Back Illumination- A technique to enhance the performance of GaAs MESFET

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ABSTRACT
An analytical model of GaAs metal-semiconductor-field-effect transistor (MESFET) with non uniform doping under back illumination is developed. The model presents the d.c. and a.c. characteristics of GaAs MESFET under back illumination with the fiber inserted up to the active layer-substrate junction. Photovoltaic effects across the Schottky junction and active channel are considered to estimate various characteristics under different illumination conditions. The Continuity equations in the gate depletion and neutral regions are solved analytically. The frequency dependence of photovoltage at the Schottky contact (V_{op}) is evaluated for estimating the current characteristic under a.c. condition. It has been observed from the results that when GaAs MESFET is illuminated from back an improvement in characteristics over front illumination is experienced due to improved absorption under back illumination.

Categories and Subject Descriptors
G.4 MATLAB

General Terms
Algorithms, Performance.

Keywords
Photodetector, Schottky Junction, Back Illumination, GaAs OPFET (Optically Illuminated Field-Effect-Transistor).

1. INTRODUCTION
Optical control has many advantages for complex microwave systems such as size reduction, signal isolation, large bandwidth and immunity to electromagnetic interference. In particular, optically controlled GaAs MESFET's (OPFET's) have drawn considerable attention for their varied applications in photonic MMIC's as well as in OEIC's. Optical control of microwave devices and circuits has been a fertile area of research for the past few decades. Some authors [1-3,6-8] have also reported high speed optical detection with GaAs MESFET's.
The possibility of making use of optical sensitivity of MESFET to form an additional signal input port justifies an increased interest in physical mechanism which occurs when MESFET is illuminated. When photonic MMIC is designed in such a way as to involve the optical phenomenon there is necessity of a good model with all major effects considered.
This paper presents a model for GaAs MESFET under back illumination. This configuration gives improved device performance under illumination.

2. THEORETICAL MODELING
The structure under consideration is a conventional GaAs MESFET with semitransparent gate. The schematic structure of the GaAs MESFET under back illumination is shown in Fig. 1. The fiber is inserted up to the junction of the active layer and the substrate where the photo absorption takes place in the active layer only and therefore the substrate affect is not taken into account.

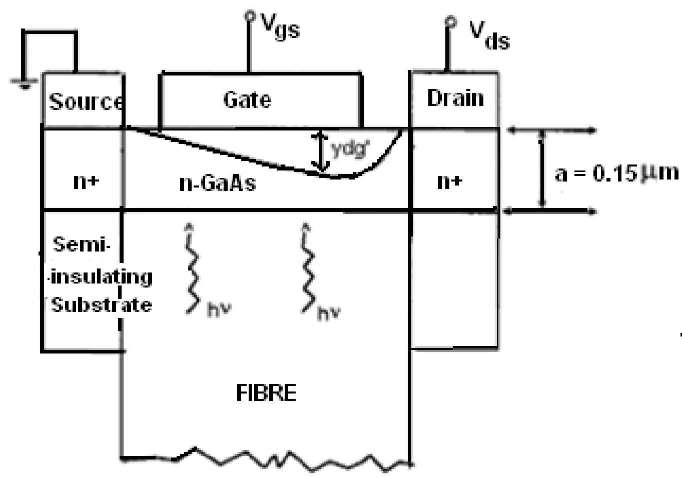

Fig 1: Schematic Structure of GaAs MESFET

The back illumination is incident along the y–direction and drain-source current flows along the x-direction of the device. Electron-hole pairs are generated due to absorption of photons in the neutral channel region and the Schottky junction depletion region. The optically generated electrons move toward the channel and contribute to the drain-source current when a drain-source voltage is applied while the holes move in the opposite direction. When these holes cross the junction a photovoltage is developed. This voltage being forward biased reduces the depletion width of both the junctions. The only photovoltage considered for modeling is the external photovoltage, V_{op} across the Schottky junction [4].

