Current Model for short Channel Illuminated Gallium Nitride HEMT

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ABSTRACT

Microwave power transistors play key role in today's wireless communication, necessary for virtually all major aspects of human activities from entertainment, business to military. HEMT is widely used due to its high speed and power amplification capabilities. The paper proposes a current Model for short channel HEMT to evaluate its sensitivity to illumination to find its application in optical monolithic microwave integrated circuits(OMMIC).

Categories and Subject Descriptors

G.4 Matlab

General Terms

Algorithms, Performance.

Keywords

2-DEG, Schottky Junction, Photo detectors, Photo voltage, short channel, Gallium Nitride, OMMIC

1. INTRODUCTION:

For high speed and large volume digital communication system optical communication and wireless and optical communication is required. For this purpose a high speed and highly efficient microwave and millimeter wave digital photo detector is required .The normal PIN diodes used for optical detections do not work in these conditions and therefore, OMMIC devices are finding wide applications in these fields. Being highly sensitive to optical signal, the light intensity will affect its parameters. Both experimental and 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 photodetector 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 speed.

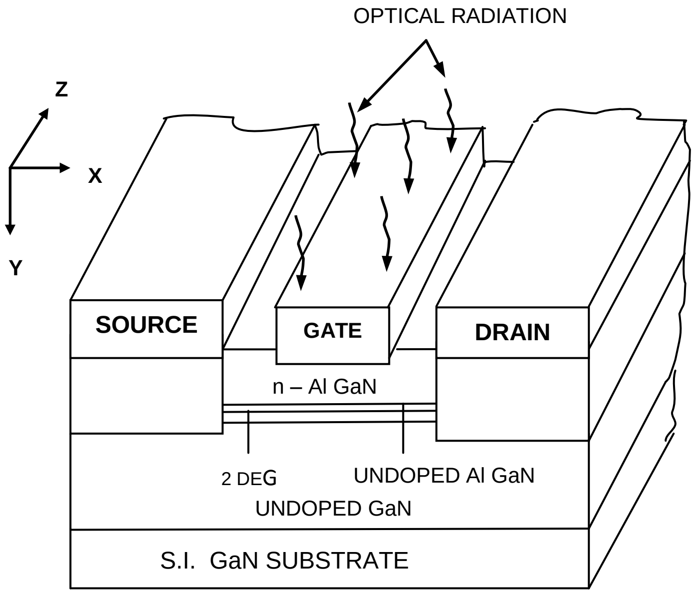

Figure 1: HEMT under illumination

Being highly sensitive to optical signal,the light intensity will affect its parameters.It can be used as a photodetector and for the design of oscillator.

The structure under consideration is a AlGaN/GaN HEMT[5] with semi- transparent gate, it is a heterojunction 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.The heterojunction is formed due to highly-doped wide-band gap n-type donor-supply layer (AlGaN)and a non-doped narrow-band gap channel layer with no dopant impurities (GaN) .The electrons generated in the n-type AlGaN thin layer drop completely into the GaN layer to form a depleted AlGaN layer, because the heterojunction created by different band-gap materials forms a quantum well (a steep canyon) in the conduction band on the GaN side where the electrons can move quickly without colliding with any impurities because the GaN layer is undoped, and from which they cannot escape [4]. The effect of this is to create a very thin layer of highly mobile conducting electrons with very high concentration, giving the channel very low resistivity i.e. "high electron mobility". This layer is called a two-dimensional electron gas. A voltage applied to the gate alters the conductivity of this layer.

