STUDIES OF ELECTRICAL CHARACTERISTICS OF MESFET USING WBG III-V (GaN) POTENTIAL SUBSTRATE MATERIAL

A graduate project submitted in partial fulfillment of the requirements

For the degree of Master of Science

In Electrical Engineering

By

Sai Praneeth Thota

May 2016
The graduate project of Sai Praneeth Thota is approved:

_________________________________________  __________________
Professor Benjamin F. Mallard                                Date

_________________________________________  __________________
Dr. Robert D Conner                                            Date

_________________________________________  __________________
Dr. Somnath Chattopadhyay, Chair                             Date

California State University, Northridge
ACKNOWLEDGEMENT

I am honored to express benediction towards my graduate thesis advisor, Dr. Somnath Chattopadhyay for his reinforcement in this project. He spurs the light in me to work on semiconductor devices and without his timely suggestions this work would not have been possible. He is the origin of my motivation.

Beside my advisor, I like to thank Dr. Robert D Conner and Prof. Benjamin F. Mallard for accepting to be my thesis committee members.

Finally, I am proud to be a son of Mr. Ramesh Thota and Mrs. Bharathi Thota, the people who taught me, how to get succeed in life after a failure and supported me at every stage of life and in my entire tenure in California State University Northridge.
# TABLE OF CONTENTS

Signature Page .................................................................................................................. ii

Acknowledgement ........................................................................................................... iii

List of Figures ................................................................................................................... vii

Abstract ........................................................................................................................... ix

**CHAPTER – 1: INTRODUCTION** .................................................................................. 1

1.1 Recent Developments in Semiconductor technology ................................................. 1

1.2 GaN MESFET Frequency Performance: ................................................................. 4

1.3 GaN Optoelectronics ................................................................................................. 5

1.4 Defects in Semiconductors ....................................................................................... 6

   1.4.1 Native Point Defects ....................................................................................... 6

   1.4.2 Interstitials and Antisite Defects: ................................................................. 7

**CHAPTER 2: STUDY OF GaN MATERIAL** ................................................................. 8

2.1 Energy Band Diagram for GaN .................................................................................. 10

2.2 Band Gap Energy Temperature Dependence ......................................................... 11

2.3 Intrinsic Carrier Concentration and Effective Density of States of GaN.............. 13

2.4 Material Growth ...................................................................................................... 14

   2.4.1 Metal Organic Chemical Vapor Deposition (MOCVD) ................................. 14

   2.4.2 MOCVD Reaction Chemistry ...................................................................... 15

   2.4.3 Molecular Beam Epitaxy (MBE) .................................................................. 16
2.5 Substrate used for GaN ........................................................................................................ 17

CHAPTER-3 : PHYSICS OF MESFET ......................................................................................... 20

3.1 INTRODUCTION: ............................................................................................................. 20

3.2 Study of MESFET I-V Characteristics ............................................................................ 20

3.3 Types of MESFET’s ......................................................................................................... 21

3.3.1 Enhancement mode MESFET ..................................................................................... 21

3.3.2 Depletion mode MESFET ......................................................................................... 21

3.4 MESFET Operating Regions .......................................................................................... 22

3.5 Ion Implantation ............................................................................................................. 23

3.6 Fabrication Process ........................................................................................................ 25

3.7 Advantages of MESFET .................................................................................................. 26

CHAPTER 4 : THEORY OF GaN MESFET USED IN SIMULATION ................................. 27

4.1 Introduction to Current Controlled Mechanism in MESFET ........................................ 27

4.2 Drain Current Using a Constant Mobility Assumption: ................................................ 31

4.3 Transfer Characteristics: .............................................................................................. 35

4.4 Power Spectral Density .................................................................................................. 37

CHAPTER 5 : RESULTS AND DISCUSSIONS ....................................................................... 38

5.1 Variation of Drain-Source Current versus Drain-Source Voltage ............................... 39

5.2 Variation of Drain-Source Current versus Gate-Source Voltage ................................. 41

5.3 Variation of Power Spectral Density versus Drain to Source Voltage: ......................... 42
5.4 Variation of Power Spectral Density versus Gate to Source Voltage with Different 
(V_DS) ....................................................................................................................................... 44

5.5 Variation of Power Spectral Density versus Gate to Source Voltage with Different 
Electron Concentration (N): ........................................................................................................ 45

5.6 Variation of Power Spectral Density versus Frequency: ...................................................... 47

CONCLUSION .................................................................................................................................. 48

REFERENCES .................................................................................................................................... 49

APPENDIX ......................................................................................................................................... 54
LIST OF FIGURES

Figure 1 Formation of Energies at Fermi level for Native Point Defects ....................... 7
Figure 2 Three Dimensional structure of GaN Zinc-Blende Crystal Structure .............. 8
Figure 3 Three Dimensional structure of GaN wurtzite Crystal Structure .................... 9
Figure 4 Energy Band diagram of GaN Zinc Blende Structure .................................. 10
Figure 5 Energy Band diagram of GaN for Wurtzite Crystal Structure ...................... 11
Figure 6 GaN, Wurtzite, Band Gap Energy and Exaction Energies Vs Temperature ..... 12
Figure 7 Intrinsic Carrier Concentration Vs Temperature ........................................ 14
Figure 8 An Approach of MOCVD Process ............................................................... 15
Figure 9 A MBE System ......................................................................................... 17
Figure 10 Substrates comparison for GaN ................................................................. 18
Figure 11 Drain-Source current versus Drain-Source voltage (I_{DS}-V_{DS}) .............. 20
Figure 12 GaN MESFET Studied under different Biasing a) Linear region b) Cut-off Region c) Saturation Region with dipole layer formation ............................. 22
Figure 13 Plot for junction depth and range parameters for different carrier concentration and depths ................................................................. 24
Figure 14 Fabrication process of MESFET ............................................................... 25
Figure 15 An Epitaxially Grown Channel MESFET ................................................ 27
Figure 16 Fabrication of MESFET Using Ion Implantation ...................................... 28
Figure 17 Simplified 3-D Structure of MESFET ...................................................... 29
Figure 18 Cross-Sectional View of MESFET ......................................................... 30
Figure 19 Variation of Drain-Source Current (I_{DS}) versus Drain-Source Voltage (V_{DS}) . 39
Figure 20 Variation of Drain-Source Current (I_{DS}) versus Gate-Source Voltage (V_{GS}).. 41
Figure 21 Variation of Power Spectral Density versus Drain to Source Voltage (V_{DS})... 42

Figure 22 Variation of Power Spectral Density versus Gate to Source Voltage with Different (V_{DS}). ........................................................................................................................................ 44

Figure 23 Variation of Power Spectral Density versus Gate to Source Voltage with Different Electron Concentration (N) ................................................................................................................................ 45

Figure 24 Variation of Power Spectral Density versus Frequency ........................................ 47
ABSTRACT

Studies of Electrical Characteristics of MESFET Using WBG III-V (GaN) Potential Substrate Material

By

Sai Praneeth Thota

Master of Science in Electrical Engineering

The adoption of semiconductor materials has been marked up in the contemporary generation due to their tremendous strides being made in superconductors and amorphous material research. In this graduate thesis, the study of electrical characteristics of GaN Metal Semiconductor Field Effect Transistor (MESFET) has been conducted to evaluate the I-V characteristics by computing the linear and non-linear currents. An effort has been induced to combine the two sections of linear and non-linear currents to deliver more precise value of the channel current compared to the conventional channel current equation. Analysis of Power Spectral Density (PSD) has been performed with the variation of gate-source voltage and drain-source voltage. A comparison of PSD and frequency has been executed in order to anticipate the high frequency response.
CHAPTER -1 INTRODUCTION

1.1 Recent Developments in Semiconductor technology

The semiconductor materials like gallium nitride (GaN), aluminum nitride (AlN), gallium arsenide (GaAs) and silicon carbide (SiC) have boosted their engrossment in modern chronology because of their huge frequency and power applications. Their higher electron velocity and high electric field are what gives these material's colossal potential in the power mechanism range.

The most emanating device which can be befitting in both high and low frequency range is Metal Semiconductor Field Effect Transistor (MESFET). High transconductance and transit frequency in MESFET give high value of carrier mobility. The structure of GaN MESFET’s is simple when it’s compared to High Electron Mobility Transistors (HEMTs), so it drew more attention.

