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ALGaN/ GaN Based HEMT Using Double Gate with Field Plate for Microwave Power Applications

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Abstract

Recently semiconductor devices play a significant role in high-power applications due to the critical feature of the hetero-junction structure. In comparison to AlGaAs/ GaAs, AlGaN/ GaN High Electron Mobility Transistors (HEMT) offer more advantages such as high-speed switching.

This article presents Double Gate-Field Plate (DP-FP) AlGaN/ GaN HEMT. Different electrical parameters such as Drain Current, Conduction band energy, Electron Concentration, transconductance, Gate-Source capacitance and Cut-off frequency are investigated. After Simulation DP-FP HEMT offers maximum drain current I_{DMAX}=0.23A/mm (Improved by 35.2941%), Electron Concentration 3 $\times 10^{19}$ (cm-3) (Improved by 66.6667%), Furthermore conduction band energy is 5 eV (Improved by 100%), transconductance 0.16 S/mm (Improved by 32.1453%), Gate-Source capacitance 3.5 $\times 10^{-13}$ F (Improved by 60.0000%) and Cut-off frequency 800 GHz (Decremented by 11.1111%). Cut-off frequency needs to be improved in future scope. Silvaco TCAD software is used for the simulation of the device.

Keywords: AlGaN, GaN, HEMT, Electrical Characteristics

1. Introduction

In current days, High electron mobility transistors (HEMTs) are trending in electronics device design field for microwave communications, high speed, and high power and frequency applications. HEMTs are the replacement of conventional field effect transistors (FETs) with tremendous features as high power applications. The two-dimensional electron gas (2-DEG) is the heart of principle of working of the HEMT device lie at the hetero-interface. Two different band gap materials are aligned. When voltage supply is given to the higher band gap material, conduction band of higher band gap material bends bellow the Fermi level to form 2-DEG. AlGaAs/GaAs HEMTs are highly preferable now a days for the operation at high frequency applications with good electrical properties such as high saturation velocity of the electrons and breakdown voltage as well [1]. Electron layers are present at the junction of hetero interface and it is pointed [2]. Furthermore, researchers have worked on the reduction of scattering of the charge by separating free electrons and ionized impurities [3]. The most critical part is Fermi-Level linearity nature the consideration during quantum well for analytical analysis of HEMT models [4]. Figure 1 shows a HEMT device model. The hetero structure is formed at the interface between GaAs and AlGaAs which are smaller and larger bandgap material respectively. Impurities are added to the wideband gap material AlGaAs with density of doping n = 7 × 10^{17} cm^{-3}.Therfore media is created near to AlGaAs/ GaAs heterojunction. Undoped material of AlGaAs tiny layer is acted to mitigate the scaterring of charge which can be utilized as a layer of spacer. Finally, a layer as a substrate of material GaAs or Si is placed [5]. The major role of the band nature in terms of not continuous at valance and conduction band is modulated for controlling the carries in and out of the device. The amount of carries gives positive rise in the electrons collection at both regions edge in the material of compressed band. The electrons collection increases the high current in such devices. The Current-Voltage AlGaN/GaN HEMT characteristics shows increase charge control [6].

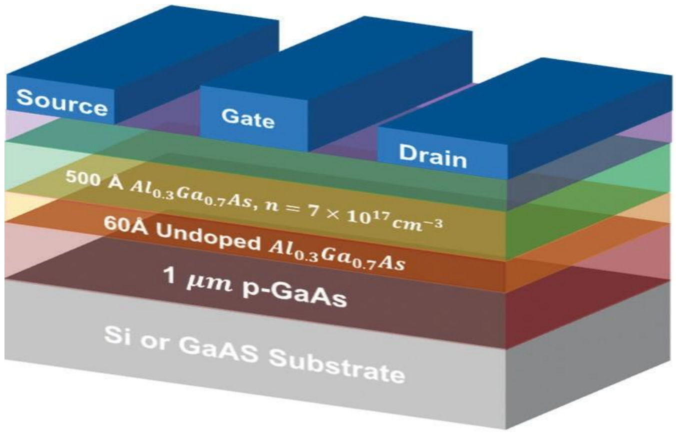

Figure 1. A HEMT device model

In research work [7], Suggested AlGaN/GaN HEMTs as a physics- based analytical model for 2 DEG density. Furthermore two major aspects compact and current collapse are shown for AlGaN/ GaN HEMTs with I-V characteristics [8]. In addition one more aspect to improve the device performance is parasitic component of the capacitance of the AlGaN/GaN HEMT device [9]. One of the ways for analysis of multi-layer HEMTs structure electrical parameters is done by using thermal model shows the thermal effects. Thermal effect is generated by placing the heat source in the layers. Moreover Analytical analysis is done by using Furrier series solution additionally validation is completed with the Raman thermography spectra [10]. More inventions are done in HEMTs devices to improve the performance of the HEMTs devices such as by modulation of 2 DEG [11], by utilizing Double Channel to improve density of 2 DEG and carrier concentrations [12]. Some models for writing equation in Newton's method are invented namely Drift-Diffusion Model and Loret's model [13], energy-transport model [14] with the limitations, The models are not able to rise the performance at the submicron level of the gate device and due to the hot electron effect respectively. Furthermore above limitations are overcome by the Monte Carlo as it offers novel insights in the device with the creation of option to increase the performance of the device [15]. The GaN HEMTs depletion mode takes the place of PIN diodes. In the PIN diode, Q-spoiling is done which is not applicable for the GaN HEMTs [16]. GaN HEMTs can be offered practically with 600 V due to the attractive features in concern with the Silicon based transistors (IGBTs and MOSFETs). Hence a HEMT switch offers extra-ordinary performances in comparison with the Si based MOSFETs [17].