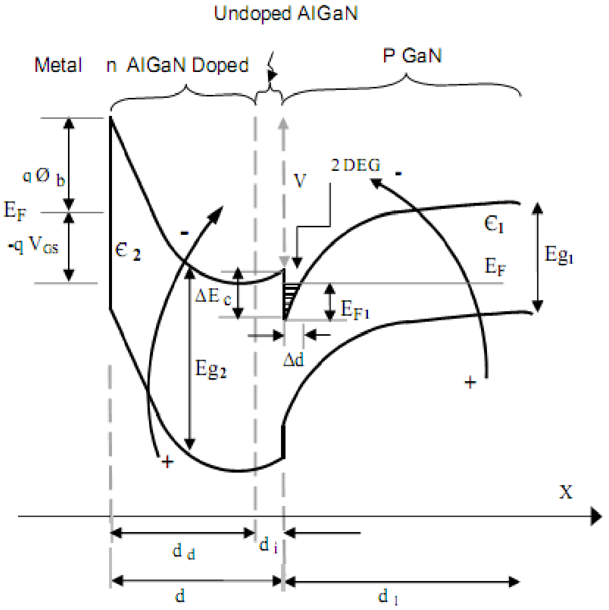

Figure 2: Formation of 2-DEG [1]

Additional electrons in AlGaN layer will result in an increase in the sheet concentration of the 2-D electron Gas. These additional carriers are generated due to optical radiation.

2. THEORY

2.1 Sheet Concentration

A Schottky gate `on the (Al,Ga)N 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, starting with F_S which is the quasi-constant electric field in the potential well (triangular well) and is related to the sheet concentration n_s by Gauss's law as

$$\varepsilon F_s = qn_s + Q_{B1} \qquad (1)$$

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

and

$$n_s = \sum_{i=0}^{\infty} n_i \qquad (2)$$

$$Q_{B1} = q\int_0^{W_{dep}} (N_{D1} - N_{A1})\, dz \qquad (3)$$

Q_{B1} is the total surface charge in GaN related to ionized impurities. The GaN layer is typically undoped , hence Q_{B1} is very less as compared to n_s [4]

Therefore

$$\varepsilon F_s = qn_s \qquad (4)$$

$$n_s = \frac{\varepsilon F_s}{q} \qquad (5)$$

F_s is obtained as [4]

$$F_s = \frac{V_p - (\emptyset_b - V_{GS} + E_{Fi} - \Delta E_c)}{d} \qquad (6)$$

Where

$$V_p = \frac{q}{2\epsilon d} N_d {d_d}^2 \qquad (7)$$

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

hence

$$n_s = \frac{\varepsilon}{qd}\left[V_{GS} - \left(\phi_b - V_p + E_{Fi} - \Delta E_c\right)\right] \qquad (8)$$

The relation between the Fermi potential E_{Fi} and n_s is given by

$$E_{Fi} = \Delta E_{FO}(T) + an_s \qquad (9)$$

Where
a ≈ 0.125×10^{-16} Vm^2
$\Delta E_{FO}=0$ at 300K
Substituting these relations in equation (8) yields the equation of sheet concentration as

$$n_s = \frac{\varepsilon}{q(d+\Delta d)}\,(V_{GS} - V_T) \qquad (10)$$

Where

$$\Delta d = \frac{\varepsilon a_o}{q} = 80A^0 \qquad (11)$$

$$V_T = \Phi_b - V_p - \Delta E_c \qquad (12)$$

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

$$n_s(x) = \frac{\varepsilon}{q(d+\Delta d)}\,\big(V_{GS} - V_T - V(x)\big) \qquad (13)$$

Where
V(x) is the Channel potential.

2.2 Current Model

2.2.1 New Model

Many researchers worked on the basic Schokley's model[6,8,9] and It was observed that Shockley's equation does not hold true for short channels 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[8].

HEMT's characteristics depend upon numerous parameters. Thus, a simple model, like Shockley equation, cannot describe its behavior under all conditions with reasonable accuracy. Improved versions of non-linear models have, therefore, been presented by different researchers to predict *I-V* characteristics of HEMTs[8].Devices with interfacial layers exhibit relatively higher gate leakage and consequently the effect of gate potential to control the channel thickness is poor. The loss of finite amount of *Vgs* due to the interfacial layer has not been incorporated in previous models. The presence of interfacial layer consumed a finite amount of *Vgs* and thus the magnitude of the potential which varies the channel height is different than the applied *Vgs*. Under such circumstances a simulation carried out by considering *Vgs* as one of the variable cannot predict the device behavior accurately.

