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AlGaN/GaN HEMT on SiC-substrate Using AlN-spacer & Nucleation Layer For Improvement Over-Pinch-Off, Saturation & Breakdown Characteristics

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Abstract: This paper work focuses on the characteristic study of AlGaN/GaN HEMT, depending on some physical parameters of the material used. AlGaN/GaN HEMTs having feature of high saturation current, low pinch-off and hence lower on-resistance and higher switching speed, due to the high electron mobility at the hetero-junction. The high electron mobility is caused by two dimensional electron gas (2-DEG).Analysis suggests that the on-resistance of AlGaN HEMTs is lower than that of SiC FETs, depending on the mole fraction of Aluminum (i.e. Aluminum composition). Device simulation was done on Silvaco ATLAS to analyze into the operation mechanism on different types of GaN HEMTs and shows that the high breakdown voltage devices design is possible with AlGaN/GaN.

Keywords: AlGaN/GaN HEMT, 2-DEG, Pinch-off, saturation, SiC-substrate and Silvaco ATLAS.

I. INTRODUCTION

In present work the different designs are presented and evaluated and the results based on substrate selection are reported. According to our choice of substrate selection, SiC reported better performance than Si. Furthermore in this thesis-work other advantages of individual and combined implementation of AlN nucleation layer and AlN spacer layer were studied separately. In this thesis-work for small signal analysis S-parameters smith chart curve also achieved which shows a close resemblance of maximum oscillation frequency f_{max} and high cutoff frequency f_T [1][2].

II. PROPOSED CONSTRUCTION DESIGN

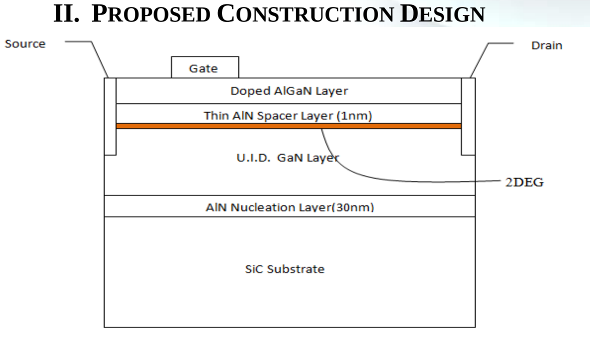

Fig.1: Schematic construction of proposed AlGaN/GaN HEMT

Here a finally proposed simulated device with implementation of both spacer layer of 1nm and Nucleation layer of 30nm with Si substrate and SiC substrate separately with sidewall doping was studied and observation shows a clear improvement in saturation current from 24mA to 30mA and pinch-off voltage rises from -5V to -7v on SiC substrate compared to Si substrate [3], [4]. From these results we can say that, a decreased performance was observed with the use of Si substrate on the device as compared to SiC substrate. Moreover from the result analysis, we can say high saturation current and low pinch-off are the results due to– two dimensional electron gas (2-DEG).

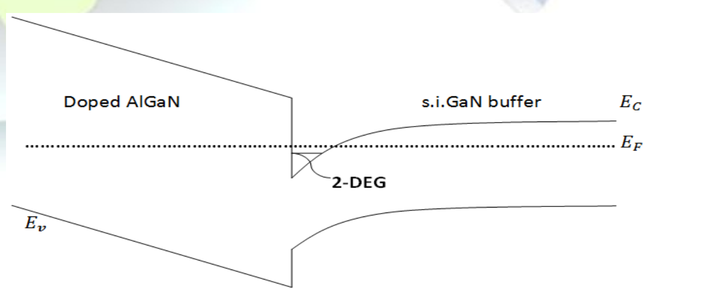

Fig.2: Energy band diagram showing 2-DEG.

As the Fermi level must be continuous over the entire semiconductor heterostructure and due to this energy bands bends and a potential well or an energy valley forms at that heterostructure. In addition to this a potential profile and hence amount of charges induced at the interface in an AlGaN/GaN due

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to its polarization fields, combindly spontaneous and pizoelectrical polarizations, and results phenomena of 2-DEG[7] .

