A FULLY ANALYTICAL BACK-GATE MODEL FOR N-CHANNEL GALLIUM NITRATE MESFET’S WITH BACK CHANNEL IMPLANT

A graduate project submitted in partial fulfillment of the requirements
For the Degree of Masters of Science
In Electrical Engineering

By

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August 2016
The graduate project of Dileep Reddy Goda is approved.

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Acknowledgement

I wholeheartedly take this opportunity to thank my advisor Dr. Somnath Chattopadhyay. He played a huge supportive role in completion of my project by providing me proper guidance. I greatly appreciate his help and suggestions from the beginning of this project. It was his inestimable assistance, technical support, timely help that gave me a better understanding of Solid State Devices concepts. It granted me a chance to glance into the business of solid-state devices.

I would simultaneously take this opportunity to show my gratitude to the rest of the committee professors, Professor Benjamin F. Mallard, Professor Barton J. Gordon for analyzing the project systematically and helping throughout the project.
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Abstract

A Fully Analytical Back-Gate Bias Model for n-channel Gallium Nitrate MESFETS with Back Channel Implant

By

Dileep Reddy Goda

Master of Science in Electrical Engineering

The primary aim of this project is to analyze the effect of back-gate biasing on electric field, threshold voltage and channel potential. A one-dimensional Poisson’s equation has been used to calculate the channel potential and electric field. A device with implanted layers in both the front and back is examined. Two threshold voltages have been analyzed: one with only one channel in the front, and the other with implanted channels in both the front and back. The channel potential and electric field have been evaluated to examine the electric parameters of MESFET with a typical device structure.
CHAPTER-1: Introduction

In today’s scenario, silicon carbide (SiC) and gallium nitride (GaN) and their use as wide-bandgap semiconductors have attracted a huge amount of interest, because of their capacity to be utilized in such a great variety of higher power and higher frequency devices. Higher frequency electronic devices are utilized for commercial reasons due to certain differences, as perceived in a number of promising electronic devices that were the subject of this study. Due to using a different material, their behaviors were dissimilar, as regards high electric field breakdown. Because of the wide-bandgap, these materials are able to produce impressively high quality for devices that demand higher frequency and power, particularly in the aviation and microwave device industry [1-4].

The innovation of GaN as a wide-band gap material offers five critical attributes: low on resistance, high dielectric quality, high working temperature, rapid exchange and high current density. Several studies have been carried out assembling amalgams that benefit from a mix of both gallium nitride and silica. In contrast with other silicon properties, the attributes of GaN show remarkable portability and electrical breakdown qualities, and three times the bandgap.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>Si</th>
<th>GaAs</th>
<th>4H SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap</td>
<td>eV</td>
<td>1.11</td>
<td>1.43</td>
<td>3.26</td>
<td>3.42</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td></td>
<td>11.8</td>
<td>12.8</td>
<td>9.7</td>
<td>9</td>
</tr>
<tr>
<td>Breakdown Field</td>
<td>MV/cm</td>
<td>0.25</td>
<td>0.35</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>W/cm°K</td>
<td>1.5</td>
<td>0.46</td>
<td>4.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 1. Comparison of Properties between Si GaAs and SiC GaN [5].
1.1 Performances of GaN MESFET

The results when using GaN materials, because of their wide-bandgap vitality demonstrating less inborn bearer fixation, mean that wide-bandgap semiconductor devices have less parasitic ability on account of their low dielectric field. Moreover, with electronic devices, which require immense power usage for their execution, it is imperative to diffuse the heat caused by the high temperatures of conductivity because of the scattered vitality in these devices. GaN indicates exceptional execution in a device, particularly the frequency and power implementations. A device based GaN MESFET demonstrates a cut-off frequency of 700 MHz, conveying a power of 54.1W yield with 79% power included productivity (PAE), and for a different GaN MESFET device, a 20W yield with a capacity of 36% at $V_D=47V$ for a cut-off frequency of 800 MHz and the most extreme frequency of 1.1 GHz was accomplished.

A pair of devices in close concurrence for the deliberate estimation of an 8 and 16GHz utilizing a Volterra-arrangement method, having a cut-off frequency ($f_i$) of 5.5GHz and greatest frequency ($f_{max}$) of 15GHz for a GaN MESFET with 0.8$\mu$m×150$\mu$m has been evaluated. With a consistent region temperature of 300K, the 1dB pressure unit and yield alluded third-arrange catchpoints were 14.3dBm and 23.2dBm respectively, and different tests accomplished the extreme frequency ($f_{max}$) of 45GHz and a cut-off frequency ($f_i$) of 20GHz. A 4GHz cut-off frequency for different GaN MESFETs at $V_{ds}=20V$ and $V_{gs} = -1V$ and a power thickness of 2.2W/mm and 29% of related power included productivity was manufactured (5). An estimation of 20$\mu$m wide devices, having the ability for a greater frequency of utilization, and an edge voltage of 6V to 22V, with greatest channel streams almost 300mA/mm and a trans-conductance range of 80mS/mm, was evaluated in different tests.

In a fair execution, the GaN MESFET was utilized in a business deployment, where cutting-edge work takes place. In that case, the robustness of the SiC MESFET was created systematically during the assembling process [7]. In present times, a GaN MESFET has attained 4.0W/mm of power density, amounting to power included productivity of more than half of what is usual. In several evaluations, devices were reproduced with units of 0.3$\mu$m of gate length ($L$), with a source-drain channel ($V_{ds}$) separating the gate width ($L$)
of 2x50µm and divided by 1µm of gate to source (Vgs), which exhibited a cut-off frequency (ft) of 12GHz. In a further test, a greater scattering and a lower radio frequency (RF) to counter a predominant noise factor was developed at 100-mm Si substrate, and produced an additional 6.5db. GaN MESFET displays a higher trans-conductance, higher frequency, and greater current thickness.

Several analysts at Urbana-Champaign, University of Illinois, which unmistakably indicated power near 2.5W/mm, manufactured GaN MESFETs. A power included productivity of 27% at Vds=28V and Vgs=-4V at 2GHz, 36mS/mm of the trans-conductance (gm) was found, being the most remarkable frequency information recorded at any time for GaN MESFETS, and twice that of any previous rate. Also found was the frequency of oscillation (fmax), measured to an estimation of 55GHz.

