Simulation, Analysis and Optimization of varied dielectrics as surface passivation on AlGaN/GaN HEMT

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CERTIFICATE

This is to certify that the I have submitted the project dissertation entitled ***Simulation, Analysis and optimization of varied dielectrics as surface passivation on AlGaN/GaN-HEMT*** as a Major Project-II in the partial fulfilment of the requirement for the reward of the degree of Master of Technology, Delhi Technological University (Formerly Delhi College of Engineering), is an authentic record of the my own work carried out by under the guidance of ***Dr. Rishu Chaujar***. The information and data enclosed in this project is original and has not been submitted elsewhere for honouring of any other degree to the best of my knowledge and belief.

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Abstract

Simulation, Analysis and Optimization of varied dielectrics as surface passivation on AlGaN/GaN HEMT

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In this work, the impact on device performance for AlGaN/GaN HEMT with varied dielectrics as surface passivation has been analysed using ATLAS device simulator. Aluminium Gallium Nitride/Gallium Nitride High Electron Mobility Transistor (HEMT) is a suitable candidate for high-power, high-speed and high- temperature applications due to AlGaN/GaN hetero-structure and the superior properties of wide band gap GaN-based materials i.e. high two-dimensional electron gas (2-DEG) density, high breakdown field, and high saturation velocity. Due to the hetero-structure formation, there is formation of quantum well at the conduction band edge (at the interface of AlGaN-GaN), this quantum well gives rise to 2-DEG. Despite of higher 2DEG density, the electron mobility also increases in the well due to reduced scattering. However, these devices suffer from current degradation that is caused by the defects and dislocations that create surface states. The trapping of electrons is due to surface states on GaN surface that causes virtual gate formation and current degradation. The surface passivation layer on AlGaN/GaN HEMT covers the device from gate to source and gate to drain region that helps to avoid the problem of current degradation with improved device performance. As surface passivation plays a key role in these devices, an enhanced device performance can be achieved by using an appropriate passivation scheme.

Various dielectric materials have been reported for surface passivation such as SiO_2, Si_3N_4, Al_2O_3 and HfO_2. SiO_2 is a commonly used oxide for MOSFET, having low dielectric constant and low thermal conductivity. Al_2O_3 with dielectric constant (k=9.5-

12) has better thermal and chemical stability against AlGaN. Si_3N_4 with dielectric constant (k=7.5-10) is a commonly used surface passivation layer on AlGaN/GaN HEMT due to the good interface stability of Si_3N_4 with GaN. Additionally, HfO_2 has high dielectric constant (k=20–25) and high thermal stability that enhances high heat handling capablity but on the other hand, HfO_2 suffers from poor interface quality with GaN. Thus, there is a need to investigate the suitable dielectric material for surface passivation. Aiming this, a comparative analysis of AlGaN/GaN HEMT with various dielectric materials i.e. SiO_2, Si_3N_4 and Al_2O_3 as surface passivation layer has been performed using TCAD Silvaco ATLAS device simulator software. In addition to these dielectrics, a stack of Si_3N_4/HfO_2 as a surface passivation layer has also been proposed. The motivation of stacked Si_3N_4/HfO_2 is attributed to the high dielectric constant and high thermal stability of HfO_2 but limiting interface quality of HfO_2 with GaN and better interface compatibility of Si_3N_4 with GaN. Consequently, stacked Si_3N_4/HfO_2 may offer integrated advantages of better thermal stability and good interface quality offered by HfO_2 and Si_3N_4 respectively for acquiring comprehensively better electrical characteristics and good surface passivation for GaN HEMTs. In this respect, the devices with same dimensional structures but with different passivation schemes are accounted for acquiring an optimum dielectric material as a surface passivation layer.

Electrical parameters evaluation show that the device passivated with a stack of Si_3N_4/HfO_2 shows high drain current, high breakdown voltage, higher gain as well as higher current switching ratio in comparison with other dielectric materials. Thus, the AlGaN/GaN HEMT with stacked (Si_3N_4/HfO_2) passivation may offer great potential for high-power applications. Furthermore, the ratio of thickness of HfO_2 and Si_3N_4 has been varied in the stack to investigate the optimum combination for passivation. The analog analysis shows that superior electrical characteristics are obtained for the higher ratio of HfO_2/Si_3N_4 used as surface passivation. The linearity for different ratio has also been analysed by evaluating various Figure of Merits (FOMs) such as higher order transconductance coefficients (g_{m2}, g_{m3}), VIP2, and VIP3. The purpose of the study is to account for the effect for surface passivation with different ratio of HfO_2/Si_3N_4 on nanoscale AlGaN/GaN HEMTs to achieve superior device performance.

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Abbreviation

2DEG = Two Dimensional Electron Gas

Al_2O_3 = Aluminium Oxide

AlGaAs = Aluminium Gallium Arsenide

AlGaN = Aluminium Gallium Nitride

CdTe = Cadmium Telluride

CMOS = Complementary Metal Oxide Semiconductor

GaAs = Gallium Arsenide

GaN = Gallium Nitride

HEMT = High Electron Mobility Transistor

HfO_2 = Hafnium Oxide

InGaAs = Indium Gallium Arsenide

InP = Indium Phosphide

InSb = Indium Antimonide

LED = Light Emitting Diode

LASER = Light Amplification by Stimulated Emission of Radiation

MOSFET = Metal Oxide Semiconductor Field Effect Transistor

SiC = Silicon Carbide

SiGe = Silicon Germanium

SiO_2 = Silicon Di-Oxide

Si_3N_4 = Silicon Nitride

TCAD = Technology Computer Aided Design

WBG = Wide Band Gap Semiconductors

ZnSe = Zinc Selenide

1

Introduction

Silicon Technology is widely used in semiconductor device industry across the world. It is well mature technology due to the material depth knowledge and very stable CMOS fabrication process. However, there are many applications where the silicon cannot work due to its limitation of material properties. Thereby, the need of III-V compound semiconductor becomes prominent for high frequency and high power applications.

1.1 Background

Transistor has been discovered by John Bardeen, Walter Brattain, and William Shockley, Bardeen at bell laboratories in 1947. They have got a noble prize for their invention of the transistor in 1956 [2]. The successor of the transistor, MOSFET has been built in 1960 by Dawon Kahng and Atalla at Bell Labs [3]. Si-based MOSFET has been widely used in different fields of industry i.e. microelectronics, power electronics, electric engines, telecommunication, etc. The electronic market grew rapidly in last decades on the basis of silicon MOSFET. Silicon is second most found material on the earth. Due to this major advantage, it has been still continuing in the industries. Since 1947, not only the production process but the materials have also been changed for the technology development. Many other materials have also been researched like compound semiconductors that belong to II-VI group i.e. CdTe, ZnSe, etc. or III-V group i.e. GaAs, InP, GaN, etc. or the IV group i.e. SiC, SiGe, etc. Apart from the binary compounds, the ternary compounds have also been developed during this era i.e. AlGaAs, AlGaN, InGaAs, etc. These compound semiconductors have shown better material properties needed for transistor technology development [4]. The performance of the device is dependent on electrical properties of material i.e. mobility, breakdown field, thermal conductivity, band gap and saturation velocity etc. The compound semiconductor like GaAs has shown 6 times higher mobility than the Silicon, GaN has the 10 times higher breakdown field than that of silicon [5]. Therefore, for high power and high frequency applications like satellite communication, Telecommunication, radars, etc. the silicon is definitely not a choice because of its inferior material properties [6, 7]. For these kinds of applications, the compound semiconductors are the only workhorse [8]. The other major application area, where the Silicon cannot be used is optoelectronics due to its indirect band gap. Many compound semiconductors have overcome silicon limitations due to direct band gap property that is essential for optoelectronics application like LED, LASER Diodes. The typical compound semiconductor III-V devices achieved significant success in this application area. The Arsenide and Nitride based compound semiconductors are now widely used in optoelectronics also. For high power applications, GaN is first choice because of its wider band gap, higher breakdown electric field and its heterostructure with AlGaN. For high frequency and high power applications like wireless communication, military applications (radars, missile seekers), GaN HEMT is a promising candidate due to electrical properties of GaN and high mobility in heterostructure i.e. AlGaN/GaN as an additional advantage [9, 10].

1.2 Motivation:

The demand for high power devices has been increased rapidly in the area of wireless communication, satellite communication, and military applications. AlGaN/GaN HEMT is a promising candidate due to its remarkable properties i.e. wider band gap, higher breakdown electric field, higher saturation velocity, higher sheet carrier density. But despite of having superior properties, it has many challenges such as current collapse, stability, etc. that needs to be addressed. AlGaN/GaN heterostructure is very complex to understand due to their polarization charges and various traps [11, 12]. The commercial growth of GaN HEMT technology is sluggish due to lack of in-depth understanding of the effect of traps on device performance. Since the device fabrication cost is too high, simulation is a better choice to understand the device physics, reproducibility, and effect of various device parameters on device performance. Silvaco ATLAS software tool is widely used to understand the device physics and operation at various voltages. It can be used to reproduce the results, predict the experimental output and compare. The work on GaN is motivated due to its electrical properties that are useful in various applications that have been discussed below.

1.2.1 Wide Band gap (WBG)Semiconductors:

Wide band gap semiconductors offer superior electrical properties than silicon. The wider the forbidden gap, higher is the breakdown voltage. WBG Semiconductors have good thermal stability, high robustness and high radiation hardness which make it suitable for high power application [13, 14]. WBG semiconductors can survive in a harsh environment which is essential for space and military applications. The comparison of various WBG semiconductors with silicon is shown in the table below:

Table 1.1 Electrical properties of different semiconductor

Material Property	**Silicon (Si)**	**Gallium Arsenide (GaAs)**	**Silicon Carbide (SiC)**	**Gallium Nitride (GaN)**	**Diamond**
Band Gap(eV)	1.12	1.42	3.2	3.4	5.5
Saturation Velocity V_{sat}(cm/s) X 10^7	1	1.3	2.0	2.5	2.7
Thermal Conductivity (V/cm-K)	1.5	0.5	4.5	1.3	20
Critical Field(MV/cm)	0.3	0.4	3	3.3	5.6
Dielectric Constant	11.8	12.9	9.7	9.5	5.5
Mobility(cm^2/V-s)	1350	8500	700	1500	1900

Silicon has low thermal stability, lower band gap, lower breakdown field, and lower mobility in comparison to other compound semiconductors as shown in Table-1.1. Therefore, silicon is not suitable for high frequency and high power applications. Diamond has a very high bandgap i.e. 5.5eV, but the processing of diamond is very difficult due to its hardness [15]. GaAs is having higher mobility but have low bandgap thus not suitable for high power applications. The bandgap of SiC is high but mobility is too low. GaN has higher bandgap as well higher 2DEG mobility due to hetero-structure formation with AlGaN. Therefore GaN is most suitable for high power as well as high frequency applications. Despite of many advantages of WBG semiconductors, they have some disadvantages i.e. fabrication difficulty, higher defect density, limited availability and higher cost [13].

1.2.2 Why GaN:

Despite of having advantages of wide band gap semiconductor, GaN has another additional advantage of having AlGaN/GaN heterostructure that leads to higher polarization charge in the channel [11]. Due to the heterostructure and formation of 2DEG, higher mobility and higher sheet carrier density are achieved in wide band gap material i.e. GaN which is suitable for high power and high frequency applications. The two types of polarization charges are present in AlGaN/GaN heterostructure. One is spontaneous polarization that is due to the electronegativity difference within the material itself and second is piezoelectric polarization that is due to strain in the material [16]. The piezoelectric polarization charge in GaN is ten times more than GaAs [8, 16]. Therefore, there is no need to dope the AlGaN layer for charge carriers in the channel. The thickness of the barrier layer i.e. AlGaN and Al composition fraction effects the charge carriers density. High doping with thin barrier layer can also be achieved in AlGaN because of its property of high breakdown electric field. For handling high power, the thermal conductivity of material must be high due to higher heat generation in power devices. The thermal conductivity of GaN is not too high, thus for handling high power, GaN on SiC is used because the thermal conductivity of SiC is better. Therefore, heat dissipation becomes easier during high power operation.

1.2.3 Applications:

GaN, wide band gap material is well suited for high power and high frequency applications. It is due to its hetero-structure with AlGaN which is also a wider band gap material. The higher sheet carrier density, higher breakdown voltage, higher thermal stability and high robustness make it suitable for space and military applications. Since silicon have low bandgap, lower thermal stability, lower mobility, so it is not suitable for high power as well as high frequency applications [9, 17]. The wide range of AlGaN/GaN HEMT applications are shown in Figure 1.1.

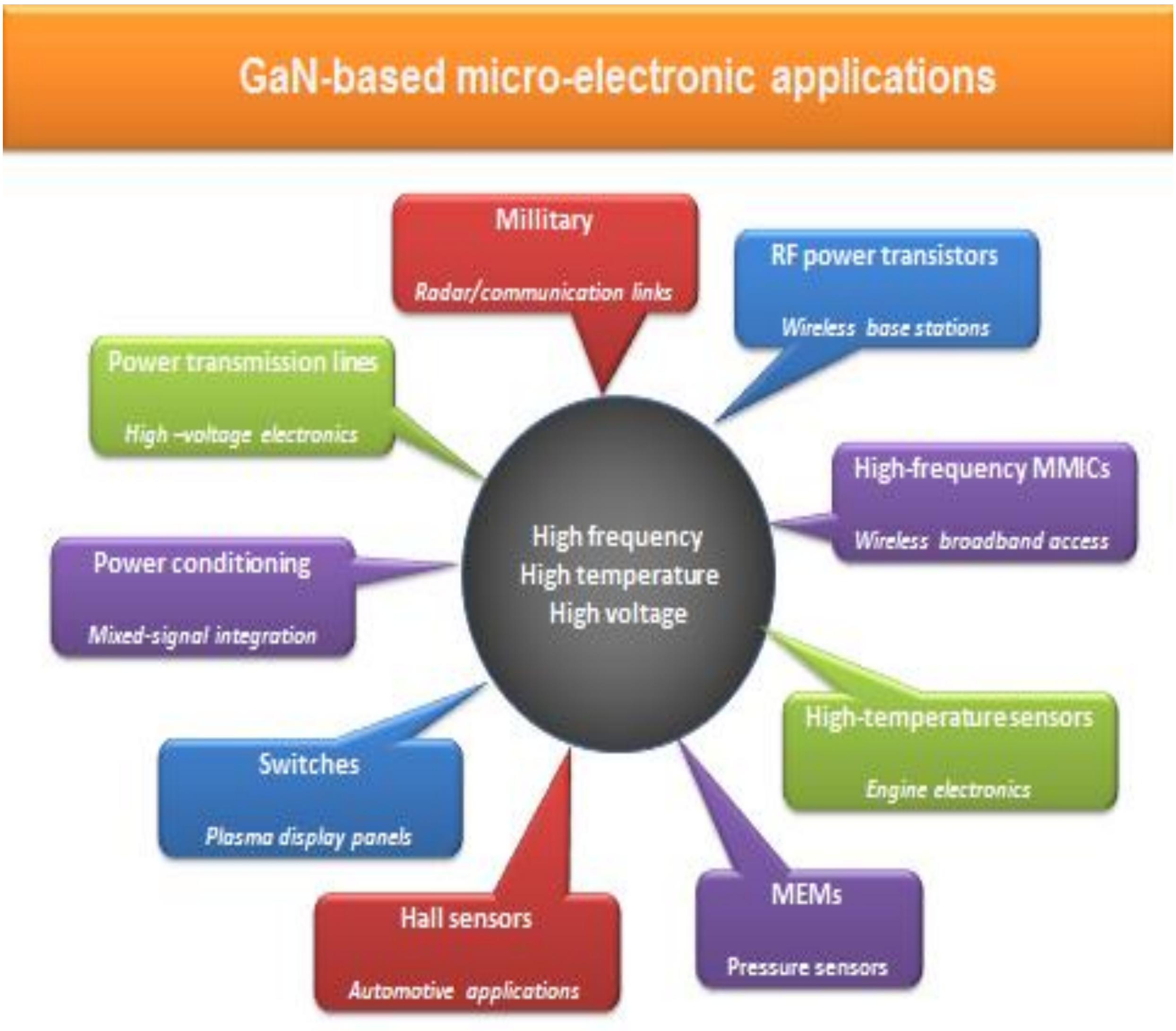


Figure 1.1 Various applications of GaN HEMT

There are many materials which have been proposed for high power and high frequency applications that include Indium Phosphide, Gallium Arsenide, and Si-Ge, etc. The application of high frequency and high power is shown in figure 1.2 along with the variety of materials that can be used. It clearly indicates that the GaN is the only candidate for military applications that includes decoy, radars, etc.