III. INDENTATIONS AND EQUATIONS

Advantages of AlGaN/GaN HEMTs as switching devices:

For power switching-devices or any high-power electronic device, breakdown voltage V_{BR} , on-resistance R_{on} and voltage control ratio $V_{BR}/\Delta V_{control}$ are the important parameters. Low R_{on} is desired for keeping power dissipation as low as possible but, due to the wide band gap of GaN, it is difficult to achieve low-resistance and to trade-off it device doping-level should be increased [5][6].

$$R_{on} = \frac{4{V_{BR}}^2}{\varepsilon_r \mu_n {E_c}^3}$$

Where ε_r is the dielectric constant μ_n is the mobility and E_c is the critical electric field. For the same breakdown voltage, R_{on} of a SiC device could be lower by two orders of magnitude than that of Si.

f_{max} is the maximum frequency at which the transistor still provides a power gain and can be expressed as [1]

$$f_{max} \approx \frac{f_T}{2\sqrt{((R_i + R_s + R_g)/R_{ds} + (2\pi f_T)R_g C_{gd})}}$$

where, f_T is the current-gain cutoff frequency and C_{gd} is the gate–drain (depletion region) capacitance, while R_i, R_s, R_g, and R_{ds} represent the gate-charging, source, gate, and output resistance, respectively.

IV. FIGURES AND TABLES

We can relate different semiconductors by comparing their $\frac{\mu_n}{\mu_p}$ ratio, in which the high value of $\frac{\mu_n}{\mu_p}$ ratio resemble for high frequency i.e. fastest switching application for microwave switching applications.

Table 1: value of $\frac{\mu_n}{\mu_p}$ *ratio* taken as a parameter for different semiconductor material

	Ge	Si	GaAs	GaN
$\frac{\mu_n}{\mu_p}$ ratio	2.1 : 1	2.6 : 1	14.5 : 1	90 : 1

Table 2: shows the fundamental material properties of GaN, SiC, diamond, Si, GaAs, and InP [2].

Property	GaN AlGaN/	Sic	Diamond	Si	GaAs AlGaAs /	InP InAlAs/ InGaAs
Band gap energy, Eg (eV)	3.44	3.26	5.45	1.12	1.43	1.35
Electric Breakdown field, Ec (MV/cm)	3	3	10	0.3	0.4	0.5
Saturated (Peak) velocity electrons, Vsat (Vpeak)(x $10^7 cm/s$)	2.5 (2.7)	2.0 (2.0)	2.7	1.0 (1.0)	1.0 (2.1)	1.0 (2.3)
2DEG density, ns(x$10^{13}/cm^2$)	1.0	N.A.	N.A.	N.A.	<0.2	<0.2
Electron mobility, µ ($cm^2/V.s$)	900	700	4800	1500	8500	5400
Thermal Conductivity, K (W/cm.K)	1.3 - 2.1	3.7 – 4.5	22	1.5	0.5	0.7
Relative Permittivity, ε_r	9.0	10.1	5.5	11.8	12.8	12.5

1. **Comparison of AlGaAs/GaAs HEMT device with AlGaN/GaN HEMT device using different gate lengths:**

GaAs device:-AlGaAs/GaAs HEM construction:

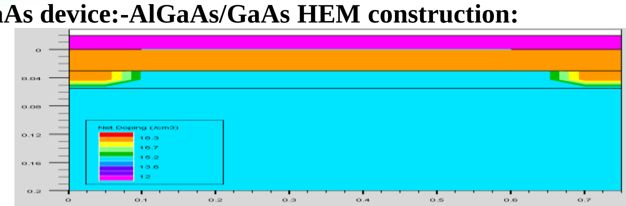

Fig.3: AlGaAs/GaAs HEMT device simulated structure with gate length = 0.5µm, showing doping construction.

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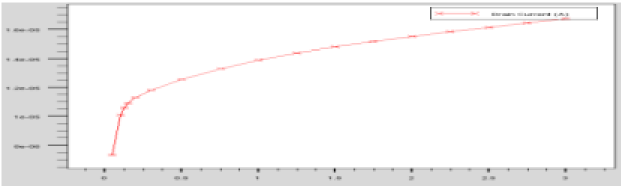

Fig.4: Showing Id Vs Vds curve.

