COMPARATIVE STUDY OF InAlN AND InGaN SUPER BACK BARRIER LAYER ON P-GATE/AlGaN/GaN HEMT

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CANDIDATE'S DECLARATION

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ABSTRACT

Attractive properties of GaN allows it to be used in power electronic devices in various space and defence 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. The common AlGaN/GaN HEMTS are normally-on due to natural induction of high density Electron gas (2DEG) in the channel. As compare to these devices normally-off devices have advantages of positive and stable threshold voltage, high breakdown field and low on-resistance. In this report, we have done comparative study of InAlN and InGaN back barrier with conventional GaN buffer in p-GaN/AlGaN/GaN HEMT using Silvaco TCAD software. Carrier spilling in the channel is reduced which resulted in better 2DEG confinement in the channel. Maximum electric field in the channel is 1.17 MV/cm that is one order higher than conventional GaN Buffer. Transfer characteristics and I_{ON}/I_{OFF} ratio are improved with back barrier. Higher I_{ON}/I_{OFF} ratio in InAlN back barrier makes it to be more power efficient and reliable p-GaN/AlGaN/GaN device than InGaN back barrier.

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TABLE OF CONTENTS

Candidate's Declaration i

Certificate ii

Abstract iii

Acknowledgement iv

Table of Contents v

List of table vii

List of Figures viii

List of Symbols & abbreviations ix

CHAPTER 1- INTRODUCTION

1.1 OVERVIEW…………………………………………………………………… 1

1.2 RESEARCH OBJECTIVES……………………………………………………. 3

1.3 THE STRUCTURE OF THESIS ………...……………………………………...3

CHAPTER 2- RELATED WORK AND RESEARCH METHDOLOGY

2.1 INTRODUCTION……………………………………………………………..4

2.2 HILIGHTS OF THE HISTRY OF GALLIUM NITRIDE (GaN)……...………...4

2.3 DESIRED SUBSTRATEES FOR HETEROEPITAXIAL GROWTH OF GaN ………………………………………………………………...5

2.4 WHY GaN? …………………………………………………………………...6

2.4.1 Traits and drawbacks of GaN …………………………………………………6

2.4.2 GaN devices compared to current alternative………………………………… 8

2.4.3 GaN applications……………………………………………………………....9

2.4.3.1 Optical application ……………………………………….…..………………10

2.4.3.2 Electronic applications…………………………………………………..11

2.4.4 Power Devices……………………………………………………………..11

2.5 COST AND MARKET…………………………………………………...12

2.6 AlGaN/GaN HIGH ELECTRON MOVILITY TRANSISTROS (HEMTs)…...13

2.6.1 Basic HEMT structure…………………………………………………...13
2.6.2 Effect of spontaneous and piezoelectric polarization ……………….……15
2.6.3 Bonded charges ……………………………………………………………16
2.6.4 Formation of 2DEG…………………………………………………...17
2.6.5 Trapping phenomena …………………………………………………....18
2.6.6 Operation theory of HEMT ….……………………………………………18
2.7 NORMALLY OFF HEMT………………………………………………...19
2.7.1P-GaN Gate HEMT ……………………………………………………...19

2.8 METHODOLOGY: TCAD SIMULATION……………………………………20

2.8.1 SOFTWARE FRAMEWORK ………………………………………………..20

2.9 CONCLUSION……………………………………………………………....22

CHAPTER 3 P-GATE/AlGaN/GaN- HEMT WITH DIFFRENT BACK BARRIER LAYERS (BBL)

3.1 INTRODUCTION …………………………………………………….….23

3.2 DEVICE STRUCTURE…………………………………………………..24

3.3 RESULTS AND DISCUSSION……………………………………………26

3.4 CONCLUSION……………………………………………….………29

CHAPTER4- FUTURE WORK..30

APPENDICES……………………………………………………………………32

REFRENCES……………………………………………………………………..34

LIST OF TABLES

Table 2.1 some properties of semiconductors…………………………..………………8

LIST OF FIGURES

Fig.2.1Some of application fields of GaN based transistors……………………………10

Fig.2.2 Basic AlxGa1-x N/GaN HEM structure………………………………….....15

Fig.2.3 Band diagram of AlxGa1-X N/GaN heterojunction and the formation of 2DEG at the heterointerface……………………………………...…16

Fig.2.4 Negative and positive bond charge at heterointerface of AlGaN/GaN……..17

Fig.2.5 Schematic cross-section of the normally-off p-GaN gate HEMT using a p-GaN cap layer…………………………………………………………...20

Fig.2.6 Inputs and outputs of ATLAS in Silvaco software…………………………21

Fig.3.1 Schematic cross-section of p-GaN/AlGaN/GaN HEMT…………………....25

Fig. 3.2 Conduction band profile of HEMT Structure……………………………..…26

Fig.3.3 Electron distribution at interface of AlGaN/GaN HEMT structure ……….....27

Fig.3.4Simulated electric field distribution of (a)InAlN BB (b) InGaN BB (c)GaN Buffer HEMT structures at V_{GS}=0V…………………………………………...28

Fig. 3.5 Shows the output characteristics of AlGaN/GaN HEMTS with/without BB layer…………………………………………………………….……………28

Fig.3.6 Transfer characteristics of the p-Gate/AlGaN/GaN HEMT device with/ without BB layer Example of a figure caption……………………………………29

