Abstract—In the current research work, we focused on the design and analysis of a semiconductor device called High-Electron-Mobility Transistor (HEMT) based on the AlGaN/GaN material system. An Aluminum Nitride spacer, Layer of Nucleation along with cap as a AlGaN and barrier of GaN with the channel of AlGaN are incorporated to enhance HEMT device performance.

The electrical characteristics of the proposed HEMT are analyzed. The Drain Current is found to be 0.18A/mm, indicating the device's ability to handle high current levels. The Electron Concentration is observed to have a maximum value of $96.12 \text{electrons/cm}^3$ and varying based on the position in the channel for GaN Barrier thickness is 0.15mm. In the analysis of AC such as Gain of the Maximum Unilateral Power is determined to be 83.41dB, indicating the ability of the device to amplify signals. The Ψ-parameters, which characterize the device's behavior at various frequencies of operation, are also determined. The capacitance between the electrode region Gate-Source (C_{GS}) is found to be $1.70 \times 10^{-11} \text{F/mm}$, and alike The Capacitance between the electrode region the Gate-Drain Capacitance (C_{GD}) is determined to be $4.76 \times 10^{-12} \text{F/mm}$. Furthermore, an Electric Field of $96.51 \times 10^{3} \text{V/mm}$ is observed, indicating the strength of the electric field across the device. For HEMT device the simulation, the TCAD Silvaco software is being practiced.


I. INTRODUCTION

The launch of new semiconductor devices is a critical aspect of any industry's department of production, as it is used in manufacturing electronics such as 5G, 6G, and next generations of technologies that are coming up in the future. Currently, Research is being done on certain new semiconductor materials devices for the same purpose.

HEMT transistors are capable to handle higher frequencies and up to millimeter wave frequencies than conventional transistors so that such transistors can be used in high-frequency products like Mobiles, Receivers of TV (Satellite), voltage converters, and equipment of RADAR. HEMT are generated by aligning two different band gap materials. The two dimensional electron gas (2-DEG) creation is made by materials with both extensive band gap material with limited band gap material by applying to the high voltage to extensive band gap material. Such HEMTs is cable to operate at high temperature and high frequency.

GaN material stands out among the semiconductor materials because of its noticeable characteristics of electrical, surpassing those of AlGaAs/GaAs. Innovators have discovered that AlGaN/GaN-based HEMT are deployed through various methods, compatible to not only larger-power applications but high-frequency applications. In addition, it proves to be suitable for low-noise applications, gives favorable outcomes, especially when the gate length is minimized [1]–[9]. In concern with the medical applications, some HEMTs have achieved prominence. These HEMTs are intricately designed using biosensors, such as it is used to the detection of diverse medical parameter such as Detection of Glucose DNA, Breast Cancer, Kidney Injury Molecule, Prostate Cancer, pH Level and Cardiovascular Disease and more. Moreover, Gate Engineering Techniques is utilized for the implementation purpose [10]–[15]. Besides, some researchers have investigated on the addition of An Aluminum Nitride layer (Thin) increases electrical different characteristics mobility and sheet charge density [16–18], An AlGaN/AIN/GaN/Al-GaN Photodetector HEMT design improves transconductance, photocurrent and offers high current [19]. The leakage current can be reduced by adding the back barrier into the structure of AlGaN/GaN based HEMT [20].

In present study, the main objective of the work is to focus on enhancing AlGaN/GaN HEMT’s performance which is compatible for high frequency as well as high power applications. At first stage, Al_{0.25}Ga_{0.75}N HEMTs with a mole fraction (x) of aluminium 25% is taken into the consideration with the addition of GaN barrier. It is also vital to know that An Aluminum Nitride spacers are sandwiched between the heterojunction GaN barrier and the AlGaN cap. Additionally, An Aluminum Nitride layer of nucleation is inserted across silicon carbide substrate and AlGaN channel as an indication of nucleation. The HEMT device of AlGaN/GaN under consideration is being modeled with the help of TCAD Silvaco Software. Following the simulation stage, diverse electrical characteristics are evaluated in both AC and DC aspects.