Thus following expression is proposed [8] which modifies *Vgs* as

$$V_{eff} = \frac{V_{gs}}{1+\eta e^{V_{gs}}} \qquad (14)$$

This expression defines *Veff with η* as a fitting variable that simulates quality of a Schottky barrier and gives component of *Vgs* that alter the gate depletion. For η= 0, the Schottky barrier is close to ideal and the effects of interface states are negligible.

The expression of Drain current with this proposed modification [6] can now be written as

$$I_{ds} = I_{dss}\left(1 - \frac{V_{eff}}{V_T+\Delta V_T+\gamma V_{ds}}\right)^2 \times tanh(\alpha V_{ds})(1+\lambda V_{ds}) \qquad (15)$$

The variable α is used to simulate the linear region *I-V* characteristics, and λ predicts the dependence of *Ids* on *Vds* after the onset of the current saturation. Hyperbolic tangent function is used to simulate *Ids* for 0 <*Vds* < *Vbreakdown* contrary to the Shockley model which simulates *Ids* only for *Vsat* < *Vds*< *Vbreakdown*.

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. The shift in V_T caused by the submicron geometry of the device into the model expression with a term ΔV_T defined by

$$\Delta V_T = \frac{4L_G}{3d_d}V_T \qquad (16)$$

$$I_{dss} = \frac{\beta}{1+\mu_e(V_{eff}-V_T-V_{ds}-\Delta V_T)} \qquad (17)$$

And

η Simulates Schottky barrier interface =0.1

α Simulates the dependence of linear region on V_{ds} =4

γ Simulates the dependence of threshold voltage on V_{ds} = -0.001

λ Simulates the dependence of I_{ds} on V_{ds} = 0.18

2.3 Effect Of Illumination

Due to illumination when the photons are absorbed only in the GaN layer, an increase in the electron concentration of the 2-DEG channel occurs (photoconductive effect). When photons are also absorbed in the AlGaN layer and a high-gate bias resistance is present, the photovoltaic effect is dominant. The photoconductive effect is dominant when the incident photon energy *Eph*= hv is equal to or greater than the GaN band gap but smaller than the AlGaN band gap ($Eg_1 \leq Eph < Eg_2$).Due to photovoltaic effect a forward voltage V_{op} is developed across the metal gate and the AlGaN Schottky barrier. This forward voltage V_{op} is imposed on Vgs hence the new value of is $V_{gs}+V_{op}$ .The amount of absorption of incident optical radiation can be found by the equation:

$$P_{op}(y) = (1-R_m)(1-R_S)P_{in}e^{-\alpha y} \qquad (18)$$

Where

P_{in}=Incident optical power

R_m=Reflection co-efficient of metal surface

R_S= 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

$$G_{op} = \frac{\alpha P_{op}(1-R_m)(1-R_s)exp(-\alpha y)}{h\vartheta} \qquad (19)$$

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 [3]:

$$\tau_L = \frac{\left[1+\frac{4(1-R_S)(1-R_m)P_{op}\,\Gamma(1-\exp(-\alpha d))}{h\nu d n_i}\right]^{\frac{1}{2}}-1}{2(1-R_S)(1-R_m)P_{op}\,\Gamma(1-\exp(-\alpha d))/h\vartheta d n_i} \qquad (20)$$

Where

Γ =Minority carrier lifetime at thermal equilibrium

n_i =Intrinsic carrier concentration

The excess photo carriers generated is given by:

$$\Delta P = \frac{\Gamma_L}{d}\left[\frac{P_{op}}{h\vartheta}\right](1-R_S)(1-R_m)(1-\exp(-\alpha d)) \qquad (21)$$

The optical voltage Vop can thus be calculated as [1]:

$$V_{op} = \frac{KT}{q}\, ln\left[\frac{p+\Delta P}{p}\right] \qquad (22)$$

$$p = \frac{n_i^2}{n} \qquad (23)$$

The Vop developed at the Schottky barrier gets imposed on Vgs and hence the effective Vgs is

$$V_{gs_{eff}} = V_{gs} + V_{op} \qquad (24)$$

Hence for the equations13,14,15 and 17 V_{gs} will be replaced by V_{gseff} .