LIST OF ABBREVIATIONS/SYMBOLS

DC: Direct current

AC: Alternative current

CO_2 : Carbon dioxide

GaN: Gallium Nitride

AlGaN: Aluminium gallium nitride

HEMT: High-electron mobility transistor

GaAs: Gallium arsenide

HEFT: Hetero-structure- field effect Transistor

2DEG: Two Dimensional Electron Gas

HEMTs: High Electron Mobility Transistors

MISHEMT: Metal Insulator Semiconductor High Electron Mobility Transistor

LPCVD: low pressure chemical vapour deposition

Si: Silicon

SiC: Silicon carbide

RF: Radio frequency

FET: Field-effect transistor

GHz: Giga hertz

LED: Light emitting diode

EV: Electrical vehicle

TCAD: Technology Computer Aided Design

NH_3: Ammonia

MOSHEMT: Metal oxide semiconductor high electron mobility transistor

HVPE: Hydride vapour phase epitaxy

MOCVD: Metal organic chemical vapour deposition

CW: continuous wave

WBG: Wide bandgap

E_g: Bandgap energy

E_C: Breakdown field

InP: Indium phosphide

InGaP: Indium gallium phosphide

LDMOS: Laterally diffused metal oxide semiconductor

HBT: Heterojunction bipolar transistor

MESFET: Metal-semiconductor field effect transistor

LDs: Light diodes

DVD: Digital versatile disc

MEMS: Micro-Electro-Mechanical Systems

IGBT: Insulated- gate bipolar transistor

SI: Semi-insulating

MBE: Molecular beam epitaxy

Al_2O_3: Aluminium oxide

AlN: Aluminium nitride

V_T: Threshold voltage

D-mode: Depletion mode

E-mode: Enhancement mode

P_{sp}: Spontaneous polarization

P_{pp}: Piezoelectric polarization

MMICs: Monolithic microwave integrated circuits

RF: Radio frequency

CHAPTER 1

INTRODUCTION

1.1OVERVIEW

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 that it can operate at much higher temperature, large critical electric field. 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 ideal power devices at microwave frequencies power amplifiers 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 built on an extraneous 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 large band gap as well as the accessibility of heterostructure, in which high voltage, high current and low on-resistance can indeed be concurrently accomplished, and way that results in such an improved high frequency and high power operation [3].

GaN based 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.

1.2 RESEARCH OBJECTIVES

This work describes AlGaN/GaN High Electron Mobility Transistor structures with different back barrier layers **.**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, specific objective has been accomplished that can be described as:

- **Comparative study of InAlN and InGaN back barrier with conventional GaN buffer in p-GaN/AlGaN/GaN HEMT:** The back barrier is introduced to the structure to reduce the carrier spilling in the channel and enhance the electron concentration which result in better two dimensional electron gas (2DEG) confinement in the channel. Also to improve the transfer characteristic and I_{ON}/I_{OFF} ratio.

1.3 THE STRUCTURE OF THESIS

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 related work that discusses different topics of AlGaN /GaN Based HEMT to help in understanding the work according to the previous researches. In addition to which the research methodology and software used for simulation.

Chapter 3 that discusses the use of different back barrier layers for normally off p-GaN HEMT device followed by the conclusion of the work.

Chapter 4 show the future scope of the work done.

CHAPTER 2

RELATED WORK AND RESEARCH METHODOLOGY

2.1 INTRODUCTION:

Electronic devices have genuinely intermingled with our lives, extending our capacities and potential. In this region growth and creativity will shape mankind's future. This field is identified as Electronic Power. Nowadays almost all the mobile devices use DC/DC converters in order to sustain a steady power output irrespective of the battery supply voltage. Improving the performance of electronic power devices remains crucial to reduce losses of switching and thus reducing CO_2 emissions.

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 HIGHLIGHTS OF 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 endeavoured because of absence of GaN asset Later on, Maruska and Tietjen tried for first time to grow centimetre--sized gallium nitride layers on sapphire substrate using hydride vapour 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 fabrication technology represent to significant perspectives that should be handled to re-establish the incredible promise that GaN-based gadgets hold.

2.3 DESIRED SUBSTRATEES FOR HETEROEPITAXIAL GROWTH OF GaN

The growth of GaN based HEMT strongly depends on the choice of the substrate. So, different types of substrate materials are used for GaN structure.

Sapphire: it is the most common substrate for GaN epi-layer due to its semiconducting property, the ability of enduring high temperature while the process of growth. Moreover it is worth more than its cost. On the contrary, it has many shortcomings such as:

- Poor thermal conductivity (about 0.47 W/cm K at 300 K)
- The lattice mismatch is high (about 13%)
- Thermal expansion coefficient is large

That make this substrate bad option for GaN devices for applications of high power. Despite this, GaN based HEFT using this particular substrate produces ten times higher power than that can be obtained by GaAs.

SiC substrate: the good thermal property (from 3.7 to 4.5W/cmK at 300K), low quantity of lattice constant and thermal expansion 3.4%and 25% respectively make it preferable material to grow GaN layers on. In addition, the two dimensional electron density in the heterointerface is much better as compared to sapphire. As a result SiC is superior substrate for high voltage –frequency applications.

Silicon: one of the advantages of growing GaN epi-layers on Si substrate is that its ability of integration with this substrate. Moreover, the abundance of the material at cheap cost, and the possibility of making large diameters of substrate allow it to desirable candidates for hetero-epitaxial growth of GaN even though the high lattice constant mismatch of about 17%.

2.4 WHY GaN?

2.4.1 Traits and drawbacks of GaN

We will discuss the material properties of GaN with conventional semiconductors, for example, Si, GaAs, InP, and 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 manufacturing of devices, having ability to operate at higher frequencies with elevated 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 comparatively low mobility however quite elevated saturation velocity and can also be easily supported at high electric fields.

On account of 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, 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_SiC	GaN
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

2.4.2 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 appeal. Expensive 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 transistors, 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 impedance 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.

