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ANALYTICAL MODEL FOR THE POTENTIAL DISTRIBUTION IN OPTICALLY BIASED SHORT GATE–LENGTH GaAs MESFETs

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ABSTRACT
A new two dimensional analytical model to determine the potential distribution and optically biased effect in the depletion layer for a short gate length GaAs MESFET has been used in this paper. The solution of the 2-D Poisson's equation has been considered as the superposition of the solutions of one-dimensional Poisson's equation in the lateral direction and the two-dimensional homogeneous Laplace equation with suitable boundary conditions to obtain the bottom potential and threshold voltage at active-substrate isolated interface. Calculations have been carried out numerically for a GaAs -MESFET to examine the effect of illumination on bottom potential for different parameters such as the drain-source voltage, gate-length, active-layer thickness and doped profile. It is observed when the gate length is increased, that bottom potential is decreased, and if the drain-source voltage is increased the bottom potential is increased. The results of this model have been verified in the dark and under illumination conditions.

Keywords: 2-D modeling potential distribution, Photodetector, Photovoltage.

I. INTRODUCTION

In recent years, the optically controlled GaAs MESFETs (OPFETs) have drawn considerable attention due to its applications and for the use as high speed photo detectors in optoelectronic integrated circuits (OEICs). An idea that has been widely investigated for performing optically controlled functions and it can be used to form an additional input port in photonic (MMICs) [1]. When the light is incident on the transparent or semi transparent gate of the device, electron-hole pairs are generated in the channel which can be utilized to control the device characteristics. The drain induced barrier lowering (DIBL) is an electrostatic effect that causes the channel charge and current of short channel FETs to be partially controlled by the drain potential rather than the gate potential. As a number of researchs on theoretical and experimental works which have reported on optically controlled MESFETs, the purpose of this paper is to describe a new two-dimensional analytical model that predicts DIBL effects in MESFETs. This paper presents a new physical model based on solving the two-dimensional Poisson's equation using a Green's function technique with appropriate boundary conditions for an optically biased nonself-alligned GaAs MESFET and by several works [2,3],to determine the potential distribution and the threshold voltage of GaAs MESFETs. Although, the method of superposition may be considered by several authors, as an acceptable technique in terms of its simplicity to understand the device physics and application of the short-gate device. This technique uses superposition to represent the 2-D Poisson equation solution as the sum of the 1-D Poisson equation solution and a 2-D Laplace equation solution. In this paper, a bottom potential and a threshold voltage models for the ion implanted short-channel GaAs MESFETs has been presented under dark and illuminated conditions of the device, appropriate modifications have been incorporated in the Poisson's equation to include the photo effects in the bottom potential and the threshold voltage of GaAs MESFETs.

II. THEORETICAL MODEL

A schematic structure of OPFET device is shown in Fig.1. The transparent gate is made of Indium Tin Oxide (ITO) material to form a Schottky rectifying contact with proper antireflection coating and all optical and electrical parameters of this model are assumed to be the ideal case.

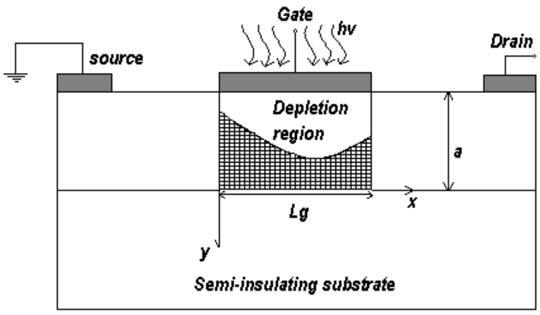

Fig.1: Schematic structure for optically biased MESFET where section under the gate denotes the depletion region in which 2D Poisson's is to be solved to obtain the potential distribution function.