In this paper, we have mainly focused on improvement of the electrical characteristics to optimize the AlGaN/GaN HEMT.

Present work has been implemented as follows:
1. We have examined the present device by varying physical element of different layers, noticed characteristics of device includes current-voltage (I-V) characteristics (output characteristics and transfer characteristics), Gain, Capacitance of different regions: Gate-Source capacitance and Gate-Drain capacitance.
2. In past decades many inventors have studied on the variations in dimensions but the reason of this work is to focus on electrical characteristics and insure to make compatible for High power and frequency application.

The present work structure is as: In section 2, the discussion followed by operation of device is introduced. Simulation Physical Models are explained in Section 3. With detailed discussion results of simulations are discussed in Section 4.
In section 5, conclusions are drawn based on the simulated results obtained from above mentioned software. Some of the Future Scopes are stated in Section 6.

**II. DEVICE OF HEMT**

The blueprint of device are illustrated in Figure 1, By launching a layer of new cap such as AlGaN cap (10 nm), and the introduction of an Aluminum Nitride spacer (2 nm) kept across both the cap of AlGaN along with the barrier of GaN (15 nm). Additionally, a 26 nm thick channel of AlGaN, preceded to an Aluminum Nitride Nucleation Layer (200 nm). 170 mm of substrate 4H-SiC is considered. An innovative feature of the device design is the discrete field plate is used. This modification serves purpose of mitigating gate-drain and the gate-source regions capacitance. An option of a Silicon Carbide (SiC) substrate with 170 mm diamensions is aiming to enhance the device's performance, especially at uplifted temperatures [15], Table 1 gives specific device structure.

![Discrete Field Plate](image)

**Table I. Geometry Diamentions of Proposed HEMT device.**

<table>
<thead>
<tr>
<th>Parameters/Electrodes</th>
<th>Proposed HEMT Device Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate Length (L_g)</td>
<td>0.25 µm</td>
</tr>
<tr>
<td>Length of Discrete Field Plate (L_{DFP})</td>
<td>0.1 µm</td>
</tr>
<tr>
<td>Gate- Drain Distance (L_{GD})</td>
<td>2.7 µm</td>
</tr>
<tr>
<td>Gate- Source Distance (L_{GS})</td>
<td>0.8 µm</td>
</tr>
<tr>
<td>Discrete Field Plate-Gate Distance (L_{DFGP})</td>
<td>0.9 µm</td>
</tr>
<tr>
<td>Discrete Field Plate- Drain Distance (L_{DFPD})</td>
<td>1.7 µm</td>
</tr>
<tr>
<td>Length of Source (L_s)</td>
<td>0.5 µm</td>
</tr>
<tr>
<td>Length of Drain (L_d)</td>
<td>0.5 µm</td>
</tr>
<tr>
<td>Length of Discrete Field Plate (L_{CFP})</td>
<td>0.1 µm</td>
</tr>
<tr>
<td>Distance Between Gate-Drain (L_{GD})</td>
<td>2.7 µm</td>
</tr>
<tr>
<td>Distance Between Source-Gate (L_{GS})</td>
<td>0.8 µm</td>
</tr>
<tr>
<td>Gate- Discrete Field Plate Distance (L_{CFPD})</td>
<td>0.9 µm</td>
</tr>
</tbody>
</table>

Normally, [21]Al_{x}Ga_{1-x}N system is used material for the fabrication of the heterojunction devices is Al_{x}Ga_{1-x}N material where x denotes mole fraction. Furthermore by tuning the mole fraction of Aluminum and Gallium, some material properties can be determined. Certain properties are determined by the mole fraction. In concern with the bandgap, conduction band gaps are bifurcated into three namely Gamma, L, and X totally depends on mole fraction. Valleys of conduction band:

\[
E_g = EG300+x.composition^*0.574+0.055*x.composition
\]

\[
E_g = 1.734+x.composition^*0.574+0.055*x.composition
\]

\[
E_g = 1.911+x.composition^*0.005+0.245*x.composition
\]

