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Depletion Layer Modeling for Short Gate Length Non-Uniformly Doped GaAs MESFET Under Dark and Illuminated Condition

Research Article

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Abstract. This paper presents an analytical expression for the depletion region height of short gate length GaAs MESFET with non-uniform doping profile in the channel region. Both, dark as well as illuminated conditions have been considered for model formulation. Depletion region height sensitivities on the doping parameters have also been demonstrated.

Keywords. Depletion region; GaAs MESFET; Illumination; Non-uniform doping

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1. Introduction

Recent technological developments have made GaAs MESFET a more powerful device [Rodriguez-Tellez *et al.* (2003), Zamanillo *et al.* (2007)]. However, the complexities involved in operating principle increase as soon as dimensions are scaled down. These complexities are increased further when the device is exposed to the light.

There are number of parameters [Chin *et al.* (1992)] that need to be modeled by taking all the major effects into consideration for the complete modeling of short-channel GaAs MESFET. Depletion layer height is one of the important parameter that should be formulated properly. As the gate length is scaled down, two-dimensional (2D) effects become considerable and determination of depletion height becomes difficult. Difficulty increases further when the device is exposed to the illumination and additional effects of optical illumination should be

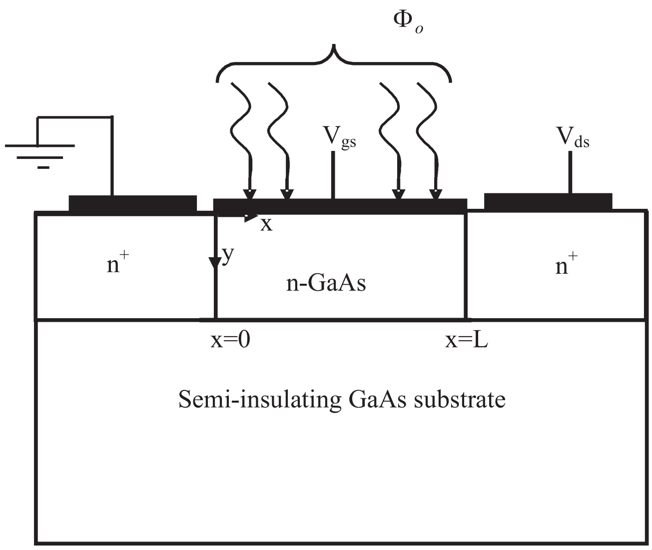

Figure 1. Schematic structure of the GaAs MESFET where, L, a and Φ_0 are the channel length, channel thickness and incident photon flux density respectively.

incorporated in the model properly. Few attempts have been made to model the depletion layer of GaAs MESFET [Chin *et al.* (1993), Chakrabarti *et al.* (1998)].

The depletion layer of the device modulates with the doping parameters variation (straggle, projected range and peak channel doping). To the best of our knowledge, model has not been reported for short channel GaAs MESFET to incorporate this issue under dark and illuminated conditions.

In the present work, an analytical model has been reported for depletion height of short gate length GaAs MESFET having non-uniform doping profile in the channel region. 2D Poisson's equation has been solved with suitable boundary conditions and proper optical effects have also been incorporated. To make the model fully analytical Gaussian like function is used in Poisson's equation in place of actual Gaussian profile [Dasgupta *et al.* (1986)]. The depletion region sensitivities on the illumination, peak doping concentration, and straggle parameter have been discussed in detail.

2. Theoretical Model

The schematic structure of optically biased GaAs MESFET used for modeling is shown in Figure 1. In Figure 1, a and L are active layer thickness and gate length respectively. The optical radiations are allowed to incident on the gate metal along the vertical y-direction. Indium Tin Oxide (ITO) has been used as the Schottky-gate metal due to its high optical transmittance of incident illumination [Bashar (1998)]. An undoped high pure LEC semi-insulating GaAs material is assumed as substrate of the device. The active channel region of the device is an n-GaAs layer which can be obtained by ion implanting Si into semi-insulating substrate.

The doping distribution in the channel can be approximately described by [Dasgupta et al. (1988)]

$$N_d(y) = N_s + (N_p - N_s)F(y) \tag{1}$$

where N_p is peak ion concentration, N_s is the substrate doping concentration and $F(y)$ is an approximate analytic form of Gaussian function [Dasgupta *et al.* (1986)] given as,

$$F(y) \approx c_c\left[\left\{a_c + \frac{2b_c\beta}{\sqrt{2}\sigma}(y-R_p)\right\}^2 - 2b_c\right]\exp\left[-\left\{\frac{a_c\beta}{\sqrt{2}\sigma}(y-R_p) + \frac{b_c}{2\sigma^2}(y-R_p)^2\right\}\right] \tag{2}$$

where $a_c = 1.7857142$, $b_c = 0.6460835$, $c_c = 0.28\sqrt{\pi}$ and $\beta = \begin{cases} +1 & \text{for } y > R_p \\ -1 & \text{for } y < R_p \end{cases}$

