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Output characteristics of Short Channel GaAs MESFET Using MATLAB

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***Abstract* – An analytical model for optically biased non-self-aligned and self-aligned short channel GaAs MESFETs is developed to show the photo effects on the Id–Vd characteristics, using Green's function technique. When light radiation having photon energy equal to or greater than the band gap energy of GaAs is allowed to fall, the drain current increases significantly as compared to dark condition due to photoconductive effect in parasitic resistances and photovoltaic effect at the gate Schottky-barrier region.**

***Keywords* – MESFET, GaAs, Photo-generation of carriers, Photovoltaic effect, Photoconductive effect.**

I. INTRODUCTION

The microwave characteristics of GaAs MESFET can be controlled by incident light radiation having photon energy greater or equal to the band gap energy of GaAs in the same manner as varying the gate bias [1,2]. By biasing the FET optically, many devices such as high-speed optical detector and converter for interaction of optical and microwave signals have been designed. In our recent work [3], it is reported that the optimum noise figure of a MESFET, reduces drastically when biased optically. Presently high speed, low cost, monolithically integrated optically biased GaAs MESFETs are in high demand for high frequency application in optical communication systems. It is also known that the device performance is greatly improved as the gate length of the device approach sub micrometer range .In this paper, we have tried to combine the above two facts: (1) use of optical radiations; and (2) shortening of gate length to study the current–voltage characteristics of non self-aligned and self aligned GaAs MESFETs. The two dimensional Poisson's equation is solved using Green's function technique with appropriate boundary conditions for optically biased GaAs MESFET

II. THEORETICAL CONSIDERATIONS

Fig. 1(a) shows the schematic cross-section of an optically biased non-self-aligned GaAs MESFET operated below turn-on region. The drain to source current flows in the *x*-direction and the optical radiation are allowed to incident on the device along the *y*-direction. The source is taken as reference potential and the hatched regions in the figure show the depletion edges of the source and drain sides.

Fig. 1(b) shows the non-self-aligned device structure in the turn-on region.

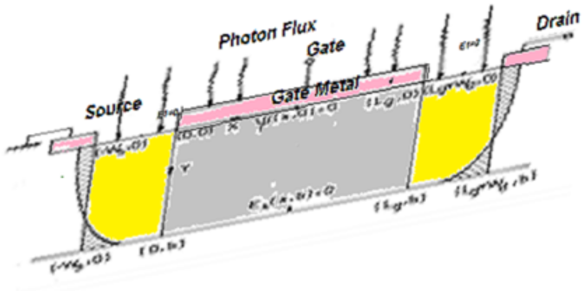

Fig.1. (a) Schematic cross section of an optically biased non-self aligned GaAs MESFET

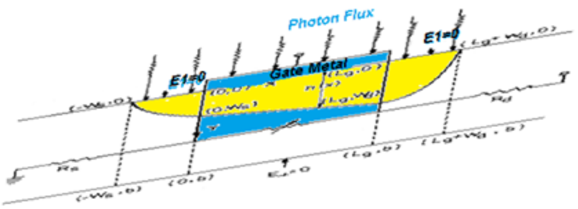

Fig.1. (b) Non-self-aligned device structure in the turn-on region

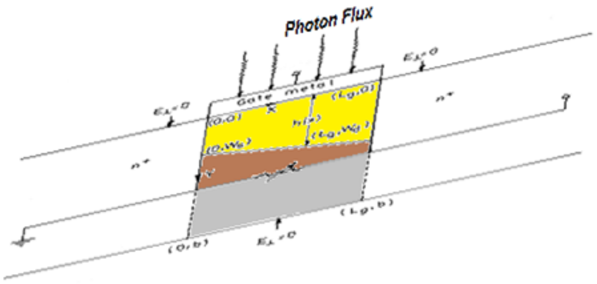

Fig.1. (c) Schematic structure for optically biased self-aligned MESFET operated in turn-on region.