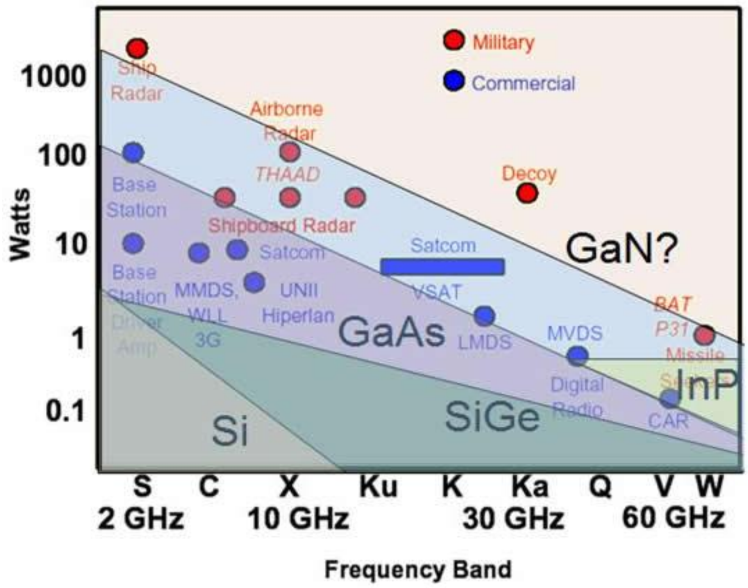


Figure 1.2 Different materials for various applications [1]

Apart from these applications, the optoelectronics applications i.e. LEDs, Lasers are also GaN-based due to the direct band gap property of GaN. A shorter wavelength laser diode can be developed through GaN since it is a high band gap material. Thus emission wavelength can be smaller. Shuji Nakamura, Isamu Akasaki, and Hiroshi Amano got Nobel prize in 2014 for a major breakthrough in lighting technology i.e. the invention of efficient blue light-emitting diodes GaN-based LED[18]. Therefore, this new era of GaN has applications in space, military and different kinds of industries.

1.3 Aim and objectives:

The aim of the work is to analysis the effect of surface passivation of AlGaN/GaN based HEMT to improve the device performance using ATLAS device simulator. The analog characteristics have been studied for various passivation layers i.e. SiO_2, Si_3N_4 and Al_2O_3. The Analog and linearity analysis has been done for the stacked Si_3N_4/HfO_2 stack passivation for AlGaN/GaN HEMT. This work includes the following steps:

- Develop a simulation deck for the AlGaN/GaN HEMT device by including the appropriate models to simulate the effects of passivation as an initial step.
- Compare the simulated results trend with respect to reported DC data.
- Propose a new stack passivation material i.e. Si_3N_4/HfO_2 for GaN HEMT and compare the results with other passivation schemes i.e. SiO_2, Si_3N_4, and Al_2O_3.
- Impact on analog and linearity performance of AlGaN/GaN HEMT with variation in ratio of surface passivation stack i.e. Si_3N_4/HfO_2 have been analysed.

1.4 Thesis organization:

The thesis has been organized in following way:

Chapter 2 introduces the material GaN and its heterostructure with AlGaN. The electrical properties of GaN have been discussed. The properties have been compared to other materials i.e. SiC, GaAs, and Silicon. The AlGaN/GaN heterostructure and formation of 2DEG has been explained in detail, and then GaN HEMT device physics has been elaborated. GaN technological challenges have also been discussed briefly.

Chapter 3 introduces simulation methodology for the GaN HEMT Device. Silvaco ATLAS software structure has been discussed. Various models that are used for the simulation has been elaborated. The steps and order of ATLAS syntax have also been discussed.

Chapter 4 concentrates the role of passivation in GaN HEMT Device. The cause of the current collapse has been discussed. The need and effect of surface passivation has been explained. The favorable properties of passivation material have been discussed briefly. The results of simulated GaN HEMTs with surface passivation dielectrics i.e. SiO_2, Si_3N_4, Al_2O_3 has been compared through ATLAS device simulator. In addition, a stack of Si_3N_4 and HfO_2 has also been proposed for surface passivation, the results have been compared with other HEMT devices with varied dielectric surface passivation layers.

Chapter 5 demonstrates the results of the varied ratio in stack passivation of Si_3N_4 and HfO_2 for AlGaN/GaN HEMT. Impact on analog and linearity performance of nanoscale AlGaN/GaN HEMT with variation in surface passivation stack has been studied through ATLAS Device simulator. The results have been discussed in detail in this chapter.

Chapter 6 summarizes the results of above mentioned chapters. It also includes the future prospects of the work.

2

AlGaN/GaN HEMT

This chapter reviews the electrical properties, AlGaN/GaN Heterostructure and basic operation of HEMT device. Some technological challenges with the device have also been discussed briefly.

2.1 Electrical properties of Gallium Nitride(GaN):

As mentioned in the previous chapter, GaN has various favorable electrical properties that are suitable for high power and high frequency applications. The electrical properties of GaN have been elaborated below:

2.1.1 Wide Band Gap:

The band gap is the energy gap between the valence and conduction energy band, also called forbidden gap as shown in Fig 2.1. Wider the energy band gap, more the energy is needed for electrons to move from valence band to conduction band. For metals, the energy gap does not exist as the valence, and conduction bands overlap each other. For insulator, the forbidden gap is too high that electrons need very high energy to move from valence band to conduction band. For Semiconductors, the forbidden gap is smaller than the insulators [19]. As temperature increase, the electron energy increases, therefore the electrons in valence band move to conduction band at certain energy.

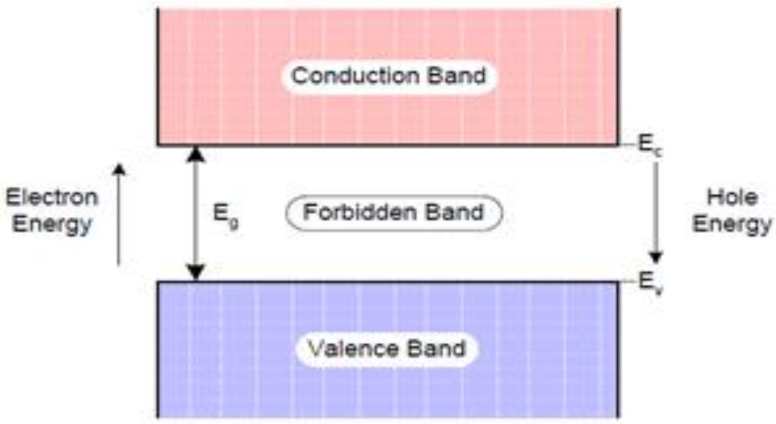


Figure 2.1 Energy band gap in semiconductors [13]

For WBG semiconductor, the electrons need more thermal energy to move from valence band to conduction band in comparison to semiconductors. Therefore, wide band Gap (WBG) semiconductors have advantages of high-temperature operation and high radiation hardness. Due to the advantage of high-temperature operation, WBG semiconductors can withstand more heat that is suitable for power devices.

2.1.2. High Saturation Velocity:

Fig. 2.2 shows the drift velocity of various semiconductors w.r.t. electric field. Silicon has lowest saturation velocity in comparison to compound semiconductors as shown in figure.

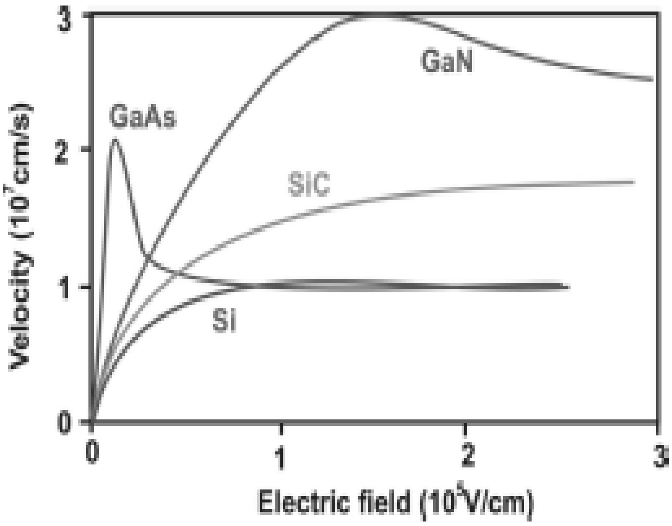


Fig. 2.2 Drift velocity versus Electric field for different material [20]

Higher the saturation drift velocity provides the higher current drive as well as higher switching capability. The drift velocity of GaN is more than twice of silicon that indicates GaN is capable of handling high current. WBG semiconductors with high saturation drift velocity can operate at high power as well as high frequency.

2.1.3 High Breakdown Electric Field:

GaN has higher breakdown electric field than that of silicon [21]. Therefore, GaN can withstand with the higher electric field. Higher breakdown electric field leads to the higher breakdown voltage of the device. Another advantage of higher breakdown electric field is that higher doping can be achieved on a thin layer of GaN, which is very useful for scaling the device. Thus, due to higher breakdown electric field, GaN is suitable for high power as well as high frequency applications.

2.1.4 Lower On Resistance:

The on resistance of GaN HEMT device is lower due to higher saturation velocity and higher mobility in 2-DEG (Two-Dimensional Electron Gas) due to AlGaN/GaN heterostructure [22]. This property is very useful for switching applications. Thus GaN HEMT can also work as a switch in high power circuits.

2.1.5 Higher 2DEG:

The AlGaN/GaN heterostructure is due to band gap difference in AlGaN and GaN. The quantum well has been formed due to the conduction band edge discontinuity between AlGaN and GaN as shown in Fig. 2.3.

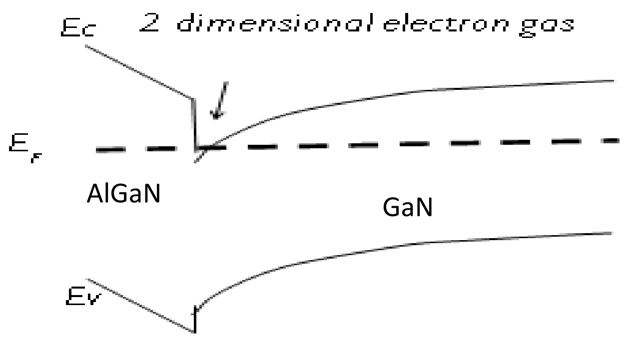


Figure 2.3 Band discontinuity of AlGaN/GaN [1]

The two-dimensional electron gas (2DEG) is formed due to lower energy occupancy of electrons at band edge discontinuity. Due to the quantum well formation at hetero-interface of AlGaN/GaN, the mobility of electrons increases in the well called as a channel. The scattering is minimized due to the quantum well formation and thereby mobility of charge carries increases that lead to increasing the current. The carrier concentration in the channel depends on polarization charge in AlGaN layer [16, 23]. Therefore, GaN HEMT possesses higher current due to 2DEG formation.

2.1.6 Higher Thermal Stability:

High heat handling is important for power devices. GaN can be operated at higher temperature due to higher band gap. SiC has higher thermal conductivity as well as higher band gap [24-26]. GaN and SiC have small lattice mismatch (~4%). Thus, GaN on SiC, provide us to have integrated advantages of higher saturation velocity as well as higher thermal conductivity. Therefore, apart from other advantages, GaN is also capable of high heat handling that is suitable for high power applications.

2.2 AlGaN/GaN Heterostructure:

AlGaN and GaN both are wide band gap materials. The bandgap of AlGaN depends on the composition fraction of Al in AlGaN. The Bandgap of GaN is ~3.4eV while the Bandgap of AlN is ~6.01eV. The band gap of AlGaN can be evaluated by Vegards's law is given below as per ref [27]:

$$E_g(Al_xGa_{1-x}N) = x.E_g(AlN) + (1-x).E_g(GaN) - bx.(1-x)$$

Where, b is bowing parameter

Thus, as the x i.e. the composition fraction of Al increases the band gap increases and due to this the conduction band discontinuity with GaN increase as the composition fraction of Al increases. The electrons can move in two dimensions while confined in one dimension that is why it is called two-dimension electron gas (2DEG). The conduction band discontinuity defines as $\Delta E_{c.}$ When these two materials are in contact, the conduction band of AlGaN/GaN gets modified due to the difference in the band gap of AlGaN and GaN. The electrons from AlGaN come into lowest energy state i.e. quantum well form at the interface of AlGaN/GaN. Due to this confinement, the electrons can reach from source to drain without any scattering. In addition, the charge carriers increase in the channel due to the polarization charges i.e. spontaneous and piezoelectric polarization. The piezoelectric polarization charge is higher for GaN than that of GaAs. Thus, the mobility and sheet carrier density are higher due to confinement and polarization respectively that leads to increase in drain current.