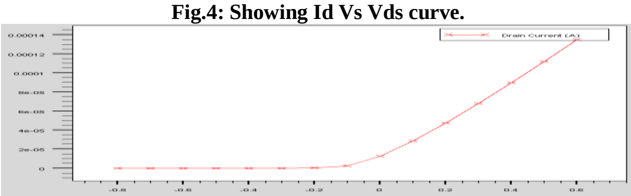

Fig5: Showing Id Vs Vgs curve.

GaN Device: AlGaN/GaN HEMT-

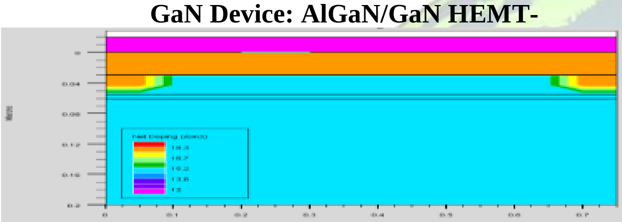

Fig.6: Basic AlGaN/GaN HEMT device simulated structure with Parameters :Lg=0.1µm ,AlGaN $_{th}$ =30nm, AlN-nucleation layer($_{th=0.005}$µm).

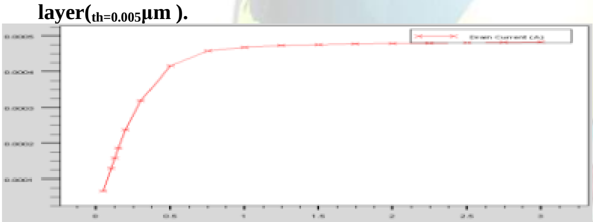

Fig.7: Showing Id Vs Vds output curve.

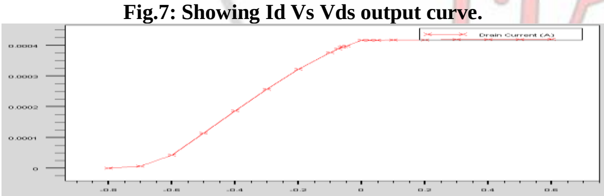

Fig.8: Showing Id Vs Vgs output curve.

Results:

When we compare GaN ($Al_x Ga_{1-x} N$) HEMT device from GaAs ($Al_x Ga_{1-x} As$) HEMT device we can see the improvement over the saturation current from 0.016 mA to 0.5mA and pinch off voltage from 0V to -0.6V.

This result analysis shows that with the advancement of technology from GaAs HEMT device to recent GaN HEMT device, there is great performance improvement can be achieved using GaN based device.