The two-dimensional Poisson's equation for the rectangular domain shown in Fig. 1 (a) can be written as

$$\frac{\partial^2\psi(x,y)}{\partial x^2}+\frac{\partial^2\psi(x,y)}{\partial y^2}=-\frac{q}{\varepsilon}N_D(y)\_(1)$$

Where $\psi(x,y)$ is the two-dimensional potential distribution, ε is the dielectric permittivity of the semiconductor and q the electron charge. Due to the incident light radiations, the carriers are generated within the semiconductor material. The generated electrons move towards the channel region and holes move towards the surface where they recombine with surface traps. The net concentration $N_D(y)$ in the active channel can be expressed as

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$$N_D(y) = N_d + G(y)\tau_{n'} - \frac{R\tau_{p'}}{b} \_(2a)$$

Where N_d represents the uniform donor impurity concentration in the channel and *b* is the thickness of active layer.

G(y) is the photo-generation rate, given by [4] ϕ .

$$G(y) = \phi\alpha\exp(-\alpha y)\_(2b)$$

Where ϕ is the total photon flux through the opening between gate and source (ϕ 1), through gate metal (ϕ2) and the opening between gate and drain (ϕ 3), i.e. ϕ= ϕ 1+ ϕ 2+ϕ 3 or

$$\phi = P_{opt}(\frac{T_1}{h\nu} + \frac{T_m}{h\nu} + \frac{T_2}{h\nu})\_(2b)$$

Where P_{opt} is the incident optical power per unit area an T_m and T_1, T_2 are the optical transmission coefficients for the gate metal and spacing between the gate and source (drain),respectively .It is assumed that the incident radiation through the spacing between gate and source(drain) suffers no radiation that is $T_1 = T_2$ = 1,and suffer radiation when it passes through the gate metal ,h is the planks constant, ν is the frequency of the incident radiation and ∝the absorption coefficient per unit length R is the surface recombination rate, given as [5].

$$R = \frac{N_t K_{n'} K_{p'}(N_{s'}P_{s'} - N_{t'}P_{t'})}{K_{n'}(N_{s'} + N_{t'}) + K_{p'}(P_{s'} + P_{t'})}\_(2d)$$

Where $K_{n'}K_{p'}$ is capture factors and $N_{s'}P_{S'}$ are the surface carrier concentrations for electrons and holes respectively. $N_{s'}$and $P_{s'}$ Take value of $N_{t'}$and $P_{t'}$ respectively .when Fermi level lies in the traps. The surface concentration can be written as [6].

$$N_S = \alpha\varphi\tau_{n'} \ \ and \ \ P_{s'} = \alpha\varphi\tau_{p'} - (2e)$$

Where $\tau_{n'}$ *and* $\tau_{p'}$ are the life time of electrons and holes respectively and $N_{t'}$ is the area density traps.

In additions to the boundary conditions in ref.[7].equation (1) is subjected to the following two conditions for optically biased MESFET:

$$\psi(x,y)\vdots_s = V_{bi} - V_{gs} - V_{op} \text{and} \psi(x,y)\vdots_d = V_{bi} - V_{gs} + V_{ds} - V_{op} - (3)$$

Where V_{gs} & V_{ds} are the gate and drain biases respectively, V_{bi} is the built in potential at the Schottky gate contact ,s,d represents the depletion layer edges at the source and drain sides respectively and V_{op} is the photo voltage developed at the Schottky junction due to illumination [8].

The solution of equation (1) using green's function [9] is obtained as

$$\psi(x,y) = \int_{V'} \frac{\rho(x',y')}{\varepsilon} G(x,y;x',y')dV' -$$

$$\int_{S'} \psi(x',y')\frac{\partial G}{\partial n'}dS' + \int_{S'} \frac{\partial\psi(x',y')}{\partial n'} G(x,y;x'y')dS'\_(4)$$