A cut-off frequency (ft) of 20GHz and a yield force of 240W was obtained at 0.29µm entryway in a different GaN MESFET exploration. In addition, the same scientist has manufactured another GaN MESFET with Vds=40V and Vgs=0V, utilizing a region current of 500mA. This device showed trans-conductance (gm) of 95mS/mm and a yield force of 2W/mm, power included productivity of 50%, a cut-off frequency of 8GHz and an additional 20dBm, which is superior to anything for SiC MESFET simulation that has yet been observed [12].

For a PAE of 38%, researchers had manufactured a GaN MESFET device where the greatest frequency (fmax) was 11.6 and the cut-off frequency (ft) was 5.4GHz, with trans-conductance of 164mS/mm. The results showed a highest power of 2.56W/mm, and the greatest trans-conductance (gm), and the most extreme cut-off frequencies were 254mS/mm and 220GHz, obtained separately for the non-surface drained GaN MESFET. Another invention was a device based on GaN MESFET with a gate length of 0.3µm, a extreme frequency of 12.25GHz and a cut-off frequency of 8.35GHz. A Zincblende for the GaN MESFET with a precious stone shape for a 0.1µm gate width showed a greatest cut frequency of 240GHz and a trans-conductance (gm) of 210mS/mm [3]. The GaN MESFET observed a total power of 5.2W, with power included productivity of 69%, which obtained 500-600MHz of bandwidth.
A number of scientists have manufactured a GaN MESFET which indicated an RF power of 200W and which had a gate length of 2x50µm. In addition, this device had 12GHz of cut-off frequency (ft), and the extreme yield power density came to 2.4W/mm and gave 28% of power-included productivity. The extraordinary power densities of 34W/mm and 21W/mm observed for a device using SiC and sapphire substrate are being considered, with the execution of a GaN-based MESFET in a microwave device.

Several Japanese organizations have achieved an immense power included productivity of 72%, with a cut-off frequency of 2GHz and a clarification of power surpassing 130W. What is more, success has been achieved with a sapphire HEMT-based device GaN/AlGaN that has an interlayer of 1nm AIN, having a portability of 1770 cm²/Vs. In addition, having an electron sheet of 1.4 x 1014cm⁻² bearer thickness at the recorded temperature, it demonstrated a thickness of 4.9W/mm and a straight pick-up PAE of 14dB, with more than 32% achieved at 12GHz, with a gate length of 1mm. A temperature of 600K with 94mS/mm of conductance (gm), cut-off frequency (ft) of 9GHz and steep frequency (fmax) of 27GHz appears in AlGaN/GaN high-electron-mobility transistors (HEMTs). SiC substrate can possibly be used for such applications. At a constant temperature for Vds=17V with a cut-off frequency (ft) of 22GHz and greatest frequency (fmax) of 70GHz, the trans-conductance became 258mS/mm [2].

Scientists from the California Santa Barbara University created AlGaN/GaN HEMTs in DC situations that gave 93mS/mm of trans-conductance with 870mA/mm of solidity. A cut-off frequency (ft) of 18GHz, having a steep frequency (fmax) at 46GHz 0.7µm gate length material was observed. A yield power at 103W solidity with a powerful solidity of 7.2W/mm and power combined capability of 36.3% was observed in the tests, leading to a 19% AlGaN/GaN mole fraction HEMT shape on a semi-isolating SiC substrate.

Yield power solidity of 1.1W/mm that had a power combined capability of 20.1% and a gate-to-drain breakdown voltage up to 220V, region streams >320mA for a cut-off frequency (f) at 37GHz, and greatest recurrence (fmax) 70GHz had been obtained in an additional examination of AlGaN/GaN HEMTs with sapphire substrate. Several scientists obtained trans-conductance of 68mS/mm with an extreme frequency (fmax) of roughly
31GHz, a cut-off recurrence (ft) of 1.8GHz, RF force of 84mW/mm, and an eminent channel to source current density of around 174mA/mm for a 1400mm wide gate.

A cut-off frequency (ft) 8GHz appeared for AlGaN/GaN HEMTs, indicating that different specialists had used 9.8W/mm in manufacture. A group from Sweden had accomplished DC trans-conductance of 150mS/mm by a soaked channel current of 950 mA/mm by S specification estimations achieved on a 100µm HEMT [46] with a cut-off frequency, and most extreme frequency (f_max) of 26GHz and 52GHz, respectively. Silicon gallium nitride has the same warm state. Each progression in the procedure was observed in situ by reflecting the great vitality of electron diffraction.

Observing a bigger cross-section with GaN and Si, analysts revealed that GaN-construct components have a low frequency when compared with silicon and other materials developed with sapphire and with SiC [8]. Each progression in the procedure was checked in situ by the impression of soaring vitality electron diffraction.

1.2 Optoelectronic Devices of GaN

The arrangement of III-V nitride makes an important blend, such as optical, piezo electrical and electrical conduction, and led to the use of MESFETs in the making of transistors, LEDs, and rectifier LEDs. They also have capability to be used as a photograph finder, pre-intensifier, tuner, RF switch and so on, which are:

1. Beyond the Schottky barriers, there was photograph-incited voltage.

2. Beneath the gate there were photo-incited transporters.

Visually incomplete GaN MESFETs have successfully been utilized in optoelectronic applications. There is an obvious potential utilization in UV LEDs and LEDs for lighting and date stockpiling, field-effect transistors (FETs) for grand-temperature and high-control electronic devices, and sun oriented UV identifiers for the visually impaired [15]. Forthcoming commercial initiatives rely on the use of LEDs for their power efficiency and expanded applications, in contrast to radiant lights and fluorescent tubes. In today’s business sector, the majority of LEDs of a white color are a blend of blue shading from a blue GaN LED and yellow shading from the phosphor energized by the blue LED. At the
point of polarity with a blue LED chip, the phosphor corrupts much more quickly, so in this instance, blue light changes to white. Notwithstanding this, phosphor contains uncommon elements that will prove to be of enormous value to the business sector in the future.
Chapter-2: GaN Material Information

Gallium nitride (GaN) is a twofold III/V blunt bandgap semiconductor, ordinarily utilized as a part of brilliant light-transmitting diodes produced in the 20th century. The compound is a strong material, which has a Wurtzite gem shape with a wide-bandgap of 3.4 eV.