2. Implementation of nucleation layer in AlGaN/GaN HEMT-:

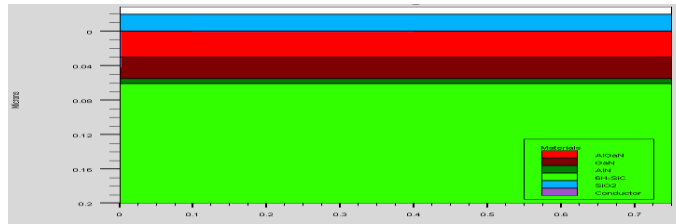

Fig.9: Lg=0.3µm ,AlGaN$_{th}$ =30nm,AlN-nucleation layer

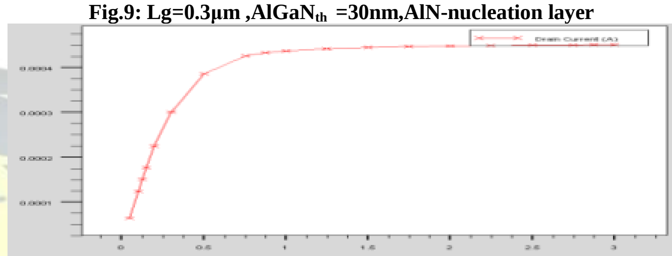

Fig.10: Id Vs Vd curve for Lg=0.3µm ,AlGaN$_{th}$ =30nm,AlN-nucleation layer

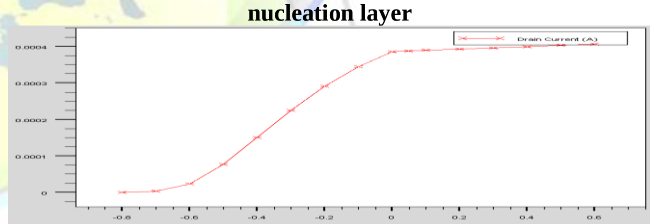

Fig.11: Id Vs Vg curve for Lg=0.3µm, AlGaN$_{th}$ =30nm,AlN-nucleation layer

Result:

Incorporation of a thin AlN (<1nm) into a standard AlGaN/GaN HEMT

• The thickness of AlN interfacial layer is below critical thickness for formation of 2DEG. The main purpose is to improve mobility.

• Thin AlN layer forms a larger effective *Ec*, which affects both mobility and carrier concentration.

For the Parameters of: Lg=0.3µm, AlGaN$_{th}$ =30nm, AlN-nucleation layer. In this second analysis, AlN-nucleation layer ($_{th=0.005}$µm) was introduced in the simulation device, this results in improvement of saturation current and pinch off voltage as 0.48mA, Vp=-0.65 V respectively.

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3. Implementation of spacer layer:

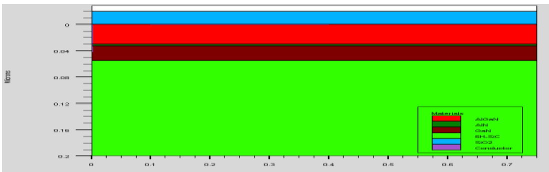

Fig.12: Simulated construction of AlGaN/GaN HEMT for -Lg=0.3µm ,AlGaN$_{th}$ =30nm,AlN-Spacer layer with thickness =0.005 µm

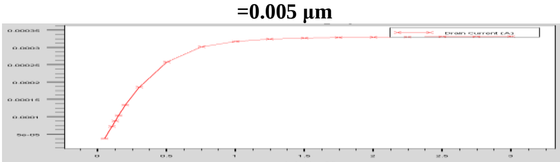

Fig.13: Id Vs Vd curve for -Lg=0.3µm ,AlGaN$_{th}$ =30nm,AlN-Spacer layer with thickness =0.005 µm.

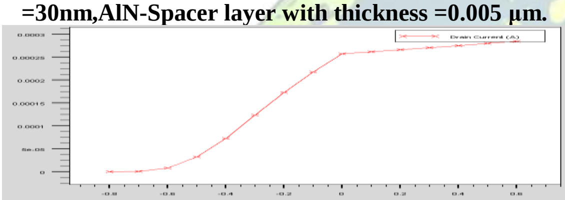

Fig.14: Id Vs Vg curve for -Lg=0.3µm ,AlGaN $_{th}$ =30nm,AlN-Spacer layer with thickness =0.005 µm.

Result:

With the Parameters of: Lg=0.3µm, AlGaN$_{th}$=30nm, AlN-Spacer (th=0.005µm) in the simulation device reported saturation current and pinch off voltage as-0.325mA, and -0.6V respectively.

4. Analysis after implementation of both spacer layer of 1nm and nucleation layer 3nm with Si substrate and SiC substrate separately with sidewall doping in the final proposed simulated device :

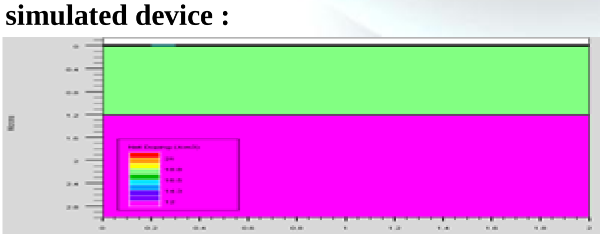

Fig.15: Simulated layered structure showing doping concentration of GaN HEMT with sidewall doping.