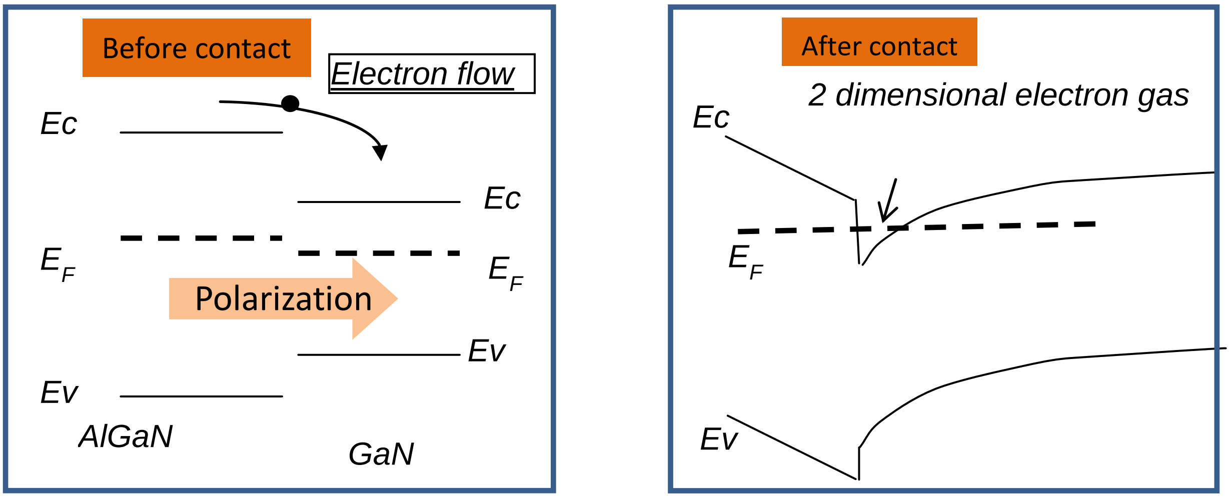


Figure 2.4 Conduction band discontinuity before and after contact of AlGaN/GaN

The factors affecting the drain current, sheet carrier density, the frequency of operation and mobility can be summarized as follows:

Maximize I	⟹	Maximize n_s, μ
Maximize n_s	⟹	Maximize P_{SP}, P_{PE} Maximize Al mole fraction without strain relaxation
Maximize f_τ	⟹	Minimize effective gate length, Minimize L_g and gate length extension
Maximize μ	⟹	Minimize dislocations, smooth interface

2.3 HEMT Device Physics:

HEMT is a High Electron Mobility Transistor also called MODFET i.e. Modulation Doped Field Effect Transistor, and HFET i.e. Heterostructure Field Effect Transistor. The device working resemble to FET in the sense that the current flows from drain to source,

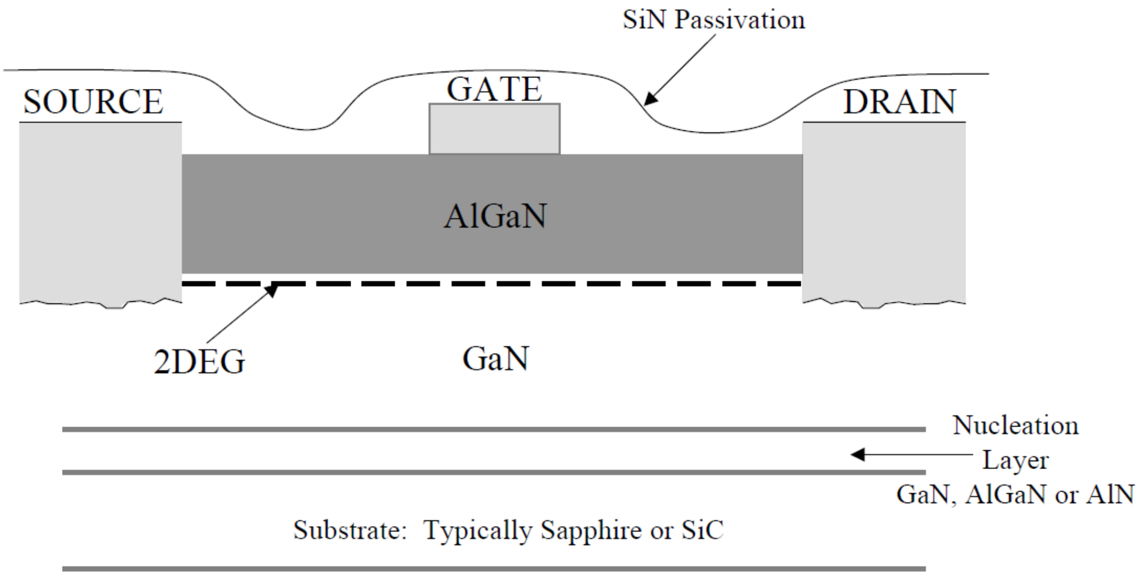


Fig. 2.5 HEMT Device Structure [1]

and this drain current is controlled by the gate electrode. It is a majority carrier device. Thus the Gate is a Schottky contact to control the flow of electrons from source to drain while the source and drain are ohmic contacts. Normally-on HEMT is a device in which the negative gate voltage is needed to turn off the device. While in the case of an enhancement type, the gate voltage is needed to turn on the device. The difference between HFET and FET is that in hetero-structure FET, the charge carriers in the channel are on the interface of AlGaN/GaN i.e. in the quantum well while in FET, the electrons flow through the bulk material itself. Thus, the mobility of the majority carriers in HFET increases drastically. There is another advantage of polarization charges in GaN HEMT. There are two types of polarization i.e. spontaneous polarization, piezoelectric polarization. Spontaneous polarization is due to electronegativity difference in gallium and nitrogen while the piezoelectric polarization is due to strain in AlGaN material [28]. The direction of both polarizations will be same if AlGaN grows with tensile strain. Thus, due to these polarization charges, there is no need to dope the AlGaN layer for charge carriers in the channel.

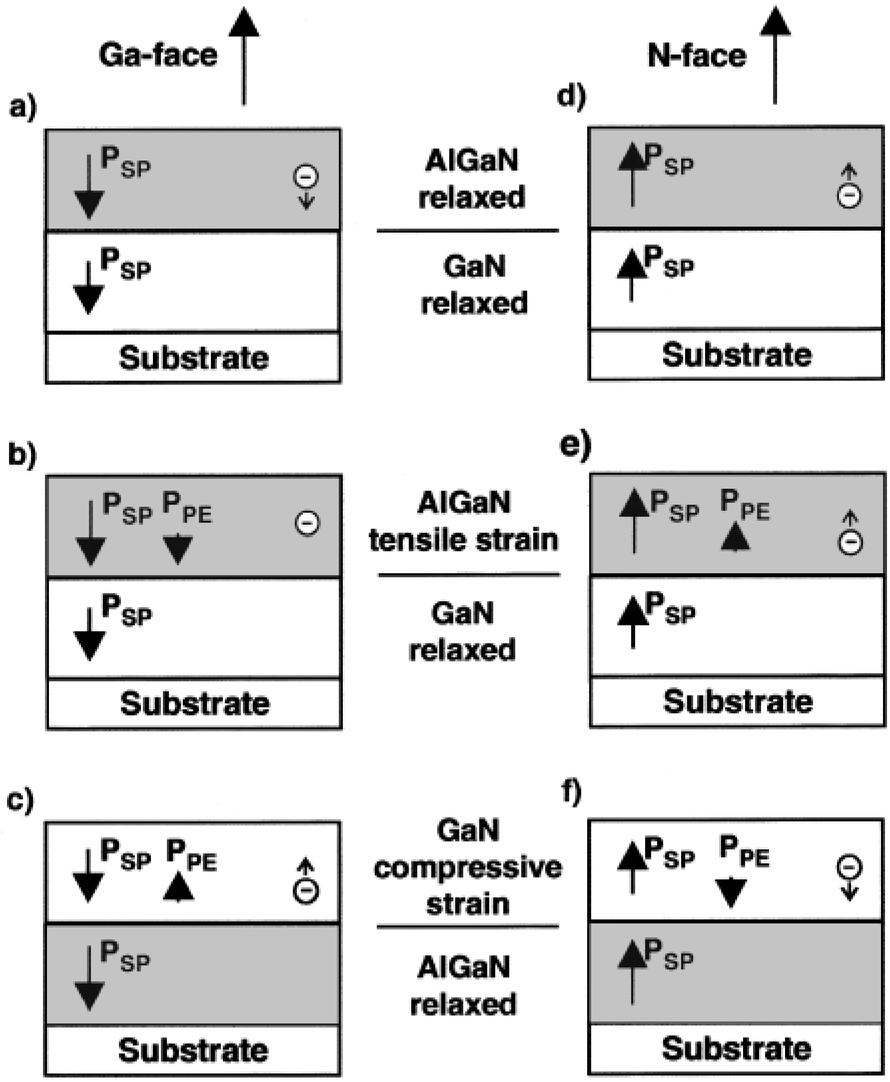


Fig. 2.6 Polarization charges in AlGaN and GaN layer [16]

The direction of polarization charges w.r.t. tensile or compressive strain in AlGaN and GaN layers are shown in Fig.2.6. When both AlGaN and GaN layers are relaxed, only spontaneous polarization are present as in Fig. 2.6 (a) and (d). When tensile strain is present in the AlGaN layer, the direction of spontaneous and piezoelectric polarization are same as in Fig 2.6 (b) and (e), in this case, total polarization charge increases. When compressive strain is present in AlGaN layer, the direction of spontaneous and piezoelectric polarization are opposite as shown in Fig. 2.6 (c) and (f) and the total polarization charge reduces. Due to the band gap discontinuity and these polarization charges, the formation of 2DEG at the interface of AlGaN and GaN takes place. The 2DEG wave function at the interface of AlGaN/GaN is shown in Fig 2.7.

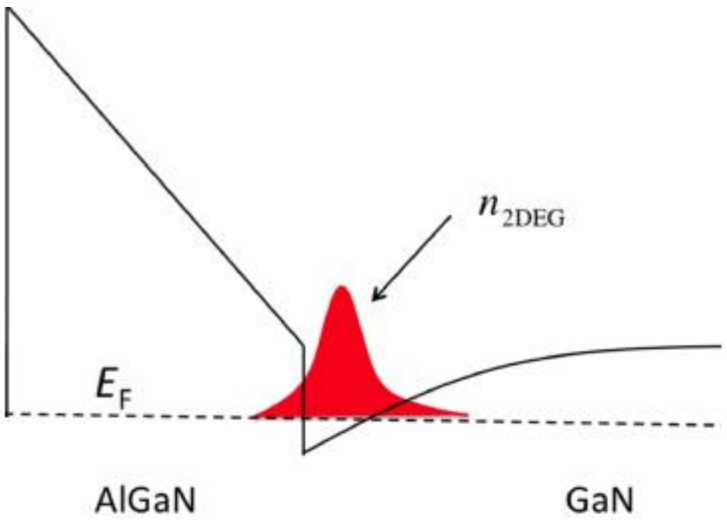


Fig. 2.7: 2DEG wave function at AlGaN/GaN interface [29]

Furthermore, the energy band is modified by the application of gate voltage that causes depletion of the channel in the HEMT. The quantum well diminishes at a particular negative gate voltage and the carriers depleted, that voltage is called pinch-off voltage in HEMT.

2.4 GaN: Technology Challenges:

2.4.1 Bulk and Surface Traps:

Due to the difference in lattice constant of two different materials, there is lattice mismatch between the two that leads to traps formation and defects in the layer structure. Furthermore, the stress in the layer in hetero-interface may also cause the point and line defects in the structure as shown in Fig 2.8.

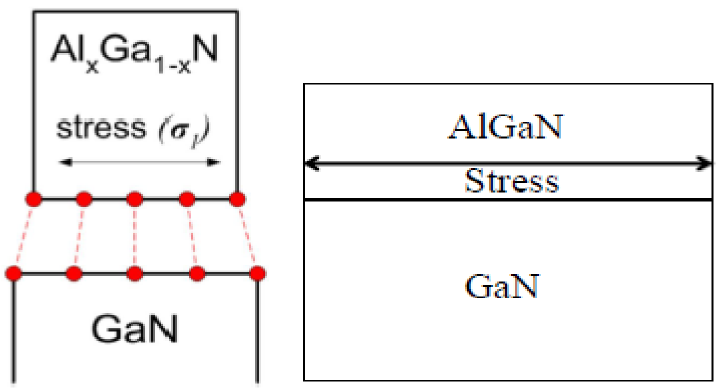


Fig. 2.8: Stress in AlGaN layer [8]

In addition to these defects, there are unintentional impurities which are inherent in fabrication processes that add up to increase defects level inside the band gap in the material. These defect levels have potential to capture electrons or holes depending on the type of states for a larger period of time. Due to these captured charge carriers, the charge carrier density decreases in the channel that consequently reduces the output current.

The surface traps in the HEMT device are generated due to the dangling bonds and surface impurities. Such defects act as donor type states as shown in Fig 2.9. These defects are known to be responsible for virtual gate formation. The electrons from gate electrode are attracted by these donor type states, leads to the formation of the virtual gate that consequently decreases the current in the channel.

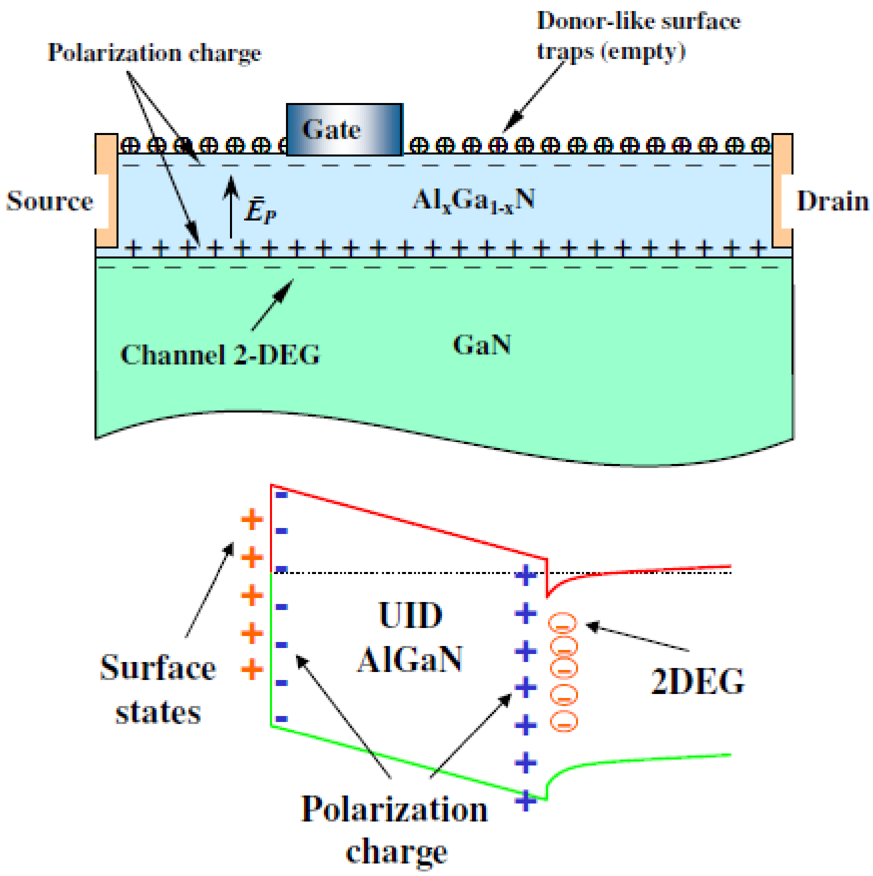


Fig. 2.9 : Surface states and polarization charges in AlGaN/GaN HEMT

2.4.2 Current Collapse/Knee walk out:

When the output current degrades at high voltage transient pulse applied to drain or gate, the phenomenon is called current collapse or knee walk out. Since the output current does not degrade at corresponding DC voltage but degrade at corresponding RF voltage that is why it is also called DC to RF dispersion. The output current recovers to its original value after some time. The gate lag, the delayed drain current response w.r.t change in gate voltage can be minimized using surface passivation reported by some researchers [12, 30]. The current collapse is a major problem when operating at high frequency. Research shows that it is due to surface traps or presence of virtual gate at the surface [31]. It is claimed that at high voltage the donor traps captured electrons and there is the formation of the virtual gate at the surface shown in Fig. 2.10.