2.4.3 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

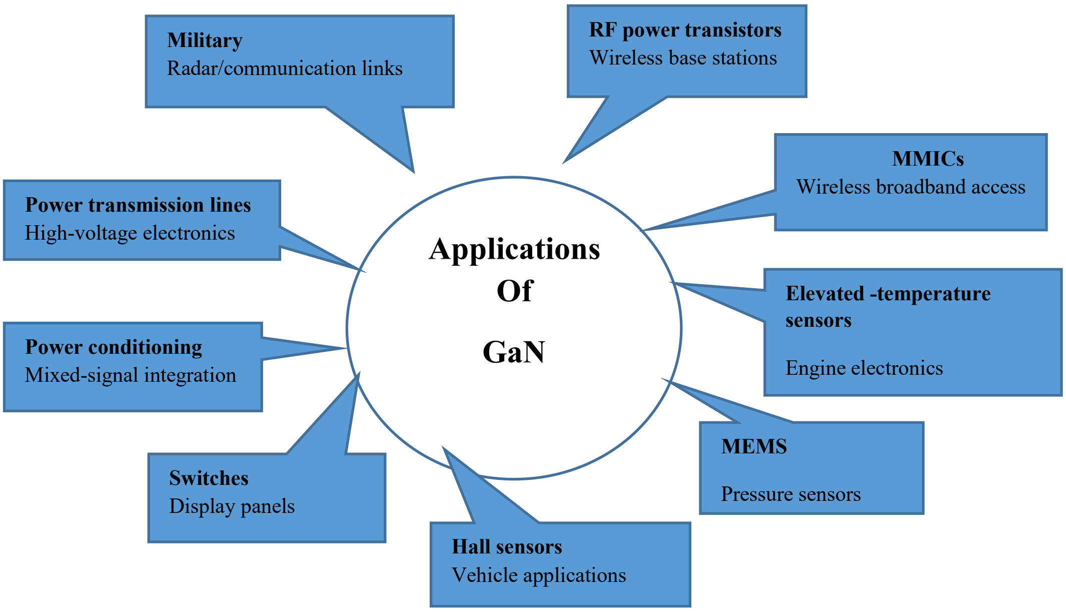

Fig.2.1 some of application fields of GaN based transistors [3]

2.4.3.1 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.

2.4.3.2 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 (1.5×10^7cm / 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 benefit 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.

2.4.4 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 function.

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,

Hetero-structure 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 heterojunction in a so called two-dimensional electron 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 hetero-structures using low pressure metalorganic chemical vapour deposition[18].

High Electron Mobility Transistors (HEMTs) devices are basically normally on based on AlGaN/GaN hetero-structure. 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].

2.5 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.

2.6AlGaN/GaN HIGH ELECTRON MOBILITY 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 to adjust 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 millimetre 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 .

2.6.1 Basic HEMT structure

The GaN High Electron Mobility Transistor 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 hetero-interfaces require incredibly sheet charge densities to be high in GaN 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 vapour deposition (MOCVD) have been applied to grow epitaxial material . The different layers that are being grown for both structures 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 aluminium 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 neighbouring 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.

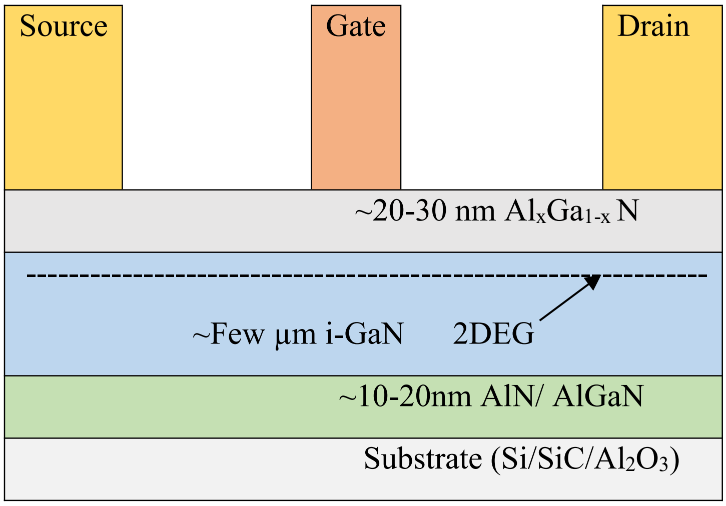

Fig.2.2 basic $Al_xGa_{1-x}N$/GaN HEMT structure [12]

2.6.2 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 Equation's polarization vectors.

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

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.

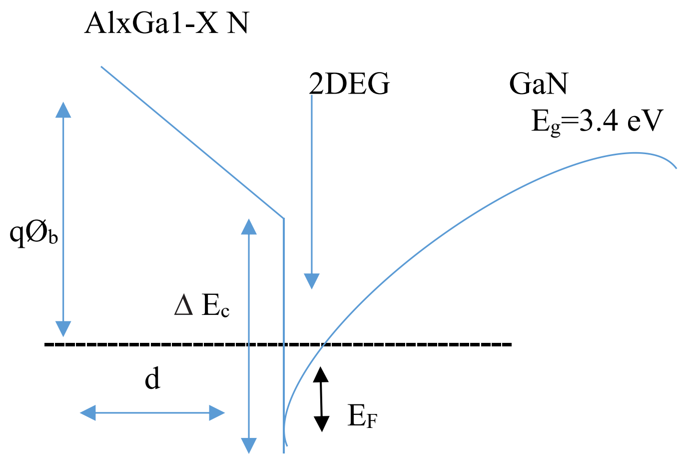

Fig.2.3 Band diagram of AlxGa1-X N/GaN heterojunction and the formation of 2DEG at the heterointerface [20]

As within a two-dimensional (2D) quantum well the electrons are well constrained and there is reduction in bulk scattering effects that 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].