The two dimensional modeling of MESFET is done using basic two dimensional (2-D) Poisson's equation in the gate-depletion region under the illuminated condition with the Schottky contact [4,5].

$$\frac{d^2\psi(x,y)}{dx^2}+\frac{d^2\psi(x,y)}{dy^2}=-\frac{q}{\varepsilon}\left(N_d(y)-G\tau_n-\frac{r_s\tau_P}{a}\right) \qquad (1)$$

The equation (1) has been solved in section under the gate denotes the depletion region, where $\psi(x,y)$ represent the 2-D component of potential in active layer, $Nd(y)$ is the doping profile in the channel active region, q is the electron charge, ε is the dielectric permittivity of the GaAs, r_s is the surface recombination rate, τ_n and τ_p are the lifetime of electron and hole respectively.

The photogenerated carriers description at the steady state derived with the following equation [6]:

$$G\tau_n=\alpha\phi\tau_n\exp(-\alpha y) \qquad (2)$$

α is the absorption coefficient per unit length, τ_n is the lifetime of the electron, $(\phi=\frac{(1-R_s)(1-R_m)P_{opt}}{h\gamma})$ is the incident optical flux density. R_m and R_s are the reflection coefficient at the entrance and at the metal semiconductor contact respectively, P_{opt} is the incident optical power density. A simple method used to solve the 2D Poisson's equation is the superposition technique in which the 2D Poisson's equation is divided into 2D Laplace equation and 1D ordinary differential equation, thus, the solution of equation (1) may be written as

$$\psi(x,y)=U(y)+\varphi(x,y) \qquad (3)$$

where

$$\frac{d^2U(y)}{dy^2}=\frac{-q}{\varepsilon}(Nd(y)-G\tau_n-\frac{r_s\tau_p}{a}) \qquad (4)$$

$$\frac{d^2\varphi(x,y)}{dx^2}+\frac{d^2\varphi(x,y)}{dy^2}=0\ . \qquad (5)$$

The boundary conditions as related to the Poisson'sequation are taken from [3,7].

$$\psi(x,0)=V_{gs}+V_{op}-V_{bi}$$
$$\psi(0,y)=V_{bi}$$
$$\psi(L,y)=V_{bi}+V_{ds} \qquad (6)$$

where V_{gs} is the gate to source voltage ,V_{ds} the drain to source voltage, V_{bi} the built in voltage at Schottky gate. Due to illumination, the device performance varies due to the photovoltage developed at the Schottky junction. V_{op} is the photo induced voltage developed at the Schottky junction , By integrating equation (4) from zero to y, we determined the term of $U(y)$, and we obtained:

$$U(y)=\frac{qNd}{2\varepsilon}y^2-\frac{qr_s\tau_p}{2\varepsilon}y-\frac{q\phi\tau_n}{2\varepsilon}\left(y+\frac{1}{\alpha}\right)\exp(-\alpha y)+\frac{q\phi\tau_n}{\alpha\varepsilon} \qquad (7)$$

The extension of the Schottky junction depletion region in the channel measured from the surface under illumination is given by

$$h(x) = \left[\frac{2\varepsilon}{qN_d} (V_{bi} + V(x) - V_{gs} - V_{op}) \right]^{\frac{1}{2}} \quad (8)$$

And the depletion widths at the source and drain ends are given respectively by

$$h_s = \left[\frac{2\varepsilon}{qNd} (V_{bi} - V_{gs} - V_{op} \right] \quad (9)$$

$$h_d = \left[\frac{2\varepsilon}{qNd} (V_{bi} + V_{ds} - V_{gs} - V_{op} \right] \quad (10)$$

Applying the separation of variables technique [7,8,9] and using the boundary conditions described by Eqns (6), the expression for $\phi(x, y)$ may be written as Green's function

$$\varphi(x, y) = A_1^s \frac{\sinh(k(L_g - x)}{\sinh(kL_g)} + A_1^d \frac{\sinh(kx)}{\sinh(kL_g)} \quad (11)$$

where $k = \frac{\pi}{a}$.

