ANALYTICAL MODEL FOR CHANNEL CONDUCTANCE AND I-V CHARACTERISTICS OF BURIED GATE MESFET

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ABSTRACT

GaAs MESFETs have the capability of amplifying small signal with wide frequency range and low noise figure. The improved performance in I-V characteristics is achieved by buried-gate GaAs MESFET under front side illumination. The modulated characteristics of buried-gate GaAs MESFETs have been analyzed by solving continuity equation. This analysis is done by using front side illumination with the ion implanted buried-gate process. As the optical fiber is inserted, in the front side of the device, the current- voltage characteristics of buried gate GaAs MESFET with front side illumination are increased. Through this analysis the photo -voltage characteristics and the channel conductance of the device have been evaluated. From this analysis, it is understood that the performance characteristic is very good, when compared with other devices like MESFET under back illumination and MESFET with front illumination having surface gate. When photo energy falls on the device, due the change in the substrate–buried gate junction temperature, flow of charge carriers increases and hence the performance of the device is improved. Buried-gate optical field effect transistor (OPFET) will be highly suitable for power device application, optical communication and optical computing.

Index Terms: AC model optically illuminated field-effect transistor (OPFET), GaAs OPFET, optically controlled metal–semiconductor–field-effect transistor (MESFET).

I. INTRODUCTION

High-speed low-cost monolithically integrated photo electronic circuits using metal semiconductor field effect transistors are highly using for varies-wavelength optical communications. In recent years GaAs is more extensively used for the fabrication of ion-implanted MESFET than any other material. MESFETs can be classified in two categories, (i) Enhancement-mode (E-MESFET) and (ii) Depletion-mode MESFET (D-MESFET). In normally on (or depletion mode) device, the MESFET has a conductive channel with the Schottky-barrier gate voltage Vgs = 0, and a negative gate bias must be applied to increase the gate Schottky-barrier depletion width to reach the semi insulating substrate and cut off the source-to drain current MESFETs are fabricated using two different buried gate technologies, namely: (a) the epitaxial buried gate process and (b) the ion-implanted buried-gate process. In this work, we have analyzed an ion-implanted buried gate GaAs MESFET with front illumination.

The MESFET has three metal-semiconductor contacts one Schottky barrier for the gate electrode and two ohmic contacts for the source and drain electrodes. The base material on which the transistor is fabricated is a semi-insulating GaAs substrate. Two ohmic contacts, the source and drain, are fabricated on the highly doped layer to provide access to the external circuit. Between the two ohmic contacts, Schottky contact is buried The electron mobility is approximately 20 times greater than the hole mobility for GaAs, the conducting channel is always n type for microwave transistors. Highly doped (n +) layer is grown on the surface to aid in the fabrication of low-resistance ohmic contacts to the transistor. This layer is etched away in the channel region. Alternatively, ion-implantation may be used to create the n channel and the highly doped ohmic contact regions directly in the semi insulating substrate. The idea of buried gate structure is also applicable to other devices. For more than two decades, the optical effect in MESFET has been studied widely because of its potential application in optoelectronic very large scale integration (OE-VLSI), optical communication, and optical computing.

The sensitivity of the device depends on the absorption coefficient of light. There are different ways by which light may be absorbed within the material. The conventional way of illuminating the MESFET is the front illumination with transparent/semitransparent gate or opaque gate [1]. However, for enhanced absorption in MESFET, de Salles [2] has suggested two alternatives: 1. the device may be illuminated from the back where the fiber may be inserted partially or fully into the substrate of the device and 2. the buried gate MESFET with front illumination.

In this paper, we analyzed theoretically the effect of the modulated light on the characteristics of buried gate GaAs MESFET under front illumination [4]. We consider the ion-implanted profile in the active region. The photo voltage drop takes place across the buried gate and substrate-active layer because fiber is inserted up to the substrate-active layer junction. The photo voltage the channel conductance, the drain current of the device has been calculated. Calculated variations of drain saturation current Ids for lambda is equal to 0.025 and 0.1 of buried gate GaAs MESFET's.