2.4 Sensitivity

Sensitivity is the ability of the detector to sense the incident photons and convert it into equivalent electrical signal. It is the ratio of difference of current in illuminated condition to the dark condition. The sensitivity of the device can be calculated by using the following equation

$$S = \frac{I(optical)-I(dark)}{I(dark)} \qquad (25)$$

3. RESULTS AND DISCUSSION

The simulation to calculate current under dark and under illuminated condition for various V_{gs} and V_{ds} was carried using the model equation to represent the system in Matlab and using the parameter values given in table 1.

The work started with simulation of New current equations for 3µm and .23µm gate length and it was observed as the gate length reduces the current increases.

Figure 3 depicts the variation of drain current in channel with L_G =3µm under dark conditions , it is very clear at zero gate biasing voltage ,with the increase in drain voltage the current increase this is the linear region.In a long channel device, the saturation occurs when the channel pinches-off due to the applied V_{ds}, and at this point the current becomes independent of V_{ds} under ideal conditions and as the value of gate bias becomes more and more negative the current reduces.

Figure 3 shows the characteristics of HEMT, by implementing the new model equations by considering the effect of saturation velocity, it was found that the characteristics are very much identical to ideal characteristics and current increases and remains constant in saturation region with an abrupt change at the onset of velocity saturation in the channel.

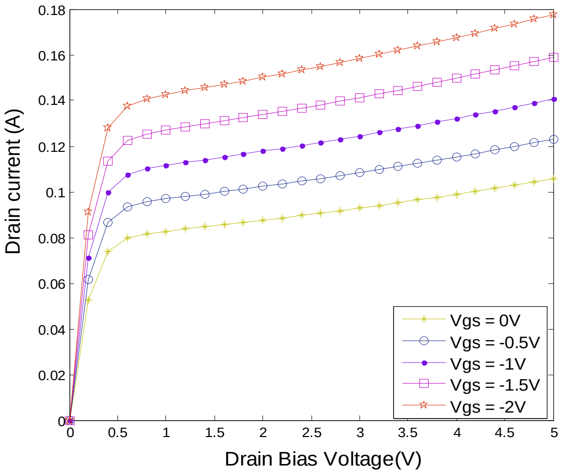

Figure 3: New Model I-V Characteristics of HEMT for L_G=3µm

The new model was simulated and it was observed with gate to source voltage was varied form -2 V to 0, the actual effective gate voltage available varied from -1.97 V to 0, this was due to interfacial layer which causes the drop in voltage.

Figure 4 shows the drain characteristics, for L_G=0.23µm using new model equations the characteristics are very much near to the ideal characteristics with an abrupt change at the onset of the velocity saturation in the channel. It was observed that the drain current increases tremendously due to shorter gate length.

Table 1: List of Basic parameters

Parameter	Symbols	Value
Height of Schottky barrier	ϕ_b	0.9eV
Doping concentration	N_d (n)	$10^{24}/m^3$
Width of the gate	W	100 μm
Length of the gate	L_G	3 μm and 0.23 μm
Epilayer thickness	d	110nm
Thickness of doped n-AlGaN layer	d_d	100nm
Mobility of electrons	μ_e	$4\, m^2/Vs$
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(GaN)	ε	$7.88*10^{-10}$F/m
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
Operating Wavelength	λ	1330nm

