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Review Article

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Review on AlGaN/GaN High Electron Mobility Transistors for Biomedical Applications

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Abstract

Primarily, AlGaN/GaN high electron mobility transistors (HEMT) have an effective properties such as being nontoxic to living cells, good thermal stability, radiation hardness, and strain effect fascinating and efficient platform in medical diagnosis and health care applications. The dielectrically modulated AlGaN-based HEMTs increase the device sensitivity. In addition, HEMTs with disposable gates and ethanolamine-modified strategy improve the proficiency of Prostate Specific Antigen (PSA) HEMT devices with multiple channels resulting in enhanced device sensitivity. A detailed review of the adopted techniques in AlGaN/GaN HEMTs is presented in the article to provide insight into the performance of the device that is suitable for biomedical applications.

Keywords

High electron mobility transistors, Prostate specific antigen, Sensitivity, Biomedical applications

Introduction

In general, human health-related problems, diseases, and illnesses cannot be eradicated by innovative technologies but they can provide an assist with medical treatment and make it easier to reach service to all individuals. A promising development of AlGaN/GaN HEMT in health care and biomedical application plays a dynamic role in recent times. The various design models of AlGaN/GaN for biosensor applications help to treat enormous health issues like monitoring glucose levels, detection of cancers, transplant rejection, and kidney injury. For the past 20 years, AlGaN/GaN technology replaced silicon technology in radio frequency and healthcare applications. The III-V nitrides such as GaN, InAlN, AlGaN and InN are exceptional and have an effective low thermal impedance and density of carrier concentration on silicon carbide substrate. The materials of III-nitrides are thermally stable, chemically inert, and radiation resistant. The crystal structure with nitride device possesses excellent properties such as direct bandgap, high thermal stability, and spontaneous polarization. Enormous research is done on nitride-based quantum wells because of their advantages like high power and speed. At high operating temperatures, electric power transmission/distribution capabilities, loss energy conversion of nitride III diodes, and field effect transistors are effective. AlGaN/GaN devices are miniature in size with excellent power handling capacities. The device elements with III-V nitride have piezoelectric and spontaneous polarization, due to the stress and strain effect in lattice mismatch causing piezoelectric polarization. Thus, researchers focus on the

development of AlGaN/GaN devices for an effectual operation with an extensive range of power levels used for application in sensing [1]. AlGaN/GaN HEMT is a frequently used nitride device for electronics, biomedical, and sensing applications. The properties of AlGaN/GaN have an off-state breakdown and higher bandgap discontinuity in the heterostructure. A large lattice mismatch causes defects at the heterointerface, in turn causing a defect in the electrical behavior [2, 3].

Existing Techniques in HEMT

Analytical model GaN/AlN/AlGaN MOS HEMT

AlGaN/GaN biosensors are evolving research areas due to the advantages including reduced dimension, rapid response, and sensitivity of biosensor integration [4]. AlGaN/GaN HEMT polarization produces an electric field that causes surface state electrons to the conduction band resulting in 2DEG formation [2, 5]. The high-density charge concentration with 2DEG channels has high mobility and sensitive detection of surface charge [6]. For biological applications, the increased accuracy and structure of HEMT are more suitable with less damage due to static electricity.

Researchers Pal et.al., investigated HEMT developments in biosensor technology [7]. The biosensor with many floating gate HEMT was reported previously, therefore the authors proposed a numerical model for AlGaN/GaN MOS HEMT with improved device sensitivity. AlGaN/GaN MOS HEMT-based biosensor was developed to analyze the biomolecules such as streptavidin, protein, uricase and ChOx using the dielectric modulation method. The dielectric constant of the device and cavity length is optimized to improve the sensitivity of HEMT. The device with $Al_{0.3}Ga_{0.7}N$ thickness 25 nm, topmost GaN buffer of 2 µm grown on sapphire substrate device structure is considered for the experimentation. To decrease the lattice mismatch, AlN with a 20 nm nucleation layer is used. To form a Schottky gate Ni/Au metal and Al is utilized for drain and source ohmic contacts. The gate length of 1.0 µm, gate-to-drain space of 4.51 µm, and source-to-gate spacing of 2.50 µm are considered to improve the drain current, in turn, increases the performance of the device [8, 9]. A substantial variation in, shift in V_t and I_d capacitance under the cavity region was done by presenting biomolecules in the nanogap cavity. Figure 1 represents the schematic of HEMT with nanogap cavity.

