STUDY OF NORMALLY-OFF HIGH ELECTRON MOBILITYTRANSISTORS (HEMT)

Thesis Submitted
In Partial Fulfilment of the Requirement
For The Award of the Degree of

Master of Technology

In

VLSI Design and Micro-Electronics Technology

Of

Jadavpur University

by

SANDEEPA DAS

(EXAMINATION ROLL NO.:M6VLSI9012)
(UNIVERSITY REGISTRATION NO.:137276 of 2016-2017)

Under the Supervision of

Dr. Chandrima Mondal

DEPARTMENT OF ELECTRONICS AND
TELECOMMUNICATION ENGINEERING
FACULTY COUNCIL OF ENGINEERING AND TECHNOLOGY
JADAVPUR UNIVERSITY
KOLKATA, INDIA
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FACULTY COUNCIL OF ENGINEERING AND TECHNOLOGY

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CERTIFICATE

This is to certify that the thesis entity, "**STUDY OF NORMALLY-OFF GaN HIGH ELECTRON MOBILITY DEVICES (HEMT)"** submitted by **SANDEEPA DAS** (Examination Roll No:- M6VLSI9012 ;University Registration No.:137276 of 2016-2017) of **JADAVPUR UNIVERSITY,KOLKATA** is a record of bonafide research work under my supervision and be accepted in partial fulfilment of the requirement for the degree of **MASTER OF TECHNOLOGY IN VLSI DESIGN AND MICROELECTRONICS TECHNOLOGY** of the institute .The research results presented in this thesis are not included in any other paper submitted for the award of the degree to any other university or institute.

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The foregoing thesis is hereby approved as a credible study of an engineering subject and presented in a manner satisfactory to authorization acceptance as pre-requisite to the degree for which it has been submitted. It is understood that by this approve any statement made, opinion or conclusion drawn there in but approve the thesis only for which it is submitted.

Committee on Final Examination
For the Evaluation of the Thesis

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Signature of Examiner

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF THE ACADEMIC THESIS

I hereby certify that this thesis entitled, “**Study of Normally-off GaN High Electron Mobility Transistors (HEMT)**”.

- Is original and has been done by me under the guidance of my supervisor.
- This work has not been submitted to any other institute for any degree.
- All the information have been obtained and presented in accordance with academic rules and ethical Code of Conduct of the institute.

I also declare that, as required by the rules and conduct, whenever I have used materials that are not original to this work, I have given credit to them by citing them in the text of the thesis and giving their details in the bibliography.

Sandeepa Das

Examination Roll No. :M6VLSI9012

University Registration No. : 137276 of 2016-2017

Thesis Title: Study of Normally-off High Electron Mobility Transistors

SANDEEPA DAS

(Signature with Date)

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Chapter 1

INTRODUCTION

1.1 Background

HEMT is a field effect transistor incorporating a junction between the two semiconductors with different band gaps as the channel.The HEMT is also known as the Two Dimensional Electron Gas (2DEG) Transistor, Modulation Doped Field Effect Transistor(MODFET) and Heterostructure Field-Effect Transistor(HFET). But instead of carrying the current through a thick channel, it relies on the formation of the Two Dimensional Electron Gas (2DEG) at the heterojunction interface.

1.2. HEMT Structure

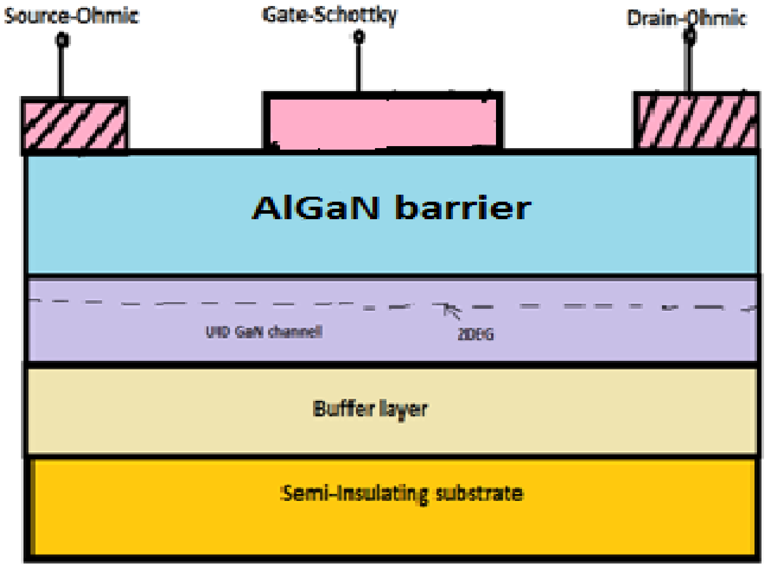

Fig-1.1: A typical cross-sectional schematic of AlGaN/GaN HEMT device is shown

A typical cross-sectional schematic of AlGaN/GaN HEMT device is shown in the figure 1.1. The device is grown on a semi-insulating substrate which has high thermal stability and which has close lattice matching with GaN. A buffer layer is grown on the top of the substrate, which acts as an isolation layer. The defects from the substrate are minimised using this GaN buffer layer. The device uses schottky gate contact and ohmic source and drain contact. The channel in HEMT is formed at the heterojunction interface of the AlGaN barrier and GaN channel layer. AlGaN /GaN based HEMTs proved to be the promising technology platform for high power and high frequency applications.

1.2.1. Layers and Contacts in HEMT

a. Different Layers in HEMT

- Semi-insulating substrate: A HEMT is grown on a semi-insulating substrate. We should use an undoped semiconductor featuring very high resistivity and with low intrinsic carrier concentration having a wide bandgap for this layer.

- Buffer layer: This layer is used to reduce the lattice mismatch between the substrate and GaN channel when GaN is grown on any substrate except sapphire leading to lattice mismatch and tensile stress which can cause crack.

- Channel layer: The GaN channel layer is grown on the top of the buffer layer and within this layer the channel will be formed.

- Barrier layer: This layer is grown on the top of the channel layer. AlGaN semiconductor is used as the barrier layer as they have higher bandgap and less electron affinity compared to GaN. The potential Quantum well is created because of the conduction band offset and electrons are trapped creating a channel.

b. Contacts in HEMT

We have two contacts in HEMT. One is the ohmic contact and the other one is schottky contact.

Ohmic Contact:

- Generally, it refers to a non-injecting contact in which the current-voltage relationship under the forward biased and reverse biased is linear and symmetrical.
- In reality,the voltage drop across the metal semiconductor interface is negligible compared to the voltage drop across the Bulk semiconductor.
- It is difficult to make ohmic contact in wide bandgap semiconductors (e.g. group Nitrides) as it does not generally exist in metal with low enough work function to yield low barrier.
- In order to obtain a low resistance ohmic contact we have to increase the doping level.
- It allows the current to pass into and out of the underlying semiconductor with ease.
- The formation of ohmic contacts with low resistivity is important for optimal device performance.
- Formation of a good ohmic contact is ideally required choosing a metal with very small work function.

Schottky Contact

- The device which is formed using schottky contact will have a great impact on the device performance.
- Diode idealities are 1, low gate leakage current to allow for effective channel modulation, small gate length to improve cut off frequency.
- The fabrication of schottky contacts on n-type material requires the use of metals with large work function.
- The Metal-Semiconductor junction must be thermally stable and gate metal must be highly conductive to minimise the gate resistance.
- High frequency RF devices require a perfect contact to work in close synchronisation with high mobility 2DEG channel.
- A schottky S/D HEMT reduces the leakage current and increases the current of the device, increases the breakdown voltage of the device.
- The schottky contact is done to achieve a high improvement on the off-state breakdown voltage of the lattice.

Why Schottky contact is done at gate and Ohmic contact at Source and Drain?

The main objective is to change the potential at the channel by applying voltage at the gate. Schottky contact produces an energy band discontinuity between the channel and the gate contact which is known as schottky barrier**.** It blocks the flow of the electrons from channel to gate and vice-versa. However, there will be no energy band discontinuity in Source and Drain if you apply ohmic contact at the source and drain the current will flow through the source and drain.

1.2.2. Types of HEMT

High Electron Mobility Transistors are of two types normally-on or deletion type and normally-off or enhancement type. Conventional HEMTs are depletion-type. But due to the application of HEMTs in the power electronic circuits, the HEMTs are required to convert to the enhancement type to avoid device destruction.

1.2.3. HEMT Operation

In the conventional HEMT structure, the wide band-gap semiconductor is doped with n-type while the narrow bandgap semiconductor remains undoped. The electrons from wide bandgap semiconductor diffuse to the narrow band-gap semiconductor due to the higher electron affinity of the undoped semiconductor (for example if we have an AlGaN/GaN HEMT, then the AlGaN is doped with an n-type material and GaN is undoped). This process continues until a balanced Fermi-Level is maintained in between these two semiconductors and equilibrium is established.

Because of the resulting electrostatics, a new triangular well is formed in the vicinity of the narrow bandgap side of the heterojunction. This well is called the Two Dimensional Quantum

Well and the electrons are confined within this quantum well formingTwo Dimensional Electron Gas also abbreviated as 2DEG.

The n-doped semiconductor in the device supplies the electrons to the undoped semiconductor, thus spatially separating channel charge carriers from their isolated donors. Thus, heterostructure channel is capable of delivering high carrier concentration and with high mobility, as impurity scattering is reduced in the undoped channel. Moreover, the surface scattering is also reduced, by moving the current-carrying region below the barrier.