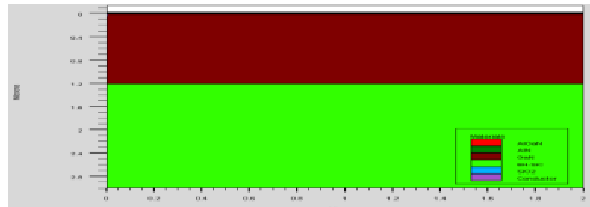

Fig.16: simulated layered structure of GaN HEMT on SiC substrate withsidewall doping.

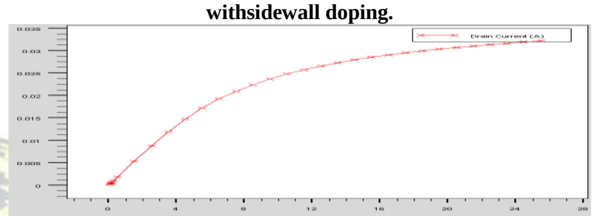

Fig.17: Showing Id Vs Vds output curve for SiC Substrate.

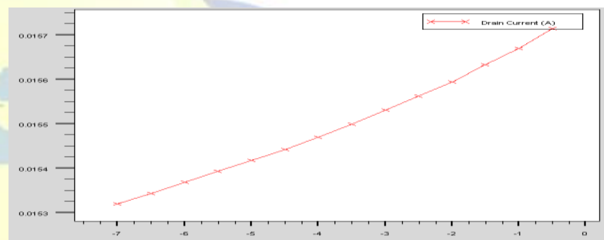

Fig.18: Showing Id Vs Vgs output curve for SiC Substrate.

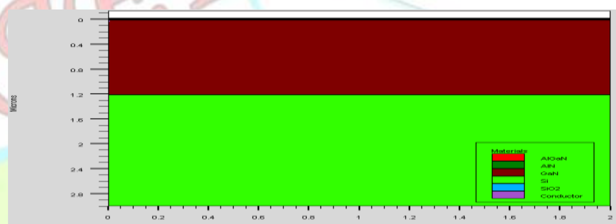

Fig.19: Simulated layered structure of GaN HEMT on Si substrate withsidewall doping.

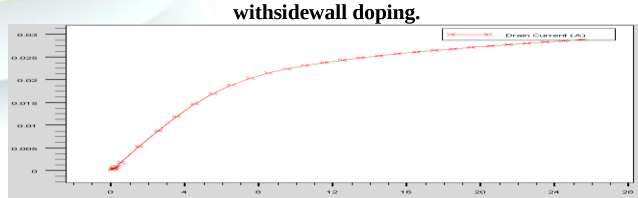

Fig.20: Showing Id Vs Vds output curve for Si Substrate.

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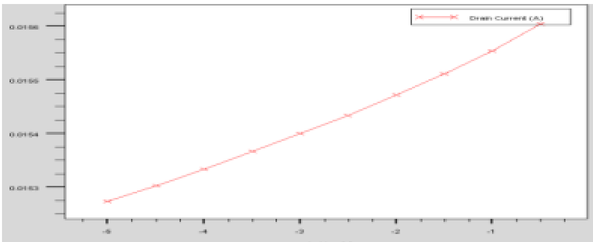

Fig.21: Showing Id Vs Vgs output curve for Si Substrate.

Final Results:

Here a finally proposed simulated device with implementation of both spacer layer of 1nm and Nucleation layer of 3nm with Si substrate and SiC substrate separately with sidewall doping was studied and observation shows a clear improvement in saturation current from 24mAto 30mA and pinch-off voltage rises from -5V to -7v on SiC substrate compared to Si substrate. From these results we can say that, a decreased performance was observed with the use of Si substrate on the device. Moreover from the result analysis, we can say high saturation current and low pinch-off are the results due to –

(i.) Thin AlN spacer layer which increase the height of the barrier layer as the conduction band discontinuity increases. This results in high density of electron accumulation at 2-DEG.