The major applications of 2DEG-based HEMTs devices are multiplication and mixing of the frequency and detection of Tetra-Hertzs [18]. There are the chances of designing sensors with the help of GaN based HEMT structure and freestanding resonators are utilized for the measurement of temperature, viscosity and pH value [19] additionally, detecting gases, ions, and chemicals [20]. Such technologies are widely used in variety of domain/ systems namely bread manufactory, farming, hygienic, environment discipline, literacy department, transport systems and smart city systems. In the era of commercial too, HEMTs are in front for the vital role in A low-noise down-converter with three GaAs MMIC chips and a 0.25 pm HEMT. Such system offers a gain of 62 dB in the frequency range from 11.7 GHz to 12.2 GHz and noise figure less than 1.3 dB [21]. Most importantly, the utilization of microwave equipment is done in the space applications. Due to the additional need of security from dangerous atmosphere at the space for survival, such equipment became too expensive. Furthermore, at the time of launching the spacecraft, equipment must be able to survive without any damage at extreme levels of shocks and vibrations. In such situations HEMTs are fabricated.

2. Device Geometry Discussion

The cross-section schematic of the AlGaN/ GaN based HEMT using Double Gate in addition of Field Plate structure is showed by Figure. 2. Progress of proposed device can be stated such as the device structure has 100 nm GaN channel layer and 0.1 μm Si_3N_4 passivation layer. Upper barrier layer is AlGaN with 23 nm placed with 31% composition. Device DC and RF performances are presented.

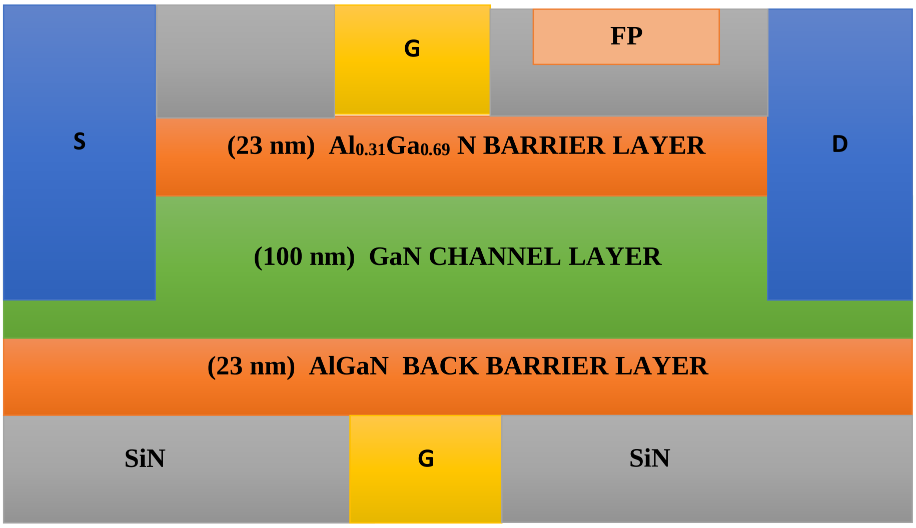

Figure 2. Proposed DG-FP AlGaN/ GaN HEMT device.

Further, an AlGaN back barrier layer of 23 nm is used to improve the carrier confinement in the channel. Schottky gate contact is used for both the gate having gate length 0.4 µm and 0.1 µm widths. Field plate is placed between gate and drain at a distance of 0.4 µm from gate. Considered Field plate Length is 0.4µm. Source/Drain length of the device is 0.1 µm and the distance between source and gate is 1.1 µm. In Table I, indicates the physical properties of wide band gap $Al_{0.31}Ga_{0.69}$ N/ GaN and narrow bandgap GaN material. During simulation at TCAD of proposed device ohmic/Schottky contacts has to be considered. Electrodes Drain/Source and Gate has work function 3.8eV and 5 eV respectively. Model is used for simulation of proposed HEMT AlGaN/GaN based structure is described in the next section.

Table 1: Electrical Properties of different material [22].

Material	Si	4H-SiC	GaAs	InP	GaN
$E_g(eV)$	1.1	3.26	1.4	1.34	**3.4**
$E_c(MV/cm)$	0.3	2.0	0.4	0.5	**3.3**
$n_i(/cm^3)$	1.5×10^{10}	8.2×10^{-9}	2.1×10^{6}	1.3×10^{7}	$\mathbf{1.9\times 10^{-10}}$
ε_r	11.8	10	12.8	10	**9.0**
$\mu_n(cm^2.V^{-1}.s^{-1})$	1350	720	8500	5400	**900**
$v_{sat}(10^7\ cm/s)$	1.0	2.0	2.0	0.9	**2.5**
$k(W.cm^{-1}.K^{-1})$	1.5	4.5	0.5	0.68	**1.3**

Where, E_g:Band gap energy, E_c:Breakdown electric field,ε_r:Relative dielectric constant, n_i:Intrinsic carrier generation rate, μ_n:Electron mobility, v_{sat}: Saturated drift velocity of electron, k : Thermal conductivity.

HEMT Technology has advantages such as High Linearity, Faster, Smarter and More Efficient

3. Simulation Models

Recombination Models, Mobility model, Polarization and carrier models are used in proposed HEMT device for the simulation in Silvaco TCAD simulator

$$P_{total} = [(bottom) + P_S(bottom)] - [P_{PE}(top) + P_{SP}(top)] \quad \text{………………(1)}$$

Models as a Shockley-Read-Hall (SRH) [22] for recombination and Trap state is used to capture the phonon transition in forbidden band gap. Newton Raphson is used for solving simulation iteration. Newton method is used to achieve the best matching between the resultant equations for the proposed work which offers convergence in quadratic manner.

