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# *I*d–*V*d Output Characteristics and Transit-Time Model For Short-Gate Length Ion-Implanted GaAs MESFET Using MATLAB

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**Abstract:-**Two-dimensional analytical model for optically biased non-self-aligned and self-aligned short channel GaAs MESFETs is developed to show the photo effects on the *I*d–*V*d characteristics. 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 This paper presents transit time model for short gate –length ion-implanted GaAs MESFET. The finite transit-time that carriers take to traverse the channel from source to drain is calculated considering the effect of onset of velocity saturation.

**Keywords:-**MESFET; GaAs; Photo-generation of carriers Component; transit-time; Gaussian-like doping profile; saturation velocity.

## 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

GaAs MESFET is a significant microwave device used in Microwave monolithic integrated circuits (MMICs) [1-2]. Since microwave characteristics can be governed very well by illuminating the Schottky metal gate of the GaAs MESFET device hence optically controlled GaAs MESFET (GaAs OPFET) are in high demand for use in Microwave circuits and systems [3-4]. Under microwave operation, two factors generally limit the frequency response of a GaAs MESFET: the transit time and the RC time constant. In view of the fact that the transit-time can also cause a serious delay in drain-source current through the channel therefore it is essential to model this for proper realization of underlying device physics of GaAs OPFET. Transit time is the result of finite time required by carriers to travel from source to drain. Normally, transit- time of an electron under the gate of a MESFET is estimated by taking the ratio of the gate length to the saturated velocity of the electron. In transient operation, high electric fields are generated due to the temporary formation of large positive potential within the channel. This field is high enough to induce saturated velocity, so it is important to have the accurate transit-time modeling. In the present analysis transit-time modeling of short gate-length ion-implanted GaAs OPFET has been done. The doping profile due to ion-implantation has been assumed as Gaussian-Like doping profile [5] since it closely resembles Gaussian doping profile produced due to ion-implantation. The transit-time has been obtained using two-dimensional potential distribution in the channel region.

## II. MODEL FORMULATION

The schematic structure of the optically controlled GaAs MESFET device considered for modeling is shown in Fig.1. where and are active layer thickness and gate length respectively. The optical radiations are allowed to fall upon the gate metal made up of Indium Tin Oxide (ITO) along vertical y-direction. The substrate of the device is assumed as un doped high pure LEC semi-insulating GaAs material. The active channel region of the device is an n-GaAs layer, obtained by ion implanting Si into semi-insulating substrate.

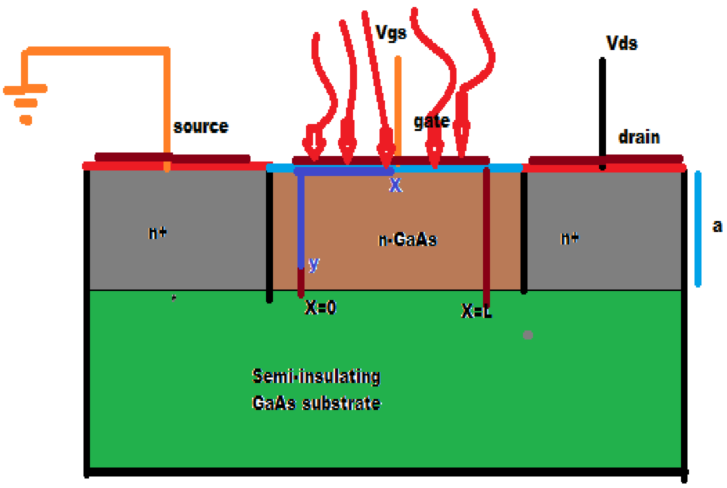


**Fig. (1).** Schematic of GaAs OPFET used for the modeling. a - is the thickness of Active channel region , L -is the length of the Schottky metal gate