1.2.4. Energy band Diagram of HEMT

Before discussing the band diagram of HEMTs we should know what happens when two hetero-structures are kept in adjacent to each other.

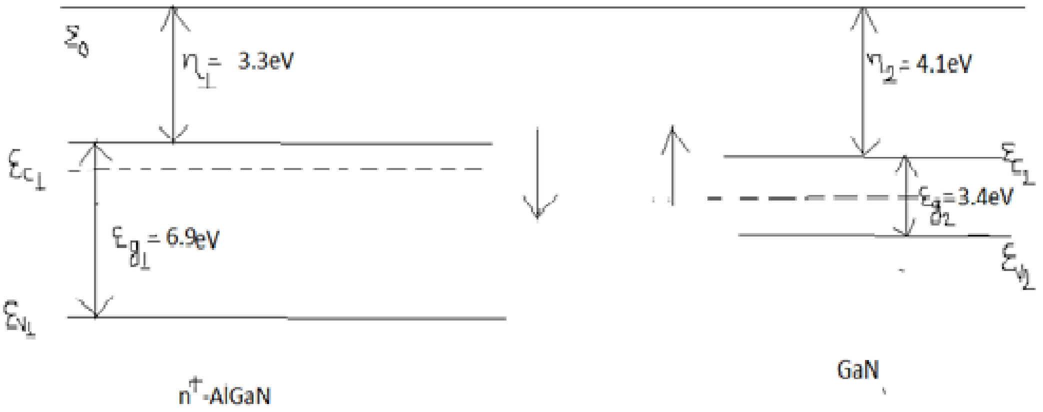

Fig-1.2 (a): Band-structure of AlGaN/GaN HEMT

The electron affinity for AlGaN is 3.3eV and band-gap (Ec_1-Ev_1=Eg_1) is 3.4eV and the electron affinity for GaN is 4.1eV and band-gap is (Ec2 -Ev2= Eg2) is 4.1eV. Now let us talk about the Fermi level. In the AlGaN layer, since it is n-doped the Fermi level (E_F) is near the conduction band (Ec_1) and for GaN if it is intrinsic then the Fermi level (E_F) is at the centre.

Now if we put these two semiconductors (AlGaN and GaN) together and, if they are in equilibrium then the Fermi level must be constant. So, the Fermi-levels of both the AlGaN and GaN must be equal.
This means, we need to bring the AlGaN band down and GaN band up making the Fermi level constant and the band structure is adjusted accordingly.

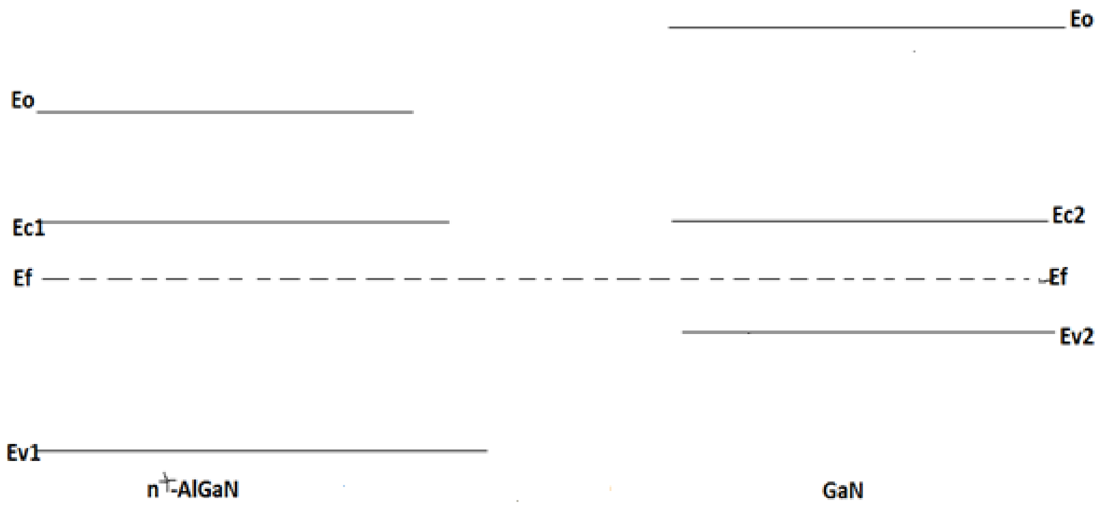

Fig-1.2 (b): Band-structure of AlGaN/GaN HEMT

Remember, that the original band structure depends at the interface. So the AlGaN band must bend up and GaN band must bend down. So in order to go back to the original band structure, there is a jump in the conduction (first up then down and then there is a jump in the conduction)

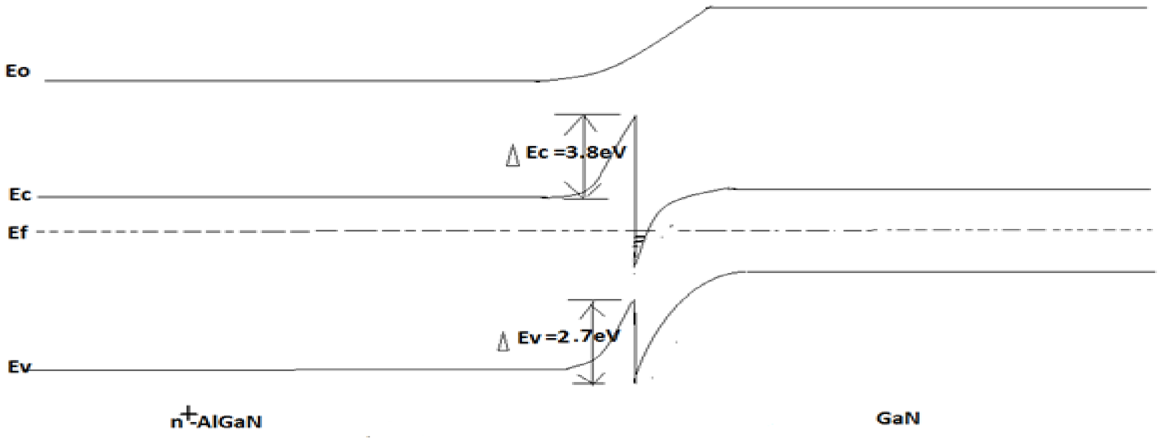

Fig-1.2 (c): Band-structure of AlGaN/GaN HEMT

So this is how the band-structure looks like and at the interface, the GaN conduction band (C.B) drops below the Fermi-level and this drop below the Fermi-level creates an interesting phenomenon.

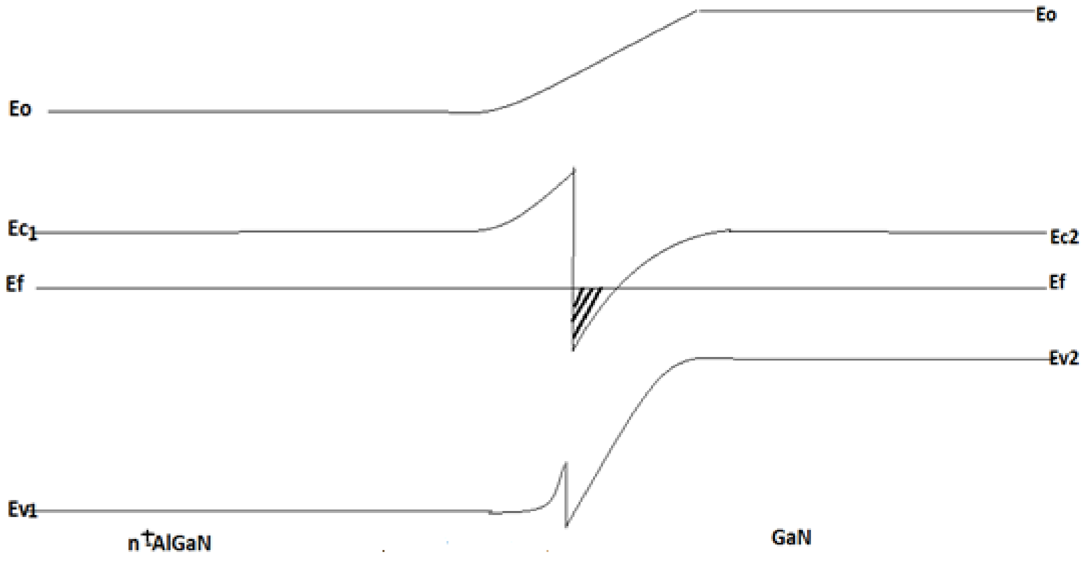

Fig-1.2 (d): Band-structure of AlGaN/GaN HEMT

1.2.5. Working Principal of HEMT

From, the AlGaN/GaN interface band diagram we expect the electrons to accumulate at the corners of the quantum well due to band-bending at the hetero-junction.Only one heterojunction is required to trap the electrons.The donors in the AlGaN layer are purposely separated from the interface by ~ 100 A°.Using this we can achieve higher mobility, since GaN channel region is spatially separated from the ionized impuritieswhich provide free carriers.

