RAPID DETECTION OF BIOMOLECULES IN A DIELECTRIC MODULATED GAN MOSHEMT

A DISSERTATION

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I, **Shaveta,** Roll No. **2K18/NST/10** of M.Tech. Nanoscience and Technology, hereby declare that the project Dissertation titled **"Rapid Detection of Biomolecule in a dielectric modulated GaN MOSHEMT"** which is submitted by me to the Department of Applied Physics, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation **titled "Rapid Detection of Biomolecule in a dielectric modulated GaN MOSHEMT"** by **Shaveta,** Roll No. **2K18/NST/10** Department of Applied Physics, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

Attractive properties of GaN allows it to be used in power electronic devices in various space and defense applications like satellites and radars. GaN has wide band gap of 3.4eV and can operate at high temperature (>300 ^{0}C) as compare to silicon, which is being used in conventional devices.

Biosensors are the devices that find application in almost every field nowadays. In this paper, GaN MOSHEMT based biosensor is proposed for detection of biomolecules such as ChOx, protein, streptavidin and Uricase. The effect of biomolecule species on the performance parameters of the device has been studied. It has been observed that there is a significant increase in the drain current and gd is observed with the addition of biomolecule in the nanocavity. The electron concentration contours are studied that shows the rise of carrier concentration with biomolecule. Maximum positive shift is observed in threshold voltage for Uricase due to lowest dielectric constant. Similarly, the change in transconductance is also obtained with biomolecules. The effect of cavity dimensions on sensitivity is also studied. The maximum increase of 10% in channel potential is noted due biomolecule presence in the cavity. This device has shown good sensing and can be used for biosensing applications efficiently in addition to the high power performance of MOSHEMTs.

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LIST OF ABBREVIATIONS/SAMBOL

GaN: Gallium Nitride

AlGaN: Aluminium gallium nitride

HEMT: High-electron mobility transistor

HEFT: Hetrostructure- Field effect Transistor

2DEG: Two Dimentional Elecrton Gas

MISHEMT: Metal Insulator Semiconductor High Electron Mobility Transistor

LPCVD: low pressure chemical vapor deposition

TCAD: Technology Computer Aided Design

MOSHEMT: Metal oxide semiconductor high electron mobility transistor

HVPE: Hydride vapour phase epitaxy

MOCVD: Metal organic chemical vapour deposition

WBG: Wide bandgap

InGaP: Indium gallium phosphside

InAlP : Indium Aluminium Phosphide

LDMOS: Laterally diffused matel oxide semiconductor

MEMS: Micro-Electro-Mechanical Systems

IGBT: Insulated- gate bipolar transistor

MBE: Molecular beam exitaxy

D-mode : Depletion mode

E-mode: Enhancement mode

MMICs: Monolithic microwave integarated circuits

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Solids with a huge band gap, for example gallium nitride are prime contender for a variety of sensor applications, especially at high temperatures and in harsh situations. From one viewpoint, the enormous band gap guarantees minimum issues because of undesirable optical or thermal generation of charge carriers (e.g UV locators, high temperature gas sensors and so forth.). Then again, the solid chemical bonding between the constituent particles not just extends the forbidden gap in the electronic density of states, and yet offers ascend to a very favourable (and some of the time even uncommon) mechanical, thermal, and chemical soundness of this class of materials.

Today, a large demand for energy tools have been made of silicon. Unluckily, the inherent material characteristics of silicon place limits on the ability of its electronic components to be applicants for future power electronics for certain areas. Therefore, the desire for a way to solve to the problems of silicon leads investigators to the doorway of new materials that have wide band gap like Gallium Nitride (GaN). The key advantages of this material compared to silicon are good performance over a large temperature range, elevated critical electric field and improved saturation velocity. GaN is indeed a wide band gap semiconductor and appears to also be an extremely attractive for a large variety of energy electronic applications, including the microwave communication, power conditioning as well as radar transmitters.

This research article aims to discuss the status of GaN device technology, in particular the AlGaN / GaN high-electron mobility transistor (HEMT). Devices for AlGaN / GaN heterostructure are able to deliver high-frequency power amplifiers and power switches that are far more efficient than those provided by conventional Silicon innovation as well as several other commonly used semiconductor technology. GaN HEMTs have captivated a lot of attention due to GaN 's extraordinary material properties, including its large band gap of 3.42eV, better electron mobility, raised breakdown voltage and higher frequencies, as well as relatively high density, that further enables GaN¬-based HEMTs to always have reasonable significant advantages over conventional Silicon(Si) and GaAs type technologies. Although, AlGaN / GaN high-electron mobility transistor is considered to be the most promising candidates recently, due to the lack of GaN bulk material, it is commonly used to be grown on a foreign substrate like Si, Sapphire, and silicon carbide (SiC). This results in irregular lattice constant or even thermal expansion coefficient discrepancy. Many experimental studies have already shown that SiC seems to be the best option to reduce such major issues and to increase the high performance and reliability of the device [1].

GaN new technologies are constantly being developed and investigated mostly on new RF record performance of GaN HEMT every year. Such innovations presently show power yield densities more prominent than that of some other RF field-impact semiconductor (FET) and would be promising contender for high-power enhancement in the recurrence extend up to or likely past 30 GHz[2].

In fact, this new technology advantages originate first from combined effect of the GaN wide band gap as well as the accessibility of the AlGaN / GaN heterostructure, in which high voltage, high current and low on-resistance can indeed be concurrently accomplished, and way that results in such a improved high frequency and high power operation [3].

Gallium Nitride High Electron Mobility Transistors (GaN HEMTs) have a wide area of power electronic applications for example (GaN HEMTs) have been used in wireless batteries, travel adapters[4], LED drivers[5], high-efficiency AC-DC data center energy supplies[6], distributed power energy - storage systems[7], , on-board EV DC-DC chargers, automotive traction inverters[8], smart home appliances, aerospace, automotive traction inverters [9],[10]and others.

In this study one of the most paramount application which is using GaN based HEMTs for biosensing for different types of biomolecules has been done.

1.2 RESEARCH OBJECTIVE

This project describes AlGaN/GaN High Electron Mobility Transistor structures and its applications in biosensing**.**The main aim of the model was to Simulate AlGaN/GaN based High Electron Mobility Transistor (HEMT) structure. First HEMT structure has been simulated using Silvaco TCAD software. After simulating HEMT structure, further two studies have been done to achieve specific objectives that can be noted as.

- **GaN based MOSHEMT simulation for biosensor application:** In order to detect different kinds of species such as ChOx, protein, streptavidin and Uricase by the device by observing many important parameters like, electron concentration, transcoductance, the cavity dimension effect on the device sensitivity, and channel potential.

1.3 THESIS ORGANIZATION

The report for this project is classified into four chapters. Every chapter deals with topics related to the topic of thesis.

Chapter 1 being introduction of thesis, gives us the brief introduction, objectives of the project and thesis organization.

Chapter 2 tells about the literature review that discuses different related issues of AlGaN /GaN Based HEMT to help in understanding the work according to the previous researches and research methodology.

Chapter 3 show the simulation of GaN MOSHEMT for bimolecular detection followed by the conclusion of this work.

Chapter 4 show the future scope of the work done.

CHAPTER 2

LITERATURE REVIEW AND RESEARCH METHODOLOGY

2.1 INTRODUCTION:

Biosensors utilize chemical responses to identify the biochemical compounds. The capacity of organic particles, for example, proteins, to tie different atoms in a particular way is fundamental guideline of sensors to identify the occurance (or nonappearance) of aimed atoms [1]. Biosensors can identify large scope of species including viruses, nucleic acids, DNA, RNA and proteins etc. As of late they are being utilized in investigation of food, development of drug, wrongdoing identification, clinical determination, ecological field checking and furthermore for the investigation of biomolecule association. A biosensor composes two components, bioelement (protein, nucleic corrosive, microbial and counter acting agent) and sensor component to sense the bioelement. The sensing element can sense electric flow, conductance, potential, temperature, force, consistency and phase. The working principle is that the sensing elements senses the change in one of the measurable parameters which results to produce an electrical signal. the chosen biosensors should be sensitive to particular type of analyte, so compatibility of analyte with sensing element plays a significant task for proper recognition.