By presenting the biomolecule in the nanogap cavity region, W_{cavity} of 20 nm and L_{cavity} of 500 nm and with 5 V of drain voltage the device is operated. The obtained current confirms good sensitivity with a large variation in I_D. With the variation in I_D of 217 mA/mm and a threshold voltage 1.055 V change in sensitivity of about 0.015 was detected when the length of the cavity is changed between 400 nm to 600 nm. Thus, for high-sensitivity healthcare applications, the AlGaN/GaN MOS HEMT device needs to be designed with a large cavity length [7].

Dielectrically modulated GaN/AlN/AlGaN MOS HEMT

Bhat et al., have proposed dielectrically modulated HEMT with nanogap embedded cavity [10]. A cavity on drain side and below the gate is investigated for the viability and sensitivity of a biosensor. The presence of various dielectric biomolecules is emulated due to the dielectric modulation of the cavity region. The investigation results that V_{TH} and I_{DS} shift up to 1.10 V and 154 mA for the neutral biomolecules. The AlGaN/GaN-based MOS HEMT for biosensing applications with 30 nm AlN nucleation layer over a sapphire substrate with 2 nm AlN spacer layer, 2 µm bulk GaN, $Al_{0.3}Ga_{0.7}N$ supply layer cavity length L_{cavity} of 0.5 µm and cavity height h_{cavity} of 13 nm are considered for the experimentation. The presence of Al_2O_3 over $Al_{0.3}Ga_{0.7}N$ layer helps the biomolecule adhesion and results in lower leakage due to a high bandgap. The high dielectric material ensures a high barrier for leakage providing higher scalability, uniform surface, and low defect density [11]. Thus, the cross-sectional view of the HEMT biosensor is represented in figure 2 and the graphical representation of dielectric molecules, current sensitivity for different di-electrics, and AlGaN region thickness dimensions are illustrated in figure 3 and figure 4, respectively.

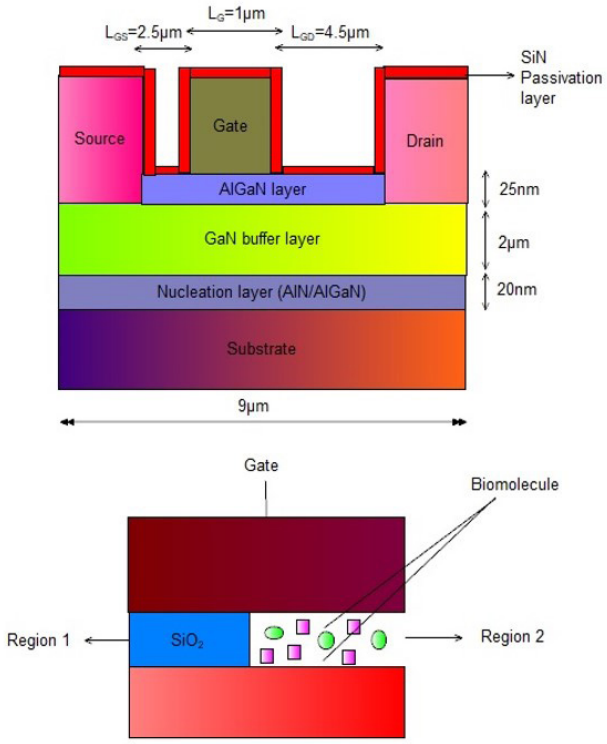


Figure 1: Schematic representation of HEMT with nanogap cavity.