(ii.) AlN nucleation layer between SiC substrate and GaN buffer layer results its efficient wetting property so, as it helps to reduce surface traps reduce lattice mismatch and hence helps in heat sink property of SiC substrate.

(iii.) Use of SiC in place of Si as a substrate improves the performance of the device i.e. shows the high thermal conductivity of SiC substrate.

4. Analysis for without sidewall doping at GaN layer

Fig.22: Simulated GaN HEMT structure without Sidewall doping.

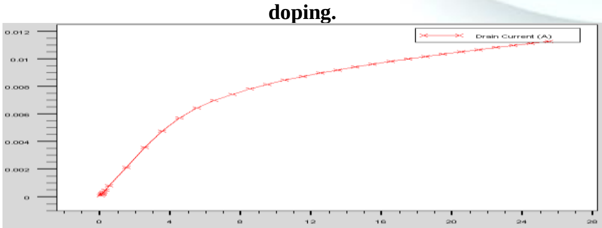

Fig.23: Showing Id Vs Vds output curve for Si Substrate without sidewall doping.

Result:

There is a degraded performance result obtained when we remove the sidewall doping. Hence it is better to implement unintentionally doping at the sidewall for improvement on saturation current.

Final DC analysis output table for different gate length and different thickness of layers:

On the basis of thesis work the observed outputs were collected and their respective values were arranged in a table.

Table3: Output table based on different parameter variation

Parameters	AlGaAs/GaAs	AlGaN (30nm)/GaN with Lg=0.5µm,without spacer/nucleation layer	AlGaN (30nm)/GaN with Lg=0.3µm with spacer	AlGaN (30nm)/GaN with Lg=0.3µm spacer & nucleation layer	AlGaN (30nm)/GaN with Lg=0.1µm spacer & nucleation layer	AlGaN (30nm)/GaN with Lg=0.1µm,undoped GaN, spacer & nucleation layer	AlGaN (10nm)/GaN (1.2µm)with Lg=0.1µm spacer & nucleation layer SiC-Substrate	AlGaN(10nm)/GaN (1.2µm)with Lg=0.1µm spacer & nucleation layer,Si-Substrate
Id(mA)	0.016	0.5	0.325	0.425	0.48	0.45	30	27
Vp(V)	-0.6	-0.6	-0.6	-0.65	-0.65	-0.7	-7	-5

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5. Breakdown voltage analysis:

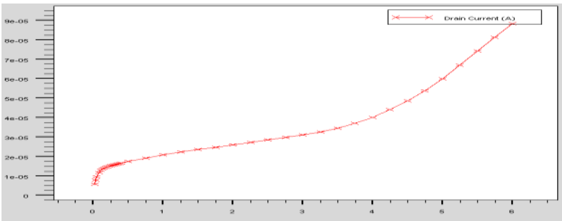

Fig.24: Breakdown curve for AlGaAs/GaAs HEMT

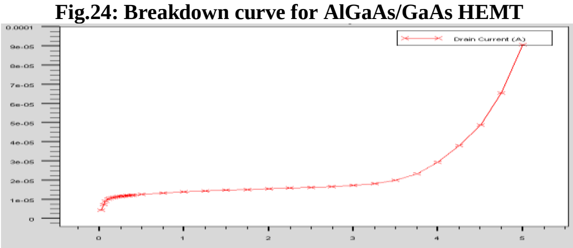

Fig.25: Breakdown curve for AlGaN/GaN HEMT

Results:

A large breakdown can be achieved with GaN HEMT device as we can see from the breakdown curve of both GaAs and GaN HEMT device.

Observed S-Parameter curves

In this thesis-work for small signal analysis S-parameters smith chart curve also achieved which shows a close resemblance of maximum oscillation frequency f_{max} and high cutoff frequency f_T when it compared with the obtained S-parameter from reference paper.