Present calculation shows that the buried gate GaAs MESFET with front illumination represents still better performance compared to the results of the conventional back illumination.

II. THEORY

The cross sectional structure of MESFET is shown in Fig. 1. The basic operation involves production of free carriers within the semiconductor material when light of photon energy equal to or greater than the semiconductor material band gap energy. The active region has a non uniform doping profile represented by the Gaussian distribution. It consists of a neutral region followed by a depletion region due to Schottky junction of the buried gate. The photo absorption takes place in both neutral and depletion regions. The gate is assumed buried, so there is no or very little absorption in the substrate region.

During photo absorption the electron-hole pairs are generated in both neutral and depletion regions. The electrons move from source to drain in the channel region when a drain-source voltage is applied. The holes move toward the substrate. In the neutral region the photo generated electrons move by the process of diffusion and recombination (both bulk and surface).In the depletion region the transport of carriers is due to drift and bulk recombination only.

Under illumination the photo generated electrons and holes in the neutral and depletion regions are obtained by solving the dc continuity equations [9].

For electrons is

$$\frac{1}{2}\frac{dJ_n}{dy}+G_n-U_n=0 \tag{1}$$

For holes is

$$-\frac{1}{q}\frac{dJ_p}{dy}+G_p-U_p=0 \tag{2}$$

In the above equations, G_p and G_n are the generation rate per unit volume ($m^{-3}s^{-1}$), U_p and Un are the recombination rates,

$$Un=\frac{n}{\tau_{\omega n}} \text{ and } G_n=\Phi\,\alpha\,e^{-\alpha y}$$

and J_n and J_p are the electron and hole current densities, respectively defined by,

$$J_n=q\,v_y+q\,D_n\frac{dJ_n}{dy} \tag{1a}$$

and

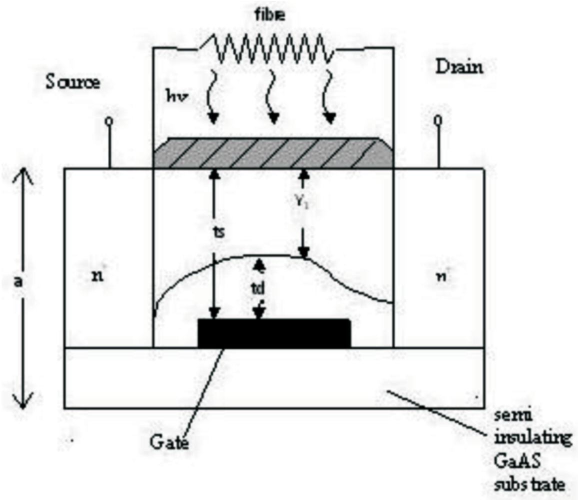

Fig. 1. Cross sectional structure of MESFET

$$J_p = q\, v_y + q\, D_p \frac{DJ_p}{dy} \tag{2a}$$

In the above equation include drift and diffusion terms.

A. Current due to depletion region

Applying the continuity equation of first order differential equation [8] in the depletion region is given by

$$\frac{dn_1}{dy} + \frac{n_1}{v_y \tau_{\omega n}} = -\Phi\, e^{\frac{-\alpha y}{v_y}} \tag{3}$$

The number of carriers generated in this region per unit volume is obtained by solving (3). From physical conditions, we assume the coefficient of the exponentially increasing function to be zero. The photo generated electrons in the gate depletion region is obtained as

$$n_1 = \frac{\alpha\, \Phi\, \tau_n}{1 + \alpha\, v_y \tau\, \omega_n}\, e^{-\alpha\, y} \tag{4}$$

$$I_{\text{dep}} = \frac{q\, \mu\, Z}{L} \int_0^{V_D} \int_{y_1}^{t_s} n_{1\; d_y}\, d_V \tag{4a}$$

