VARIATION IN DC PARAMETERS OF GALLIUM NITRIDE HEMT DUE TO ILLUMINATION

B.K. Mishra, Lochan Jolly & Sonia Behra*
Thakur College of Engg. and Technology (EXTC), Thakur Village, Kandivli(E),Mumbai-400101,India
*Mobile :-9869647548, Email : Soniarb16@gmail.com

ABSTRACT

Mobile phones or portable Hand Set (PHS) use the combination of wireless communication and optical fiber communication. Microwave power transistors play key role in today's wireless communication. HEMT is finding wide application due to its high speed. Analytical results for various DC parameters under the optical illumination are presented. The photovoltaic effect at the gate junction is considered which increases the sheet concentration of 2-DEG layer.

Keywords: *HEMT (High Electron Mobility Transistor), GaAs, GaN, Drift Velocity, 2-DEG layer, Channel Conductance, Trans-Conductance, Photo-sensitive.*

1. INTRODUCTION

Over the past years, semiconductor device researchers have proposed many competing devices and technologies in order to satisfy the growing demands for high power, high frequency, high temperature, high linearity and high efficiency communication system in commercial as well as in military applications. Si transistors, GaAs high electron mobility transistors (HEMTs) and hetero-structure bipolar transistors (HBTs), SiGe HBTs and SiC metal semiconductor field effect transistors (MESFETs) have established a well-reputed position in these areas. Analytical studies have been carried out by different investigators on the effect of illumination in GaAs MESFET as they show significant effect of incident light on the electrical parameters of the devices for applications in circuits for working in first window for optical communication. But as the rate of data transmission is increasing we require large bandwidth photo-detector for working in second and the third window for optical communication. HEMT is one of these emulsive optical electronic devices for high speed optical detection.

Recently power transistors based on AlGaN materials are the most emerging and demanding devices for high power, high temperature and high frequency microwave applications. AlGaN/GaN HEMT is finding wider application because of the following properties:

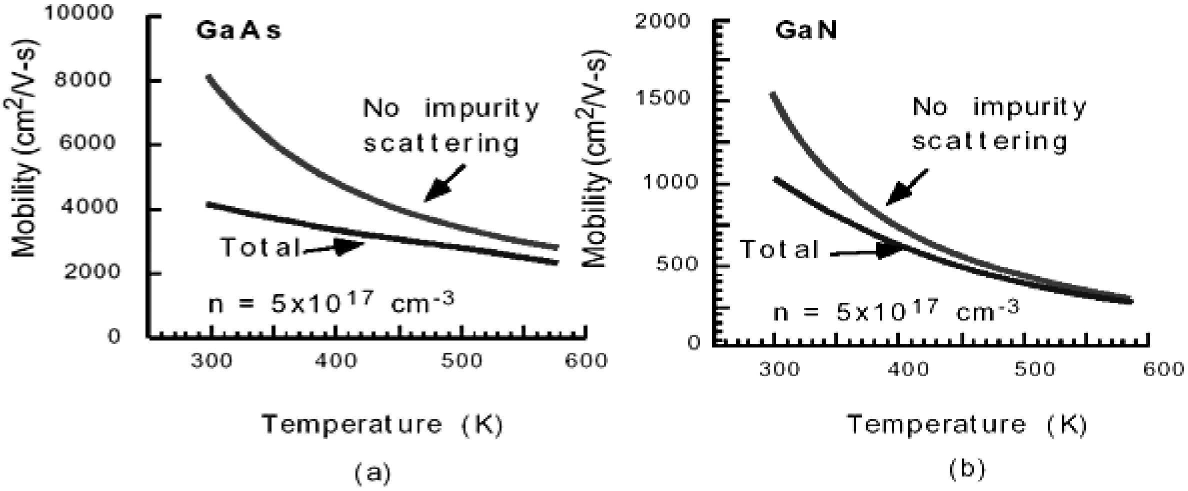
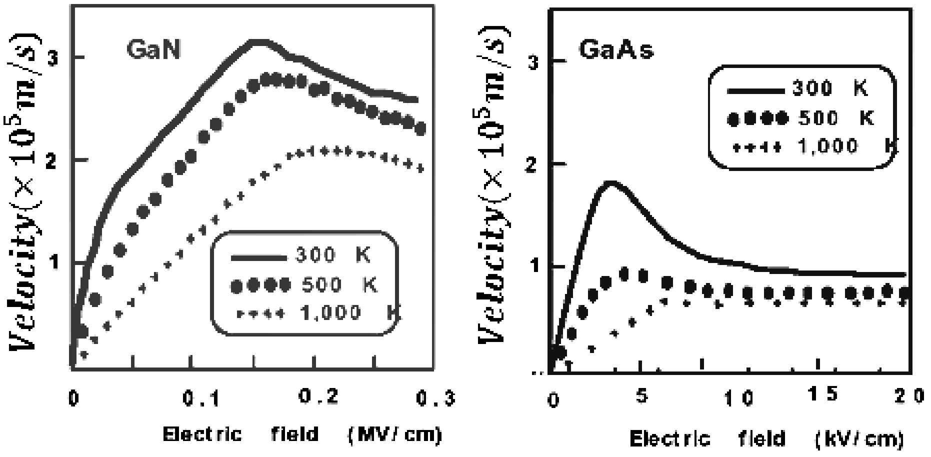