2.1 Crystal Structure

Gallium nitride and its particular associated compounds are crystallized, the pair having a Zincblende structure and a Wurtzite structure. The changes in GaN are associated with AlN InN in a Zincblende structure and a Wurtzite structure. In some circumstances, they get other magnitudes to do their work, as they disclose important modifications.

The bundle arrangement of the Zincblende lattice is given by:

\[ \text{GaANAGaBNBCNCGaANAGaBNBGaCNC} \]

The arrangement of the Wurtzite web is given by:

\[ \text{GaANGaBNBGaNGaBNBGaANAGaBNB} \]

The web constants for the Wurtzite structures ‘a’ and ‘b’ are the same, and they acquire C\text{4}_6\text{v} because of lure face designation. At the combinations of (zero, zero, 0) and at (2/3, 1/3, 1/2), the gallium atoms are dispersed [5]. At the combinations of (zero, zero, u) and (1.5, 0.33, 0.5+u) the nitride atoms are separated, where ‘u’ is near 3/8.

At this value of ‘u’, the Wurtzite design is similar to a zinc plate design. This is because the coordinate with u=3/8 adjusts the hexagonal design towards a tetrahedral.
2.2 GaN Energy Band Diagram

Applying Zincblende, Wurtzite designs of gallium nitride are elucidated. Figure 2.2 explains that the carrier transport, energy-band diagram [9] of GaN of the X-valley is 4.6eV, and the energy of the L-valley is near 4.8eV, 5.1eV, with an energy gap of 3.2eV.
The Wurtzite design of GaN has M-L-valleys and A-valleys and they have an energy of 4.7eV and 4.5eV, respectively. This is long enough for fabrication of an immense power MESFET, as the energy gap in this situation is approximately 3.39eV.

Figure 2.3 below displays the energy band diagram of GaN.

![GaN Energy Band Diagram](image_url)
2.3 Properties of Semiconductor Materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Bandgap (eV)</th>
<th>Electron Mobility (cm²/Vs)</th>
<th>Hole Mobility (cm²/Vs)</th>
<th>Critical Field $E_c$ (V/cm)</th>
<th>Thermal Conductivity $\sigma T$ (W/m·K)</th>
<th>Coefficient of Thermal Expansion (ppm/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InSb</td>
<td>0.17, D</td>
<td>77,000</td>
<td>850</td>
<td>1,000</td>
<td>18</td>
<td>5.37</td>
</tr>
<tr>
<td>InAs</td>
<td>0.354, D</td>
<td>44,000</td>
<td>500</td>
<td>40,000</td>
<td>27</td>
<td>4.52</td>
</tr>
<tr>
<td>GaSb</td>
<td>0.726, D</td>
<td>3,000</td>
<td>1,000</td>
<td>50,000</td>
<td>32</td>
<td>7.75</td>
</tr>
<tr>
<td>InP</td>
<td>1.344, D</td>
<td>5,400</td>
<td>200</td>
<td>500,000</td>
<td>68</td>
<td>4.6</td>
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<tr>
<td>GaAs</td>
<td>1.424, D</td>
<td>8500</td>
<td>400</td>
<td>400,000</td>
<td>55</td>
<td>5.73</td>
</tr>
<tr>
<td>GaN</td>
<td>3.44, D</td>
<td>900</td>
<td>10</td>
<td>3,000,000</td>
<td>110 (200 Film)</td>
<td>5.4-7.2</td>
</tr>
<tr>
<td>Ge</td>
<td>0.661, I</td>
<td>3,900</td>
<td>1,900</td>
<td>100,000</td>
<td>58</td>
<td>5.9</td>
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<tr>
<td>Si</td>
<td>1.12, I</td>
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<td>450</td>
<td>300,000</td>
<td>130</td>
<td>2.6</td>
</tr>
<tr>
<td>GaP</td>
<td>2.26, I</td>
<td>250</td>
<td>150</td>
<td>1,000,000</td>
<td>110</td>
<td>4.65</td>
</tr>
<tr>
<td>SiC (3C, b)</td>
<td>2.36, I</td>
<td>300-900</td>
<td>10-30</td>
<td>1,300,000</td>
<td>700</td>
<td>2.77</td>
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<tr>
<td>SiC (6H, a)</td>
<td>2.86, I</td>
<td>330 - 400</td>
<td>75</td>
<td>2,400,000</td>
<td>700</td>
<td>5.12</td>
</tr>
<tr>
<td>SiC (4H, a)</td>
<td>3.25, I</td>
<td>700</td>
<td>3,180,000</td>
<td>700</td>
<td>5.12</td>
<td></td>
</tr>
<tr>
<td>C (diamond)</td>
<td>5.46-5.6, I</td>
<td>2,200</td>
<td>1,800</td>
<td>6,000,000</td>
<td>1,300</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2. Comparison of Different Behaviors of Semiconductor Materials [15]

2.4 GaN Defects

A. Threading Dislocation

D. Kapolnek et al. (1995) suggested that in GaN materials developed by a metalorganic compound vapor grown on sapphire, the hotspot for disengagement is the nucleation layer itself. Amid an island mixture, edge threading separation fragments might be created when loner edge disengagements between adjoining islands are spatially out of alignment. The era of screw disengagements has all the indications of being more perplexing; it was discovered that immaculate screw or blended threading separations do diminish with film thickness, because of the simplicity of cross-slip or screw disengagements.
B. Stacking Faults
It is acknowledged that stacking shortcomings shaped in GaN sheets developed on polar and non-polar substrates are distinctive. In the course of the development of electronegativity, assemblage flaws are framed on the beginning plane (c-plane) subsequent to their arrangement, and vitality is the most reduced on this plane. On the off chance that development is occurring on the c-surface, flaws will be situated on planes parallel to the substrate. For development in non-polar heading, stacking flaws are framed on beginning planes (c-planes) that are along development bearing (Lilienthal-Weber, 2008), since their arrangement and vitality on the cited planes is the most reduced, and they will be arranged opposite to the substrate.