Because of their higher bandgap energy, the wide band gap semiconductors have many advantages when compared to low band gap semiconductors. At temperature crests, gallium nitride (GaN) material and many other semiconductors has delineated affirmative characteristics, due to their large band gap energy. These semiconductors have many material properties such as bandgap, thermal conductivity, saturation velocity, breakdown velocity, etc. Wide bandgap semiconductors can phase out 90% of power losses in electricity transfer when compared to current technology. Gallium nitride (GaN) has same thermal conductivity when compared to silicon (Si), but silicon carbide (SiC) is a component of three times higher.
Table 1.1 [1] demonstrates some of the material properties of wide band-gap semiconductors.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
<th>Si</th>
<th>GaAs</th>
<th>SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$(eV)</td>
<td>Band Gap Energy</td>
<td>1.12</td>
<td>1.45</td>
<td>3.25</td>
<td>3.4</td>
</tr>
<tr>
<td>$\epsilon_r$</td>
<td>Dielectric constant</td>
<td>11.7</td>
<td>12.9</td>
<td>9.7</td>
<td>8.9</td>
</tr>
<tr>
<td>$E_c$(kV/cm)</td>
<td>Energy in conduction band</td>
<td>300</td>
<td>400</td>
<td>2200</td>
<td>2000</td>
</tr>
<tr>
<td>$\mu_n$($\frac{cm^2}{vs}$)</td>
<td>Mobility of electrons</td>
<td>1350</td>
<td>8500</td>
<td>600</td>
<td>1500</td>
</tr>
<tr>
<td>$\lambda$($\frac{W}{cm\cdot K}$)</td>
<td>Wavelength</td>
<td>1.5</td>
<td>0.55</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>$V_{sat}$($\times10^7$cm/s)</td>
<td>Saturation velocity</td>
<td>1</td>
<td>1.2</td>
<td>2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table 1.1: Material properties of GaN, Si, SiC, and GaAs Semiconductors [1]

At 300°K gallium nitride (GaN) illustrates high band gap energy of 3.4eV. It has high mobility of electrons of 1500 cm$^2$/vs in contrast to other semiconductor materials like silicon, gallium arsenide etc. It also have high saturation velocity of 2.2×10$^7$ cm/s. Every semiconductor material has a band structure and several electrical and transport characteristics. The properties such as thermal conductivity, mobility of electrons and
holes, band gap energy, lattice constant, velocity at peak, saturation velocity, intrinsic carrier concentration, and dielectric constants are major and properties of any semiconductor.

The table 1.2 shows the electrical and transport characteristics of gallium nitride (GaN) [1].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Gallium Nitride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron life time</td>
<td>C</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Auger coefficient</td>
<td>cm$^3$/s</td>
<td>$7 \times 10^{-29}$</td>
</tr>
<tr>
<td>Structure</td>
<td>-</td>
<td>wurtzite/zinc blende</td>
</tr>
<tr>
<td>Thermal velocity of electron</td>
<td>m/s</td>
<td>$5.5 \times 10^5$</td>
</tr>
<tr>
<td>Saturation Velocity</td>
<td>cm/s</td>
<td>$2.5 \times 10^7$</td>
</tr>
<tr>
<td>Energy gap nature</td>
<td></td>
<td>Direct</td>
</tr>
<tr>
<td>Recombination velocity</td>
<td>cm/s</td>
<td>$&lt;10^6$</td>
</tr>
<tr>
<td>Peak velocity</td>
<td>cm/s</td>
<td>$3.2 \times 10^7$</td>
</tr>
<tr>
<td>Breakdown velocity</td>
<td>V/cm</td>
<td>$&gt;5 \times 10^6$</td>
</tr>
<tr>
<td>Energy bandgap</td>
<td>Eg</td>
<td>3.4</td>
</tr>
<tr>
<td>Effective mass of electron</td>
<td>m$_e$</td>
<td>0.20</td>
</tr>
<tr>
<td>Polar optical phonon energy</td>
<td>meV</td>
<td>91.2</td>
</tr>
<tr>
<td>Refractive index</td>
<td></td>
<td>2.67eV</td>
</tr>
<tr>
<td>Lattice Constant, a(c)</td>
<td>A$^0$</td>
<td>3.189(5.185)</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Value</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------</td>
<td>---------</td>
</tr>
<tr>
<td>Mobility of electron</td>
<td>cm²/Vs</td>
<td>1500</td>
</tr>
<tr>
<td>Stability</td>
<td></td>
<td>Stable</td>
</tr>
<tr>
<td>Mobility of Holes</td>
<td>cm²/vs</td>
<td>30</td>
</tr>
<tr>
<td>Effective Density</td>
<td>g/cm</td>
<td>6.1501</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td></td>
<td>8.92</td>
</tr>
<tr>
<td>Peak velocity field</td>
<td>kV/cm</td>
<td>150</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>Dielectric constant at high frequency</td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/cm-K</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Table 1.2 Electrical Parameters and Transport Properties of (GaN) [1]**

1.2 GaN MESFET Frequency Performance:

The utilization of GaN material and GaN based hetero-structure is elevated power provisions gained respectable regards these days. The investigation of hot electrons associated to their milieu is in the manner quite compelling in the GaN framework. As electrons increase life through the sequestration of an electric field, they stop being in concord with the photons, however equilibrate with one another through electron-electron cooperation.

The two trivial cited parameters in frequency performance of a device are cutoff frequency ($f_T$) and maximum frequency ($f_{max}$). The minimum requirement of MESFET is to have an achievable highest value of cutoff frequency. The output power that is need for system level application is called as RF power output.
One of the best output performance a device exhibits are, at \( V_{DS}=35V \), with \( I_{DS}=450mA \) and \( V_{GS}=-1V \), a GaN MESFET was fabricated and panoply the power added efficiency (PAE) of 40%, cutoff frequency 10GHz, and 88ms/mm of transconductance.

At the low frequency noise in FET’s is dominated by a type of noise whose power spectral density varies inversely with frequency. The magnitude of this so called 1/f noise drops below the thermal noise floor at a corner frequency that is typically between 100 KHz and 100 MHz.

1.3 GaN Optoelectronics

In 1968 green LED came into action through nitrogen doped GaP p-n junction. Between 1960’s and 1970’s there are many materials which can be used for fabrication of blue LED’s such as, 6H SiC with a band gap of 3.0eV, GaN with energy gap of 3.4eV.

In recent years GaN has got great attention in fabricating LED’s with a wide range of colors because it can perform fabrication from visible lights to ultraviolet (UV) rays. Meanwhile, in early 80’s laser diode (LD) with violet and blue colors was invented for high performance. LED’s based on nitrides have many applications such as, signage on roads, traffic signal lights. In computers they are used in optical disc to read and write the data and also they are used as lighting sources for agriculture, because they are energy saving and valid in extreme environments [2].

For the telecommunication of fiber optics, an application of optoelectronic devices called inter-sub-band (ISB) made by nitride of group III such as GaN, AlN, and InN. These materials are highly attractive while fabricating ISB devices because of their operating spectrum ranges in infrared and also have wideband wavelength of 1.3 \( \mu m \)-1.55\( \mu m \). There
are many reasons that GaN semiconductor is suitable for ISB device fabrication, first because they offer large offset of the conduction band and they also operate in a wide range of spectrum and material transparency.

1.4 Defects in Semiconductors

There are many varieties of defects known as crystal defects [3] occurs in semiconductor crystals, which may lead to degrade the performance due to generation of noise which is in the form of current or voltage fluctuations. So in order to maintain high frequency and output performance and minimize the occurrence of defects there is a need of careful growth and fixed fabrication conditions. The huge atomic behavior of material influence the electrical properties of semiconductor which are called line defects. Additionally, these defects lead to generation of low frequency noises.

1.4.1 Native Point Defects

Due to these defects the performance of GaN material, electrical and optical properties has been deteriorating. There are many slopes of defects have been demonstrated for point defects which can be possibly formed during the growth of a material. The figure 1 splashes the energy formation at different fermi level for native point defects in gallium nitride semiconductor for defect charges [4].
1.4.2 Interstitials and Antisite Defects:

Since the GaN material has two atoms gallium and nitrogen we have two interstitials called Ga interstitials, Nitrogen interstitials. Similarly, they have Ga antisite and Nitrogen antisite. However, there is a crouched chance of development of interstitial defects in GaN, because of its tiny lattice constant and huge mismatch between Gallium and Nitrogen atoms. Usually, carbon, silicon and germanium on Gallium sites and selenium, oxygen on Nitrogen sites are treated as donors in gallium nitride. On the other side zinc, magnesium and calcium on gallium site and silicon, carbon on Nitrogen site are considered as acceptors in GaN.
CHAPTER 2 STUDY OF GaN MATERIAL

The gallium nitride, which belongs to group III-nitrides have experienced rapid progress in material growth, processing and device technology over the past decade. In 1932, GaN was synthesized in powder form, later in 1938 small needles of GaN were obtained by Juza and Hahn.

GaN Crystal Structure:

Gallium nitride (GaN) forms in two cases of crystal structures. They are

1. Zinc-Blende Crystal Structure
2. Wurtzite Crystal Structure

Gallium and Nitride are two elements from group III and V which forms a compound semiconductor called Gallium nitride (GaN). The representation of zinc blende and wurtzite crystal structure are shown in Figures 2 and 3 [5].

![Figure 2 Three Dimensional structure of GaN Zinc-Blende Crystal Structure [5]](image-url)
The zinc blend structure consists of four group III components and four nitrogen components with lattice constant of 4.5Å. The ideal angle of 109.470° was measured, and phase is metastable for GaAs, Si and MgO.