Figure 1: Temperature Dependence of Mobility [6]



(a) (b)

Figure 2: Drift velocity at room and elevated temperature [7]

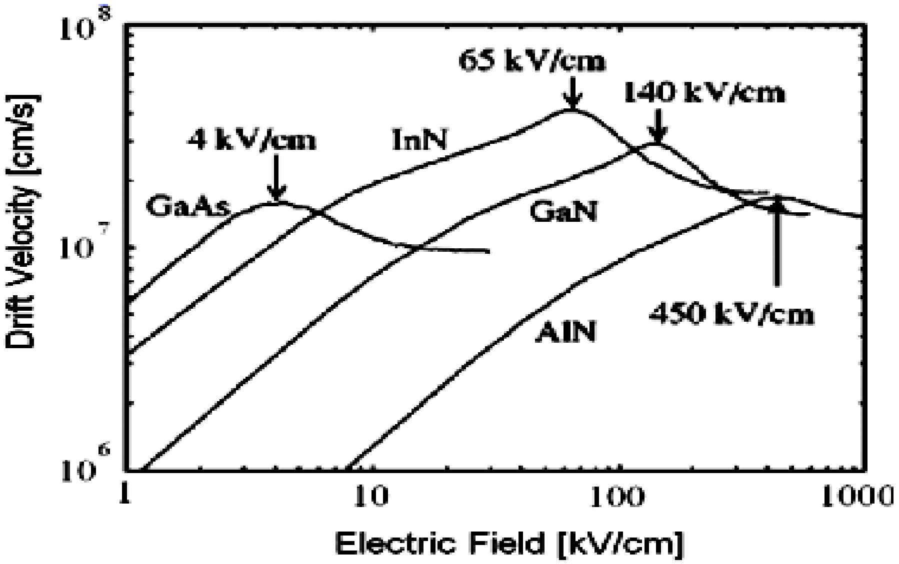


Figure 3: Comparison of Drift velocity [3]

Table 1: Comparison of the basic material properties of GaN with other well-known semiconductors.

Semiconductor		**Si**	**(AlGaS/ InGaAs)**	**SiC**	**(AlGaN/GaN)**
Characteristics	**Unit**				
Bandgap	eV	1.1	1.42	3.26	3.49
Electron Mobility at 300K	cm^2/Vs	1500	8500	700	1000-2000
Saturated electron velocity	$\times 10^7 cm/s$	1.0 (1.0)	1.3 (2.1)	2.0 (2.0)	1.3 (2.1)
Critical breakdown field	MV/cm	0.3	0.4	3.0	3.0
Thermal conductivity	W/cm-K	1.5	0.5	4.5	>1.5
Relative Dielectric constant	ε_r	11.8	12.8	10.0	9.0
Johnsons figure of merit	$(\alpha\ Vbr^2 *Vsat^2)$	1	11	180	760

From the figure 1, figure 2 and figure 3 it is very much evident that there is weaker impurity scattering in GaN due to its heavy mass and it has higher drift velocity as compared to GaAs. Table 1 gives the comparison of various electrical parameters of some semiconductors.

The GaN has attractive material properties such as large band gap (3.4eV comparing with 1.4eV of GaAs), high breakdown voltage (3MV/cm compared to 0.4MV/cm of GaAs), high peak carrier velocity (2.1x 10^7 cm/s compared to 2.1 x 10^7 cm/s of GaAs) and good thermal conductivity (1.5W/cm-K compared to 0.5 W/cm-K of GaAs).For GaN, the Johnson figure of merit (α Vbr^2 x $Vsat^2$) is 70 times that of GaAs. Therefore, GaN is definitely a very adequate and outstanding candidate for high performance HEMT.