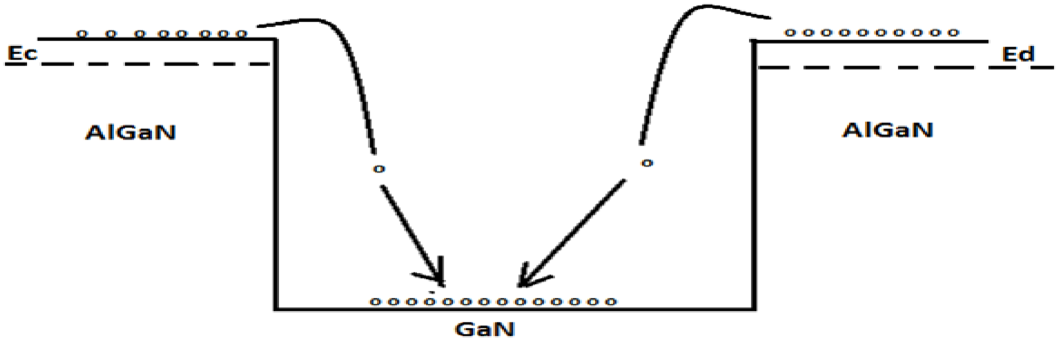

Fig-1.3: Electrons trapped in the quantum well

Here, the mobile electrons generated by the donors in the AlGaN diffuse into the small bandgap GaN layer as the electron affinity of GaN is higher. At the interface the electrons are trapped inside the lowest energy level of the quantum well as they try to occupy the lowest energy state, where they are confined properly.Thus, they are prevented from returning back to the AlGaN layer by the potential barrier at the AlGaN/GaN interface.

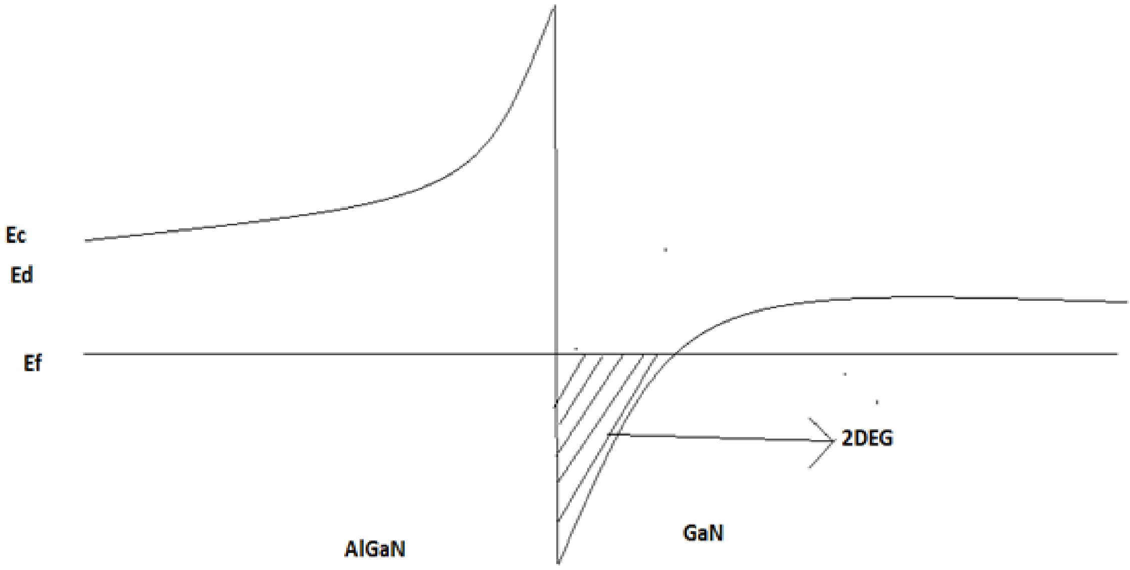

Fig-1.4: Band-diagram of AlGaN /GaN HEMT

The electrons confined in the triangular quantum well forms the Two Dimensional Electron Gas (2DEG).Ionised impurity scattering is greatly reduced simply by separating the electrons from donors.Screening effects due to extremely high density of two dimensional electron gas (2DEG) can reduce the ionised impurity scattering.Conduction Band electrons in the AlGaN/GaN heterojunction are confined to the discrete quantum states given by :

$E_n=(n^2\pi^2h^2)/(2m_n^* L^2)$ for $V_o=\infty$

Where m_n^* is the effective mass of the electron at E_n where n=1,2,3,…. And for Vo ->∞, m_n^*.

For GaN m is replaced by m_n^* plus the equation should be modified for a finite well.

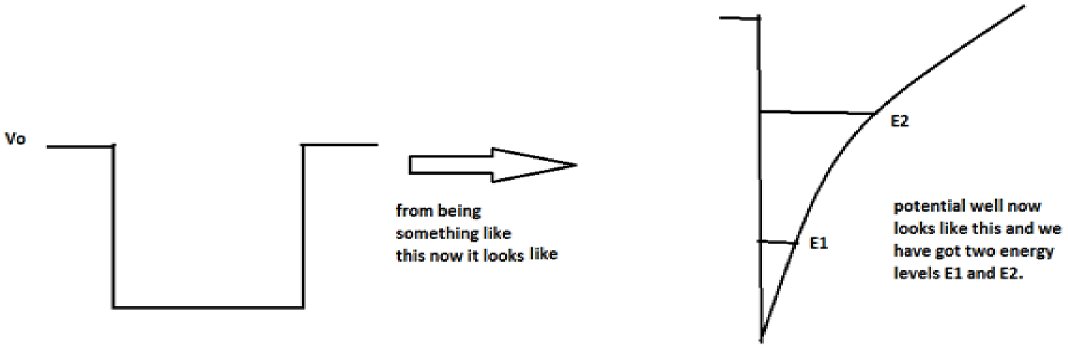

Fig-1.5: Formation of potential well in the of AlGaN /GaN interface

When a gate voltage (V_{GS}) is applied which is greater than the threshold voltage, then the electrons accumulates at the interface and this quantum mechanical confinement in a very narrow dimension forms Two Dimensional Electron Gas (abbreviated as 2DEG). If we apply a voltage across the Source and Drain or there is a voltage drop across the Source and drain (V_{DS}), we see a current in our channel and thecurrent drops down and grow across all over the channel.If we change the drain to source voltage V_{DS}, first we see there is a linear rise in the current and then when there will be no more electrons and the current saturates.

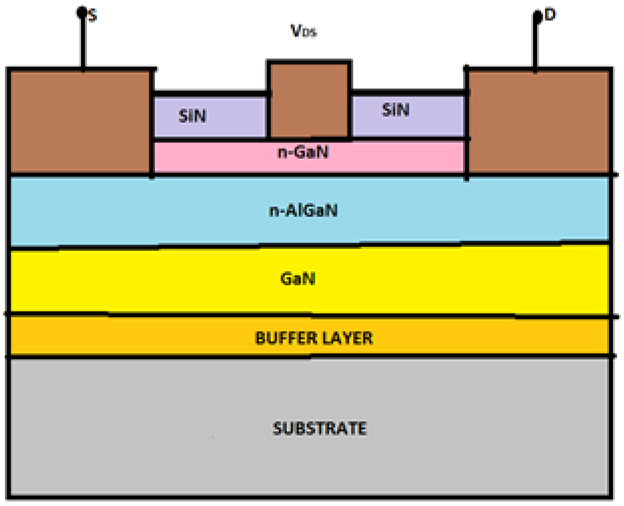

Fig-1.6: Schematic diagram of the HEMT

1.2.6. HEMT works in Depletion-mode or Enhancement-mode

HEMT relies on the formation of the 2DEG at the heterojunction interface. Hence it remains on, even when zero bias is applied at the gate, making them depletion type. The gate controls the flow of the electrons. If depletion layer is more, then effective channel layer is less. If channel is thick then current will increase. Since, the power electronics applications required normally-off or Enhancement mode characteristics, we have to make HEMTs normally-off.

1.3. Literature Survey

We know that the conventional HEMTs are depletion type. Power electronic applications require normally-off HEMT to prevent device destruction due to short circuit conditions and to reduce gate leakage current. In my thesis work, I have studied the normally-off GaN HEMT. Various methods have been proposed by different authors in order to make the HEMTs normally-off.

1.3.1. p-GaN/AlGaN/GaN High Electron Mobility Transistors

This work was done by Author Hamady et al. in [1]. He proposed a new design for the normally off HEMT by introducing a p-doped in the UID (unintentionally doped) GaN layer just below the AlGaN/GaN interface only under the gate electrode**.** This makes the HEMTs normally off by shifting the threshold voltage to the positive values.

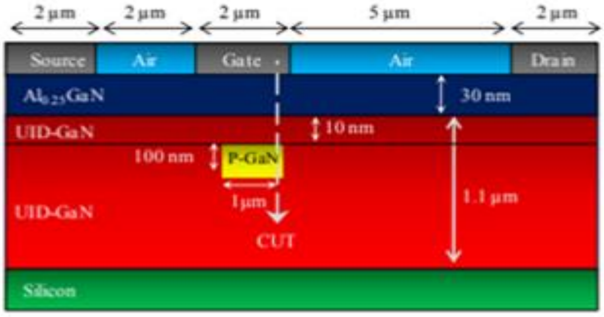

Fig-1.7: Schematic diagram normally-off HEMT with buried p- GaN region [1]

Author Hamady et al. in [1] concluded that it is avery efficient method as p-doping is done here which provides superior confinement to the Two Dimensional Electron Gas (2DEG).Author Hamady et al. in [1] concluded that these devices can attain high on-state resistance and high switching frequency.This approach does not affect the thickness of barrier.