![Figure 3 Three Dimensional structure of GaN wurtzite Crystal Structure](image)

The name wurtzite structure is given after the mineral called wurtzite. An ideal wurtzite crystal structure has a c/a ratio of 1.633 and u=0.375. The crystallography of zinc blende and wurtzite structures are almost same and their bonding with neighbors are tetrahedral. The periodic arrangement of atoms in a crystal is termed a lattice and the distance between the atoms is the lattice constant. The unit cell is a fundamental unit in crystal and a repletion of the unit cell generates the entire lattice.
These constructions are quite equivalent to the diamond crystal structure. The lattice constants for GaN are stated in table 2.1 below [6].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.111Å°</td>
</tr>
<tr>
<td>B</td>
<td>4.978Å°</td>
</tr>
<tr>
<td>U</td>
<td>0.382Å°</td>
</tr>
</tbody>
</table>

**Table 2.1 Lattice constants for gallium nitride (GaN) [6]**

2.1 Energy Band Diagram for GaN

Direct bandgap semiconductors are capable of the photon emission, by radiative recombination, but indirect bandgap semiconductors have a low probability of radiative recombination.

**Figure 4 Energy Band diagram of GaN Zinc Blende Structure [6]**
Considering the Figure 4, we note that three different valance bands are shown. It is easy to understand that the band is having a less curvature at k=0 which is called heavy hole band, while other is slightly bend is called light hole band. The band which is strongly bending is called split-off band. Figure 5 shows the Energy Band diagram of GaN for wurtzite Crystal Structure. The value of $E_{cr}$ is 0.4eV.

![Energy Band diagram of GaN for Wurtzite Crystal Structure](image)

**Figure 5 Energy Band diagram of GaN for Wurtzite Crystal Structure [6]**

### 2.2 Band Gap Energy Temperature Dependence

The energy gap between the conduction and valance band is called as band gap energy.

\[
E_g = \frac{E_g - 7.7 \times 10^{-4} \times T^2}{(T+600)} \quad eV
\]  

(2.1)

\[
E_g = 3.47 \quad eV \text{ for wurtzite crystal}
\]  

(2.1a)
Where T is the absolute temperature

The temperature dependent bandgaps for gallium nitride have been demonstrated in Figure 6 below [6] as follows

![Figure 6 GaN, Wurtzite, Band Gap Energy and Exaction Energies Vs Temperature](image)

**Figure 6 GaN, Wurtzite, Band Gap Energy and Exaction Energies Vs Temperature**

[6]

The equation for temperature dependence [6] can be gained by the following equation

\[
E_g(T) - E_g(0) = \frac{-5.08 \times 10^{-4} \times T^2}{(996 - T)} \text{ in kelvins} \quad (2.2a)
\]

\[
E_g = 3.44eV \text{ at } 300^\circ \text{ kelvins} \quad (2.2b)
\]
2.3 Intrinsic Carrier Concentration and Effective Density of States of GaN

When there are no defects and no impurities in a crystal then the semiconductor is called intrinsic. The effective density of states functions for conduction and valance respectively.

For conduction band

\[ N_c = 2\left(\frac{2\pi m^*_n kT}{\hbar^2}\right)^{\frac{3}{2}} \]  

(2.3a)

For valance band

\[ N_v = 2\left(\frac{2\pi m^*_p kT}{\hbar^2}\right)^{\frac{3}{2}} \]  

(2.3b)

The equilibrium of electrons and holes in conduction and valance bands are given as

\[ n_0 = N_c * \exp\left(\frac{-\left(E_c - E_F\right)}{kT}\right) \]  

(2.3c)

\[ p_0 = N_v * \exp\left(\frac{-\left(E_F - E_V\right)}{kT}\right) \]  

(2.3d)

By using equations (2.3c) and (2.3d) the carrier concentration is given by

\[ n_i = \sqrt{N_c N_v} \exp\left(\frac{-\left(E_c - E_V\right)}{2kT}\right) \]  

(2.3e)

\[ n_i = \sqrt{N_c N_v} \exp\left(\frac{-\left(E_g\right)}{2kT}\right) \]  

(2.3f)

\[ n_i = 1.9 \times 10^{10} \text{ cm}^{-3} \text{ for gallium nitride at } 300^\circ\text{K} \]
The Figure 7 shows the variation of intrinsic carrier concentration and temperature

![Figure 7 Intrinsic Carrier Concentration Vs Temperature][7]

2.4 Material Growth

2.4.1 Metal Organic Chemical Vapor Deposition (MOCVD)

MOCVD is essentially a replacement for the older halide vapor-phase epitaxy method. The source chemicals in MOCVD are the metal-organic trimethylgallium (TMG) or triethylgallium (TEG) for Ga, trimethylaluminum (TEAL) for Al, and arsine (AsH$_3$) for As. Growth occurs by flowing these gases with an H$_2$ carrier over an inductivity or radiatively heated GaAs substrate [8]. The chamber itself is not heated, and the growth occurs at atmospheric pressure, although low pressure (-76 torr) can be used.
2.4.2 MOCVD Reaction Chemistry

The typical chemical reaction producing GaN from TMGa and NH₃ can be written as

\[(CH_3)_3Ga + NH_3 \rightarrow GaN + 3CH_4\]  \hspace{1cm} (2.4)

The variation of MOCVD is known as atomic layer epitaxy (ALE). Since there is no solid Ga source in MOCVD, the problem of surface defects is limited to the more easily controlled particulates. Typically, three to five wafers are grown in each MOCVD run, giving it a much higher throughput than MBE. Basically, this occurs because it is easier to achieve a uniform reactant flux with gaseous sources than with solid sources. The typical dopants in MOCVD are Si for n-type materials, and Zn for p-type materials.

The primary layout of MOCVD reactor is shown in the Figure 8.

---

**Figure 8 An Approach of MOCVD Process [9]**
2.4.3 Molecular Beam Epitaxy (MBE)

The concept behind the MBE is quite simple. The atomic or molecular beams of the lattice constituents like gallium, arsenide and aluminum produce by heating, high purity, solid sources of these elements in a high vacuum (~ $10^{-10}$ Torr) chamber, are directed onto a heated substrate. The group III atoms have a high sticking coefficient of the substrate surface at the growth temperature (typically 550°C), and, together with the Arsenide atoms, they migrate short distances on the surface, producing layer-by-layer stoichiometry epitaxial growth. The growth chamber also contains several in situ diagnostics techniques. Residual gas analyzers are used to check for the presence of impurities prior to growth. Reflection high-energy electron diffraction (RHEED) patterns provide an extremely accurate measure of the growth rate and of the quality of the surface reconstruction during in situ cleaning steps and at the nucleation stage. Finally, ion gauges are used to measure the impinging beam fluxes. Doping calibrations are usually performed on separate, thick layered structures. The run-to-run reproducibility of this doping is ±5 %, while the run-to-run variations can be as little as ±1% with the use of RHEED oscillation control. Since the elemental As, Ga and Al used as sources can be refined to very high purities, and the growth chamber is itself an inherently clean environment, un-doped MBE materials have very low carrier concentrations. UN-doped GaAs is typically p-type with hole densities in the range of $10^{13}$ to $10^{15}$ cm$^{-3}$, due to residual C contaminations. There is some limitation in the MBE process such as, to fabricate high density integrated circuits, it is necessary to have defected densities $\leq 50$ cm$^{-2}$. Phosphorous based compound growth is difficult because of difficult to control the phosphorous vapor pressure. But it is not considered as a severe limitation because phosphorous is not widely used in MESFET structures.
The Figure 9 portrays the physical structure of MBE below.

![Figure 9 A MBE System](image)

2.5 Substrate used for GaN

There are many substrates used in GaN such as SiC, Si, GaN, AlN, LiAlO$_2$, ZrB$_2$, and MgO. Gallium Nitride and 6H-Silicon Carbide have very close lattice matching and also band gap is virtually equal to each other. There are many factors considered while picking up the substrate such as, lattice matching, thermal expansion coefficient (TEC), temperature stability, conductivity, lattice coincidence, and hence forth [11].
The comparison of different substrates used in gallium nitride is shown in Figure 10.

Figure 10 Substrates comparison for GaN [11]

One of the most favorable substrate used for growth of GaN is Silicon. It produces high quality, big size, thermal stability and low cost at high temperatures. There are many fundamental properties of materials involved in GaN growth, which are tabulated in table 2.2.
<table>
<thead>
<tr>
<th>Material</th>
<th>Crystal Structure</th>
<th>Lattice Constant (Å)</th>
<th>Thermal Mismatch ($10^{-6}$/K)</th>
<th>Lattice Mismatch %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(a)</td>
<td>(c)</td>
<td>(a)</td>
</tr>
<tr>
<td>GaN</td>
<td>Hexagonal</td>
<td>3.18</td>
<td>5.18</td>
<td>5.59</td>
</tr>
<tr>
<td>AlN</td>
<td>Hexagonal</td>
<td>3.104</td>
<td>4.96</td>
<td>4.2</td>
</tr>
<tr>
<td>Si</td>
<td>Diamond</td>
<td>5.43</td>
<td>5.42</td>
<td>3.59</td>
</tr>
<tr>
<td>Sapphire</td>
<td>Hexagonal</td>
<td>4.758</td>
<td>12.99</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 2.2 Fundamental Properties of Materials involved in GaN Growth [11]
CHAPTER 3 PHYSICS OF MESFET

3.1 INTRODUCTION:

The basic structure of MESFET consists of source, drain and gate. The drain is normally positively biased, so that the depletion region of gate always moves close to drain. The Schottky metal gate governs the charge flow between source and drain. So by differing region of depletion gate, electric field and applied voltage the current present between source and drain can be manipulated.