The V_t - threshold voltage patterns for various AlGaN/GaN region thicknesses and biomolecule dielectrics show how sensitivity increases with biomolecule dielectric and AlGaN layer thickness. The device's geometrical differences lead to the conclusion that the best sensitivity is achieved when AlGaN thickness is used properly, and the maximum fill height is used. The device's feasibility for use in highly delicate biomedical applications is confirmed by the performance factors attained [12, 13].

Disposable gate AlGaN/GaN MOS HEMT

The proposed HEMT structures are developed by organic chemical vapor depositions on silicon substrate. AlGaN/GaN

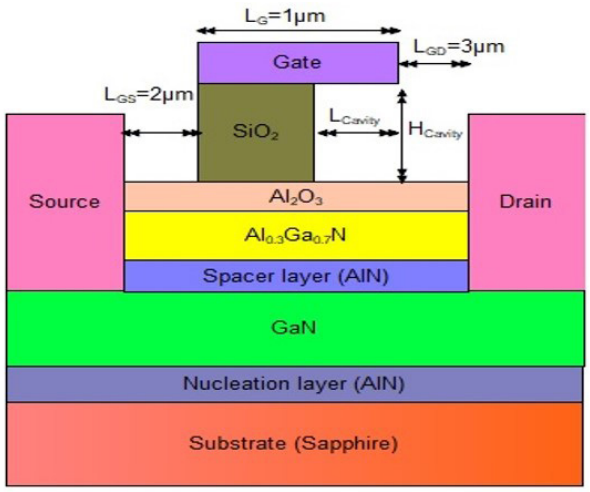


Figure 2: Cross-sectional view of HEMT for biomedical application.

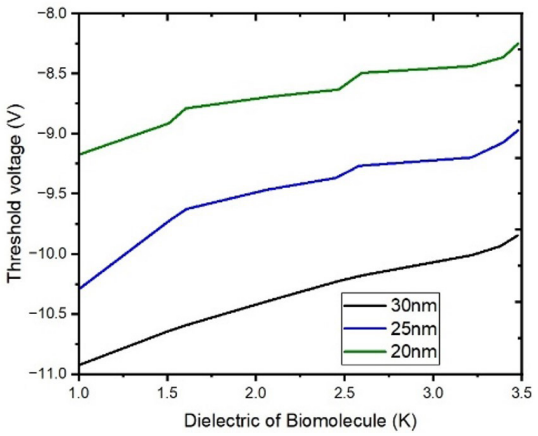


Figure 3: Graphical representation of dielectric molecules.

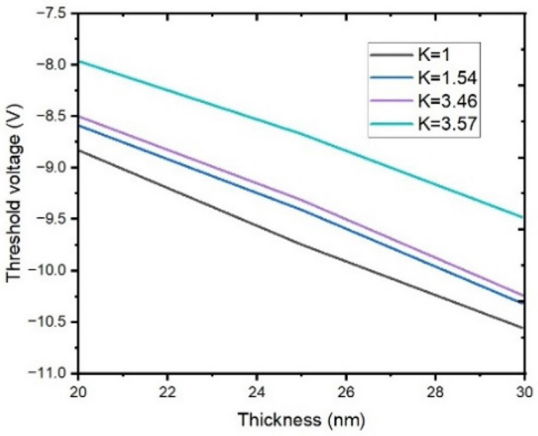


Figure 4: Graphical representation of current sensitivity for assorted dielectrics and thickness of AlGaN layer.

HEMT consists of GaN buffer layer thickness of 1.5 µm, GaN cap layer of 1.5 nm thickness, and AlGaN barrier layer of 18 nm thickness. The representation of disposable gate functionalization is illustrated in figure 5 and the voltage-current (V-I) characteristics of the disposable gate are presented in figure 6.

