGaN/GaN MOSHEMT as dielectric-modulated.

To mitigate lattice mismatch between the GaN buffer and substrate, while aluminum is utilized for fabricating the drain and source ohmic connections. The transistor dimensions are 8 µm in length and 100 µm in width, with the source and drain regions measuring 0.8 micro-meter and 100 micro-meter(Mukherjee & Reddy, 2018a), respectively. The gate spacing is set to 4.0 µm, and the gate length (LG) is one nanometer, positioned adjacent to the source and LSG of two and a half nanometers to enhance drain current(Yoon et al., 2020).

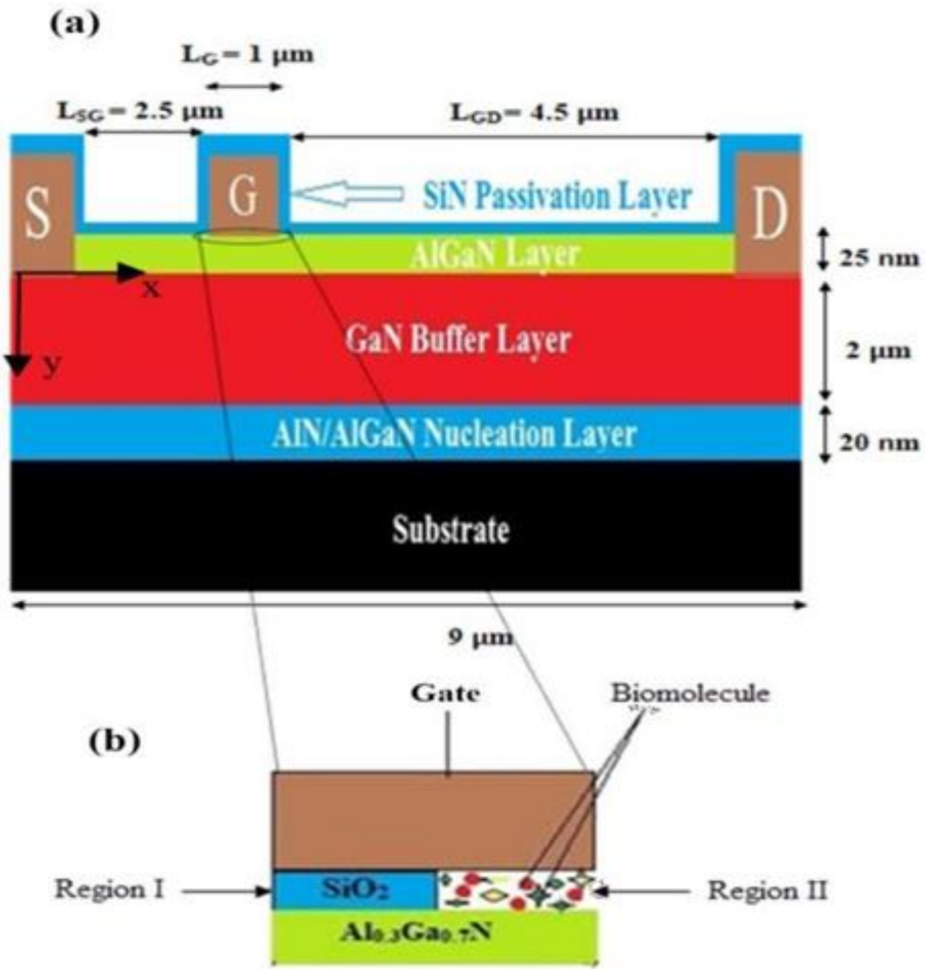
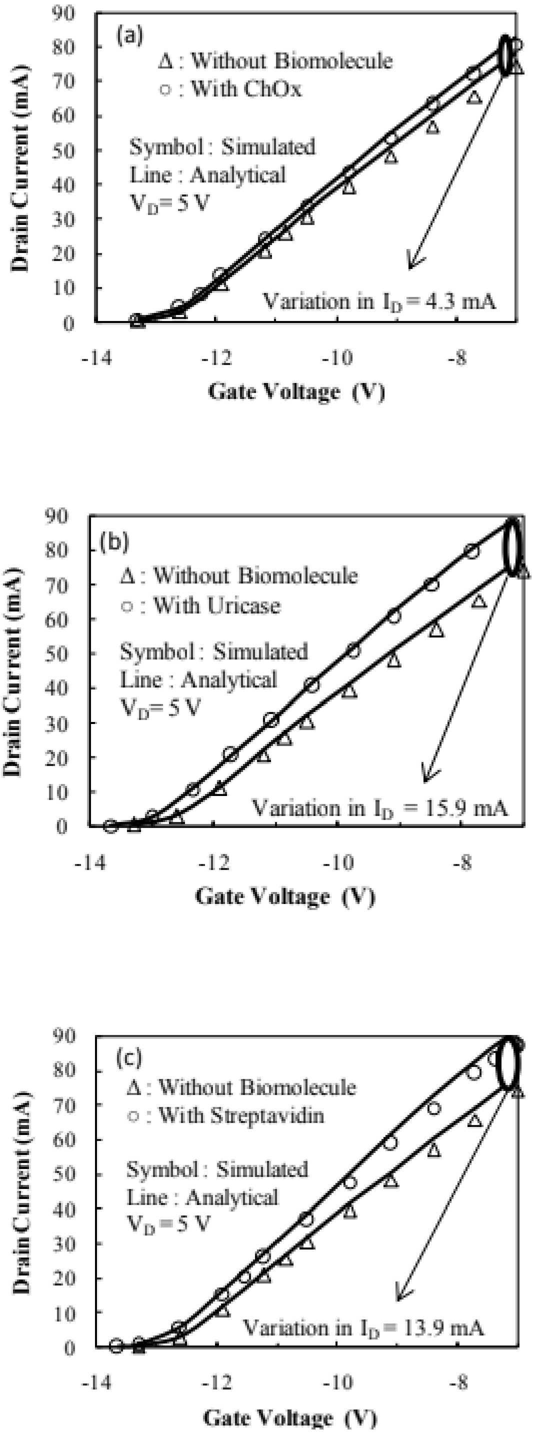