Thus, using the resultant expression for 2D Potential function from Eq. (7) and (11), the accurate channel potential can be expressed by:

$$\psi(x, y) = \frac{qNd}{2\varepsilon} y^2 - \frac{qr_s\tau_p}{2\varepsilon} y - \frac{q\phi\tau_n}{\varepsilon}\left(y + \frac{1}{\alpha} \right)\exp(-\alpha y) + \frac{q\phi\tau_n}{\alpha\varepsilon} + A_1^s \frac{\sinh(k(L_g - x)}{\sinh(kL_g)} + A_1^d \frac{\sinh(kx)}{\sinh(kL_g)} \quad (12)$$

$$A_1^s = V_p\left[a_1 + b_1\left(\frac{V_{bi} - V_{gs} - V_1 - V_{op}}{V_p} - c_1 \right)^{\frac{1}{2}} \right] \quad (13)$$

$$A_1^d = V_p\left[a_1 + b_1\left(\frac{V_{bi} - V_{gs} - V_1 + V_{ds} - V_{op}}{V_p} - c_1 \right)^{\frac{1}{2}} \right] \quad (14)$$

A_1^s *and*, A_1^d are the first Fourier coefficient for the excess sidewalls potential at the source and drain sides of the gate, respectively. The above coefficients are used for uniform profile case, these coefficients can be derived as $: a_1 = -0.77, b_1 = 1.26, c_1 = 0.33, V_1 = 0.67V_p$ [10].

The bottom potential $\psi(x,a)$ with respect to the source potential can be written as

$$\psi(x, a) = \frac{qNd}{2\varepsilon} a^2 - \frac{qr_s\tau_p}{2\varepsilon} a - \frac{q\phi\tau_n}{\varepsilon}\left(a + \frac{1}{\alpha} \right)\exp(-\alpha a) + \frac{q\phi\tau_n}{\alpha\varepsilon} + A_1^s \frac{\sinh(k(L_g - x)}{\sinh(kL_g)} + A_1^d \frac{\sinh(kx)}{\sinh(kL_g)} - V_{gs} + V_{bi} - V_{op} \quad (15)$$

The position of the minimum bottom potential $x_{\min}$ may be obtained by solving the following equation:

$$\frac{\partial\psi(x, a)}{\partial x} = 0 \text{ at } x = x_{\min} \quad (16)$$

Using Eq. (15) and (16), $x_{\min}$ may be given by :

$$\frac{\cosh(k(Lg - x_{\min}))}{\cosh(kx_{\min})} = \frac{A_1^d}{A_1^s} \quad (17)$$

For the short-channel devices with moderate values of L_g, we may use the following approximations for the hyperbolic functions in Eq. (17):

$\cosh(k(Lg - x_{\min})) \approx (\frac{1}{2})\exp(k(Lg - x_{\min}))$ and

$\cosh(kx_{\min}) \approx (\frac{1}{2})\exp(kx_{\min})$ with

$$x_{\min} \approx \frac{L_g}{2} - \frac{1}{2k}\ln(\frac{A_1^d}{A_1^s}) \quad (18)$$

The minimum bottom potential may be obtained by substituting $x = x_{\min}$ from (18) in (15). Since $A_1^d = A_1^s$ for $V_{ds} = 0$ i.e., with no drain bias, the position of the minimum bottom potential occurs at the middle of the channel $x_{\min} = L_g/2$. The situation is changed for the short-channel devices for $V_{ds} > 0$. In this case, from (18), it may be observed that A_1^d is increased with the increase of V_{ds} and $A_1^d \rangle A_1^s$ resulting that $x_{\min}$ decreases with the increase in V_{ds} and shifted toward the source (18).

III. THRESHOLD VOLTAGE

The threshold voltage V_{th} of an optically biased MESFET has been obtained as [3]:

$$V_{th} = V_{th}^{0} - KA_{1}^{s} \tag{19}$$

where, V_{th}^{0} is the threshold voltage of long channel optically biased , K is the parameter used to describe the short gate-length effects, it is defined as

$$K = \sec h\left(\frac{k_1 L_g}{2}\right)$$ and

$$V_{th}^{0} = V_{bi} - V_{op} - \left(\frac{qNd}{2\varepsilon}a^2 - \frac{qr_s\tau_p}{2\varepsilon}a - \frac{q\phi\tau_n}{\varepsilon}\left(a+\frac{1}{\alpha}\right)\exp(-\alpha a) - \frac{q\phi\tau_n}{\alpha\varepsilon}\right) \tag{20}$$

IV. RESULTS AND DISCUSSION

In this section we have presented some numerical results for determining the potential distribution presented in Fig.2 versus x direction of the channel length and y direction of the active layer for various values of illumination .It clearly shows that the potential in the channel increases towards the drain side. This is because the biasing is applied at the drain, these variations can be seen in Fig 3 that shows the variation of the bottom potential versus a normalized length of the gate for illumination and dark conditions at level GaAs layer/semi-insulating substrate.