Now, the net doping concentration $N_D(y)$ in the active channel region under illuminated condition can be given as [Bose *et al.* (2001)]

$$N_D(y) = N_d(y) + G(y)\tau_n - \frac{R\tau_p}{a} \tag{3}$$

where $N_d(y)$ represents the doping profile defined by (2). R is the surface recombination rate, α is the absorption coefficient of GaAs material, τ_n and τ_p are the life time of electrons and holes, respectively and $G(y)$ is the photo-generation rate [Sze (1981)].

The 2D Poisson's equation for the channel region under the gate can be written as

$$\partial^2\phi(x,y)/\partial x^2 + \partial^2\phi(x,y)/\partial y^2 = qN_D(y)/\varepsilon_s \tag{4}$$

ε_s is the dielectric permittivity of GaAs semiconductor, q is electron charge.

Using superposition technique [Kabra *et al.* (2007)], eq. (4) can be resolved as

$$\phi(x,y) = \varphi_{1D}(y) + \varphi_{2D}(x,y) \tag{5}$$

where, $\varphi_{1\mathrm{D}}(y)$ is 1D potential function of the long-channel MESFETs and $\varphi_{2\mathrm{D}}(x,y)$ is the 2D potential function responsible for the short channel effects.

$\varphi_{1\mathrm{D}}(y)$ can be obtained by solving following Poisson's equation for the MESFET structure in one dimension along y-axis,

$$\partial^2\varphi_{1D}/\partial y^2 = -qN_D/\varepsilon_s \tag{6}$$

in conjunction with following boundary conditions [Kabra *et al.* (2007)]

$$\varphi_{1D}(y)\Big|_{y=0} = V_{bi} - V_{gs} - V_{op} \tag{7}$$

$$\left.\frac{\partial\varphi_{1D}(y)}{\partial y}\right|_{y=h(x)} = 0 \tag{8}$$

where V_{bi} is the Schottky-barrier built-in potential, V_{gs} is the applied gate bias and V_{op} is the photovoltage developed at the Schottky junction due to illumination which can be obtained as [Jit *et al.* (2005)].

$\varphi_{1D}(y)$ has been obtained as

$$\begin{aligned}\varphi_{1D}(y) = \frac{q(\sigma\sqrt{2})^2}{\varepsilon_s}&\left[\frac{N_s}{2}\left(\frac{y-R_p}{\sqrt{2}\sigma}\right)^2 + c_c(N_p-N_s)\exp\left[-\left(a_c\left(\frac{y-R_p}{\sqrt{2}\sigma}\right) + b_c\left(\frac{y-R_p}{\sqrt{2}\sigma}\right)^2\right)\right]\right.\\ &\left.+\frac{\Phi_0\tau_n\exp(-\alpha R_p)\exp(-\alpha(y-R_p))}{\alpha^2(\sigma\sqrt{2})^2} - \frac{R\tau_p}{a}\left(\frac{y-R_p}{\sqrt{2}\sigma}\right)^2 + A\left(\frac{y-R_p}{\sqrt{2}\sigma}\right) + B\right]\end{aligned} \tag{9}$$

where A, B, are

$$A = -\frac{q\sigma\sqrt{2}}{\varepsilon_s}\left[\left(\frac{h(x)-R_p}{\sqrt{2}\sigma}\right)(N_s - R\tau_p a^{-1}) - c_c(N_p - N_s)\left(a_c + 2b_c\left(\frac{h(x)-R_p}{\sqrt{2}\sigma}\right)\right)\right.$$
$$\left.\times\exp\left[-\left(a_c\left(\frac{h(x)-R_p}{\sqrt{2}\sigma}\right) + b_c\left(\frac{h(x)-R_p}{\sqrt{2}\sigma}\right)^2\right)\right] - \frac{(\Phi_0\tau_n\exp(-\alpha R_p)\exp(-\alpha(h(x)-R_p)))}{\alpha\sigma\sqrt{2}}\right] \tag{10}$$

$$B = -\left[-\frac{\varepsilon_s(V_{bi}-V_{gs}-V_{op})}{q(\sigma\sqrt{2})^2} + c_c(N_p - N_s)\exp\left[-\left(a_c\left(\frac{-R_p}{\sqrt{2}\sigma}\right) + b_c\left(\frac{-R_p}{\sqrt{2}\sigma}\right)^2\right)\right]\right.$$
$$\left.+\left(\frac{N_s}{4} - \frac{R\tau_p}{2a}\right)\left(\frac{-R_p}{\sigma}\right)^2 + A\left(\frac{-R_p}{\sqrt{2}\sigma}\right) + \frac{\Phi_0\tau_n\exp(-\alpha R_p)\exp(\alpha R_p)}{\alpha^2(\sigma\sqrt{2})^2}\right] \tag{11}$$