4. Results And Discussions

4.1 Drain Current verses Gate Voltage

In order to improve the drain current different techniques has been implemented by modifying the negative differential conductance (NDC) [23], by adding source field plate structure near gate [24]. Comparison between Single and Quantum Well has been introduced such as the double quantum well HEMT structure performs greater for high power GHz frequency application than single quantum well HEMT structure [25]. Furthermore Simulation study of DC characteristics of double quantum well AlGaN/GaN double gate HEMT structure is introduced for high power applications. [26-27]. Effect of barrier layer thickness on AlGaN/GaN Double Gate MOS-HEMT device is utilized for high-Frequency application. AlGaN/GaN Double Gate MOS-HEMT device Offers great gate control, therefore change in barrier thickness layer has become key-parameter between drain current and electrostatic gate control [28]. The performance of the HEMT degrades as temperature increases [29]. 2D Simulation Study of DC and RF Characteristics of Double Heterostructure AlGaN/GaN DG-HEMT Device for High-Frequency application are investigated using Silvaco TCAD Software [30-31], Refer Figure 3: To get the drain current with respect to the gate voltage, we have kept drain voltage constant equal to 1V and simultaneously we have increased gate voltage in negative direction from 0V to -4V with the step of 0.1V. Obtained the maximum drain current is 0.209 A, Percentage Improvement in drain current is 39% with respect to conventional HEMT [32]. The contact between gate and AlGaN barrier is schottky contact so the increases in electron density in the channel. Carrier concentration in the channel is less when the gate voltage is less than or equal to the threshold voltage (-2.8V) ultimately the drain current is null as shown in figure 3.

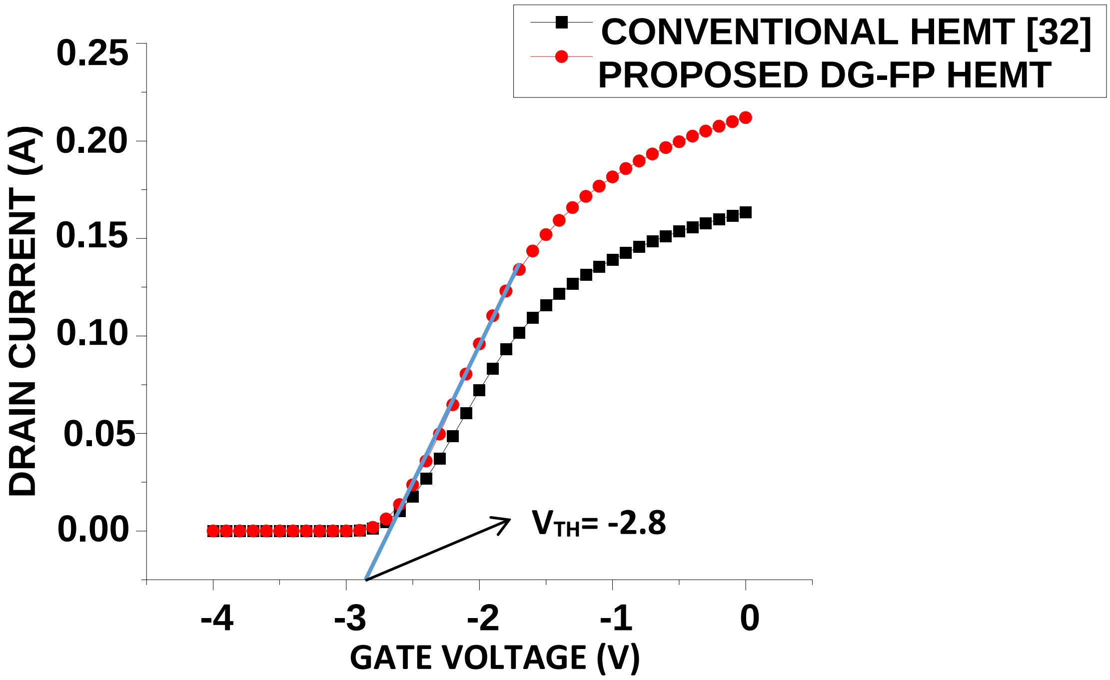

Figure 3. Drain Current versus Gate Voltage

4.2 Structure File of DG-FP HEMT

Different types of files are supported by Silvaco TCAD software such as command file, log file, solution file and structure file. To get the structure file of the proposed DG-FP HEMT, we have considered all the electrical characteristics of the AlGaN / GaN materials with the device parameters mentioned in above sections 2 in command window. Hence after simulation we have got the structure file as shown in following Figure 4 which consists of different layers.

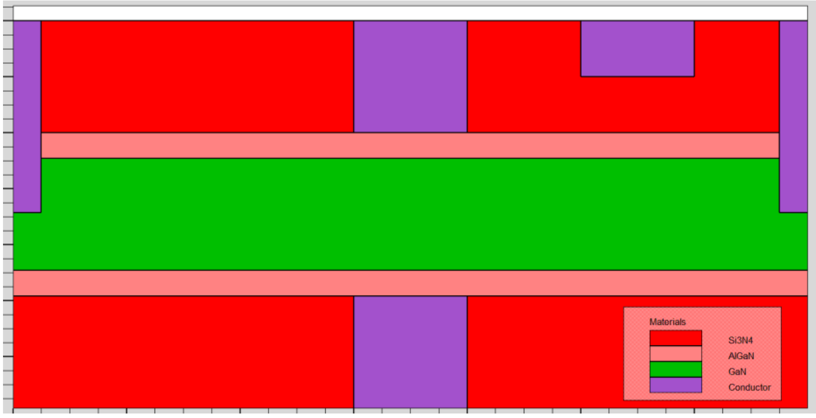

Figure 4. Structure of the Proposed DG-FP HEMT device

4.3 Conduction Energy Band Diagram and Electron Concentration

Figure 5 presents Conduction band Energy and Electron Concentration with respect to the channel position. 2DEG is formed at the channel with high electron concentrations.