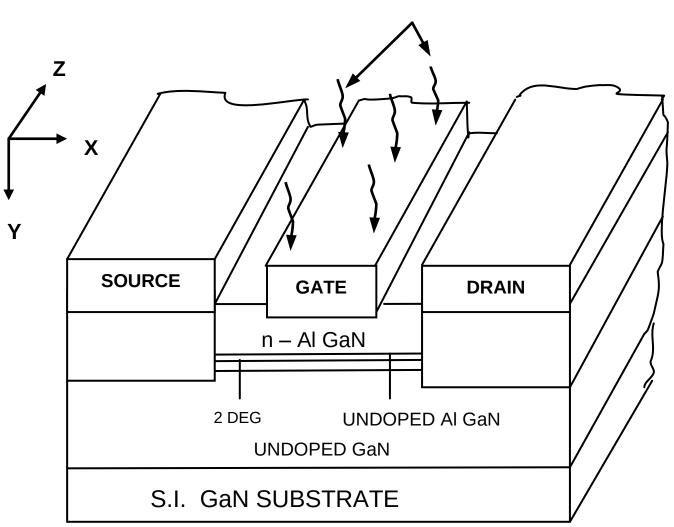


Figure 4: HEMT under illumination

The structure under consideration as shown in figure 4 is a AlGaN/ GaN HEMT [7] with semi- transparent gate, it is a hetero-junction device which utilizes the high mobility and high velocity of 2-DEG. The device is illuminated in the Y-direction and the flow of current is in the X-direction.

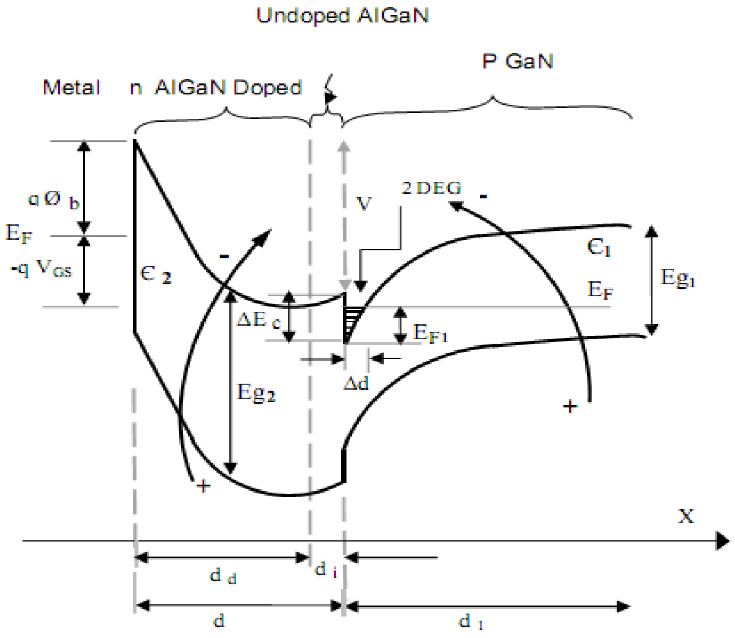


Figure 5: Formation of 2-DEG under illumination

When the device is illuminated additional carriers are generated. Additional electrons in AlGaN layer will result in an increase in the sheet concentration of the 2-Dimensional Electron Gas.

2. THEORY

The DC Parameters of the device is studied to see the effect of biasing voltage (i.e. V_{GS} and V_{DS}) on the device. The different parameters which will show the effect are:

2.1 Sheet Concentration

A Schottky gate on the AlGaN layer results in the depletion region beneath the gate, when a large negative voltage at the gate is applied ,the gate depletion and the junction depletion regions will overlap. In this case the sheet concentration of 2-DEG is determined as [5, 6]

$$n_s = \frac{\varepsilon}{q(d+\Delta d)}(V_{GS} - V_T) \tag{1}$$

Where
n_s =Sheet concentration
q=Charge of an electron
ε =Permittivity of semiconductor
d=Epilayer thickness

$$\Delta d = \frac{\varepsilon a_o}{q} = 80A^0 \tag{2}$$

$$V_T = \Phi_b - V_p - \Delta E_c \tag{3}$$

$$V_p = \frac{q}{2\in d} N_d {d_d}^2 \tag{4}$$

Where
Φ_b =Height of Schottky barrier
d_d =Thickness of doped n-AlGaN layer
N_d =Doping concentration

The sheet concentration in the channel using the gradual channel approximation is given by

$$n_s(x) = \frac{\varepsilon}{q(d+\Delta d)}\left(V_{GS} - V_T - V(x)\right) \tag{5}$$

Where
$V(x)$ = Channel potential.