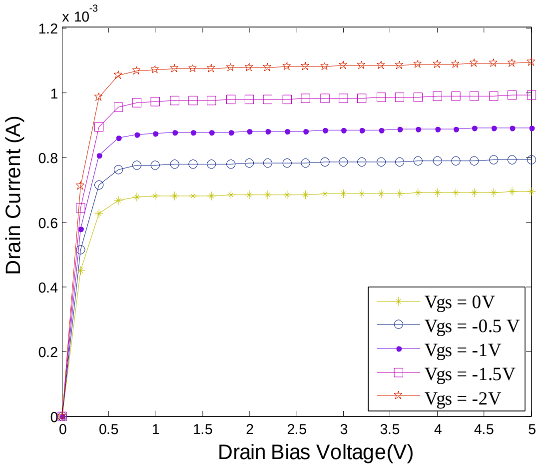

Figure 4: New Model I-V Characteristics of HEMT

Effect of illumination:

Figure 5 gives the amount of absorbtion of optical radiation,it was observed that as the distance in the vertical direction increases,the absorbtion of radiation decreases exponentially.At the active layer thickness(110nm) for the optical radiation of 1.5mW ,the amount of optical power absorbed was maimum(1.21mW) at the top of AlGaN layer and the minimum observed was1.07mW.

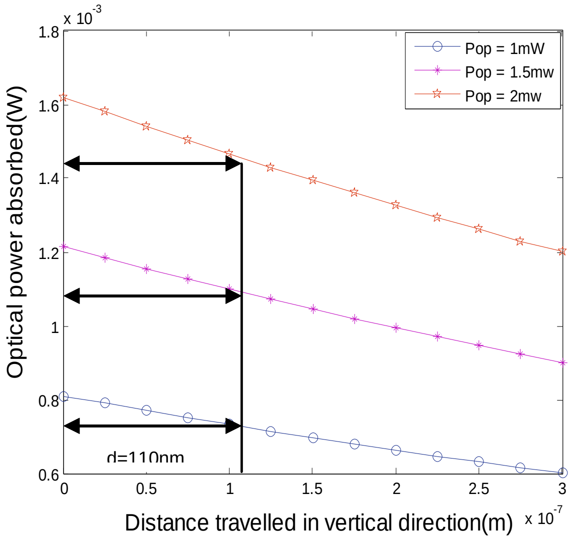

Figure 5: Absorption of optical power in the direction of illumination

Figure 6 shows the optical generation rate under illuminated condition.The optical generation rate increases as the operating wavelength increases,for the working wavelength of 1330nm the optical generation rate is $7.2*10^{21}/m^3$ at the incident radiation of 1.5mW.

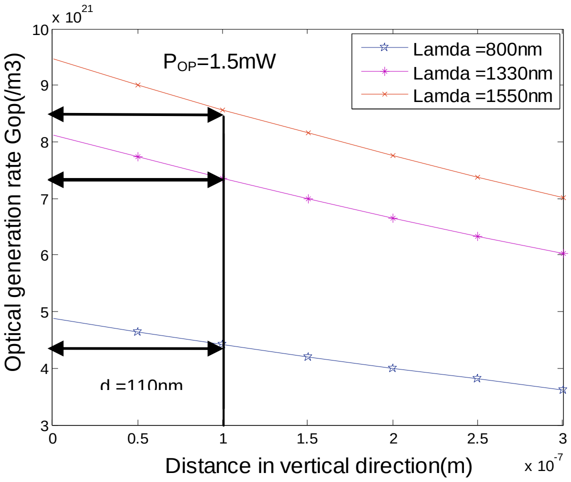

Figure 6: Variation of optical generation rate with wavelength

The absorption of incident radiation in AlGaN results in generation of excess electron-hole pairs.These excess carriers cause achange in the lifetime of the minority carriers which in turn effects the optical voltage (V_{op}) developed across the Schottky gate.