2.5 Interstitials and Antisite Defects

A. Point Flaws
There are three primary types of mark deformity: opportunities, interstitials and substitutional molecules. An abandoned general precious stone site is called an opportunity.

B. Dislocations
Disengagements are generally because of misalignment of iotas or the occurrences of opportunities along a line.

C. Atom Barriers
Polycrystalline components contain grains of individual precious stones with various crystallographic introductions. A sheet of limited interrelated molecules encompasses every atom in a formless stage, called atom barriers.

D. Lattice Mismatch
At the point when a film is developed on a substrate of various consistent cross-sections, the film will extend (elastic strain) or contract (compressive strain) to oblige the distinctive steady grid of the substrate.

E. Thermal Mismatch
The warm development coefficient depicts the long adjustment (direct warm extension coefficient) or volume (warm extension coefficient) of a material.
F. Nano Pipes

Another kind of deformity found in GaN films are Nano pipes, also called micro pipes by some scientists. This imperfection has the nature of a clear center spiral separation. The oxygen polluting influence is thought to be, firmly connected with the arrangement of this imperfection, by harming the uncovered feature dividers, subsequently avoiding complete layer blend. There is such proof from the perception of void arrangement along disengagements. Here it prompts the harming of {10 one zero} lateral dividers, so that it permits Nano pipes to spread, or the arrangement of a clear separation (Brown, 2000).

2.6 Applications:

1. LEDs
GaN-based violet laser diodes are utilized to peruse Blue-beam Disks. At the point when doped by all adequate transition metals, for example, manganese, GaN is a promising spintronic device.

2. High Frequency, Steep Voltage, High Temperature, High Efficiency
GaN HEMTs have been on the market since 2006. Benefits were quickly discovered in different remote foundation utilizations because of their immense effectiveness and valuable voltage service. Further innovation with decreased gate space is developing rapidly in telecom and aviation utilizations. MOSFET and MESFET GaN-based transistors additionally display points of interest, incorporating fewer defects in high performance hardware, particularly in cars and auto-electric applications.

GaN-based hardware can possibly radically cut energy utilization in consumer applications, as well as use energy more efficiently. It enables greater productivity and a speedier exchange of frequency. It has tremendous ramifications, not just for the efficient use of power device frameworks, but also for their physical size and steadiness. In comparison to silicon transistors, which fluctuate because of an increase in power, GaN transistors are regularly in an exhausted condition. However, various organizations, along with the US Government and some colleges, have helped create GaN transistors by means
of materials designed to be useable as improvement mode (normally off) devices, very similar to silicon-based transistors.

3. Synthesis

GaN precious stones can be developed from liquid Na/Ga held under 100 airs of weight of N2 at 650 °C. As GaN will not respond with N2 beneath 1100°C, the powder must be produced using something more receptive, normally by one of the methods discussed below.

4. Molecular Beam Epitaxy

Finally, GaN precious stones can be developed utilizing sub-atomic bar epitaxy. This procedure can be further altered to decrease disengagement densities. Initially, a particle bar is connected to the development surface to create nanoscale roughness. At that point, the surface is cleaned. This procedure takes place in a vacuum.

Figure 2.4. Benefits of Gallium Nitride [8]
CHAPTER-3: Understanding of MESFET

3.1 Physics of MESFET
The abbreviation of metal-semiconductor field-effect-transistor is MESFET. A MESFET is almost comparable to a JFET in particulars of technology and manufacturing. As represented in the figure below, it contains a prominent channel bounded by a source and drain contact field where charge carriers are guarded by a Schottky rectifying contact flow. It also serves as a p-n junction gate. The varying depletion layer width beneath the metal connection, which improves the dimensions of the operating channel, helps in obtaining control. Figure 3.1 below is a cross-sectional view of a metal-semiconductor field-effect-transistor (MESFET).

3.2 Discrete Types of MESFET
The detachment of charge bearers from the surface by the depletion layer and its maneuverability is equal to the mass material. There has been immense progress in the multi-use, strength of currents, trans-conductance, and transfer frequency of devices. As there are high travel frequencies, its use is of major significance in a microwave circuit.
The essential factor of the MESFET contribution to the microwave speaker or circuit, the diode turn-on diode bias, is readily approved.

1. Enhancement Mode (Normally OFF) MESFET

2. Depletion Mode (Normally ON) MESFET

Two different modes of MESFET in graphical representation are exhibited in Figure 3.2.

![Graphical Representation of Normally OFF and Normally ON](image)

**Figure 3.2. Graphical Representation of Normally OFF and Normally ON [13]**

Enhancement-mode MESFETs consist of common switching elements, which is FET-based (field-effect transistor) technology, which will be OFF at zero gate-source voltage, the same as $V_{DD}$. When the voltage is in the way of drain voltage by dragging the gate voltage, it could be turned ON. For the two logics, n-doped and p-doped, these are absolute and negative respectively.

In logic circuits, the above mentioned depletion mode instruments are used as load resistors. There is a negative threshold voltage for n-doped depletion load materials and there is an absolute value for gate voltages in p-type.
3.3 Fabrication of MESFET

As hugely doped n$^+$ source and drain regions are convoluted in the fabrication process in MESFET, two regions are formed by two silicon ion implantations, one of which is used to form the n-channel region, and other to form low resistance.

To build the ohmic contacts for the source and drain regions and to get the Schottky gate, a gold-germanium-nickel metal and an ejection aluminium metal are used, respectively, and metal pads for probing thicker, E-beam evaporation for metal deposition are used.