2.6.3 Bonded charges

This negative or positive charge is formed at the heterointerface when two disaccorded layers are built on each other with different polarization domains. This charge may be either positive or negative based on the deviation of the field of polarization. The bonded chare is obtained using the equation below:

$$\rho_f = -\nabla.\mathbf{P} \tag{2.2}$$

Where ρ_f is the density of the charge, **P** is the field of polarization.

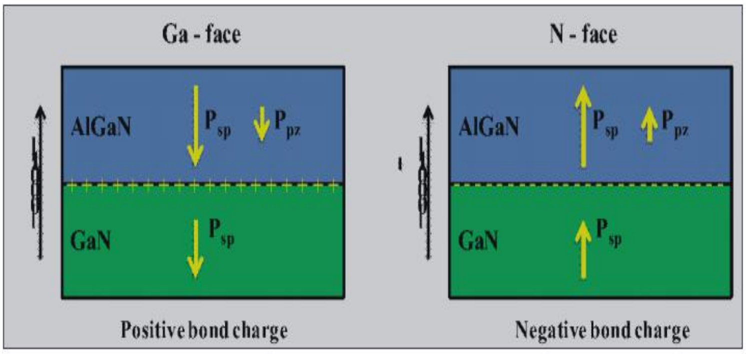

Fig.2.4 negative and positive bond charge at the heterointerface of AlGaN/GaN [21]

2.6.4 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 of 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

2.6.5Trapping phenomena

The researches have proved that AlGaN/GaN based HEMTs are outstanding devices to deliver high power and high frequency. Howsoever, HEMT construct languish from trapping of the electrons inside the layers and at the surface of the semiconductor. The effect of trapping is caused due to many concepts such as the concentration of the carriers inside the channel, the scattering of electrons due to the temperature, as well as the applied electrical field. This effect leads to lower the output current as a result, the expected microwave power will be dramatically lower than DC standard condition.

2.6.6 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):

$$I_D = q\, n_s\, \upsilon_{eff}\, W_G \qquad (2.3)$$

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:

$$I_D = \varepsilon_{AlGaN} \frac{V_{sat}\, W \ (V_G - V_T)}{(d_{AlGaN} + \Delta d)} \qquad (2.4)$$

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.

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} \qquad (2.5)$$

Carriers in the GaN buffer layer experience a decreased mobility and reduced velocity. The valuable carrier velocity diminishes and tends to cause g_m to diminish with high $V_{G.}$

2.7 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].

2.7.1 P-GaN Gate HEMT

In p-GaN gate HFETs, metal gate is replaced by p-type doped GaN (Figure 5). 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.

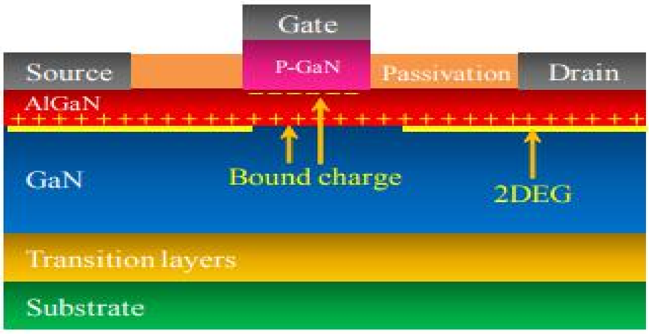

Fig.2.5 Cross-sectional view of the normally-off HEMT [21]

2.8 METHODOLOGY: TCAD SIMULATION

Technology Computer Aided Design (TCAD) tools are modelling 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 property 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.

2.8.1 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. The important 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.