2.2 New Current Model

It was observed that Shockley's equation does not hold true in HEMT because according to the Shockley model, the current saturation in channel occurs when the channel is pinched-off at the drain side of the gate, whereas in microwave HEMT,s it is due to the velocity saturation[5].

Thus a new model was proposed with the expression of drain current as [5, 8]

$$I_{DS} = I_{dss}\left(1 - \frac{V_{eff}}{V_T + \Delta V_T + \gamma V_{DS}}\right)^2 \times tanh(\alpha V_{DS})(1 + \lambda V_{DS}) \tag{6}$$

Where

$$V_{eff} = \frac{V_{GS}}{1 + \eta e^{V_{GS}}} \tag{7}$$

According to simple one-dimensional device models, the value of V_T is independent of L_G. But in fact V_T is a function of L_G. Thus ΔV_T is defined as the shift in V_T caused by the submicron geometry of the device

$$\Delta V_T = \frac{4\,L_G}{3d_d}V_T \tag{8}$$

And

η = Schottky barrier interface and is 0.1
α = Dependence of linear region on V_{DS} and is 4
γ = Dependence of threshold voltage on V_{DS} and is -0.001
λ = Dependence of I_{DS} on V_{DS} and is = 0.18
L_G=Length of the gate

2.3 Trans-conductance

The trans-conductance of any device is given by

$$g_{m=\frac{\partial I_{DS}}{\partial V_{GS}}/V_{DS}=constant} \tag{9}$$

Thus differentiating equation (5) with respect to V_{GS} we get

$$g_m = 2I_{dss}\left[1-\frac{V_{eff}}{V_T+\Delta V_T+\gamma V_{DS}}\right]\left[\frac{V_{eff}}{V_{GS}}(1-\eta e^{V_{GS}})\right]\left[\frac{-1}{V_T+\Delta V_T+\gamma V_{DS}}\right][tanh(\alpha V_{DS})(1+\lambda V_{DS})] \tag{10}$$

2.4 Channel Conductance

The channel conductance of the device is

$$g_d = \frac{\partial I_{DS}}{\partial V_{DS}}/V_{GS} = constant \tag{11}$$

Thus differentiating equation (5) with respect to V_{DS} we get

$$\begin{aligned} g_d = {} & 2I_{dss}\left[1-\frac{V_{eff}}{V_T+\Delta V_T+\gamma V_{DS}}\right]\left[\frac{\gamma V_{eff}}{(V_T+\Delta V_T+\gamma V_{DS})^2}\right][tanh(\alpha V_{DS})(1+\lambda V_{DS})] \\ & + I_{dss}\left[1-\frac{V_{eff}}{V_T+\Delta V_T+\gamma V_{DS}}\right]^2[1-tanh^2(\alpha V_{DS})](1+\lambda V_{DS}) \\ & + \lambda I_{dss}\left[1-\frac{V_{eff}}{V_T+\Delta V_T+\gamma V_{DS}}\right]^2 tanh(\alpha V_{DS}) \end{aligned} \tag{12}$$

2.3 Effect Of Illumination

Due to illumination when the photons are absorbed an increase in the electron concentration of the 2-DEG channel occurs (photoconductive effect).The photoconductive effect is dominant when the incident photon energy E_{ph}= hυ is equal to or greater than the GaN band gap but smaller than the AlGaN band gap ($E_{g1} \leq E_{ph} < E_{g2}$).The amount of absorption of incident optical radiation can be found by the equation:

$$P_{op}(y) = (1-R_m)(1-R_S)P_{in}e^{-\alpha y} \tag{13}$$

Where
P_{in}=Incident optical power
R_m=Reflection co-efficient of metal surface
Rs= Reflection co-efficient of semiconductor surface
α = optical absoption co-efficient of AlGaN at operating wavelength.