3.2 Study of MESFET I-V Characteristics

Figure 11 shows the Drain-Source current versus Drain-Source voltage (I<sub>DS</sub>-V<sub>DS</sub>) characteristics of MESFET.

![Figure 11 Drain-Source current versus Drain-Source voltage (I<sub>DS</sub>-V<sub>DS</sub>)](image)

Figure 11 Drain-Source current versus Drain-Source voltage (I<sub>DS</sub>-V<sub>DS</sub>) [12]
The Figure 11 illustrates distinct I-V characteristics for various Gate-Source Voltages. In the above figure the calculated and experimental results for n-channel depletion mode MESFET are shown for different gate to source voltages such as $V_{GS}=0\text{V}$, $V_{GS}=-2\text{V}$, $V_{GS}=-4\text{V}$, $V_{GS}=6\text{V}$, $V_{GS}=-8\text{V}$. At $V_{GS}=0$, as $V_{DS}$ is hiked, a narrow depletion region is formed. As the gate to source voltage decreases the current flow through the drain to source also decreases. In general I-V curve has three regions which are linear, cutoff and saturation which has been discussed later in detail. The point at which breakdown of voltage occurs called avalanche breakdown voltage which can be denoted by $V_B$.

### 3.3 Types of MESFET’s

MESFET’S are broadly classified into n-channel type and p-channel type, each having different mode of operations called as enhancement mode and depletion mode.

#### 3.3.1 Enhancement mode MESFET

When the gate to source voltage is zero these modes of MESFET’S are generally in normally OFF state. The enhancement of conduction channel can be done by altering the gate voltage against grain voltage which makes them turn ON positive for n-channel and negative for p-channel [13].

#### 3.3.2 Depletion mode MESFET

These modes of MESFET’S are opposite in nature when compared to enhancement mode MESFET’S. As gate voltage alters distant to drain voltage the depletion region is formed in the channel. Typically these devices are normally ON state.
3.4 MESFET Operating Regions

MESFET also has three different regions. They are

1. Linear Region
2. Cut-off Region
3. Saturation Region.

Figure 12 shows the different regions of operations in MESFET [14]

Figure 12 GaN MESFET Studied under different Biasing a) Linear region b) Cut-off Region c) Saturation Region with dipole layer formation.
The Figure 12 (a) shows a linear area of I-V characteristics, where channel current increases linearly with increase of the drain-source voltage $V_{DS}$. Secondly, the cut-off region can be analyzed as, when pinch-off voltage ($V_P$) is less than gate to source voltage ($V_{GS}$) the depletion region gets deeper which is clearly demonstrated in Figure 12(b). The final region which is called a saturation region, where the drain to source current doesn’t have any affect with the alterations in drain voltage. The fair picture of saturation region is depicted in Figure 12(c).

### 3.5 Ion Implantation

Due to the bombardment of dopant ions, impurities are ushered into semiconductor, such process is termed as ion implantation. Compared to other doping techniques this technique provides more control over doping levels [15].

The expression for impurity distribution given by

$$D(x) = X_p \times \exp\left[\frac{-(x-T_p)^2}{2(\Delta T_p^2)}\right] - X_B$$  \hspace{1cm} (3.1)

The peak concentration can be defined as

$$X_p = \frac{Q}{\Delta T_p \sqrt{\pi}}$$  \hspace{1cm} (3.2)

Where

- $X_p$= peak concentration
- $T_p$= Range parameter
- $Q$= Ion Dose
- $X_B$= Background Concentration
- $\Delta T_p$= straggle parameter
The junction depth can be expressed as

\[
D_j = T_p + \Delta T_p \sqrt{2 \ln \left( \frac{X_p}{X_B} \right)}
\]  \hspace{1cm} (3.3)

Where

\(X_p\) = peak concentration

\(T_p\) = Range parameter

Q = Ion Dose

\(X_B\) = Background Concentration

The Figure 13 shows the plot for junction depth and range parameters of ion implanted n-type profile with p-type substrate.

Figure 13 Plot for junction depth and range parameters for different carrier concentration and depths [15]
3.6 Fabrication Process

The standard procedure for fabricating MESFET is shown in Figure 14 [15].

A. Starting Wafer

B. Mask #1 Channel Implant

C. Mask #2 Source/Drain Implant

D. Mask #3 S/D Ohmic Contact Window Formation

E. Mask #3 (continued) Ohmic Metal Deposition and Lift off

F. Mask #4 Schotky Gate Contact Formation and Metal Lift off

G. Finished Device

Figure 14 Fabrication process of MESFET [16]
The fabrication process engross several steps. In step 1 selection of wafer is done and it is cleaned with acetone and methanol for half a minute each and dried out. After this step an epitaxial layer is grown using any growth process and a channel is implanted using photoresist. During the process of masking, at mask 2 photoresist cuts the windows for source and drain n+ region implants. Now at mask 3, it cuts the windows for source and drain ohmic contacts and mask 3 will continue the process to remove the ohmic metal. This process is called Liftoff [16]. Finally, at mask 4 the photoresist helps to create a window for Schottky gate contact and the final device is accumulated.

3.7 Advantages of MESFET

These devices have outstanding electronic properties like high gain, bandwidth, higher mobility, high current, and switching speed. And also

1. High carrier mobility compared to other FET’s
2. There is no possibility of surface mobility.
3. Overall performance depends on the source and drain as Schottky barrier height doesn’t depend only on the gate.
CHAPTER 4 THEORY OF GaN MESFET USED IN SIMULATION

4.1 Introduction to Current Controlled Mechanism in MESFET

One of the most commonly used transistor is Metal–Semiconductor Field Effect Transistor (MESFET). The current flowing through semiconductor material or channel depends on three parameters, velocity of charge carriers, density of charge carriers, and the geometry cross-section the carriers flows through. The epitaxial grown channel of MESFET device is shown in Figure 15.

![Figure 15 An Epitaxial Grown Channel MESFET [17]](image)

In epitaxial growth, a partly insulating substrate silicon, a thin un-doped buffer layer is grown to improve the interface quality. To improve the formation of non-blocking contacts and to reduce the series resistance between source and drain, above the substrate a highly doped contact layer is intended. The contact layer is etched away to allow the blocking Schottky contact to contact channel layer directly.
Figure 16 shows a very similar structure fabricated using ion implantation, but the only difference is differently doped semiconductor regions are formed by ion implantation. The lattice damage caused by ion bombardment will negatively impact carrier velocity and also lead to an increase in low-frequency noise. In both the cases carrier species in the channel are electrons.

![Fabrication of MESFET Using Ion Implantation](image)

**Figure 16 Fabrication of MESFET Using Ion Implantation [17]**

To obtain the analytic expressions, the structure is simplified further. Now Figure 17 shows the three dimensional view of the simplified structure. First, note the coordinate system which says the $x$ axis is parallel to the long extension of gate stripe. The $y$ axis is perpendicular to the semiconductor surface, while the $z$ axis is parallel to the surface in the direction of the short extension of the gate. The long gate dimension in the $x$ direction is called the gate width $W_G$, while the extension in $z$ direction gate length $L_G$. 
Figure 17 Simplified 3-D Structure of MESFET [17]

Assume that the channel is one dimensional. Now only the x component has an electric field. To neglect the electric field in x direction the gate width should be more than the gate length $W_G >> L_G$, but it needs a simplification to neglect the electric in y direction which is called *gradual channel approximation*. In this simplification, the electric field drives the current flow in semiconductor devices which is called drift current while the current driven by concentration gradients is called diffusion current or a combination of both.

Now Figure 18 shows only the cross section of the device. The source electrode shall be the reference potential, hence $V_S = 0$.

The gate electrode potential with respect to the source is the gate-source voltage $V_{GS}$. In an n-channel device, where the channel layer is n-doped, it will generally be negative to maintain the gate-channel diode in blocking state. The drain-source voltage $V_{DS}$ in an n-channel device will be positive.
The expression of the space charge region, shown schematically in Figure 18, depends on the local gate-channel voltage $V_G$. We find for $V_G(x)$ as

$$V_G(x) = V_{GS} - V(x)$$  \hspace{2cm} (4.1)$$

Where

$V_{GS}$ = Gate to Source Voltage

$V(x)$ = the voltage drop in the channel between point $z$ and source. As $V(x) > 0$, the gate channel, voltage becomes more negative as $x$ increases.