The device consists of a p-type uniformly doped semi-insulating substrate followed by an epitaxially grown ion-implanted active layer of n-type doping. The ion-implanted profile, $N_d(y)$ along y direction is represented by the Gaussian distribution given by [3]

$$N_d(y) = \frac{Q}{\sigma\sqrt{2\pi}} \exp\left(-\left(\frac{y - Rp}{\sigma\sqrt{2}} \right)^2 \right) \quad (1)$$

where
Q Ion implanted dose,
σ straggle parameter
R_p projected range.

2.1 Photovoltage across Shottky junction

In the proposed modeling of ion-implanted GaAs MESFET the investigations are done using basic continuity equation in the gate-depletion region with the Schottky contact under back illumination [5]

The photovoltage is developed due to flow of holes across the junctions. The transport mechanism of carriers in the depletion region is due to drift and recombination [6]. Thus the continuity equation for holes is represented by the first-order differential equation,

$$\frac{\partial p}{\partial t} = -\frac{\partial p}{y} - \frac{p}{\upsilon_y \tau_p} + \frac{\alpha\phi}{\upsilon_y} e^{-\alpha(a-y)} \tag{2}$$

Under back illumination, carrier generation is maximum at the substrate end at y = a and y = 0 refers to the surface of the device where generation is minimum. This is evident from (2) for generation rate. So the constant associated with the exponentially decreasing function is assumed zero from physical condition. The ac solution for the hole density is obtained as

$$p(y) = \frac{\alpha\phi\tau_{wp}}{(1+\alpha\upsilon_y\tau_{wp})} e^{-\alpha(a-y)} \tag{3}$$

Where $\frac{1}{\tau_{\omega p}} = \left(\frac{1}{\tau_p}\right) + j\omega$, τ_p is the life time of holes under ac condition.

Using (3), the number of holes crossing the junction at Schottky junction is calculated. The external photovoltage across the Schottky junction is calculated using the following relation

$$V_{op} = \frac{kT}{q}\ln\left(\frac{q\upsilon_y p(0)}{J_{s1}}\right) \tag{4}$$

p(0) is the number of holes crossing the junction at y = 0 and is also calculated from (3).
Where J_s is the reverse saturation current density across the Schottky junction.

$$J_s = A^* T^2 \exp(-qV_{bi}/kT)$$

Where

$$A^* = \frac{4\Pi q m_n^* k^2}{h^3} \tag{5}$$

m_n^* being the effective mass of the electron.

And y_{dg} is the distance from the surface to edge of the gate depletion region across the Schottky junction of the semi-transparent gate [7] and is expressed as

$$y_{dg} = \sqrt{\frac{2\varepsilon\left[V(x) - \Delta - Vg + \phi_B\right]}{qN_{Dr}}} \tag{6}$$

Under illumination y_{dg} is modified to y'_{dg}, is the distance from the surface to the modified gate edge of the gate depletion region due to photo voltage developed across the Schottky barrier and is given as

$$y_{dg} = \sqrt{\frac{2\varepsilon\left[V(x) - Vg - \Delta + \phi_B - V_{op}\right]}{qN_{Dr}}} \tag{7}$$

ε Permittivity of the GaAs,
υ_y Frequency of the incident radiation,
α Optical absorption coefficient of the semiconductor at the operating wavelength,
q Electron charge,
N_{Dr} The equivalent constant of ion-implanted profile,
Δ Fermi level position at the neutral region below the conduction band,,
V(x) The channel voltage,
Φ_B Schottky barrier height.

3. I-V CHARECTERISTICS

Under illumination the photo generated electrons and holes in the depletion regions [8] and are obtained by solving the continuity equation,

$$\frac{1}{q}\frac{dJn}{dy} + Gn - Un = 0 \tag{8}$$

for electrons and

$$-\frac{1}{q}\frac{dJp}{dy} + Gp - Up = 0 \tag{9}$$

for holes.

In the above equations, (8) and (9), Gn and Gp are the generation rates per unit volume. Un and Up are the recombination rates, and Jn and Jp are the electron and hole current densities respectively, defined by

$$J_n = q\upsilon_y n + qD_n\frac{dn}{dy} \tag{10}$$

and

$$J_p = q\upsilon_y p - qD_p\frac{dp}{dy} \tag{11}$$

which include both drift and diffusion terms.

