Analytical Modeling for an Ion- Implanted Gallium Nitride MESFET

A graduate project submitted in partial fulfilment for the degree Master of Science in Electrical Engineering

By

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ABSTRACT

ANALYTICAL MODELING FOR AN ION-IMPLANTED GALLIUM NITRIDE MESFET

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Master of Science in Electrical Engineering

When it comes to high-frequency and high-power applications, GaN ion-implanted Metal-Semiconductor Field-Effect Transistors (MESFETs) have great promise. A comprehensive understanding of the electrical characteristics of them and their full potential requires an analytical model. In this article, I offer an analytical model of an ion-implanted GaN MESFET (metal-oxide-semiconductor field-effect transistor). The model relies on a Poisson calculation and a continuity equation that were solved for the device's depletion zone. The model's predictions are compared to existing experimental data. The model's predictions of the device's electrical properties, such as its threshold voltage, transconductance, and drain current, are validated by the experiments. With the aid of this analytical model, the most effective ion-implanted GaN MESFETs over diverse high-frequency and high-power applications may be built.
Chapter One

Introduction

There has been a lot of research on gallium nitride (GaN) recently [1, 2] because of its large band gap, low thermal generation rate, and robust breakdown field. GaN's versatility stems from its ability to withstand high power, high temperatures, and microwaves. Devices based on gallium nitride (GaN) perform very well in military and aerospace [2] settings. GaN's resistance to heat of 253 W/mk [3] also makes it a promising semiconductor for use in high-temperature applications. This is much higher than the heat conductivity of silicon, which is 149 W/mk. Due to its exceptional properties, GaN is the substance of choice for state-of-the-art optoelectronics.

Figure 1.1 is a graphic showing how GaN is superior than GaAs.

Gallium Nitride's (GaN) significant band-gap energy of approximately 3.4 eV at 300K distinguishes it from other materials such as GaAs-based (1.42 eV) along with Silicon (1.01 eV). GaN, with its wide bandgap, high sensitivity, and low noise, is an excellent material for UV range detectors. The density of power and the maximum achievable system frequency are both determined by a number of factors, including but not limited to conductivity efficiency, switching efficiency, breakdown voltage, size, and cost, as identified by [4].
GaN has a higher thermal conductivity than silicon (1.3) but a lower one than silicon carbide (4.0). This factor takes into account the breakdown of voltage and the material, while also accounting for GaN mobility. Due to its high breakdown field and increased thermal conductivity, GaN is a promising contender for use in high-power and high-frequency devices. It also has a relatively low heat generation rate. Because of these qualities, it is a promising contender for use in developing high-power, high-frequency optoelectronic devices. The voltage breakdown durability, band gap energy, as well as carrier mobility of GaN-based devices are much greater than those of Si- and GaAs-based devices [5, 6]. Figure 1 demonstrates how these features elevate GaN beyond GaAs in a variety of applications. The advantages of GaN over GaAs are presented in a condensed manner illustrated Figure 1.1 [5].

GaN's distinct properties make it a promising candidate for use in higher frequencies and high-power electrical systems. However, further research into GaN semiconductors and their evaluation of power device frequencies is required. While analytical modeling frameworks have been used to examine GaN MESFETs, further research is required to fully understand these devices. Numerical computations are used to determine the enhancing mode's voltage threshold whilst considering different fabrication parameters; this is because the implantation of ions is the preferred approach of assessing GaN MESFETs, and it allows for precise control over the amount of doping and how it distributes across the device structure.

### 1.1 Field-Effect Performance of Gallium-nitride Metal-Oxide Semiconductors

GaN's unique material properties may find useful use in high-performance devices, particularly those concerned with frequency and power. According to [6], GaN MESFETs have the potential to attain a limit frequency of 900 MHz while still producing 51.1 W of power at 78% power-added efficiency. The maximum frequency of a GaN MESFET device
was reported to be 1.8 GHz, and its saturation occurred in the 700 MHz region [7]. Also, with Vds = 48V, this device's power output was 10W and its PAE was 34. The results presented in [8] show that the saturation frequency of a Gallium Nitride MESFET measuring 0.8 µm x 150 µm and a maximum frequency of 14 GHz are both very close to the values obtained via the Volterra series method (6 GHz as well as 14 GHz, respectively). A consistent channel operating temperature of 300K yielded values of 16.3 dBm and 22.2 dBm for the 1-dB compression position with the production-referred quarter-order intercepting point, respectively (source: [9]). The maximum frequency of a GaN MESFET transistor has been measured at 50 GHz, while its cutoff frequency has been measured at 20 GHz by certain studies. It was stated in [10] that a different The Vds power-added efficiency of this GaN MESFET device was 27%, its cutoff frequency was 2GHz, and its power density was 2.2W/mm. The threshold voltage of GaN MESFETs has been measured between 4V and 20V, and their drain current and transconductance have been measured at up to 300mA/mm and 60mS/mm, respectively [11]. These investigations show promise for high-frequency applications with a bias width of 100 m.

GaN's superior material properties, notably in the departments of bandwidth and power, have proved it to be superior to Silicon-Carbide (SiC) with Gallium Arsenide, often known as (GaAs), in a variety of applications. GaN MESFET devices have been demonstrated to be particularly successful in high-power and high-frequency applications. GaN-based devices have carrier mobilities that are likely to approach 2000 cm2/Vs, which is much higher than those of devices based on silicon (Si) with gallium arsenide (GaAs). This high mobility is useful for power electronics made from GaN and other high electron mobility devices (HEMTs) because it enables them to switch at higher frequencies and/or pack larger amounts of power into a smaller volume.
Researchers have observed that several different GaN MESFET devices possess very high cutoff frequencies as well as peak frequencies. A device was shown to have a 900-megahertz cutoff frequency, 78% energy-added effectiveness, with 51.1 W of output power. Another device demonstrated its power output of 10 W while operating on 48V and achieved a PAE of 34% via power addition efficiency. Additionally, it demonstrated that it was stable at frequencies ranging from 700 MHz to 1.8 GHz of operation.

GaN MESFET device obtained 2.2 W/mm energy rating and 27% energy-added effectiveness at Vds, which are both promising findings. For a bias width of 100 m, measurements of GaN MESFETs revealed threshold voltages between 4 V and 20 V, maximum drain currents of up to 300 mA/mm, and transconductances of up to 60 mS/mm; these properties make them ideal for high-frequency applications like those found in wireless transmission systems, electromagnetic waves systems, navigation systems for satellites, electric vehicles, and similar devices.

GaN MESFETs are superior to SiC MESFETs in terms of density of power (approximate 4.0 W/mm) and power-added efficiency (over 50%), resulting in a promising technology for use in modern commercial settings. The cutoff frequency of 1 m gate-to-source GaN MESFET devices has been experimentally determined to be 11 GHz. It was found that 36 GHz was the maximum frequency of oscillation, with an increase of 7.5 dB at that frequency. High density of current, strong transconductance, higher frequency efficiency (above 100 GHz), limited direct - current-to-RF dispersion, as well as small gate along with drain leakage currents [14] were also among the desirable qualities of a GaN MESFET produced on a 100 mm Si substrate that made it suitable for use in high-frequency applications.

Researchers at the University of Illinois have created a metal-oxide-semiconductor field-effects transistor (MESFET) [15] made of GaN that has exceptional performance characteristics. 2.2 W/mm2 power density and 27% power-added efficiency were observed at
VDS when the device was running at 2.0 GHz, 30 V, and -2 V for VGS. We calculated a transconductance \( gm \) of 36 mS/mm, a \( fT \) cutoff frequency of 28 GHz for the unit current gains, and an oscillation maximum frequency \( f_{\text{max}} \) of 55 GHz. These findings for GaN MESFETs were nearly twice as great as anything else that has been reported in the literature for frequency.

According to a different study [16], a GaN-based MESFET having a gate width around 0.25 meter may produce 230W of electrical power at \( f_{\text{T}} \)s of 30 GHz. Power dissipation, cutoff frequency, and transconductance \( (gm) \) are all measured at 40 V in the drain and 0 V in the source. (at 500 mA drain current) of these GaN MESFET devices were respectively 8 GHz, 93 mS/mm, and 4 W/mm. Its gain of 20 dBm and 50% energy-added performance beat out a simulated SiC MESFET by the same researcher [17]. The transconductance of this GaN MESFET device was measured to be 164 mS/mm, and its cut-off frequency \( (f_{T}) \) was 7.2 GHz, with an ultimate frequency at which it operates \( (f_{\text{max}}) \) of 15.6 GHz. Specifically, at \( V_{DS} = 3.5V \) [18], this part's power-added efficiency is 38%. A quasi-surface depletion GaN MESFET with a minimum operating frequency of 230 GHz and an ultimate transduction \( (gm) \) of 244 mS/mm produced an output power density of 2.66 W/mm [19].