After the fabrication process, the disposable gate HEMT

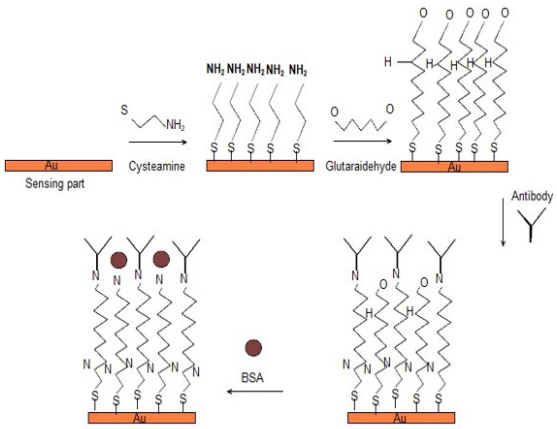


Figure 5: Schematic representation of disposable gate functionalization.

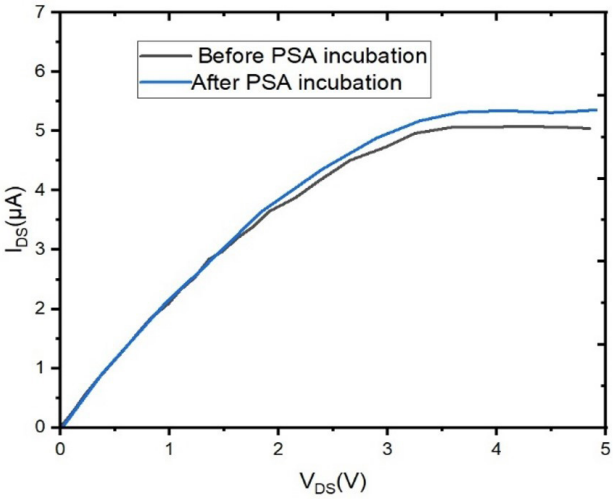


Figure 6: V-I characteristics of the disposable gate.

sensor observes the variations in the concentration of PSA due to the effect of negatively charged phosphate buffer saline solution [12]. The disposable gate negative charge is transferred to the GaN surface resulting in a 2DEG concentration reduction causing source-drain in the current drop [13].

The AlGaN/GaN disposable gate HEMT sensors provide a stable and reliable analysis of bioassays. The AlGaN/GaN disposable gate HEMT maintains a PSA concentration of 100 fg/ml lowest level with good specificity and selectivity. The disposable gate - AlGaN/GaN HEMT is concluded as a promising strategy for biomedical, health care, and clinical diagnosis applications with efficient stability and reliability.

Ethanolamine modified strategy of AlGaN/GaN MOS HEMT

Gu et al. [14], proposed HEMT with a highly efficient ethanolamine modification strategy for the examination of molecular immobilization in bioassay application. AlGaN/GaN HEMT PSA and pH are investigated to verify the device performance is a suitable biosensor. The molecular-gated HEMT biosensor has attained good sensitivity, stability, and linearity. In addition, immobilization of PSA antibody onto the ethanolamine aminated - GaN surface limits the detection

of PSA as 1 fg/ml in phosphate buffer saline buffer. The sensitivity PSA biosensor was substantially increased up to 2.04% for 100 ng/ml. Ethanolamine modified surface provides more opportunities and active sites for bonding of biomolecular. As a result, biosensor sensitivity enhances respectively. The representation of the PSA antibody modification process and V-I characteristics of HEMT biosensors with PSA are shown in figure 7 and figure 8.

The results of pH and PSA measurements using an ethanolamine-modified biosensor show that the proposed device's surface modification method significantly enhances the functionality of the AlGaN HEMT based biosensor. The surface layer coating quality and protein biomolecule detection efficiencies are greatly improved by an ethanolamine method. The performance of molecular gated AlGaN/GaN HEMT biosensors had improved by the biocompatible surface's highly defeating nature of biomolecule adhesion [14].