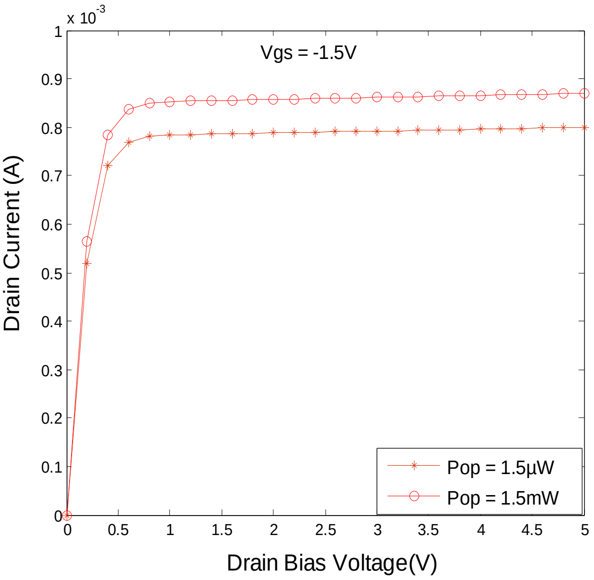

Figure7: Variation of Minority carrier Lifetime with

Figure 7 Shows the variation of τ_L with incident optical power.It is observed as the optical power increases τ_L decreases which in turn increases the photovoltage V_{op} as seen in figure8.At an incident optical power Pop=2 mW the photovoltage was found to be 0.51V

Figure 9 gives the variation of sheet concentration with the channel voltage ,it was observed that the sheet concentration decreases with the increase in the channel potential.This is because as the channel potential increases. the depletion width increases and hence the sheet concentration the sheet concentration decreases.it is also observed that additional electrons in the AlGaN layer increases the sheet concentration,This is because due to illumination excess electrons are generated and this increases the sheet concentration as can be seen.

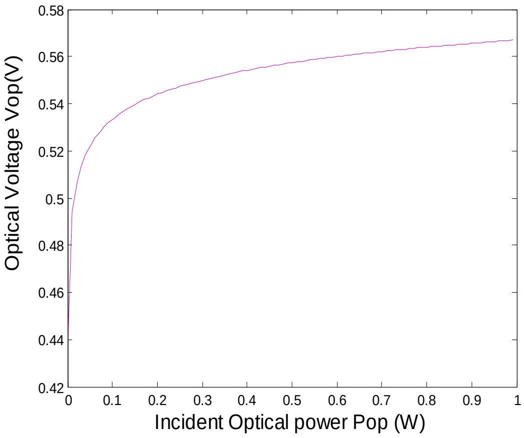

Figure8: Variation of Vop with Optical

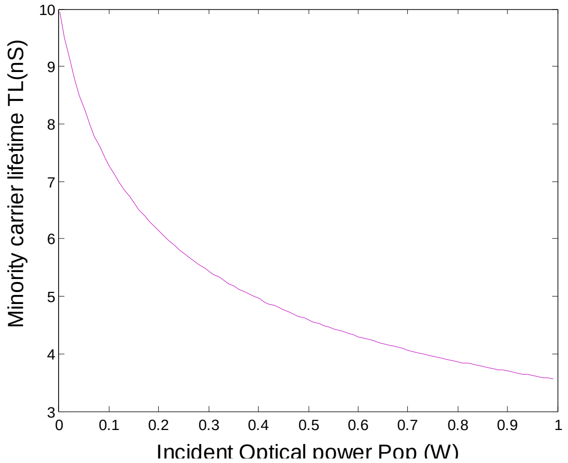

Figure 9: Effect of illumination on Sheet Concentration

With the optical power radiation to be Pop=1.5mW (V_{op}=0.4493V)the effect on short channel was considered at V_{gs}=-1.5V.

Figure10 shows the effect of illumination on the device it was observed that the drain current increases tremendouly under illuminated condition because the photovoltage developed is superimpossed on V_{gs} which forward biases the gate junction.This in turn increases the drain current.