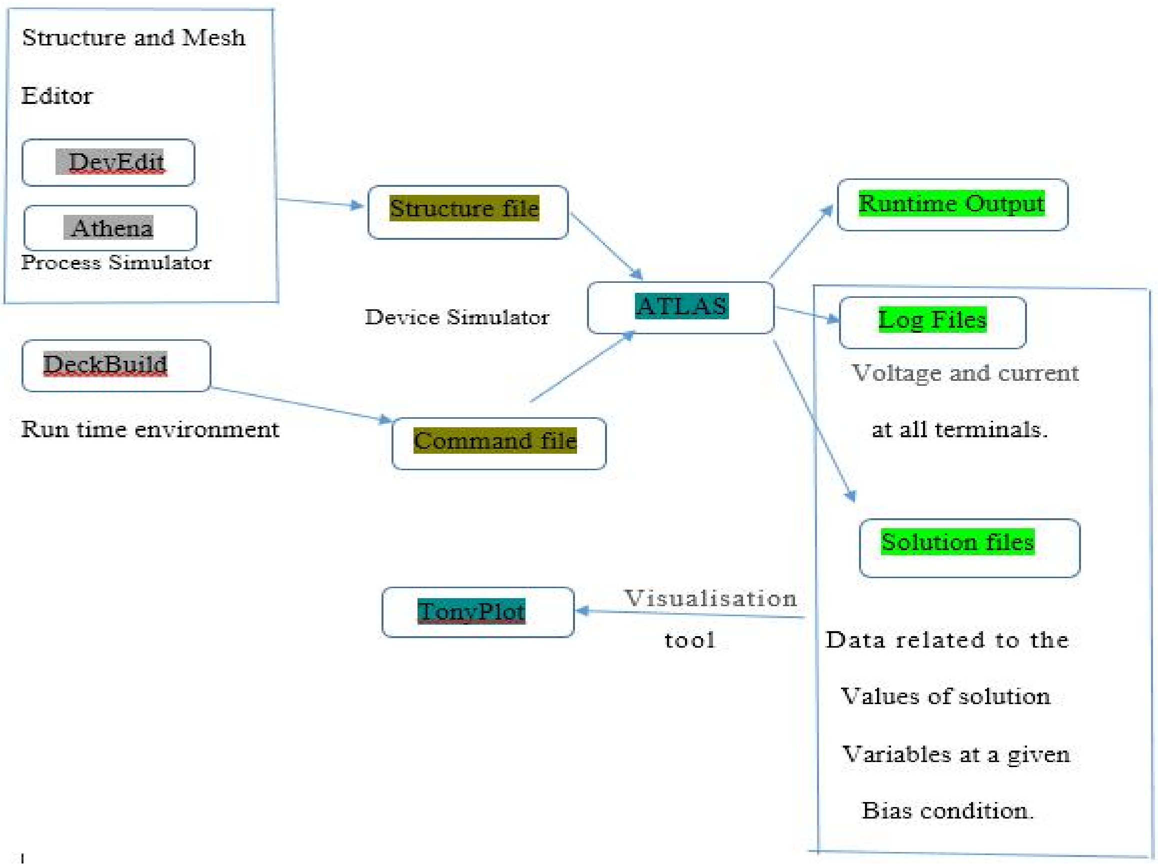

Fig.2.6 Inputs and outputs of ATLAS in Silvaco software [22]

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.

2.9 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

P-GATE/AlGaN/GaN- HEMT WITH DIFFRENT BACK BARRIER LAYERS (BBL)

3.1 INTRODUCTION

Gallium Nitride (GaN) is emerging as one of the most promising material due to very promising properties. 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 to fabricate conventional devices. Apart from this they have high electric field, high mobility, high saturation velocity, and polarization nature [23], [3].

The common AlGaN/GaN HEMTS are normally-on due to natural induction of high density Electron gas (2DEG) in the channel. As compare to these devices normally-off devices have advantages of positive and stable threshold voltage, high breakdown field and low on-resistance [24]. GaN based high electron mobility transistors (HEMTs) provides excellent performance in high frequency and high power electronics [24]. The reliability of the device is limited by some factors like scattering of carriers into buffer layer, which results in weakening the carrier concentration in channel and reliability [25-29].To solve this problem, introducing a barrier (known as back barrier) region between channel and the buffer layer can reduce spilling of carriers and enhance the carrier confinement in the channel.

Several researchers reported the use of different back barrier (BB) layers. For a 65-nm gate length Lee D.S. reported the current gain cut-off frequency (f_T) of a transistor with an AlGaN back barrier is 210 GHz, which is higher than that of the standard device with the same gate length [30]. T.Palacio et.al. Reported the use of InGaN BB layer up to f_T of 128GHz, f_{max} of 168GHzand improved linearity performance [31]. Y.L.Fang et.al. Reported use of AlN super back barrier layer by totally replacing conventional GaN buffer and reported buffer leakage current of 10^{-5}A/mm, which is two order of magnitude lower than GaN Buffer [32]. X.G.He et.al investigated the use of InAlN with 0.62-0.67 Al composition to improve carrier confinement and eliminate parasitic channel [33].In this paper, thick GaN buffer is completely replaced by InAlN and InGaN BB layers for the AlGaN/GaN HEMT to improve the 2DEG confinement.

Here, aim is to do comparative study between structures with InAlN BB, InGaN BB and GaN Buffer for AlGaN/GaN normally-off HEMT. From different approaches, p-GaN gate is preferred due to excellent performance parameters [24]. The three structures are simulated using Silvaco TCAD software. Conduction band energy and electron concentration are investigated. The electric field distribution, output characteristics, transfer characteristics and I_{ON}/I_{OFF} ratio are studied.

The chapter is organized as follows: Structure schematic is described in Section 3.2, Results and discussions in section 3.3, conclusion in section 3.4.

3.2 DEVICE STRUCTURE

Figure 3.1 highlights the schematic cross-section of three different configurations of p-GaN/AlGaN/GaN HEMT for comparison. Structure I with InAlN Back barrier (BB), Structure II with InGaN BB, and Structure III with GaN Buffer is taken as reference. Each structure has 150nm GaN channel, 1nm AlN spacer, 18nm $Al_{0.20}Ga_{0.80}N$ barrier, 70nm thick Mg doped p-GaN layer having concentration of ~$2x10^{19}cm^{-3}$, 1µm thick BB (structure I & II) and 1µm thick GaN buffer (structure III). The gate length (L_G) is 4µm, length between source and gate (L_{SG}) is 4µm and between gate and drain (L_{GD}) is 15µm. The structure is passivated by thin film of Si_3N_4 layer to reduce surface states effect. Contact taken at the gate terminal is Schottky and at source & drain is ohmic.