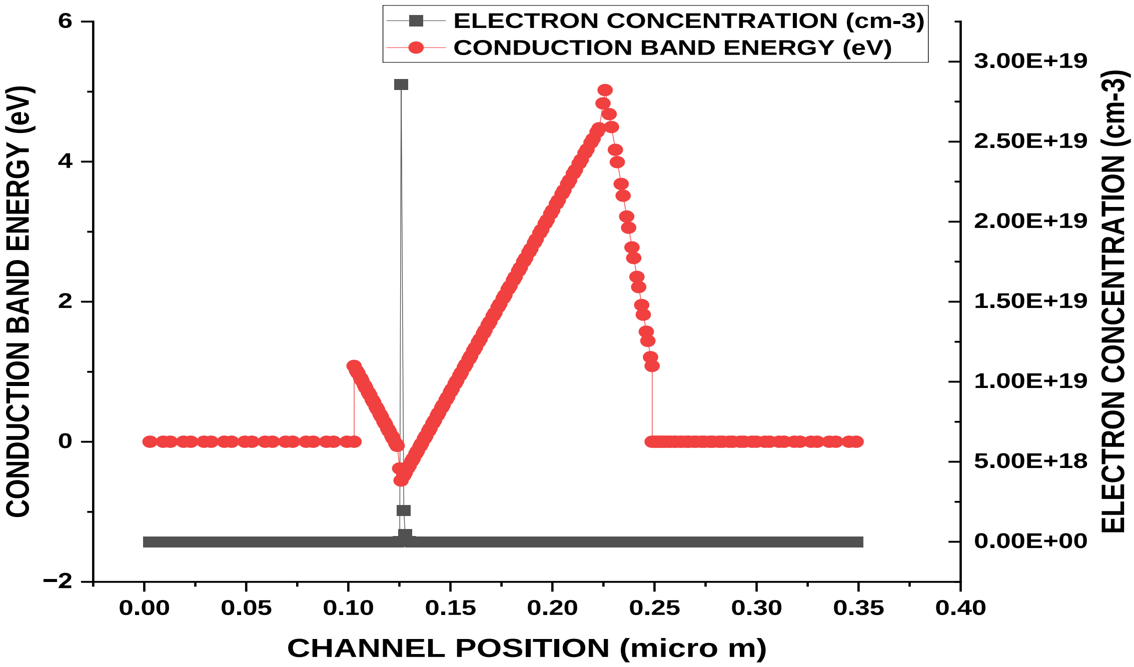

Figure 5. Conduction band Energy and Electron Concentration

4.4 Transconductance versus Gate Voltage

As shown in Figure 6 it has been observed that change is gate voltage changes are observed in trancondantance. In concern with the CMOS applications greater value of the transconductance is recommended. After simulation it is found that with addition of the field plate in HEMT Double Gate – Field Plate High Electron Mobility Transisitor (DG-FP HEMT) 32.1453% improvement in transconductance with a fine peak at gate voltage -2.1V