Due to absorption of optical radiation excess carriers are generated in the AlGaN region, the rate of generation is given by

$$G_{op} = \frac{\alpha P_{op}\,(1-R_m)(1-R_s)exp\,(-\alpha y)}{h\vartheta} \tag{14}$$

Where
h= Planck's Constant
ϑ = Frequency of incident optical radiation

The excess carriers generated in the AlGaN region affect the minority carrier life-time. The lifetime τ_L of the minority carriers in the illuminated conditions can be obtained from following equation [4]:

$$\tau_L = \frac{\left[1+\frac{4(1-R_S)(1-R_m)P_{op}\,\Gamma(1-\exp(-\alpha d))}{hvdn_i}\right]^{\frac{1}{2}}-1}{2(1-R_S)(1-R_m)P_{op}\,(1-\exp(-\alpha d))/h\vartheta dn_i} \tag{15}$$

Where
Γ =Minority carrier lifetime at thermal equilibrium
n_i =Intrinsic carrier concentration

The excess photo carriers generated is given by:

$$\Delta P = \frac{\Gamma_L}{d}\left[\frac{P_{op}}{h\vartheta}\right](1-R_S)(1-R_m)(1-\exp(-\alpha d)) \tag{16}$$

The optical voltage V_{op} can thus be calculated as [1, 2]:

$$V_{op} = \frac{KT}{q}\,ln\left[\frac{p+\Delta P}{p}\right] \tag{17}$$

$$p = \frac{n_i^2}{n} \tag{18}$$

The V_{op} developed at the Schottky barrier gets imposed on V_{GS} and hence the effective V_{GS} is

$$V_{GS_{eff}} = V_{GS} + V_{op} \tag{19}$$

Thus the optical equations for the Drain current, trans- conductance, Channel conductance is obtained by replacing V_{GS} by $V_{GS_{eff}} = V_{GS} + V_{op}$ in equation 6, 10 and 12.

3. RESULTS AND DISCUSSION

Numerical calculations have been carried out for AlGaN/GaN HEMT considering optical effect. The relevant dimensions and material properties used in the analysis are given in table 2. It has been presented [5] that the device sensitivity improves as the device dimension reduces. It shows that as the device dimensions reduce the device current increases and the photosensitivity increases.

Figure 6 compares the I-V characteristics of GaAs and GaN HEMT for the same dimensions and same biasing conditions. The current in GaN increases as can be seen in the plot.

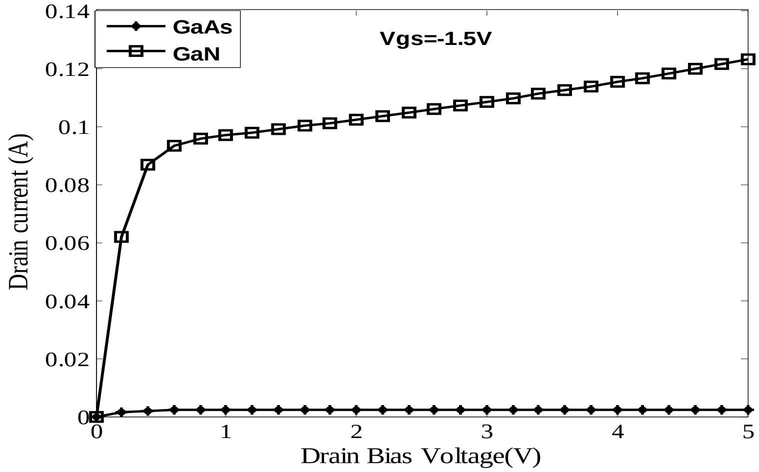


Figure 6: Comparison of I-V Characteristics for GaAs HEMT and GaN HEMT

Parameter	**Symbols**	**Value**
Height of Schottky barrier	ϕ_b	0.9eV
Doping concentration	N_d (n)	$5 * 10^{24}/m^3$
Width of the gate	W	100 μm
Length of the gate	L_G	0.23 μm
Epilayer thickness	d	110nm
Thickness of doped n-AlGaN layer	d_d	100nm
Mobility of electrons	μ_e	1.4 4 m^2/Vs (GaN) *0.75m²/Vs(GaAs)*
Reflection coefficient of metal surface	R_m	0.1
Reflection coefficient of semiconductor interface	R_s	0.1
Optical absorption coefficient of AlGaN at operating wavelength	α	10^6/m
Incident optical power	P_{op}	0.1mW to 1mW
Charge of an electron	q	1.6×10^{-19}Coulomb
Temperature	T	300K
Boltzmann's constant	K	$1.3806504*10^{-23}$ JK^{-1}
Permittivity of semiconductor	ε	$7.88*10^{-10}$ F/m (GaN) $1.14*10^{-10}$ F/m (GaAs)
Planck's constant	h	6.6 606*10^{-34} Js
Frequency of incident optical radiation	ϑ	$2.25*10^{14}$Hz
Intrinsic carrier concentration	n_i	$10^{16}cm^{-3}$
Minority Carrier lifetime at thermal equilibrium	τ	10^{-8} s
Minority carrier concentration in active layer	p	$2*10^7/m^3$
Difference between the electron affinities	ΔEc	0.6ev(GaN) 0.4eV(GaAs)
Operating Wavelength	λ	1330nm

Table 2: List of Basic parameters

Figure 7 illustrates the effect of illumination on the lifetime of minority carriers. It is seen that the minority carrier lifetime under illuminated condition decreases exponentially .This is due to the fact that as the device is illuminated generation of carriers initially is very fast, and then slows down because of increase in rate of recombination.