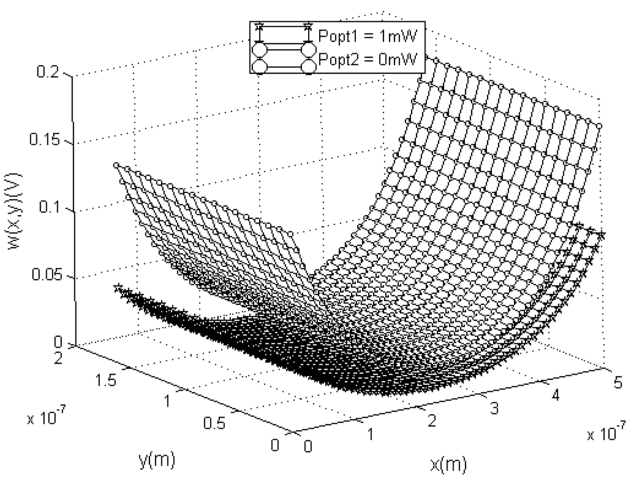

Fig.2: Mesh plot of Potential versus x and y directions in the dark and illumination conditions $(Popt1 = 0mW, Popt2 = 1mW)$.

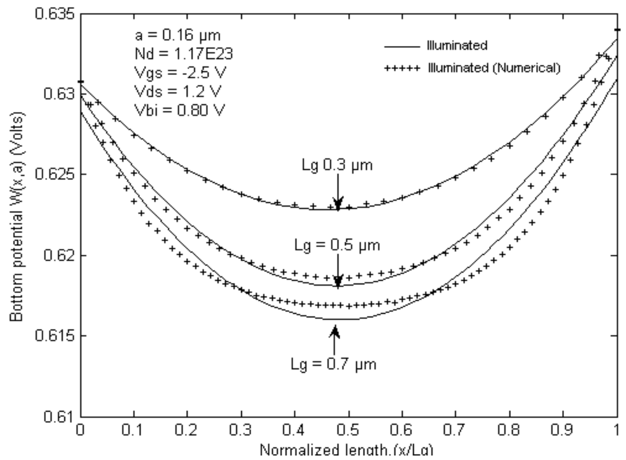

Fig.3: Variation of bottom potential versus normalized length for different gate lengths.

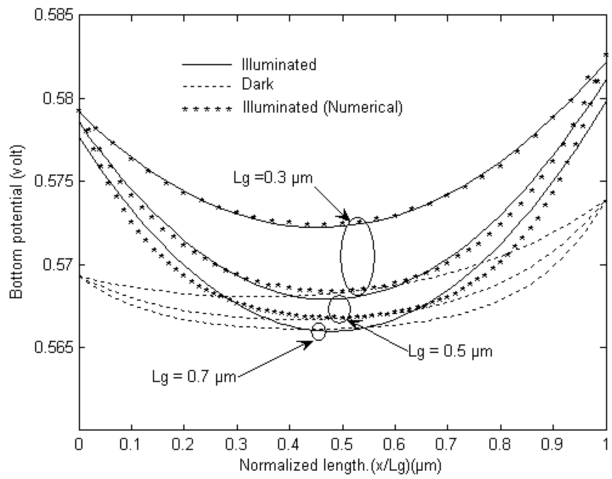

Fig.4: Plot of bottom potential versus normalized length in dark and illumination conditions for different gate lengths.