Where, x.composition is fraction of mole when temperature is 300K and EG300 is band gap of the aluminium stated in the REGION statement. The band gaps are also depend on the temperature and mathematically formulated as follows:

\[
E_g(T) = EG(300) + EGALPHA \times \left(\frac{T}{300} + EGBETA\right)
\]

The value of EG(300) are considered as the minimum of E_g(T). However, dielectrics Permittivity constant of the material is calculated as follows:

\[
\varepsilon_{AlGaN} = 13.8 + 2.9 \times x.composition
\]

For the simulation process, GaN was characterized by, an electron energy gap of 3.5 eV, an electron mobility of 1200 cm²/Vs, an electron affinity of 4.0 eV, a permittivity (\(\varepsilon\)) of 8.9, a density of conduction band is 2.23x10^18 cm⁻³, density of valence band is 2.51x10^18 cm⁻³ and an electron saturation velocity of 2.5x10^7 cm/s.

![Discrete Field Plate](image)

**Interface two different material with different Energy Band Gap**

![Discrete Field Plate](image)

**Apply Gate voltage**

![Discrete Field Plate](image)

**Current starts flowing from Source to the Drain which is forming at interface of two materials**

![Discrete Field Plate](image)

**At Equilibrium state, Fermi level is constant AlGaN band goes up and GaN band goes down results in jump in conduction**

![Discrete Field Plate](image)

**Formation of 2 Dimensional Gas (2-DEG)**

![Discrete Field Plate](image)

**Effects on high Mobility of electrons**

![Discrete Field Plate](image)

**High Electron Mobility Transistors (HEMT)**

Furthermore, specific electrical properties were employed for the proposed HEMT device, a permittivity (\(\varepsilon\)) of 8.8, a density of conduction band is 2.71x10^18 cm⁻³, an electron affinity of 3.41 eV, an electron mobility of 300 cm²/Vs, an electron saturation velocity of 1.1x10^7 cm/s. Gap in energy is 4.9 eV, density of valence band 2.06x10^15 cm⁻³ mole fraction (x) is 25% for Al_{x}Ga_{1-x}N cap. The simulation was conducted using Silvaco TCAD software, and the working
mechanism of the AlGaN/GaN HEMT is elucidated in Figure 2. Indicates the operational phenomenon of the device.

III. SIMULATION PHYSICAL MODELS [21]

Utilization of Silvaco TCAD software is done to simulate the proposed HEMT device. Different models are taken into consideration by mentioning MODELS and IMPACT statements while simulating the present device. Certain parameters represented by terminologies such as MODELS, MATERIALS, IMPACT and MOBILITY are categorized in different classes: recombination, mobility, impact ionization carrier statistics and tunneling. Model SRH (Shockley-Read-Hall recombination) is considered. SRH recombination model is function of both electrons and holes lifetime $\tau_p$ and $\tau_n$ respectively, temperature, trap energy level $E_{trap}$ [21]

$$R_{SRH}^{net} = \frac{n - n_{ie}^2}{\tau_p \left[ p + n_{ie} \exp \left( \frac{-E_{trap}}{KT} \right) \right]} + \frac{\alpha \left( \frac{\beta}{\alpha} \right)}{\tau_n \left[ p + n_{ie} \exp \left( \frac{-E_{trap}}{KT} \right) \right]} \left( \frac{T}{300} \right)^{3/2}$$

The Mathematical representation of mobility model $\mu_0(T, N)$ is as follows [22]:

$$\mu(T, N) = \mu_{min} \left( \frac{T}{300} \right)^{3/2} + \frac{(\mu_{max} + \mu_{min}) \left( \frac{T}{300} \right)^{3/2}}{1 + \left( \frac{N}{N_{ref}} \right)^{1/3} \left( \frac{T}{300} \right)^{1/3}}$$