Nowadays, large number of electronic components has been made of semiconductor materials like silicon. In fact, silicon is arriving at its hypothetical breaking point as far as gadget execution. The excursion for a response for silicon limitations drives scholars to the sea for wide bandgap materials, for instance Gallium nitride and Silicon Carbide. Because of their built-in polarization area, GaN is better than SiC for constructing heterostructures. Therefore GaN is the preferred material for devices such as HEMT.

2.2 THE HISTORY OF GALLIUM NITRIDE (GaN):

GaN appears as though it is the better candidate inferable from its unique highlights like enormous bandgap, high electron mobility, immersed speed, and high breakdown electric field. In like manner, in this speculation the material of intrigue is the large-bandgap III-V compound semiconductor gallium nitride (GaN). Juza and Hahn in 1930 synthesized GaN, in which ammonia (NH3) was passed over fluid gallium at raised temperatures [11]. Subsequently, in this technique a concentrate containing of little needles and platelets were shaped for examination of the cross section consistency and crystal structure. Epitaxial development was never endeavored because of absence of GaN asset Later on, Maruska and Tietjen tried for first time to grow centimeter--sized gallium nitride layers on sapphire substrate using hydride vapor phase epitaxy (HVPE) approach in 1968

In the earliest reference point of 1990s GaN is viewed as an exceptional semiconductor material therefore, gallium nitride was regarded a steller material for cutting edge device applications in optics and high power device. The achievements made by Akasaki, Amano, and Nakamura added to the restoration of the GaN material technique. Analysts in the fields of optical and microelectronic applications have exhibited a restored enthusiasm for GaN as the most very well created semiconductors, for example, silicon (Si) and GaAs. Actually, first the Gallium Nitride based optical devices have arrived at the production level, while high power microwave devices are viewed as on Edge of their business achievement.

In 1991, in a heterojunction AlxGa1-xN / GaN grown on sapphire by MOCVD, Khan et al. First evidence published concerning the formation of two-dimensional electron gas (2DEG) [12]. Khan et al. in 1993 and 1994. The first GaN field-effect semiconductor transistor and heterostructure field-effect transistor synthesized by Metal Organic Chemical Vapour Deposition on sapphire substrates [13],[6] were reported. In 1993, Nakamura et al. recognised the first double-heterostructure (DH) GaN LEDs with high-brightness (HB) blue [15]. Stated in 1996 by Nakamura et al. The first continuous wave (CW) of GaN LD[16] in blue.

Effectiveness, reproducibility, and dependability of the epitaxial material and fabication technology represent to significant perspectives that should be handled to reestablish the incredible promise that GaN-based gadgets hold.

2.3PERSPECTIVE OF GaN:

2.3.1 GaN benefits and drawbacks:

We will discuss the material properties of GaN with conventional semiconductors, for example, Si, GaAs, and InP a,SiC, Diamond etc. Truth be told, a high voltage can be applied to the devices made of GaN due to ability to withstand high field. Moreover, it encourages this material to operate at harsh environmental conditions. the band gap of GaN and SiC is around three times the bandgap energies of typical semiconductors, for example, Si, GaAs, and InP.

The electrical breakdown fields are excellent and very high for the WBG materials, usually one order of magnitude greater than for traditional semiconductors. In general, high carrier mobility and high velocity of saturation results in fabrication of devices having ability to operate at high frequencies with high current carrying capability. High efficiency field-effect transistors (FETs) can be fabricated due to high electron mobility. A key drawback of transistors manufacturing from bulk GaN is the comparatively low electron mobility values that are about 900 cm^2 / Vs for GaN. Such values are however appropriate for transistors designed especially for service at high capacity. Basically, large bandgap semiconductors provide comparitively low mobility however quite elevated saturation velocity and can also be easily supported at high electric fields.

Due to piezoelectric and spontaneous polarization mediated effects, the sheet charge density (n_s) due to two dimensional electron gas in $Al_xGa_{1-x}N$ / GaN structure is indeed high The density of the evaluated sheet charge is about ten times greater than that of the heterostructures $Al_xGa_{1-x}As$ / $In_xGa_{1-x}As$ and In_xAl_{1-x} As/ In_xAl_{1-x} As. The 2DEG's room temperature (RT) stability, which usually ranges from 1200 cm_2 / V to 2000 cm^2 / V, is slightly higher than that of bulk counterpart.

Thermal conductivity (k) of a material that is a semiconductor is essential because this factor is a way of measuring of how simple it is to extract dissipated power from the system. Poor thermal conductivity at high temperatures contributes to impaired performance of the instrument. Usually, conventional semiconductors, mainly GaAs and InP, are poor thermal conductors.

Relative permittivity (ε_r) is an indication of a transistor's capacitive load and influence terminal impedances of the device. Table 2.1 displays that the WBG semiconductor values of ε_r are markedly smaller than those of conventional semiconductor materials. On account of GaN and SiC, 20 percent lower ε_r values, while on account of diamond, the ε_r esteem is just around 55 percent lower. For example, this permits a GaN based devices to be around 20 percent higher throughout the area for a given impedance. Actually, improved area prompts the formation of more noteworthy flows and higher microwave power yield.

Table 2.1: Some properties of semiconductors [1]

Parameter	The unit	Silicon	4H_Silicon Carbide	Gallium Nitride
Bandgap	eV	1.1	3.26	3.4
Electric breakdown strength	V/cm	0.3×10^6	3.5×10^6	3.3×10^6
Saturation velocity of electron	Cm/s	1×10^7	2×10^7	2.5×10^7
Mobility of electron	$cm^2/V.s$	1300	900	900 - 2000
Conductivity (thermal)	W/cm.K	1.5	3.7	1.3

2.3.2 GaN devices compared to current alternatives:

In addition to AlGaN / GaN HFETs, a wide variety of current solid state microwave energy storage technologies are accessible, such as, Si laterally diffused metal oxide semiconductor (LDMOS), Si bipolar/AlGaAs/InGaAs HFET, GaAs MESFET, GaAs/InGaP/InP and Silicon Germanium (SiGe) heterojunction bipolar transistors (HBT) and MESFETs based on SiC etc. Microwave power output densities of 4-7 W / mm and 10-12 W / mm, similarly, are possible from SiC MESFETs and GaN HFETs. GaAs has many downsides for high-power / high-frequency applications. High substrate prices and poor thermal conductivity are one of these.

GaAs has numerous drawbacks for high-power/high-recurrence applications. High substrate costs and poor thermal conductivity are one of these The latter makes it challenging when it is used in high-power applications, to actually eliminate heat. Additional disadvantage is that its serious electrical area, that is much thinner than the resources of the WBG. It therefore, enlightens why GaN HFETs can have 10 times higher output power densities than pHFETs from GaAs.

The SiC MESFETs profit from the substrate's outstanding thermal conductivity. Even so, their electron mobility in this material system is markedly smaller than that of GaN HFETs that is related to the shortage of heterojunction technology.

Since GaN field effect transistors exhibit much higher linearity than Si metal oxide transostors, this could be feasible on a device layer for reducing the linearization circuit complexity needed for wireless high bandwidth services. Since LDMOS innovation can just deliver moderate power density, it is imperative to utilize extremely enormous peripheral gate gadgets and in like manner very low band pad impedances in the die to understand the extraordinary power required. Result of this the transfer speed of the circuit is diminished. These different issues can be overwhelmed by utilizing an innovation of larger power density which permits higher total output power and improved bandwidth.