The photo generated holes in the gate depletion region is obtained as

$$\frac{dp_1}{dy} - \frac{P_1}{v_\gamma \tau_{\omega n}} = -\Phi\, \alpha\, e^{-\frac{\alpha y}{v_y}}$$

TABLE I
Parameter Values

Device Parameter	Symbols	Values
Photon absorption coefficient	α	1.0×10^{6} m^{-1}
Carrier velocity in y-direction	v_y	1.2×10^{5} m/s
Equivalent constant doping profile	N_{de}	0.658×10^{23} m^{-3}
Straggle parameter	σ	0.383×10^{-6} m
Permittivity	ε	1.04×10^{-10} f/m
Total effective thickness of active layer	t_s	0.1 ìm
Projected range	Rp	0.861×10^{-7} m
Schottky barrier height	Φ_B	0.9 eV
Trap density	N_t	1.0×10^{15} m^{-2}
Channel width	Z	100×10^{-6} m
Channel length	L	3×10^{-6} m
Electron mobility	μ_n	0.85 m^2/v.s
Hole mobility	μ_p	0.04 m^2/v.s
Active layer thickness	a	0.25 μm

B. Current due to Generation in the Neutral Region

The channel being neutral, there is no field within this region in the absence of any drain-source voltage, so and the transport of carriers will be only due to diffusion and recombination.

$$\frac{d^2 n_2}{dy^2} = \frac{n_2}{Dn\, \tau_{\omega n}} - \frac{\Phi}{Dn}\, e^{\frac{-\alpha y}{v_y}} + \frac{Rs\, \tau_{\omega n}}{\alpha\, L^2_{\omega n}} \tag{6}$$

From the above equation, we find

$$n_2 = C_1 \exp \frac{y}{Dn\, \tau_{\omega n}} +$$

$$C_2 \exp\left[\frac{-y}{Dn\, \tau_{\omega n}}\right] - \left[\frac{\alpha\, \Phi\, e^{-\alpha y}}{Dn\left[\alpha^2 - \frac{1}{L_n^2}\right]}\right] - \frac{R_s}{\alpha\, L_n^2} \tag{7}$$

At boundary condition, C_1=0 and C_2 becomes

$$C_2 = \Phi\, \alpha[\tau_{\omega n} + \frac{1}{D_n\left[\alpha^2 - \frac{1}{Ln^2}\right]}$$

Substitute C_1 and C_2 in (7) and the photo generated electron concentration in the neutral region is

$$n_2 = \alpha\,\Phi\left[\tau_{\omega n}\frac{1}{Dn\left[\alpha^2-\frac{1}{Ln^2}\right]}\right]\exp\left[\frac{-y}{D\gamma\,\pi_{\omega n}}\right]-$$

$$\left[\frac{\alpha\Phi e^{-\alpha y}}{Dn\left[\alpha^2-\frac{1}{Ln^2}\right]}\right]-\frac{Rs}{\alpha\,L_n^2} \qquad (8)$$

Rs is the surface recombination rate. Rs is calculated using the relation [7]

$$D_n = \frac{KT}{q}\mu_n$$

The optical flex density being assumed to be modulated by the signal frequency, with small signal as

$$\Phi = \Phi_0 + \Phi_1\, e^{j\omega t}$$

$$n = n_0 + n_1\, e^{j\omega t}$$

$$p = p_0 + p_1\, e^{j\omega t}$$

$$G = G_0 + G_1\, e^{j\omega t}$$

Where "zero" indicates the dc value and "one" indicates the ac value.