Where $\rho(x',y')$ is the charge density distribution and $G(x,y;x',y')$ is the Green's function satisfying the relation,

$$\nabla'^2 G(x,y;x',y') = -\partial(x-x')\partial(y-y');\partial(x-x')$$

and $\partial(y-y')$

are the Dirac functions

Using the suitable Green's function [7] satisfying the above relation, the potential distribution Under the gate can be evaluated as

$$\psi(x,y) = \psi_1(x,y) and \psi_2(x,y)\_(5)$$

Where $\psi_1(x,y) and \psi_2(x,y)$ are the potential distributions due to the depletion-layer charges under the gate and in the un gated portion respectively and are given as

$$\psi_1(x,y) = \frac{q}{\varepsilon}(\int_0^y N_D(y')y'dy' + y\int_y^{h(x)} N_D(y')dy') + V_{bi} - Vgs - Vop\_(5a)$$

and

$$\psi_2(x,y) = \sum_{m=1}^{\infty}(A_m^s \frac{\sinh(k_m(L_g - x))}{\sinh(k_m L_g)} + A_m^d \frac{\sinh(K_m x)}{\sinh(K_m L_g)})\sin(K_m y) - (5b)$$

Where $h(x)$ represents the depletion –layer thickness, L_g is the gate length and $Km(= m - \frac{0.5}{(\pi/2)})$ is the Eigen value of the green's function in the gate region with m as integer and $A_m^{s(d)}$ is the Fourier coefficient for excess side wall potential at the source (drain) side of the gate .

Hence the channel potential $\psi_c(x)$ keeping the first term of the Fourier coefficient, can now be written as

$$\psi_c(x) = \frac{q}{\varepsilon}(\frac{N_d h(x)^2}{2} - \phi\tau_{n'}(\exp(-\alpha h(x))(h(x) + \frac{1}{\alpha}) - \frac{1}{\alpha}) - \frac{R\tau_{p'}}{b}\frac{h(x)^2}{2})$$

$$+ A_1^s \frac{\sinh(K_1(L_g - x))}{\sinh(K_1 L_g)} + A_1^d \frac{\sinh(K_1 x)}{\sinh(K_1 L_g)} + V_{bi} - V_{gs} - V_{op} - (6)$$

By assuming $\frac{1}{\sinh(K_1 L_g)} \approx 0$ [10], A_1^s and A_1^d can be written as

$$A_1^s = V_p(a_1 + b_1(\frac{V_{bi} - V_{gs} - V_1 - V_{op} + I_{ds}R_s}{V_p} - C_1)^{\frac{1}{2}})\_(7a)$$

$$A_1^d = V_p(a_1 + b_1(\frac{V_{bi} - V_{gs} - V_1 + V_{ds} - V_{op} + I_{ds}(R_s + R_d)}{V_p} - C_1)^{\frac{1}{2}})\_(7b)$$

Where a_1, b_1, V_1 and V_p are elsewhere and I_{ds} is the drain to source current.

The value for parasitic source (drain) resistance R_s, R_d is obtained from the following expressions

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$$R_S = \frac{b^2}{2\varepsilon}\left(\frac{L_{gs}}{V_p \mu_{no} Z}\right) \text{ and } R_S = \frac{b^2}{2\varepsilon}\left(\frac{L_{gd}}{V_p \mu_{no} Z}\right)\_(8)$$

Where $L_{gs(d)}$ is the length of gate to source (drain) spacing, Z-is the gate width, $\mu_{no} = 0.45m^2/Vs)$ is the low-field mobility of electron and $\mu_{po} = 0.04m^2/Vs)$ is the low-field mobility of the hole.

The drain to source current (I_{ds}) for the optically biased non self aligned GaAs MESFET can be calculated from the expression:

$$\int_{-w_S}^{L_g+W_d} I_{ds} d_x = \int_{W_s}^{W_d} \frac{q^2 Z\mu_n}{\varepsilon} S(N_d + \alpha\phi\tau_{n'} \exp(-\alpha h(x)))h(x)dh(x)$$

$$-\int_{W_s}^{W_d} \frac{q^2 Z\mu_p}{\varepsilon} S \frac{R\tau_{p'}}{b} h(x)dh(x) - \int_{-W_s}^{L_g+W_d} qZ\mu_n k_1 S(A_1^s \frac{\cosh(k_1(L_g - x)}{\sinh(k_1 L_g)}$$

$$-A_1^d \frac{\cosh(k_1 x)}{\sinh(k_1 L_g)})dx \; -(9)$$

Where Z is the gate width, $S = \int_{h(x)}^{b} N_D(y)dy$ and $\mu_{n(p)}$ is the mobility of the electron (hole) and $W_{s(d)}$ is the position of the depletion layer edge at the source (drain) of the gate, given as