The approximate doping distribution in the channel can be given as [6]

$$N_d(y) = N_s + (N_p - N_s)F(y) \_(1)$$

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 [5] given as

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

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

Where $a_c = 1.7857142, b_c = 0.6460835, C_c = 0.28\sqrt{\pi}\ and \beta = \{+1 \text{ for } y > R_p, -1 \text{ for } y < R_p$

The net doping concentration $N_D(y)$ in the active channel region under illuminated condition can be given as [7]

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

Where $N_d(y)$ represents the doping profile defined by (1) .R is the surface recombination rate, $\propto$ is the absorption coefficient of GaAs material, $\tau_n$ and $\tau_p$ are the life time of electrons and holes .respectively and $G(y)$ is the photo generation rate given as [8]

$$G(y) = \phi\alpha\exp(-\alpha y) \_(4a)$$

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

$$\phi = P_{opt}\left(\frac{T_1}{h\nu} + \frac{T_m}{h\nu} + \frac{T_2}{h\nu}\right) \_(4b)$$

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, $\nu$ is the frequency of the incident radiation and $\propto$ the absorption coefficient per unit length

R is the surface recombination rate

In additions to the boundary conditions in ref.[8].equation (1) is subjected to the following two conditions for optically biased MESFET:

$$\psi(x,y)\vdots_s = V_{bi} - V_{gs} - V_{op} \text{ and } \psi(x,y)\vdots_d = V_{bi} - V_{gs} + V_{ds} - V_{op} - (5)$$

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

The Poisson's equation for the partially depleted channel under Schottky metal gate of the device can be given as [9]

$$\frac{\partial^2\phi(x,y)}{\partial x^2} + \frac{\partial^2\phi(x,y)}{\partial y^2} = \frac{qN_D(y)}{\varepsilon_s} \_(6)$$

$\varepsilon_s$ is the dielectric permittivity of GaAs semiconductor and $q$ is electron charge

Above equation when solved with boundary conditions yields potential distribution in the channel region [9]

$$\phi(x,0) = V_{bi} - V_{gs} - V_{op} \_(7)$$

$$\phi(0,y) = V_{bi} \_(8)$$

$$\cdot\phi(L,y) = V_{bi} + V_{ds} \_(9)$$

$$\frac{\partial\phi(x,y)}{\partial y}\vdots_{y=h_x} = 0 \_(10)$$

Where $V_{bi}$ the Schottky barrier is built potential, $V_{gs}$ is the gate-source voltage, $V_{op}$ Is the photo voltage developed across Schottky metal gate , $V_{ds}$ is the drain –source voltage and $h_x$ is the depletion region height same as [10].when equation(5) is solved using above boundary conditions then two –dimensional potential distribution obtained in [10] with respect to ''x'' we can obtained the transverse electric field (E0 as

$$E(x) = \sum_{n=1}^{\infty} \frac{\sinh(k_1 y)}{\sinh(k_1 y)} \left[ -\frac{3\pi}{2a} A_1 \cosh(k_1 (L - x)) + \frac{3\pi}{2a} B_1 \cosh(k_1 x) \right] \_(11)$$

Where $A_1$ and $B_1$ are the values of the coefficients of the two dimensional potential distribution and $k_1$ is same as [10].

The transit –time ( $\tau_1$ ) can be computed if the carrier velocity in the channel is known .The transit –time can be given as [11].

$$\tau = \int_0^L \frac{dx}{v(x)} + \frac{(L - L_s)}{v_s} \_(12)$$

Where $v_s$ is the bulk saturation v velocity [11] and $L_s$ is the length of saturation region as[13]

$$L_s = 2.06 K_d \sqrt{\frac{\varepsilon_s (V_{ds} - V_{sat})}{q\sqrt{n_{cr} N_D (y)}}} \_(13)$$

Where $K_d$ is a domain parameter ( $K_d \approx 1$ for the devices with self aligned gate.), $n_{cr}$ is the characteristic doping density of GaAs (typically $3X10^{21} / m^3$ ) and $V_{sat}$ is the saturation voltage same as[13].
V(x) can be given as

$$v(x) = \mu_0 E(x) \_(14)$$

Where $\mu_0$ is the low field carrier mobility [12] and E(x) is the transverse electric field given by equation(9).