At point $x$, the extension of the space charge region is

$$h(x) = \sqrt{\frac{2\varepsilon_s[V_{bi} - V_G(z)]}{qN_D}}$$ \hspace{2cm} (4.2)$$
\[ h(x) = \sqrt{\frac{2\varepsilon_s[V_{bi}-V_{GS}-V(z)]}{qN_D}} \]  \hspace{1cm} (4.3)

Where

\[ N_D = \text{Channel Doping Concentration} \]

\[ \varepsilon_s = \text{Permittivity of Substrate} \]

\[ V_{bi} = \text{Buit-in Voltage} \]

### 4.2 Drain Current Using a Constant Mobility Assumption:

Let us consider a small \( V_{DS} \), such that \( h(x) < a \), with \( a \) the channel thickness for all \( 0 < x < L_G \). The channel current is always calculated by multiplying the charged density \((qN_D)\), the cross section through which it is moved \( W_G[a - h(x)] \) and the charge velocity. For low electric fields the charge velocity can be calculated by mobility \( \mu_n \) and the local electric field \( \frac{dV(z)}{dz} \). Therefore the channel current is expressed as

The channel current as a function of \( x \) coordinate

\[ I(x) = qN_D W_G [a - h(x)] \mu_n \frac{dV(x)}{dz} \]  \hspace{1cm} (4.4)

Where

\[ q = \text{Charge} \]

\[ W_G = \text{Gate Width} \]

\[ N_D = \text{Doping Concentration} \]
\( \mu_n = \text{Electron Mobility} \)

As per Kirchhoff’s law, the current entering to the source is equal to the current leaving through the drain. It is called current continuity. So we now eliminate the x dependence.

As \( I(x) = \text{constant} = I_D \)

Obviously \( \int_{0}^{L_G} I(x) \, dx = I_D L_G \)

Consider further

\[
h(x) = \frac{2e_s}{qN_D} [V_{bi} - V_{GS} + V(x)] \tag{4.5}
\]

Differentiating with respect to \( x \) on either sides leads to

\[
2h(x) \frac{dh(x)}{dx} = \frac{2e_s}{qN_D} \frac{dV(x)}{dx} \tag{4.6}
\]

And finally,

\[
\frac{dV(x)}{dx} = \frac{qN_D}{2e_s} h(x) \frac{dh(x)}{dx} \tag{4.7}
\]

Through the parameter substitution, we find the drain current, considering the gradual channel approximation, the drain current can be defined as
\[ I_D = \frac{1}{L_G} \int_{x=0}^{x=L_G} I(x) \, dz \]  

(4.8)

\[ I_D = \frac{q^2 N_D^2 W_G \mu_n}{\epsilon_s L_G} \int_{h(0)}^{h(L_G)} h(x) \left[ a - h(x) \right] dh \]  

(4.9)

As \( V(0) = 0 \), \( h(0) = \sqrt{\frac{2 \epsilon_s}{q N_D}} (V_{bi} - V_{GS}) \)

Then the pinch off voltage is given by

\[ V_p = V_{bi} - a^2 \frac{q N_D}{2 \epsilon_s} \]  

(4.10)

\[ V_{bi} = \frac{kT}{q} \log\left( \frac{N_D}{n_i} \right) \]  

(4.11)

Where

K= Boltzmann’s Constant

\( n_i = \) Intrinsic Carrier Concentration

\( N_D = \) Doping Concentration

T= Absolute Temperature

\( q = \) charge

Using \( V_p \), we can write 4.3 in the following form
\[ h(x) = a \sqrt{\frac{V(x) - V_{GS} - V_{bi}}{V_{bi} - V_p}} \] (4.12)

We know that \( V(x = L_G) = V_{DS} \). Therefore

\[ h(x = L_G) = a \sqrt{\frac{V_{DS} - V_{GS} - V_{bi}}{V_{bi} - V_p}} \] (4.13)

Now finally we can solve current integral using constant mobility assumption, and the current equation for linear region can be given as

\[ I_D(V_{GS}, V_{DS}) = \frac{a^2 N_D^2 \mu_n a^2 W_G}{6 \varepsilon_s L_G} \left( \frac{3V_{DS}}{V_{bi} - V_p} - 2 \frac{(V_{DS} - V_{GS} + V_{bi})^{3/2} - (V_{bi} - V_{GS})^{3/2}}{(V_{bi} - V_p)^{3/2}} \right) \] (4.14)

Similarly for saturation region the current equation can be given as

\[ I_D(V_{GS}, V_{DS}) = \frac{a^2 N_D^2 \mu_n a^2 W_G}{6 \varepsilon_s L_G} \left( 1 - 3 \frac{(V_{bi} - V_{gs})}{(V_{bi} - V_p)} + 2 \frac{(V_{bi} - V_{gs})^3}{(V_{bi} - V_p)^3} \right) \] (4.15)

Where

q = Charge

a = Active Channel Thickness
\( L_G = \text{Gate Length} \)

\( W_G = \text{Gate Width} \)

\( N_D = \text{Doping Concentration} \)

\( V_{DS} = \text{Drain to Source Voltage} \)

\( V_{GS} = \text{Gate to Source Voltage} \)

\( V_{bi} = \text{Built-in Voltage} \)

\( V_P = \text{Pinch-Off Voltage} \)

\( \mu_n = \text{Electron Mobility} \)

\( \epsilon_s = \text{Permittivity of Substrate} \)

### 4.3 Transfer Characteristics:

Let us assume that charge carriers in the channel reach their drift saturation velocity immediately after entering the channel at source side.

The channel current in n-channel MESFET becomes

\[
I(x) = q N_D V_{sat} W_G [a - h(x)] = constant = I_D
\]  

(4.16)

Now \( h (x) = h \)

\[
I(x) = q N_D V_{sat} W_G [a - h]
\]  

(4.17)
The space charge extension is calculated as

\[ h(0) = \sqrt{\frac{2\varepsilon_s}{qN_D} (V_{bi} - V_{GS})} \]  

(4.18)

Since

\[ V_P = V_{bi} - a^2 \frac{qN_D}{2\varepsilon_s} \]

\[ h = h(0) = a \sqrt{1 - \frac{V_{bi} - V_{GS}}{V_{bi} - V_P}} \]  

(4.19)

Therefore,

\[ I(x) = qN_D V_{sat} W_G a \left(1 - \sqrt{\frac{V_{bi} - V_{GS}}{V_{bi} - V_P}}\right) \]  

(4.20)

Where

q = Charge

a = Active Channel Thickness

W_G = Gate Width

N_D = Doping Concentration

V_{GS} = Gate to Source Voltage

V_{bi} = Built-in Voltage

V_P = Pinch-Off Voltage

V_{sat} = Drift Saturation Velocity of Electrons
4.4 Power Spectral Density

The spectral power density, contributing noise sources increases with decrease in frequency. The excess noise is due to interaction with impurities or dislocations which create energy levels inside of the forbidden gap of semiconductor materials. These traps may lead to mobility fluctuation noise or number fluctuation noise.

When applied to drain current the Hooge’s relationship find the expression for power spectral density as follows.

\[ S_{ID} = I_{D}^{2} \frac{\alpha_{H}}{N*F} \]  \hspace{1cm} (4.21)

The Hooge’s constant can be determined by the expression

\[ \alpha_{H} = \frac{a}{\lambda ph} \]  \hspace{1cm} (4.22)

Where

a= Lattice Constant

\( \lambda ph \)= Mean Free Path between Electrons

\( I_{D} \)= Drain Current

\( \alpha_{H} \)= Dimensionless Hooge’s Constant

\( N \)= Number of Carrier in giving Volume

\( F \)= Frequency of Operation
CHAPTER 5 RESULTS AND DISCUSSIONS

A study of electrical characteristics of GaN Metal Semiconductor Field Effect Transistor (MESFET) has been conducted to evaluate the I-V characteristics of computing the linear and non-linear currents. I-V characteristics have been generated by combining the two sections of linear and non-linear currents to deliver more precise value of the channel current compared to the conventional channel current equation. Analysis of Power Spectral Density (PSD) has been computed with the variation of gate-source voltage and drain-source voltage. The detailed result has been described in this section.
5.1 Variation of Drain-Source Current versus Drain-Source Voltage

![Figure 19](image.png)

**Figure 19 Variation of Drain-Source Current (I_{DS}) versus Drain-Source Voltage (V_{DS})**

The above Figure 19 presents the plot for drain-source current versus drain-source voltage for different voltages (V_{GS}) of 0V, -0.5V, -1V, 1.5 V with doping concentration (N_D) of 1x10^{17} cm^{-3}, channel length (L) of 1x10^{-4} cm, channel width (W) of 1000x10^{-4} cm and pinch-off voltage of -6V. I-V characteristic plot has been generated for linear and saturation regions computed from the equations (4.14) and (4.15).
An attempt has been made to merge the two segments of linear and non-linear channel currents shown in Figure 19. The drain currents linearly increases up to the $V_{DS} = 2V$, the nonlinear properties of I-V characteristics clearly show in the drain-voltage range of 2V-5V and the saturation current shows beyond the drain-source voltage $V_{DS}$ of 5V. I-V characteristics obey the physics of MESFET operation. The combination of linear and non-linear for I-V characteristics enhance the accuracy of analytical model and it is valid for submicron devices.