Therefore a device of almost the same size could withstand higher power resulting in lower power expenses of power per watt, and reduced power prices. In fact, the larger levels of impedance of those other smaller devices make matching inputs and high-bandwidth design significantly easier.

2.3.3 GaN applications

GaN 's direct bandgap require the material to be utilized both for electronic and optical applications. The bandgap of 3.44 eV refers to that same optical spectrum wavelength in the near-ultra-violet range. The $Al_xIn_yGa_{1-x-y}N$ composites could be seen covering forbidden gap energies between 1.90 eV to 6.20 eV that corresponds to light between red to dark Ultraviolet. To huge degree, gallium nitride is being utilized in so numerous different application fields

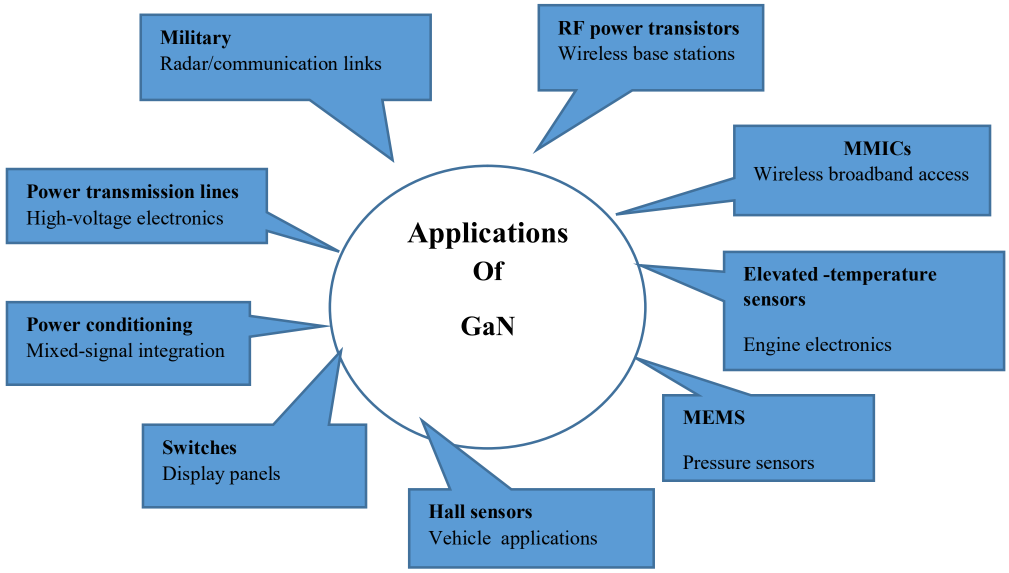


Figure 2.1: Some of application fields of GaN based transistors [3]

2.3.3.1 Optical Application

In 1993 Nakamura et al solved that problem in solid-state lighting. Through display blue GaN-based LEDs around hundred times clearer than the prior blue Silicon Carbide LEDs, which made a massive multi touch screen system noticeable in sunlight accessible.

- **LED Applications**

The major social upsides of LED-based lighting include low power consumption, outstanding performance and good durability. Additionally, solid-state design makes LEDs unaffected by electrical and mechanical shock, reverberation, repeated having switched, and severe environmental factors. The $Al_xInyGa_{1-x-y}N$ and LED group bulb keeps giving light by using several LEDs, even if one or per often considering a life expectancy of further than 100,000 hours (about 11 years), Other significant GaN-based LED technologies include led lights (cell phones, PDAs), white light (headlamps, torches for cars), artificial light (indoors and outdoors), water treatment, and clinical (detectors, medical goggles).

- **Laser Applications**

In 2003, Sony Corporation, headquartered in Tokyo, has become the first consumer electronics company to start selling DVD recorders with the next decade. Sony leads a group called Blu-ray Disc that supports a few of two rival standards for the design of disks, displays, and recording devices using GaN-based LDs in blue.

2.3.3.2 Electronic Applications

GaN is a great alternative for high-power / high-temperature microwave applications with regard to electronics owing to its increased electrical detailed analysis field (3MV / cm) and high electron saturation velocity ($1.5x10^7$cm / s). The latter is a product of the large bandgap (3.44eV) and allows for both the implementation of high input voltages and high output power criteria. Furthermore, the wide bandgap causes the process to resist high operating temperatures (300^oC-500^oC). A significant benifit of GaN is the opportunity to fabricate high electron mobility transistors.

- **Military Applications**

Advancement of GaN technology to be used in modules like surface radars, broadband seekers, jammers, battlefield and high-power broadband amplifiers, and low-noise amplifiers is generally the target of defensive system research programmes. Frequencies of investment range from 2 GHz-40 GHz for these application areas.

2.3.4 Power Devices

An ideal switching characteristic is required for high power application . Nil voltage drop and no barrier on current are some features of ideal switch in on-state. During the off state, should have high resistance for no spilling of current and ability to hold very high voltages. But in practical switches, a trade off is made for proper functiong.

It is important to note that notable changes to Si devices (Super Junction, High Speed IGBT) as well as the emergence of materials such as (SiC, GaN) will combine efficiency and reliability to device. For the situation, gallium nitride on Silicon devices is required to be essentially quick and undeniably more successful than MOSFETs. Recently GaN-based power alternatives have been forecast to expand efficiency, reduce size of the system and optimize ultimate design process and therefore can minimize losses due to conversion of power from heating,

Hetrostructure Field Effect Transistor (HEFT) was first invented in 1979 by Taskashi Mimura. The main idea of the device is the utilization of enhanced electron mobility due to the presence of hetrojuction in a so called two_dimentional elecrton gas (2DEG). In 1969 at IBM Research studied physics of carrier mobility of this kind of transport and the effect of quantum mechanics in the field of semiconductors [17].

In 1991 M. Asif Khan was stated first remark of High Electron Mobility GaN/AlGaN hetrostructures using low pressure metalorganic chemical vapor deposition[18]. AlGaN/GaN High Elecrton Mobility Transistors (HEMTs) devices are used for delivering high-frequency power amplifiers and power switches with superior performance more than those of conventional silicon technology and other sophisticated semiconductor technologies.

High Electron Mobility Transistors (HEMTs)devices are basically normally on based on AlGaN/GaN hetrostructure. Howsoever, it is desirable that HEMTs operation requires normally off in several power electronics applications. Recently many researchers have dedicated a massive related work on some aspects on normally off GaN HEMT [19].

2.4 COST AND MARKET

The technology of GaN should always be cost-competitive across the frequency spectrum currently being addressed to suit the wide variety of applications described above. As a matter of fact, the technology should be specified on the basis cost requirements big diameter, low priced substrates like Si or HVPE grown bulk GaN. Price reduction at a device level becomes achievable due to the high-temperature operation of GaN.

Besides, GaN devices don't need so much assurance from off chip circuits as Gallium Arsenide semiconductors, so use of such circuit results in reduction of weight and cost. It must be seen that the cost models remain as an unmistakable difference to military applications that are principally powered by execution.

2.5 AlGaN/GaN HIGH ELECTRON MOVILITY TRANSISTROS (HEMTs)

High Electron Mobility Transistor (HEMT) is an electronic device that is field effect semiconductor which is developed by combining layers of materials of different bandgap. Generally as result interface charges are induce due to polarization field discontinuity. When positive charge is induced, channel formation takes place due toadjust the charge induced. Since the electrons in the channel become bound to a quantum well at the interface in a very little spatial area, this is known as two Dimensional Electron Gas. Such confinement gives high mobility to electrons that outperform bulk mobility for the material where the electrons go in AlGaN/GaN HEMTs. These days are promising up comers in high-power applications,microwave and millimeter wave communication, imagery and radars, because of the GaN highlights and the HEMT's topology.