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

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

$$- \int_{-W_s}^{L_g + W_d} qZ\mu_n k_1 S\left(A_1^s \frac{\cosh(k_1 (L_g - x)}{\sinh(k_1 L_g)} - A_1^d \frac{\cosh(k_1 x)}{\sinh(k_1 L_g)}\right)dx - (15)$$

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

$$W_s = \left(\left(\frac{2\varepsilon}{qN_{d,0}^{s}}\right)\left(V_{bi} - V_{gs} - V_1 - V_{op} + I_{ds}R_s - \frac{2}{\pi}A_1^{s}\right)\right)^{\frac{1}{2}} - (16a)$$

$$W_d = \left(\left(\frac{2\varepsilon}{qN_{d,0}^{d}}\right)\left(V_{bi} - V_{gs} + V_{ds} - V_1 - V_{op} + I_{ds}(R_s + R_d) - \frac{2}{\pi}A_1^{d}\right)\right)^{\frac{1}{2}} - (17b)$$

Where $N_d^{s(d)}$ is given elsewhere [10]. The field dependent expressions [12,13 ]for $\mu_n$ and $\mu_p$ are given as

$$\mu_n = \mu_{n0}\frac{1 + \frac{v_{ns}}{\mu_{n0}E}\left(\frac{E}{E_0}\right)^4}{1 + \left(\frac{E}{E_0}\right)^4} \quad and \quad \mu_p = \mu_{p0}\frac{1}{1 + \left(\frac{\mu_{p0}}{v_{ps}}\right)^4} - (18)$$

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

## III. RESULTS AND DISCUSSIONS

The result for the computed using MATLAB for Id-Vd characteristics and Transit –time of Short-gate –length ion implanted GaAs MESFET is shown in the plot for the different values of parameters

| Sr.No | Parameter | Values |
|---|---|---|
| **1** | a -active layer thickness and gate length respectively | 0.4 µm |
| **2** | $R_p$ - is the projected range | 0.2 µm |
| **3** | $V_{bi}$ is the Schottky barrier built in potential | 2.02 V |
| **4** | $T_m$ - is the optical transmission coefficient for the gate metal | 0.9 |
| **5** | L is the gate length | 0.6 µm |

| | | |
|---|---|---|
| **6** | σ is the projected straggle | 0.02 µm |
| **7** | $\alpha$ is the absorption coefficient of GaAs material | 10e6 /m |
| **8** | $\lambda$ - is the optical wavelength | 0.9 µm |
| **9** | $\tau_n$ life time of electrons | 10e-6 S |
| **10** | $\tau_p$ life time of holes | 10e-8 S |
| **11** | $N_P$ peak ion concentration | 6*10e23 me-3 |
| **12** | $N_S$ substrate doping concentration | 2*10e21m e-3 |
| **13** | $P_{in}$ is the incident optical power | 0.1mW |