3.1 Current due to Ion-Implantation

The channel current due to ion –implantation is obtained using the relation [8]

$$Iion = \frac{\mu Z}{L}\int_0^{V_{ds}} Q_{ion}\, dV \tag{12}$$

In which Q_{ion} is the channel charge due to ion-implanted obtained from the relation

$$Q_{ion} = q\int_{y_{dg}}^{a} N_d(y)dy \qquad (13)$$

Where $N_d(y)$ being given by (1).

On substitution of Q_{ion} into I_{ion} we have

$$I_{ion} = \frac{\mu Z}{L}\int_{0}^{V_{ds}} Q_{ion}dv \qquad (14)$$

3.2 Current due to Carrier Generation in the Depletion Region

Since the transport mechanism is drift and recombination in depletion region [8], the continuity equation becomes

$$\frac{\partial n_3}{\partial y} - \frac{n\tau_n}{\upsilon_y} + \frac{\alpha\phi}{\upsilon_y}e^{-\alpha(a-y)} = 0 \qquad (15)$$

As the surface recombination is not considered, the photo generated electrons in the gate depletion region are given by

$$n_3 = \frac{\alpha\phi\tau_n}{(1+\alpha\upsilon_y\tau_n)}e^{-\alpha(a-y)} \qquad (16)$$

The charge developed due to electrons contributed from the gate depletion region is

$$Q_{dep} = q\int_{0}^{y_{dg}} n_3 dy \qquad (17)$$

The corresponding current,

$$I_{dep} = \frac{\mu Z}{L}\int_{0}^{V_{ds}} Q_{dep}dv \qquad (18)$$

3.3 Current due to Generation in the Neutral Region

In neutral region, carrier transport is done due to diffusion and recombination. Again neglecting the recombination, the continuity equation becomes,

$$\frac{d^2 n_1}{dy^2} = \frac{n_1}{D_n\tau_n} - \frac{\alpha\phi e^{-\alpha(a-y)}}{D_n} \qquad (19)$$

where Dn is the diffusion coefficient.

Boundary condition at y=0, $n_2=\alpha\varphi\tau_n$ is used to solve it. The photogenerated electron concentration in the neutral region is given by

$$n_1 = \varepsilon\phi\tau_n\left[1+\frac{1}{(\alpha^2 L_{Dn}^2-1)}\right]\exp(-\alpha(a-y'_{dg}))\times \exp\left[-\left(\frac{y'_{dg}-y}{L_{Dn}}\right)\right] - \frac{\alpha\phi\tau e^{-\alpha(a-y'_{dg})}}{(\alpha^2 L_{Dn}^2-1)} \qquad (20)$$

L_{nw} is the diffusion length of electrons and is given as,

$$L_{Dn} = \sqrt{D_n\tau_n} \qquad (21)$$

The charge density developed due to electrons generated in the active channel is give by

$$Q_{ch} = q\int_{y'_{dg}}^{a} n_1 dy \qquad (22)$$

So the drain-source current contributed by photogenerated electrons in the channel neutral region is calculated as

$$I_{ch} = \frac{\mu Z}{L}\int_{0}^{Vds} Q_{ch}dv \qquad (23)$$

So the total drain-source current is obtained by summing up the (14), (18) and (23)

$$I_{total} = I_{ion} + I_{dep} + I_{ch} \qquad (24)$$

In this model, we have followed the model similar to that for high pinch off MESFET devices [9]. The procedure followed to calculate the actual drain-source current in the device under consideration is given below.

$$I_{ds} = I_{sat}(1+\lambda V_i)tanh\eta V_i \qquad (25)$$

Where

$$V_i(The\ input\ voltage) = V_{ds} - I_{sat}(r_s + r_d)$$

$\eta = \frac{G_{ch}}{I_{sat}}$ G_{ch} is the channel conductance

λ =0.025 (constant)

r_s and r_d are the source and drain resistances

Saturation current is defined as

$$I_{sat} = I_{total}\left[K - (K^2 - 1 + U_{gs})^2\right] \qquad (26)$$

Where

$$K = 1 + \frac{r_s I_{total}}{2V_{po}}$$

V_{po} is the pinch off voltage
And

$$U_{gs} = \frac{V_{bi} - V_{gs}}{V_{po}}$$

Modeling of GaAs MESFET under the front illumination is reported in [10].