There are various steps in the fabrication of a MESFET. They are as follows:

1. Four levels:
   a. Channel implant
   b. Source/drain implant
   c. Ohmic contact evolution
   d. Schottky gate forming.
2. When the wafer is cleaned, by employing a reactive sputtering Silicon nitride cap, deposition is carried out.
3. By applying positive resistance, resist patterning for the channel implant is achieved.
4. With maximum ion energy and with the help of the ion species Si$^+$ (individually ionized) and at a constant dose, silicon ion implantation of the device channel region is developed.
5. For arrangement registration reasons, shallow etching of silicon nitride is done.
6. A buffered HF solution is created through plasma etching.
7. Ashing in oxygen plasma and resist stripping is carried out.
8. Employing the positive resist, resist patterning for source/drain implant is done.
9. Using the maximum ion energy and ion species and a constant dose of silicon ion implantation, metal source and drain regions are formed.
10. Employing rapid thermal annealing with maximum temperature and ambient (forming gas) at a specific time (seconds), annealing of ion implants is achieved.
11. Resist patterning for ohmic contact formation is carried out.
12. For ohmic contacts, silicon nitride etching is done.
13. For the semiconductor surface CF₄, plasma etching is done.
14. Finally, wet etch cleaning and deposition of AuGe/Ni metal for ohmic contacts is applied to the source and drain.
15. E-beam evaporation and patterning by liftoff process are completed.
16. By rapid thermal heating, ohmic contact alloying is executed.
17. For Schottky gate formation, resist patterning for nitride etching is done.
18. For Schottky gate formation Silicon nitride etching performed.
19. Wet etch cleaning is finally executed.
20. Aluminum metal deposition for Schottky gate formation using e-beam evaporation and patterning by liftoff technique is completed.
The primary fabrication process for developing a GaN MESFET is shown below.

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 Schottky Gate Contact Formation and Metal Lift off

G. Finished Device

Figure: 3.3. Outline of GaN – MESFET Fabrication [16]

3.4 Metal Semiconductor Schottky Barrier

Understanding the boundaries of JFETs and MOSFETs is becoming problematic, and discussions have not appeared about MESFETs in semiconductor-based research. It was
1996 when Mead made the discovery of this device and gave recommendations for its use, in order to overcome the problems faced by JFETs and MOSFETs.

Three forms of metal-semiconductor connections are present. The most prominent in these connections is the gate electrode Schottky barrier. The increment in this barrier height in GaN is expressed by $\chi_{\text{GaN}}$. The barrier is shown in Figure 3.4.

![Figure 3.4. Schottky Barrier of Metal-Semiconductor](image)

The Schottky barrier is created when the doped region is near to the depletion layer. There is a different sort of semiconductor contact for the source electrodes. As in the n-type, the component and extrinsic semiconductors were coupled mutually. Where, in the contact of these two, a probable imbalance is existing, it is labeled as ohmic contact and is created when GaN is massively doped [19].

The movement of electrons that takes place from source to GaN materials is indicated as $\phi_M>\phi_S$, and this is due to the shortcoming in potential between material ($\phi_M$), work metal function, and source ($\phi_S$). When it is a position of $\phi_M<\phi_S$, then it breaks the execution of movement, which acts as fast as a switch.
3.5 Ion Implantation

For the past 30 years, ion implantation has proven to be an attractive and effective method in many applications related to ion cutting, electrical isolation, dry etching, doping for choosing a range etc., and using GaN-based device fabrication [33]. Generally, GaN empty donors have Ge, Si, and C holding the aforementioned locations of Ga and Se. In addition, the section of N engaged by S and O, until GaN shallow acceptors receive Ca, Mg, Zn, and Cd, and occupy the site of Ga, Ge and N, is engaged by Si and C. Ahead of achieving an ion implantation approach, mandatory doping is launched by SRIM. The mode was to manage the silicon in a gaseous state by diffusing the material that had been stored over the surface [40].

Provision for the device processing requires a restriction, carrying a shortfall of resilience in the abovementioned mechanism of diffusion. By employing the dopant atom when ion implantation was submitted, recognition was obtained. By applying the description, the implantation dose can be established by:

\[
\text{Dose } \varnothing = \frac{\text{ion beam current in amps}}{\text{electron charge}(q)} \times \frac{x \text{ (implanted area)}}{\text{ion beam scanning area}}
\]

By production of less resistive layers in GaN, the ionization energy of dopants was analogously high, and, as a result, there was a tremendous increase in the introduction of dopants. There is, however, danger of a damaged or amorphous layer when doping is carried out at immense-dose implantations. Formation of less than $10^{16}$ ions.cm$^{-2}$ is made by 1mA medium ion beam current doses at a period of 10 seconds [22]. The essential impurities, like high-energy dopants, are bombarded on the surface of the semiconductor lattice, called ion implantation.

Eradication of an ion implantation system is made by the ion source that yields a focused beam that advances when transformed into a surge of ions. To resolve this, a beam is passed towards the mass annotator. To make it differ from neighboring mass numbers regularly, this analyzer is delicate. The option in vital implant ions of the opening beam is built by the ratio of charge to mass ions. Lastly, it proceeds to the final part of the process,
where there will be marginal electrostatic deflection of ion beams, and it is separated from the neutral atoms.

By individual adjustment or by the pair, electrostatically and mechanically, the wafer surface of the beam is scanned. Moreover, to enable electrons to rise to the surface, a comparable base is likened to the wafer, and evades the charge, in order to enhance the insulating face, such as, silicon oxide or silicon nitride.

In retrieving the p-type conductivity in sole shot at room temperature, boron, aluminum, gallium and thallium are fixed for gallium nitride [23, 24]. In today’s world, there is no lucrative means for ion implantation for the pair donor and acceptor dopant ions in the direction of mono-crystalline gallium nitride, which gains almost equally to electrically stimulated n and p-type components. The intention of the current development was ion implantation of doping ions within the doped gallium nitride substrate. [25].

**Ion Implantation System**

![Image of ion implantation system](image.png)

**Figure 3.5. Organization of Simple Ion Implanter [25]**

3.6 Impurity Distribution

Establishing the loss of energy is achieved by proceeding in an irregular direction, as per nuclear and electronic properties, by all ions in moving from the destination in ion
implantation. For the doses employed in implantation at $10^{16}$ ions /cm$^3$ and by observing the analytical measures, the orbiter path of the ions can be estimated [35]. Range $R$ is observed as the mean of overall dimension through which it is drawn, by taking the pair of perpendicular and parallel indications. The mean intensity of implanted ions and the straggle parameter $\Delta R_p$ as the resemblance of depth is the same as the projected range $R_p$ established with the guidance of Gaussian circulation of implanted ions.

$$N_k = N_p \exp \left\{ -\frac{y-R_p}{2\Delta^2} \right\} - N_t$$  \hspace{1cm} (3.1a)

$N_p$ = Peak concentration of the device

$R_p$ = Projected range of the device

$\Delta$ = Straggle Parameter of the device

$N_t$ = Background concentration of the device

$N_p = \Phi / \sqrt{2\pi}\sigma$

Where

$\Phi$ = the ion dose

Over an area of peculiar circulations, a Pearson IV fit conveys a more specific fit to some ion implantation that probably employed Gaussian distribution. Beneath the non-confronting settings, the matched circulations are correlated energies for a preliminary boron sketch between 40KeV and 900KeV.