Assuming that only negative trap centers are present and that the traps close to the surface

Therefore

$$R_s \approx N_t\, k_p\, p_s$$

and

$$D_n = \frac{KT}{q}\mu_n$$

$$\frac{1}{\tau_{\omega p}} = \frac{1}{\tau_p} + j\omega$$

$$\frac{1}{\tau_{\omega n}} = \frac{1}{\tau_n} + j\omega$$

are the lifetime of holes and electrons under ac condition

If $\frac{1}{\tau_{\omega p}} \geq \omega$, is independent of ω

The corresponding charge density is obtained as

$$Qact = q\int_0^{y_{11}} n_2\, dy \qquad (9)$$

$$Y_1 = t_s - \frac{2\varepsilon}{qN_{de}}\left[\Phi_B - \Delta + V(x) - V_{GS}\right]^{\frac{1}{2}} \qquad (10)$$

$$Qact = q\int_0^{y_1}\left\{\alpha\,\Phi\left[\tau_{\omega n}\frac{1}{Dn\left[a^2-\frac{1}{Ln^2}\right]}\right]\right.$$

$$\left.\exp\left[\frac{-y}{Dn\,\tau_{\omega n}}\right]-\left[\frac{\alpha\,\Phi\, e^{-\alpha y}}{Dn}\left[a^2-\frac{1}{Ln^2}\right]-\frac{Rs}{\alpha\,L_n^2}\right\}dy\right]$$

Where, Y_1 is the distance from the surface to edge of the gate depletion region in the channel under dark region.

Current due to generation in the neutral active region is

$$I_{act} = \frac{q_1\,\mu\, Z}{L}\int_0^{y_1}\int_0^{V_D} n_2\, d_y\, d_v$$

$$Iact = \frac{\mu Z}{L}\int q\left\{\alpha\,\Phi\left[\tau_{\omega n}\frac{1}{Dn\left[\alpha^2-\frac{1}{Ln^2}\right]}\right]\right.$$

$$\left.\exp\left[\frac{-y}{Dn\,\tau_{\omega n}}\right]-\left[\frac{\alpha\,\Phi\, e^{-\alpha y}}{Dn\left[\alpha^2-\frac{1}{Ln^2}\right]}\right]-\frac{Rs}{\alpha\,L_n^2}\right\}dy\, d_v \qquad (11)$$

C. Current Due to Ion-Implantation

The semi-insulating substrate is p-type doped and has uniform doping profile [7], which is represented by

$$N(y) = \frac{Q}{\sigma\sqrt{\pi}}\exp\left[-\left[\frac{Y-RP}{\sigma\sqrt{2}}\right]\right]-N_{sd}+N_{de}$$

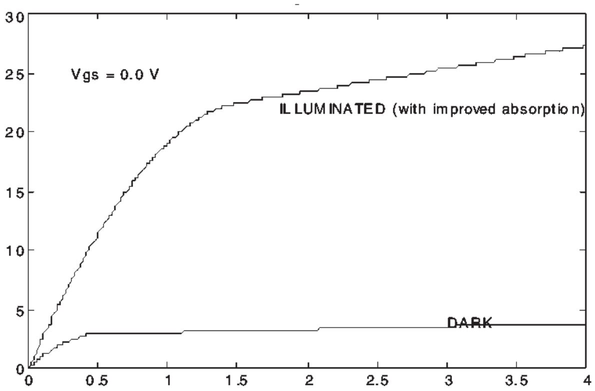

Fig. 2 Drain-source current versus drain-source voltage under dark and illuminated condition for buried gate structure MESFET at zero gate-source voltage with modulated frequency is 0.1 G HZ.

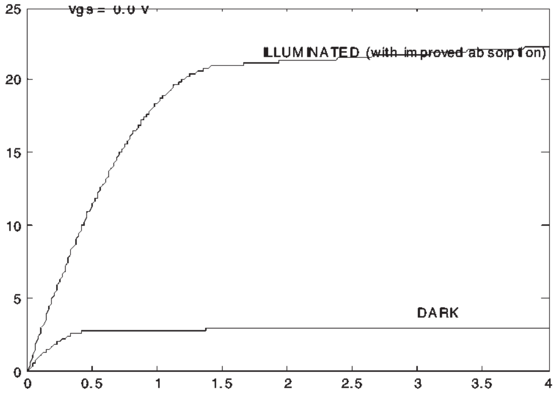

Fig. 3 Modulated Drain source current verses drain source voltage for $\lambda = 0.025$ with modulated frequency is 0.1G HZ.