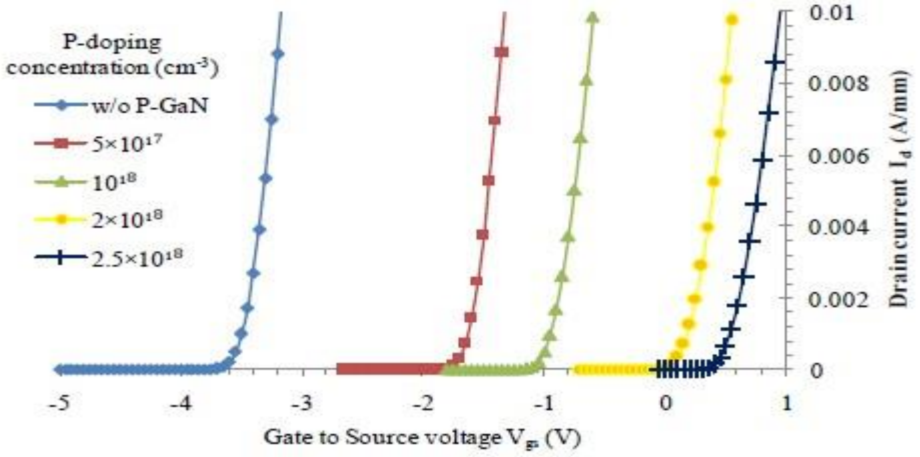

Fig-1.8: I_D (V_{GS}) curve shown for different p-doping concentration [1]

The above Fig-1.8 shows the variation of I_D with respect to the V_{GS} curve for different concentration of p-doping. Hamady et al. in [1] shows the increase in threshold voltage with the p-doping concentration. Hamady et al. in [1] stated that the normally-off operation is achieved with a threshold voltage of 0.5 V with the p-doping concentration of 2.5×10^{18} cm^{-3}.

1.3.2. Recessed-Gate Structure Approach

This work was done by Saito et al. in [2]. It is a very attractive method for realizing the normally-off high voltage AlGaN/GaN HEMTs. Saito et al. proposed a new structure to achieve normally-off HEMT.He stated that the threshold voltage can be increased with the reduction of the Two Dimensional Electron Gas (2DEG) only under the gate without affecting the 2DEG in the other channel regions between drain and gate. Saito et al. in [2] also stated that most of the AlGaN/GaN HEMTs demonstrated had normally-on characteristics with a gate threshold voltage of -4V.

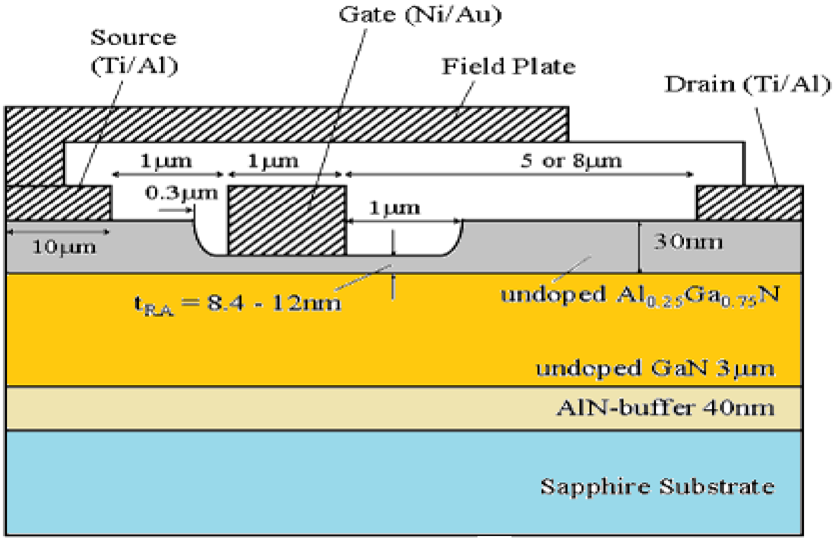

Fig-1.9: Schematic diagram of fabricated AlGaN/ GaN HEMT with buried recessed gate [2]

He stated that the proposed structure can be used to achieve a high voltage normally-off AlGaN/GaN HEMT for power electronic applications. The threshold voltage of the device can be controlled by etching the depth of recess without increasing the on-resistance characteristics.

Due to the presence of large electric fields and high carrier mobility, the AlGaN/GaN HEMTs can realize ultrahigh power density operations with low power losses.Recessed gate structure [2] is useful to realize the selective 2DEG reduction because the selective thinning of the AlGaN layer can be easily done by the etching process.Saito et al. reported shift in the threshold voltage.The fabricated device has same level of the on resistance and breakdown voltage trade-off as the normally-on devices with a higher threshold voltage of -0.14V.

1.3.3. Fluorine Ion Treatment

This work was done by Author Cai et al. in [3] to achieve a normally-off HEMT.Cai et al. in [3] proposed that with the help of Fluoride-Based Plasma Treatment one can convert the HEMTs from Depletion Mode to Enhancement Mode and using [3] we can control the threshold voltages (V_{th}) of AlGaN/GaN high-electron mobility transistors accurately. The mobility of the Two Dimensional Electron Gas (2DEG) is affected by the plasma-induced damages. Cai et al. in [3] stated that these damages can be healed and even the mobility can be recovered back by some post-gate annealing method at 400ºC. The post-gate annealing does not affect the shift in threshold voltage as it has a good thermal stability. The threshold voltage of the AlGaN/GaN HEMTs depends on the design of the epitaxial structure, the composition of Al, doping concentration and thickness of the AlGaN barrier layer [3].

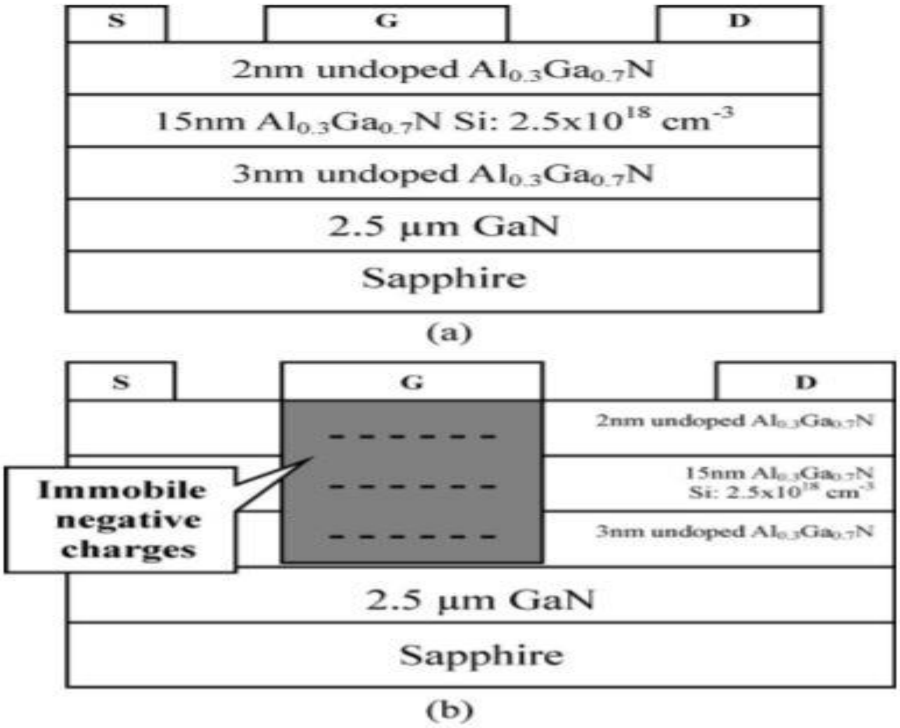

Fig-1.10: Schematic cross-section of (a) HEMT (b) AlGaN /GaN HEMT with immobile negative charges incorporated directly under the gate [4]

Cai et al. in [3] said that without varying the thickness of AlGaN layer the threshold voltage can be easily controlled by the modulation of energy bandgap by implanting negatively charged fluorine ions in the AlGaN/GaN heterostructure during the plasma treatment.

The threshold voltage of the conventional AlGaN/GaN HEMT is [3]

$V_{th} = \phi_B/e - d\sigma/\varepsilon - \Delta E_C/e + E_{fo}/e - e/\varepsilon \int_0^d dx \int_o^x N_{si}(x)\, dx - (ed\, N_{st})/\varepsilon - eN_b/C_b$ (1)

Threshold voltage for modified structure ofHEMT proposed by Cai et al. in [3] is

$V_{th} = \phi_B/e - d\sigma/\varepsilon - \Delta E_C/e + E_{fo}/e - (e/\varepsilon)\int_0^d dx \int_0^x \big(Nsi(x) - NF(x)\big)dx - edN'_{st}/\varepsilon - \varepsilon N_b/C_b$

(2)

Cai et al.in [3] suggested that with the help of his proposed method [3], the V_{th}can be shifted from −4V in a Depletion-mode AlGaN/GaN HEMT to 0.9 V in an enhancement-mode AlGaN/GaN HEMT [3].

Cai et al. in [3] reported that the proposed structure of normally-off HEMT shows a transconductance and cut-off frequencies that is comparable to the Depletion-mode HEMTs.Cai et al. in [3] results confirmed that the shift in the threshold-voltage started when the fluorine ions are incorporated in the AlGaN barrier.Cai et al. in [3] proposed method is capable of reducing the gate leakage current, in both forward and reverse bias.