3.4. Calculation of Channel Conductance

The channel conductance of the device are calculated using the following relations [6],

$$g_d = \left[\frac{dI_{ds}}{dV_{ds}} \right]_{V_{gs} constant} \tag{27}$$

4. RESULTS AND DISCUSSIONS

Computations and simulations have been carried out for GaAs MESFET at 300 K under various illuminated conditions using model equations presented in section 3 .The parameters used in the calculations are shown in Table 1.

Table 1 Parameters used in the modeling

Parameter	Values
Channel length, L	3 µm
Channel depth, a	0.15 µm
Device width, Z	12.7 µm
Absorption coefficient, α	10^6 /m
Intrinsic carrier concentration, n_i	1.79 x 10^{12} /m^3
Built-in voltage of Schottky gate, Φ_{bi}	0.85 V
Temperature, T	300 K
N_{dr}	0.658 x10^{23}/m^3
R_p	0.861x10^{-7}m
μ_b	3000cm^2/s/V
μ_n	3483cm^2/s/V
Δ	0.02
r_d	1KΩ
r_s	100Ω

Fig 2 shows the comparison plot for the variation of photo-voltage with frequency under back and front illumination. It shows that the photovoltage developed at the Schottky junction is higher for front illuminated GaAs MESFET. This is because under back illumination the no. of photo carriers generated at the gate active layer depletion region is less than that in front illumination. The photovoltage decreases with the increase in frequency due to the change in the minority carrier lifetime with the change in the frequency [7].

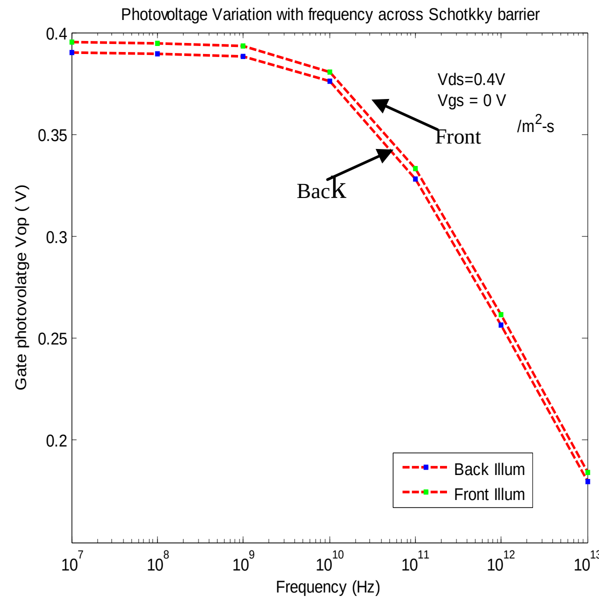

Fig 2: Vop Vs Frequency for front and back illuminated MESFET

Fig 3 shows the variation of Ids with Vds for front and back illuminated GaAs MESFET for different illumination. The device is illuminated with a flux density of 10^{14} Wb/m^2 (LI) and 10^{16} Wb/m^2 (HI). The simulation of the model shows higher current for higher illumination as tabulated in table 2. It is also observed that with back illumination as compared to front illumination higher current exists due to improved absorption in the active channel region. The similar results have been reported by [7-8].

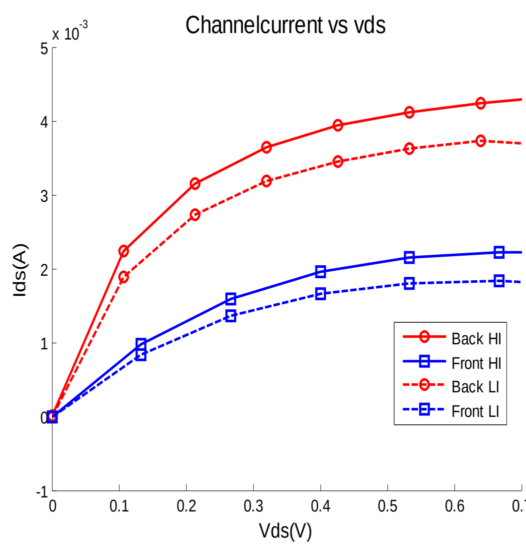

Fig 3: Ids Vs Vds for front and back illuminated MESFET

Table 2 Comparison of Current in GaAs MESFET for front illumination and back illumination for d.c. condition at V_{ds} =0.5V