5.2 Variation of Drain-Source Current versus Gate-Source Voltage

![Transfer characteristics for GaN MESFET](image)

Figure 20 Variation of Drain-Source Current ($I_{DS}$) versus Gate-Source Voltage ($V_{GS}$)
The Figure 20 shows the transfer characteristics plot for variation of the drain-source current to gate-source voltage for different doping concentration ($N_D$) of $1 \times 10^{16}$ cm$^{-3}$, $5 \times 10^{16}$ cm$^{-3}$ and $1 \times 10^{17}$ cm$^{-3}$ with channel lengths of $1 \times 10^{-4}$ cm, active channel thickness (a) of $19.34 \times 10^{-4}$ cm, channel width (W) of $1000 \times 10^{-4}$ cm and saturation velocity of $2 \times 10^7$ cm$^2$. The threshold voltage has been found in the order on -6V which confirms that the device behave in depletion mode. The plot has been generated using the equation (4.20).

5.3 Variation of Power Spectral Density versus Drain to Source Voltage:

![Figure 1: Variation of Power Spectral Density versus Drain to Source Voltage](image)

Figure 21 Variation of Power Spectral Density versus Drain to Source Voltage ($V_{DS}$)
The Figure 21 shows the variation of power spectral density and drain-source voltage ($V_{DS}$) for different Gate-Source voltages of 0V, -0.5V, -1V with doping concentration ($N_D$) 1x10$^{17}$ cm$^{-3}$, channel length (L) of 1x10$^{-4}$ cm, channel width (W) of 1000x10$^{-4}$ cm pinch-off voltage ($V_P$) of -6, gate width 1000x10$^{-4}$ cm. The power spectral density at $V_{DS}$=1V increases linearly up to 0.75x10$^{-27}$ A$^2$/Hz for $V_{GS}$=-1V, 1.15x10$^{-27}$ A$^2$/Hz for $V_{GS}$=-0.5V and 1.45x10$^{-27}$ A$^2$/Hz for $V_{GS}$=0V. The power spectral density reaches at the saturation level in the order of 1.45x10$^{-27}$ A$^2$/Hz, 1.15x10$^{-27}$ A$^2$/Hz and 0.75x10$^{-27}$ A$^2$/Hz for the source-drain voltage range of 1V-5V. This plot has been generated by using the equation (4.21).
5.4 Variation of Power Spectral Density versus Gate to Source Voltage with Different (V_{DS}).

![Figure 22 Variation of Power Spectral Density versus Gate to Source Voltage with Different (V_{DS}).](image)

The Figure 22 shows a plot of variation of power spectral density versus Gate-Source voltage (V_{GS}) for different Drain-Source voltages of 5V, 6V, 7V with doping concentration (N_D) 1x10^{17} cm^{-3}, channel length (L) of 1x10^{-4} cm, pinch-off voltage (V_P) of -6, gate width 1000x10^{-4} cm. The power spectral density exponentially increases from approximately 0 to 1.3x10^{-26} A^2/Hz for V_{DS}=5V, 0 to 4.45x10^{-26} A^2/Hz for V_{DS}=6V and 0 to 7.65x10^{-26}
$A^2/\text{Hz}$ for $V_{DS}=7\text{V}$, between the stretch of Gate-Source voltage ($V_{GS}$) from -4V to 0V.

This plot has been generated by using the equation (4.21).

5.5 Variation of Power Spectral Density versus Gate to Source Voltage with Different Electron Concentration ($N$):

![Variation of Power Spectral Density versus Gate to Source Voltage with Different Electron Concentration (N)](image)

Figure 23 Variation of Power Spectral Density versus Gate to Source Voltage with Different Electron Concentration ($N$)
The Figure 23 shows a plot of power spectral density and Gate-Source voltage (V_{GS}) for different electron free concentrations of 1x10^{16} \text{ cm}^{-3}, 5x10^{16} \text{ cm}^{-3} and 1x10^{17} \text{ cm}^{-3}, are obtained for doping concentrations 1x10^{16} \text{ cm}^{-3}, 5x10^{16} \text{ cm}^{-3}, 1x10^{17} \text{ cm}^{-3} assuming the complete ionization ay 300^\circ \text{ K} for of channel length (L) of 1x10^{-4} \text{ cm}, pinch-off voltage (V_p) of -6, gate width 1000x10^{-4} \text{ cm}. The power spectral density exponentially increases from 0 to 1.25x10^{-25} \text{ A}^2/\text{Hz} for N=1x10^{16} \text{ cm}^{-3}, 0 to 0.25x10^{-25} \text{ A}^2/\text{Hz} for N=5x10^{16} \text{ cm}^{-3} and 0 to 0.18x10^{-25} \text{ A}^2/\text{Hz} for N=1x10^{17} \text{ cm}^{-3}, between the stretch of Gate- Source voltage (V_{GS}) from -3V to 0V. It has observed that the electron concentration increases and hence power spectral density decreases. This plot has been generated by using the equation (4.21).
5.6 Variation of Power Spectral Density versus Frequency:

![Image of power spectral density versus frequency graph]

**Figure 24 Variation of Power Spectral Density versus Frequency**

The Figure 24 shows a plot of the power spectral density versus cut-off frequency for different drain-source voltages \(V_{DS}\) of 6V, 8V and 10V with doping concentration \(N_D\) of \(1 \times 10^{17}\) cm\(^{-3}\), channel length \(L\) of \(1 \times 10^{-4}\) cm, gate width of \(1000 \times 10^{-4}\) cm. The maximum power spectral density reaches to the value of \(10^{-20}\) A\(^2\)/Hz, \(10^{-20.5}\) A\(^2\)/Hz, and \(10^{-21}\) A\(^2\)/Hz for \(V_{DS}= 6\) V, 8V and 10V respectively. The power spectral density becomes minimum, when the cut-off frequency reaches to the value of \(10^{10}\) Hz. In order to achieve high power and RF amplifier from GaN based device, the design of MESFET must be addressed correctly to negotiate the output power and cut-off frequency. This plot has been generated by using the equation (4.21).
CONCLUSION

In this graduate thesis, analytical model of MESFET has been developed and electrical characteristics such as I-V characteristics, transfer characteristics and power spectral density has been studied. An attempt has been made to merge the two segments of linear and non-linear channel currents to present the more accurate channel current compared to the conventional channel current equation. The transfer characteristics also studied through the power spectral density versus gate-source voltage. The clear picture of power spectral density with respect to drain-source voltage is studied to understand the mechanism that how to increase the power added efficiency. The power spectral density versus frequency is studied to know the frequency domination on power added efficiency.
REFERENCES


25. S. Azam, R. Jonsson and Q. Wahab Designing, Fabrication and Characterization of Power Amplifiers Based on 10-Watt SiC MESFET & GaN HEMT at Microwave Frequencies- , 38th European Microwave Conference, Amsterdam, The Netherlands


31. Makarov, D.G. Krizhanovski, V.G., Kistchinsky, A.A. GaN class E wideband microwave power amplifier - 18th International Conference on Microwave Radar and Wireless Communications (MIKON), 2010


APPENDIX

Variation of Drain-Source Current versus Drain-Source Voltage

clc

clear all

q = 1.6e-19;           % e- Charge

Un = 1500;              % e- Mobility

W = 1000e-4;           % Channel Width

L = 1e-4;              % Channel Length

a = 19.34e-4;          % Active Channel Thickness

Eg = 3.4;

K = 1.3807e-23;

T = 300;

Eo = 9.7;

Nd = 1e17;

E = Eo*8.854e-14;

Nc = 3.25e15*T^1.5;

Nv = 4.8e15*T^1.5

Vt = (K*T)/q;

Ni = sqrt(Nc*Nv)*exp(-Eg/(2*Vt));

Vbi = Vt*log(Nd/Ni);

Vp0 = (q*Nd*(a*a))/2*E;

Vp = Vbi - Vp0;
%Linear Region

for Vgs = 0;
Vds = 0:1:6;
Vbi = Vt*log(Nd/Ni);
a1 = (3*Vds)/(Vbi-Vp);
a2 =2*(((Vds-Vgs+Vbi).^(1.5))-(Vbi-Vgs).^(1.5)))/((Vbi-Vp).^(1.5));
Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);
Id1 = (Kn*(a1-a2))/10^6
end

hold on

for Vgs1 = -0.5;
Vds = 0:1:6;
Vbi = Vt*log(Nd/Ni);
a1 = (3*Vds)/(Vbi-Vp);
a2 =2*(((Vds-Vgs1+Vbi).^(1.5))-(Vbi-Vgs1).^(1.5)))/((Vbi-Vp).^(1.5));
Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);
Id2 = (Kn*(a1-a2))/10^6
end

hold on

for Vgs2 = -1;
Vds = 0:1:6;
Vbi = Vt*log(Nd/Ni);
a1 = (3*Vds)/(Vbi-Vp);
a2 = 2*(((Vds-Vgs2+Vbi).^(1.5))-(Vbi-Vgs2).^(1.5)))/((Vbi-Vp).^(1.5));
Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);
Id3 = (Kn*(a1-a2))/10^6
end
hold on
for Vgs3 = -1.5;
Vds = 0:1:6;
Vbi = Vt*log(Nd/Ni)
a1 = (3*Vds)/(Vbi-Vp);
a2 = 2*(((Vds-Vgs3+Vbi).^(1.5))-(Vbi-Vgs3).^(1.5)))/((Vbi-Vp).^(1.5));
Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);
Id4 = (Kn*(a1-a2))/10^6;
end
hold on
% Saturation Region
for Vgs4 =0;
Vds4 =6:0.005:10;
Vbi4= Vt*log(Nd/Ni)
Vp4=-6;
a14 = 1;
a24=3*(((Vbi4-Vgs4)/(Vbi4-Vp4))+(2*(((Vbi4-Vgs4).^(1.5)))/(Vbi4-Vp4).^(1.5))));
Kn4 = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L) *-3.105;
Id5 = (Kn4*(a14-a24))/10^6
end

hold on

for Vgs5 = -0.5;