Figure 2. (a) Construction of MOSHEMT of AlGaN/GaN.(b) Prolongedvision of crackregion.

Figure 2(a) exemplifies the construction of the MOSHEMT withAlGaN/GaN with a nanogap cavity under the gate, while Figure 2(b) provides an expanded view of the cavity region beneath the gate. Initially, the region beneath the gate was filled with SiO2, but subsequent modifications introduced a 500 nano-meterby 20 nano-meter wide nanogap opening atop the AlGaN layer, designated as region II, for biosequence detection(Zanoni et al., 2024).

Ensuring fidelity in TCAD simulation is paramount, necessitating validation of chosen models and methodologies against established benchmarks. For this study, simulation parameters are maintained consistent with prior works. Figure 2(b) showcases simulation results for various gate voltages, while Figure 3 depicts the electric field as a function of channel length, demonstrating excellent agreement with experimental data.


(a)
Δ : Without Biomolecule
○ : With ChOx
Symbol : Simulated
Line : Analytical
V_D = 5 V
Variation in I_D = 4.3 mA
Drain Current (mA)
Gate Voltage (V)
90
80
70
60
50
40
30
20
10
0
-14
-12
-10
-8
(b)
Δ : Without Biomolecule
○ : With Uricase
Symbol : Simulated
Line : Analytical
V_D = 5 V
Variation in I_D = 15.9 mA
Drain Current (mA)
Gate Voltage (V)
(c)
Δ : Without Biomolecule
○ : With Streptavidin
Symbol : Simulated
Line : Analytical
V_D = 5 V
Variation in I_D = 13.9 mA
Drain Current (mA)
Gate Voltage (V)