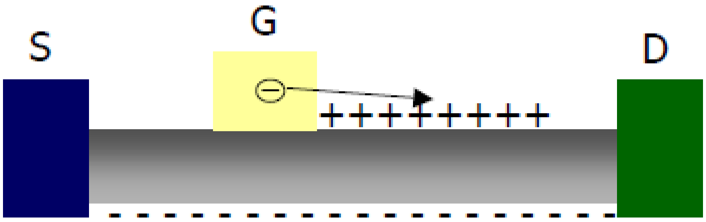


Fig. 2.10: Formation of virtual gate in AlGaN/GaN HEMT [31]

Due to virtual gate formation, the electrons in the channel deplete, and consequently currently degrade. Fig 2.11 shows the current collapse phenomenon in the device.

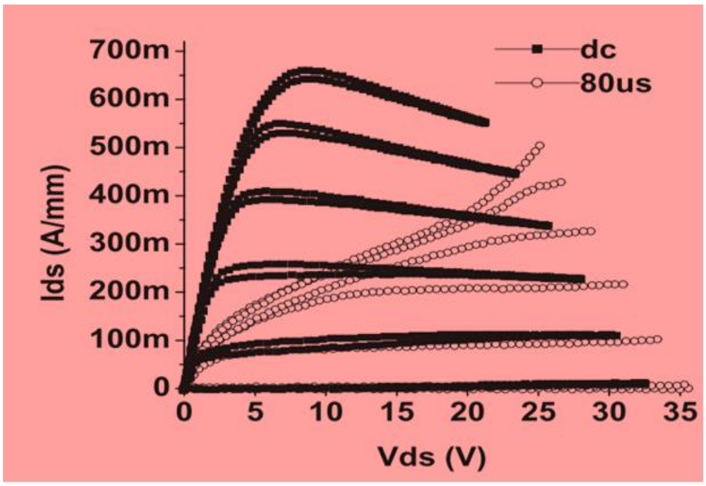


Fig. 2.11: Current Collapse phenomenon in AlGaN/GaN HEMT [32]

The surface passivation helps to improve DC to RF dispersion. Silicon nitride is well-reported surface passivation on GaN HEMT to avoid current collapse [33, 34].

2.4.3 Self-Heating:

The high current flow in GaN substrate at high voltages causes heating of the device that degrades the device performance. The temperature dependent material properties change at high temperature i.e. mobility, bandgap etc. The heating effect in GaN HEMT is shown in Fig. 2.12. The negative slope in DC characteristics is due to heating effects. The degradation of mobility causes the degradation of current. It is suggested that the GaN on SiC improves the device performance by eliminating the heating effects due to high

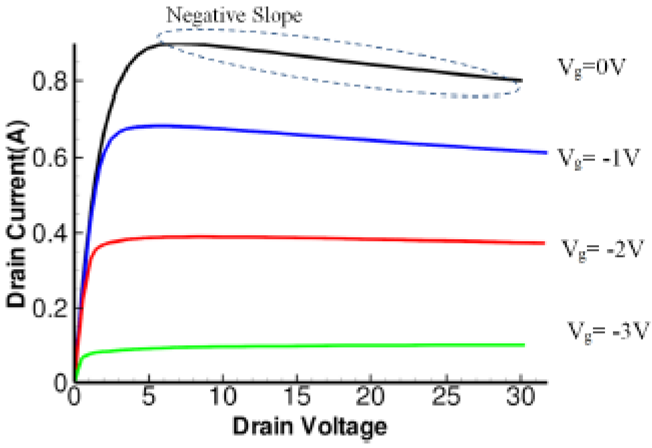


Fig. 2.12 Self-Heating of the HEMT device due to high current [8]

thermal conductivity, Therefore it dissipates the heat very quickly [35]. Many other solutions like heat sink has also been reported to cure self-heating effects in the power devices [36].

3

Simulation Methodology

This chapter describes the simulation methodology used for the AlGaN/GaN HEMT device. Silvaco ATLAS software structure has been discussed. The physical models that has been used for simulation of AlGaN/GaN HEMT has been elaborated. The steps and order of ATLAS syntax has been discussed briefly.

3.1 Introduction:

Simulation is a useful tool to understand the working of the device and reproduce the results. The software is also utilized to predict the behavior of the device with a respective change in device parameter and material parameter. It provides information of the device inside. Device simulation tools simulate the electrical characteristics of semiconductor devices, as a response to external electrical, thermal or optical boundary conditions imposed on the structure. Since the device fabrication is very complex and costly, simulation is better option to study the device without the real fabrication and utilize it for further improvement of the device. TCAD (Technology Computer Aided design) is simulation software for semiconductor device operation analysis and processing that is used for technology development. The simulation software tool that has been used for this project work is Silvaco ATLAS that has been discussed below.

3.2 Silvaco ATLAS:

In ATLAS simulation, there are two input files, one is structure file that can be built using Athena or Devedit and another input file is a text file that contains commands for Atlas to execute. ATLAS produces three types of output files. The first type of file is the run time output file, which gives the progress, warnings, and errors as simulation proceeds. The second type of output file is the log files, which stores all terminal voltages and currents from the device analysis. The third type of file is the solution file, which stores 2D and 3D data relating to the value of the solution variables within the device at a given bias point [37]. The ATLAS tool supports the calculation of various AC parameters like Hybrid (H), Admittance(Y), Impedance (Z), Scattering(S), etc. The gain analysis can also be done as a part of the small signal analysis. AC sinusoidal small-signal analysis should be performed after solving for a DC condition. The full newton method must be used for this analysis. The frequency range of interest, device width and the method for ac analysis has to be selected. A direct parameter is included which is robust for all range of frequencies. The gate terminal is selected as input port where ac bias will be applied, while drain terminal is selected as output port indicating that device works in common source configuration. The structure of ATLAS is shown in Fig.3.1.

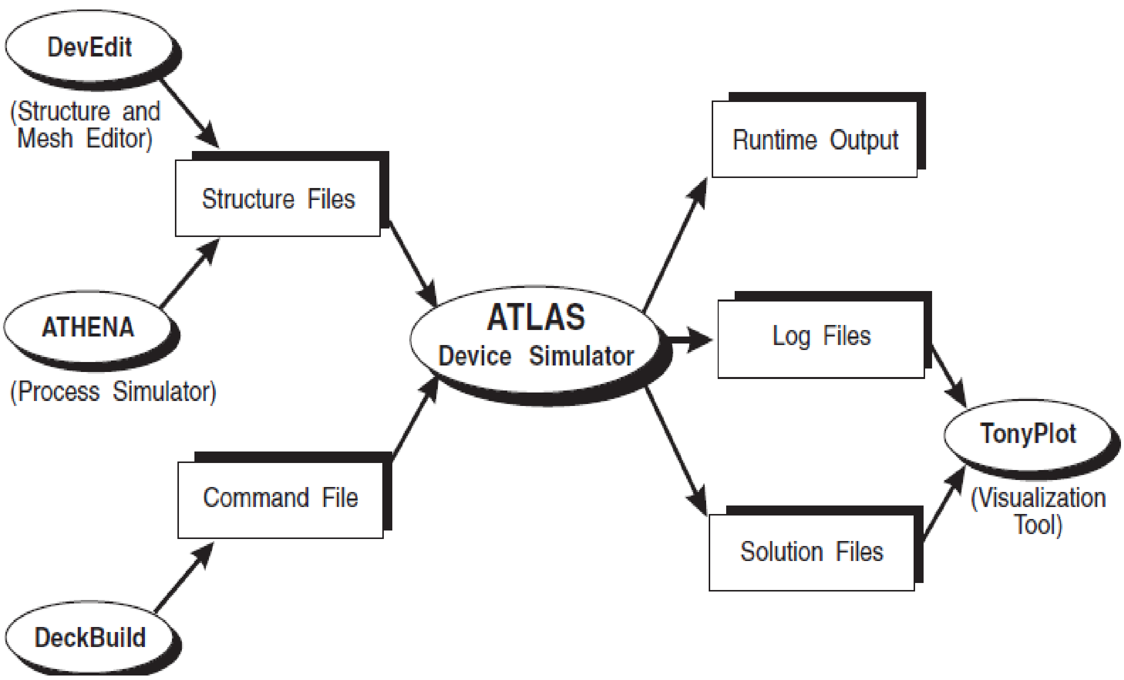


Fig. 3.1 Structure of the ATLAS Device simulator [38]

3.3 <u>Physical Models:</u>

The physical models are used in simulation to include physical phenomenon in the device. In TCAD ATLAS software, many physical models are available to describe the device physics as real as possible. These models have to be included to perform simulations and to do reliable predictions about the device characteristics. The models can be included using MODELS, MOBILITY, and IMPACT statements. In this section, various models that have been used for AlGaN/GaN HEMT simulation are discussed briefly.

3.3.1. Polarization Model:

Some III-V compound semiconductors have polarization property within the material. Wurtzite materials have two types of polarization:

a) Spontaneous polarization

b) Piezoelectric polarization

The total polarization is the sum of both spontaneous and piezoelectric polarization. Spontaneous polarization is due to the electronegativity difference within the material, but piezoelectric polarization is due to the stress/strain in the material. It is necessary to include the both effects when the material has polarization characteristics. The total polarization is P_t is given by:

$$P_t = P_{SP} + P_{PE}$$

Where P_{SP} is spontaneous polarization

P_{PE} is piezoelectric polarization

The piezoelectric polarization is determined as per O.ambacher et.al. [39] :

$$P_{PE} = 2((a_s - a_o)/ a_o)* (e_{31} - e_{33}*(C_{13}/C_{33}))$$

Where, e_{31} and e_{33} = piezoelectric constants

C_{13} and C_{33}= elastic constants

a_0= lattice constant of the material in question

a_s= Average value of lattice constants of the layers

The polarization charge can be taken into account using MODELS statement. The strain is calculated by lattice mismatch or directly introduced. To include piezoelectric polarization, specify CALC.STRAIN in model statement. The value of polarization will be automatically calculated by a device simulator.

3.3.2 Velocity Saturation Model:

In a semiconductor, the velocity of charge carriers depend on the electric field, but at the very high electric field, drift velocity saturates. It is the maximum velocity, a charge carrier can attain. This phenomenon when there is no effect of electric field on velocity of charge carrier is called velocity saturation. Mobility is a material dependent property which is a proportionality constant of the velocity versus electric field. To account the velocity saturation effect, MOBILITY statement is used. Nitride specific field dependent mobility models can be included by specifying GANSAT.N and GANSAT.P in the mobility statement. This model is based on fit to Monte-Carlo data for bulk nitride which is described in equations below as mentioned in ref [38]:

$$\mu_n = \frac{\mu_{n0}(T,N) + VSATN \dfrac{E^{N1N.GANSAT-1}}{ECN.GANSAT^{N1N.GANSAT}}}{1 + ANN.GANSAT\left(\dfrac{E}{ECN.GANSAT}\right)^{N2N.GANSAT} + \left(\dfrac{E}{ECN.GANSAT}\right)^{N1N.GANSAT}}$$

$$\mu_p = \frac{\mu_{p0}(T,N) + VSATP \dfrac{E^{N1P.GANSAT-1}}{ECP.GANSAT^{N1P.GANSAT}}}{1 + ANP.GANSAT\left(\dfrac{E}{ECP.GANSAT}\right)^{N2P.GANSAT} + \left(\dfrac{E}{ECP.GANSAT}\right)^{N1P.GANSAT}}$$

Where μ_{n0} (T,N) = low field mobility

E= Electric Field

VSATN, ECN.GANSAT, N1N.GANSAT, ANN.GANSAT, N2N.GANSAT are default field dependent mobility model parameters. The parameter values for GaN are:

VSATN= 1.9064 x 10^7 cm/s

ECN.GANSAT= 220.8936 KV/cm

N1N.GANSAT= 7.2044

ANN.GANSAT=6.1973

N2N.GANSAT=0.7857

3.3.3 Shockley Read Hall (SRH) Model:

It includes the temperature-dependent minority carriers lifetime. SRH (SCHOKLEY READ HALL) is recombination through defects in a material. Every material have some defects; SRH model includes the temperature-dependent recombination due to these defects. The temperature dependence of electrons and holes in the SRH recombination model has the forms as mentioned in ref [38]:

$$R_{SRH} = \frac{pn - n_{ie}^2}{TAUP0\left[n + n_{ie}\exp\left(\frac{ETRAP}{kT_L}\right)\right] + TAUN0\left[p + n_{ie}\exp\left(\frac{-ETRAP}{kT_L}\right)\right]}$$

Where ETRAP=difference between trap energy level and intrinsic fermi level

T_L = Temperature in Kelvin

TAUN0 and TAUP0= electrons and hole life times

3.4 <u>Steps and order of ATLAS Syntax:</u>

In ATLAS device simulator, the commands and the order of commands are very important. For simulating a device, we need to specify the meshing, regions, and materials, doping in the specified material, electrodes dimension and its work function. The detailed discussion of syntax using for the device and its order in ATLAS is elaborated below:

3.4.1 Specify the Mesh:

The first statement must be:

MESH SPACE.MULT=<VALUE>

This is followed by a series of X.MESH and Y.MESH statements.

X.MESH LOCATION=<VALUE> SPACING=<VALUE>

Y.MESH LOCATION=<VALUE> SPACING=<VALUE>

.