1.3.4. Thin AlGaN Barrier

We know HEMT is made up of two semiconductors for eg. AlGaN (E_g =6.9 eV) and GaN (E_g = 3.4 eV), having different bandgap.One is having lower bandgap and the other one is having higher bandgap .The higher bandgap semiconductor is doped and the lower bandgap semiconductor is undoped. The former is doped with an n-type material, which has a lot of free mobile electrons. At the AlGaN /GaN interface a triangular quantum well is created and 2DEG is formed. Now all the electrons which are trapped inside the triangular quantum well diffuse from the AlGaN layer. So if we reduce the thickness of AlGaN, the number of mobile electrons present will be reduced thus affecting the 2DEG density making HEMTs normally-off. In order to increase the threshold voltage or make it more positive the thinning of AlGaN barrier enough is not sufficient.

1.3.5. Schottky-Ohmic Drain with Reverse Drain Blocking Capability

Zhou et al. in [4] introduces a Schottky–Ohmic drain electrode in the device. Here in between the gate and the conventional ohmic drain contact, this method inserts a Schottky controlled normally-off channel. When the negative reverse drain voltage is applied then the normally-off channel provides an energy barrier. This energy barrier blocks the reverse current conduction and the schottky gate is turned on due to the negative drain voltage. This would result in a high gate current flow which can cause the failure of the device and the system. The bidirectional switches are an important application of the reverse-conduction blocked HEMTs which can reduce the components as well as increase the functionality of the system. If we integrate a schottky barrier diode at the drain terminal of a GaN MOSFET, we can achieve reverse drain blocking capability. This approach was implemented in the normally-on AlGaN/GaN HEMTs [21] by direct contacting the high conductive two dimensional electron gas channel with the schottky metal. This is done in order to reduce the forward onset voltage. The negatively charged fluorine ions are incorporated into the AlGaN layer under both the drain-schottky and gate-schottky contacts. This shifts the threshold voltage towards a positive value.

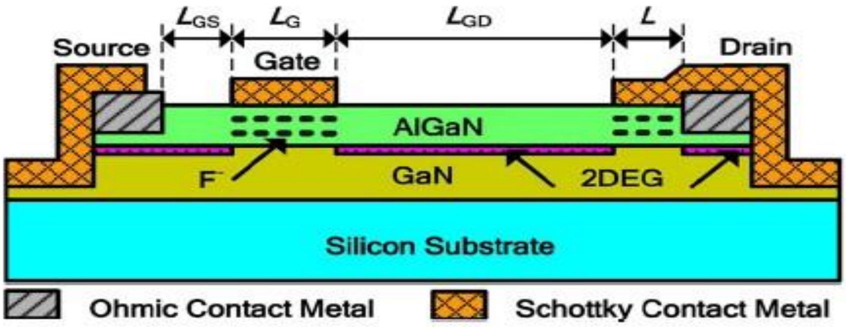

Fig-1.11: Schematic cross section of the normally-off AlGaN/GaN off reverse conduction-blocked HEMT with Schottky-ohmic drain [4]

Zhou et al. in [4] proposed structure does not show any degradation of the drain saturation current.This approach does not require any extra photo-mask or any extra process steps to fabricate. But in the proposed structure of Zhou et al. in [4] the drain-schottky barrier suffers from the trade-off between the schottky barrier height/low onset voltage and the reverse bias tunnelling current. This degrades the reverse blocking capability.

Several methods have been proposed [5],[6],[19],[7],[21],[22] But in this thesis, we have selected the method of getting Normally-Off GaN HEMTs with p-GaN Gate [8] as the above methods are neither stable nor reliable since for recess gate technology, reproducibility is an issue as it is very hard to control the etching depth and hence the threshold voltage varies. Sometimes, implanting fluorine makes the device very unstable and degrades the drain breakdown voltage of the devices. The effectiveness of the agent used to obtain normally-off,whether it is implanting fluorine or recessed gate or introducing a cap layer, increases as the agent comes closer to the AlGaN/GaN interface. But, as we introduce a cap layer or do recessed gate structure or implanting fluorine, coming closer to the interface means decreasing the barrier thickness which strongly affects the 2DEG density [8]. Meneghini et al. in [8] proposed a new design for enhancement-mode GaN HEMT.The normally-off operation of the HEMT in [8] was achieved by using a p-doped GaN gate above the GaN HEMT. The p-type layer lifts the band diagram [8] of the heterostructure and this results in a complete depletion of the 2DEG with V_{GS}=0 V. There are some specific issues [8] of the HEMTs with p-GaN gate i.e. the time dependent degradation of gate stack, and trapping effects related to the Mg-acceptor.

The simulation results in [8] shows that, this proposed technique by the author Meneghini et al. is capable of shifting the threshold voltage greater than 1 V. The proposed structure in [8] seems to be more effective when it comes to p-doped GaN to achieve normally-off HEMT.

1.4. Thesis Objective and Organisation

We know that the conventional HEMTs are normally-on but most of the power electronic applications require normally-off HEMT]. If we implant the negatively charged fluorine ions in the GaN channel, then the threshold voltage can be shifted towards more positive values. Thus we have modified the structure by implanting the Fluorine ions into the GaN channel.

Chapter 2

This chapter explains the simulated device structure and its simulation scheme.

Chapter 3

The result and discussion are given in this chapter. The modification of the normally-off GaN HEMT with p-GaN gate is done by implanting the negatively charged fluorine ions and the structure can be further modified by varying the thickness of the AlGaN barrier layer to check the shift in threshold voltage from

Chapter 4

Conclusion and future scope of this work is discussed here.

Chapter 2

DEVICE STRUCTURE and SIMULATION SCHEME

2.1. Device Structure

2.1.1. Basic Structure of Normally-off GaN HEMT with p-GaN gate

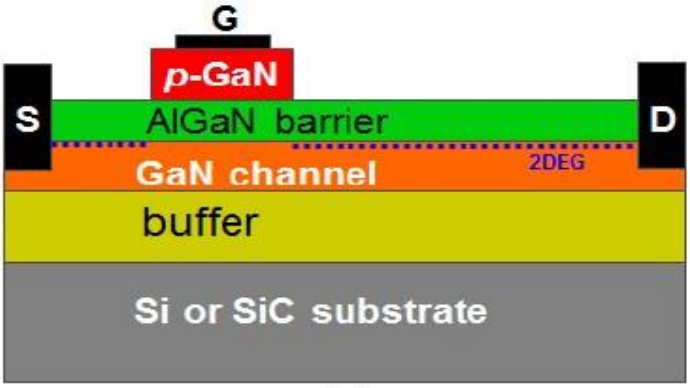

Fig-2.1: Schematic cross-section of Normally-off GaN HEMTs with p–GaN gate [8]

This normally-off GaN HEMT structure was proposed by Meneghini et al in [8].Meneghini et al used a Silicon substrate as the base for the growing process. The comparison of the four substrates according to the cost, available size , thermal conductivity and lattice constant, etc. compared with GaN is shown in Fig 2.2. Because of the low cost of the Silicon wafers most of the GaN devices use Silicon substrate.

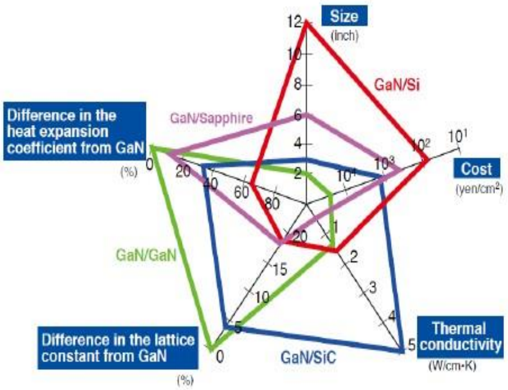

Fig-2.2: Comparison between the substrates on which GaN can be grown [9]

2.1.1.1. Gallium Nitride (GaN)

The Wide bandgap group III-Nitride semiconductor materials possess many superior material properties than conventional Si, GaN or any other III-V compounds. Gallium Nitride has an energy bandgap of 3.4eV and thus it can be operated at very high temperatures with an excellent control of channel current. The breakdown field of GaN is 3.3 MV/cm, which is higher than that of Silicon i.e. 3.0 MV/cm [8].This means that a 1µm thick GaN layer can theoretically withstand a voltage of 330V [8], whereas a Silicon layer with the same thickness can withstand a voltage of 30V because of the high breakdown field of GaN [8]. The compound semiconductors of the group III Nitrides are composed of group III elements like Aluminum, Gallium, Indium and Nitrogen and their associated alloys. These materials have characteristics like their wide energy bandgap and a wurtzite crystal structure which can bring out the significant polarization effects. Table 2.1 shows the comparison of the main material properties of the prevalent semiconductors. The GaN combines the best properties of GaAs and SiC and these materials can be used in Radio Frequency and power electronic applications, thus making it suitable for a wide range of applications.

Table 2.1: Comparison of different material properties used in HEMT at 300K [2]

Properties	Si	GaAs	SiC	GaN
Bandgap E_g(eV)	1.12	1.42	3.25	3.40
Breakdown field (MV cm^{-1})	0.25	0.4	3.0	4.0
Electron Mobility μ(cm^2 V^{-1} s^{-1})	1350	6000	800	1300
Thermal conductivity k(W cm^{-1} K)	1.5	0.5	4.9	1.4
Relative dielectric constant ε_r	11.8	12.8	9.7	9.0

The interest in group III Nitride Semiconductors has been increased in the last two decades because of the inherent material properties of them, which offers attractive advantages for the optoelectronic and high power device applications starting from consumer electronics to military radars.