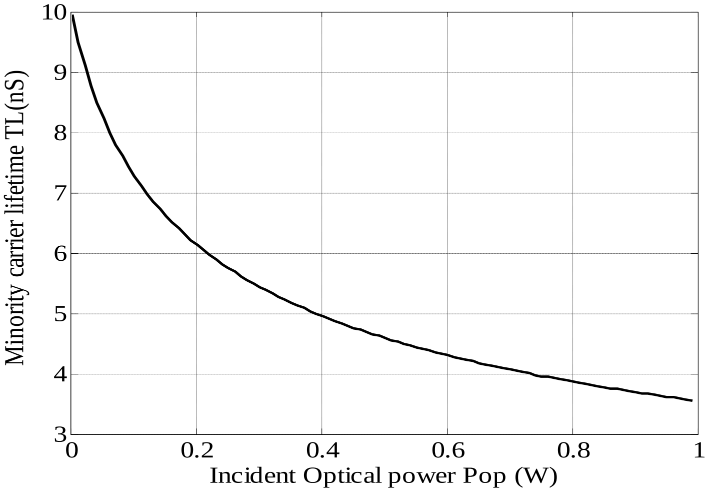


Figure 7: Variation in τ_L with incident power

Figure 8 gives the variation in the optical voltage developed with the incident optical power. The optical voltage developed increases initially as depicted in figure 8 and finally saturates as the rate of generation becomes equal to rate of recombination.

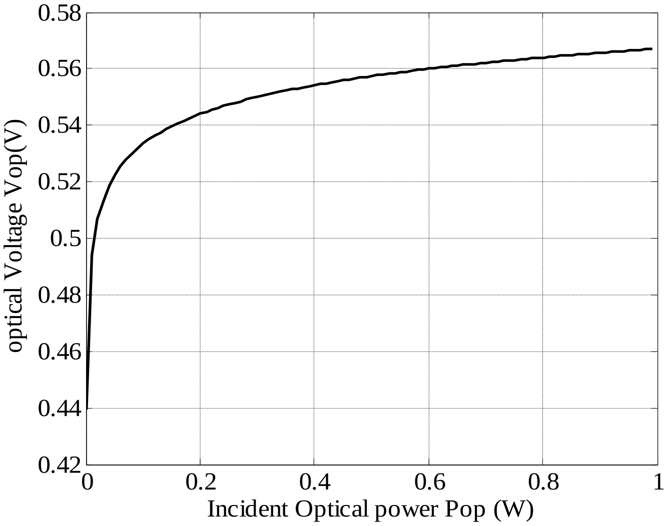


Figure 8: Variation in V_{op} with incident optical power

Figure 9 gives the I-V characteristics of GaAs HEMT and figure 10 gives the I-V characteristics of GaN HEMT. A comparison of both the graphs shows that sensitivity increases in GaN HEMT. Table 3 gives the comparison of sensitivity of GaAs and GaN HEMT and it is observed that GaN HEMT is more sensitive with the same biasing condition.