The SPACE.MULT parameter value is used as a scaling factor for the mesh created by the X.MESH and Y.MESH statements. The default value is 1. Values greater than 1 will create a globally coarser mesh for fast simulation. Values less than 1 will create a globally finer mesh for increased accuracy. The X.MESH and Y.MESH statements are used to specify the locations in microns of vertical and horizontal lines, respectively, together with the vertical or horizontal spacing associated with that line. You must specify at least two mesh lines for each direction. ATLAS automatically inserts any new lines required to allow for gradual transitions in the spacing values between any adjacent lines. The X.MESH and Y.MESH statements must be listed in the order of increasing x and y. Both negative and positive values of x and y are allowed.

3.4.2 Specify the Regions and Materials:

Once the mesh is specified, every part of it must be assigned a material type. This is done with REGION statements. For example:

REGION number=<integer> <material type> <position parameters>

Region numbers must start at 1 and are increased for each subsequent region statement. You can have up to 200 different regions in ATLAS. A large number of materials are available. If a composition-dependent material type is defined, the x and y composition fractions can also be specified in the REGION statement.

The position parameters are specified in microns using the X.MIN, X.MAX, Y.MIN, and Y.MAX parameters. If the position parameters of a new statement overlap those of a previous REGION statement, the overlapped area is assigned as the material type of the new region. Make sure that materials are assigned to all mesh points in the structure. If this isn't done, error messages will appear, and ATLAS won't run successfully.

3.4.3 Specify the Electrodes:

Once you have specified the regions and materials, define the electrodes that contact a semiconductor material. This is done with the ELECTRODE statement. For example:

ELECTRODE NAME=<electrode name> <position_parameters>

You can specify up to 50 electrodes. The position parameters are specified in microns using the X.MIN, X.MAX, Y.MIN, and Y.MAX parameters. Multiple electrode statements may have the same electrode name. Nodes that are associated with the same electrode name are treated as being electrically connected. Some shortcuts can be used when defining the location of an electrode. If no Y coordinate parameters are specified, the electrode is assumed to be located on the top of the structure. The RIGHT, LEFT, TOP, and BOTTOM parameters can also be used to define the location. For example:

ELECTRODE NAME=SOURCE LEFT LENGTH=0.5

specifies the source electrode starts at the top left corner of the structure and extends to the right for the distance LENGTH.

3.4.4 Specify the Doping:

Doping in the material can be specified using the DOPING statement.

For example:

DOPING <distribution_type> <dopant_type> <position_parameters>

Analytical doping profiles can have uniform, gaussian, or complementary error function forms. The parameters defining the analytical distribution are specified in the DOPING statement. Two examples are shown below with their combined effect as given in ref [38]:

DOPING UNIFORM CONCENTRATION=1E16 N.TYPE REGION=1

DOPING GAUSSIAN CONCENTRATION=1E18 CHARACTERISTIC=0.05 P.TYPE \
X.LEFT=0.0 X.RIGHT=1.0 PEAK=0.1

The first DOPING statement specifies a uniform n-type doping density of 10^{16} cm^{-3} in the region that was previously labeled as region #1. The position parameters X.MIN, X.MAX, Y.MIN, and Y.MAX can be used instead of a region number.

3.4.5 <u>The Order of ATLAS Commands:</u>

The order in which statements occur in an ATLAS input file is important. There are five groups of statements that must occur in the correct order specify in Fig 3.2 as mentioned in ref [38]. Otherwise, an error message will appear which may cause incorrect operation or termination of the program. For example, if the material parameters or models are set in the wrong order, then they may not be used in the calculations.

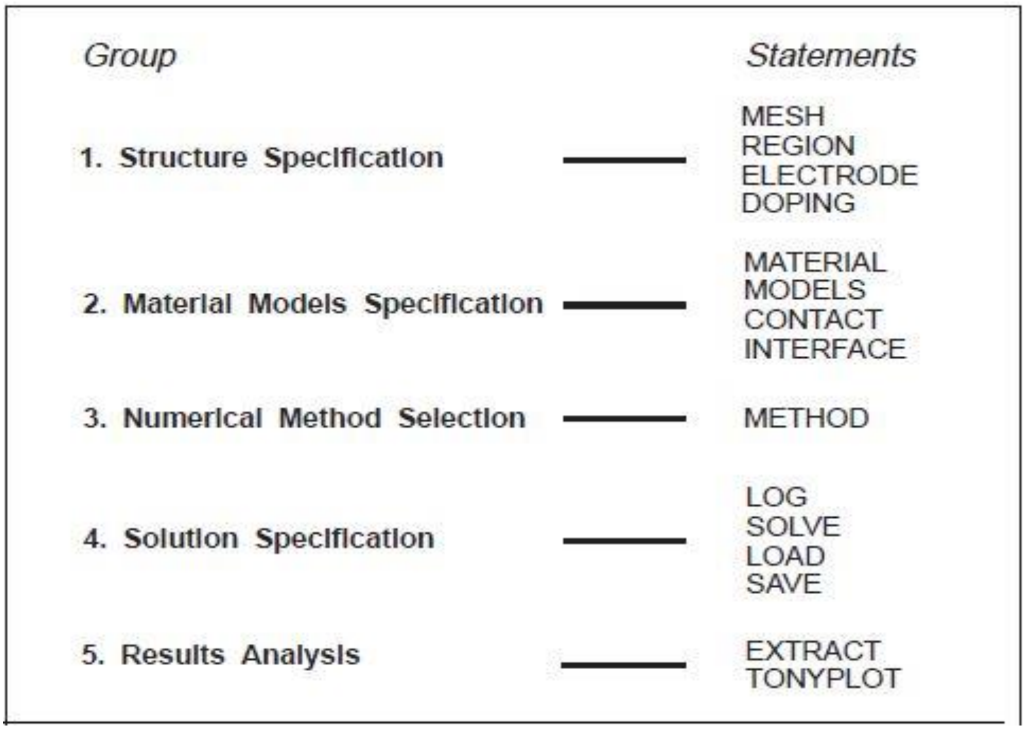


Fig.3.2 ATLAS Command Groups with the Primary Statements in each Group [38]

The order of statements within the mesh definition, structural definition, and solution groups are also important. Otherwise, it may also cause incorrect operation or termination of the program.

4

Analysis of varied Dielectrics as Surface Passivation for GaN HEMT

4.1 <u>Introduction:</u>

This chapter describes the role of surface passivation in AlGaN/GaN HEMT. Different materials that can be used for passivation has also been discussed briefly. The results of simulated GaN HEMTs with surface passivation dielectrics i.e. SiO_2, Si_3N_4, Al_2O_3 has been compared through ATLAS device simulator. In addition, the analog characteristics have been analyzed for the stack passivation i.e. Si_3N_4 and HfO_2 and compare with various dielectrics as surface passivation on simulated GaN HEMT.

4.1.1 Role of surface passivation:

Despite of various advantages of GaN HEMT, it has some challenges too as discussed in Chapter 2. The surface traps play an important role in GaN HEMT device which has been discussed briefly. The effect of traps has been increased at high RF voltages. The electron trapping is due to these traps have a significant impact on RF performance. The RF performance is not same as DC performance at equal voltages; this is called DC to RF Dispersion or knee walk out or current collapse as discussed earlier. The drain current degrades due to surface traps created by dangling bonds and dislocations. The electrons from gate electrode trapped on surface donor states which lead to the formation of the virtual gate that deplete the electrons in the channel and consequently degrades the device performance. To avoid this DC to RF Dispersion in GaN HEMT, many researchers had suggested to passivate the surface with silicon nitride [30, 40]. Surface passivation helps to avoid trapping by satisfying these dangling bonds. Surface passivation plays a key role in GaN HEMT device as reported [41, 42]. A comparative study of GaN HEMT with and without passivation has been reported [33].

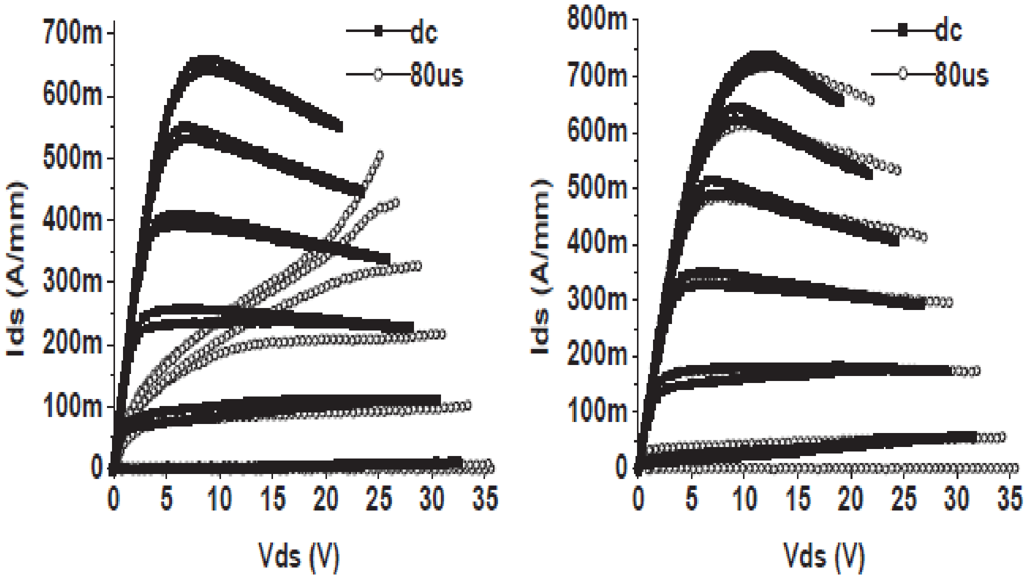


Fig. 4.1 Electrical Characteristics of AlGaN/GaN HEMT without passivation and with surface passivation [32]

Device characteristics of a GaN HEMT device are shown in Fig. 4.1. which have clearly shown the effect of passivation [32]. The dotted current shows pulse characteristics while continuous current is DC characteristics. The drain current degrades at high voltage pulse or RF voltage because of trapping the charge carriers.

Therefore, the benefits of the surface passivation can be described as:

- Prevention of “virtual gate” formation
- Passivation neutralizes the donors
- Modifies the energy level of the surface states
- Prevent current degradation

4.1.2 Different passivation materials for GaN:

The passivation material for high power devices must be chemically inert, thermally stable and its dielectric constant must be high so that the passivation material can withstand high electric fields. Apart from the brighter side of surface passivation as prevention of current collapse, it has its darker side too. The effect of surface passivation is not limited to prevent current collapse, but it has an effect on other DC parameters like breakdown voltage, transconductance, leakage current, etc. The breakdown voltage and leakage current have been studied with surface passivation [33, 43].

As surface passivation plays an important role in AlGaN/GaN HEMT device; an enhanced device performance can be achieved by using an appropriate passivation scheme [33, 44, 45]. Various dielectric materials have been reported for surface passivation such as SiO_2, Si_3N_4, Al_2O_3 and HfO_2 [43, 45-48]. SiO_2 is a commonly used oxide for MOSFET, having low dielectric constant and low thermal conductivity. Al_2O_3 with dielectric constant (k=9.5-12) has better thermal and chemical stability against AlGaN [46]. Si_3N_4 with dielectric constant (k=7.5-10) is a commonly used surface passivation layer for AlGaN/GaN HEMT. The good interface of Si_3N_4 with GaN makes it suitable surface passivation layer for AlGaN/GaN HEMT [43]. HfO_2 has high dielectric constant (k=20–25) and high thermal stability that enables high heat handling capacity but on the other hand, HfO_2, however, suffers from poor interface quality. Moreover, the interface and oxide trap densities of HfO_2 is one to three orders of magnitude larger than that in SiO_2 [47].

Thus, there is a need to investigate the suitable dielectric material for surface passivation. Aiming this, a comparative analysis of AlGaN/GaN HEMT with various dielectric materials i.e. SiO_2, Si_3N_4 and Al_2O_3 as surface passivation layer has been performed. In addition to these dielectrics, a stack of Si_3N_4/HfO_2 as a surface passivation layer has been proposed. The motivation of stacked Si_3N_4/HfO_2 is attributed to the high dielectric constant and high thermal stability of HfO_2 but limiting interface quality of HfO_2 with GaN and better interface compatibility of Si_3N_4 with GaN. Consequently, stacked Si_3N_4/HfO_2 may offer integrated advantages of better thermal stability and good interface quality offered by HfO_2 and Si_3N_4 respectively for acquiring comprehensively better electrical characteristics and good surface passivation for AlGaN/GaN HEMTs. In this respect, the devices with same dimensional structures but with different passivation schemes are accounted for acquiring an optimum dielectric material for surface passivation layer.

4.2 Device Structure and Simulation Methodology:

The simulated device structure of AlGaN/GaN HEMT is shown in Fig 4.2(a) that consists of GaN/AlGaN/AlN/GaN layers on SiC substrate. In the structure, GaN buffer layer (1.5µm) is followed by AlN (1nm), which is spacer layer between GaN and AlGaN. AlN reduces the 2DEG electron wave-function penetration into the AlGaN layer due to wide band gap. $Al_{0.3}Ga_{0.7}N$ (20nm) layer is followed by an undoped GaN cap layer (2nm). Source and drain are ohmic contacts while the gate is a Schottky contact. The thickness of dielectric i.e. Si_3N_4 or SiO_2 or Al_2O_3 that is used for surface passivation between gate-drain and the gate-source region is 100nm. For stacked passivation of Si_3N_4 and HfO_2 layer, the thickness is 50nm for each (i.e. Si_3N_4 and HfO_2) as shown in Fig. 4.2(b).

The device simulation has been performed using the technology computer-aided design (TCAD) Silvaco ATLAS software device simulator [37]. The models used for simulation are polarization model for accounting the spontaneous and piezoelectric polarization, SRH (Shockley-Read-Hall) model for recombination with fixed carrier lifetimes. It is important when high carrier concentration is involved, at the AlGaN/GaN interface. Albrecht mobility model has been accounted for separate control over electrons and holes, and high field mobility model is considered for accounting the velocity saturation [49].