### 3.7 Doping Impurity Distribution of Ion Implantation after Annealing

Mostly, the surface donors of GaN maintain a zone of Ga, Se holds Ge, Si and C, and N is engaged through S and O. At the same time, the surface acceptors of GaN hold Ca, Mg, Zn, and Cd and Be, catching the zone of Ga and Ge, and the zone of N is hold by Si and C. Its properties are classified in the table below.


\[
J_d = R_p \pm \Delta R_p \sqrt{2 \ln(N_p/N_b)} 
\]

(3.1b)

The impurity distribution can be operated

\[
N(z) = \frac{Q}{\Delta' R_p \sqrt{2\pi}} \exp \left[ \frac{(z - R_p \Delta R_p \sqrt{2})^2}{{\Delta'} R_p \sqrt{2}} \right] - N_b
\]

Where

\[
\Delta' R_p = \sqrt{\sigma^2 + 2Dt}
\]

D=Diffusion during annealing

T= Annealing time

3.8 Utilizations of MESFET

Different fabrication techniques are used to manufacture MESFET. Several of the main utilizations are:

1. Military and navy, in distinct areas.

2. Low capability RF amplifiers, where MESFET plays a critical part to reduce synthesizer costs.

3. As an essential electronic material in steep frequency areas such as RADAR and satellite communication
4. At the manufacturing stage, in microwave links it can be used as a power amplifier.

5. Monetary optoelectronics.
Chapter-4: Mathematical Computation

Keeping in view the end goal to finish the electric field and potential in the channel region, the Poisson’s mathematical statement is

\[
\frac{\partial \varphi}{\partial z} = - \frac{q}{\varepsilon_{GaN}} \quad (1)
\]

\[
\frac{\partial^2 \varphi}{\partial z^2} = - \frac{q}{\varepsilon_{GaN}} N_D \quad (0 < z < z_j) \quad (2)
\]

Mathematical statement (1) is the physical capacity of the MESFET utilized as a part of this project.

Where

Q = Charge density of the device

\(\varepsilon_{GaN}\) = Permittivity of the GaN semiconductor device

\(\varphi\) = Channel potential

z = Position in the channel

\(z_j\) = Channel junction depth

Limitation cases indicates that the electric field at the edge of the gate depletion is zero. Thus, the channel potential is likewise zero [12, 13].

Therefore, the electric potential is indicated as

\[\varphi(z) = \frac{q}{2\varepsilon_{GaN}} N_D (z - z_{ch})^2 + \varphi(z_{ch}) \quad (3)\]

Where

q = Charge of the Electron

\(\varphi(z_{ch})\) = the electrostatic potential in the channel

Along the side of the back channel implanted region it has the edge of the depleted region is \((z_d < z_b)\)

\[
\frac{\partial^2 \varphi}{\partial z^2} = \frac{q}{\varepsilon_{GaN}} N_A \quad (z_j < z < z_d) \quad (4)
\]
Where

\( N_A = \text{Effective doping density in the back channel implanted area} \)

\( z_d = \text{Area of exhaustion edge underneath the channel} \)

\[
\varphi(z) = \frac{q}{2\varepsilon_{GaN}} N_A (z - z_d)^2 + \varphi(z_d) \tag{5}
\]

\[
z_{ch} = \frac{N_A N_z}{N_D} z_j - \frac{1}{N_D} \left( \frac{N_A N_D}{N_D} \right)^2 z_j^2 + \frac{2\varepsilon_{GaN}}{q} N_A \left[ \varphi(0) - \varphi(z_d) - \frac{q}{2\varepsilon_{GaN}} N_z z_j^2 \right] \tag{6}
\]

\[
N_z = N_D \left( \frac{N_D}{N_A} + 1 \right) \tag{7}
\]

\[
\varphi(z = 0) = \text{Electrostatic potential at the surface of Gallium Nitrate} \]

\[
\varphi(z = 0) = \chi + \frac{E_g}{2q} + \frac{kT}{2q} \ln \frac{N_C}{N_V} - \phi_m + V_g \tag{8}
\]

\( E_g = \text{Band gap energy} \)

\( \chi = \text{Electron affinity of material} \)

\( \phi_m = \text{Work function of the Schottky contact} \)

\( V_g = \text{Gate voltage} \)

\( K = \text{Boltzmann constant} \)

\[
\varphi(z_{ch}) = \frac{q}{2\varepsilon_{GaN}} N_D z_{ch}^2 + \varphi(0) \tag{9}
\]

From the threshold voltage of a GaN MESFET, a short changeover between the turn-off and turn-on areas is observed. To take care of the electric field, a voltage should be adapted to the gate, to compose the device to off state.

There is an indication in threshold voltage, when the channel potential comes to \(-F_n\)

\[
V_T = V_g [\varphi(z_{ch}) = -F_n] = -F_n - \frac{q}{2\varepsilon_{GaN}} N_D z_{ch}^2 - \left( \chi + \frac{E_g}{2q} + \frac{kT}{2q} \ln \frac{N_C}{N_V} - \phi_m \right) \tag{10}
\]

\( V_g = \text{Gate voltage} \)
\( \phi_m \) = work function of the Schottky contact.