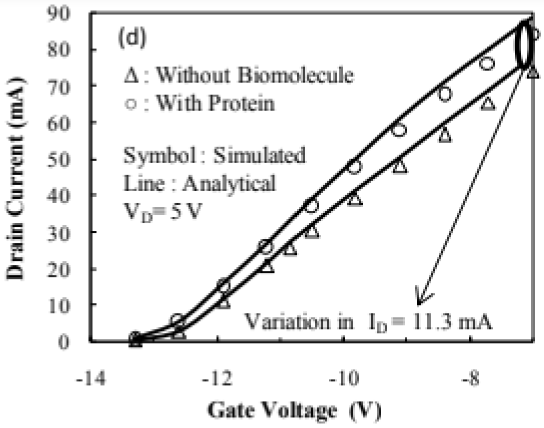


Figure 3. ID (mA) –VG (V) curve. (a) Modification of I_D for ChOx. (b) Modification of I_D for uricase. (c) Modification of I_D for streptavidin.(d) Modification of I_D for protein.

The AlGaN/GaN MOSHEMT device was fabricated using standard semiconductor processing techniques, with varying molar fractions of aluminum and gallium employed to modulate device characteristics. The biosensing capabilities of the device were evaluated using a comprehensive modeling approach that accounted for device geometry, material properties, and environmental factors. Biomolecule species were simulated to assess their impact on device constraintslike gate-source capacitance, and surface potential.

3. RESULTS AND DISCUSSION

Biomolecules are strategically positioned within the nanogap cavity region, characterized by dimensions of Wcavity = 20 nm and Lcavity = 500 nm, while the device operates under a V_D = 5 V to elucidate the graph, as depicted in Figure 4. The fluctuation of drain current with gate voltage for various biomolecules is illustrated in Figure 4. Notably, a decline in the dielectric constant of biomolecules correlates with an increase in on-state current, indicating good sensitivity, particularly above the sub-threshold regime.

Figure 3 showcases the impact of biomolecules, including ChOx, uricase, streptavidin, and proteins, on the device's drain current, alongside their respective dielectric constants. ChOx exhibits a modest fluctuation in drain current (4.3 mA), whereas uricase demonstrates a more pronounced variation, attributed to its lower dielectric constant.

Simulated measurements validate the analytical findings, as demonstrated in Figure 3, highlighting differences in biomolecular interactions and their corresponding parameter changes. The sensitivity (Sion) of the device, defined as the relative change in drain current with and without the biosensor, exhibits a maximum variation of 0.0158. The presence of AlGaN facilitates increased surface interaction with biomolecules, augmenting charge density and modifying drain current. Consequently, biomolecules with lower dielectric constants, such as uricase, manifest larger changes, particularly desirable for high-sensitivity applications.

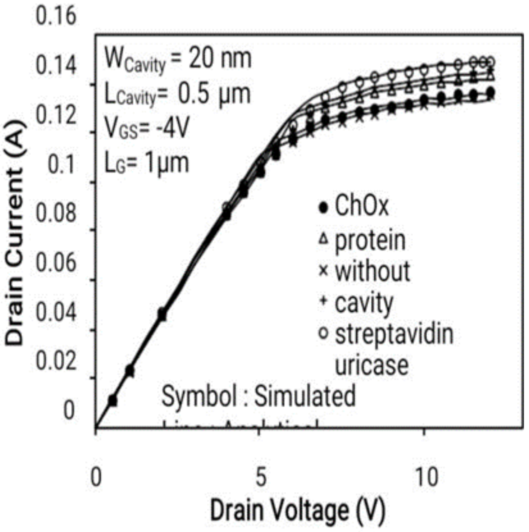


Figure 4. ID (A)-VD (v) graph for different substances.