Engineers at UC Santa Barbara found a way to mass-produce AlGaN/GaN HEMTs, or highly emitter-follower transistors. Devices with a gate measure of 0.7 m demonstrated a transconductance of approximately 93 mS/mm in dc conditions, a frequency cutoff \( (f_t) \) approximately 19 Gigahertz with a top frequency \( (f_{\text{max}}) \) about 46 GHz. Another study looked at a HEMT architecture with a 17% AlGaN moles fraction on quasi-insulating silica carbide (SiC) substrates and discovered that this device could generate 103 watts of energy at a density of power of 5.2 watts per millimeter \( (W/mm) \) with a total power added effectiveness \( (\text{PAE}) \) around 35.3% [21]. AlGaN/GaN driven HEMTs on the sapphire substrates only managed to produce an energy density of 1.1W/mm at a PAE of 20.1%. The findings include
a cut-off frequency (fT) ranging 36 Gigahertz\(^2\) channel current of over 300mA/mm, and a breakdown voltage of up to 230V from gate to drain, with optimum wavelengths (fmax) around 70 GHz [22]. The transconductance has been measured at 68 mS/mm using an external frequency of 31 GHz plus the arrestment frequency of around 1.8 GHz by certain experimentalists. A 1400 mm wide gate AlGaN/GaN HEMT produced 84 mW/mm of RF power at VGS = -1.1V and VDS = 6V, whereas the greatest drain-to-source current density was around 174 mA/mm [23].

Research showed that AlGaN/GaN HEMTs with a frequency cutoff equivalent to 8 GHz having power density equal to 9.8 W/mm [24] were feasible to manufacture. Another study looked at silicon carbide-substrate AlGaN/GaN HEMT semiconductors and found that these devices can transmit current from DC at a rate of 150 mS/mm using a cut-off frequency (ft) of around 25 GHz and a maximum frequency (fmax) of 50 GHz. During S-parameter testing on a 100 m HEMT, a drain current (Id) approximately 950 mA/mm was recorded. Since GaN and its alloys have a straight bandgap [25], they find widespread application in a wide variety of electrical and optical applications. GaN's near-ultraviolet (UV) light emission is due to its bandgap of 3.44 eV, or 300 kelvins. The UV photonic spectrum and the relationship between bandgap energy alongside lattice constant for a selection of semiconductors is shown in Figure 1.2 [26]. These semiconductors include silicon carbide, GaN, and alloys that utilize InN and AlN, all of which have large bandgaps. Bandgap energy in Al\(_x\)In\(_y\)Ga\(_{1-x-y}\)N alloys spans the whole visible-to-ultraviolet-infrared spectrum, from roughly 1.9 (electron volts to 6.2 Ev/A/cm. GaN has a wide variety of potential uses [27], including in the military, laser light, LED, and optical applications.
Lattice constants and energy band gaps are shown to be related in Figure 1.2.

Wide-bandgap GaN's energy band vs lattice constant reveals the potential use of heterojunctions. The material's characteristics make it useful in high-temperature, high-power electrical devices like blue and UV emitters. High power and high frequency performance is anticipated to rely heavily on GaN. GaN MESFET recovery time is normally set by the device's capacitance and resistance. For applications that need ultra-high frequency performance, their picosecond-level recovery time is a perfect fit. GaN MESFETs' quick recovery time may lead to rapid switching and more efficiency with power [28].

1.2 Electric Vehicles' Use of GaN MESFETs

The high-power density, rapid switching speed, and small conductivity and switching losses of Gallium Nitride (GaN) MESFETs have made them an attractive option for use in the power electronics of electric vehicles (EVs). When applied to EV power electronics, GaN MESFETs have the potential to boost efficiency, decrease charging time, and lengthen the
EV's range. The inverter, DC to DC converters, and onboard charger are just a few of the many places in an EV where GaN MESFETs may be found. GaN MESFETs may boost the power electronics' performance, resulting in a more satisfying EV ride for the driver. Improved power electronics may help ease range anxiety and lower the cost of EV ownership; therefore, this technology might play a significant part in the shift to electric transportation.

1.2.1 Methods of Powering Electric Motors

The drive system of an EV is the most important component since it regulates the speed and torque of the electric motor. The motor drive system's efficiency and the vehicle's range are both boosted using GaN-based power electronics. Yole Développement found that using GaN-based devices could improve motor drive system efficiency by up to 5% compared to using Si-based devices, and that using IGBT could extend range by up to 10% [29].

1.2.2 Internal Power Supply

When an electric vehicle (EV) is parked, its battery may be charged through an on-board charger. By using power electronics based on gallium nitride (GaN), we may increase the vehicle's range and decrease the time it takes to charge. Nissan found that incorporating GaN-based devices into the in-vehicle charging infrastructure may boost efficiency by as much as 95%.

1.2.3. Direct Current to Direct Current Converters

To power the EV's ancillary equipment, such the lights and the music system, DC-DC converters reduce the high voltage from the battery to a more manageable level. With the help of GaN-based power electronics, DC-DC converters may operate more efficiently,
extending the battery life of electric vehicles. An EPRI study found that DC-DC converters using GaN-based devices improved efficiency by as much as 3 percent.

1.2.4 Power inverters

The electric motor is powered by inverters, which transform the direct current (DC) from the battery into alternating current (AC). The inverter's efficiency may be increased by GaN-based power electronics, which in turn decreases power loss and lengthens the vehicle's range. Toyota found that by including GaN-based devices into the inverter, efficiency may be improved by as much as 10%.

1.2.5 Power Source Control Units

A battery's charge level, temperature, and voltage may all be managed with the use of a battery management system (BMS). By using GaN-based power electronics, BMS efficiency may be increased, which in turn decreases power loss and lengthens the driving range. Using GaN-based semiconductors in BMS has been shown in an MIT research to improve efficiency up as much as 5 [30].

1.2.6 Wireless Power Transfer

With the use of wireless charging technology, an electric vehicle may be charged by just setting it on a charging pad. Wireless charging systems may benefit from GaN-based power electronics, which can speed up the charging process and extend the battery life of the car. Research from Duke University found that by including GaN-based devices into wireless charging systems, efficiency may be improved by as much as 25%.
1.2.7 Braking with Energy Recapture

With the use of regenerative braking technology, an electric vehicle may replenish its battery whenever it applies the brakes. Regenerative braking systems may benefit from GaN-based power electronics by lowering power loss and boosting efficiency. GaN-based devices, according to research from the University of Tokyo, may boost the efficiency of regenerative braking systems by up to 5% [31].

1.2.8 Refrigeration Methods

In order to keep the EV's power electronics at a safe temperature, cooling devices are used. GaN-based power electronics may boost the cooling system's thermal performance, allowing for a smaller, lighter design.

1.3 Purpose

To better understand how to simulate and implant ions in GaN MESFETs is the major focus of this study. Ion dosage, concentration of the substrate, device parameters (length and breadth), implanted range, and straggle values are only some of the many important device factors considered by the model. This model successfully predicts the threshold voltage's behavior in enhancement mode by computing the intrinsic concentration of carriers and transconductance. The model's predictions were checked using MATLAB.
Chapter 2

A Brief Description of Gallium Nitride (GaN)

2.1 The GaN Component

A III/V direct semiconductor, GaN falls under this category. It has a thermal conductivity of 2538.8% W/mK, which is around 60% of the value found for SiC [32], and a large heat capacity, making it a very stable and long-lasting material. GaN's melting temperature is 4532 degrees Fahrenheit (2500 degrees Celsius), and its dielectric constant is only 5.3 at high frequencies. You can make n-type material by doping it with oxygen or silicon, and p-type material by doping it with magnesium. Common dopants for transforming GaN into n-type employ either oxygen or silicon. These dopants augment the GaN crystal lattice with extra electrons, elevating the electron concentration and leading to an abundance of negative charge carriers. Because the extra electron is free to move about in the crystal lattice, n-type GaN is an excellent electrical conductor. However, magnesium is often utilized as a dopant to produce p-type GaN. Magnesium causes a shortage of electrons by adding positively charged carriers, termed holes, to the crystal lattice. Because the holes in p-type GaN may move about freely in the crystal lattice, it is also an excellent electrical conductor [33, 34]. GaN materials are very dependable because of their robust bond forming. In addition, the dislocation density in GaN compounds is rather high, often falling in the range of $10^8$ to $10^{10}$ defects per square cm$^2$ [35].