$$W_S = \left(\left(\frac{2\varepsilon}{qN_{d,0}^{S}}\right)(V_{bi} - V_{gs} - V_1 - V_{op} + I_{ds}R_S - \frac{2}{\pi}A_1^S)\right)^{\frac{1}{2}} -(10a)$$

$$W_d = \left(\left(\frac{2\varepsilon}{qN_{d,0}^{d}}\right)(V_{bi} - V_{gs} + V_{ds} - V_1 - V_{op} + I_{ds}(R_S + R_d) - \frac{2}{\pi}A_1^d)\right)^{\frac{1}{2}} -(10b)$$

Where $N_d^{s(d)}$ is given elsewhere [10]. The field dependent expressions [11, 12] for μ_n and μ_p are given as

$$\mu_n = \mu_{n0} \frac{1 + \frac{v_{ns}}{\mu_{n0}E}\left(\frac{E}{E_0}\right)^4}{1 + \left(\frac{E}{E_0}\right)^4} \quad and\ \mu_p = \mu_{p0} \frac{1}{1 + \left(\frac{\mu_{p0}}{v_{ps}}\right)^4} -(11)$$

Where E is the electric field, E_0 (= $4X10^5$ V/m) is characteristic field , $v_{ns}(= 8.5X10^4$ m/s) is electron saturation velocity and $v_{ps}(= 10^5$ m/s) is hole saturation velocity.

In case of a self –aligned devices structure shown in fig.(1.c),we assume that the light radiations is falling only on the semitransparent gate metal ,i.e. $\phi = \phi_2$

For such a structure equations (7a,7b, 10a, 10b) become

$$A_1^S = \frac{4}{\pi}(V_{bi} - V_{gs} - V_{op}) - B_1 \text{ and}$$

$$A_1^d = \frac{4}{\pi}(V_{bi} - V_{gs} + V_{ds}V_{op}) - B_1 \quad --(12)$$

$$W_S = \left(\left(\frac{2\varepsilon}{qN_{d,0}^{S}}\right)(V_{bi} - V_{gs} - V_{op})\right)^{\frac{1}{2}} \text{ and}$$

$$W_d = \left(\left(\frac{2\varepsilon}{qN_{d,0}^{d}}\right)(V_{bi} - V_{gs} + V_{ds} - V_{op})\right)^{\frac{1}{2}} -(13)$$

Where B_1 has same expression as in ref.[10]. The drain to source current (I_{ds}) for the optically biased self –aligned GaAs MESFET is obtained as

$$\int_0^{L_g} I_{ds} dx = \int_{W_s}^{W_d} \frac{q^2 Z\mu_n}{\varepsilon} S(N_d + \alpha\phi\tau_{n'} \exp(-\alpha h(x)))h(x)dh(x)$$

$$-\int_{w_s}^{W_d} \frac{q^2 Z\mu_p}{\varepsilon} S \frac{R\tau_{p'}}{b} h(x)dh(x) - \int_0^{L_g} qZ\mu_n K_1 S(A_1^s \frac{\cosh(K_1(L_g - x)}{\sinh(k_1 Lg)}$$

$$-A_1^d \frac{\cosh(k_1 x)}{\sinh(k1Lg)})dx \; -(14)$$

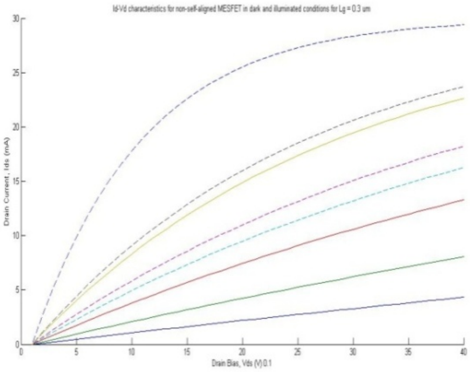

Fig.2. Id–Vd characteristics for non-self-aligned MESFET in dark and illuminated conditions for Lg . 0:3 mm