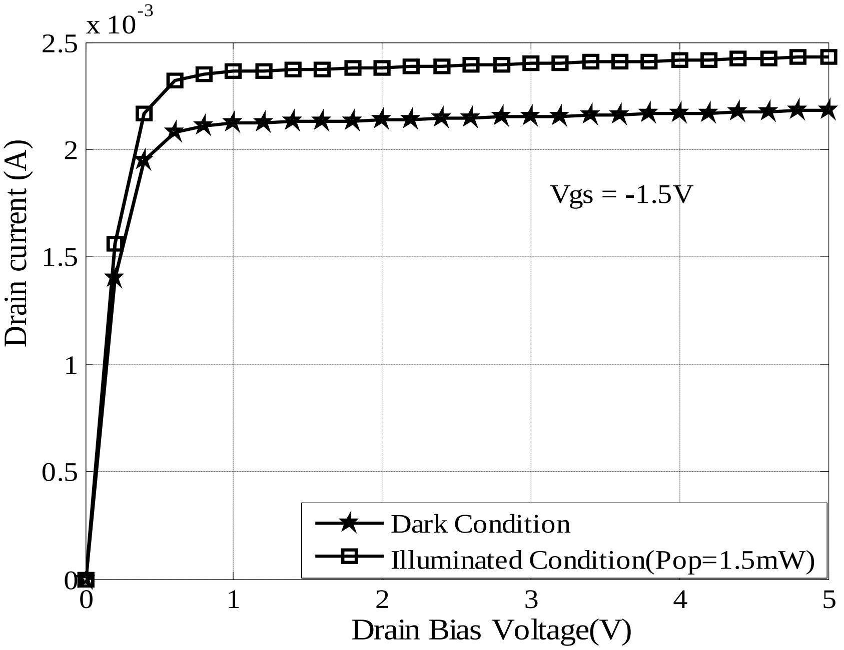


Figure9: I-V Characteristics of GaAs HEMT

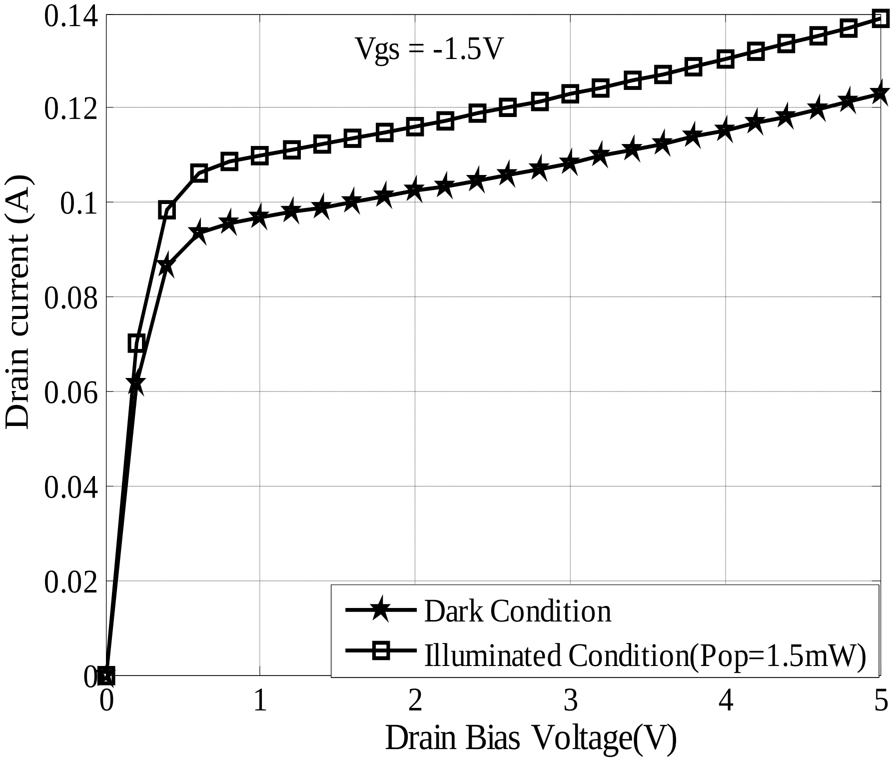


Figure10: I-V Characteristics of GaN

Table 3: *Comparison of Sensitivity of GaAs and GaN HEMT at Vgs=-1.5V and Vds=1V*

Pop (mW)	Id (A) GaAs	Id (A) GaN	Sensitivity GaAs	Sensitivity GaN
0	.0021	0.0923	14.28%	23.94%
1.5	.0024	0.1144		

This paper compares the I-V characteristics, Trans-Conductance and channel conductance of GaN HEMT with a channel length of 0.23µm under D.C. condition. Table 4 gives the effect of illumination on the various DC parameters of GaN HEMT.

Figure11 shows the effect of illumination on the channel conductance, it is seen that as the drain biasing increases the channel conductance decreases, this is because as the increase in the drain biasing increases the depletion width which reduces the channel available and hence conductance decreases and finally saturates when the device saturates. Due to illumination there are excess carriers generated in the channel and hence the conductance in the channel increases.