As the matter of fact GaN-based HEMTs have shown significant role in application fields specially for amplifiers that work in robust environments at higher power levels, high temperatures and some areas include radar, missiles, satellites and lightweight low-cost .

2.5.1 Basic HEMT Sturcture

The GaN High Electron Mobility T is a device structure specifically compelling for high-power and additionally high-frequency applications. Dissimilar to other regular III-V HEMTs that require n-type doping, piezoelectric and spontaneous polarization-related polarization induce electrical fields in nitride-based (III-N) polarization doping in this material system, HEMTs and valence band discontinuities at the heterointerfaces require incredibly high sheet charge densities in GaN device channels.

Common GaN HEMT seen in Figure 2.2. There is two dissimilar approaches being used Epitaxial substance production is the epitaxy of molecular beams (MBE) and metalorganics chemical vapor deposition (MOCVD) have been applied to grow epitaxial material . The different leyers that are being grown for both strucutres are the following layers (from up to down):

Cap layer the thin GaN layer (1-2 nm) is normally placed upon the barrier layer so that any problem such as oxidation of the surface will be avoided and creating low resistance ohmic contact on the heterointerface. In addition to, lowering the electric field on the surface.

Barrier layer is very important for structures. This is a bit of material with a bandgap bigger than the channel layer. Barrier layer, semi-insulating (SI) or GaN AlxGa1-x N for this situation. The bandgap in the material relies upon the part of the aluminum mole, x.

Channel / buffer layer this is the lower bandgap material than the Barrier plate, semi-insulating (SI) or high GaN resistivity plate to guarantee low high frequency misfortune and low cross-talking between neighboring system devices.

Nucleation layer the main target of this interlayer is to decrease disparity stress and lattice to the non-native surface. the type of this layer depends on the substrate used to grow the epitaxial layers and epitaxial growth technique (e.g., MBE or MOCVD). A very thin AlN, AlGaN or GaN are grown before a thicker, semi-insulating (SI) buffer layer is formed.

Substrate as substrate such as SI SiC [5], c-plane sapphire (Al_2O_3)[6], or Si(111)[7] are used to grow GaN epitaxy due to the absence of native substrate

Upon growth of the HEMT structure source (S), gate (G), and drain (D), three metal contacts, are taken from the top AlGaN or AlN barrier layer as shown in Figure 2.2 the source and drain are Ohmic contacts to provide minimum loss of signal.. The source is usually grounded while a positive supply is applied on the drain, which results the electrons in the channel to move from source to drain. The voltage between drain and source is called V_{DS}, while the V_{GS} is called the voltage from the gate source.

The gate terminal is a rectifying metal-semiconductor (Schottky contact). By applying a negative bias the channel is depleted from carriers by enforcing a strong negative gate bias, and then no current can flow between through the channel. The gate bias required for the channel to pinch-off is called threshold voltage (V_T). If for depletion mode (D-mode) HEMT the voltage threshold is negative.

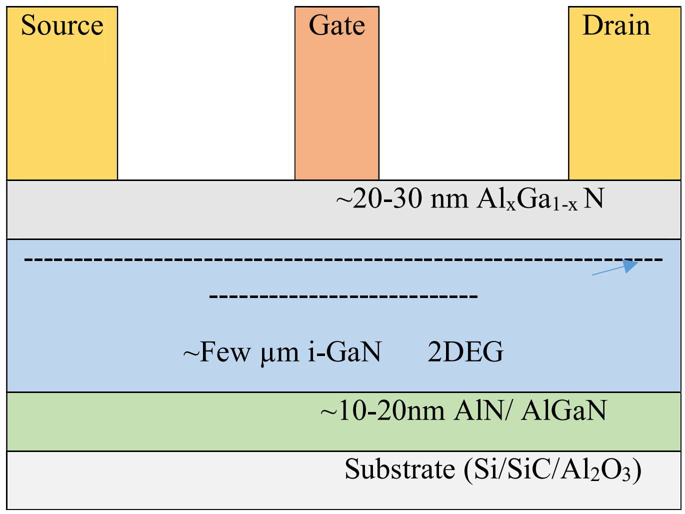


Figure2.2: Basic $Al_xGa_{1-x}N$/GaN HEMT structure [12]

2.5.2 Effects of Spontaneous and Piezoelectric Polarization

GaN's crystal structure is wartzite, which consist of layers of Ga atoms and N atoms spaced in hexagon. The absence of centre of symmetry and high ionic strength of the covalent bonds results in the polarization of the structure layer. This effect of is called spontaneous polarization, PSP, no external electric field is applied.

When on GaN thin layer of AlGaN is grown, due to lattice mismatch both layers experience strain. This strain gives rise to a piezoelectric polarization, PPE [1].

The density of charge triggered by polarization, σ (C / cm2), is related to Eqn's polarization vectors.

$$\sigma(x) = P_{SP,AlGaN}(x) + P_{PP,AlGaN}(x) + P_{SP,GaN} \quad (2.1)$$

By raising the Al-content of the AlGaN layer, the intensity of charge caused by the total polarization rises. AlGaN / GaN energy band structure is shown in Figure 2.3, where band discrepancy produces a wide conductive offset band. The offset conductive band successfully creates a potential well at the interface between AlGaN and GaN.

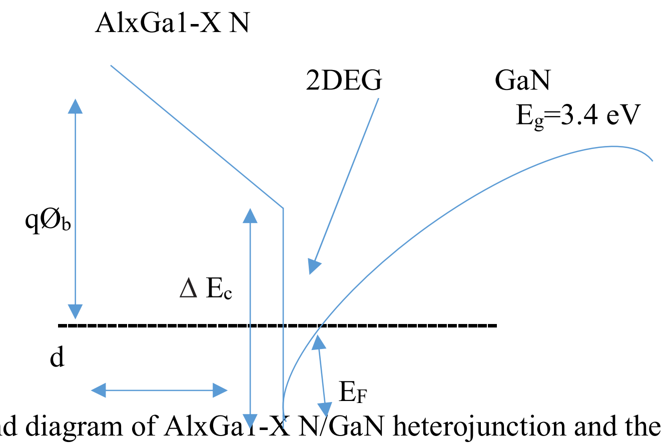


Figure 2.3: Band diagram of AlxGa1-X N/GaN heterojunction and the formation of 2DEG at the heterointerface [20]

Free electrons appear to compensate for a positive polarization induced sheet charge (+σ) that is bound for Ga(Al)-face structures at the lower AlGaN / GaN interface.

As within a two-dimensional (2D) quantum well the electrons are well constrained and there is reduction in bulk scattering effects thet result in much higher mobility than for bulk GaN. Interface, alloy and dislocation scattering are the key factors affecting 2DEG mobility. Thusly, so as to accomplish high power densities for RF/microwave gadgets, high current handling capacity it appears to be fitting to utilize AlGaN/GaN heterostructures with high Al-content [20]

2.5.3 Formation of 2DEG

Ground trapping are conditions of energy in a semiconductor's band-gap. We come through causes such as crystal defects, fractures, or impurities. Categorization of these cages based on the local location within the band gap of the energy levels. Traps with energy just above level of Fermi are linker-like, resulting in negative charge once filled. But this appears to apply only to specific thickness of the barrier. Take into account a thin protective barrier with fairly tiny thickness; under the Fermi energy is the exterior trap. However as the thickness of the barrier rises, the surface trap energy exceeds the Fermi energy till it correlates with at a critical thickness.

Unless ground traps are extremely tired, the 2DEG density would not be increased more by the barrier thickness. Currently, if the individual frame is not stretched by the channel layer, then the subsequent relax. Defaults are generated at the AlGaN / GaN interface when relaxed, and piezoelectric polarization can disappear allowing degradation of the 2DEG density.