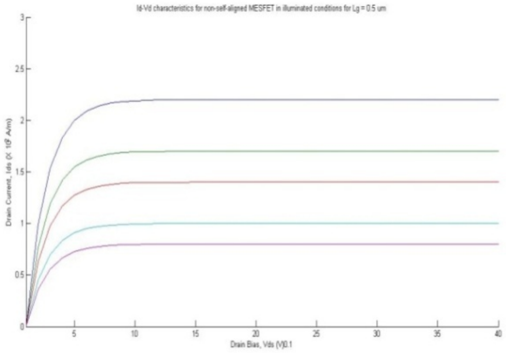

Fig.3. (a) Id–Vd characteristics for non-self-aligned MESFET in illuminated condition for Lg . 0:5 mm

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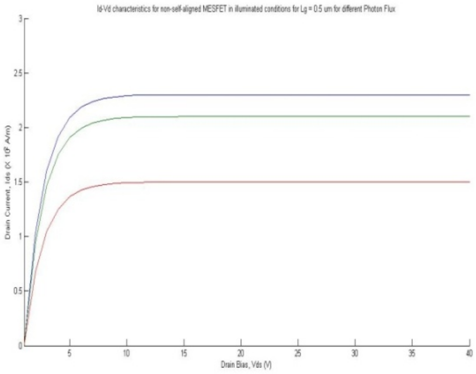

Fig.3. (b) Id–Vd characteristics for non-self-aligned MESFET with Lg .0:5 mm at different photon flux

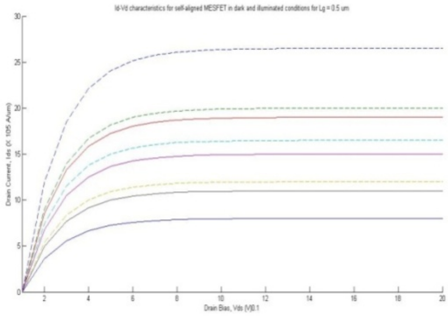

Fig.4. Id–Vd characteristics for self-aligned MESFET in dark and illuminated conditions for Lg. 0:5 mm

III. RESULTS AND DISCUSSION

Fig. 2 shows the variation of drain to source current with drain bias for a non-self-aligned structure at different gate biases in dark and illuminated conditions for a given gate length .(*L*g = 0:3 μm.) As it is seen, for a given incident optical power in the illuminated condition, the current increases significantly. When the device is exposed to the incident light radiation, the spacing between gate and source and between gate and drain allow penetration of radiation which is absorbed in the active region of the device. The gate metal also allows some of the radiation through it. The absorbed light radiation in the active layer of the device produces free carriers, which reduces the parasitic source and drain resistances. This phenomenon is known as the photoconductive effect. Also, a photo voltage is developed across the Schottky junction who effectively reduces the barrier height and the depletion layer width which in turn broaden the channel width. This phenomenon is known as photovoltaic effect. Due to increase in channel width, more number of carriers passes through the channel. So, as a whole, due to photoconductive effect and photovoltaic effect, the drain to source current increases. The theoretical prediction is in good agreement with the experimental data.

Fig. 3(a) shows the *I*ds versus *V*ds plot at various *V*gs for anon-self-aligned device in the illuminated condition with *L*g = 0:5 μm: Fig. 3(b) shows the plot of *I*ds versus *V*ds at a given *V*gs and for different photon flux. With the increase influx, the current increases because the number of free carrier's increases as mentioned above which lead to the increase in current. The plot of *I*ds versus *V*ds for a self-aligned structure is shown in Fig. 4. In a self-aligned structure, we have assumed the light radiation to fall only on the gate metal. As a result a photo voltage is developed at the Schottky junction, which reduces the barrier width and depletion layer width and increases the channel width and hence current.

IV. CONCLUSION

The effect of illumination on the *I*d–*V*d characteristics of both non-self-aligned and self-aligned short gate length GaAs MESFET is studied analytically by solving the two-dimensional Poisson's equation using Green's function technique. In the present work, it is found that the drain to source current can be increased by not only reducing the gate length but also by exposing the device to light radiations having photon energy equal to or greater than the band gap energy of GaAs.

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