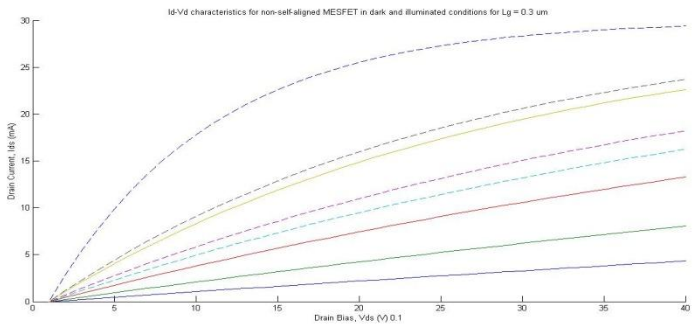


**Fig.(2)** *I*d–*V*d characteristics for non-self-aligned MESFET in dark and illuminated conditions for *L*g . 0:3 mm

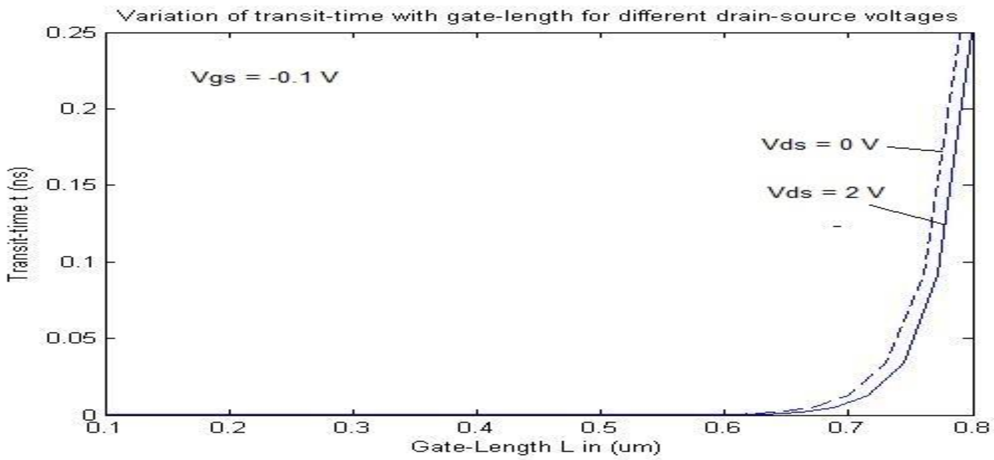


**Fig.(3)** Variation of transit-time with gate-length for different drain-source voltages

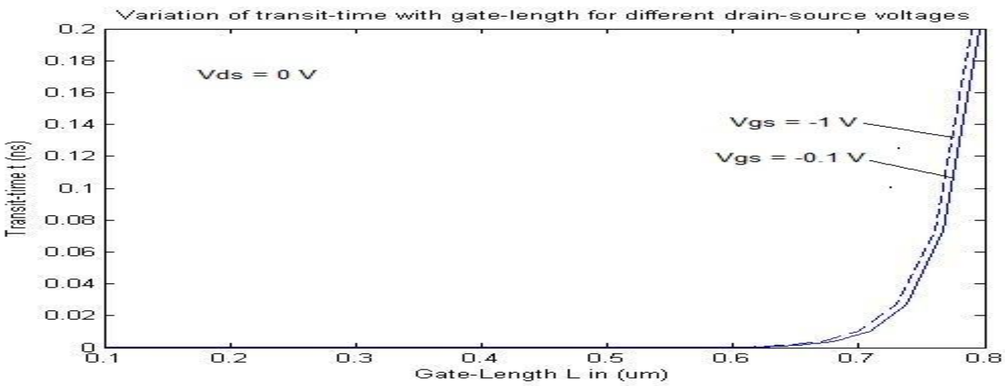


**Fig. (4)** Variation of transit-time with gate-length for different gate-source voltages

Fig.(2) shows the variation of drain to source current with drain bias for a MESFET 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) shows the variation of transit-time with gate-length for different drain-source voltages. It can be observed that as the gate length increases transit-time increases. It may be due to the fact that the distance between source and drain terminal increases with the increase in gate-length and carriers traversing the channel takes more time to reach drain terminal from the source terminal. It can also be observed from Fig.(3) that transit time is more the smaller value of drain bias. At small value of *Vds* the carriers traverse the distance between source and drain with small velocity so transit time is large. As the drain-source voltage *Vds* increases the carrier velocity reaches saturation velocity *vs* and transit-time is reduced. In Fig.(4) variation of transit-time with gate length is shown for different gate-source voltages. It can be seen that for gate-source voltages near pinch off, transit time is very large and recedes as the gate-source junction is shifted toward less negative values. For all above results obtained using MATLAB.

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