Where, lattice temperature is denoted by $T$ where as $N$ denotes total doping concentration, $\alpha$ is ionization rate. Mobility of electrons and holes are referred with the equation of ALBRECHT MODEL where ALBRECHT.P and ALBRECHT.N are elaborated as [23]:

$$\frac{1}{\mu_0(T, N)} = \frac{AN.ALBRECHT.P}{NON.ALBRECHT} \left( \frac{T_L}{TON.ALBRECHT} \right)^{-3/2}$$

$$\ln \left[ 1 + 3 \left( \frac{T_L}{TON.ALBRECHT} \right)^2 \left( \frac{T_L}{TON.ALBRECHT} \right)^{-2/3} \right]$$

$$+ B.N.ALBRECHT \times \left( \frac{T_L}{TON.ALBRECHT} \right)^{3/2}$$

$$+ C.N.ALBRECHT \times \exp \left( \frac{CN.ALBRECHT}{T_L} - 1 \right)$$

To get convergence in quadratic type, the equation of resultant to maintain fine matching method of Newton is being used.

IV. RESULTS & DISCUSSIONS

A. Effect of variation in GaN barrier (gb) layer

In this work, The GaN barrier layer is assorted from 0.05 mm till 0.25mm by steps of 0.05mm and examined the I-V characteristics Electron concentration versus channel position, Diagram of Energy of Conduction band, Electric Field, Capacitances between two electrodes namely Gate-Source and Gate-Drain, Y-Parameters and Gain as follows.

B. Drain current verses gate voltage

Figure 3 represents device’s the current(I)-voltage(V) characteristics. However, to optimize the device one needs to check the drain current electrical property of the device. Initially, thickness of the GaN barriers layer is kept at 0.15 mm (Let’s say Mid-point) and drain currents is noticed. Further in this phase the obtained current of drain ($I_D$) of 0.123A/mm, the just for the validation we have varied the thickness of the GaN barrier layer two points left to the mid-point and two points right to the mid-point. It has been observed that as the GaN barrier layer goes on increase, the drain current also increases. The respective thickness and drain currents for different cases are GaN barrier (gb) layer ($I_D$), 0.05mm (0A/mm), 0.10mm (0.08A/mm), 0.15mm (0.13A/mm), 0.20mm (0.16A/mm), 0.25mm(0.18A/mm). Hence, Maximum drain current ($I_{Dmax}$) is 0.18A/mm that is improved by 0.119A/mm (0.061A/mm(Conventional HEMT)[19] when the gb later is 0.25mm kept. Moreover the GaN later of 0.05 mm is neglected for finding the further results.

C. Electron Concentrations

In Figure 4, The recorded electron concentration in accordance with channel position of device is being shown which offers electron concentration for different dimensions of the GaN Layer:gb=0.10mm at channel position 0.28µm and 0.54µm are -58e/cm³ and -84e/cm³ respectively. Moreover, 0.28µm and 1.02µm are -47 and -96.12e/cm³ respectively for gb=0.15mm; -0.48µm and 3.08µm are -48.9 and -84.12 e/cm³ respectively for gb=0.20mm. 0.8µm and 3.02µm are -34 and -23e/cm³ respectively for gb=0.25mm.GaN barrier thickness is proportional to the electron concentration.
D. Conduction Band Energy (CBE)

Figure 5 shows the conduction diagrams for the different GaN layer dimensions. For gb=0.10mm, CBE (Channel position(CP)) 37eV(0.3µm) and 6.0eV(0.5µm), For gb=0.15mm, 17.01eV(0.38µm) and 9.99eV(0.98µm), For gb=0.20mm, 17.23eV(0.5µm) and 6.13eV(3.08µm ), For gb=0.25mm, 6.7eV(0.2µm) and 18.15eV(0.9µm).

E. Electric Field

Electric Field (EF) for gb=0.10mm, gb=0.15mm, gb=0.20mm and gb=0.25mm are found such as 48.28 ×10^3 V/mm (CP=0.32), 53.19×10^3V/mm (CP=0.28), 95.85×10^3 V/mm (CP=0.2), 96.81×10^3V/mm (CP=0.28). Hence it can be clearly stated that electric field is directly proportional to the GaN barrier as shown in following Figure 6.