Now, $\varphi_{2D}(x,y)$ in the eq. (5) is the solution of 2D Laplace equation given as

$$\partial^2\phi(x,y)/\partial x^2 + \partial^2\phi(x,y)/\partial y^2 = 0. \tag{12}$$

We can use the following boundary conditions [Kabra *et al.* (2007)] for solving eq. (12):

$$\varphi_{2D}(x,0) = 0 \tag{13}$$

$$\varphi_{2D}(0,y) = V_{bi} - \varphi_{1D}(y) \tag{14}$$

$$\varphi_{2D}(L,y) = V_{bi} + V_{ds} - \varphi_{1D}(y) \tag{15}$$

$$\left.\frac{d\varphi_{2D}(x,y)}{dy}\right|_{y=a} = 0 \tag{16}$$

where V_{ds} is the applied drain-source voltage.

Applying the standard technique of separation of variables for solving $\varphi_{2D}(x,y)$, the resulting expression for $\varphi_{2D}(x,y)$ can be obtained as,

$$\phi_{2D}(x,y) = (\sin(k_1 y)/\sinh(k_1 L))[A_1 \times \sinh[k_1(L-x)] + B_1\sinh(k_1 x)] \tag{17}$$

where k_1, A_1 and B_1 are the constants defined in Tripathi *et al.* (2011).

Now, the resulting expression for the potential distribution ($\phi(x,y)$) under the gate can be obtained as,

$$\phi(x,y) \approx \varphi_{1D}(y) + (\sin(k_1 y)/\sinh(k_1 L)) \times \sinh[k_1(L-x)] + B_1\sinh(k_1 x)] \tag{18}$$

The depletion region height $h(x)$ under the gate of the GaAs MESFET can be obtained by solving above equation under certain approximations and can be given as

$$h(x) = \left(\frac{\varepsilon_s}{qN_s}\right)\left[-(D_1 + D_2 - 2R_p)\left((D_1 + D_2 - 2R_p)^2 + \frac{2qN_s}{\varepsilon_s}(\phi_{ch}(x) + D\right.\right.$$
$$\left.\left.-(V_{bi} - V_{gs} - V_{op}) + \frac{D_1}{k_1} + \frac{D_2}{k_1} - \frac{qN_s R_p^2}{2\varepsilon_s}\right)\right)^{\frac{1}{2}}\right] \tag{19}$$

where

$$D = \frac{q(\sigma\sqrt{2})^2}{\varepsilon_s}\left[\frac{N_s}{4}\left(\frac{-R_p}{\sigma}\right)^2 - \frac{R\tau_p}{2a}\left(\frac{-R_p}{\sigma}\right)^2 + c_c(N_p - N_s)\exp\left[\left(a_c\left(\frac{R_p}{\sqrt{2}\sigma}\right) - b_c\left(\frac{-R_p}{\sqrt{2}\sigma}\right)^2\right)\right]\right.$$
$$\left. + \frac{\Phi_0\tau_n \exp(-\alpha R_p)\exp(\alpha R_p)}{\alpha(\sigma\sqrt{2})^2}\right] \tag{20}$$

$$D_1 = \frac{(-2V_{bi} + V_{gs} + V_{op} - D)\sinh[k_1(L - x)]}{\sinh(k_1 L)} \tag{21}$$

$$D_2 = \frac{(-2V_{bi} + V_{gs} + V_{op} - V_{ds} - D)\sinh(k_1 x)}{\sinh(k_1 L)} \tag{22}$$

3. Results and Discussions

The calculation for depletion region height under the gate of non-uniformly doped short channel GaAs MESFET has been carried out under dark and illuminated conditions. The values of the parameters used for computation of the model results are: $a = 0.2\mu$m, $R_p = 0.08\mu$m, $V_{bi} = 0.9$V, $T_m = 0.9$, $L = 0.3\mu$m, $\sigma = 0.02\mu$m, $\alpha = 10^6$/m, $\lambda = 0.87\mu$m, $\tau_n = 10^{-6}$s, $\tau_p = 10^{-8}$s, $N_p = 1\times10^{23}$m^{-3} and $N_s = 1\times10^{21}$m^{-3}.