2.2 The Nature of the Crystal

Since it contains atoms from more than one element, GaN is classified as a compound semiconductor. The presence of a complex crystal structure is responsible for its durability. The most common crystalline forms for GaN are Wurtzite and Zinc-blend. Wurtzite with
Zinc-blend crystals are similar in appearance despite their distinct structural variances. For example, four nitrogen atoms in one structure are paired with gallium atoms in the other [36]. Both crystal formations consist of atoms, but their stacking order is different. Wurtzite crystals have Ababa structures for their 0001 plains, whereas Zinc-Blend crystals have AaBbCc structures for their 111 planes [36]. In addition, the crystal structures of GaN materials are polar planes. Figure 2.1 depicts a ball and stick representation of a GaN crystal, representing the polar planes 111 and 0001 for either Zinc-blend or Wurtzite, respectively [37].

Crystal plane arrangements of GaN (a) in a zinc-blend structure and (b) in a wurtzite structure are shown in Figure 2.

2.2.1 The Structure of a Zinc Alloy

The crystal structure of zinc-blend semiconductors is a cubic component cell with one fcc lattice and two atoms at the bottom. Atom A's position in this structure is indicated by the notation (0, 0, 0), whereas Atom B's position is written as (1/2, 1/2, 1/2) [38]. The Zinc-blend structure was estimated to have a lattice constant of 4.5Å at an angle of 109.470 degrees. The structure of Zinc blends is shown in the following figures [39]:

![Crystal plane arrangements of GaN (a) in a zinc-blend structure and (b) in a wurtzite structure are shown in Figure 2.](image)
The semiconductor industry finds many uses for these structures, with zinc-blend gallium nitride, also known as GaN, emerging as a viable semiconductor for electronic devices.

2.2.2 The Structure of Wurtzite

Wurtzite's crystal structure deviates from the zinc blend's due to its hexagonal matrix arrangement and two matrix constants (a and c). Each hexagonal compartment bonds to two tetrahedra of different atoms, generating molecules like those shown in Figure 2.3(a) [38][39]. Last hexagonal compartment has $c/a = 1.6333$, and $u = 3/8$, or 0.375, which is dimensionless and equates to $c/a$. Figure 2.3(b) depicts the basal plane, which is the plane parallel with the lateral either horizontal axis and is also known as the bond length when looking at the c direction [40][41]. As can be seen in Figure 2.3(c), GaN semiconductors have a wurtzite crystalline structure.

Figure 2.3(a): Wurtzite Crystal Cell Component Arrangement
The structure of a wurtzite GaN crystal in three dimensions (b) a basic hexagonal lattice cell
In general, GaN semiconductors may be broken down into two distinct crystal structures: the Zinc-blend structure and the Wurtzite structure. Wurtzite's hexagonal matrix contrasts with Zinc-blend's cubic component cells. Different lattice constants and patterns of atomic organization may be found in each structure. Crystal structure has an important role in influencing the electrical and optical characteristics of GaN semiconductors.

2.3 Band Structure of Energy Levels

2.3.1 Band Structure of Zinc-Blende GaN

![Band structure of a zinc-blende GaN crystal, shown in Fig. 2.4](image)

Four unique energies at the valleys may be seen in the crystal structure of zinc blends, as shown in the above figure [42]. The energy gap of zinc-blend GaN semiconductors is 3.2 eV, with non-zero values for the conduction minimum and valence maximum at the wave vector. Ex, the energy gap between bands, is 4.6 eV in the X-valleys, while EL, the energy gap between L-valleys, is between 4.8 and 5.1 eV. The band energy of the valence band's derivative is 0.02 eV. The following equation [43] may be used to calculate the energy gap dependency vs temperature:

\[
E_g = E_g(0) - 7.7 \times 10^{-4} \times T^2 / (T + 600) \]  

\[3.427eV = 3.2eV - 7.7 \times 10^{-4} \times T^2 / (T + 600)\]

\[T= 509.7K\]
The energy gap as a function of temperature may be calculated with the use of the Varshni formula. [34]

\[
E_g = E_g(0) - 9.39 \times 10^{-4} \times T^2 / (T + 772)
\]  

(2.2)

\[
9.39 \times 10^{-4} \times T^2 / (T + 772) = 3.2 \text{ eV} - 3.427 \text{ eV}
\]

\[
9.39 \times 10^{-4} \text{ eV} \cdot \text{K}^2 \times T^2 / (T + 772 \text{ K}) = 3.2 \text{ eV} - 3.427 \text{ eV}
\]

\[
T_1 = (-0.227 \text{ eV} \cdot \text{K} + 23.195 \text{ eV}) / (1.878 \times 10^{-3} \text{ eV} \cdot \text{K}^2) = 11,956 \text{ K}
\]

Temperature, expressed in degrees Kelvin (K), is represented by \(T\), and its GaN bandgap in a Zinc-blende crystal, expressed in electronvolts (eV), is given by \(E_g(0) = 3.427 \text{ eV}\) in the equation. This is shown as the excitation energy at absolute zero degrees Kelvin.

Energy in the fifth Band as a function of temperature for a GaN/ZnBlend/MgO(11) substrate is shown in Figure 2.5

This graph shows the temperature dependence of the excitation energy bandgap in the Zinc-blende crystal structure of GaN. The figure [45] demonstrates that the GaN layers were grown on a magnesium oxide (1x1) substrate.
Energy in the sixth band as a function of temperature for a GaN/ZnBlend/Si substrate

**Figure 2.6**

The gap in GaN's excitation energy as a function of temperature in its zinc-blende crystal structure may be observed above. GaN films were produced on silicon substrates, eliminating the need for pseudo dielectric function as shown in the preceding figure, thanks to two alternative models [46]. The band energy gap on a MgO (1X1) substrate decreases from 3.3 eV through 3.23 eV when the temperature is raised from 0K to 300K, as seen in the diagram. Furthermore, the silicon substrate exhibits a band energy gap variation from 3.18-3.24 eV through 3.03-3.07 eV.

### 2.3.2 Wurtzite gallium nitride band structure

GaN has five unique energy levels, as seen in the following figure, which represents the Wurtzite crystal arrangement [42]. Minimum versus maximum levels along the vector of
waves (k=0) were used to calculate the energy band gaps. It was determined that the energy band gap in the GaN Wurtzite crystal’s -valleys is 3.39 eV. Similarly, the energy difference between the M-L valleys' band gaps (EML) and the A valleys' band gaps (EA) is between 4.5 and 5.5 eV.

The spin-orbit energy of the valence band, denoted by Eso, is measured to be 0.008 eV, whereas the crystal energy, denoted by Ecr., is 0.040 eV. GaN with a Wurtzite crystal structure has an energy band gap (Eg) of 3.428 eV, as shown by equations 2.1 and 2.2. The temperature dependency of the energy band gap may be computed using these formulae. This formula [37] is used to determine the energy excitement in GaN at temperatures less than 295 K for Wurtzite crystals:

$$E_{g} - E_{g}(0) = -5.08 \times 10^{-4} \times T^2/(996 - T)$$  \hspace{1cm} (2.3)

When working with GaN Wurtzite crystals at temperatures below 300 K, the accompanying equation is utilized to determine how the excitation energy changes as a function of temperature. As can be seen in the corresponding value for Eg at 300 K is calculated to be 3.44 eV [37] based on the reactivity of Wurtzite GaN with temperatures under 300 K, as shown in Figure 2.8. It is clear from the graph that as the temperature rises, so does the rate at which the amount of energy contained within Wurtzite crystal structure decreases.

![Exciton energies in GaN show Wurtzite crystals vs temperature, seen in Fig. 2.8.](image-url)
Figure 2.9 shows a temperature vs energy bandgap diagram for the GaN Wurtzite crystal structure [43]. GaN's energy bandgap depends on its Wurtzite crystal structure, as seen in this graph.

2.4 Concentration of Intrinsic Carrier

The inherent carrier concentration is an essential factor to consider while learning about gallium nitride. The density of free charge carriers in a semiconductor's conduction and valence bands is defined by the intrinsic concentration of carriers \( n_i \), which occurs when an electron is thermally activated and travels via the valence band towards the conduction band. When contrasted to other wide-gap semiconductors, GaN has a relatively low concentration of inherent carriers. The concentration of carriers may be calculated using an equation found in reference [48].

\[
n_i = \left( N_c N_v \right)^{1/2} \exp \left( - \frac{E_g}{2kT} \right)
\]  

\[
n_i = \left( 4.3 \times 10^{14} \times 300^{3/2} \times \left( 8 \times 9 \times 10^{15} \times 300^{3/2} \right) \right)^{1/2} \exp \left( - \frac{3.427}{2 \times 1.38 \times 300} \right) = 1.6 \times 10^{-10}
\]
The term ‘Nc’ stands for the Density of States in the conduction band.