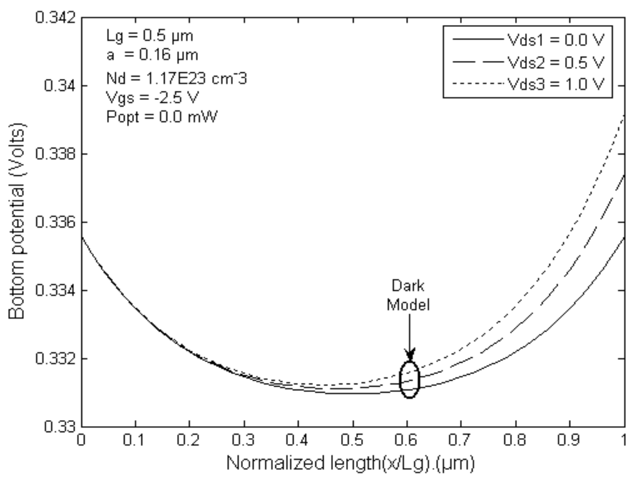

Fig.5: Variation of bottom potential with normalized length (x/L_g) for different values of drain-source bias in the dark conditions.

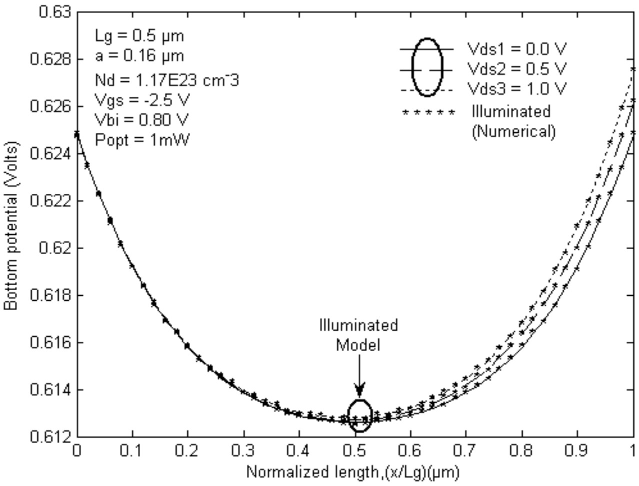

Fig.6: Variation of bottom potential with normalized length $\left(x/L_g\right)$,for different drain-source biases in the illuminated conditions.

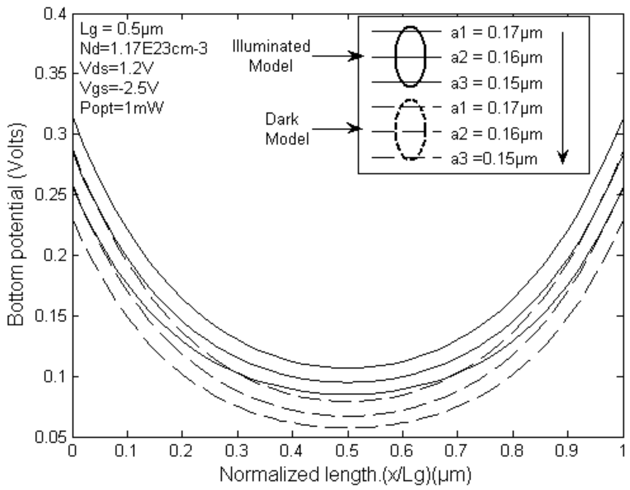

Fig.7: Plot of bottom potential versus normalized length for different valuesb of channel thickness in dark and illuminated models.

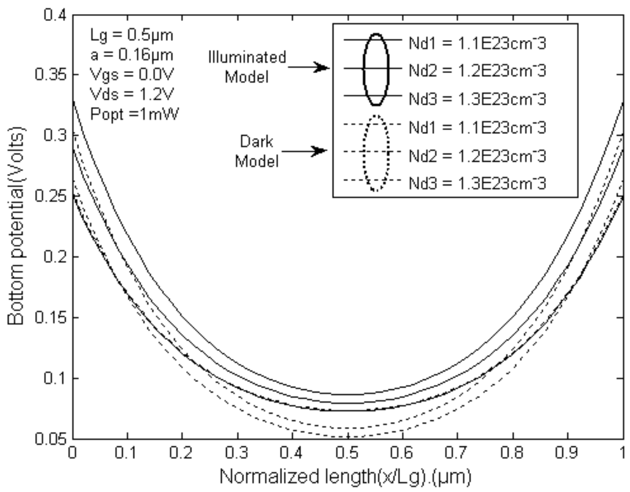

Fig.8: Variation of bottom potential with normalized length for different doping profiles Nd in the dark and illuminated models.