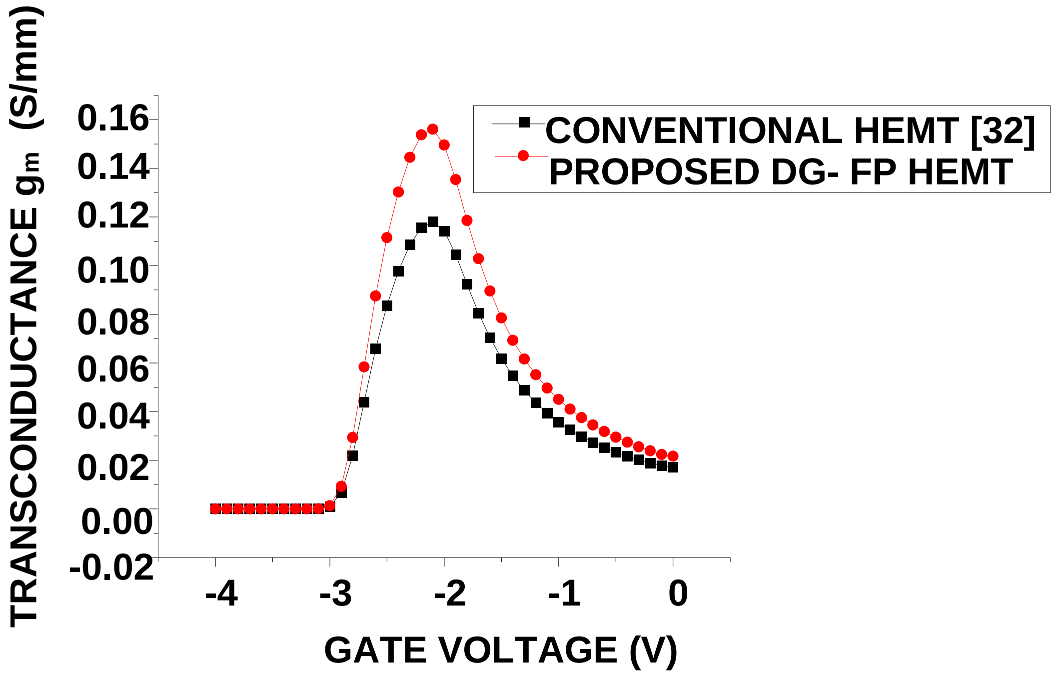

Figure 6. Transconductance versus Gate Voltage

4.5 Gate- Source Capacitance versus Gate Voltage

For AlGaN/GaN HEMT, The Calculation of gate capacitance with parasitic component is presented by Zhang et al. [33]. A calculation of density of sheet charge and capacitance can be obtained by calculating control equations for charge additionally using surface charge potential concept respectively. The simulated result using Silvaco TCAD software tools are shown in Figure 7. It has been observed after simulation that the value capacitance between gate and source is 3.5×10^{-13} F (0.35pF) remain constant after -1.7V which is greater than the conventional HEMT [32] 2.6×10^{-13} F (0.26 pF).

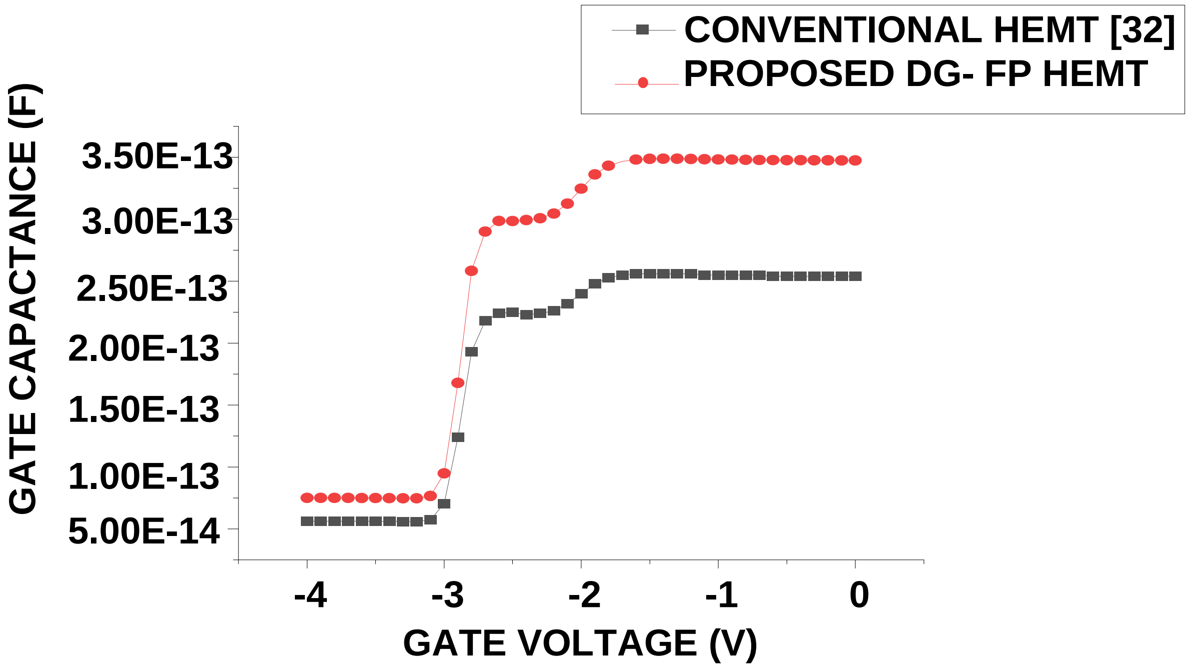

Figure 7. Gate-Source Capacitance versus Gate voltage.

4.6 Cut-Off Frequency versus Gate Voltage

Cut-off frequency f_T has a greater significance in RF characteristics in HEMT device modelling. In this work is has been obtained that gate-source capacitance is increased. The frequency and capacitance are inversely proportional consequently cut-off frequency is decreased. In this work obtained cut off frequency is 800 GHz for DG-FP AlGaN/GaN HEMT shown in Figure 8. Cut-off frequency is the highest frequency at which device is capable for current amplifications. It is calculated by [34]

$$f_T = \frac{g_m}{2\pi C_{gs}} = \frac{v_{sat}}{2\pi L_g} \quad \text{.................. (2)}$$

Where, $C_{gs} =$ Capcitance between Gate and Source, $v_{sat} =$ Saturation Velocity, $g_{m=}$Transconducatnce and $L_g =$ Gate Length