Barrier thickness isn't the only element that influences the density of 2DEG. The portion of the x-mole as well plays a key part. in case o AlGaN the piezoelectric polarization throughout the layer of stressed barriers depends on the mole fraction of the Al content. With the mole fraction expanding, the interaction with the lattices shrinks. It results in increase of piezoelectric polarization in the layer. Increasing difference between both barrier as well as the stream layer of the polarization area induces higher bound surface charge. Where even the density of the connected cash buyers only with Al-mole fraction rising. Like the AlGaN thickness, nevertheless, yet another increase in the Al content induces a reluctance in the AlGaN layer and therefore a degradation in the 2DEG density. As that of the proportion of Al rises, total polarization rises. Even so, whereas the spontaneous polarization for x-mole fractions beyond 0.4 keeps growing, piezoelectric magnification needs to undergo a dramatic drop signalling relaxing of the AlGaN layer [30]. It's indeed important to note that higher stretched AlGaN thicknesses could be developed when smaller percentages of the x-mole are being used

2.5.4 Operation Theory of HEMT

The current flowing between source and drain can be written as (rate at possible value of zero which the 2DEG load moves through the gate):

$$I_D = q\, n_s\, \upsilon_{eff}\, W_G \qquad (2.2)$$

Where υ_{eff} is velocity of electron inside the channel, n_s is the two dimensional electron gas carriers density and W_G is gate length. Depending on the gate bias the sheet carrier density could fluctuate from a maximum value of n_{s0} to a lowest.

When HEMTs are biased at low drain voltages, such as V_D (V_G $-V_)$ the effective velocity of the electron saturate. Equipment in the saturated regime for intensive reasons.

In the saturation region the drain current is given by:

$$I_D = \frac{\varepsilon_{AlGaN} V_{sat} W \quad (V_G - V_T)}{(d_{AlGaN} + \Delta d)} \tag{2.3}$$

Realize that I_D is independent of V_D, presuming that electrons move at their saturated velocities. I_D is not in fact totally V_D -independent. The gm is another very important parameter that measures the gate's activeness to modulate the current drain.

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} \tag{2.4}$$

Carriers in the GaN buffer layer experience a decreased mobility and reduced velocity. The valuable carrier velocity diminishes and tends to cause gm to diminish with high V_G

2.6 NORMALLY OFF HEMT

Although HEMT devices are very useful in the field of switching application, they are basically normally –on (depletion mode; Vth < 0). Hence, to hinder current flow a negative voltage has to be applied. In order to reduce the power consumption enhancement mode (normally-off) is needed to maintain safe operation and reducing the circuit intricacy. In fact, there are many different structures of normally-off HEMT that have been suggested such as Gate recess structure , Thin barrier layer, Gate Injection Transistor, P-GaN Gate HEMT , and Fluorine implantation [21]

2.6.1p-GaN Gate HEMT

In p-GaN gate HFETs, metal gate is replaced by p-type doped GaN (Figure 4). Magnesium is considered as p-type dopant. With proper p-type doping, the thickness of the GaN channel layer extends over the depletion zone for zero-volt gate bias and thus the channel is off at zero gate bias. This structure is called normally-off.

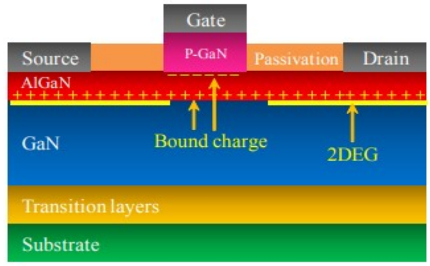


Figure 2.4. Cross-sectional view of the normally-off HEMT [21]

2.7 METHODOLOGY: TCAD SIMULATION

Technology Computer Aided Design (TCAD) tools are modeling methods being used in order to study the behaviour and encoding of electrical appliances. The software could even anticipate the system usually results across many treatment processes (process simulation) or predict the electrical properties of electronic components under given specific operating conditions (device simulation). The properties of the material are given test system through which the device would be made [22].

In addition, physical models are introduced, describing the actions of the carrier. After that, the configuration will be discretized by generating a grid or even equating all such physical characteristics including its domains with nodes. The processor can detect a number of defined calculations, alongside defined models, to know the electrical peoperty of the device. The transfer properties of GaN based MOSHEMT for biosensor detection have been examined in this work by using TCAD simulation tool from Silvaco.

2.7.1 SOFTWARE FRAMEWORK

In general various technique are used in order to model the framework using Silvaco TCAD. Throughout this study, we will concentrate on ATLAS, a 2D-3D computer solvers which always measures the characteristics of power electronics under defined bias conditions. The system structure including both the mesh and doping profiles have been inserted into the ATLAS. One way to build project is to begin utilizing the ATHENA technique to show the means expected to get the ideal arrangement and a while later work this with a program named DEVEDIT. Models, bias conditions and computational methods for accomplishing electrical conduct behaviour are shown in ATLAS.

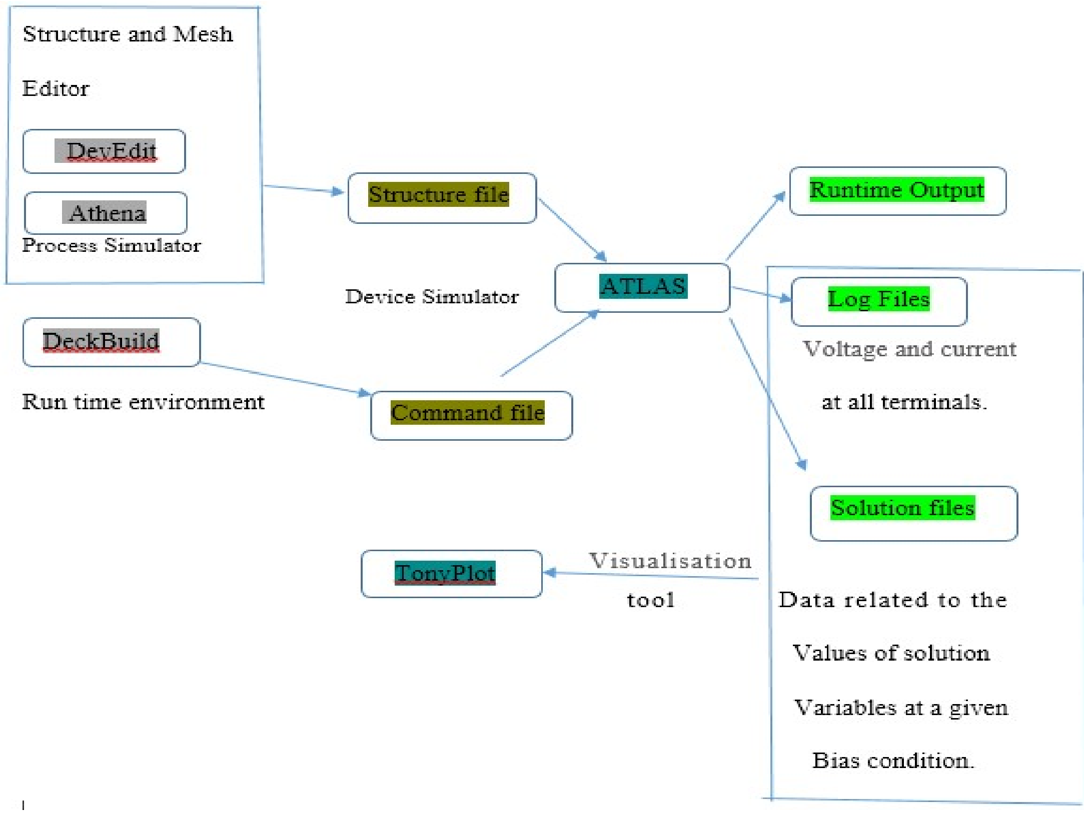


Figure 2.5: Inputs and outputs of ATLAS in Silvaco software [22]

Customary simulators, to handle the physical equations that control the activities of the carriers and their transport , the framework to be displayed is discretized into a matrix and furthermore the formulas are resolved through each hold level. The grid and its focuses are some of the time called the mesh and nodes separately. In the work the work was made inside DECKBUILD. As it is realized the most delicate space is the interface of AlGaN/GaN in HEMT structure. Thus, it is fundamental to appropriately refine the mesh at this area where the majority of the changes occurs in the physical properties.