AlGaN/GaN HEMT with double channel technique

Varghese et al. [15], proposed the applicability of the double channel technique in AlGaN/GaN HEMT for future biosensing applications. In AlGaN/GaN HEMT a double-channel technique device sensitivity is compared with the previously existing single-channel device. The device obtained a sensitivity of 136%, the obtained result was 74% more than the sensitivity of a device with single channel. AlGaN/GaN HEMT first barrier thickness of 18 nm, GaN first channel thickness of 6 nm, AlGaN second barrier thickness of 15 nm, GaN second channel thickness of 6 nm, GaN buffer thickness of 5 µm and silicon substrate of 100 µm thick is considered for the experimentation. The diagrammatic representation of double-channel HEMT is shown in figure 9 and then the comparative results of single and double-channel HEMT devices are illustrated in figure 10 and figure 11, respectively.

In general, the device sensitivity is measured using sensing factors such as maximum on current ($I_{DS, MAX}$) [16], threshold voltage (V_{TH}) [17], and output conductance (g_{ds}) [15]. From these factors, g_{ds} is more subtle to drain voltage due to the derivative of I_D wrt V. This strongly proves that sensitivity highly increases with the introduction of multiple channels in the HEMT device. The conclusion of the author's proposed work illustrates the sensors standard is absolutely suitable for future biosensing applications that demand high detection limits. The use of multiple channels HEMT overcomes the drawbacks of less resolution in an existing sensor. Thus, double channel techniques in AlGaN/GaN- HEMT devices are excellently used in intelligent medical care systems.

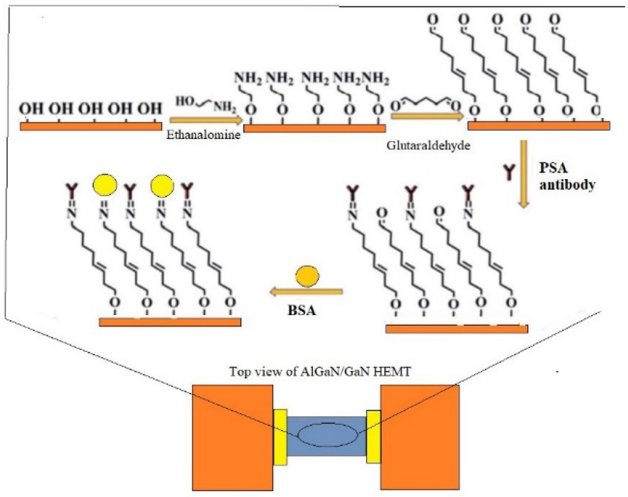


Figure 7: Schematic representation PSA antibody modification process.

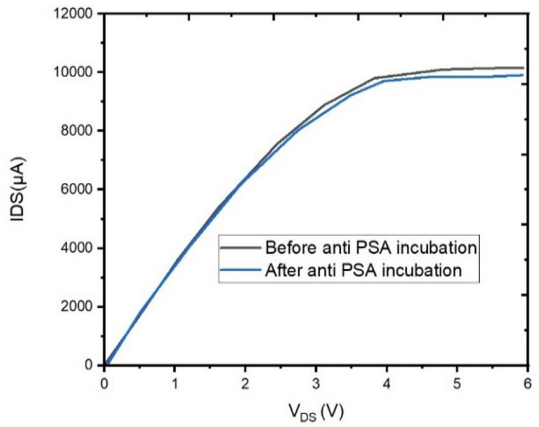


Figure 8: V-I characteristics of HEMT biosensor with PSA.