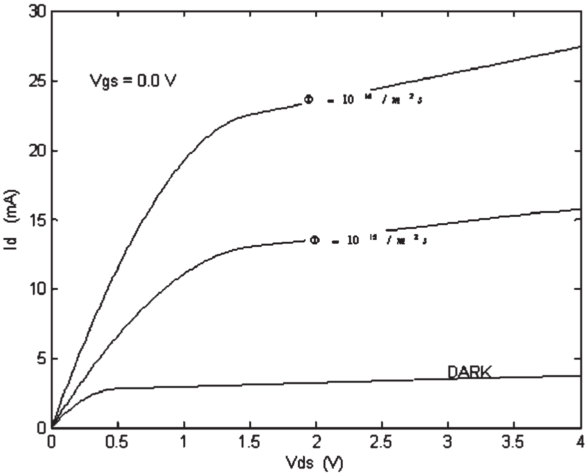

Fig. 4 Drain source current verses drain source voltage for various flux densities

Where *Q*, *Rp* and are the implanted dose per unit area, projected range and straggle parameter in length respectively

The corresponding channel charge due to ion-implantation is obtained as

$$Q_{\text{ion}} = q \int_{0}^{Y_{11}} N(y)\, dy$$

N(y) is being given by (10) it is obtained as

$$Q_{ion} = q\left\{ \frac{Q}{2}\left[erf\frac{Y_{11} - RP}{\sigma\sqrt{2}} \right] - \frac{Q}{2}\left[\frac{-RP}{\sigma\sqrt{2}} \right] - N_{sd}\,Y_{11} + N_{de}\,Y_{11} \right\}$$

$$Y_{11} = t_s - \frac{2\varepsilon}{qN_{de}}(\Phi_B - \Delta + V_{gs} - V_{op})^{\frac{1}{2}}$$

Where Y_{11} is the distance from the surface to the modified edge of the gate depletion region due to photo voltage developed across the Schottky junction of the buried gate

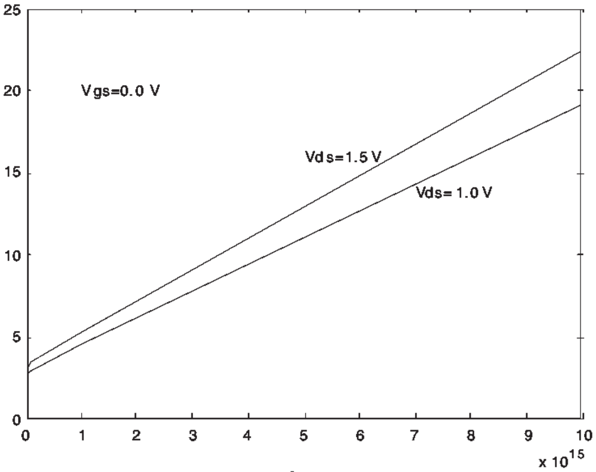

Fig. 5 Drain-source current with flux density at different drain-source voltages

The channel current due to ion-implantation is obtained using the relation

$$I_{ion} = \frac{\mu Z}{L}\int_{0}^{V_D} Qion\,dv \qquad (12)$$

Where

$V_D$is the channel voltage.

D. Calculation of Photovoltage

The photo voltage is developed due to the transport of holes across the schottky junction [1].

$$\frac{dp_1}{dy} - \frac{p_1}{v_y \tau_{\omega p}} = \frac{\alpha \Phi e^{-\alpha y}}{v_y} \tag{13}$$

The boundary condition at $y = y_{dg}, p_1 = (\tau_p \Phi \alpha e^{-\alpha y\, dg}$ is used to solve (13). The hole density is thus found to be

$$p_1 = \frac{t_p \Phi \alpha}{1 - \alpha v_y \tau_{ap}}$$

$$\left(e^{-\alpha y} - a v_y \tau_p \exp\left(\frac{1}{v_y \tau_{\omega p} - \alpha} \right) Y\, dg^{e^{\frac{y}{\tau_p v_y}}} \right) \tag{14}$$

The number of holes crossing the Schottky junction at $(y = t_s)$ is calculated. The photo voltage is obtained using the relation.