From the Fig.4 for different gate lengths and a fixed value of V_{ds} it is observed that the minimum bottom potential is increased with the decrease in gate length. The position of the minimum bottom potential is also shifted in this case towards the source with the decrease in L_g and we may observe that DIBL effect is more dominant for a gate length $L_g = 0.3\mu m$ than that for $L_g = 0.5\mu m$ and $L_g = 0.7\mu m$ which indicates that the DIBL is the most pervasive effect in the submicrometer regime of operation of the MESFETs. We observe that as the gate length is decreased, the bottom potential is increased and we observe that as the DIBL effect increased, the gate length is decreased thus an abrupt change occurs due to the effect of the optical power in comparison to the dark condition.

From the Fig.5, and Fig.6 it is observed that as the drain to source voltage V_{ds} is increased for a fixed value of V_{gs} , the bottom potential is increased at the drain side, whereas the increase in V_{ds} bias degraded the short channel barrier FETs known as the DIBL, however it is observed that the excess of the incident optica power density affects the bottom potential to increase resulting in the significant decrease in the channel barrier due to the effect of illumination. It is seen that, the bottom potential in the illuminated condition is more high in comparison to the dark because when the light radiation is allowed to fall on the Schottky gate contact, a photovoltage is developed across the junction, which effectively reduces the barrier height, and decreases the depletion layer width, which in turn also broadens the channel width. The position of the minimum bottom potential is approximatly unchanged for. $L_g = 0.5\mu m$, it is shifted towards the source as the drain-source voltage increased .

From the Fig.7 we presented respectively the effects of active layer thickness a on the bottom potential. It is observed that for a fixed gate length, the bottom potential is increased as the channel thickness is also increased, this implies that the short channel effects due to the reduction of the gate length may be minimized by reducing the channel thickness. This suggests that the degradation of the potential due to the short gate length L_g may be minimized by reducing the active channel thickness. It is seen that the bottom potential in the illuminated case is more than in the dark as the barrier height becomes reduced due to photovoltage developed across the Schottky junction when the light radiation is allowed to fall. The dependence of the bottom potential the doping profile has been shown in Fig.8 It is observed that as the doped profile increased, the bottom potential is increased. Thus, if the DIBL effect is increased the doping concentration is increased, it is increased under illumination than in the dark .

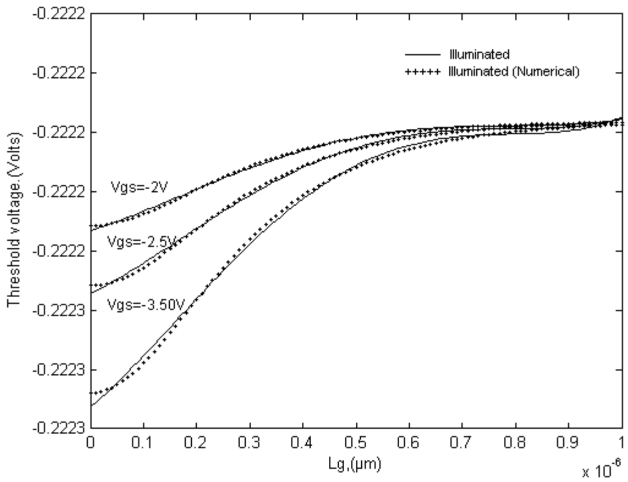

Fig.9: Variation of threshold voltage with channel length (L_g) for different drain-source voltages and dark condition .used for calculation :

$Popt = 0mW$ $N_d = 1.17E23cm-3$, $a = 0.16\mu m$, $L_g = 0.5\mu m$ $V_{ds} = 1.2V$.

