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Analytical Model for I-V Characteristics of Buried Gate MESFET

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Abstract

A theoretical model for the I-V characteristics of buried-gate GaAs metal semiconductor field-effect transistors has been developed by solving dc continuity equation. This analysis includes the ion implanted buried-gate process. It is shown that the current- voltage could be rather increased when introducing an optical fiber to the buried-gate GaAs MESFETs structure. The current -voltage characteristics and the channel conductance of the device have been evaluated. The results indicate very good performance of the device compared to other devices like MESFET under back illumination and MESFET with front illumination having surface gate. Buried-gate optical field effect transistor (OPFET) will be highly suitable for power device application, optical communication and optical computing.

Keywords: *Metal Field Effect Transistor (MESFET), Enhancement-mode (EMESFET), Depletion-mode MESFET (D-MESFET), optical field effect transistor (OPFET).*

1. 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 DC light on the characteristics of buried gate GaAs MESFET under front illumination [5]. 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 and the drain current of the device have 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 front and back surface state illumination.

2. Theory

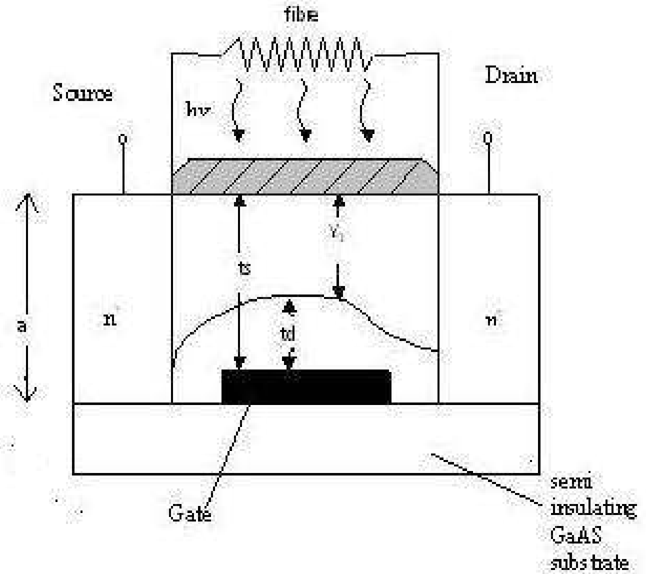

Figure 1 cross sectional structure of MESFET

The Schematic Structure of MESFET is shown in Figure 1. The fundamental physical mechanism arising in optical illumination of the MESFET is the production of free carriers within the semiconductor material when light of photon energy equal to or greater than the semiconductor material band gap energy is absorbed. 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.

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

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

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,

$$Un=\frac{n}{\tau_n};$$

$$G_n=\Phi\alpha e^{-\alpha y}$$

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

$$J_n=qv_y+qD_n\frac{dJ_n}{dy} \tag{1a}$$

and

$$J_p=qv_y+qD_p\frac{dJ_p}{dy} \tag{2a}$$

In the above equation include drift and diffusion terms.

3. 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

3.1 Current due to depletion region

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

$$\frac{dn_1}{dy} - \frac{n_1}{v_Y \tau_n{}^2} = -\Phi \alpha e^{-\frac{\alpha y}{v_y}} \tag{3}$$

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

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

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

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

$$\frac{dp_1}{dy} - \frac{p_1}{v_Y \tau_p} = -\Phi \alpha e^{-\frac{\alpha y}{v_y}} \tag{5}$$

TABLE I. PARAMETER VALUES

Device Parameter	**Symbols**	**Values**
Photon absorption coefficient	α	$1.0\text{x}10^{6}$ m^{-1}
Carrier velocity in y-direction	v_y	$1.2\text{x}10^{5}$ m/s
Equivalent constant doping profile	N_{de}	$0.658\text{x}10^{23}$ m^{-3}
Straggle parameter	σ	$0.383\text{x}10^{-6}$ m
Permittivity	ε	$1.04\text{x}10^{-10}$ f/m
Total effective thickness of active layer	t_s	0.1 μm
Projected range	Rp	$0.861\text{x}10^{-7}$ m
Schottky barrier height	Φ_B	0.9 eV
Trap density	N_t	$1.0\text{x}10^{15}$ m^{-2}
Channel width	Z	$100\text{x}10^{-6}$ m
Channel length	L	$3\text{x}10^{-6}$ 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

3.2 Current due to Neutral Region

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

$$\frac{d^2 n_2}{dy^2} = \frac{n_2}{Dn\ \tau_n} - \frac{\Phi}{Dn} e^{-\frac{\alpha y}{v_y}} + \frac{Rs\ \tau_n}{\alpha L_n^2} \tag{6}$$

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

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

The corresponding charge density is obtained as

$$Qact = q\int_0^{y_1} n_2 dy \tag{7}$$

$$Y_1 = t_s - \frac{2\varepsilon}{qN_{de}}\left[\Phi_B - \Delta + V(x) - V_{GS}\right]^{\frac{1}{2}} \tag{8}$$