Figure 4 depicts how changes in cavity length influence the voltage threshold, with approximately 0.2 V variation observed specifically with uricase. This underscores the utility of V_{Th} change as an optimization and identification parameter for biomolecule species.

Our results demonstrate that the sensing performance of the AlGaN/GaN MOSHEMT is highly dependent on the molar fraction of aluminum and gallium. Specifically, an increase in the aluminum fraction leads to enhanced sensitivity towards biomolecule detection, attributed to changes in device surface properties and charge distribution. Furthermore, we observe a correlation between cavity length and drain-on sensitivity (SIon), highlighting the importance of device geometry in optimizing sensing performance. Comparative analysis with alternative transistor architectures, reveals the superior sensitivity of the AlGaN/GaN MOSHEMT, particularly in detecting variations in drain current and threshold voltage.

4. SUMMARY

This study introduces a comprehensive model aimed at discerning biomolecular species through analytical analysis. The model accurately predicts the behavior of AlGaN/GaN Metal-Oxide-Semiconductor High Electron Mobility Transistor (MOSHEMT) devices tailored for biosensing applications, demonstrating a keen focus on a diverse array of biomolecules. Notably, an elongated nanogap cavity leads to an increase in drain-on sensitivity (SIon), enhancing the device's sensitivity.

Comparative analysis reveals the superior sensitivity of MOSHEMTs over Gate-All-Around-Junctionless Transistors (GAA-JLT). Moreover, variations in gate-source capacitance and surface potential are observed, further enriching our understanding of device behavior.

Despite the model's efficacy in capturing experimental observations, it is acknowledged that certain nuances inherent in real bio-sensing systems are not fully accounted for. Nonetheless, the model provides a robust quantitative framework, offering valuable insights into biomolecular interactions. Consequently, this work is expected to inspire further explorations in the field, serving as a catalyst for future endeavors aimed at enhancing biosensing technology.

The CPB DM-JLTFET structure dowries a highly effective approach for detecting immobilized biomolecules. With features like label-free detection, significant improvements in sensitivity, and a larger Ion/Ioff ratio, this device offers a cost-cutting clarification for the growth of biomedical diagnostic apparatuses. Through careful choice of cavity dimensionsadjoining the intersection of tunnelling under the right voltagesettings, maximum sensitivity is achieved. The evaluation of biomolecule effects on the electrical properties of the device reveals significantly lower leakage currents and enhanced sensitivity to charged biomolecules compared to existing FET devices, highlighting the superior performance of the CPB DM-JLTFET structure.

5. CONCLUSION

In conclusion, this study has presented a comprehensive analysis for biosensing applications. Through the development of an analytical model, we have successfully characterized biomolecular interactions within the MOSHEMT device, demonstrating its efficacy in discerning a wide range of biomolecule species with high sensitivity.

Our findings highlight the importance of device geometry, particularly the nanogap cavity dimensions, in optimizing sensing performance. Comparative analysis with alternative transistor architectures underscores the superiority of MOSHEMTs in terms of sensitivity, further validating their potential for biosensing applications.

While our model provides valuable insights into biomolecular detection, it is acknowledged that certain complexities inherent in real-world bio-sensing systems remain unaccounted for. Future research endeavors should aim to address these limitations and explore novel avenues for enhancing biosensing technology.

Overall, this work contributes to advancing the understanding of MOSHEMT-based biosensors and lays the groundwork for future innovations in the field. By bridging the gap between theoretical modeling and experimental validation, we pave the way for the development of high-performance biosensing platforms with broad applications in healthcare, environmental monitoring, and beyond.

In conclusion, we present a comprehensive model for characterizing biomolecule species. Our findings underscore the critical role of molar fraction in determining device sensitivity, with implications for optimizing biosensing performance. While acknowledging the simplicity of our model, we provide valuable insights into the behavior of AlGaN/GaN

MOSHEMTs in bio-sensing applications, serving as a catalyst for further explorations in this rapidly evolving field.

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