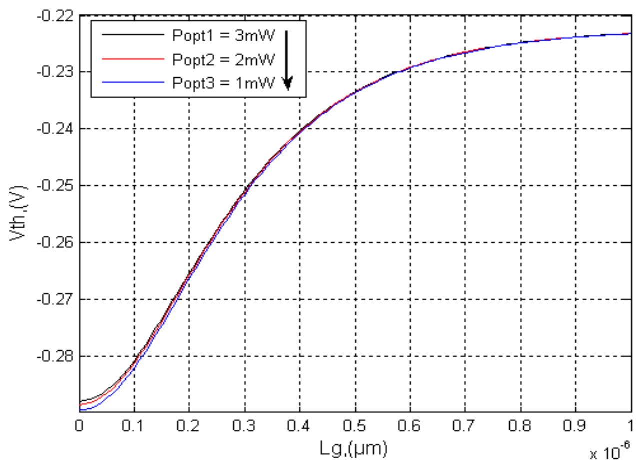

Fig.10: Variation of threshold voltage Vth with channel length (L_g) for different illuminations

$(Popt1 = 1mW, Popt2 = 2mW, Popt3 = 3mW)$. For calculation : $N_d = 1.17E23cm-3$, $a = 0.16\mu m$, $L_g = 0.5\mu m$, $V_{ds} = 1.2V$.

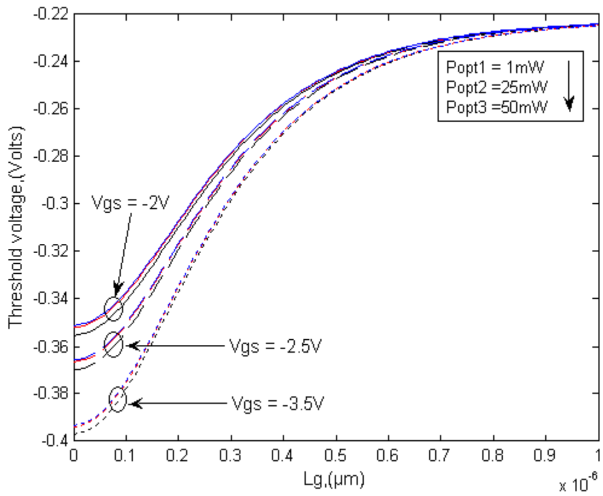

Fig.11:. Variation of threshold voltage with channel length (L_g) for different illuminations: $(Popt1 = 1mW, Popt2 = 25mW, Popt3 = 50mW)$. for different variations of $V_{gs} = (-2V, -2{,}5V, -3{,}5V)$, $N_d = 1.17E23cm-3$, $a = 0.16\mu m$, $L_g = 0.5\mu m$.

The effect of the gate-source voltage V_{gs} on the threshold voltage has been presented in the Fig.9. It is observed that for a fixed value of V_{gs} , the threshold voltage is degraded as the gate length is decreased and becomes constant for larger gate length and for a fixed value of gate length the threshold voltage is increased as the gate-source voltage is increased.

From the Fig.10, the threshold voltage variation with gate length for different illuminations values, it is observed that, the threshold voltage is decreased with the incident optical power density $Popt$ is decreased, and it is shifted to more negative values that the incident optical power density take the minimum value in mW. The threshold voltage versus the gate length L_g has been plotted in the From Fig.11 for different values of the gate-source bias V_{gs} and different illuminated values, it is observed that V_{gs} bias is increased the threshold voltage is increased and thus if the incident optical power density decreased the threshold voltage is decreased.

V. CONCLUSION

A new 2-D model for the potential distribution and the threshold voltage of fully depleted short channel ion implanted GaAs MESFET's has been presented in this paper. A detailed analytical study to see the effect of illumination and various parameters of device on GaAs MESFET, has been made by solving the two-dimensional Poisson's equation using a Green's function technique. The proposed model has been compared with numerical data using PDE toolbox of software MATLAB that shows the validity of the analytical model and gives an excellent approximation for the bottom potential and threshold voltage.

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