Where,

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

$$I_{act} = \frac{q\mu Z}{L}\int_0^{y_1}\int_0^{V_D} n_2 d_y d_v \tag{9}$$

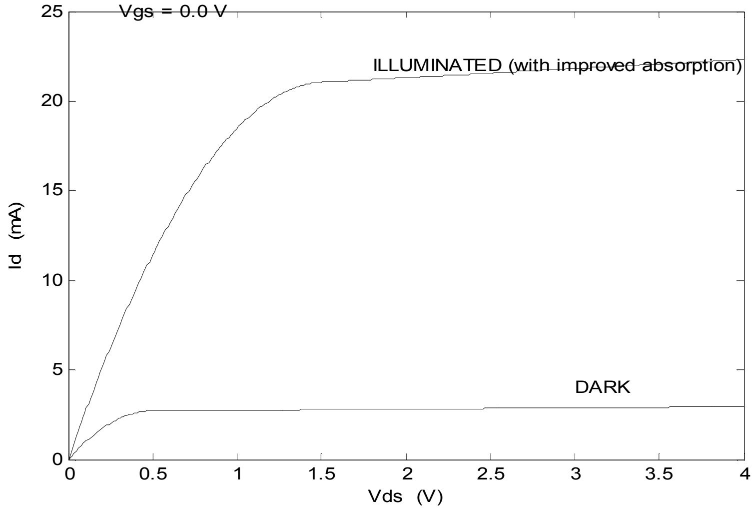

Figure 2 Drain-source current versus drain-source voltage under dark and illuminated condition for buried gate structure MESFET at zero gate-source voltage.

3.3 Current Due to Ion-Implantation

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

$$N(y)=\frac{Q}{\sigma\sqrt{\pi}}\exp\left[-\left[\frac{Y-Rp}{\sigma\sqrt{2}}\right]^{2}\right]-N_{sd}+N_{de} \qquad (10)$$

Where

Q, Rp and σ 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

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

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

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

$$y_{11}=t_{s}-\frac{2\varepsilon}{qN_{de}}(\Phi_{B}-\Delta+V_{gs}-V_{op})^{\frac{1}{2}}$$

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.

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

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

Where

V_D is the channel voltage.

3.4 Calculation of Photo voltage

The photo voltage is developed due to the transport of holes across the schottky junction [4].

$$\frac{dp_{1}}{dy}-\frac{p_{1}}{v_{Y}\tau_{p}}=\frac{\alpha\Phi e^{-\alpha y}}{v_{y}} \qquad (13)$$

The boundary condition at y =y_{dg}, $p_{1=}\left(\tau_{p}\Phi\alpha e^{-\alpha y_{dg}}\right)$ is used to solve (13). The holes density is thus found to be

$$p_{1=}\frac{\tau_{p}\Phi\alpha}{1-\alpha v_{y}\tau_{p}}\left(e^{-\alpha y}-\alpha v_{y}\tau_{p}\exp\left(\frac{1}{v_{y}\tau_{p}}-\alpha\right)y_{dg}e^{-\frac{y}{\tau_{p}v_{y}}}\right) \qquad (14)$$