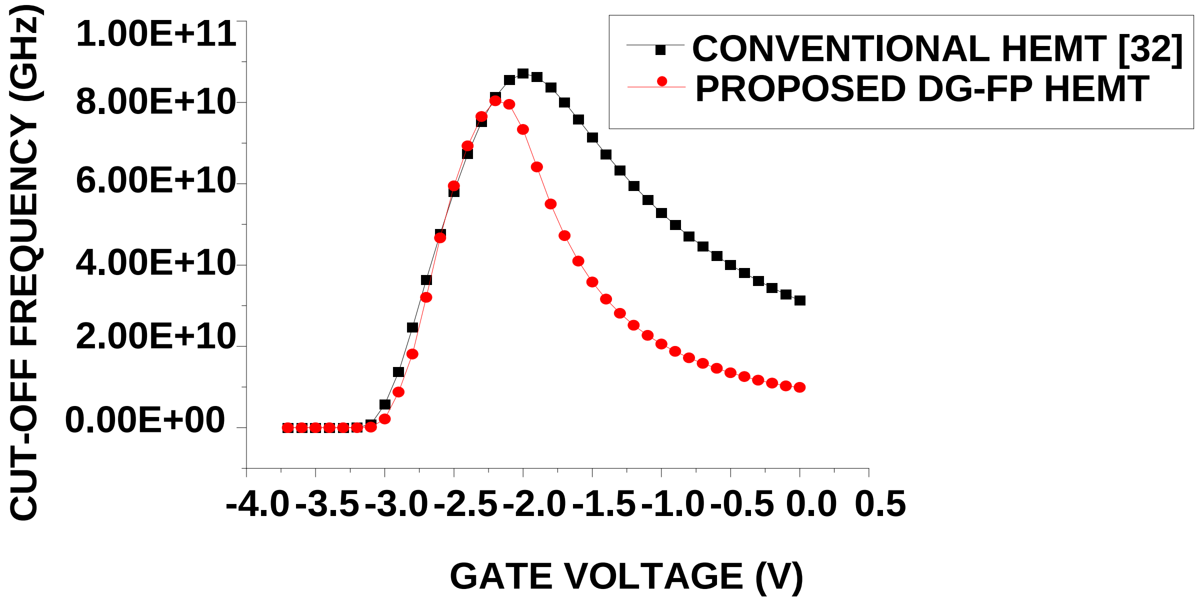

Figure 8. Cut-off frequency versus Gate Voltage.

4.7 Total Current Density

Furthermore, the total current density obtained is 26794726.6 A/ m² at the channel position 0.12 micro meter as shown in Figure 9.

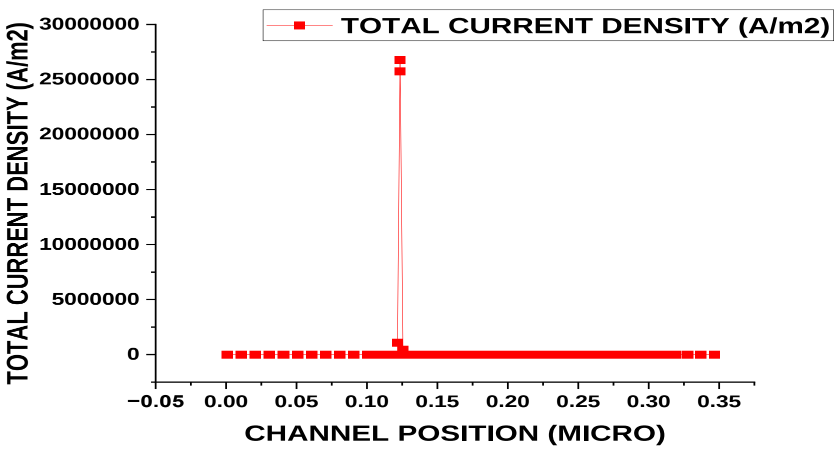

Figure 9. Total current density versus Channel position

As shown in Figure 9 total current density 26794726.6 A/ m² at the channel position 0.12 micro meter. Gain of the HEM devices gives maximum amplification of the high frequency signal ultimately produces less distortion promotes low noise. Maximum gain is 140.42 dB at 10 KHz as shown in Figure 10. As shown in Figure 11. Larger electric field is present in HEMT device results into less amount of current flow through the gate electrode. The Gate current offers the reliability and the functioning of the device. To optimize the device gate leakage current must be as less as possible because Gate current normally leads to the self-heating and lifetime of the device. Gate leakage current is very small -1.2×10^{-15} V when -4 V gate voltage is applied and goes on increasing linearly with rise in gate voltage. Simulation can be extended for achievement of Y parameters such as Y_{11}, Y_{12}, Y_{21}, and Y_{22} to insure the performance of the device for microwave applications. The Simulated results are 8.38 mho/mm, -1.950 mho/mm, -6.853 mho/mm, and 10.7395 mho/mm at 5×10^{10} Hz for Y_{11}, Y_{12}, Y_{21}, and Y_{22} respectively as shown in Figure 12. By referring Figure 13, Maximum Gate-Source Capacitance is of -1.5×10^{-13} F at a gate voltage of -4 V. Figure 14 shows the breakdown voltage graph which clearly interpreted as breakdown voltage (V_{BR}) is 350 V at 1.60 A/mm of drain current.

4.8 Gain versus Frequency

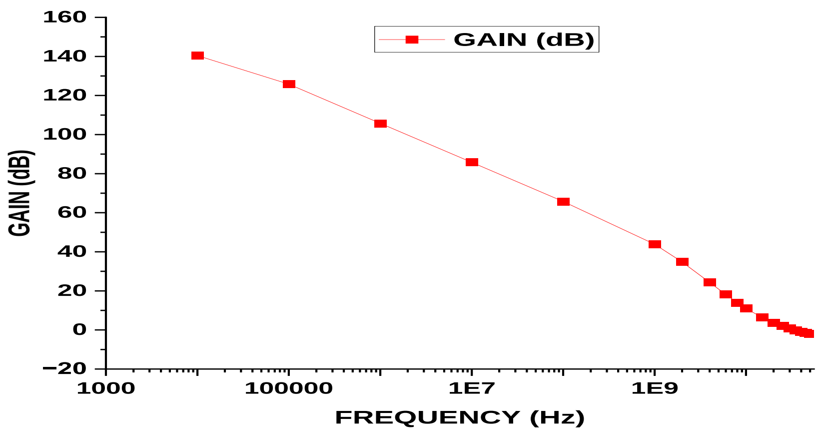

Figure 9. Gain versus Frequency.