The variation of gate depletion height with distance along the channel under dark and illuminated conditions is shown in Figure 2. It can be observed from the figure that the width of the gate depletion region at any point in the channel decreases in the presence of illumination. This may be accounted by the fact that the photovoltaic effect in the illuminated condition reduces the applied gate bias and causes the net reduction in the width of the gate depletion region in the illuminated condition.

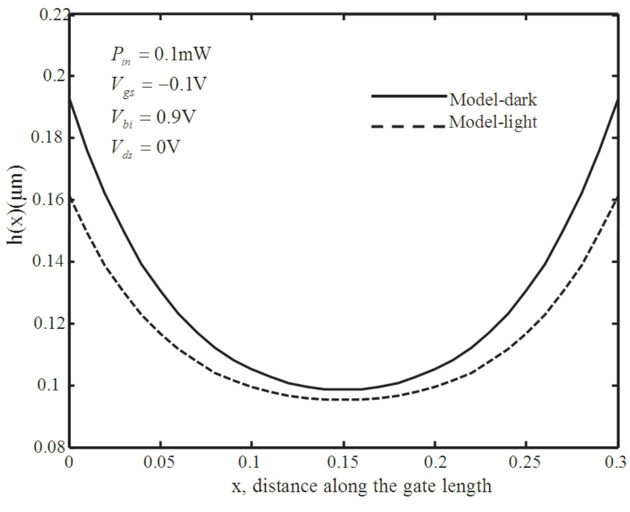

Figure 2. Variation of the gate depletion height ($h(x)$) in the channel with distance under dark and illuminated conditions.

The dependence of depletion region height ($h(x)$) on different peak concentration (N_p) and straggle parameter (σ) of the doping profile is shown in Figures 3-4. When the peak doping concentration in the channel region is increased, the average implanted ion density in the active channel region of the MESFET is increased. Since increased doping produces more ions that means sooner a very large potential barrier will built up, that will stop the further flow of carriers. This is achieved within a smaller portion of the active channel region and hence the depletion region is decreased. Similarly with the increase in the value of σ the average implanted ion density in the active channel region of the MESFET increases and the depletion region height decreases. Further under illuminated condition it can be observed that depletion height is decreased in both the Figures 3-4.

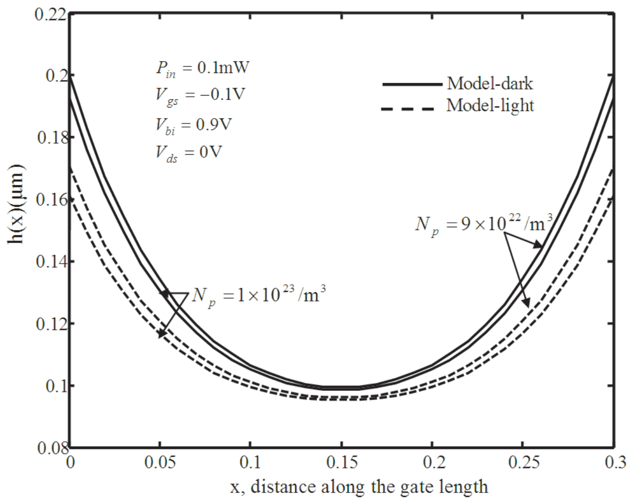

Figure 3. Variation of the gate depletion height ($h(x)$) in the channel with distance x for different peak doping concentrations (N_p) under dark and illuminated conditions.

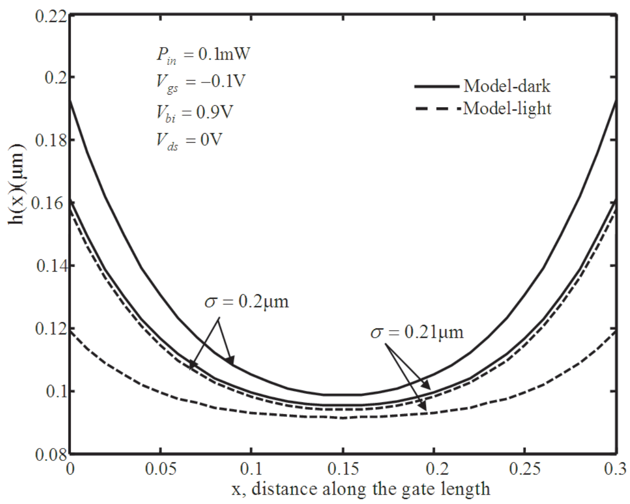

Figure 4. Variation of the gate depletion height ($h(x)$) in the channel with distance x for different straggle parameter (σ) under dark and illuminated conditions.

4. Conclusion

The presented model is completely based on the physics of the device and considers into all the major effects of illumination. It can help in the characterization of short channel GaAs

MESFET for optically controlled conditions and can be very useful in predicting the I-V and C-V characteristics of the device.

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