‘Nv’ stands for Density of State in the valence band, while ‘Eg’ denotes the "composition gap energy."

\[ k_B = 8.6173 \times 10^{-5} \text{ eV } K^{-1} \]

T is the temperature measured in kelvin (K).

Following these steps, one may calculate the exact density of elements inside the conduction band:

\[ N_C \cong 4.82 \times 10^{15} \cdot \frac{(m \tau / m_0)^{3/2} T^{3/2}}{T^3} (cm^{-3}) \]

\[ \cong 2 \cdot 3 \times 10^{14} \times T^{3/2} (cm^{-3}) \quad (2.5) \]

For the wurtzite structure,

\[ N_C \cong 4.82 \times 10^{15} \cdot \frac{(m \tau / m_0)^{3/2} T^{3/2}}{T^3} (cm^{-3}) \]

\[ \cong 4 \cdot 3 \times 10^{14} \times T^{3/2} (cm^{-3}) \quad (2.6) \]

Also provided is an exact count of valence band elements,

\[ N_V \cong 8.0 \times 10^{15} \times T^{3/2} (cm^{-3}) \quad (2.7) \quad \text{for the zinc-blend configuration.} \]

\[ N_V \cong 8.9 \times 10^{15} \times T^{3/2} (cm^{-3}) \quad (2.8) \quad \text{is the value for the wurtzite mixture.} \]

---

Figure 2.10 Temperature dependence of intrinsic carrier concentration in GaN, Zinc-blend, and Wurtzite.
Figure 2.10 from [43] depicts the temperature dependence of the diffusing component in wurtzite and zinc-blende structures. It is important to note that the zinc-blende structure is more suited to the production of GaN MESFETs than the wurtzite structure due to the latter's higher concentration.

2.5 Gallium Nitride Drift-Velocity

In Figure 2.11, we see how the electric field affects the drift velocity of GaN on wurtzite or zinc-blende crystal formations. Wurtzite's crystal structure is in the (1010) axis, whereas zinc-blende's is in the (100) axis, as seen by the arcs labeled (1) and (2), respectively [49]. Both structures' drift velocities rise exponentially up to a specific electric field, and then drop again. At 100 kV/cm, drift velocity starts to drop in zinc-blende, while at 200 kV/cm, it begins to decrease in wurtzite.

Drift velocity against electric field for GaN, zinc-blende, with wurtzite crystal structures are shown in Figure 2.11.
Figure 2.12 demonstrates how temperature affects the drifting velocity of a GaN crystal. The graph shows how the temperature, field of electricity strength, and electron drift velocity vary with temperature. The graph shows the velocity of drift of GaN at 77K, 300 Kelvin, 500K, and 1000K in a range of electric fields (curves 1, 2, and 3, 4 respectively) [50].

2.6 GaN Component Qualities:

GaN's chemical, electrical, and transport capabilities are limited by composition, as shown in Table 2.1. These features are crucial in establishing the base capabilities of GaN devices.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton Molecular Weight</td>
<td>83.73</td>
</tr>
<tr>
<td>Band Gap</td>
<td>3.4Ev</td>
</tr>
<tr>
<td>Static Dielectric constant</td>
<td>8.9</td>
</tr>
<tr>
<td>High-Frequency electrical Constant</td>
<td>5.35 3</td>
</tr>
<tr>
<td>Direct Lattice Gap Constants</td>
<td>5.35 3.189Å (5.186Å°)</td>
</tr>
<tr>
<td>Intrinsic Carrier Concentration</td>
<td>$1 \times 10^{10}/cm^3$</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>Mobility of Electron</td>
<td>$\leq 1000 \text{ cm}^2/\text{Vs}$</td>
</tr>
<tr>
<td>Mobility of Holes</td>
<td>$\leq 350 \text{ cm}^2/\text{Vs}$</td>
</tr>
<tr>
<td>Coefficient of Electron Diffusion</td>
<td>$\leq 25 \text{ cm}^2/\text{s}$</td>
</tr>
<tr>
<td>Coefficient of Hole Diffusion</td>
<td>$\leq 9 \text{ cm}^2/\text{s}$</td>
</tr>
<tr>
<td>Velocity at Saturation2</td>
<td>$2.5\times10^7 \text{ cm/s}$</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>$3.1\times10^7 \text{ cm/s}$</td>
</tr>
<tr>
<td>Acceleration Field Maximum</td>
<td>$150 \text{kV/cm}$</td>
</tr>
<tr>
<td>Velocity of Disintegration</td>
<td>$\geq 5\times10^6 \text{V/cm}$</td>
</tr>
<tr>
<td>Sub-Melting Point</td>
<td>$250^\circ\text{C}$</td>
</tr>
<tr>
<td>Temperature Transfer</td>
<td>$0.43 \text{cm}^2/\text{s}$</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>$1.5 \text{W/cm-K}$</td>
</tr>
</tbody>
</table>

GaN’s chemical and electrical characteristics as well as its other material attributes are listed in Table 2.1.

Many features of GaN semiconductors are superior than alternatives like silicon. These features include a larger band gap, higher critical field, more electron mobility, and a higher saturation velocity. The high temperature and power density operation are made possible by its broad band gap. Because of its large critical field, it can withstand high voltages with little leakage current. The elevated electron mobility plus saturation velocity make high-frequency operation in GaN possible.
Chapter 3
Fabrication of GaN Metal-Emitter-Semiconductor Field

3.1 How GaN MESFET is made.

The creation of a GaN MESFET is seen in Fig. 3.1.

Gold, germanium, as well as nickel metallization is utilized to produce ohmic connections for the source and drain regions of a GaN wafer during manufacture. Aluminum deposition creates a Schottky gate. When aluminum is deposited, a thicker metallic pad forms that may be easily probed. E-beam evaporation is used to deposit the metal, and a metal liftoff procedure defines the metal layer [51].

The sequence of events leading up to a finished piece of GaN is as follows:

- The manufacturing of GaN often begins with a cleaning phase. The first step in the epitaxial development process is to clean the substrate wafer's surface. Depending on
the nature of the process, the cleaning procedure may include more than one stage, such as a solvent clean, an acid clean, or a plasma clean. The cleanliness of the finished GaN material as well as devices is critical to their performance and reliability.

- Reactive sputtering is used to deposit a layer of silicon nitride cap with a thickness of 100 nm.
- Positive resist of thickness 1.6μ is used to shape the implant site for the channel.
- The channel portions of the device are implanted with silicon ions at a dosage of $5 \times 10^{12} cm^2$ and an ion energy of up to 180KeV. Ion implantation of silicon (Si+) into the device channel area of GaN is frequent because of the material's high electron mobility and the need to increase electrical conductivity. Electronic devices built on GaN benefit greatly from low resistivity and high electron mobility, hence this is crucial to their functioning. Ion implantation of silicon atoms in the GaN lattice may boost device performance by increasing the amount of free electrons available for conduction. Si+ is also favored for GaN devices because it is simple to manipulate and implantation parameters may be finely tuned.
- Silicon nitride is etched superficially with a buffered HF solution with plasma etching for alignment registration.
- Oxygen plasma is used to resist stripping and ashing.
- For either a source or drain implant, a positive resist is used to design the implant.
- The device's drain and source areas are implanted with silicon ions at a dosage of $1 \times 10^{13} cm^2$. and an ion energy of up to 200KeV.
- The highest ion energy that may be absorbed is 200KeV.
- Si+, which is ionized singly, is the ion species of choice.
- The ion dose employed is $1 \times 10^{13} cm^2$. 
• After ion implantation, the material is subjected to high-temperature rapid furnace annealing. Rapid Heat Annealing is often employed in GaN-based devices, and the average annealing duration is between 80 and 120 seconds at temperatures between 900 and 1200 degrees Celsius. Different processes and applications call for different annealing temperatures and times. If the annealing temperature is too high, it may severely damage the material and negatively impact device performance. The melting point of GaN is roughly 2600 degrees Fahrenheit.

• For ohmic contact production, resist is patterned with an intended thickness of 0.8\(\mu\)m. Silicon nitride etching produces ohmic connections.

• After the etching with CF4 plasma, the GaN surface is cleaned with 50% HCl in a final wet etch.

• Depositing AuGe/Ni metal by e-beam evaporation, then patterning it via liftoff, is how ohmic connections are made to the source and drain.

• Rapid thermal heating forms alloys for the ohmic connections, with 475-5000\(^\circ\)C as the highest temperature and 120 seconds as the time required.

• The Schottky gate is formed via resist patterning followed by a nitride etch [52].