For Long model and Short model it was observed that as the optical radiation increases the drain current increases due to increases in V_{op} and more forward biasing of gate

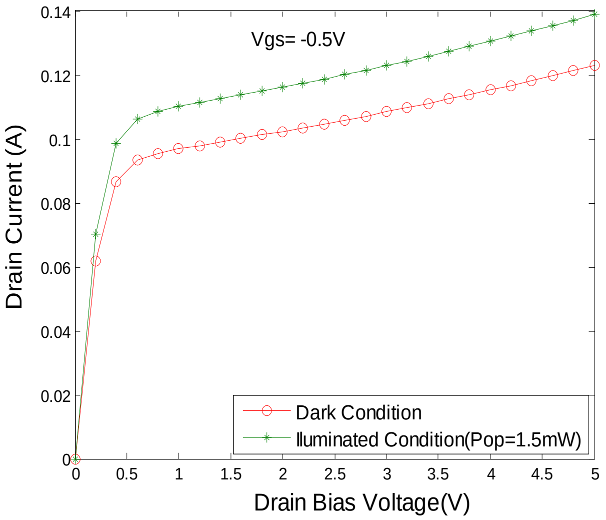

Figure 10: Variation of Drain current in HEMT (L_G=3µm) with optical power.

junction. Figure11 and Figure12 give these variations of drain current with drain voltage for different illuminated conditions. For L_G 3µm and .23µm respectively.

The sensitivity of the channel with L_G=3µm under illumination was evaluated and it was found that the sensitivity is 9% when power is increased from 1.5mW to 15W.Under the same condition the sensitivity of the channel with L_G=.23µm was evaluated and it was found that the sensitivity is 20%.

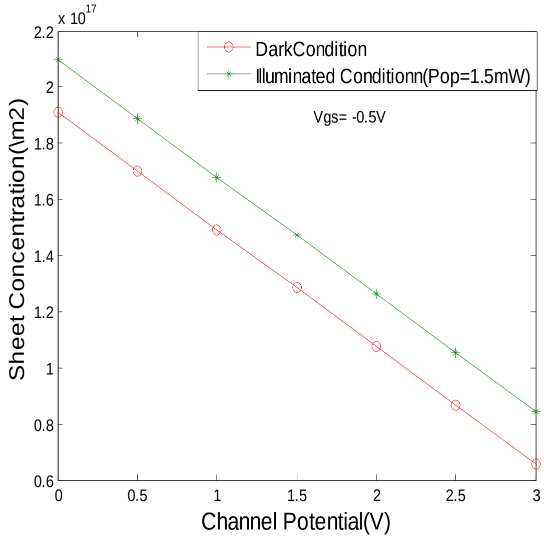

Figure11: Effect of Illumination on I-V characteristics of HEMT (L_G=0.23µm)

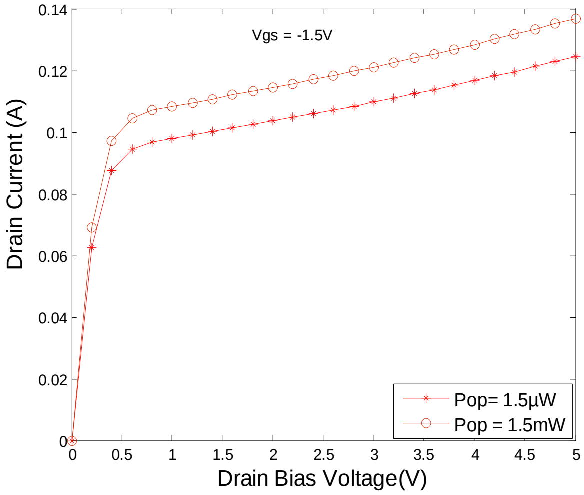

Figure 12: Variation of Drain current in HEMT (L_G=0.23µm) with optical power.

4. CONCLUSION:

This paper compared the current equations of the new model for L_G=3µm and L_G=.23µm,it was found that this model gives better results and the current increases as the length of the gate decreases. The model for submicron GaN HEMT defined in this paper shows that the optical radiation develops a photo-voltage at the Schottky junction. It increases the photo-voltage as the radiation increases and causes more current to flow. This nature of variation is similar to the results reported by [6] for GaAs HEMT.

The sensitivity has also been found and it is observed that short channels devices are more sensitive to light radiations and hence find applications in OMMIC's.

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