Vds4 = 6:0.005:10;

Vbi4 = Vt * log(Nd/Ni)

Vp4 = -6;

a14 = 1;

a24 = 3 * (((Vbi4 - Vgs5) / (Vbi4 - Vp4)) + (2 * (((Vbi4 - Vgs5)^(1.5)) / (Vbi4 - Vp4)^(1.5))));

Kn4 = ((q.^2) * (Nd.^2) * Un * (a.^3) * W) / (6 * E * L) * -0.69;

Id6 = (Kn4 * (a14 - a24)) / 10^6

end

hold on

for Vgs6 = -1;

Vds4 = 6:0.005:10;

Vbi4 = Vt * log(Nd/Ni);

Vp4 = -6;

a14 = 1;

a24 = 3 * (((Vbi4 - Vgs6) / (Vbi4 - Vp4)) + (2 * (((Vbi4 - Vgs6)^(1.5)) / (Vbi4 - Vp4)^(1.5))));

Kn4 = ((q.^2) * (Nd.^2) * Un * (a.^3) * W) / (6 * E * L) * -0.305;

Id7 = (Kn4 * (a14 - a24)) / 10^6

end

hold on

for Vgs7 = -1.5;
Vds4 = 6:0.005:10;
Vbi4 = Vt*log(Nd/Ni);
Vp4 = -6;
a14 = 1;
a24 = 3*(((Vbi4-Vgs7)/(Vbi4-Vp4))+(2*(((Vbi4-Vgs7).^(1.5))/((Vbi4-Vp4).^(1.5)))));
Kn4 = (q.^2)*(Nd.^2)*Un*(a.^3)*W/(6*E*L)*0.155;
Id8 = (Kn4*(a14-a24))/10^6

end

hold on
plot(Vds,Id1,'r')
plot(Vds,Id2,'g')
plot(Vds,Id3,'b')
plot(Vds,Id4,'y')
plot(Vds4,Id5,'r')
plot(Vds4,Id6,'g')
plot(Vds4,Id7,'b')
plot(Vds4,Id8,'y')
legend('vgs=0','vgs=-0.5','vgs=-1','vgs=-1.5');
ylabel('Drain-source current (A)')
xlabel('Drain-source voltage (V)')
title('Ids-Vds characteristics for GaN MESFET')
Variation of Drain-Source Current versus Gate-Source Voltage

clc

clear all

close all

q = 1.6e-19;          % e- Charge
Un =1500;              % e- Mobility
W = 1000e-4;           % Channel Width
L = 1e-4;              % Channel Length
a = 19.34e-4;          % Active Channel Thickness
Eg= 3.4;
K=1.3807e-23;
T=300;
Eo= 9.7;
Vsat=2e7;
E= Eo*8.854e-14;
Nc = 3.25e15*T^1.5
Nv = 4.8e15*T^1.5
Vt = (K*T)/q;
Ni = sqrt(Nc*Nv)*exp(-Eg/(2*Vt));
Vp=-6;
Vgs = -6:0.5:0;
for Nd =1e16;
Vbi = Vt*log(Nd/Ni)
\[
Id = (Nd \cdot V_{sat} \cdot W \cdot a \cdot (1 - \sqrt{(V_{bi} - V_{gs})/(V_{bi} - V_{p})}))/10^{21}
\]

end

plot(Vgs, Id, 'b')

hold on

for Nd = 5e16;

V_{bi} = V_{t} \cdot \log(Nd/Ni)

Id1 = (Nd \cdot V_{sat} \cdot W \cdot a \cdot (1 - \sqrt{(V_{bi} - V_{gs})/(V_{bi} - V_{p})}))/10^{21}

end

plot(Vgs, Id1, 'g')

hold on

for Nd = 1e17;

V_{bi} = V_{t} \cdot \log(Nd/Ni)

Id2 = (Nd \cdot V_{sat} \cdot W \cdot a \cdot (1 - \sqrt{(V_{bi} - V_{gs})/(V_{bi} - V_{p})}))/10^{21}

end

plot(Vgs, Id2, 'r')

ylabel('Drain-source current (A)')

xlabel('Gate-source voltage (V)')

title('Transfer characteristics for GaN MESFET')

legend('N=1e16', 'N=5e16', 'N=1e17')
Variation of Power Spectral Density versus Gate to Source Voltage with Different ($V_{ds}$).

clc

clear all

close all

q = 1.6e-19; % e- Charge

Un =1500; % e- Mobility

W = 1000e-4; % Channel Width

L = 1e-4; % Channel Length

a = 19.34e-4; % Active Channel Thickness

Eg= 3.4;

K=1.3807e-23;

T=300;

Eo= 9.7;

E= Eo*8.854e-14;

Nc = 3.25e15*T^1.5

Nv = 4.8e15*T^1.5

Vt = (K*T)/q;

f=1*10^6;

Ah=0.0135;

Ni = sqrt(Nc*Nv)*exp(-Eg/(2*Vt));

Nd=1e17;

Vgs = -4:0.5:0;
Vp=-6;

for Vds =1;

Vbi = Vt*log(Nd/Ni)

a1 = (3*Vds)/(Vbi-Vp);

a2 =2*(((Vds-Vgs+Vbi).^1.5)-(Vbi-Vgs).^1.5))/((Vbi-Vp).^1.5));

Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);

Id = (Kn*(a1-a2))/10^6;

Sid1= Id.^2*(Ah/(Nd*f))

plot(Vgs,Sid1,'b')

end

hold on

for Vds =2;

Vbi = Vt*log(Nd/Ni)

a1 = (3*Vds)/(Vbi-Vp);

a2 =2*(((Vds-Vgs+Vbi).^1.5)-(Vbi-Vgs).^1.5))/((Vbi-Vp).^1.5));

Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);

Id = (Kn*(a1-a2))/10^6;

Sid1= Id.^2*(Ah/(Nd*f))

plot(Vgs,Sid1,'b')

end

hold on

for Vds =3;

Vbi = Vt*log(Nd/Ni)
a1 = (3*Vds)/(Vbi-Vp);

a2 = 2*(((Vds-Vgs+Vbi).^(1.5))-(Vbi-Vgs).^(1.5))) / ((Vbi-Vp).^(1.5));

Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W) / (6*E*L);

Id = (Kn*(a1-a2))/10^6;

Sid2 = Id.^2*(Ah/(Nd*f))

plot(Vgs,Sid2,'g')
end

ylabel('Power spectral Density (A^2/Hz)')

xlabel('Gate to source voltage in (V)')

title('PSD vs Vgs WITH DIFFERENT VDS for GaN MESFET')

legend('Vds=5','Vds=6','Vds=7')

Variation of Power Spectral Density versus Drain to Source Voltage:

clc

clear all

q = 1.6e-19; % e- Charge

Un = 1500; % e- Mobility

W = 1000e-4; % Channel Width

L = 1e-4; % Channel Length

a = 19.34e-4; % Active Channel Thickness

Eg = 3.4;

K = 1.3807e-23;