Phi	Id (mA) (Front illumination)	Id m(A) (Back illumination)
Phi1(LI)	1.79	3.616
Phi2(HI)	2.149	4.119

Fig 4 shows the variation of Ids with frequency for front and back illuminated GaAs MESFET under different illumination and the comparative results are tabulated in table 3. It shows that back illuminated GaAs MESFET has a broader bandwidth as compared to device with front illumination. This is due to the change in minority carrier life time with frequency.

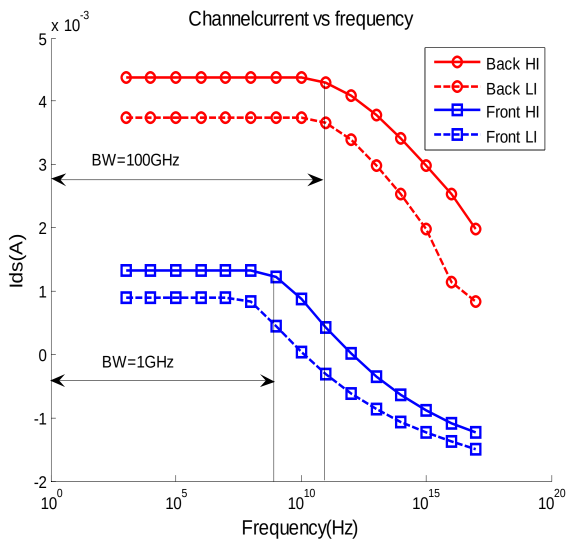

Fig 4: Ids Vs Frequency for front and back illuminated MESFET

Table 3 Comparison of current of GaAs MESFET for front illumination and back illumination for a.c. condition

w(Hz)	Id (mA) Front illumination		Id (mA) Back illumination	
	Phi1(LI)	Phi2(HI)	Phi1(LI)	Phi2(HI)
10^8	0.8346	1.329	3.75	4.375
10^9	0.445	1.231	3.749	4.374
10^{10}	0.03286	0.8793	3.738	4.366

Fig 5 shows the variation of channel conductance (gd) with Vds for front and back illuminated MESFET under different illuminations. It shows that the channel conductance increases with the increase in illumination at the gate. It also shows that the channel conductance is higher for the back illuminated GaAs MESFET and the results are tabulated in table 4. This is because more carriers are induced in the channel due improved absorption in the active channel region for the back illuminated GaAs MESFET.

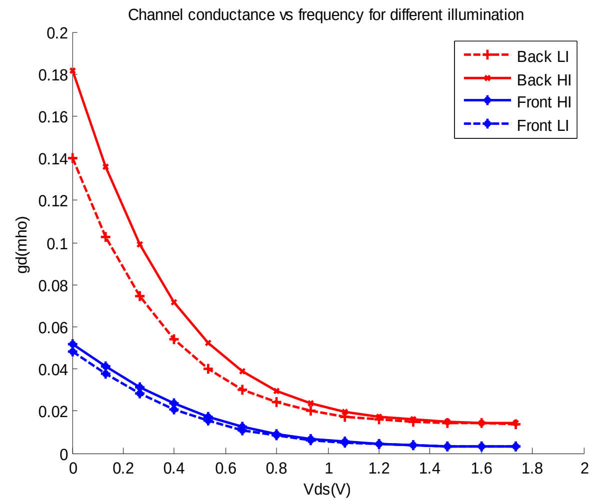

Fig 5: gd VsVds for front and back illuminated MESFET with different illumination

Table 4 Comparison of channel conductance of GaAs MESFET for front illumination and back illumination for d.c. condition

Phi	gd (mmho) Front illumination	gd (mmho) Back illumination
Phi1(LI)	15.22	39.88
Phi2(HI)	17.07	52.25

Fig 6 shows the variation of channel conductance (gd) with frequency for back illuminated MESFET under different illumination. It shows that the channel conductance increases with the increase in illumination at the gate. It is also observed that the conductance reduces after 100GHz.This is because optical potential at the gate decreases at higher frequencies.