After defining the mesh there are so many set of fundamental equations that are related to semiconductors such as Poisson', continuity and transport equations have to be solved using different kind of physical models.

2.8 CONCLUSION

AlGaN / GaN HEMTs give practical benefits in a variety of conditions, as a generation of two-dimensional electron gas (2DEG) at the interface of two semiconductor materials of different bandgap. It is capable of attaining 2DEG with high sheet carrier concentrations (n_s) around and higher than 1×10^{13} cm^{-2}, without additional doping, as appose to the other conventional semiconductors.

In addition, high electron mobility (μ) of more than 1000 cm^2 / V.s at room temperature and reduced scattering effect is due to fact that electrons from the wider bandgap material (i.e. AlGaN) are transported to the material with lower bandgap (i.e. GaN) to form 2DEG. GaN based HEMTs have proved their ability to fulfil the requirements to produce high gain of microwave power amplifiers as well as high reliability due to the ability of achieving high velocity of electron that is attained under features of high break down voltages and high electric field.

In order to obtain safe operation of HEMT normally-off structure (E-mode) is required. Moreover, GaN –based HEMT is considered to be the top selection for high power and high frequency applications.

CHAPTER 3

GALLIUM NITRIDE MOSHEMT DEVICE SIMULATION FOR BIOSENSOR APPLICATION

3.1 INTRODUCTION

Biosensors can distinguish the biochemical mixes, for example, antibodies, organic particles, proteins and so forth by chemical response. So they are broadly utilized in numerous applications, for example, observing of infections, food investigation, wrongdoing recognition and in addition for the investigation of biomolecules collaboration [23],[24] . Presently Gallium Nitride is developing as largely progressive matter because of empowering property. Gallium Nitride has 3.4eV forbidden gap and ability to work at temp greater than 300^0C as contrast with Si, that is utilized to create ordinary gadgets. Aside from this material have high breakdown field, excellent stability in the organic environment, low degree of harmfulness to the live cells, and the capacity to integrate easily [25],[3],[26],[27]. Nanoparticles of biomolecule could easily connect and produce charges at the interface and hence in return behaviour of channel varies. So high electron mobility transistor based gas sensors, ionic particle sensors glucose sensor, disease biomarker identifier, strain sensors and so forth have been developed [28].

Broad efforts were done by different specialists on FET based biosensors for discovery of different species. Schwarz et al. have revealed a novel HEMT sensor to identify DNA [29]. Khazanskaya. N et al. have announced field impact semiconductor biosensor for ammonium [30]. K.H.Chen et al. utilized Au-gated HEMTs to identify c-erbB-2 [31]. N. kannan detailed GaN HEMT to identify biomarkers [32]. G.H. Chung et al. shown HEMT gas sensor at extraordinary situations [33]. As of late, Giwan Seo et al. announced a FET based sensor that utilize graphene sheet for distinguishing SARS-CoV-2 in clinical examples [34].

Here Simulation of GaN MOSHEMT for different species like ChOx, protein, streptavidin and Uricase has been illustrated. GaN MOSHEMT gadgets have excellent parameters under both low and high cross over fields [35],[36]. Modulation of permittivity is utilized for simulation of structure procedure.

3.2 DEVICE STRUCTURE

Fig 3.1(a) shows the diagram of GaN MOSHEMT. This device has:

- GaN buffer layer thickness: 1µm
- AlN thickness: 1nm
- Oxide thickness: 20nm
- AlGaN barrier layer thickness: 18nm
- Length of gate: 5µm
- Source and gate gape: 1µm and gate and drain gap:2µm.
- Device length and width : 9 µm & 100 µm.
- Gate contact is Schottky and source & drain contact is ohmic
- Initially SiO_2 is filled in the area below the cavity as shown in figure 3.1(b) cavities of 1.5 µm are considered below gate.

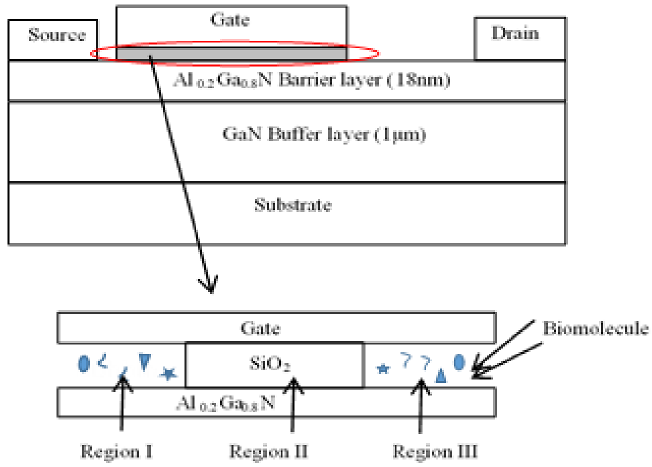


Fig 3.1(a) Diagram of GaN MOSHEMT with cavity 3.1(b) Region underneath the electrode [39]

Table 3.I Biomolecules dielectric constant [39]

Species	Dielectric Constant
ChOx	3.50
Protein	2.50
Streptavidin	2.10
Uricase	1.50

3.3 DEVICE CURRENT MODEL

Simulation software used is TCAD Silvaco. As shown in Figure 3.1(b) species are added in the two side cavity region. Cap. of different regions is given by equation (3.1) & (3.2)

$$C_{SiO_2} = \frac{\varepsilon_{SiO_2}}{t_{ox}} \quad (3.1)$$

$$C_{Bio} = \frac{2\varepsilon_{Bio}}{t_{Bio}} \qquad (3.2)$$

Where, ε_{SiO2}, ε_{Bio}, t_{ox} and t_{Bio} are dielectric constant and thickness of SiO_2 and species correspondingly. Cap. of three regions is given by equation (3.3)

$$C_{Total} = C_{SiO_2} + C_{Bio} \qquad (3.3)$$

MOSHEMT device capacitance is given by equation (4.4)

$$\frac{1}{C_{MOSHEMT}} = \frac{1}{C_{HEMT}} + \frac{1}{C_{total}} \qquad (3.4)$$

Where, C_{HEMT} is the capacitance of the Device [37]. The equation (3.5) gives I_d for the device Ref. [38],

$$I_D = -q\mu\frac{W_G}{L_G}\left(\frac{2}{5}\gamma_0\left(n_{drain}^{\frac{5}{3}} - n_{source}^{\frac{5}{3}}\right) + V_{th}(n_{drain} - n_{source}) + \frac{q}{2C_{MOSHEMT}}\left(n_{drain}^2 - n_{source}^2\right)\right) \qquad (3.5)$$

γo =2.12x10^{-12} V.m$^{4/3}$ is constant. n_{source} is carrier conc. at source and n_{drain} is carrier conc. at drain. W_G is width of gate and L_G is length of gate. μ is the low field mobility.

3.4 RESULT AND DISCUSSION

Fig 3.2 gives the I_d-V_d feature of the GaN based MOSHEMT without biomolecule. The centre current models utilized in can replicate the device attributes quite well. Oneself warming impacts are not considered in the simulation.