3.1.1. GaN metal-oxide-semiconductor field-effect transistor substrate

Researchers have shown that due to thermal expansion and contraction, GaN material grown on a silicon substrate is of worse quality than that grown on a sapphire as well as silicon carbide substrate. Compatibility issues [53] between GaN and Si. During the transition between developing temperature to the room temperature, tensile tension was introduced into the GaN layers formed on Si. As a result of the inhibition of epitaxial layer growth on Si, GaN MESFETs typically have a thinner profile on Si than MESFETs on sapphire. In this research, the
maximum thickness of the developed layer was set at 1.5 m to prevent cracking and provide a uniform morphology over the surface. To isolate the device, we used a BCl3 plasma with 10W of RF power and 3Pa of chamber pressure to perform a mesa dry etch down beneath the i-GaN layer. Silicon is a suitable substrate substance for high-power GaN-based devices, especially when used as a substrate enabling heteroepitaxial development, despite its drawbacks, like its inability to support epitaxial growth. Trimethylgallium (TMG), trimethylaluminum (TMA), with NH3 were used as reactant species, while H2 was used as the carrier gas in a Nippon Sanso MOCVD system (SR-2000) dedicated to the development of GaN MESFETs. The growth was done on a 0.015 -cm resistive Sb-doped n-type Si (111) substrate. Monosilane (SiH4) diluted in H2 (10ppm) was used to dope the n-type substrate. Cleaning in solvents was followed by an etch of 5 minutes with H2O2:H2SO4 (1:4) and an etch of 1 minute using HF: DI H2O (1:10) prior to the substrate being prepared. First, an AlN nucleation layer was grown at 1100°C and 80nm in thickness; next, layers of i-Al0.27 G0.73 N and GaN were produced at 1080°C & 0.8m thick, respectively; finally, a 0.2m thick layer of n-GaN was formed at 1080°C and doped with around 2 x 1017 cm-3 of silicon. To grow the i-AlN layer, the flow rates for NH3 and TMA were 51.1/min and 6.1mol/min. The TMG and TMA stream rates, for the formation of this i-Al0.27 G0.73 N layer's component, were 13.9mol/min and 6.1mol/min, respectively [54].

3.2 Ion Implantation

Ion implantation involves the ionization of gas and subsequent acceleration of the resulting ions under a high electric field. Then, several hundred nanometers deep into a target wafer, these ions are injected [55]. Despite Shockley's first proposal of ion implantation in 1954, the technology didn't see widespread commercial application until the 1970s. Historically, wafers were doped before ion implantation via gaseous diffusion emanating from the surface either
chemical diffusion using a source placed on the wafer's surface. This diffusion-based approach, however, lacked the necessary flexibility and precision. As a result, ion implantation emerged as a preferred method of incorporating dopant atoms. Particle accelerator technology is the backbone of today's ion implanters, allowing them to function at energies from 100eV to several MeV. Heat activation at temperatures between 600 and 1100 °C commonly follows the implantation procedure, which may inject ions anywhere from a couple of nanometers to several micrometers deep. Ion implantation typically employs the following parameters:

- Phosphorus, arsenic, antimony, boron, indium, oxygen, silicon, and the oxygen ions.
- Dose: $10^{11} \text{cm}^2 - 10^{18} \text{cm}^2$
- Energy of Ions: 1-400 KeV
- Reproducibility and consistency: +/-1%
- As for temperature, ion implantation via GaN-based devices is normally performed at 20-25 degrees Celsius, or room temperature. The GaN material may be damaged by heat, thus it's best to do the ion implantation operation at ambient temperature. It is important to keep in mind, however, that cryogenic implantation and high-temperature implantation are two specialized ion implantation procedures that may need distinct temperatures for maximum performance.
- Flux of ions, $10^{12} - 10^{14} \text{cm}^2 / s$

Ion implantation allows for very precise dosimetric regulation. In order to precisely monitor the current and keep the implanted dosage consistent, the ion implanter develops a simple electric circuit. As long as the implantation period is at least 10 seconds and the current sensitivity is I/A, dosages as low as $10^{11} \text{cm}^2$ may be detected. This manufacturing procedure is very hygienic since it happens in a high vacuum atmosphere. Ion implantation provides
better control over diffusion processes in terms of peak depth and propagation range, in combination with precise dosage control.

Fig. 3.2 (a) Diffusion-based doping and (b) Ion-implanted doping.

The precision with which ion implantation accomplishes doping is seen in Figure 3.2, which also compares the diffusion method (top) with ion implantation (bottom). Ion implantation has several advantages, including those listed below.

- It occurs at relatively mild temperatures,
- several options for masking,
- milder to surface cleaning methods,
- Complex, fast profiles may be attained with the use of multi-energy implants.
3.2.1 Implantation tools that use ions:

Figure 3.3: Ion implanter schematic for a medium current [56].

Figure 3.2 is a simplified diagram of the main parts that comprise a medium-current ions implanter. To get started, a certain molecular species is converted into ions in an ion source. After the ions have been accelerated, they are sent into an analyzer for mass so their masses may be calculated. The intended implant ions' exit beam is chosen according to their charge-to-mass ratio, and the analysis device is sufficiently sensitive to discriminate between ions with neighboring mass numbers. After then, the ions are accelerated once again, leading to a little electrostatic deflection of the ion beam that helps to keep it apart from the newly produced neutral atoms. Next, either an electrostatic or mechanical scanner, or sometimes both, moves the beam over the wafer's surface. The charge accumulation on insulating surfaces like silicon oxide as well as silicon nitride may be avoided by placing an electron source close to the wafer and flooding the surface with electrons. Failure of the gate oxide, which prevents current from flowing from the gate towards the substrate, might result if this accumulation is not removed. These are the duties of the many subassemblies that make up an ion implanter:
1. At high voltages (typically 25KV), the ion source converts electrically neutral gas-phase dopant atoms into plasma ions and a few undesirable species. Ion sources allow for the sputtering of elements such as arsine, phosphine, and diborane.

2. By angling the ion beam, the mass spectrometer can separate the particular impurity ion from the background noise. Those ions that make it past the filter are sent on their way via a small opening.

3. The accelerator may boost the beam's energy by up to 5MeV.

4. The beam is scanned over the wafer surface along the x- and y-axes by deflection plates to ensure consistent implantation of the target dosage. The beam is deflected such that it cannot strike the target, therefore preventing neutral particles from colliding with it.

3.2.2 Annealing

When a GaN device is damaged throughout the ion implantation procedure, deep-level holes as well as electrons are created, increasing the resistivity of the device and impeding the free movement of carriers in the channels. This is why annealing is necessary to reverse this effect. Due to the intensive bombardment caused by the implanted ions, the lattice of the host atoms is damaged, and amorphous crystals form as a consequence. Sheet resistance shifts as a result of reduced carrier movement. Annealing is required to repair the broken crystal structure [57].

3.2.3 Annealing in a Furnace

The electrical characteristics of a semiconductor wafer may be modified by a process called furnace annealing. The concentration difference between the film and the substrate allows for this transition. Annealing in a furnace may be used in conjunction with other procedures, such as heat treating or oxidation. It might take many hours a day for a furnace to process a
big batch of wafers. Slow furnace annealing has led to the development of a new technique, Rapid Thermal Anneal (RTA). By using RTA, the boron dopant may be preserved while the annealing period is reduced from hours to minutes [58].

3.2.4 Annealing at High Temperatures

For the purpose of fabricating semiconductor devices, especially those made from gallium nitride (GaN), rapid heat annealing (RTA) is a common thermal processing method. In RTA, a material is heated to an extremely high temperature for a very short period (a couple of seconds to a few minutes) using a high-intensity light source, such as a tungsten incandescent lamp or a laser. In semiconductor materials, RTA's fast heating and cooling rates may activate dopants, recrystallize amorphous areas, and reduce flaws and impurities, among other positive effects. RTA may also boost a material's thermal durability and resistance to deterioration, in addition to its electrical and optical capabilities. After ion implantation, GaN-based devices often use RTA to activate the implanted dopants along with repair any implantation-induced damage. By fine-tuning the RTA procedure's temperature and time interval, we may achieve the desired annealing effects without inflicting any thermal damage or degradation to the material. When it comes to fabricating high-performance semiconductor devices, RTA is a potent process, especially for those using GaN or other wide bandgap materials.

3.3.1 The equation describing the distribution of impurities after annealing.

The following equation describes how contaminants settle in after annealing [59]:

\[
    n(x, t) = \frac{Q_0}{\sqrt{2\pi t}} \frac{1}{\sqrt{\Delta R_p^2 + 2Dt}} \exp \left[ \frac{-(x-R_p)^2}{2(\Delta R_p^2 + 2Dt)} \right]
\]  

(3.1)

Where:

Q= Dose of ions.
The range parameter is abbreviated as RP.