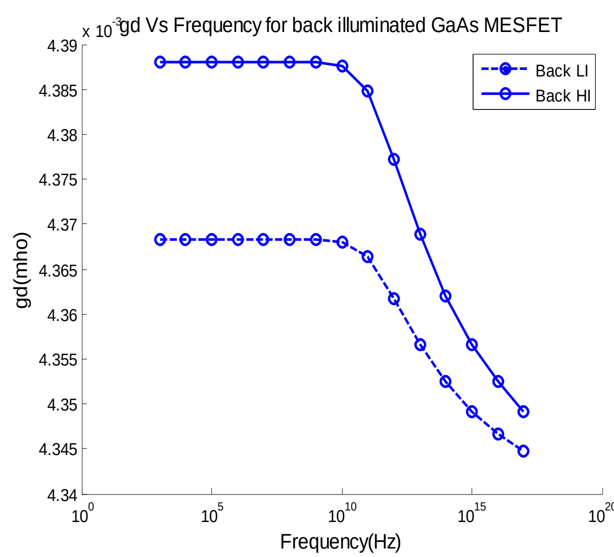

Fig 6: gd Vs frequency for front and back illuminated MESFET with different illumination

Fig 7 shows the comparison of the variation of channel conductance (gd) with frequency for front and back illuminated MESFET. It shows that the conductance is much higher for the back illuminated GaAs MESFET at fixed illumination and the results are tabulated in table 5.

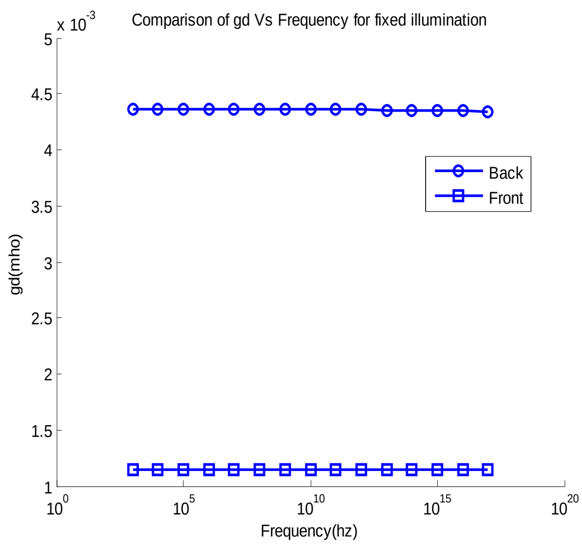

Fig7: gd Vs frequency for front and back illuminated MESFET at fixed illumination

Table 5 Comparison of channel conductance of GaAs MESFET for front illumination and back illumination for a.c. condition

w(Hz)	gd (mmho) Front illumination	gd (mmho) Back illumination
10^8	1.147	4.368
10^9	1.146	4.368
10^{10}	1.145	4.368
10^{11}	1.144	4.366
10^{12}	1.143	4.362

5. CONCLUSION

A simulation program for non-uniformly doped GaAs MESFET with back illumination has been developed. The program solves analytically the basic semiconductor equations (Continuity Equation). The model has been applied to simulate the characteristics under different illuminated conditions. The results discuss about the variation of photovoltage with the frequency. It also discusses the Ids-Vds, Ids-ω, gd-Vds and gd-ω curve for various illuminations.

It has been observed that back illuminated MESFET has higher current and channel conductance. It has been observed from the results that the characteristics of the device with back illumination are more influenced by the incident optical illumination than the front illumination. It also shows that back illuminated MESFET has broader bandwidth. The results obtained from the simulation compares satisfactorily with reported results for similar structures.

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