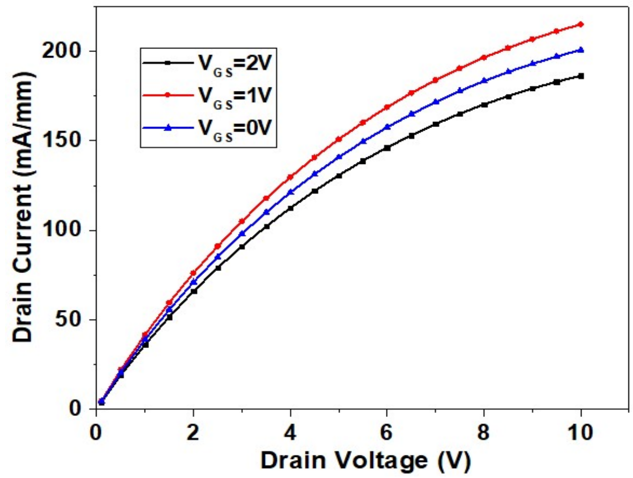
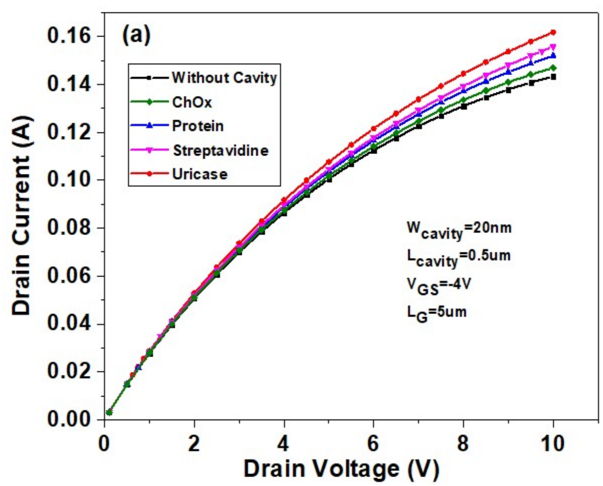


Figure 3.2 I_d vs V_d curve without species at various V_g [39]

Cavity of dimension Wcavity=20 µm and Lcavity= 1.5 µm on each side of oxide layer when species are added. In the channel carrier concentration is increased which causes drain current to rise due to adding species in cavity. for Uricase greatest rise of 18mA in current is found. g_d Vs Vd plot is shown in Figure 3.3. Parallely the change in g_d is also observed.



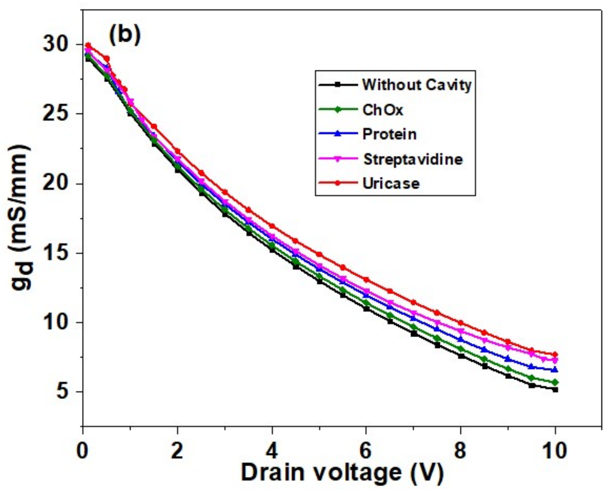


Figure 3.3 (a) Id vs Vd characteristics (b) g_d vs V_d of MOSHEMT with dissimilar biomolecules species [39]

Figure 3.4 (a-e) shows the electron concentration contour. 4.4(a) shows the no change of concentration without biomolecule. In the region below the cavity more charges are generated when species are added. The dielectric constant of the species decides the amount of charges produced is seen from figure 4.4 (b-e). The rise of drain current is inferred from the fact that maximum charges are introduce due to lowest dielectric constant of Uricase shown in Figure 3.4(a).

As biomolecule is presented, charges get prompted in the portion below the cavity. Amount of carriers produced relies upon the dielectric constant of the species can be seen from figure 3.4 (b-e). Because in case of Uricase in the channel due to low dielectric constant in maximum charges are produced.

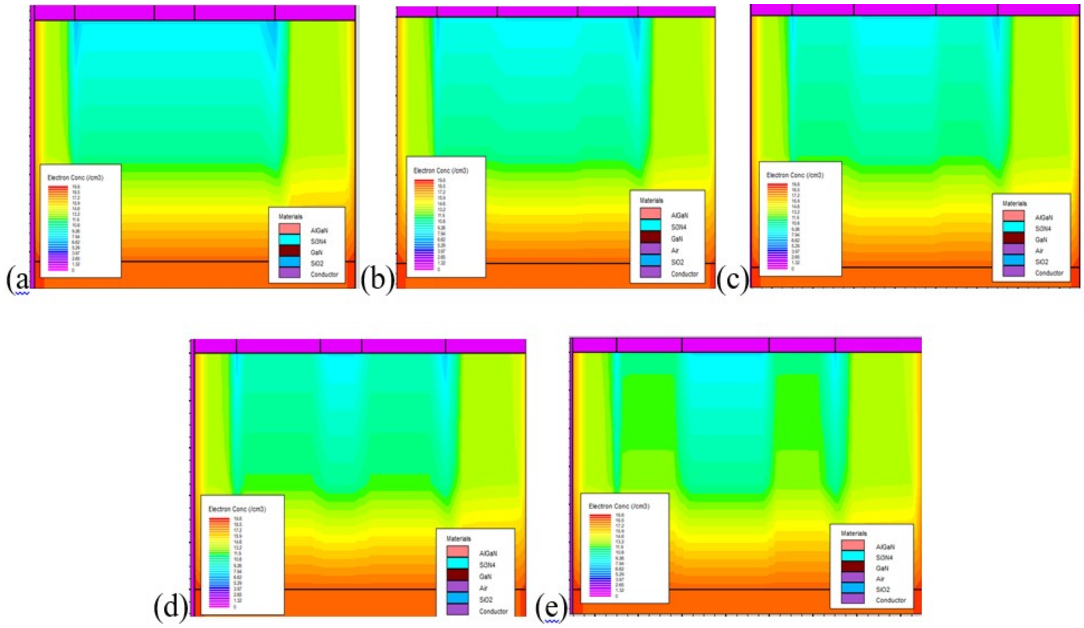


Figure 3.4 Electron concentration contour (a) w/o biomolecule species (b) with ChOx (c) with Protein (d) with Streptavid (e) With Uricase. [39]

Plot of Id vs Vg and g_{m} vs vd are given in Fig 3.5. A Positive change in V_{th} is observed on addition of species. As improved creation of Two Dimensional Electron gas takes place at lower V_g in the channel. Without species the threshold voltage was -12v and that shifted to -5.5V at V_{DS}=1V with Uricase. In the same way change in g_m is also found shown in Figure 3.5. The highest g_m is 2mA/mm with no biomolecule and that changes for different species as shown in figure below.