D=Diffusion Constant.

t= Time.

Material maximum depth ΔRp

3.4 STOP RANGE AND ION RANGE IN MATERIALS

The SRIM software is used to calculate the ion's range and halting in matter, and it can deal with ions with energies of as much as 2 GeV/amu. The collisions between ions and atoms in this software are treated as if they were quantum mechanical, with the moving atom treated as an ion with all target atoms treated as standard atoms. Thanks to statistical techniques, SRIM is able to execute very efficient computations by letting the ion skip between estimated collisions and averaging the collision outcomes across the intervening time. The SRIM program is used to generate stopping/range tables [60], as illustrated in Table 3.1.

Fig 3.4. A stopping/range table is created with the help of the SRIM program.

GaN's Range and Straggle characteristics are determined with the use of SRIM at ion energies that vary from 100 keV through 280 keV with 10 keV increments, with phosphorus
serving as the target ion. Range as well as Straggle parameters [61] are tabulated and shown in Table 3.1.

SRIM for GaN with phosphorus as the target ion is shown in Table 3.1.
3.5. Annealing-induced dispersion of impurities.

As shown in Table 3.1, the implantation profile is widened, and the ultimate junction depth is formed as a result of diffusion of the implanted impurities during successive high-temperature procedures after implantation. [62]

![Figure 3.5 Annealing-induced impurity distributions.](image)

3.6. Damage Caused by the Ion Implantation Process

- Although silicon doping through ion implantation is feasible but involves risks due to the use of high-energy ions. These ions can lead to various forms of damage, including crystal lattice disruption, interstitial and vacancy defects, strain, surface damage, and charge imbalances. Despite these challenges, ion implantation is a crucial and controlled method in semiconductor industry for precisely modifying material properties.
- If the lattice is damaged in this way, then vacancies and interstitials will emerge in a uniform fashion.
- Clusters and dislocations may also occur as a consequence of point flaws.
- The lattice of the crystal may be annealed back to its original state.
- The implantation range is characterized by a substantial supersaturation of point defects, which leads to enhanced dopant diffusion inside the dopant.
At a low dosage of $10^{12} cm^2$, the lifespan of the minority carrier falls below 1ns.

With an implant dosage of $10^{13} cm^2 - 10^{14} Cm^2$ in materials like Si and GaAs, charge carrier mobility may be decreased to below $1cm^2/Vs$ [63].
Chapter 4

Properties of The GaN MESFET

4.1 GaN Device Substrate

The production of GaN semiconductors has advanced greatly, which has necessitated the creation of a special epitaxial layer which may be put on a substrate of another material. The manufacture of GaN-based devices has been hindered by the lack of high-quality GaN wafers [64], despite the fact that homoepitaxial techniques are favored over heteroepitaxial approaches. Substrates including silicon carbide, silicon, as well as sapphire are used in heteroepitaxy, making it one of the most used techniques. However, while using the heteroepitaxy method, it is important to take into account the fact that the substrate with the epilayer may have different crystal lattices. As can be seen in Figure 4.1 [65], a buffer layer is needed after GaN has been deposited on Si as well as SiC substrates to account for the lattice mismatch. The processing cost rises because more resources are needed to create the buffer layer. Since it is chemically and structurally compatible with a GaN substrate, aluminum nitride makes an excellent buffer layer.

Figure 4. 1 Shows a Cross-Sectional Representation of GaN, Illustrating the Need for Interlayer Dielectrics.
4.2 Basic Structure of GaN MESFET

The schematic cross-section of Gallium Nitride MESFET is shown in Fig 4.2

![Figure 4.2 Typical GaN MESFET Structure](image)

The layer of GaN n-type is stored on the substrate of the semi-isolating silicon. The used substrate is with a metal Au/Ge combination, which is typically joined with the source terminal throughout the calculation. The combination of source and the drain are joined with the layer of the n-type through n+ ohmic contacts [65]. The gate is a thin layer of metal, usually aluminum coated with Au, deposited on top of the n-type layer between drain and source. The metal semiconductor junction of the gate represents a Schottky barrier junction. This is utilized to control the stature of the channel of the active layer underneath by applying a voltage of the bias at the gate [66]. The section which is underneath the gate is charged according to the bias. The most extents of a MESFET materials are the length of gate (L), width (W) and depth of the active channel[67]. Those sizes portray the mechanism. A mechanism could be pointed as 0.3x300  when the length of the gate is equivalent to 0.3µm and width of the gate is equivalent to 300 µ m. The length of the gate verifies the periodicity. As the length of the gate reduces, the recurrence will increment. Additionally, the width of the gate confirms the nature of the material, for example the current capability. The channel of the active region translates the voltage of pinch off MESFET materials [66].
4.3 **Gallium Nitride MESFET Operation principles:**

A MESFET material is biased by applying the different voltages: $V_{GS}$ is between the source and the gate, and $V_{DS}$ is between the source and the drain. The applied voltage will control the current of channel present between source and drain by differing the region of the depletion of gate and the electric field. Different cases could be distinguished for the $I_{DS}$-$V_{DS}$ characteristic of the MESFET materials, if $V_{GS}$ is bigger than the voltage $V_p$ of the pinch off, level $V_{DS}$ voltage where $I_{DS}$ directly relative to $V_{DS}$. $V_{DS}$ is the steady value [68]

4.4 **GaN MESFET I-V Characteristics**

The current of the drain-source against the voltage of the drain-source ($I_{DS}$-$V_{DS}$) characteristics of Gallium Nitride MESFET on silicon is shown in Figure 4.3

![Figure 4.3 Ids vs Vds characteristics of Vgs for GaN MESFET](image)

Various I-V curves of the MESFET are demonstrated in Figure 4.3 for a perfect, ideal MESFET. "The characteristics are plotted for values of $V_{gs}$. It is evident that the ideal I-V curve displays limited positive slope in the region of saturation. Numerous explanations may be a reason for this situation. For the short gate device, the reason is the junction of the carrier into the substrate of the semi-insulating. This curve is the source for the conductance in the output in a MESFET model. Solid curves are drawn for indication of the ideal current whereas, the actual current is indicated by the dashed curves. When $V_{GS}$=0, the depletion region under the Schottky-barrier gate is relatively narrow, and as $V_{ds}$ is raised, a
longitudinal electric field and current are established in the channel. Because of $V_{DS}$, the voltage across the depletion region is greater at the drain end than at the source end, so the depletion region becomes wider at the drain end. The reducing of the channel and the processing of the expanding of the $V_{DS}$ develop the electric field near the channel, making the electrons to move rapidly. The situation when $V_{GS}=V_p$, the voltage squeeze off, the channel and the channel current is zero, paying small regard to the nature of $V_{DS}$. The voltage pinch off is determined by the active channel depth, as the depth of the active channel is to be constant throughout the process of fabrication it is situated to voltage breakdown and the pinch-off voltage [69-72].

Different regions of the GaN MESFET’s operating voltage range are shown in Figure 4.4: (a) the linear zone ($V_{ds}$ is extremely low), (b) the region where saturation begins, and (c) the region where $V_{ds}$ is quite large.

As the Voltage is been further raised from drain to source ($V_{DS}$), as illustrated in Figure 4.4(b), when the pinch off voltage is lesser than the voltage of gate to source($V_V$), there will be an increasing in the channel current, the region of the depletion gets deeper at the end of
the drain, and the channel of the conductive gets narrower. The current should be steady throughout the channel. Therefore, if the conductive channel of the drain gets narrower, there will be rapid movement in the electrons [73-74]. As the Vds is above the value that creates the saturation of the velocity (normally just a tenths of volt), the concentration of the electrons other than the velocity should increase to attain the continuity of the current. Therefore, the region of accumulation of the electrons is formed near the gate end. “Therefore, as the electrons move throughout the channel and move at velocity into between the drain and the gate, a region of depletion of electrons formed. The depletion region is absolutely charged due to the ions of the positive donor. If Vds increases as shown in Figure (c), the more of the increasing of the voltage is dropped over the region to implement the electrons to cross it and the lesser is dropped over the channel which is the part of unsaturated. This region is known as charge domain. A situation is attained where the increasing in Vds is dropped completely over the charge domain, and there is no increase in the drain current [75].