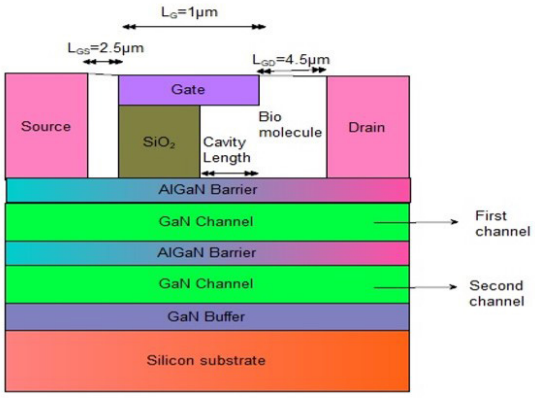


Figure 9: Schematic representation of double channel HEMT sensor.

Applications of HEMT in Biomedical

Biosensing application of HEMT

An excessively sensitive and quick FET sensor based on ions was available in the past [18]. Graphene, silicon nanowires, and carbon-based nanotubes are a few examples of silicon-based nanoscale structures that can be used as integrated sensors in healthcare applications. However, they are nonetheless subject to limitations such as low reliability, instability, and material deterioration brought on by persistent performance shifts [19]. Utilizing AlGaN devices made of III-V materials, which have excellent biocompatibility and stability, eliminates these drawbacks [20, 21]. HEMTs are commonly used in the detection of parameters like proteins, glucose and so on [21] to analyze sensitivity. The process of AlGaN/GaN HEMT in bio-detection is used for analyzing numerous diseases like kidney injuries, breast cancer, and diabetes detection. For bio-

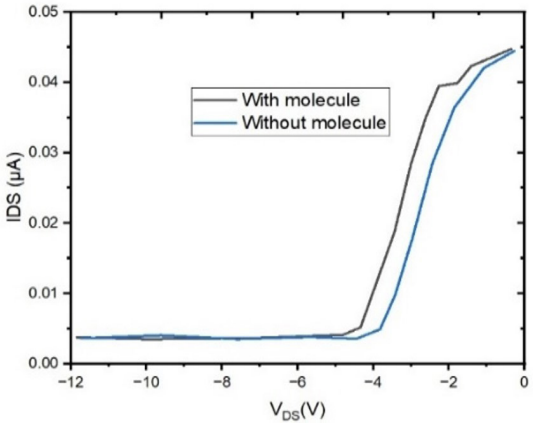


Figure 10: V-I characteristics of single channel HEMT.

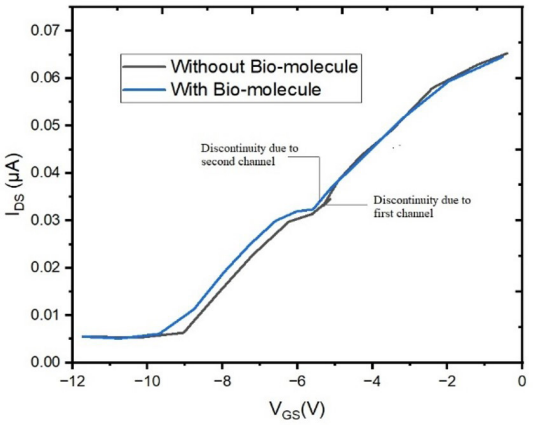


Figure 11: V-I characteristics of double channel HEMT.

medical and healthcare purposes, highly sensitive sensors are essential; hence, HEMT devices need to optimize the design.

Conclusion

In summary, AlGaN/GaN HEMT with various techniques is reported. The sensitivity of the device is improved to be used in biomedical and healthcare applications. The methods implemented by various researchers are HEMTs were dielectrically modulated, introduced disposable gates were in the design model, ethanolamine modified strategy is adopted and multiple channels in the device structure are developed to improve the device performance to be suitable for biomedical applications. The comparative analyses conclude that the applicability of AlGaN/GaN HEMT with double channel achieves high sensitivity of about 136% with remarkable stability and reliability in the device providing suitable for demanding biomedical applications.

Acknowledgments

None.

Conflict of Interest

None.

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