4.9 Gate Voltage versus Gate Voltage

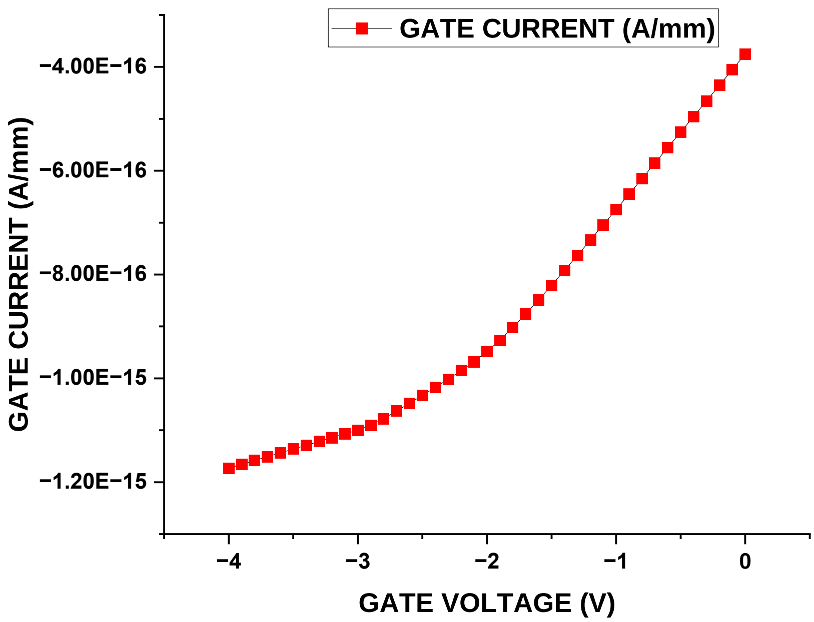

Figure 11. Gate Current versus Gate Voltage

4.10 Y parameters versus Frequency

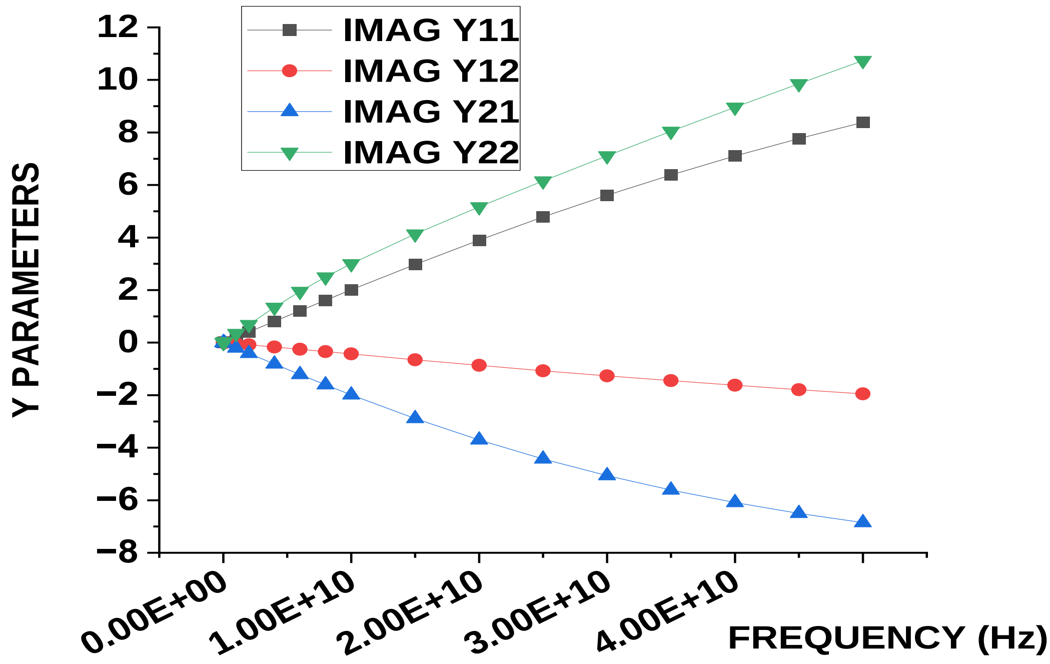

Figure 12. Y parameter versus Frequency

4.11 Gate Capacitance versus Gate Voltage

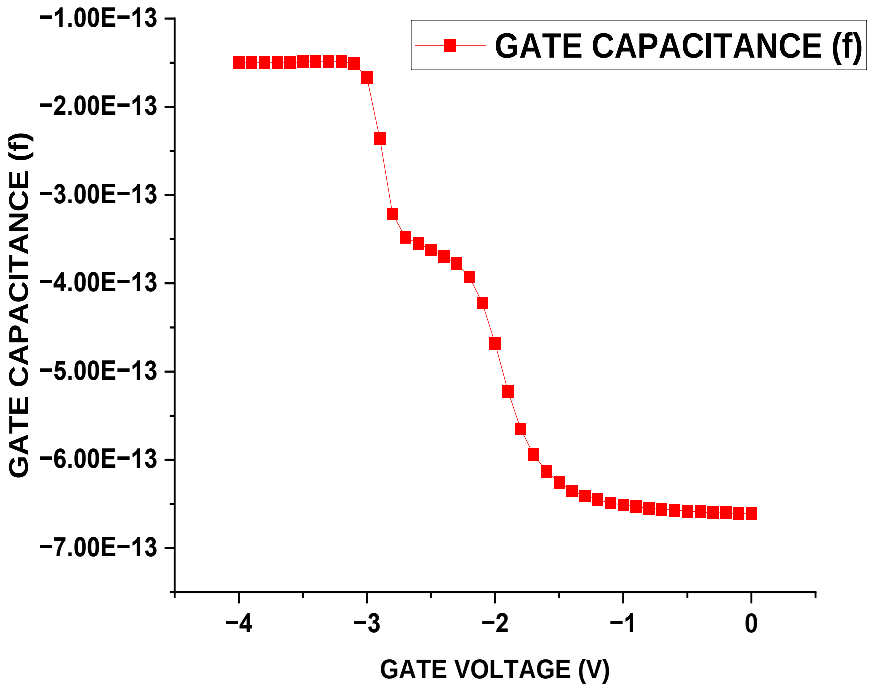

Figure 13. Gate Capacitance versus Gate Voltage

4.12 Breakdown Voltage

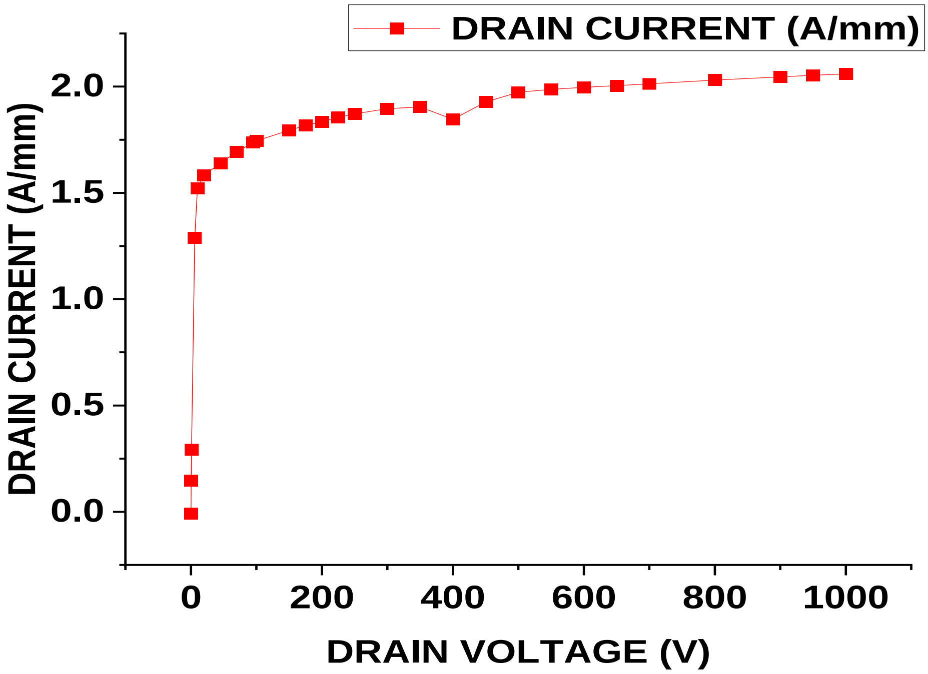

Figure 14. Breakdown voltage of proposed device.

Table 2 shows exact percentage improvement in different electrical characteristics. However decrement in the cut-off frequency has been obtained which need to take the consideration as future scope.

Table 2: Result analysis of proposed device compared with [32].

ELECTRICAL PARAMETERS ↓	PROPOSED ALGAN/ GAN BASED HEMT USING DOUBLE GATE WITH FIELD PLATE	[32]	PERCENTAGE IMPROVEMENT (%) W. R. T. [32]
DARIN CURRENT (A/mm)	**0.20**	0.15	**31.81**
GATE - SOURCE CAPACITANCE ($C_{GS\ MAX}$)(F/mm)	**3.47**	2.5	**39.33**
TRANCONDUCTANCE (g_m)(S/mm)	**0.15**	0.09	**32.1453%**
BREAKDOWN VOLTAGE(V_{BR})(V)	**350 at I_D=1.60 (A/mm)**	-	**INVESTIGATED SOME ADDITIONAL ELECTRICAL CHARACTERISTICS**
MAXIMUM DRAIN VOLTAGE ($V_{D\ MAX}$) (V)	**750**	-	
Y PARAMETERS At 50 GHz Y_{11}	**8.38**	-	
Y_{12}	**-1.95**		
Y_{21}	**-6.85**		
Y_{22}	**10.73**		
GAIN(dB)	**140 dB**		
CUT-OFF FREQUEQY (GHz)	**800 GHz**	850 GHz	**- 11.1111%**

5. Conclusion