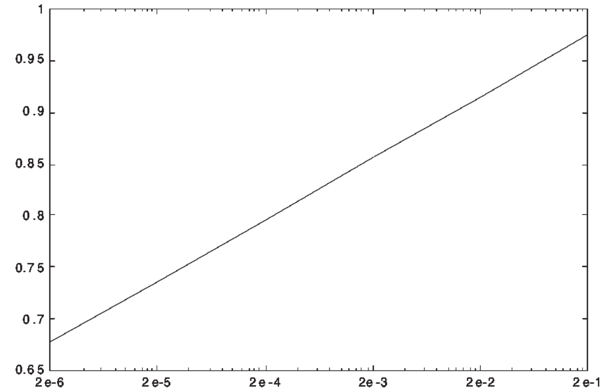

Fig. 6 Variation of photo voltage with optical power density

$$V_{op} = \frac{KT}{q} ln \frac{v_y q p_{1\,(y = t_s)}}{J_s} \tag{15}$$

E. Channel current and drain current

The channel current is contributed by the carriers from ion implantation and optical generation in the channel and depletion region. The total channel current is the summation of ion implantation and current in the active and depletion region

$$I_{ch} = I_{ion} + I_{ddp} + I_{act} \tag{16}$$

The drain current is expressed as [6]

$$Ids = Isa\,(1 + \lambda V_1) \tan h\,(\eta V_i) \tag{17}$$

F. Channel Conductance

The channel conductance of the device has been calculated Shubha et al [4] by differentiating the drain-source current with respect to drain- source voltage, when gate-source voltage is constant

$$g_d = \frac{dI_{ds}}{dV_{ds}} / V_{gs} = \text{ constant} \tag{18}$$

After differentiation of the drain-source current with respect to drain- source voltage, the channel conductance of the device is

$$g_d = I_{sat} [\eta\, (1 - \tan h^2\, (\tan V ds))\, (1 + \lambda V ds)$$
$$+ \lambda \tan h\, (\eta\, V ds)] \tag{19}$$

The saturation current for this device is

$$I_{sat} = I_{ch} [M - (M^2 - 1 + H_{gs}]^{\frac{1}{2}} \tag{20}$$

Where

$$M = 1 + \left(\frac{r_s + I_{ch}}{2 V_{po}} \right)$$

$$H = \frac{(V_{bi} - V_{gs}}{V_{po}}$$

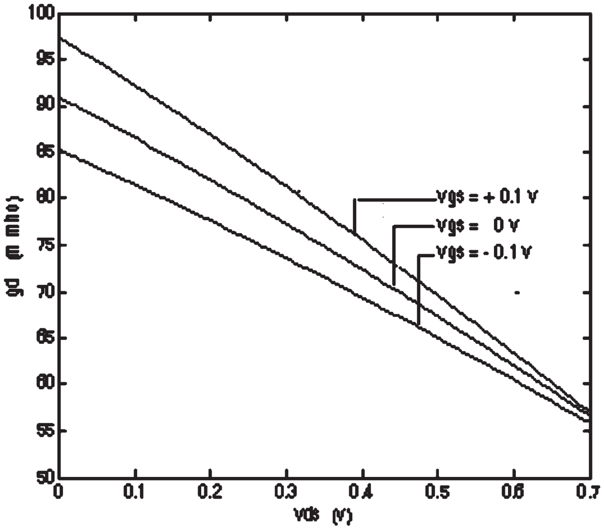

Fig. 7 Channel conductance verses drain source voltage for various gate source voltage