Where

\[
Z_{ch} = Z_j - \sqrt{\frac{2e_{GaN}}{q_N}} \left( 1 + \frac{N_D}{N_A} \right)^{-1} \left( -F_n - V_B + F_p \right)
\]  

(11)

\( F_n \) = Fermi potential in n-channel

Where

\[
F_n = V_t \ln \left( \frac{N_D}{n_i} \right)
\]

\( V_B \) = Back gate bias

The back channel implanted range comprises of the depletion edge at its underneath \( Z_d > Z_B \), the poisons equation can be resolved as

\[
\frac{\partial^2 p}{\partial z^2} = \frac{q}{\varepsilon_{GaN}} N_A \quad Z_j < z < Z_B
\]

(12)

\[
\frac{\partial^2 p}{\partial z^2} = \frac{q}{\varepsilon_{GaN}} N_{Sub} \quad Z_B < z < Z_d
\]

(13)

Where

\( N_{Sub} \) = Substrate doping Concentration.

From the equations (12) and (13)

\[
\frac{\partial p}{\partial z} = \frac{q}{\varepsilon_{GaN}} N_A Z + D_{21} \quad ( Z_j < z < Z_B )
\]

(14)

\[
\frac{\partial p}{\partial z} = \frac{q}{\varepsilon_{GaN}} N_{Sub} Z + D_{31} \quad ( Z_B < z < Z_d )
\]

(15)

The electric field is zero because the edge of the depleted region is \( z = Z_d \)

Therefore from the equation (15),

\[
\frac{\partial p}{\partial z} = 0
\]

The limitation constant can be indicated as below because of the limitation situations,
$D_{31} = - q/\varepsilon_{GaN} N_{sub} z_d$  \hspace{1cm} (16)

Achievement of the depletion width at drain end is as below

$$z_d = \sqrt{\frac{2\varepsilon_{GaN}}{qN_D}} (V_{bi} + V_{DS} - V_{GS} - \Delta)$$  \hspace{1cm} (17)

Where

$V_{bi}$ = Built in voltage

$V_{DS}$ = Drain to source voltage

$V_{GS}$ = gate to source voltage and

The depth of fermi level can be pointed as

$$\Delta = \frac{kT}{q} \ln\left(\frac{N_c}{N_D}\right)$$  \hspace{1cm} (18)

Where

$N_c = 4.3 \times 10^{14} \times T^3$

When $z = z_b$, the electric field obtained from the mathematical statements, 14 and 15 are equivalent.

Hence the conclusion is

$$D_{21} = q/\varepsilon_{GaN} N_{sub} (z_B - z_d) - q/\varepsilon_{GaN} N_A z_B$$  \hspace{1cm} (19)

Where

$z_b$ = back channel implanted area

By integrating the mathematical statements, the electrostatic potential converts into

$$\Phi(z) = \frac{q}{2\varepsilon_{GaN}} N_A (z - z_B)^2 + \frac{q}{\varepsilon_{GaN}} N_{sub} (z_B - z_d)^2 + D_{22} \hspace{1cm} (z_j < z < z_B)$$  \hspace{1cm} (20)

$$\Phi(z) = \frac{q}{2\varepsilon_{GaN}} N_{sub} (z - z_d)^2 + D_{32} \hspace{1cm} (z_B < z < z_d)$$  \hspace{1cm} (21)
Thus the electrostatic potential when the possibilities from the above two mathematical statements when their possibilities are equivalent where

\[ D_{32} = \Phi(z_d) \text{ and} \]
\[ \Phi(z_d) = V_B - F_{SUB} \]

Where

\[ F_{SUB} = \text{Substrate potential} \]
\[ D_{22} = (q/2\varepsilon_{GaN})N_{sub}(z_b - z_d) + \Phi(z_d) - q/\varepsilon_{GaN}N_{sub} (z_b - z_d) \cdot z_b \]

\[ \Phi(z) = \frac{q}{2\varepsilon_{GaN}}N_A(z - z_b)^2 - \frac{q}{\varepsilon_{GaN}}N_{sub}(z_d - z_b)(z - z_b) + \frac{q}{2\varepsilon_{GaN}}N_{sub}(z_d - z_b)^2 + \Phi(z_d) \]

\[ (z_j < z < z_b) \]

The electrostatic potential is static, at the intersection between the channel and the back channel embedded area.

In this way by the mathematical statements (3) and (21)

\[ z_j - z_{ch} = -c + \sqrt{c_1^2 - c_2} \]

Where

\[ c_1 = \frac{N_{sub}}{N_D} \left[ z_j - \left( \frac{N_A}{N_{sub}} - 1 \right) (z_b - z_j) \right] \]

\[ c_2 = \frac{N_{sub}}{N_D} \left[ \left( \frac{N_A}{N_{sub}} - 1 \right) \times (z_b - z_j)^2 - N_D z_j^2 - \frac{2\varepsilon_{GaN}}{q} [\Phi(0) - \Phi(z_d)] \right] \]

\[ \Phi(z_{ch}) = \frac{q}{2\varepsilon_{GaN}}N_D z_{ch}^2 + \Phi(0) \]

The mathematical statements of 10 indicate as 22 and 25 the threshold voltage

\[ V_T = -F_n - \frac{q}{2\varepsilon_s} N_D z_{ch}^2 - \left( x + \frac{E_s}{2q} + \frac{kT}{2q} \ln \frac{N_c}{N_v} - \phi_m \right) \]
Where

\[ z_{ch} = z_J - \frac{1}{2c_1} \left( -c_2 + \sqrt{c_2^2 - 4c_1c_3} \right) \]  \hspace{1cm} (29)

\[ c_1 = \frac{q}{2\varepsilon_{GaN}} N_D \left( \frac{N_D}{N_{sub}} + 1 \right) \]  \hspace{1cm} (30)

\[ c_2 = -\frac{q}{\varepsilon_{GaN}} N_D \left( \frac{N_A}{N_{sub}} - 1 \right) (z_B - z_J) \]  \hspace{1cm} (31)

\[ c_3 = \frac{q}{2\varepsilon_{GaN}} N_A \left( \frac{N_A}{N_{sub}} - 1 \right) (z_B - z_J)^2 + F_n + V_B - F_{SUB} \]  \hspace{1cm} (32)

Where

\[ z_{ch} \] = Length of the channel

\[ V_B \] = back gate voltage

\[ F_{SUB} \] = substrate potential
Chapter-5: Results and Analysis

A physics based analytical model for non-self-aligned GaN MESFET has been developed. There has been continuous research going on to develop a better analytical model. By using MATLAB, an analytical model has been simulated to study the threshold voltage versus back gate bias voltage for different doses and different substrate doping concentrations and the resulted graphs are plotted for electric field along the length of the channel for different back gate biases and different drain to source voltages.