This article presents Double Gate-Field Plate (DP-FP) AlGaN/ GaN HEMT. Different electrical parameters Drain Current, Conduction band energy, transconductance, Gate-Source capacitance and Cut-off frequency are investigated. DP-FP HEMT gives maximum drain current (I_{DMAX}=0.209V) After Simulation 39% improvement in drain current, Conduction band energy, transconductance 32.1453%, Gate-Source capacitance 3.5 $\times 10^{-13}$ F. The Total current density 26794726.6 A/ m^2 at the channel position 0.12 micro meter. Maximum gain is 140.42 dB at 10 KHz. Gate leakage current is very small -1.2$\times 10^{-15}$ V when -4 V gate voltage is applied and goes on increasing linearly as the gate voltage increases. The Y parameters simulated results are 8.38 mho/mm, -1.950 mho/mm, -6.853 mho/mm, and 10.7395 mho/mm at 5$\times 10^{10}$ Hz for Y_{11}, Y_{12}, Y_{21}, and Y_{22} respectively. Maximum Gate-Source Capacitance is of -1.5$\times 10^{-13}$ F when -4 V gate voltage. Breakdown voltage (V_{BR}) has been obtained as 350 V at 1.60 A/mm of drain current. Except Cut-off frequency 800 GHz which is suitable for Microwave Power Applications Silvaco TCAD software is used for the simulation.

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Ethical Compliance

This is not Applicable to proposed work

Conflicts of Interest

The authors declare no conflicts of interest.

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