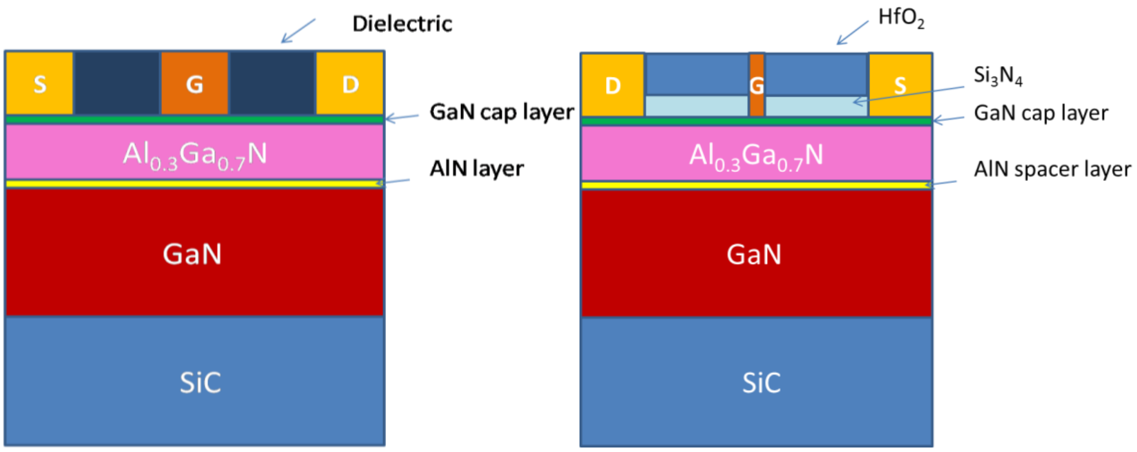


Fig. 4.2: (a) AlGaN/GaN HEMT structure with a 100nm dielectric with different passivation layer i.e. Si_3N_4 or SiO_2 or Al_2O_3 (b) Structure with a stack of Si_3N_4 and HfO_2 with a thickness of 50nm each as a surface passivation layer on AlGaN/GaN HEMT [52]

The simulated devices are of same structure with a gate length of 2µm, gate-drain and gate-source spacing of 3µm each but with different dielectric schemes for surface passivation. The work function of gate schottky contact is taken 5.04 eV. The dielectric constant for Al_2O_3 and HfO_2 is considered 10 and 25 respectively for entire analysis. The electrical parameters like current-voltage characteristics, transconductance, breakdown characteristics and current switching ratio for varied surface passivation layers have been examined. The electric field and potential profile have also been evaluated for the same. The obtained results trend agree well with the data available in the literature [45].

4.3 Results of varied dielectric on GaN HEMT:

The impact on the electric field in AlGaN layer due to various surface passivation layers i.e. SiO_2, Si_3N_4, Al_2O_3 and a stack of Si_3N_4/HfO_2 is shown in Fig. 4.3. It is analysed that the electric field for the stack (Si_3N_4/HfO_2) passivation is higher in source and gate region that enhance the carrier concentration in the channel. This is due to the high dielectric that leads to high polarizability and thereby results in a high surface charge that enhances the electric flux density and consequently increases the carrier concentration in the channel.

The potential profile in GaN channel region for different passivation layers has been shown in Fig. 4.4. It is found that the surface potential for the stack (Si_3N_4/HfO_2) passivation is highest among all four dielectrics i.e. SiO_2, Si_3N_4, Al_2O_3 and a stack of Si_3N_4/HfO_2 used as a passivation layer on AlGaN/GaN HEMT.

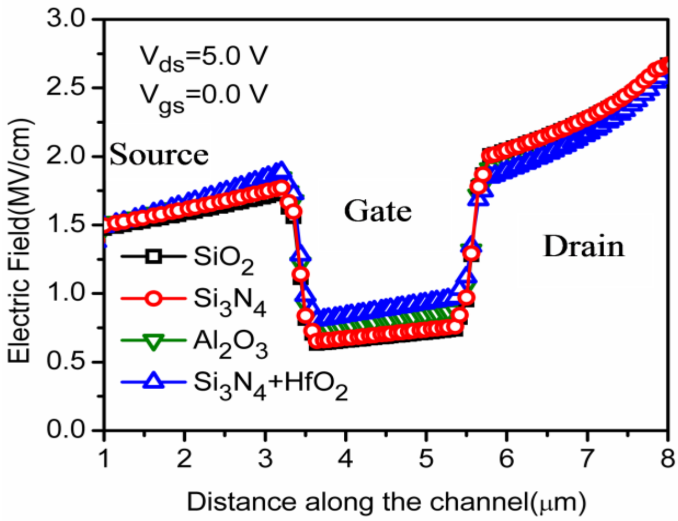


Fig. 4.3: Electric field profile variation of AlGaN/GaN HEMT in AlGaN layer for SiO_2, Si_3N_4, Al_2O_3 and for a stack of Si_3N_4 and HfO_2 as surface passivation [52].

Moreover, it is analysed that the surface potential for Al_2O_3 is also higher than Si_3N_4 followed by SiO_2. Thus it indicates that the surface potential in GaN channel region increases with increase in dielectric constant of the passivation layer.

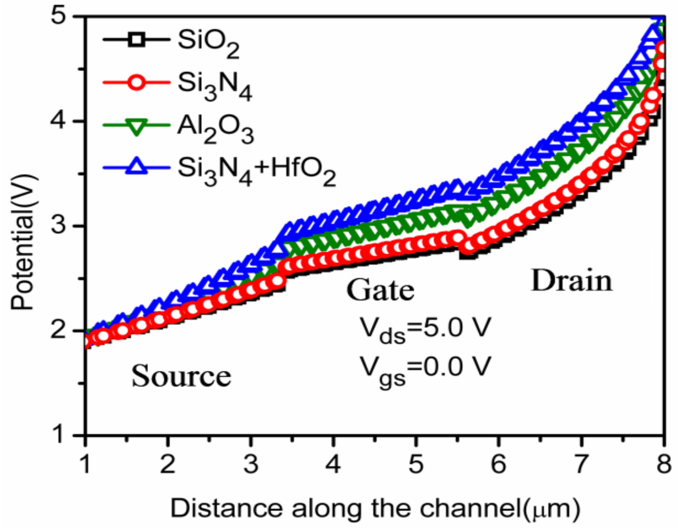


Fig. 4.4: Potential profile variation of AlGaN/GaN HEMT for different surface passivation layer i.e. SiO_2, Si_3N_4, Al_2O_3 and for a stack of Si_3N_4 and HfO_2 w.r.t distance along the channel [52].

Furthermore, the electron current density for all different passivation schemes at the hetero-interface AlGaN/AlN/GaN is shown in Fig. 4.5. The electron current density for the stack (Si_3N_4/HfO_2) passivation is the highest. It is calculated that the electron current density for the stack is increased by ~13 % and ~37% in comparison to Al_2O_3 and Si_3N_4 respectively.

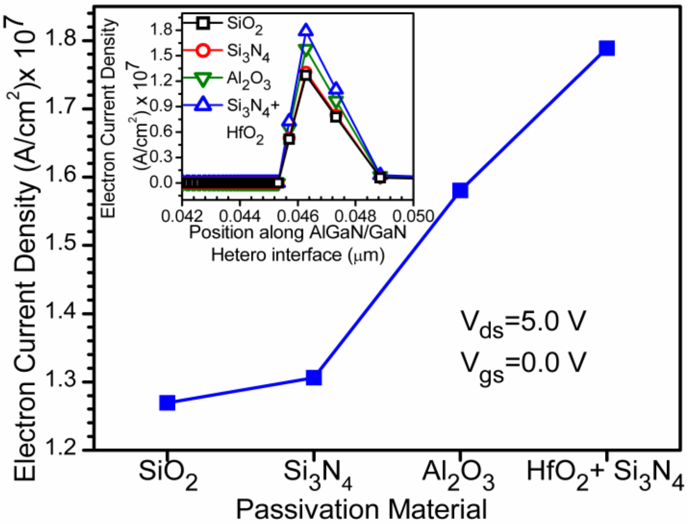
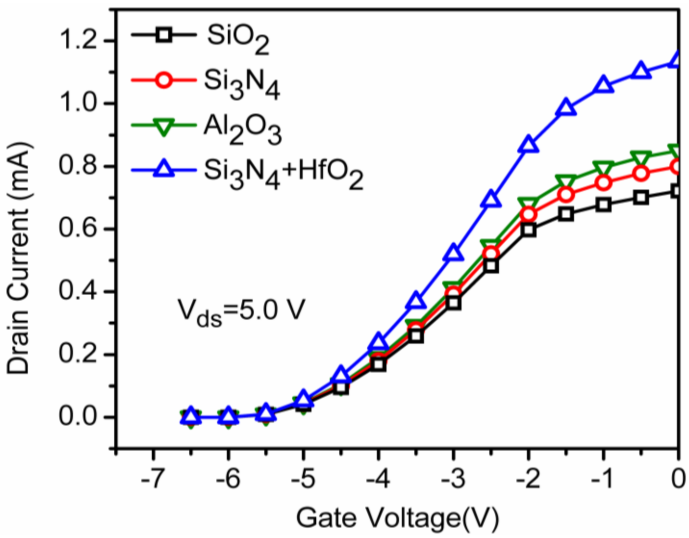


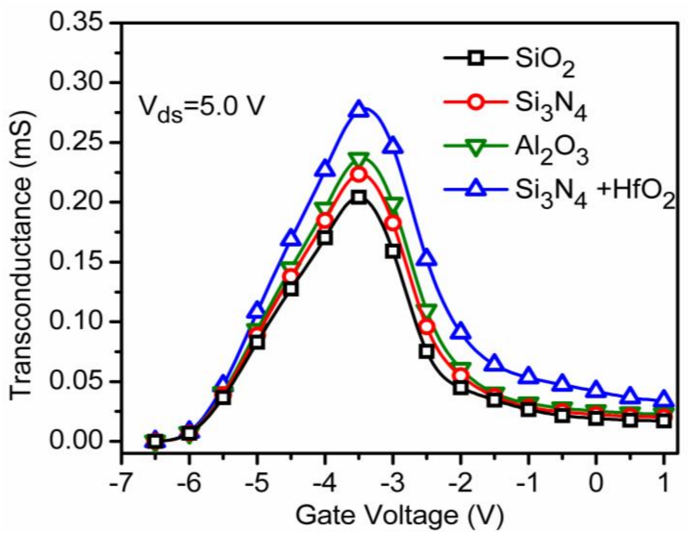
Fig. 4.5: Electron current density for varied surface passivation layers i.e. Si_3N_4, SiO_2, Al_2O_3 and a stack of Si_3N_4/HfO_2. Inset: Profiles for electron current density at hetero-interface [52].

Moreover, there is a little increment in electron current density of Si_3N_4 w.r.t. SiO_2. It validates that the high-k with Si_3N_4 stack contribute more number of carriers in the channel than other dielectrics used for surface passivation. The inset of Fig. 4.5 shows the electron current density profile at the hetero-interface for the all dielectric surface passivation layers i.e. SiO_2, Si_3N_4, Al_2O_3, and a stack of Si_3N_4/HfO_2 on AlGaN/GaN HEMT.

The analog characterization for AlGaN/GaN HEMT device with different passivation layers has also been investigated. The impact of different surface passivation layers i.e. SiO_2, Si_3N_4, Al_2O_3 and a stack of Si_3N_4/HfO_2 on transfer characteristics is shown in Fig. 4.6(a). It is observed that the drain current for the stack of dielectric (Si_3N_4/HfO_2) is highest and is lowest in the case of SiO_2. It is investigated that with an increase in dielectric constant of the material, the drain current increases. This increase in drain current is attributed to the fact of increased electric field in source and gate region which in turn enhances the number of carriers in the channel with high-k. Moreover, for the stack passivation, the attributed factor of increasing in drain current is also due to the good interface of Si_3N_4 to GaN. It is evaluated that in the case of stack (Si_3N_4/HfO_2) passivation, the drain current increases by 27% and 36% w.r.t. Al_2O_3 and Si_3N_4 respectively.



(a)



(b)

Fig. 4.6(a) Transfer characteristics drain current w.r.t. gate voltage at constant V_{ds}=5.0V (b) Transconductance variation for different surface passivation layers i.e. Si_3N_4, SiO_2, Al_2O_3 and a stack of Si_3N_4/HfO_2 [52].

The Transconductance (g_m) is an important analog parameter that defines gain of the device. The variation of g_m with gate voltage for different passivation layer is shown in Fig. 4.6(b). It is observed that g_{max} i.e. peak in transconductance curve is highest for stack passivation. The increase in maximum transconductance is ~35%, 16% and 9% for a stack of Si_3N_4/HfO_2, Al_2O_3, Si_3N_4 w.r.t SiO_2 respectively. Also, Si_3N_4/HfO_2 (SiO_2) has the highest (lowest) transconductance and hence highest (lowest) gain among the four passivation layers used.

The breakdown voltage for different passivation layer on AlGaN/GaN HEMT is shown in Fig. 4.7. The profile of breakdown voltage that has been evaluated by applying high drain voltage in the pinch-off region is shown in the inset of Fig. 5.6. The breakdown in AlGaN/GaN HEMT is avalanche breakdown due to impact ionization. Surface passivation helps to improve breakdown voltage by relaxing the high electric field near drain edge [42, 50]. It has been found that the breakdown voltage is highest for stack and lowest for SiO_2 as a passivation layer on AlGaN/GaN HEMT. There is variation in electric field near the drain for different dielectrics used for surface passivation. The high-k surface passivation helps to suppress electron trapping near drain thereby relaxing the high electric field at drain edge. The surface interface trap densities are smaller for Si_3N_4 due to good interface with GaN than other dielectric materials. The stack passivation, a combination of high-k and Si_3N_4 offers the advantage of low interface trap densities and

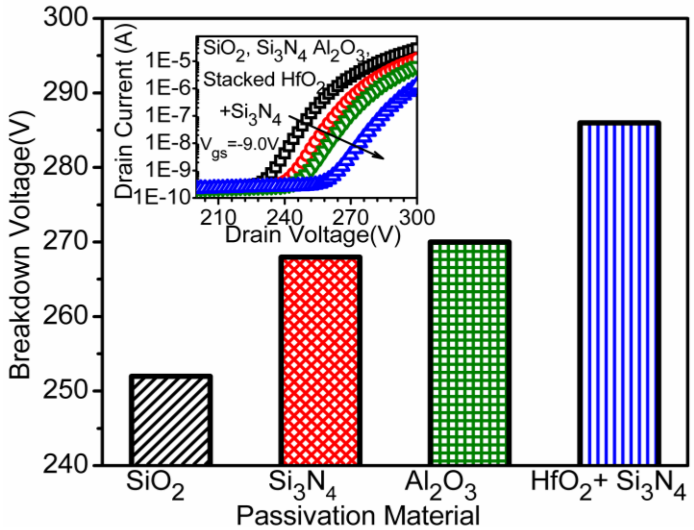


Fig. 4.7: Breakdown voltage of AlGaN/GaN HEMT with varied surface passivation layers. Inset: Profile of breakdown in pinch-off region of AlGaN/GaN HEMT with various surface passivation layers [52].

suppressing electron trapping at surface states due to high-k which consequently leads to high breakdown voltage. While in the case of SiO_2, the surface related traps increases that result in high leakage current and thereby low breakdown voltage.