Gallium Nitride (GaN) and its associated alloy emerged as the most promising Nitride semiconductor for commercial applications. The complicated material properties of Gallium Nitride material system must be well known so that one can fully use the advantages offered by this semiconductor in devices.

2.1.1.2. Crystal Structure of GaN

The group III Nitrides may occur in either a hexagonal or a cubic structure. The hexagonal structure is called as wurtzite crystal structure and the cubic structure is known as zincblende crystal structure. The hexagonal structure is the thermodynamically stable at room temperature.

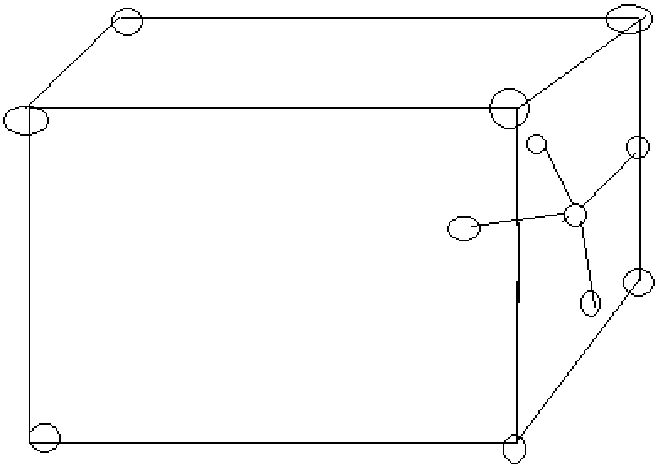

Fig-2.3: This formation is called Wurtzite

Nitride comes and fits itself in the middle. The crystal structure is important in the formation of the heterostructure and the band-gap (Eg) in eV affects the fundamental properties. So,consider the change in the bandgap of these two materials AlGaN and GaN and their lattice parameters.

While fabricating these hetero-structures we can use.
(a)Molecular Beam Epitaxy (MBE)
(b)Metal Oragnic Chemical Vapour Deposition (MOCVD)

So, when we grow these materials on each other then there is a possibility lattice mismatch which can be reduced by using a spacer layer. The zincblende form of group III Nitrides can be epitaxially grown on specific substrate planes making them thermodynamically stable.But growing the zincblende form requires more technological effort than the wurtzite crystal structure.

2.1.1.3. Advantages of GaN over GaAs

GaAs can be used while making HEMTs in the High Frequency analog devices like satellite communication, wireless communication.GaAs can be used in high frequency operations as it has very high electron mobility but GaN are new to market.GaN can be used in the potential applications including Military applications, Satellite applications, Aircrafts (which requires broad range of frequencies). These applications require high power and low noise devices.Moreover, the GaN has higher Bandgap 3.4eV than GaAs. Thus GaN is seen as a potential solution for these devices.

2.2. Simulation Scheme

2.2.1. TCAD Simulation

Technology Computer Aided Design simulation tools are used to predict the device structure resulting from various process simulation and also predict the electrical behaviour of the devices at given bias conditions which is known as the device simulation. The material properties from which the device is made including the dimensions and the doping concentration and type of the doping of all the regions of the device are the inputs of the device simulator. After all these, the device structure is then discretised by properly meshing it. The simulator then solves some set of physical equations along with the defined models in order to predict the electrical behaviour of the device.

In this work, the device structure of the normally-off GaN HEMT with p-GaN gate [8] is madeand normally-off GaN HEMT with p-GaN gatewith the implantation of fluorine is made and examined and the comparison between them has been done.In this chapter the calibration strategy using this simulator is explained.

In order to calibrate the simulation we have considered the experimental results from the Normally-off GaN HEMT with p-GaN gate [8].The thickness of the Silicon substrate is 175nm. Thickness of buffer is 25nm, we have considered the SiO_2 as buffer.The GaN channel is having a thickness of 10nm. AlGaN layer thickness is 10nm. The GaN layer below the gate is of width 275nm and it is doped with Magnesium to make it p-type GaN with a concentration of 4e12.

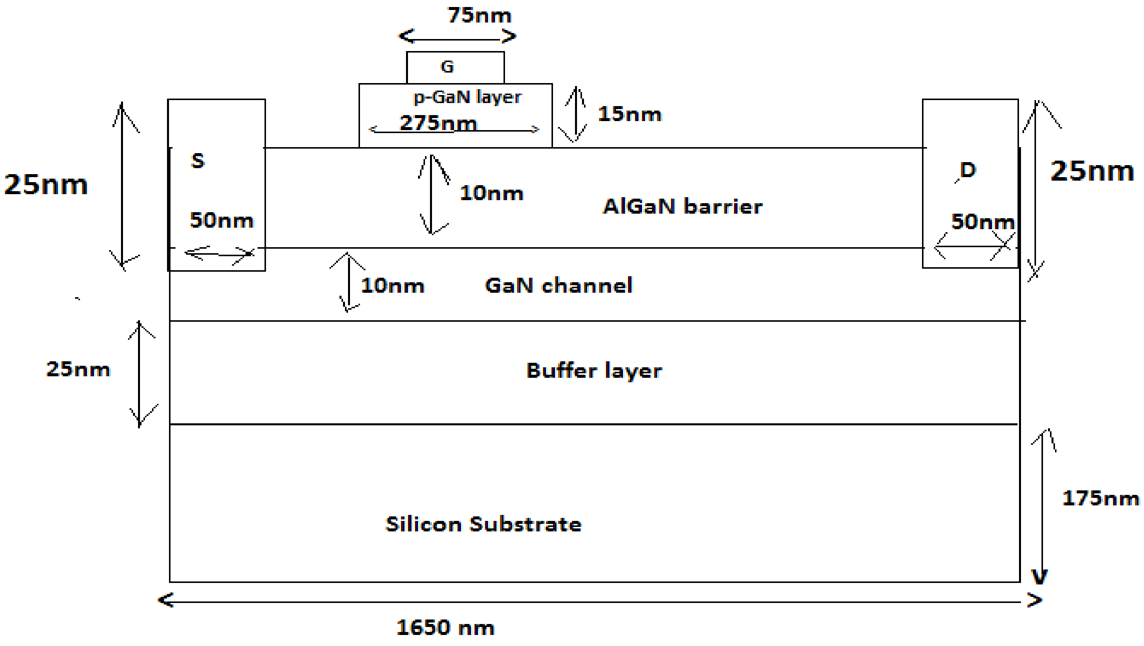

Fig-2.4: Geometrical & Technological parameters used for the simulation of the normally-off GaN HEMT with p-GaN gate [8]

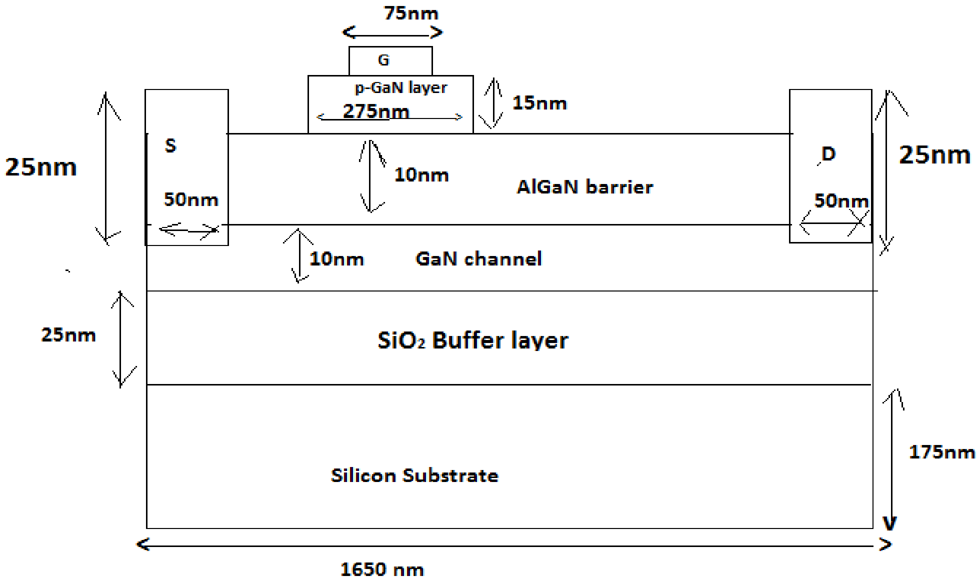

Fig-2.5: Schematic cross-section of the device structure that is to be simulated.

In Sentaurus TCAD, the buffer layer is substituted by the SiO_2. Therefore, the SiO_2 acts as a buffer layer.

2.3.2. Meshing

In every device simulator, to solve the physical equations related to the behaviour of the transport of the carriers. The device that has to be simulated is discretised into grids and at every grip point the equations has to be solved. The grid and the grip points are also called as the mesh and the nodes.In HEMTs the most sensitive region is the AlGaN / GaN interface where the meshing has to be done properly. Hence, a very fine meshing has to be done in that region.