![Figure 1](image)

Figure 5.1: Electrical field in Channel (V/m) versus Length of the Channel (µm)

The Figure 5.1 shows how the electric field in channel changes with the length of the channel for different drain-source voltages ($V_{ds}$) of 30V, 60V, 90V with substrate concentrations of ($N_a$) of $2\times10^{16}$ cm$^{-3}$, doping concentration of channel ($N_d$) of $9\times10^{15}$
cm$^3$, and dose of $3.5 \times 10^{12} \text{ cm}^2$. As shown in the figure electric field increases linearly with increase of channel length. At $V_{ds} = 30V$, 60V, 90V the drain edge is more reverse bias compared to the source side. Hence, the electric field increases at the drain side, which clearly indicated in the graph. Further the electric field increases because of the increase in drain-source voltage $V_{DS}$ by a range of 30V to 90V. So for a given drain to source voltage ($V_{ds}$) of 30V the maximum electric field is $3.6 \times 10^5 \text{ V/m}$, and the electric field is found to be $3.7 \times 10^5 \text{ V/m}$ at drain to source voltage $V_{DS}$ of 60V. And at a $V_{DS}$ of 90V, electric field is reached to the value $3.9 \times 10^5 \text{ V/m}$. The nature of increase of electric field obeys the physics of MESFET. The equation has been computed by using the equation 14.

Figure 5.2 Threshold voltage ($V_{TH}$) versus Back Gate Voltage ($V_B$) for different doses ($D_S$)
The Figure 5.2 exhibits a plot of the threshold voltage versus back gate $V_B$ for different doses ($Q$) of $0.5 \times 10^{13} \text{ cm}^{-2}$, $1 \times 10^{13} \text{ cm}^{-2}$, $5 \times 10^{13} \text{ cm}^{-2}$ with constant effective doping ($Na$) of $4 \times 10^{15}$ and active channel thickness $Z_J$ of $0.152 \times 10^{-4} \text{ cm}^{-3}$. At Lower ion dose, the threshold voltage varies from $-5.75 \text{ V}$ to $-4.25 \text{ V}$. The threshold voltage varies from $-8.23 \text{ V}$ to $-7.1 \text{ V}$ for the ion dose of $5 \times 10^{13} \text{ cm}^{-2}$. Hence higher ion dose pushes the threshold voltage more negative. The device behave as a depletion MESFET. The performance that the MESFET device can behave as enhance MESFET by using the threshold voltage for referred ion dose, which is extremely challenging. The graph is based on the equation (28). The characteristics of the threshold voltage for this analytical GaN MESFET at different doses is observed from the graph 5.2.

The Figure 5.3 presents a plot of the threshold voltage versus back gate voltage ($V$) for different substrate doping concentrations ($N_{\text{sub}}$) of $0.5 \times 10^{15} \text{ cm}^{-3}$, $1.5 \times 10^{15} \text{ cm}^{-3}$, and...
3.5x10^{15}\text{cm}^3, with a junction depth of 0.152x10^{-4}\text{cm}^3. The threshold voltage decreases as the back-gate bias voltage increases from -5V to 0V. The threshold value at $V_b = -5V$ for a substrate doping concentration of 1.5x10^{15}\text{cm}^{-3}$ is -1.18V and decreases to -2.71V. It has been observed that the threshold voltage shows low value for higher substrate doping, because the substrate depletion width is narrow. So small gate voltage (threshold voltage) will make the MESFET device ON STATE. This graph has been generated by the equation (28).

Figure 5.4 Electrostatic Potential distribution in n-channel versus Channel Length

The Figure 5.4 presents that, how the electrostatic potential (V) distribution in n-channel varies along the channel length(X) for the variation of back-gate-biasing values from -1V to -5V. The electrostatic potential distribution along the channel length for different back-gate biasing voltages of ($V_b$) of -1V -3V -5V is observed, the electrostatic potential linearly
decreases along the channel length in the range of $0.5 \times 10^{-5}$ to $3.5 \times 10^{-5}$ cm. For back-gate biasing $V_{b} = -5$ V, the maximum electrostatic potential is observed at 42 V and the minimum potential is found to be 8 V. Hence, the potential exponentially decreases with increase of channel for different back-gate biasing. From the equation (10), the above graph is generated.
Chapter-6: Conclusion

A one-dimensional analytical model of a GaN MESFET has been constructed in order to evaluate the primary concept of the back channel boron implant for the device structure. Analytical modeling employing software simulations and numerical tallies have been carried out to analyze the threshold voltage. It was found that when using a back-gate bias, the threshold voltage changes from -5.8V to -4.3V for dose (Ds) of $0.5 \times 10^{13}$ cm$^2$. A back-gate bias also has a significant effect in terms of causing the threshold voltage to decrease from -1.1V to -2.65V for substrate concentration (Nsub) of $3.5 \times 10^{15}$ cm$^{-3}$. Furthermore, the electric field increases linearly along the channel as the drain source voltage varies. The outcome clearly demonstrates the potential use of the device for high power and high frequency amplification in defense and aviation communication and telemetry applications.
References


SYMBOLS AND NOTATIONS USED:

- $q$: Electronic charge
- $\epsilon$: Permittivity
- $L$: Channel length
- $W$: Width of the device
- $\mu$: Mobility
- $\Delta X_j$: Change in junction depth
- $V_{bi}$: Built in voltage
- $V'$: Channel potential at the surface end
- $V_D$: Channel potential at the drain end
- $V_G$: Gate potential
- $V_{GS}$: Gate to Source voltage
- $V_{DS}$: Drain to Source voltage
- $V_{GD}$: Gate to Drain voltage
- $V_{th}$: Threshold voltage
- $V_p$: Pinchoff voltage
- $V_{BS}$: Substrate to source voltage
- $Q_T$: Total space charge in the depletion region
- $P_T$: Total charge density in the depletion region
- $f_T$: Cutoff frequency
- $N_B$: Substrate concentration
\( N_s \): Average concentration

Q: Ion implant dose

\( R_p \): Ion implant projected range

D: Diffusion coefficient of ion implant