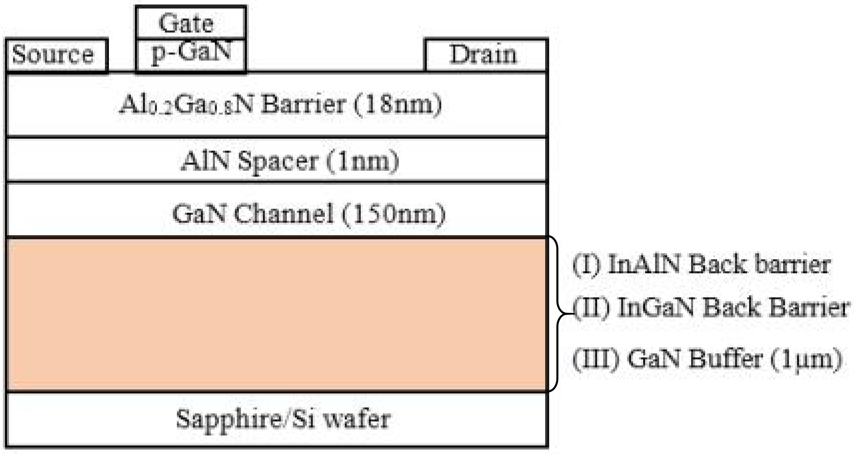

Fig. 3.1 Schematic cross-section of p-GaN/AlGaN/GaN HEMT

Two mobility models has been considered to define various scattering mechanisms. The low field mobility model can be given by

$$\frac{1}{\mu(N,T)} = a(\frac{N}{10^{17}})(\frac{T}{300})^{-\frac{3}{2}} X \ln[1+3(\frac{T}{300})^2 \left(\frac{N}{10^{17}}\right)^{-\frac{2}{3}} + b(\frac{T}{300})^{-\frac{3}{2}} + \frac{c}{\exp(\frac{1065}{T})-1}$$

$$\frac{1}{\mu(N,T)} = a(\frac{N}{10^{17}})(\frac{T}{300})^{-\frac{3}{2}} X \ln[1+3(\frac{T}{300})^2 \left(\frac{N}{10^{17}}\right)^{-\frac{2}{3}} + b(\frac{T}{300})^{-\frac{3}{2}} + \frac{c}{\exp(\frac{1065}{T})-1}$$

(3.1)

Where, a = $2.61\times10^{-4}/V\cdot s\cdot cm^{-2}$, b = $9.8\times10^{-4}/V\cdot cm^{-2}$ and c = $1.7\times10^{-2}/V\cdot s\cdot cm^{-2}$. μ (N, T) is the mobility as a function of doping and ambient temperature, N is the total doping concentration and T is the ambient temperature. The high field mobility model can be specified as follows:

$$\mu(E) = \frac{\mu(N,T)+v_{sat}\frac{E^{(N_1-1)}}{Ec^{N_1}}}{1+a_n(\frac{E}{Ec})^{N_2}+(\frac{E}{Ec})^{N_1}}$$ $$\mu(E) = \frac{\mu(N,T)+v_{sat}\frac{E^{(N_1-1)}}{Ec^{N_1}}}{1+a_n(\frac{E}{Ec})^{N_2}+(\frac{E}{Ec})^{N_1}}$$

(3.2)

Where μ (N, T) is the low field mobility, v_{sat} is the saturation velocity, E is the electric field. The values of E_c, a_n, N1, N2 are as per reference [34].

Polarization modelling is critical for GaN based devices. The total polarization-induced polarization charge density is defined as:

$$P_{total} = [P_{PE\ (bottom)} + P_{SP\ (bottom)}] - [P_{PE(top)} + P_{SP(top)}] \quad (3.3)$$

Here, P_{PE} and P_{SP} represent the piezoelectric polarization and spontaneous polarization, respectively. The difference in both polarizations will result in the formation of layer of charges at the interface.

3.3 RESULTS AND DISCUSSION

As mentioned earlier, all simulations are carried out in Silvaco TCAD software. Important physical models like drift diffusion transport, Fermi Dirac, low field mobility, high field mobility, Shockley-Read Hall (SRH) and polarization have been used during simulation. Following simulation parameters are taken for GaN; the band gap is 3.42eV, the saturation velocity for electron is $2x10^7$ cm/s, the spontaneous polarization is $-0.034C/m^2$, the Hall electron mobility is 1900 $cm^2/V.s$.

Figure 3.2 shows the conduction band profile of the three AlGaN/GaN HEMTs. It is observed that for structure I & II the conduction band at the end of channel is elevated as compared to structure III. As positive polarization in both InAlN and InGaN causes conduction band edge to raise, thereby resulting in better 2DEG confinement [3].

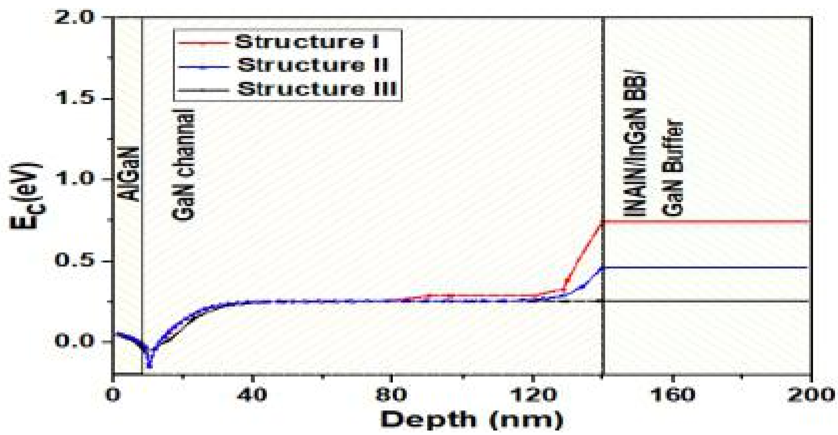

Fig. 3.2 Conduction band profile of HEMT Structure

The effect of confinement can be seen from simulated electron distribution profile shown in figure 3.3. Structure I & II indicate electron concentration of $2.15x10^{19}cm^{-3}$, $2.16x10^{19}$ cm^{-3} that is more than concentration of $8.7x10^{18}$ cm^{-3} in structure III. So higher concentration and narrow distribution of carriers in the channel region will give better control over the device performance parameters.