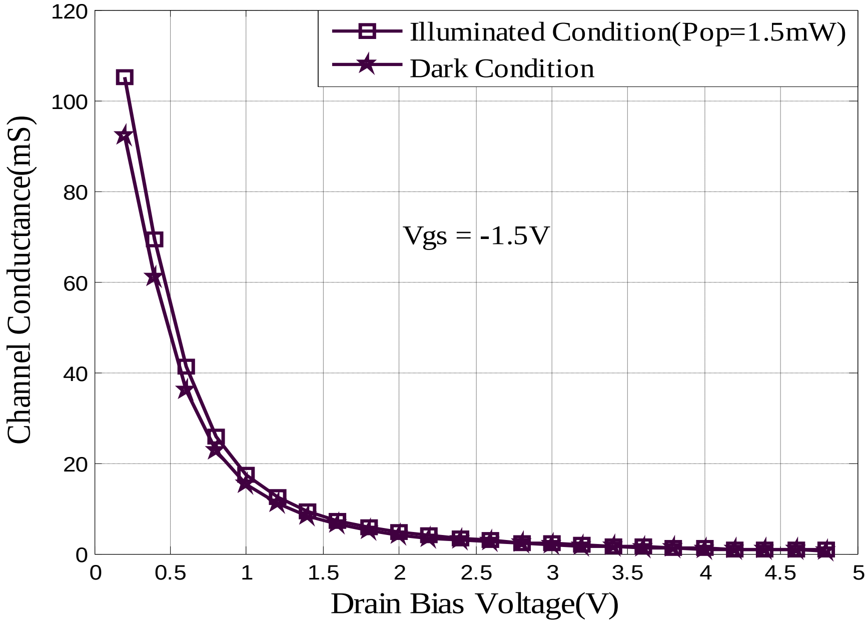


Figure 11: Effect of Illumination on Channel Conductance.

Table4: Variation in DC parameters of GaN HEMT under illumination at Vgs=-1.5V and Vds=1V

DC parameters	Dark	Illuminated
Drain current(A)	0.0969	0.1084
Trans-Conductance(mS)	20.25	20.75
Channel Conductance(mS)	15.2345	17.3381

Figure 12 shows the effect of illumination on transconductance,The figure clearly shows that with Vgs to be more and more positive the transconductance increases this is due to the fact that with increase in the gate biasing thedepletion width decreases and the channel available increases and hence the conductance increases. For illumination there is increase in the conductance because of excess carriers generated.

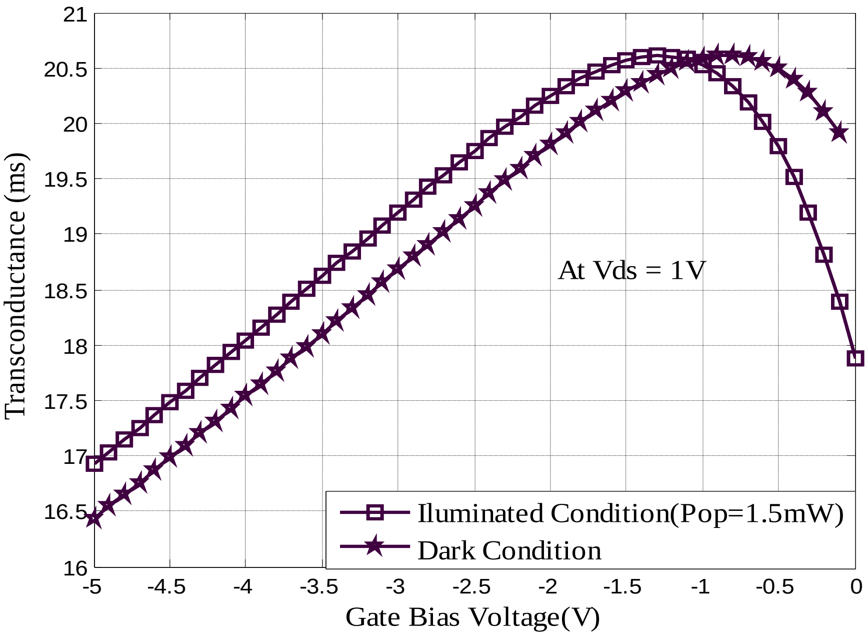


Figure12: Effect of Illumination on Trans-Conductance

5. CONCLUSION

For high speed applications GaN is a better choice that GaAs. GaN HEMT has been analyzed under the condition of optical illumination. The various DC parameters have been plotted and discussed. The results of GaN HEMT are compared with GaAs HEMT under dark and under illumination. The results show that GaN is more photo-sensitive than GaAs and hence is a better photo-detector. The results also indicate the increase in all the DC parameters due to illumination which is due to increase in the sheet concentration of 2-DEG.

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