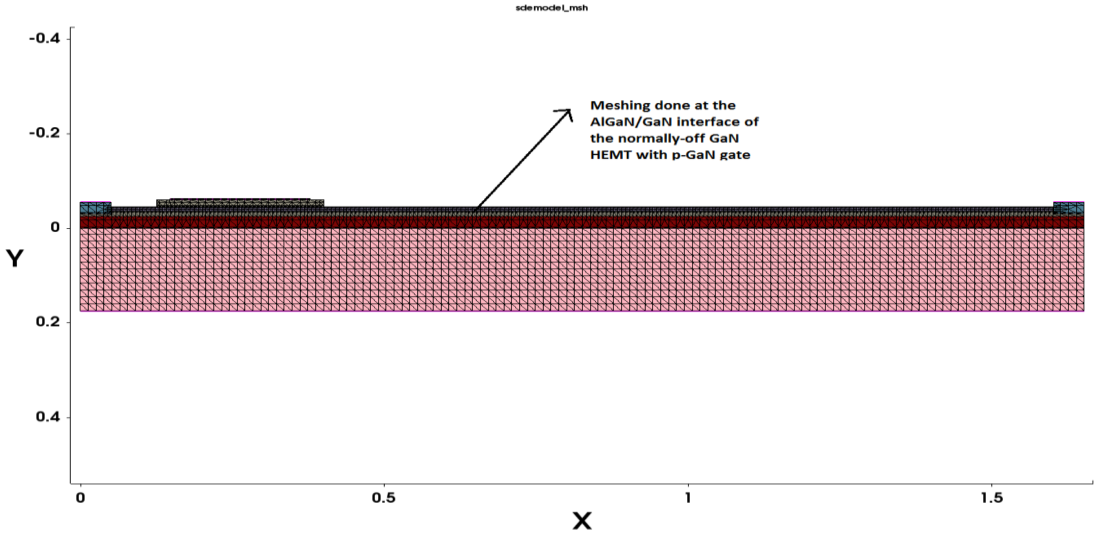

Fig-2.6: The mesh with the cross-section of the simulated Normally-Off GaN HEMT with p-GaN gate showing the refined mesh at the AlGaN / GaN interface.

However, it is very important to refine the mesh at the heterointerfaces. Thus meshing has to be done properly in the AlGaN/GaN interface where the in the physical properties changes abruptly. Moreover, we get more accurate results when fine meshing is done and the numerical efficiency is good when less grid points are used. It takes a lot of time to simulate, if we have an increased number of grid points in the simulated structure.

2.3.3. Physical Models

The physical models adopted for this work are Mobility models, Shockley-Read-Hall recombination model, Polarization model, Poisson equation and other typical models are adopted for normally-off GaN HEMT and the standard parameters of III-N are also employed.

2.3.3.1. Doping Dependent Mobility Model

Scattering of the carriers by charged impurity ions which causes mobility degradation as happened in my case after implanting the fluorine in the normally-off GaN HEMT. Sentaurus device supports three built-in models, one multistate configuration–dependent model, and two PMIs for doping-dependent mobility.The different mobility models used in the Sentaurus are: Masetti Model [9], Arora Model [9], University of Bologna Bulk Mobility Model [9], Alternative Philips Model [9] (which is used for doping).

2.3.3.1 Masetti Model

Default model used by Sentaurus to simulate the doping dependent mobility in Silicon. This model was proposed by Masetti et al. [9,10]

$\mu_{dop} = \mu_{min1} \exp(- P_c /(N_{A,0} + N_{D,0})) + [(\mu_{const} - \mu_{min2})/1+((N_{A,0} + N_{D,0}) / C_r)^{\alpha}] - \mu_1 / 1+((C_s /(N_{A,0} + N_{D,0})))^{\beta}$

2.3.3.3.2. Arora Model

From synopsys manual [9],
$\mu_{dop} = \mu_{min} + \mu_d /(1+((N_{A,0} + N_{D,0})/N_0)^{A^*}$

$\mu_{min} = A_{min} (T/300K)^{am}$ and $\mu_d = A_d (T/300K)^{ad}$

2.3.3.3. Mobility Degradation at Interface

When the GaN below the gate is doped with Magnesium it makes it p-doped GaN, the holes penetrate through the AlGaN barrier layer and interferes the channel electrons causing degradation of mobility. This happens due to the scattering between the electrons present in the channel and the holes that penetrate into the channel layer.

2.3.3.4. Poisson Equation

Poisson equation and the above models were used for the simulation of GaN-based HEMTs. Based on the polarization vector, the piezoelectric charge is given by:

$$q_{PE} = -\text{activation}\, \nabla P$$

where activation is a non-negative real calibration parameter and the default value is 1.This value canbe defined in the Physics section:

```
Physics (MaterialInterface="AlGaN/GaN") {

Piezoelectric_Polarization (strain activation=0.5)
}
```

q_{PE} value is added to the right-hand side of the Poisson equation

$$\nabla \varepsilon.\ \nabla \phi = -q\,(p - n + N_D - N_A + q_{PE})$$

Only the first d components of the polarization vector are used to compute the polarization charge, where d denotes the dimension of the problem [9].

The standard parameters for III-N materials are used in order to simulate the GaN based normally-off HEMTs.

2.3.4. Simulator Calibration

Experimental datas from normally-off GaN HEMT by Meneghini et al. in [8] were used in order to calibrate the simulation. Now, the simulated device of the normally-off GaN HEMT with p-GaN is shown below.This structure is simulated using the Sentaurus Software.The thickness of the Silicon substrate is 175nm. Thickness of the buffer is 25 nm, we have considered the SiO_2 as buffer.The GaN channel is having a thickness of 10nm. AlGaN layer thickness is 10nm. The GaN layer below the gate is of width 275nm and it is doped with Magnesium to make it p-type GaN with a concentration of 4 x 10^{12} cm^{-3}.

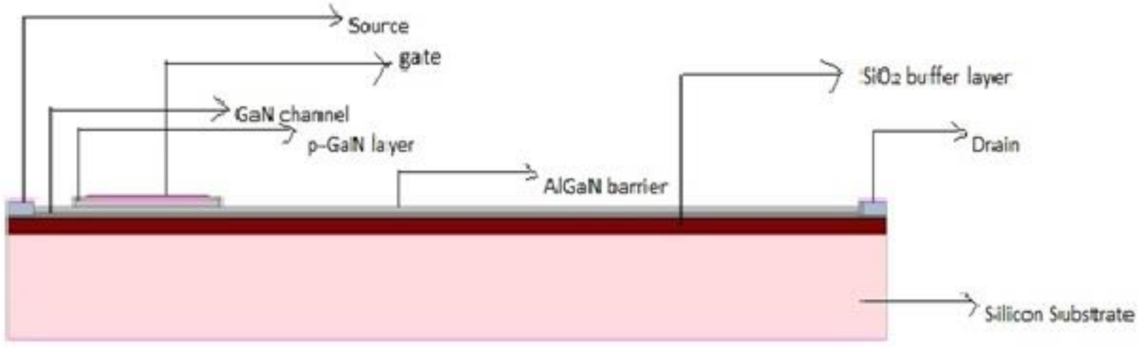

Fig-2.7: Simulated Device Structure

A new design for the enhancement-mode GaN HEMT has been proposed by Meneghini et al. in [8]. He achieved the normally-off operation of the HEMT by using a p-GaN gate above the top of the AlGaN/GaN heterojunction. The simulation results in [8] shows this technique is capable of shifting the threshold voltage to positive values usually greater than 1V, thus making them normally-off. The proposed structure by the Author Meneghini et al. in [8] seems to be more effective when it comes to the p-GaN gate to achieve normally-off operation and offers superior confinement for the 2DEG.On the other hand we have degradation issues due to high drain voltage in the off-state and by applying positive gate bias.

The p-type layer lifts the band diagram of the heterostructure, and this results in a complete depletion of the 2DEG with V_{GS}=0 V [8]. In order to know the advantages and disadvantages of this proposed structure a comparison with the HEMT structure using AlGaN buffer and using UID GaN buffer was performed [8].

Lee et al.in [11]stated that the work function of the gate metal has an impact on the electrical parameters of the devices like off-state leakage, threshold voltage, forward operating current. Recent papers studied the impact of temperature on the metal gate of the device.If high temperature annealing is done on devices with Al/Ti gate may lead to changes of the schottky barrier height and gate leakage.

Hao et al. [12] proposed a new technique to fabricate a p-GaN/AlGaN HEMT. Hao et al. [12] have used the Hydrogen plasma to compensate the holes in p-GaN above the 2DEG instead of using the etching technology and thus form a very high resistivity area to reduce the leakage current. Using this method [12] he got a threshold voltage of 1.75 V.This shows that Hydrogen may have an impact on the electrical characteristics of thedevices, as it compensates the Mg acceptors. Hydrogen atoms can diffuse faster in the GaN as reporter in the papers [14,15] causing changes in the properties of the metal/p-GaN interface[16].

Wu et al.[17] reviewed in his paper that when high positive gate bias is applied, electrons are injected from channel to the p-GaN region, where a high electric field is present. The electrons are accelerated by the high electric field [17] and the avalanche process may lead to breakdown. Moreover, the light emission was supposed to take place in the p-GaN layer by the following mechanisms. The electrons flow from the channel towards the p-GaN and gets accelerated by the high electric field and gain very high energy thus emitting light due to multi-step transition. The electrons may also recombine with the holes present in the p-GaN layer by two process (a) band to band process [18] and the other one is (b) through defect states.

Author Hu et al. proposed p-GaN HFET [21], he reported that the holes are injected from p-GaN gate when a positive voltage is applied at the gate.Hu et al in [21] reported that the injected holes accumulates at the p-GaN/AlGaN interface or at AlGaN/GaN interface which leads to the temporary increase in 2DEG density, and resulted in the negative shift in threshold voltage [8].