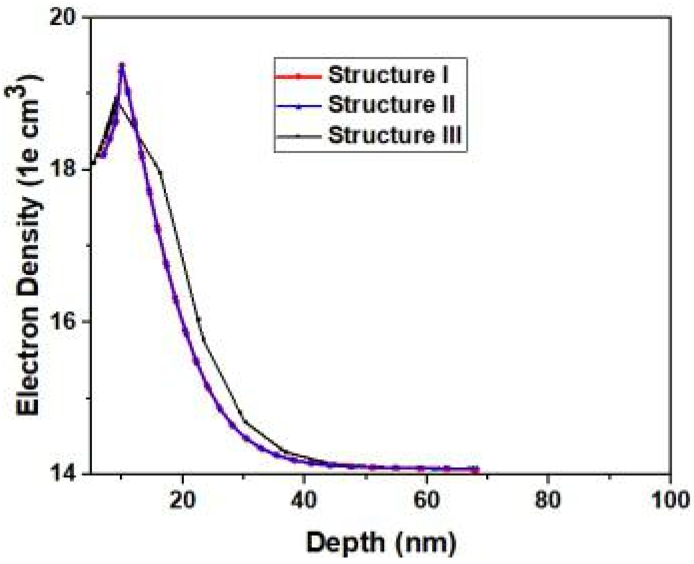

Fig. 3.3 Electron distribution at interface of AlGaN/GaN HEMT Structure

Figure 3.4 shows the electric field distribution contours at V_{GS}=0V. An electric field is generated due to inbuilt polarization and carrier distribution at channel interface. It is seen from our simulation results, the built in electric field in region 1 of structure I&II is more concentrated at AlGaN/GaN interface, as compared to structure III. The field strength is 1.17 MV/cm, approximately one order higher than structure III. Narrower and improved carrier distribution will result in more concentrated field in the channel, which is here observed in structure I&II. The reason for increase in current is better carrier confinement of 2DEG in the channel. Although drain current is comparable in both back barrier layers, that might be due to almost similar electron concentration [33].

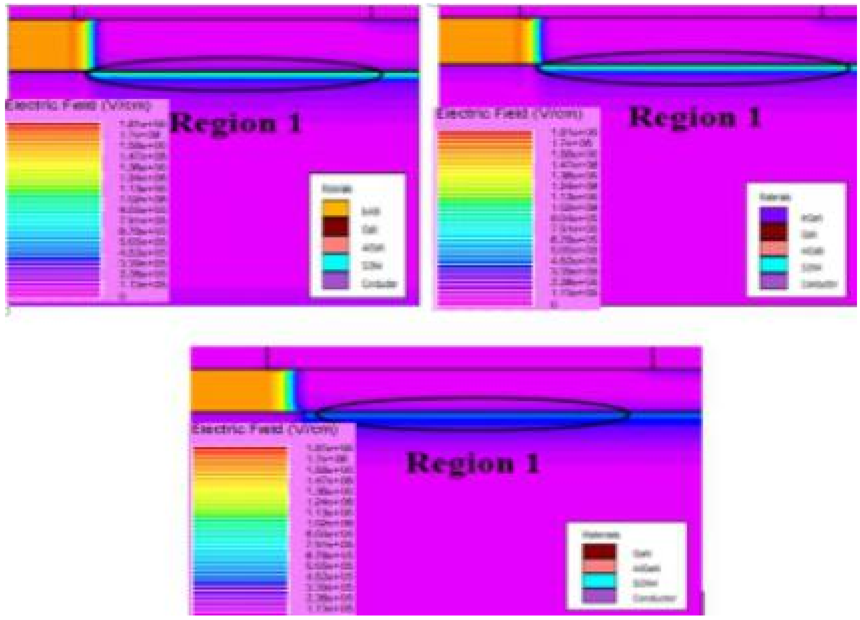

Fig. 3.4 Simulated electric field distribution of (a)InAlN BB (b) InGaN BB (c)GaN Buffer HEMT structures at V_{GS}=0V

The Figure 3.5 highlights the output characteristics of different structures under investigation. The maximum drain saturation current in structure I&II is ~332mA/mm at V_{GS}=6V, that is 35% higher than structure III. The reason for increase in current is better carrier confinement of 2DEG in the channel.

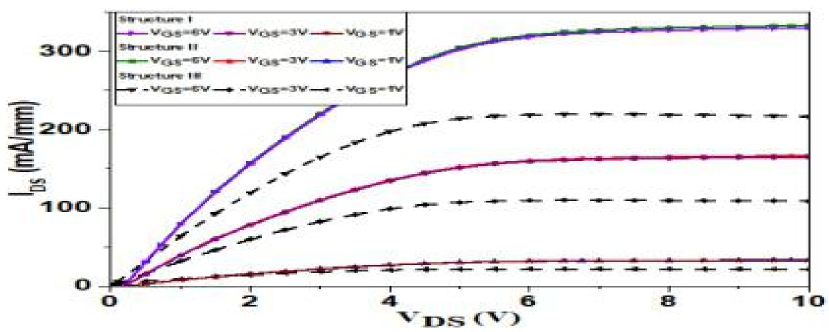

Fig. 3.5 shows the output characteristics of AlGaN/GaN HEMTS with/without BB layer.

The transfer characteristics is shown in figure 3.6(a). The threshold voltage is increased by ~5% with BB layer showing improved carrier concentration.