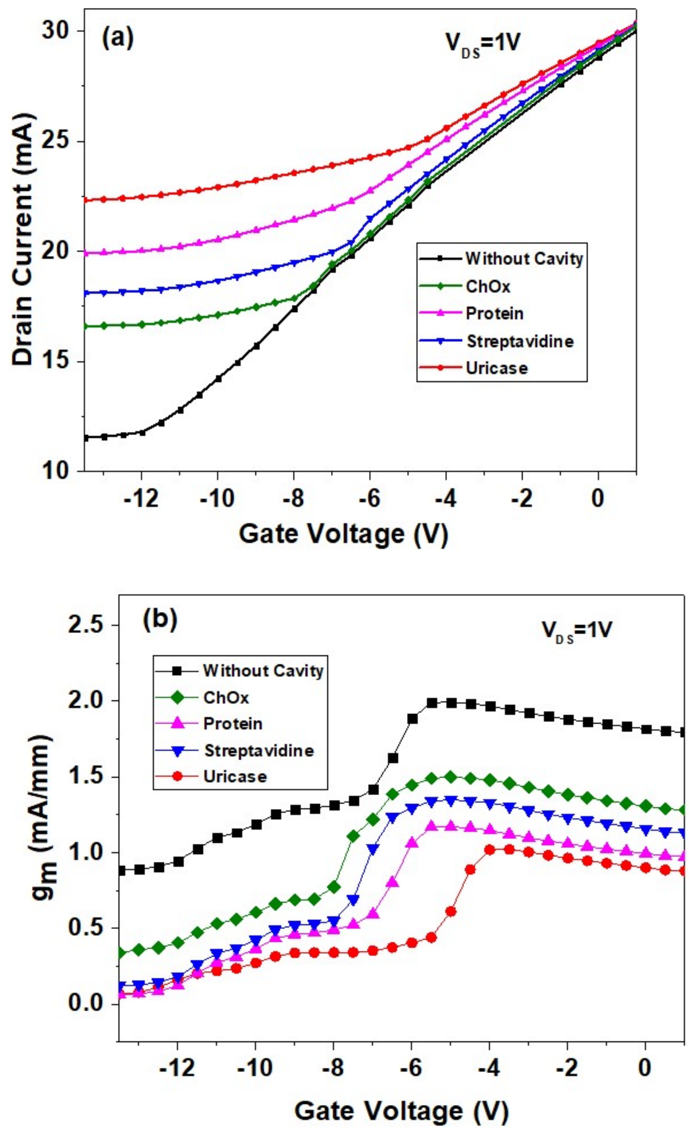


Figure 3.5 (a) Id vs Vg plot (b) g_m vs V_d with biomolecules added in the cavity [39]

Figure 3.6 shows sensitivity analysis. as cavity length is increased to 2µm from 1 µm sensitivity raises by 0.141. Because when cavity length is raised, the neutral species present for reaction at the interface increases. So the area of contact i.e. cavity dimension should be more for highest sensitivity.

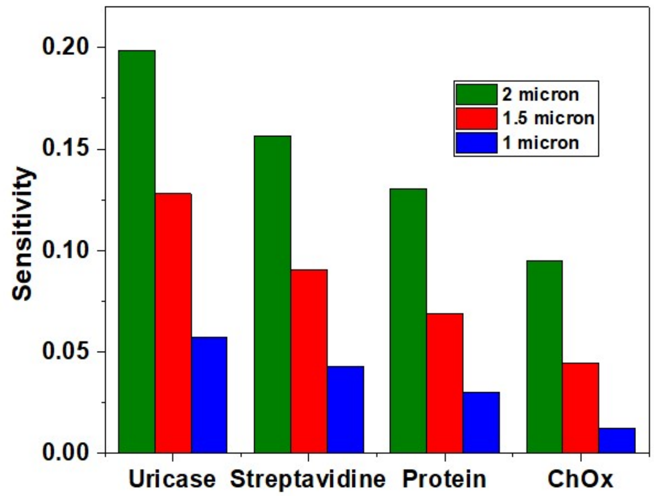


Figure 3.6 Sensitivity analysis [39]

Figure 3.7 gives chemical potential along channel length on addition of species in the cavity. As potential developed is different in the channel region because of permittivity difference of different species present. 10% change in Uricase and 3% change in ChOx is found.

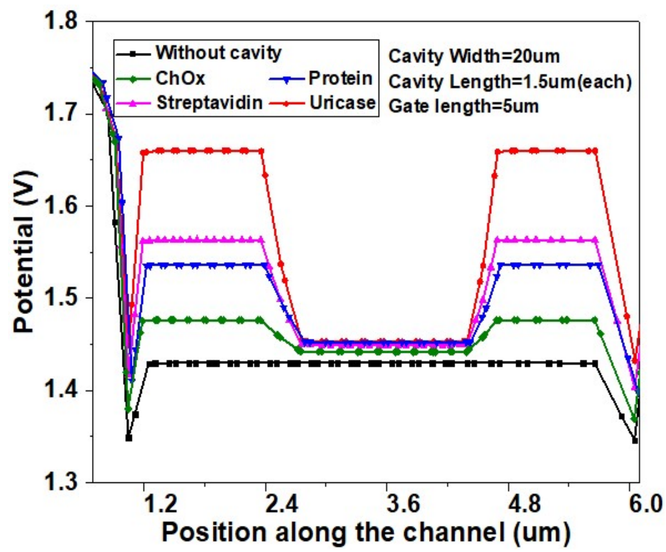


Figure 3.7 Potential Within the Channel potential for species [39]

3.6 CONCLUSION

In this work, GaN MOSHEMT performance is studied on adding neutral biomolecules. output & transfer charaterictics, gm and gd changes with biomolecule presence. By adding biomolecule visible change in electron concentration is observed.. Due to increase of cavity length, four time rise of sensitivity is found. maximum incease of 10% in Chemical potential is observed for Uricase. Accordingly, it may be inferred that the simulated device gives notable change in performance and help to utilized for biomolecule detecting application efficiently.

CHAPTER 4

FUTURE WORK

In 1962 the historical backdrop of biosensors started with the innovation of chemical terminals by L. C. Clark. From that point forward, biosensors have made some amazing progress with synchronous commitments in different fields, for example, science, science, material science, gadgets and material science. With the development in science and innovation, it is reality to build more delicate and trustworthy biosensors. But requirement of savvy, complex, solid, hearty biosensors that can be utilized to distinguish numerous sorts of species stays a scientific test to be determined.

Contrasted with develop Silicon technology, AlGaN/GaN gadgets are at present at the prelude phase of its development and manufacture. Carrier spillage, traps and surface deformities are some factors that slows down the commercialization of elite wide bandgap GaN devices. But since of huge possibility, GaN may be the sensor of things to come .

Accordingly, a material science based logical model to anticipate the device conduct is of most extreme significance. Counting the impacts of following problems would help comprehend the device conduct more precisely:

- higher gate voltage to Parasitic parallel conduction
- effect of temperature on drain current and source resistances Leak currents
- Trapping effects

In our work, the output and transfer characteristics of device are studied. Model additionally added to foresee responses of a sensor for various types of species. The biosensor performance can be enhanced by:

- The effect of interferers to be included

- Use of other charged biomolecules to approve the model
- Lab-on-a-chip device development

APPENDICES

APPENDIX 1:

LIST OF PUBLICATIONS (ACCEPTED)

RAPID DETECTION OF BIOMOLECULES IN A DIELECTRIC MODULATED GAN MOSHEMT

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Abstract: Biosensors are the devices that find application in almost every field nowadays. In this paper, GaN MOSHEMT based biosensor is proposed for detection of biomolecules such as ChOx, protein, streptavidin and Uricase. The effect of biomolecule species on the performance parameters of the device has been studied. It has been observed that there is a significant increase in the drain current and g_d is observed with the addition of biomolecule in the nanocavity. The electron concentration contour are studied that shows the rise of carrier concentration with biomolecule. Maximum positive shift is observed in threshold voltage for Uricase due to lowest dielectric constant. Similarly, the change in transconductance is also obtained with biomolecules. The effect of cavity dimensions on sensitivity is also studied. The maximum increase of 10% in channel potential is noted due biomolecule presence in the cavity. This device has shown good sensing and can be used for biosensing applications efficiently in addition to the high power performance of MOSHEMTs.

Keywords—Biosensor, Biomolecule, HEMT, 2DEG, MOSHEMT.

Introduction

The recent COVID-19 pandemic has again brought in forefront the importance of electronic biosensors in detection of biomolecules & biological warfare agents. The electronic biosensors may find applications in real time monitoring of airborne biomolecules in transport systems like aircrafts & metro rail and centrally air conditioned buildings like schools, hospitals, etc. Therefore, the need of the hour is to design & develop fast and accurate biosensors.

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