The current switching ratio i.e. I_{ON}/I_{OFF} ratio has also been evaluated for different surface passivation layers and is shown in Fig. 4.8. In this respect, the I_{ON} and I_{OFF} are defined as I_{ds} @ V_{gs}= 0V and -6.5V respectively. Since the I_{ON} is highest for stack passivation scheme Si_3N_4/HfO_2 among the four dielectric passivation layers, i.e. SiO_2, Si_3N_4, Al_2O_3 and a stack of Si_3N_4/HfO_2., the ratio between on and off current is also highest.

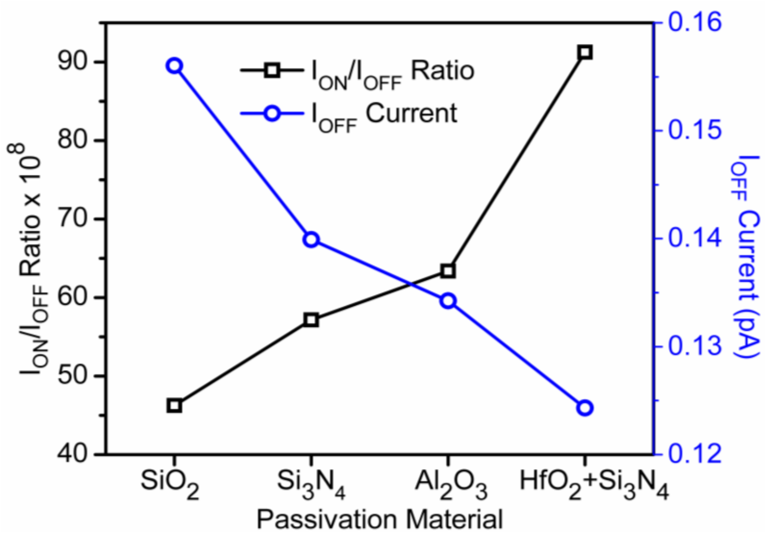


Fig. 4.8: Current switching i.e. I_{ON}/I_{OFF} ratio and I_{OFF} variation for varied dielectric as surface passivation layers on AlGaN/GaN HEMT [52].

Although the change in I_{OFF} is very small, still it contributes to increase the I_{ON}/I_{OFF} ratio. In consistence with aforementioned results, it is evident that the stack passivation of Si_3N_4/HfO_2 has better electrical characteristics than other dielectric material i.e. SiO_2, Si_3N_4, and Al_2O_3.

4.4 Summary:

In this work, the evaluated electrical parameters for varied passivation layers of AlGaN/GaN HEMT have been analysed using ATLAS device simulator. It is obtained that the drain current and transconductance increases for high-k passivation layers. High-k dielectric can also withstand with high electric fields. Therefore, for high power devices, SiO_2 has major disadvantage of a low dielectric constant as well as lower thermal stability. The comparison of various electrical parameters of GaN HEMT devices with different dielectrics i.e. SiO_2, Al_2O_3, and Si_3N_4 has been done. HfO_2 has high dielectric constant and high thermal stability, but it has poor interface quality with GaN.

In order to mitigate the limitation of poor interface quality of HfO_2, a stack of Si_3N_4 and high-k HfO_2 is also proposed. It is obtained that the stack of Si_3N_4 with HfO_2 as surface passivation layer results in good passivation interface due to smaller interface (Si_3N_4/GaN) trap densities and better electrical characteristics due to high-k. Therefore, due to the higher value of effective dielectric constant, a combination of HfO_2 and Si_3N_4 can be a better choice for passivation of AlGaN/GaN HEMT device than an individual Si_3N_4 layer. Thus, the high current and high breakdown voltage acquired by HfO_2/Si_3N_4/AlGaN/GaN HEMT makes the device suitable for the high power applications.

5

Impact on device performance of nanoscale AlGaN/GaN HEMT with variation in surface passivation stack

This chapter includes the study of variation in surface passivation stack ratio of Si_3N_4 and HfO_2 on AlGaN/GaN HEMT. The effect on analog and linearity characteristics have been analysed with variation in surface passivation ratio.

5.1 Introduction:

As discussed in Chapter 4, due to small interface trap densities, Si_3N_4 have good interface properties with GaN. While HfO_2 suffers from poor interface quality with GaN due to larger interface trap densities but have advantages of high dielectric constant (k=20–25) and high thermal stability that enables high heat handling. Therefore, the stack of Si_3N_4/HfO_2 is incorporated on the nanoscale AlGaN/GaN HEMT for acquiring comprehensively better electrical characteristics and good surface passivation due to integrated advantages of HfO_2 and Si_3N_4 respectively. But to find out the optimum combination in stack passivation, the ratio of HfO_2 and Si_3N_4 has been varied in the stack to investigate the suitable combination for the surface passivation of AlGaN/GaN HEMT.

Aiming this, a comparative analysis of HEMT devices with a varied thickness of HfO_2/Si_3N_4 i.e. 90/10 nm, 70/30 nm, 50/50 nm, 30/70 nm as surface passivation material has been performed. The total thickness of stack has been kept constant i.e. 100nm. In this respect, the AlGaN/GaN HEMT devices with same dimensional structures but having different ratios of HfO_2/Si_3N_4 as surface passivation schemes are accounted for acquiring an optimum combination to obtain better device performance. The linearity analysis has also been done for the varied passivation layers to get the better device performance for different ratios of Si_3N_4 and HfO_2.

5.2 Simulated Device Structure:

Fig. 5.1 shows the simulated device structure of AlGaN/GaN HEMT. The device contains GaN buffer layer with a thickness of 1.5μm on SiC substrate. The buffer layer is followed by AlN, which is a spacer layer of 1nm between GaN and AlGaN. The spacer layer is followed by $Al_{0.3}Ga_{0.7}N$ having a thickness of 18nm.

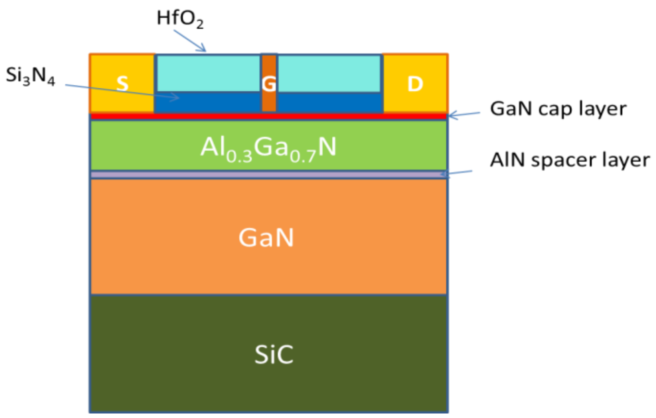


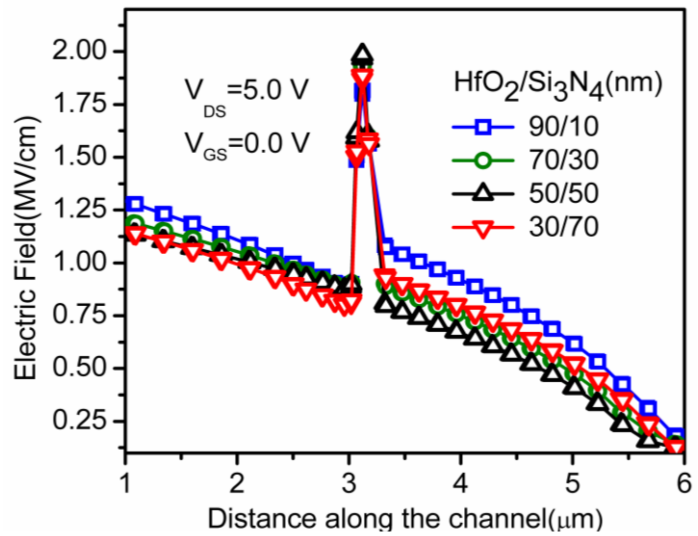
Fig. 5.1: AlGaN/GaN HEMT structure with 100nm surface passivation with a stack of Si_3N_4 and HfO_2 with variable thickness [53].

The AlGaN layer is followed by an undoped GaN cap layer of 2nm. Source and drain contacts are ohmic while the gate contact is a Schottky. The total thickness of surface passivation layer is 100 nm that is a stack of Si_3N_4 and HfO_2. The different thickness of HfO_2 i.e. 90nm, 70nm, 50nm, and 10nm has been varied on the device while keeping the stack thickness constant i.e. 100nm. The gate length is 100nm for the entire comparative analysis.

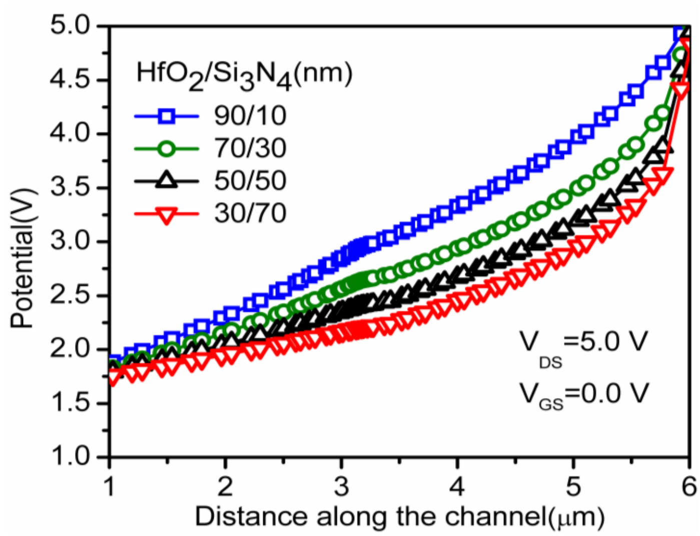
The device simulation has been performed using the technology computer-aided design (TCAD) Silvaco ATLAS software device simulator. The models invoked during simulation are polarization model, SRH (Shockley-Read-Hall) model, Albrecht and high field mobility model [49]. The electrical parameters like current-voltage characteristics, Transconductance and linearity parameters like higher order transconductance coefficients (g_{m2}, g_{m3}), VIP2, VIP3 have been examined for different ratio of the HfO_2/Si_3N_4 surface passivation layer. The electric field, potential, electron velocity and electron current densities have also been evaluated.

5.3 <u>Results of the varied ratio for stack passivation on GaN HEMT:</u>

The impact on the electric field and potential along the channel of AlGaN/GaN HEMT due to different ratio of HfO_2/Si_3N_4 is shown in Fig. 5.2(a) and (b) respectively.



(a)

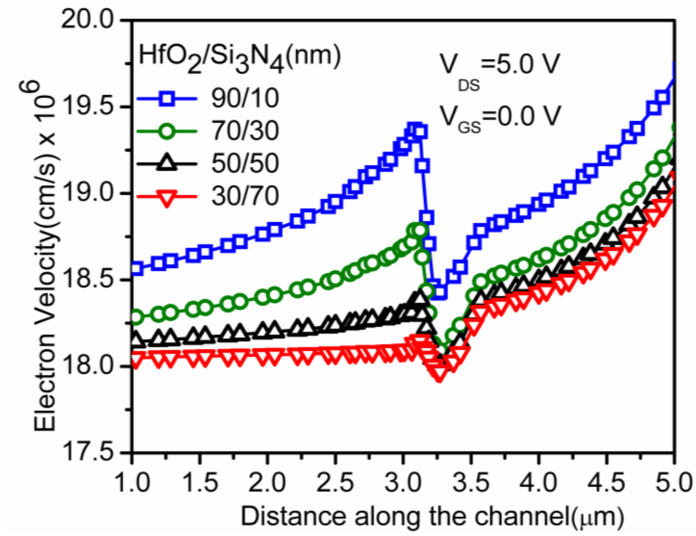


(b)

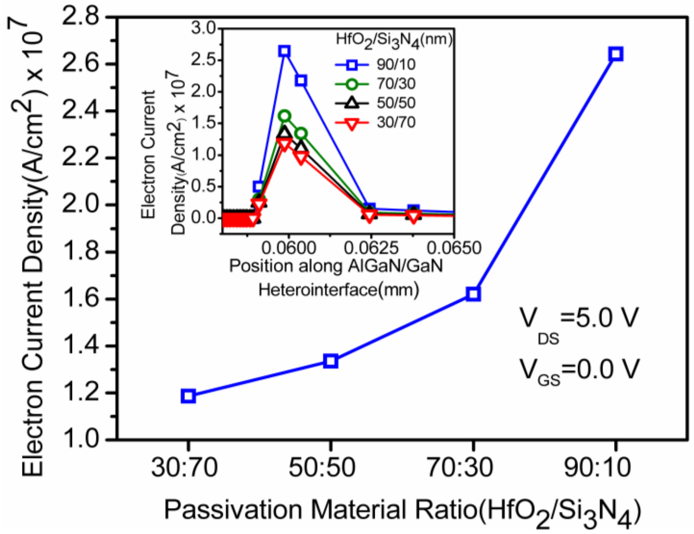
<u>Fig 5.2: (a) Electric field along the channel for the varied ratio of stack HfO_2/Si_3N_4 on AlGaN/GaN HEMT (b) Potential profile variation along the channel GaN for different ratios [53].</u>

It is analyzed that the electric field and potential are higher for the higher value of HfO_2. It is attributed due to high dielectric constant that leads to high polarizability and thereby increases surface charge which enhances the electric flux density and potential along the channel.

The electron velocity along the channel is shown in Fig 5.3(a). It is observed that the electron velocity has been increased for the higher value of HfO_2. Furthermore, the electron current density at the hetero-interface AlGaN/AlN/GaN for all different ratio of HfO_2/Si_3N_4 as surface passivation for AlGaN/GaN HEMT is shown in Fig 5.3 (b).