4.5 Carrier Mobility in Gallium Nitride (GaN):

Carrier mobility is related to temperature, quality of semiconductor, doping fixation, electric field. The latter is dependent on substrate. Because of the difference of lattice constant, the crystals of the nitride developed on sapphire attained at some point splits when cool down, and mobility of the hall is around the range of 10-30 cm2/Vs. “The mobility carrier of GaN is alternately improved. As the measurement of the hall, the change was ten times to the value 350-400 cm2Ns [76].
Figure 4.5 Mobility vs Electron Concentration for GaN

The statistical data in Figure 4.5 suggest that mobility of the electrons reduces accordingly as the electronic concentration increases. Regardless of how thick the layers of the buffer are, and which substrate was utilized for the development the precise consistent movement of the decrease shows that it is somewhat exponential and not straight in nature. The minor spread in the quantities from different sources is mainly because of lack of insufficient growth optimization, distinct in techniques of the measurement of the hall, difference in layers and substrates of buffer utilized, and the variations at several growth temperature[77].
Chapter 5

Theoretical Model for GaN MESFET

5.1 Theoretical Foundations of the Model for GaN MESFETs

The GaN MESFET's cross-sectional configuration is shown in Figure 5.1.

GaN metal-oxide-semiconductor field-effect transistor (MESFET) cross-section Fig. 5

Several factors, including gate length (L), gate widths (W), and channel depth, describe the device construction. To keep things simple, let's pretend the distance between the gates is the same on both the source and drain sides. A Gaussian curve (83) describes the ion-implanted profile.

\[
N(x, t) = \frac{Q}{\sqrt{2\pi} \sigma^2 + 2D^2 t} \exp \left( -\frac{x-R_p}{\sqrt{2\sigma^2 + 2D^2 t}} \right) - NA
\]  \hspace{1cm} (5.1)

Post-annealing causes changes in the junction's depth, shown by the symbol \(XX\), such that \(R'p = R_p + kXj\). The given equation is used to make an estimate, with the assumption that \(K\) lies between 0 and 1 [76]. For this situation, we have the following variables:

- \(Q\) = ion dosage.
- \(R_p\) = implant range parameter.
- \(\sigma\) = straggle parameter.
- \(D\) = diffusion coefficient.
- \(t\) = diffusion time (annealing time).
- \(NA\) = substrate concentration.
The post-implant annealing diffusion coefficient is believed to be independent of the concentration of the implant. Phosphorus ions with a dosage of 51010 to 11013 are implanted at a depth of the active channel with an implantation potential of about 14 KeV [77]. The model takes into account the range as well as straggle parameters determined by the SPRIM program and uses an annealing duration of one hour. The following Poisson’s equation has been used [76] to determine the electric field as well as potential at different places.

\[ \phi''(x) = \frac{d^2 \phi}{dx^2} = -\frac{d \varepsilon}{dx} = -\frac{\rho(x)}{\varepsilon_0} \]  

(5.2)

Where:

\( \varepsilon \) denotes the electric field strength.

\( \rho(x) \) Space charge density is denoted by \( (x) \).

The dielectric constant, denoted by \( K \),

Free space has a permittivity of \( \varepsilon_0 = 8.854 \times 10^{-14} \text{ F/cm} \), which is determined by the boundaries of the universe.

\[ \phi (0) = V_0 - \phi_B \]  

(5.2a)

\[ \phi'(XDG) = 0 \]  

(5.2b)

\[ \phi (XDG) = -\Delta + V(y) \]  

(5.2c)

Difference in work function between metal and semiconductor \( \phi_B \), surface potential \( \phi_0 \), depth of Fermi level below conduction band in depleted channel and gate depletion region width (XDG). Using a boundary condition (5.2b), we are able to figure out Poisson's expression (5.2) for an electric field, which yields an expression for the electric field, [78]:

\[ \phi^1(x) = \frac{qQ}{2\varepsilon} \left[ erf \left( \frac{x_{DG} - R_p}{\sqrt{2\varepsilon\sigma^2 + 2D'T}} \right) - erf \left( \frac{x - R_p}{\sqrt{2\varepsilon(\sigma^2 + 2D'T)}} \right) \right] + \frac{qN_A}{\varepsilon} (x - x_{DG}) \]  

(5.3)

Integrating equation (5.3) with proper boundary conditions as specified in (5.2b) and (5.2c) yields potentials at different locations along the channel.
\[
\phi(x) = -\frac{qQ}{2\varepsilon}(x - R'p)\left[erf\left(\frac{x-R_p}{\sqrt{2\sigma^2+2D^T}}\right) - erf\left(\frac{x_{DG}-R_p}{\sqrt{2\sigma^2+2D^T}}\right)\right] + \frac{qN_A}{2\varepsilon} - \frac{q\sqrt{\sigma^2+2DT}}{\varepsilon\sqrt{2\pi}}\left[\exp\left(-\frac{(x-R_p)^2}{2(\sigma^2+2D^T)}\right) - \exp\left(-\frac{(x_{DG}-R_p)^2}{2(\sigma^2+2D^T)}\right)\right] - v - \Delta
\] (5.4)

Substituting boundary condition (5.2a) into equation (5.4), we get [76] for the surface potential assessment.

\[
v - (V_{GS} - \phi_B) = \frac{qQ}{2\varepsilon} (R'p)\left(\frac{R'p}{\sqrt{2}\sqrt{\sigma^2+2D^T}} - \frac{x_{DG}-R_p}{\sqrt{2}\sqrt{\sigma^2+2D^T}}\right) - \frac{q\sqrt{\sigma^2+2DT}}{\varepsilon\sqrt{2\pi}}\left[\exp\left(-\frac{(x-R_p)^2}{2(\sigma^2+2D^T)}\right) - \exp\left(-\frac{(x_{DG}-R_p)^2}{2(\sigma^2+2D^T)}\right)\right] - \frac{qN_A}{2\varepsilon} (x_{DG})^2 + \Delta
\] (5.5)

where:

- \(V_{GS}\) represents the voltage at the gate.
- \(\varepsilon\) is the GaN permittivity.

### 5.2 Determining the Number of Intrinsic Carriers

The concentration of intrinsic carriers (\(n_i\)) may be determined by using the formula:

\[
n_i = \sqrt{N_c \times N_v} \times e^{-\frac{E_g}{2kT}}
\]

The Boltzmann constant (kB) in this case is 8.6173 \times 10^{-5} \text{ eV k}^{-1} the standard value of 1 \text{ eV k}(-1) and 300 K (room temperature, in degrees K)

The wurtzite structure has an energy gap (\(E_g\)) of 3.39 eV at 300 K. Below we see how to calculate NC and NV using equations (2.6) and (2.8):

\[
NC \approx 4.3 \times 10^{14} \times T^{3/2} \,(\text{cm}^3)
\]

Specifically, with \(T = 300\,\text{K}\), \(NC \approx 4.3 \times 10^{14} \times 300^{3/2} \,(\text{cm}^3) = 2.2343 \times 10^{18} \,(\text{cm}^3)\)

\[
NV \approx 8.9 \times 10^{15} \times T^{3/2} \,(\text{cm}^3)
\]
For $T = 300$ K, $NC \cong 8.9 \times 10^{15} \times 300^{3/2} (Cm^3) = 4.6246 \times 10^{19} (Cm^3)$

With these numbers in hand, we can calculate the wurtzite structure's intrinsic carrier concentration at 300 K.

$n_i = (NC \cdot N_v)^{1/2} \exp(-E_g/(2kBT)) = 3.4061 \times 10^{-10} (Cm^3)$

The threshold voltage was calculated using the calculated values in a MATLAB simulation.

5.3 The GaN MESFET's I-V characteristics:

$$I_{ds} = I_{ds} (1 + \lambda v_{ds}) \left(\frac{T_0}{T}\right)^{1.5} \left(1 - \left(\frac{v_{gs}}{v_{th} - v_{ds}}\right)\right)^2 \times \tanh \left(\frac{av_{ds}}{v_{gs} - v_{th} - v_{ds}}\right)$$  \hspace{1cm} (5.6)$$

is the formula for the drain current.

Where:

$Id_s$ is the source-drain current.

Assuming a gate voltage of 0, the drain current is denoted as Idss.

Drain-source voltage ($V_{ds}$)

Threshold voltage ($V_{th}$)

$V_{gs}$ = voltage at the gate source

$T$ Kelvin Scale of Temperature

$T_0 = 300$ K, the temperature of a typical room.