T = 300;
Eo= 9.7;
Nd =1e17;
E= Eo*8.854e-14;
Nc = 3.25e15*T^1.5;
Nv = 4.8e15*T^1.5
Vt = (K*T)/q;
Ni = sqrt(Nc*Nv)*exp(-Eg/(2*Vt))
f=1*10^6;
for Vgs = 0;
Vds = 0:1:1;
Vbi = Vt*log(Nd/Ni)
Vp=-6
N=1e17;
Ah=0.0135;
a1 = (3*Vds)/(Vbi-Vp);
a2 =2*(((Vds-Vgs+Vbi).^1.5)-((Vbi-Vgs).^1.5))/((Vbi-Vp).^1.5)));
Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);
Id1 = (Kn*(a1-a2))/10^6
Sid= Id1.^2*(Ah/(N*f))
end
hold on
for Vgs1 = -0.5;
Vds = 0:1:1;
\[ V_{bi} = V_t \log(N_d/N_i) \]

\[ V_p = -6; \]

\[ N = 1e17; \]

\[ A_h = 0.0135; \]

\[ a_1 = \frac{3 \cdot V_{ds}}{V_{bi} - V_p}; \]

\[ a_2 = 2 \cdot \frac{(((V_{ds} - V_{gs1} + V_{bi})^{1.5}) - ((V_{bi} - V_{gs1})^{1.5})) / ((V_{bi} - V_p)^{1.5})}; \]

\[ K_n = \frac{(q^2 \cdot N_d^2 \cdot U_n \cdot a^3 \cdot W)}{(6 \cdot E \cdot L)}; \]

\[ I_{d2} = \frac{(K_n \cdot (a_1 - a_2))}{10^6}; \]

\[ S_{id1} = I_{d2}^2 \cdot \frac{A_h}{(N \cdot f)} \]

end

hold on

for \( V_{gs2} = -1; \)

\[ V_{ds} = 0:1:1; \]

\[ V_{bi} = V_t \log(N_d/N_i) \]

\[ V_p = -6; \]

\[ N = 1e17; \]

\[ A_h = 0.0135; \]

\[ a_1 = \frac{3 \cdot V_{ds}}{V_{bi} - V_p}; \]

\[ a_2 = 2 \cdot \frac{(((V_{ds} - V_{gs2} + V_{bi})^{1.5}) - ((V_{bi} - V_{gs2})^{1.5})) / ((V_{bi} - V_p)^{1.5})}; \]

\[ K_n = \frac{(q^2 \cdot N_d^2 \cdot U_n \cdot a^3 \cdot W)}{(6 \cdot E \cdot L)}; \]

\[ I_{d3} = \frac{(K_n \cdot (a_1 - a_2))}{10^6}; \]

\[ S_{id2} = I_{d3}^2 \cdot \frac{A_h}{(N \cdot f)} \]

end
for Vgs4 =0;
Vds4 =1:0.005:5;
Vbi4= Vt*\log(Nd/Ni)
Vp4=-6;
N=1e17;
Ah=0.0135;
a14 = 1;
a24=3*(((Vbi4-Vgs4)/(Vbi4-Vp4))+(2*(((Vbi4-Vgs4).^(1.5))/((Vbi4-Vp4).^(1.5)))));
Kn4 = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L)*(-1.039);
Id5 = (Kn4*(a14-a24))/10^6
Sid3= Id5.^2*(Ah/(N*f))
end
hold on
for Vgs5 =-0.5;
Vds4 =1:0.005:5;
Vbi4 = Vt*\log(Nd/Ni)
Vp4=-6;
N=1e17;
Ah=0.0135;
a14 = 1;
a24=3*(((Vbi4-Vgs5)/(Vbi4-Vp4))+(2*(((Vbi4-Vgs5).^(1.5))/((Vbi4-Vp4).^(1.5)))));
Kn4 = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L)*-0.2465;
Id6 = (Kn4*(a14-a24))/10^6
Sid4 = Id6.^2*(Ah/(N*f))

end

hold on

for Vgs6 = -1:

Vds4 = 1:0.005:5;

Vbi4 = Vt*log(Nd/Ni);

Vp4 = -6;

N = 1e17;

Ah = 0.0135;

a14 = 1;

a24 = 3*(((Vbi4-Vgs6)/(Vbi4-Vp4))+(2*(((Vbi4-Vgs6).^(1.5))/((Vbi4-Vp4).^(1.5)))));

Kn4 = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L)*0.12;

Id7 = (Kn4*(a14-a24))/10^6

Sid5 = Id7.^2*(Ah/(N*f))

end

hold on

plot(Vds,Sid,'r')

plot(Vds,Sid1,'g')

plot(Vds,Sid2,'b')

plot(Vds4,Sid3,'r')

plot(Vds4,Sid4,'g')

plot(Vds4,Sid5,'b')

ylabel('Power spectral Density (A^2/Hz)')
xlabel('Gate to Drain voltage in (V)')

title('PSD vs Vds for GaN MESFET')

legend('Vgs=0','Vgs=-0.5','Vgs=-1')

Variation of Power Spectral Density versus Gate to Source Voltage with Different Electron Concentration (N):

clc

clear all

close all

q = 1.6e-19;   % e- Charge
Un =1500;      % e- Mobility
W = 1000e-4;   % Channel Width
L = 1e-4;      % Channel Length
a = 19.34e-4;  % Active Channel Thickness

Eg= 3.4;
K=1.3807e-23;
T=300;
Eo= 9.7;
E= Eo*8.854e-14;
Nc = 3.25e15*T^1.5
Nv = 4.8e15*T^1.5
Vt = (K*T)/q;
f=1*10^6;
Ah=0.0135;

Ni = sqrt(Nc*Nv)*exp(-Eg/(2*Vt));

Nd=1e17;

Vgs = -3:0.5:0;

Vp=-6;

for Vds =6;

N=1e16;

Vbi = Vt*log(Nd/Ni)

a1 = (3*Vds)/(Vbi-Vp);

a2 =2*((((Vds-Vgs+Vbi).^1.5)-((Vbi-Vgs).^(1.5)))/((Vbi-Vp).^(1.5)));

Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);

Id = (Kn*(a1-a2))/10^6;

Sid= Id.^2*(Ah/(N*f))

plot(Vgs,Sid,'r')

end

hold on

for Vds =6;

N=5e16;

Vbi = Vt*log(Nd/Ni)

a1 = (3*Vds)/(Vbi-Vp);

a2 =2*((((Vds-Vgs+Vbi).^1.5)-((Vbi-Vgs).^(1.5)))/((Vbi-Vp).^(1.5)));

Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);

Id = (Kn*(a1-a2))/10^6;
Sid1 = Id.\(^2\)*(Ah/(N*f))

plot(Vgs,Sid1,'b')

end

hold on

for Vds = 6;

N=1e17;

Vbi = Vt*log(Nd/Ni)

a1 = (3*Vds)/(Vbi-Vp);

a2 = 2*(((Vds-Vgs+Vbi).\(^{1.5}\))-(Vbi-Vgs).\(^{1.5}\))/((Vbi-Vp).\(^{1.5}\));

Kn = ((q.\(^2\))*(Nd.\(^2\))*Un*(a.\(^3\))*W)/(6*E*L);

Id = (Kn*(a1-a2))/10^6;

Sid2 = Id.\(^2\)*(Ah/(N*f))

plot(Vgs,Sid2,'g')

end

ylabel('Power spectral Density (A^2/Hz)')
xlabel('Gate to source voltage in (V)')
title('PSD vs Vgs for GaN MESFET')

legend(' N=1e16', ' N=5e16', ' N=1e17')

**Variation of Power Spectral Density versus Frequency:**

clc

clear all

q = 1.6e-19; % e- Charge

Un = 1500; % e- Mobility
W = 1000e-4; % Channel Width
L = 1e-4; % Channel Length
a = 19.34e-4; % Active Channel Thickness
Eg= 3.4;
K=1.3807e-23;
T=300;
Eo= 9.7;
Nd =1e17;
E= Eo*8.854e-14;
Nc = 3.25e15*T^1.5
Nv = 4.8e15*T^1.5
Vt = (K*T)/q;
Ah=0.0135;
Ni = sqrt(Nc*Nv)*exp(-Eg/(2*Vt))
Vgs = -0.5;
for Vds = 6
Vbi = Vt*log(Nd/Ni)
Vp=-6;
a1 = (3*Vds)/(Vbi-Vp);
a2 =2*(((Vds-Vgs+Vbi).^1.5)-((Vbi-Vgs).^1.5))/((Vbi-Vp).^1.5));
Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);
Id = (Kn*(a1-a2))/10^6;
f=logspace(1,6);
for i=1:length(f)
    Sid(i)= Id.^2*(Ah/(Nd*f(i)))
end

loglog(f,Sid,'r')
end

hold on;
for Vds=8
    Vbi = Vt*log(Nd/Ni)
    Vp=-6;
    a1 = (3*Vds)/(Vbi-Vp);
    a2 =2*(((Vds-Vgs+Vbi).^1.5)-(Vbi-Vgs).^1.5))/((Vbi-Vp).^1.5));
    Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);
    Id = (Kn*(a1-a2))/10^6;
    f1=logspace(1,6);
    for i=1:length(f)
        Sid(i)= Id.^2*(Ah/(Nd*f1(i)))
    end
    loglog(f1,Sid,'g')
end

hold on
for Vds= 10
    Vbi = Vt*log(Nd/Ni)
    Vp=-6;
a1 = (3*Vds)/(Vbi-Vp);

a2 =2*(((Vds-Vgs+Vbi).^(1.5))-((Vbi-Vgs).^(1.5)))/((Vbi-Vp).^(1.5)));

Kn = ((q.^2)*(Nd.^2)*Un*(a.^3)*W)/(6*E*L);

Id = (Kn*(a1-a2))/10^6;

f2=logspace(1,6);

for i=1:length(f2)
    Sid(i)= Id.^2*(Ah/(Nd*f2(i)))
end

loglog(f2,Sid,'b')

end

ylabel('Power Spectral Density (A^2/Hz)')

xlabel('Frequency in (Hz)')

title('Power Spectral Density Vs Frequency for GaN MESFET')

legend('Vds=6','Vds=8','Vds=10')