F. Gate –Source and Gate –Drain Capacitance

Capacitance is categorized in two regions namely; the capacitance between gate and source (Cgs) and capacitance between gate and drain (Cgd) are taken. The effect on capacitance of two regions are investigated when change in GaN barrier layers are done. Figure 8 and Figure 9. Shows the capacitance-voltage (C-V) curve of two regions Gate-Source and Gate-Drain respectively. Cgs and Cgd for gb=0.10mm are 1.60×10⁻¹¹F/mm and 1.3×10⁻¹¹F/mm respectively. 1.82×10⁻¹¹F/mm and 8.9×10⁻¹¹F/mm for 0.15mm are obtained Cgs and Cgd respectively. Similarly for gb=0.20mm Cgs is found as 1.71×10⁻¹¹F/mm and Cgd is 4.71×10⁻¹¹F/mm. At last, 1.7×10⁻¹¹F/mm is simulated value of Cgs and 4.72×10⁻¹²F/mm is the obtained value of Cgd for gb=0.25mm.
Fig. 8. Gate–Drain Capacitance

G. Y-Parameter for different GaN Barrier (gb) dimensions

In order to validate for the optimization of the device, we have found the parameter of the device for varying the later dimension of the barrier. Initially, gb layer is kept at 0.10mm and then increased by the step of 0.05mm. The simulated results are mentioned in four cases:

Case I: gb=0.10mm; Y_{11} and Y_{22} are 60.38 ohm and 50.27 ohm respectively. Y_{12} and Y_{21} are -13.48 ohm and -32.67 ohm.

Case II: gb=0.15mm; Y_{11} and Y_{22} are 61.73 ohm and 61.12 ohm respectively. Y_{12} and Y_{21} are -12.42 ohm and -34.04 ohm.

Case III: gb=0.20mm; Y_{11} and Y_{22} are 61.07 ohm and 62.69 ohm respectively. Y_{12} and Y_{21} are -11.02 ohm and -34.13 ohm.

Case IV: gb=0.25mm; Y_{11} and Y_{22} are 60.27 ohm and 64.00 ohm respectively. Y_{12} and Y_{21} are -10.97 ohm and -33.95 ohm. Hence from the result it can be stated that, as the thickness of the GaN barrier increased the Y-parameters also increases. The graphical representations of the all parameters for all the cases are shown in Figure 9, Figure 10, Figure 11, and Figure 12.

Case I: gb=0.10mm  Case II: gb=0.15mm

H. GAIN

Gain is the vital characteristics electrical of the device for insuring the reliable performance of the devices for high power and high frequency applications. Like above here also we have varied the thickness of the GaN barrier layer and noticed the respective gain parameter. The GaN barrier layer is varied from 0.10mm to 0.25mm by the step of 0.05 mm. The obtained simulated results are 78.63dB for gb=0.10mm, 80.83dB for gb=0.15mm, 83.41dB for gb=0.20mm, 83.09dB for gb=0.25mm. Figure 13. shows the gain curve for different GaN barrier layer.
and mobility as well offers performance of the transistor [26]-[27] in positive manner.

The current conduction gets interrupted at the interface of layer of Si/ Aluminum Nitride due to 2DEG modulation [28]. Aluminum Nitride Nucleation layer is varied Initially layer is from 100mm to 400mm by the steps of 100mm. Secondly, same layer is kept at 50mm for clarity in optimization and focused on the I-V characteristics. In this case we have taken GaN barrier layer of 0.25mm and AlGaN barrier layer is of 36nm (Obtained Maximum drain current (I_D)). Simulated results for I-V characteristics for Aluminum Nitride nucleation layer are shown in Figure 15 as follows. We have found that change in Drain current (I_D) in accordance with the applied voltage is extremely very negligible. Even thought if we discuss about slight change in I_D we need to take the consideration of threshold voltage (V_TH) as well. When AlGaN barrier layer is kept at 200nm the highest threshold voltage is recorded for that stage and later it goes on decreasing manner for AlGaN barrier layer at 300nm, 400nm, 100nm, and 500nm as shown in following Figure 15. The maximum threshold voltage is -0.86V for AlGaN barrier layer is 200nm. At last we have shown the structure file generated in Silvaco TCAD software by Figure 16. The structure contains different layers such as Si:N, AlGaN Cap layer, Aluminum Nitride spacer, GaN barrier AlGaN channel, Aluminum Nitride Nucleation layer and 4H-SiC Substrate from top to bottom.