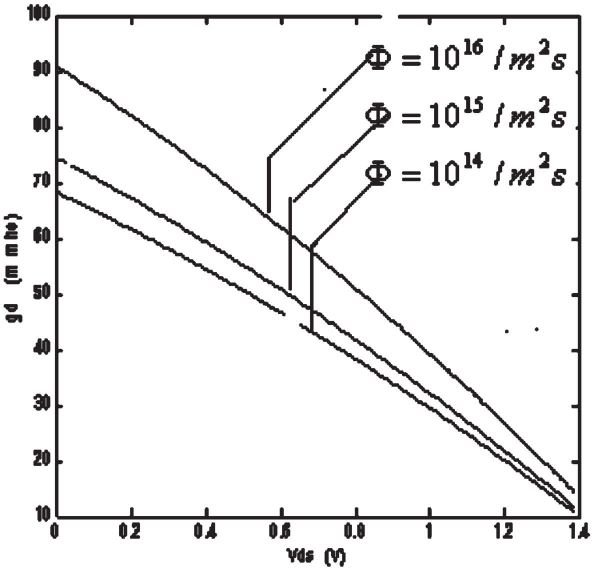

Fig. 8 Channel conductance verses drain source voltage for various flux densities

III. RESULTS AND DISCUSSION

The drain-source current variation with respect to the drain-source voltage with modulated frequency 0.1GHZ using buried gate MESFET with optical fiber inserted up to the active layer-substrate junction with front illumination, as shown in Fig 2. This plot shows I-V characteristics under dark and illumination ($\Phi = 10^{16}/\text{m}^2\,\text{s}$). It is observed that the drain-source current is more in the condition of buried gate MESFET with optical fiber inserted up to the active layer-substrate junction with front illumination. It is also observed that under illumination drain-source current tends to saturate at higher values of drain-source voltage. If we compare the result with back illumination Roy et al [1], the drain source current is more because of gate is buried and also compared with back and front illumination de Salles [2], Shubha et al [4], the drain source saturation level is increased. As the optical fiber is not used light may be scattered and hence the mobility of charge carrier cannot be that much induced but here, since the optical fiber is used the scattering of light can be avoided so that the mobility of charge carrier is increased and hence the magnitude of drain current is increased. I-V characteristics of buried gate MESFET under dark and illumination ($\Phi = 10^{16}/\text{m}^2\,\text{s}$) with $\lambda = 0.1$ as shown in Figure 2, drain current changes with respect to change in Vds. In the figure 3 is obtained with $\lambda = 0.025$ drain-source current tends to saturate at higher values of drain-source voltage.

The drain-source current against drain-source voltage for various flux densities shown in Figure 4, this shows increase in current compared with Roy et al [1], de Salles [2], Lo and C.P. Lee [3], Shubha et al [4], S. Mishra et al [7]. The drain-source current against flux density at different drain-source voltages are as shown in Figure 5, the current increases in a nonlinear form as flux density increases.

The photo voltage against optical power density incident on the device is shown in Figure 6, the photo voltage effect depends upon substrate active layer and depletion layer effect. This increase in logarithmic in nature is good compared with M. Madheswaran et al [8]. The photo voltage has a significant role in the channel width modulation and hence the conductivity variation is good in buried gate GaAs MESFET with front side illumination.

The channel conductance variations with drain-source voltage for various gate source voltages are, as shown in Figure 7. This represents the channel conductance decreases with respect to drain to source voltage and is independent of gate source voltage. Figure 8 represents the plot of Channel conductance versus drain source voltage for various flux densities under illuminated condition. The performance characteristic of channel conductance is good compared with Shubha et al [4].

IV. CONCLUSION

In this paper the modulated characteristics analysis of the buried gate GaAs MESFET with ion-implanted profile under front illumination has been carried out. The present OPFET, with buried gate and fiber inserted up to the substrate-active layer junction appeared to be the most sensitive to optical illumination because the optical absorption is more prominent in the neutral region than in the depletion region. The device thus may be useful in high power application, optical communication and computer.

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