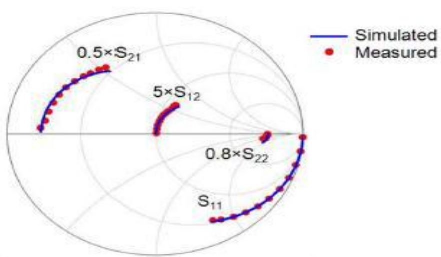

Fig.26: Reference S-parameter curve for 60nm gate length HEMT, Resulted $f_T = 70GHz$ and f_{max}=300 GHz.[1]

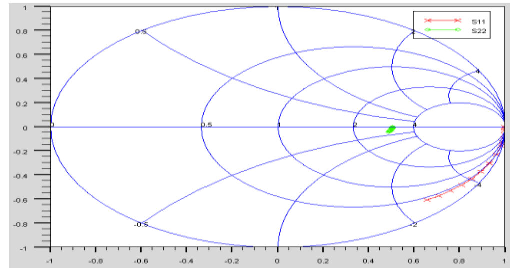

Fig.27: Obtained S-parameter $-S_{11}, S_{22}$ curves for 100nm gate length HEMT.

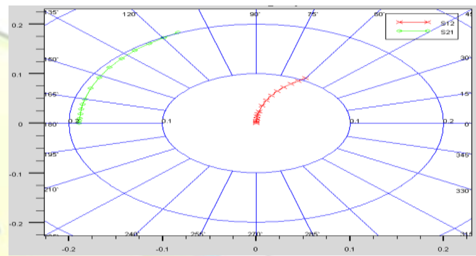

Fig.28: Obtained S-parameter $-S_{12}, S_{21}$ curves for 100nm gate length and 30nm AlGaN layered HEMT.

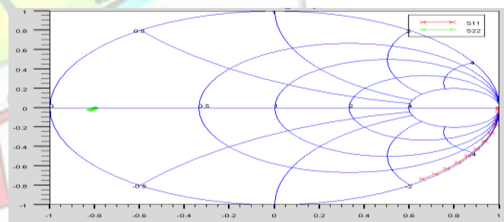

Fig.29: Obtained S-parameter $-S_{11}, S_{22}$ curves for 100nm gate length and 15nm AlGaN layered HEMT.

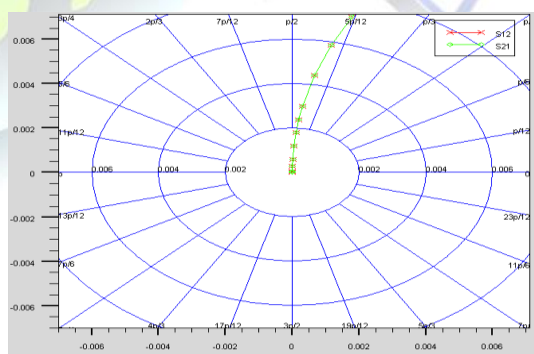

Fig.30: Obtained S-parameter $-S_{12}, S_{21}$ curves for 100nm gate length and 15nm AlGaN layered HEMT.

V. Conclusion

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On the basis of the work-done ,we can collectively say that the GaN based HEMT device is more advantageous to the GaAs based HEMT device in terms of Higher saturation current which, results as , higher current density and high mobility of electrons at the hetero-junction layer between doped AlGaN and undoped GaN where, 2-DEG formation takes place. In the thesis work 100nmgate length with thin AlGaN barrier is chosen for reducing the scattering effects. A thin AlN layer of 0.005µm thickness is introduced as a spacer layer which increases the conduction band discontinuity at the hetero-junction and helps to reduce the penetration of electrons wave-function into the AlGaN barrier. Use of thin AlN layer also prevents the ionized impurity scattering at the hetero-junction and directly helps to improve the mobility at 2DEG.

Here we proposed SiC as a substrate in place of Si or sapphire. SiC is having the properties of good thermal conductivity, less lattice mismatch and relatively low thermal expansion coefficient (TEC) mismatch compared to Sapphire and Si which is the advantageous property for microwave high power amplifiers.

Moreover AlN is proposed to place in between GaN and SiC substrate as AlN has efficient surface wetting property which, helps to reduce the surface traps and lattice mismatch. Altogether we can conclude that GaN based HEMT device is preferable as its material properties are suitable for manufacturing HEMT device.

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BIOGRAPHY

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