The following equation describes the drain current when the gate voltage is zero:

$$I_{dss} = \frac{Ifc}{2} \left(\alpha a^2 - \frac{4}{\nu_p} \left(\nu_p - (v_{bi} + v_{gs})\right)\right)^{1/2}$$  \hspace{1cm} (5.7)$$

Where:

$$ha = \text{breadth of the depletion zone}$$

$$Ifc = \text{Saturation Current at Maximum}$$

Voltage at pinch point, or $V_p$
46

Qa = Charge in the Conducting Channel

Nd = Percentage of Donors

Vbi = Voltage at Isolated Bus

Vgs = voltage at the gate source

In the saturation area, the drain current is described by the equation,

\[ I_D = \frac{\mu_{C0} W}{2} \frac{x^2}{L} (V_{GS} - V_{th})^2 \]  

(5.8)

Drain Flow = ID

\( \mu_{C0} \) = CMOS Parameter Process

Vgs = voltage at the gate source

Threshold voltage (Vth)

W x L Indicates Channel Width x Length

5.4 Transconductance

Transconductance is a key characteristic in high-frequency device design. To determine a GaN MESFET’s transconductance (\( g_m \)), one must hold the voltage at the drain source (\( V_{DS} \)) constant in saturation mode and subtract the \( I_{DS} \) drain current (\( I_{DS} \)) from its gate-source voltage (\( V_{GS} \)) [76]. A constant VDS is required of both the \( I_{DS} \) & \( V_{GS} \) gradients for precise transconductance valuation. The following formula is used to calculate the transconductance:

The formula \( g_m = \left| \frac{\delta I_D}{\delta V_{GS}} \right|_{v_{DS}} \) is constant.  

(5.9)

holds true under all conditions.

To determine a GaN MESFET's transconductance, one may use the following formula:

\[ g_m = \frac{q\mu Q}{4L} \left( \frac{1}{\nu_1 \alpha p} + \frac{1}{\nu_2 (\alpha + 1 - \alpha)} \right) (V_{GS} - V_T) \]  

(5.10)

where Z represents the breadth of the gadget,

L represents the length,
\[ v_1 = \frac{qQ^2}{8N_A\varepsilon} \]

\[ v_2 = \frac{qQ\sqrt{\sigma^2 + 2DT}}{\sqrt{2}\pi\varepsilon} \]

\[ a_p = \frac{2N_A}{Q} \sqrt{\frac{2\varepsilon}{qN_A}}(v_{b_1} - v_{B_s} + v_p) \]

\[ \alpha = \frac{R^1 p}{\sqrt{\frac{\pi}{2}}} \]

By applying a voltage of

\[ v_p = \frac{q\alpha^2 ND}{2\varepsilon_s} \]

the drain is pinched off under a certain drain-source biasing condition.

The electron charge, q, the length of the active channel, \( \alpha \), and the amount of doping, \( N_d \), are all variables in this equation.

The material's permittivity is represented by \( \varepsilon_s \).
Chapter 6
Mathematical calculations, outcomes, and discussions.

For a full understanding of the threshold voltage's vibrant effects in enhancement mode, this discussion's findings are essential. Several inferences may be made from the threshold voltage along with additional transconductance estimations shown in the figures below.

over a GaN metal-oxide-semiconductor field-effect transistor (MESFET) implanted with depletion ions, the threshold voltage (VT) against ion dosage (Q) over a range of substrate concentrations is illustrated in Figure 6.1.

![Ion Dose vs. Threshold Voltage](image)

**Figure 6.1** shows a MATLAB plot of the equation (6) for a reduced ion-implanted GaN MESFET's threshold voltage (VT) vs ion dosage (Q) for a variety of substrate concentrations.

Different substrate concentrations were considered, with calculations performed for $NA=1\times10^{15} \, cm^3$, $2.5 \times 10^{15} \, cm^3$, and $5 \times 10^{15} \, cm^3$, in a device structure with $Z=1000\mu m$ and
L=1m. The findings indicate that when ion dosage increases, threshold voltage decreases immediately.

The threshold voltage varies from -1.26V to -0.89V, demonstrating depletion mode behavior in the device. The threshold voltage was calibrated to change from -1.21V to -0.89V throughout a range of ion doses from $8.7 \times 10^{12} \text{cm}^2$ to $10 \times 10^{12} \text{cm}^2$, with a NA substrate concentration of $5 \times 10^{15} \text{cm}^3$. The threshold voltage shifted between -1.26V and -0.89V for the same ion dosage variation between substrate concentrations of $2.5 \times 10^{15} \text{cm}^3$ and $1 \times 10^{15} \text{cm}^3$.

In conclusion, the graph demonstrates that the GaN device generally displays depletion mode behavior for a given ion dosage and substrate concentration.

![Graph](image)

Figure 6.2 For GaN metal-oxide-semiconductor field-effect transistors (MESFETs), the threshold voltage (VT) is correlated with the ion dosage (Q) at varying substrate concentrations.
The relationship between the threshold voltage of a GaN MESFET and the ion dosage applied is seen in Figure 6.2. Equation (6) was used to construct the figure in MATLAB, and different substrate concentrations \( NA = 1 \times 10^{15} cm^3, 2.5 \times 10^{15} cm^3, \) and \( 5 \times 10^{15} cm^3 \) were used. The channel lengths (\( L \)) of the device is 1 \( \mu m \), while its width (\( Z \)) is 1000\( \mu m \). Peak positive threshold potentials of 1.185 V, 1.160 V, and 1.138 V were measured with an ion dosage of \( 1 \times 10^{11} \) cm\(^2\) and substrate doping of \( 5 \times 10^{15} cm^3, 2.5 \times 10^{15} cm^3, \) and \( 1x10^{15} cm^3 \), respectively. Doping the substrate with \( 1x10^{15}/cm^3 \) causes a linear change in the threshold voltage from +1.13 V through + 1.00 V. The GaN MESFET device is concluded to be an enhancement mode device based on the direct shift in the threshold voltage due to various substrate doping, ranging from +1.18 V towards + 1.04 V, +1.15 V to +1.01 V, as well as +1.13 V through +1.00 V over an ion dose ranging from \( 2 \times 10^{11} cm^2 \) to \( 9 \times 10^{11} cm^2 \) respectively.

![Id vs Vd characteristics](image)

**Figure 6.3: Characteristics of the Drain-to-Source Current and Voltage**
Gate-to-source voltages of -10V, -5V, 0V, 5V, and 10V are shown in Figure 6.3 as a function of drain-to-source voltage. The fabrication parameters, including implant range parameter (Rp) of $0.0723 \times 10^{-4}$ and straggle parameter ($\sigma$) of $0.0264 \times 10^{-4}$ were also obtained from SRIM based on the annealing process and an ion implantation energy of 100KeV. For a phosphorous ion with an activation energy of 40meV, the diffusion characteristics length is determined to be $2.8328 \times 10^{6}$ at a temperature of 1900°C, and the doping concentration displays a compatible value to explain the width of the Fermi level of 0.0103 shown in the graph. Highest drain current is seen at a drain to source potential of 80V, with the drain current varies from 2.0A to 2.4A to 2.6A to 2.8A to 3.0A for gate voltages of $V_{gs} = -10V$ to $V_{gs} = 0V$ to $V_{gs} = 5V$ to $V_{gs} = 10V$. GaN-based MESFET drain currents are compliant with the constructed device when various post-implanted factors are taken into account.

Transmittance vs. Gate Voltage, Fig. 6.4
Using a persistent mobility of 440cm²/Vsec, a gate width of 2cm, a gate length of $1 \times 10^{-4} cm$ and an active layer state density of $1 \times 10^{17}$ an illustration of transconductance (gm) vs gate-source voltage (Vgs) is shown in Figure 6.4 for four different drain-source voltages (Vds) of 5V, 10V, 15V, and 20V. Transconductance's saturation-region behavior was estimated using a gm-plot estimate to determine the maximum frequency response. As the gate-source voltage (Vgs) is changed from -15V to +25V, the transconductance grows exponentially, proving that the device is operating in depletion mode. The concentrations of acceptor dopant (Na) and donor dopant (Nd) used in the computation of this graph are $1 \times 10^{15} cm^3$ and $1 \times 10^{17} cm^3$, respectively. The maximum frequency response was calculated by extrapolating the Transconductance (gm) chart to the saturation area to examine the action of transconductance within the non-linear region. As the gate-source voltage (Vgs) changes from -15 to +25V, the transconductance grows exponentially, proving that the device is operating in depletion mode.
Chapter 7

SUMMARY AND DISCUSSION

In order to determine the voltage threshold as well as transconductance for an ion-implanted GaN MESFET, researchers have used analytical modeling in addition to numerical simulations. Conventionally, a GaN MESFET operates as a depleted mode device; however, for years, scientists have been working to create a depletion mode device that utilizes wide-bandgap semiconductors. While CREE has created a depletion device for SiC MESFETs, creating one for GaN MESFETs has proven more difficult owing to the material’s unique features, suggesting that further study is required before it can be created in the near future. Research on the threshold voltage qualities and transconductance properties of a GaN MESFET depletion device is a first step in this direction. These properties may be derived from a comparison of ion implantation doses and substrate concentrations. This study has important implications for the direction of future research and should be expanded upon to determine relationships between theoretical and manufacturing parameters.
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