But Meneghini et al. in [8] proposed depletion GaN HEMT with p-GaN gate.Meneghini et al. reported that the p-doped GaN layer on the top of AlGaN barrier and GaN channel forms a pin-diode which turns on when you increase the positive gate voltage [8] and thus we get an on-state gate current of 10µA/mm [8].Meneghini et al. in [8] showed that the degradation occurs when positive gate voltageis applied which results in a threshold voltage higher than one volt [8]. Meneghini et al. in [8] also reported that the devices must be turned on with V_{GS}=4 to 7 V in order to reduce the on-resistance of the device.

Meneghini et al. in [8] reported that when the applied gate bias is greater than threshold voltage, change in the band diagram of the transistor is reported in [8] which cause the V_{th} to drop on the p-GaN layer.Meneghini et al. [8] reported that this drop of the threshold voltage on p-GaN layer increases the field which in turn results in the band-bendingon the p-GaN layer. Meneghini et al. in [8] which shows the band diagram calculated for three different gate voltages.

Chapter 3

RESULT AND DISCUSSION

There are several proposed structures for normally-off HEMTs. Out of which we have considered the normally-off GaN HEMT with p-GaN gate reported by Meneghini et al. [8]. The structure proposed by Meneghini et al. in [8] can be modified in various ways to shift the threshold voltage more towards the positive value.

3.1. Modified structures to improve Threshold Voltage

3.1.1. By varying the thickness of the AlGaN layer

In this method the thinning of AlGaN barrier is done to achieve the normally-off GaN HEMT. The maximum drain current is directly proportional to AlGaN barrier thickness and varies inversely with threshold voltage and breakdown voltage.

Table-3.1: Variation of threshold voltage w.r.t AlGaN barrier thickness

Barrier layer thickness (AlGaN) (nm)	V_{th} (V)	$I_{ds\ max}$ (A/µm)	Break down voltage (V)
10	1.94	0.313	860
15	1.34	0.41	848
20	0.717	0.528	809

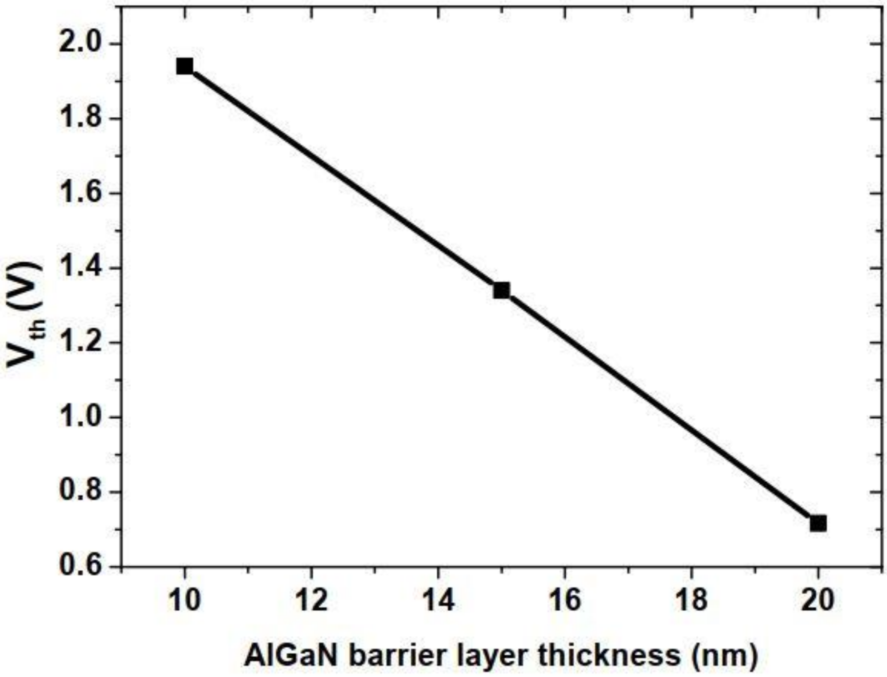

Fig-3.1: Variation of V_{th} w.r.t. AlGaN barrier thickness

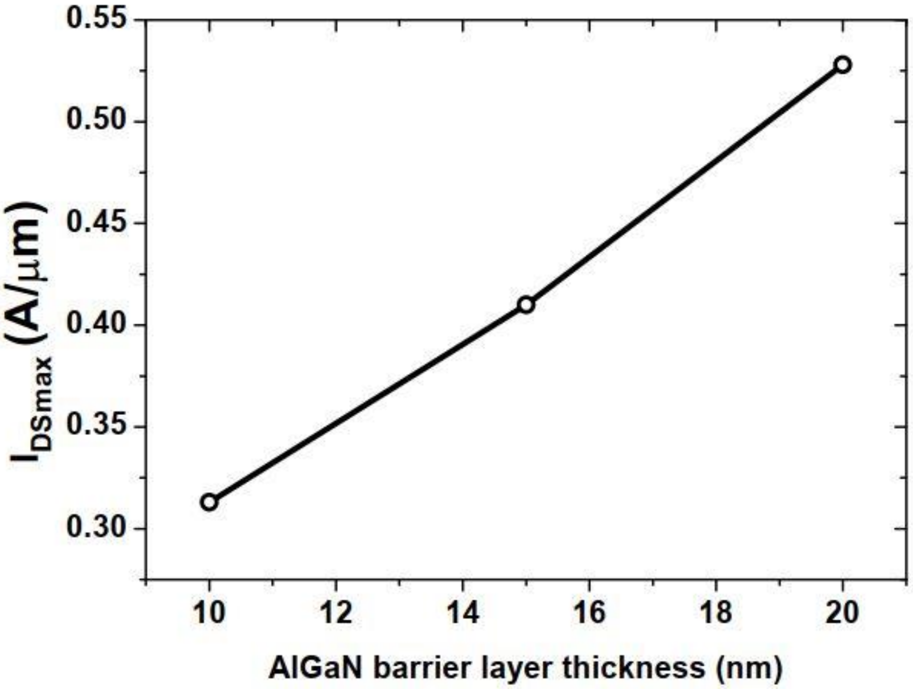

Fig-3.2: Variation of $I_{ds\ max}$ w.r.t. AlGaN barrier thickness

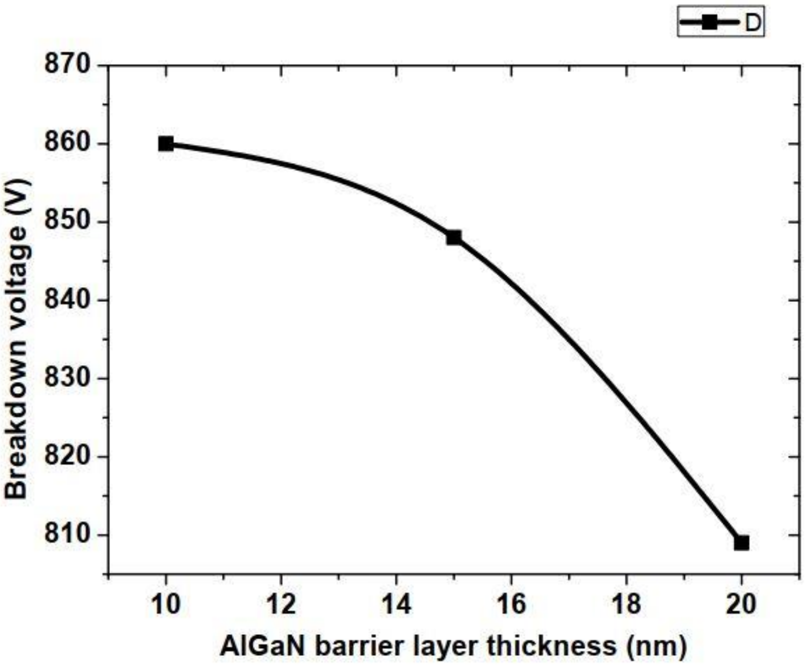

Fig-3.3: Variation of breakdown voltage w.r.t. AlGaN barrier thickness

It has been observed that as the AlGaN barrier thickness is reduced the threshold voltage is increased making HEMTs normally-off. Threshold voltage, breakdown voltage and the maximum drain current are the three important parameters for HEMT. It was observed that the highest on current is 0.528 A/µm for 20 nm AlGaN barrier thickness and maximum breakdown voltage is 860 V for 10nm AlGaN barrier thickness.

Chapter 4

CONCLUSION AND FUTURE SCOPE OF THE WORK

We know that conventional High Electron Mobility Transistors are Depletion-type means they are normally-on devices. But as they are normally-on a lot of power is wasted and gate-leakage current occurs and even the power electronic circuits require normally-off HEMTs to prevent device destruction when the short circuit occurs. Thus the normally-on HEMTs should be converted to the normally-off HEMTs also known as the Enhancement-type HEMT. Several methodologies have been proposed by different authors [1-4]. But these methods are neither stable nor reliable since for recess gate technology, reproducibility is an issue as it is very hard to control the etching depth and hence the threshold voltage varies. Sometimes, implanting Fluorine makes the device very unstable and degrades the drain breakdown voltage of the devices for which I have studied the topic of Normally-off GaN HEMT with p-GaN gate.

Here we modified the structure given in [8] by varying the AlGaN barrier thickness and it has been observed that increase in the threshold voltage with the thinning of AlGaN barrier thickness. Future work is to achieve the modified proposed structure given in [8] by Meneghini et al. and show the improvement in the threshold voltage from the proposed structure in [8]. The modified structure with the implantation of Fluorine ions in the GaN channel may cause reduction in mobility due to the scattering between the electrons present in the channel. The future work is also to recover the degradation in mobility problem.

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