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

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

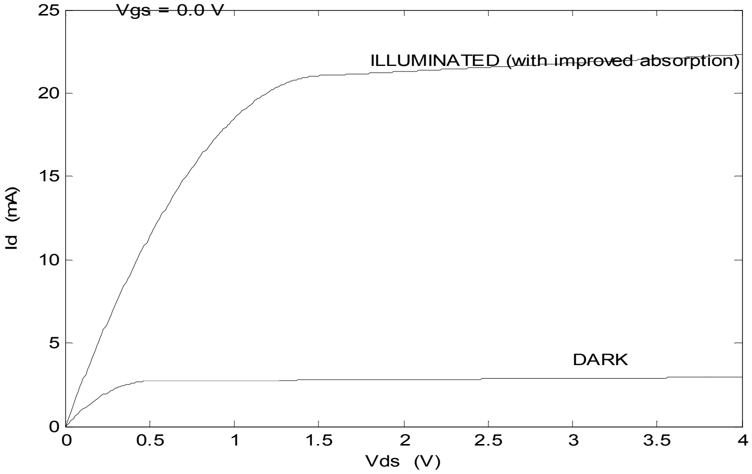

Figure 3 Drain-source current with drain-source voltages for λ=0.1

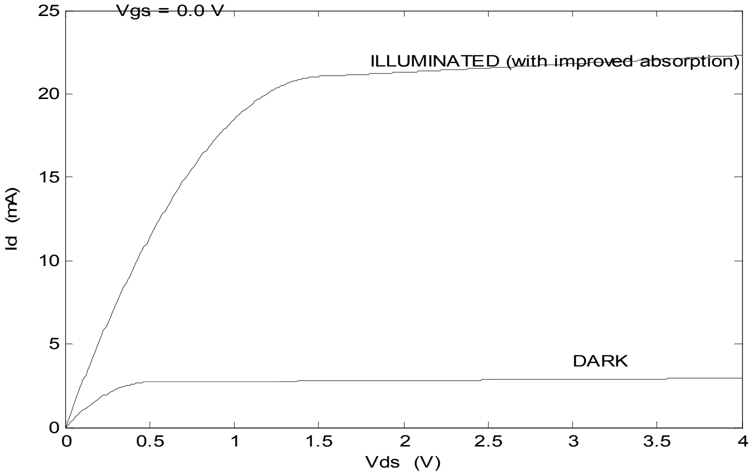

Figure 4 Drain source current verses drain source voltage for λ=0.025

The total channel current is the summation of ion implantation and current in the active and depletion region is obtained as

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

The drain current is expressed as [6]

$$Ids = Isat\,(1 + \lambda V_i)\tanh(\eta V_i)) \tag{17}$$

3.5 Channel Conductance

The channel conductance of the device has been calculated [3] by differentiating the drain-source current with respect to drain- source voltage, when gate-source voltage is constant.

$$g_d = \frac{dI_{ds}}{dV_{ds}} / V_{gs} = cons\tan t \qquad (18)$$

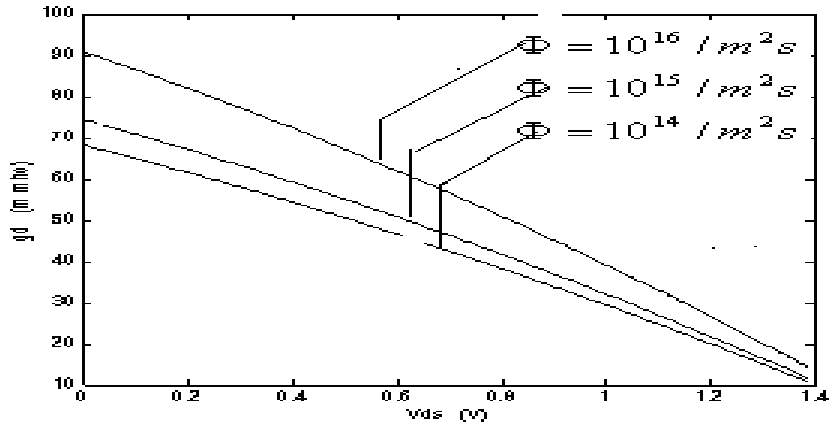

Figure 5 Channel conductance verses drain source voltage for various flux densities

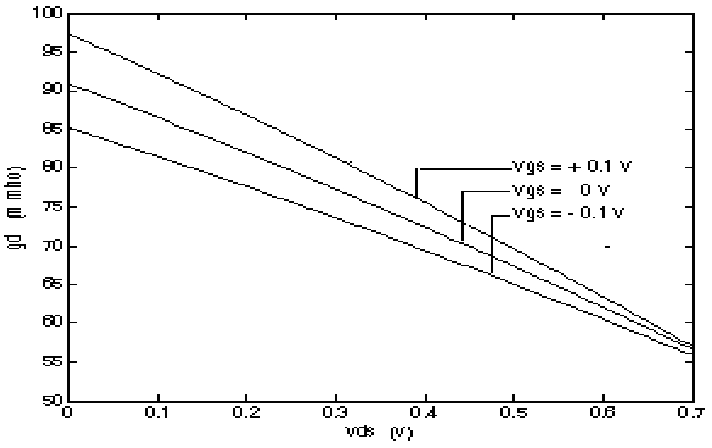

Figure 6 Channel conductance verses drain source voltage for various gate source voltages

4. Results and Discussion

Figure 2 Shows the plot of I-V characteristics under dark and illumination ($\Phi = 10^{16}$ / m^2s). 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.

Figure 3 shows the drain source verses drain source voltage for λ is equal to 0.1. This increases I-V characteristic compared with the previous figure 2.the drain source current changes with respect to change drain source voltage

Figure 4 shows the drain source verses drain source voltage for λ is equal to 0.025.it is observed that under front illumination the drain source current reaches to saturation after threshold level.

Figure 5 shows the channel conductance verses drain source voltage for various flux densities ($\phi=10^{16,}$ / m^2s), ($\phi=10^{15}$/ m^2s) & ($\phi=10^{14}$ / m^2s).The channel conductance decreases with increase in drain source voltage.

Figure 6 shows the plot of channel conductance drain-source voltage for various gate source voltages. The channel conductance decreases with increase in drain source voltage for various values of drain source voltage. Initially the channel conductance is more when gate source voltage is positive, compared with gate source voltage is zero, but after some drain source voltage level channel conductance is constant.

4 Conclusion

A theoretical model for the I-V characteristics and channel conductance of buried-gate GaAs metal semiconductor field-effect transistors has been developed using optical fiber under front side illumination .The DC 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 optical communication and computer.

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