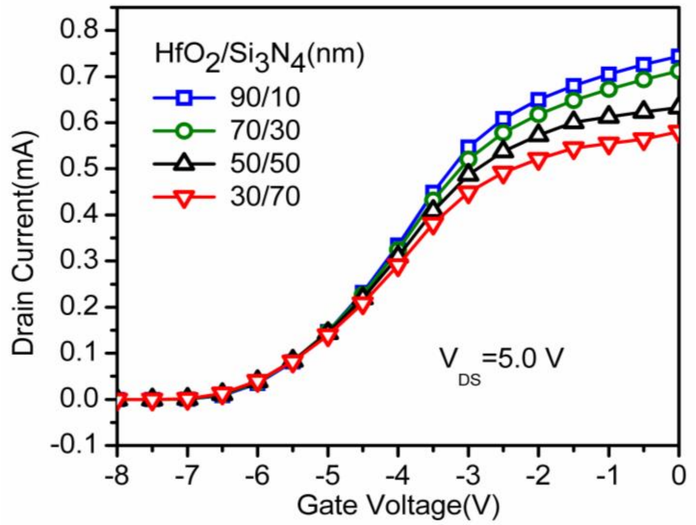
(a)



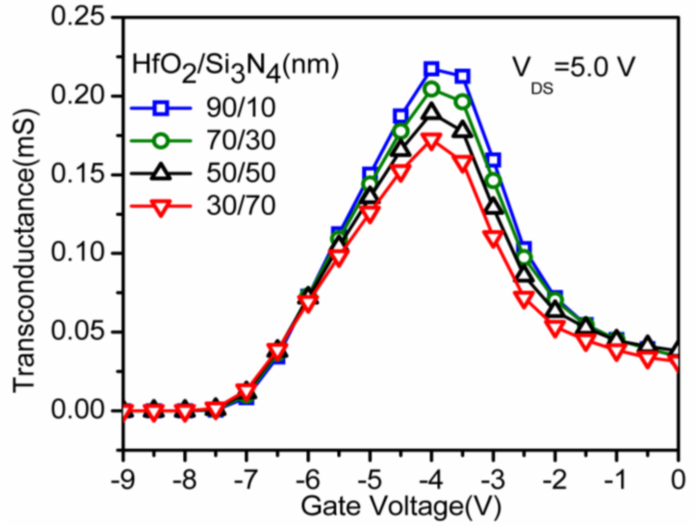
(b)

Fig. 5.3: (a) Electron velocity w.r.t distance along the channel for the varied thickness of HfO_2 (b) Electron current density at AlGaN/GaN Hetero-interface for different ratio of HfO_2/Si_3N_4 as surface passivation on AlGaN/GaN HEMT, Inset: Electron current density profiles for different ratio of stack HfO_2/Si_3N_4. [53].

The electron current density is highest for the HfO_2/Si_3N_4 thickness (90nm/10nm) among all other combination of the stack. It is due to the fact that high effective dielectric constant contributed high surface charge that consequently increases the carrier concentration in the channel.



(a)

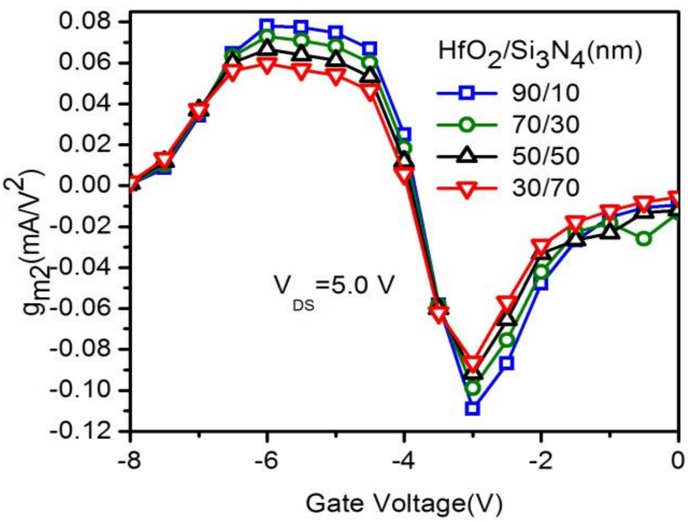


(b)

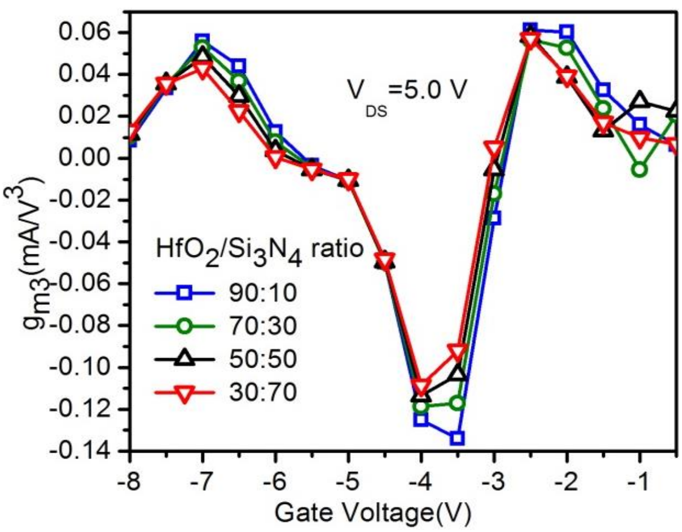
Fig. 5.4: (a) Transfer characteristics drain current versus gate voltage for different ratio of HfO_2/ Si_3N_4 as surface passivation on AlGaN/GaN HEMT (b) Transconductance (g_m) variation for different thickness of HfO_2 in the stack of surface passivation at constant V_{ds}=5.0V [53].

The impact of the different ratio for HfO_2/Si_3N_4 as a surface passivation layer on transfer characteristics is shown in Fig. 5.4(a). The transconductance variation with different thickness of HfO_2 is shown in Fig. 5.4(b). It is observed that the drain current and peak of transconductance (g_{max}) is highest (lowest) for the highest (lowest) thickness of HfO_2 in the stack. The increase in drain current and peak of transconductance g_{max} is due to the fact of increased electron velocity and electron carrier concentration in the channel because of the higher electric field with high dielectric constant.

The linearity analysis has also been done for the varied HfO_2/Si_3N_4 ratio of the surface passivation layer on AlGaN/GaN HEMT.



(a)

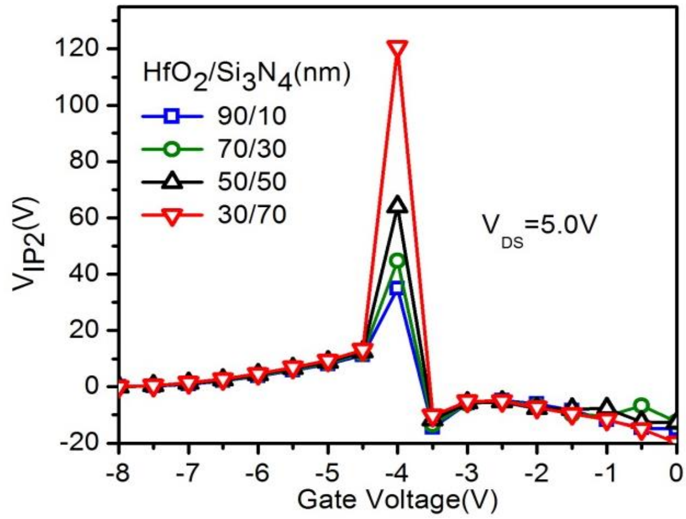


(b)

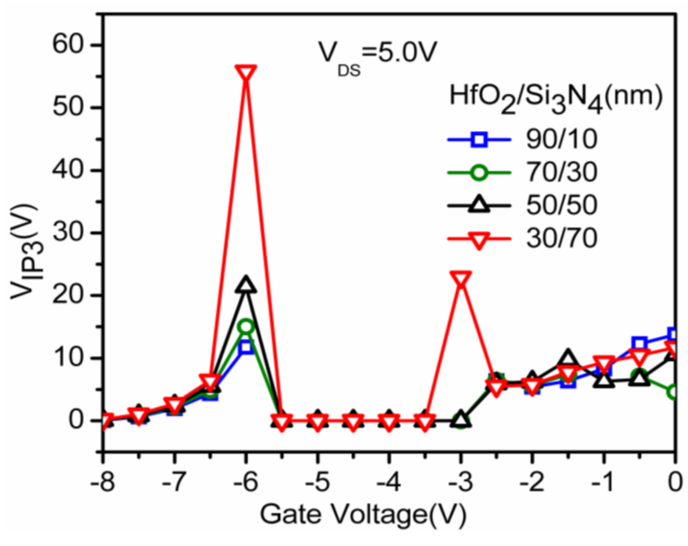
Fig. 5.5 : (a) Second order of transconductance (g_{m2}) and third order transconductance (g_{m3}) w.r.t gate voltage for different ratio of HfO_2/ Si_3N_4 as surface passivation on AlGaN/GaN HEMT [53].

The various figure of merits (FOMs) i.e. higher order transconductance coefficients (g_{m2}, g_{m3}), VIP2, and VIP3 have been evaluated for linearity analysis. Fig. 5.5(a) and (b) shows the second order of transconductance i.e. g_{m2} and third order of transconductance i.e. g_{m3} respectively. g_{m2} is a second order transconductance i.e. second order derivative of drain current versus gate voltage of HEMT or first order derivative of transconductance; its unit is A/V^2.While g_{m3} is a third order transconductance i.e. third order derivative of drain current versus gate voltage or second order derivative of transconductance, its unit is A/V^3. Fig. 5.6 (a) and (b) shows the VIP2 (Voltage Intercept Point) and VIP3 respectively. VIP2 (Voltage Intercept Point) is extrapolated gate voltage where fundamental tone and second harmonics are equal. VIP2 can be defined as:

$$VIP_2 = 4 \times \frac{g_{m1}}{g_{m2}}$$



(a)



(b)

Fig. 5.6 : (a) VIP2 (b) VIP3 versus gate voltage for the varied thickness of HfO_2 in the stack of surface passivation at constant V_{ds}=5.0V [53].

VIP3 (Voltage Intercept Point) is extrapolated gate voltage where fundamental tone and third harmonics are equal. VIP3 can be defined as:

$$VIP_3 = \sqrt{24 \times \frac{g_{m1}}{g_{m3}}}$$

VIP2 and VIP3 must be as high as possible while second order transconductance (g_{m2}) and third order transconductance (g_{m3}) must be as small as possible for better linearity [51]. A small decrement in second order transconductance makes a large increment in VIP2 as second order transconductance is inversely proportional to VIP2. While for third voltage intercept point depends on third order transconductance, a very small change in g_{m3} makes large increment in VIP3. The results show that the better linearity characteristics have been obtained for the lower thickness of HfO_2 and greater value of Si_3N_4.

5.4 <u>Summary:</u>

In order to mitigate the limitation of poor interface quality of HfO_2, a stack of Si_3N_4 and high-k HfO_2 is incorporated on the nanoscale AlGaN/GaN HEMT device as a surface passivation layer. The effect of the varied ratio of HfO_2/Si_3N_4 as a surface passivation layer on the electrical characteristics and linearity parameters of the device is analyzed. Results show that the drain current and transconductance increases for the higher thickness of HfO_2, while the linearity parameters are better for the lower thickness of $HfO_{2.}$ Thus, due to the tradeoff between the electrical and linearity parameters, the optimum ratio of HfO_2/Si_3N_4 has to cogitate for acquiring better device performance.

6

Conclusion

The aim of the work was to optimize the different dielectrics as surface passivation for AlGaN/GaN HEMT. The ATLAS device simulator has been used for understanding and improving the device performance with different surface passivation.

6.1 Summary:

GaN is a suitable candidate for high power and high frequency applications due to its superior property and its heterostructure with AlGaN. The various favored properties of GaN have been discussed in detail in Chapter 2 that includes wide band gap, high breakdown electric field, high saturation velocity and high thermal stability. The formation of 2DEG, due to its heterostructure with AlGaN, has also been discussed in the same. The sheet carrier density is high due to 2DEG and because of high saturation velocity; the drain current in HEMT device is high. The simulation of the device gives the platform to understand the device inside. The simulation methodology and models have been discussed in Chapter 3. Apart from the superior properties, the challenges with the GaN technology has also been discussed i.e. surface and bulk traps, current collapse and self- heating. The current collapse is due to surface traps, the charge carriers being trapped into surface donors and due to this virtual gate formation take place and consequently current decrease. This phenomenon is also called DC to RF dispersion, which is described in Chapter 2 and Chapter 4. Surface passivation helps to improve device characteristics by preventing the formation of the virtual gate. The role of passivation has been explained in chapter 4. Various dielectrics have been used as surface passivation to analyze the effect on DC characteristics. For power devices, surface passivation material must withstand with the high electric field. Therefore high-k and thermally stable dielectrics would be suitable. Electrical parameters have been evaluated for devices with different dielectrics i.e. SiO_2, Si_3N_4, and Al_2O_3 as surface passivation. In this respect, HEMT devices with different dielectrics i.e. SiO_2, Si_3N_4, and Al_2O_3 but with the same dimension have been compared. A stack of Si_3N_4 and HfO_2 has also been proposed as surface passivation, due to good interface property of GaN with $Si_3N_{4,}$ and high dielectric constant as well as the high thermal stability of HfO_2 that makes it suitable for GaN HEMT surface passivation. Results show that higher the dielectric constant of passivation material, better the device characteristics. These results have been explained in detail in Chapter 4.

Furthermore, the ratio of stack passivation has also been varied as surface passivation of nanoscale AlGaN/GaN HEMT. The effects on DC and linearity parameters have been studied with a varied ratio of stack passivation on GaN HEMT. Results show that the DC performance is better for the highest thickness of HfO_2 in the stack, as the effective dielectric constant increases with increase thickness of HfO_2 while the linearity parameters have been improving for higher thickness of $Si_3N_{4.}$ The results have been discussed in detail in Chapter 5. The optimum combination of Si_3N_4 and HfO_2 in the stack has to cogitate to obtain better device performance for RF applications.

Therefore, the role of surface passivation is very important, choice of passivation material affect the device performance drastically. In the view of above, the study has been done using ATLAS device simulator to understand the effect of surface passivation and to find out suitable passivation material for AlGaN/GaN HEMT.

6.2 Future Outlook:

The effects on the surface traps and polarization charges can be further analyzed w.r.t. different passivation layers for GaN HEMT. To determine the surface charge effects, the interface charge density has to be estimated carefully. Further AC analysis can be carried out for GaN HEMT with variation in a stack of Si_3N_4/HfO_2 as surface passivation. The effect on gain, frequency, and S-parameters can be further studied w.r.t different passivation layers. The current collapse phenomenon can also be studied for the various passivation layers on GaN HEMT. To study the current collapse/knee walkout/DC to RF dispersion, RF characteristics or pulse characteristics have to be analyzed with a different passivation layer on GaN HEMT. Gate-source Capacitance (C_{gs}) can also be evaluated and utilized it for further study of polarization charges and trapping.

To explore further, gate-drain capacitance (C_{gd}) can also been analyzed. Breakdown voltage and gate leakage current can also be further evaluated for different ratio of stack passivation. This work is based on simulated device structure and evaluated electrical parameters using the calibrated models used for GaN HEMT. Exact traps charges and its energy levels play an important role in defining the AC performance that needs to be verified. For this, a fabrication of GaN HEMT with these varied passivation layers and stack passivation can be done and measure to get the actual results.

List of Publications

International Conference:

[1] Henika Arora, Jaya Madan, Rishu Chaujar, "Analysis of varied dielectrics as surface passivation on AlGaN/GaN HEMT for analog applications", accepted in IEEE, The International Conference on Microelectronics Devices, Circuits and Systems (ICMDCS 2017), Vellore, India,10th- 12th August 2017.

[2] Henika Arora, Jaya Madan, Rishu Chaujar, "Impact on Analog and Linearity performance of nanoscale AlGaN/GaN HEMT with variation in surface passivation stack", accepted in 9th International conference on Advanced Nanomaterials, ANM 2017, Portugal,19th -21st July 2017

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