Figure 3.6(b) shows I_{ON}/I_{OFF} ratio of the three structures. I_{ON}/I_{OFF} ratio is very important parameter as is related switching applications. Structure I showing better ratio as compared to rest two structures. Although in structure I the pinch-off current is less than Structure II indicating improved pinch-off characteristics as well as I_{ON}/I_{OFF} ratio. Lower band gap of InGaN BB than GaN may cause parasitic electron channel [11] that is hard to pinch-off and result in higher leakage current in sub threshold region, poorer I_{ON}/I_{OFF} ratio in the structure II.

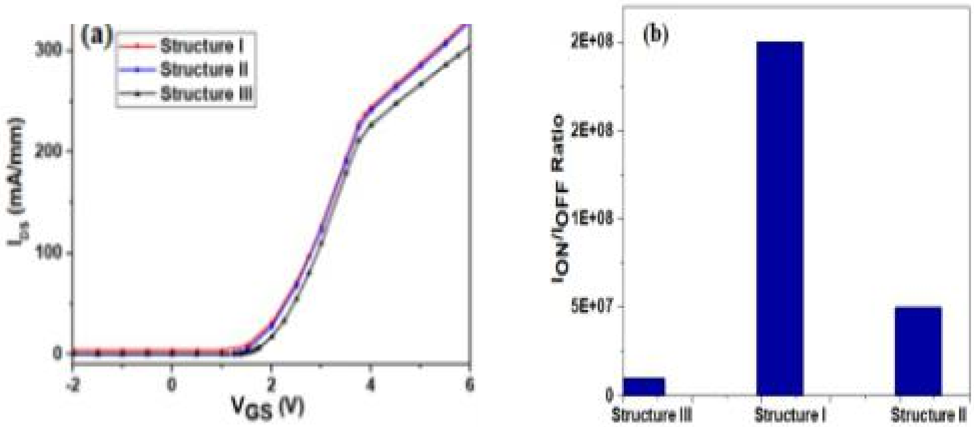

Fig. 3.6 (a) Transfer characteristics (b) Switching ratio of the p-Gate/AlGaN/GaN HEMT device with/ without BB layer Example of a figure caption.

3.4 CONCLUSION

In this paper, a comparative study of three different structures are carried out. Due to lifting of conduction band in structure I&II (i.e. InAlN and InGaN BB respectively), the scattering of carriers in the channel has reduced, which in turn resulted in improved 2DEG confinement. Maximum electric field in the channel is one order higher than conventional GaN Buffer. The drain current is increased in structure I&II due to enhanced electron concentration in the channel. AI_{ON}/I_{OFF} ratio is higher in both structures I&II as compare to structure III which leads to better power efficiency. So with the addition of both back barrier layers in p-GaN/AlGaN/GaN HEMT performance is improved as compared to conventional GaN buffer. Out of two back barrier layers, InGaN showed poorer I_{ON}/I_{OFF} ratio due to large leakage current in the sub threshold region. Therefore device with InGaN back barrier may lead to higher off state losses and reduced reliability as compared to InAlN Back barrier.

CHAPTER 4

FUTURE WORK

In HEMT devices the paramount layer in the structure is the barrier layer of the semi- insulating or aluminum gallium nitride that is usually grown on GaN buffer. In fact, the barrier of this layer puts limits on the electron confinement in the device channel in which the carriers tend to scatter in buffer layer that results in weakening the electron concentration and reliability that leads to decrease the output current of the device, so that the researchers have introduced different materials as back barrier layer between the two layers that are the channel and buffer layer in order to reduce the spilling of carriers into the buffer layer. The new barrier materials such as AlGaN, InAlN, InGaN, P-GaN, AlN super back barrier layer, and Al- rich AlGaN are used in different GaN based-HEMT structures to obtain an improvement in the device performance. With the development in science and innovation, it is needed to carefully build more delicate and trustworthy HEMT devices with proper back barrier materials.

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. In our work, the output and transfer characteristics of device are studied. The device performance can be enhanced by studying the impact of many parameters that would help to comprehend the device conduct more precisely:

- Nosie analysis and linearity analysis of GaN HEMTs with the InAlN BB, InGaN BB and GaN buffer.

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

APPENDICES

APPENDIX 1:

1. LIST OF PUBLICATIONS (ACCEPTED)

COMPARATIVE STUDY OF InAlN AND InGaN SUPER BACK BARRIER LAYER ON P-GATE/AlGaN/GaN HEMT

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Abstract

Attractive properties of GaN allows it to be used in power electronic devices in various space and defence applications like satellites and radars. In this paper, we have done comparative study of InAlN and InGaN back barrier with conventional GaN buffer in p-GaN/AlGaN/GaN HEMT. Carrier spilling in the channel is reduced which resulted in better 2DEG confinement in the channel. Maximum electric field in the channel is 1.17 MV/cm that is one order higher than conventional GaN Buffer. The drain current is ~332mA/mm with back barriers due to enhanced electron concentration in the channel. Transfer characteristics and I_{ON}/I_{OFF} ratio are improved with back barrier. Higher I_{ON}/I_{OFF} ratio in InAlN back barrier makes it to be more power efficient and reliable p-GaN/AlGaN/GaN device than InGaN back barrier.

Keywords—HEMT, Back Barrier (BB), 2DEG, I_{ON}/I_{OFF} ratio

Introduction

Gallium Nitride (GaN) is emerging as one of the most promising material due to very promising properties. 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 to fabricate conventional devices. Apart from this they have high electric field, high mobility, high saturation velocity, polarization nature [1-3]. The common AlGaN/GaN HEMTS are normally-on due to natural induction of high density Electron gas (2DEG) in the channel. As compare to these devices normally-off devices have advantages of positive and stable threshold voltage, high breakdown field and low on-resistance [4].

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