Fig. 13. Gain verses Frequency

I. Effect of variation in GaN barrier layer

In [24], AlGaN barrier layer has been taken into the consideration for increment of HEMT device’s the electrical characteristics by varying Al content. The AlGaN barrier layer is changed from 0.6mm till 4.6mm with steps of 1 mm and noticed the I-V characteristics. In this case thickness of the GaN barrier later is 0.25nm (Obtained Maximum Drain current). Figure 14. shows I-V characteristics for different AlGaN barrier layer. There is Slight change in drain current in accordance with voltage across gate as shown in following Figure 14. I_D (AlGaN Barrier Length) = 0.181A/mm(6mm), I_D=0.184(16mm), I_D=0.180(26mm), I_D=0.186(36mm) and I_D=0.182(46mm).

Fig. 14. Drain current verses gate voltage

J. Effect of variation in Aluminum Nitride Nucleation layer

The impact of introducing a thin Aluminum Nitride spacer layer is also investigated [25]. Aluminum Nitride spacer layer induced to the simultaneous progress in electron density
V. CONCLUSION

With respect to AlGaAs/ GaAs HEMTs, the AlGaN/GaN HEMTs reflects better electrical characteristics for both high power and frequency applications. A 200-nm-thick mesa isolation has been formed by Cl₂/BCl₃-based inductively coupled plasma reactive-ion etching (ICP RIE) at 18/sccm for the flow rate Cl₂/BCl₃ with a process pressure of 5 mTorr [29] for the fabrication process of AlGaN/GaN layer HEMT. With respect to the cost effectiveness and performance Si based HEMT fabrication process double surface passivation, and post-gate annealing processes has been taken into the consideration [30]. In present study, the addition of spacer as Aluminum Nitride layer of Nucleation with cap as AlGaN and barrier of GaN AlGaN/GaN based HEMT. If fabrication is done with vapour deposition (MOCVD) with metal organic chemical via the growth of certain epitaxial layers does not affect in fabrication process [31]. To protect the AlGaN surface damage and to mitigate the distortion related phenomenon SiN layer has been deposited for the protection [32].

The registered drain current after simulating the proposed HEMT device by considering the electrical properties of AlGaN/GaN is 0.18A/mm which shows the remarkable improvement of 0.119A/mm, indicates compatibility of handling high current. The approached highest value of Electron Concentration obtained is at 96.12electrons/cm³, with respect to the channel position for 0.15mm thickness of GaN Barrier. To signal amplification, the Maximum Unilateral Power Gain and Electric Field measuring is observed at 83.41dB and 96.51×10⁵V/mm respectively. Furthermore the capacitance between gate and drain region (C_GDMN) is 4.7×10⁻¹²F/mm where the quantified capacitance between gate and source region (C_GSMN) is at 1.7×10⁻¹¹F/mm. Y parameters, gives the performance of the device at various operating frequencies, are also acquired. Simulated obtained results gives validation of electron density and mobility are the major factor influences the transistor performance and is enhanced by the addition of Aluminum Nitride layer in the structure of the device [33]. Therefore presented device has ability to operate at high power applications [34] with higher temperature too. In order to model HEMT device, TCAD Silvaco simulation software is inclined.

VI. FUTURE SCOPE

After working on this device, it is found that gain has to be increased. In addition to that, drain current can also be increased by using different methodology such as Gate Engineering or High-K techniques with the fact that the device design is compact in nature. Such device can be used and incorporates into the compact system for applications of higher power and higher frequency.

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