RP Current Trends in Engineering and Technology
Vol. 1, No. 6 (December 2022) pp. 117–120
e-ISSN: 2583-5491

Cite this article: T. Singh, Enhanced time-dependent characteristics of MOSFET under backside illumination, *RP Cur. Tr. Eng. Tech.* **1** (2022) 117–120.

Original Research Article

Enhanced time-dependent characteristics of MODFET backside illumination

Tejinder Singh
Department of Electronics and Communication Engineering, Dr. B.R. Ambedkar Institute of Technology, Portblair, India
*Corresponding author, E-mail: tejinder.dbrait@gmail.com

ARTICLE HISTORY
Received: 15 October 2022
Revised: 19 Dec. 2022
Accepted: 21 Dec. 2022
Published online: 22 Dec. 2022

KEYWORDS
Two dimensional electron gas; MODFET; Photo-voltage; Time dependent characteristics.

ABSTRACT
Under backside optical illumination, the time-dependent properties of n-AlGaAs/GaAs Modulation Doped Field Effect Transistors (MODFET) are examined, and the transient behaviour of the device has been estimated. For direct lighting into the GaAs layer, a device construction with fibre introduced into the substrate up to that layer is taken into consideration. The active zone may be partially depleted. The time dependent continuity equation is solved to determine the extra carriers resulting from photo-generation. The creation of carriers changes the energy levels. Plots and discussions of the time-dependent I-V characteristics have been made. At a specific gate source voltage under lighted conditions, the time-dependent I-V characteristics are compared with the theoretical data that is currently available, exhibiting good agreement.

1. Introduction

Due to their use in fibre optical communication and optical integration, there is a growing interest in the study of optical effects in high speed devices. Optical Field Effect Transistors (OPFET) can be utilised as a radio frequency switch, gain control for amplifiers, locking and frequency modulation, oscillator tuning, mixing, phase shifting, and other things [1]. Investigating the time-dependent properties of MODFET under backside illumination is desirable since MODFET outperforms MESFET in terms of frequency and noise.

In this study, we simulated the time-dependent properties of the device MODFET under the assumption that the optical radiation strikes the GaAs layer straight from the back. We have determined the Two Dimensional Electron Gas (2DEG) time-dependent sheet concentration in both darkness and light. Plots and discussions of the time-dependent I-V characteristics have been made. At a specific gate source voltage under lighted conditions, the time-dependent I-V characteristics are compared with the theoretical data that is currently available, exhibiting good agreement. Here is a presentation of the theory.

2. Theory

The n-AlGaAs/GaAs Modulation Doped Field Effect Transistor is depicted in Figure 1 with radiation striking the GaAs layer directly through an optical fibre inserted in the substrate region. The device structure consists of a layer of n-AlGaAs followed by an undoped layer of the same material, then followed by heterojunction and GaAs layer. AlGaAs/GaAs make up the heterojunction. The GaAs being considered here is undoped. In order to avoid the shadowing effect of the metals, we assumed in this research that optical light strikes the GaAs layer directly from its reverse side. Inserting an optical fibre into the substrate region and bringing it into contact with the GaAs layer eliminates the substrate's attenuation effect.

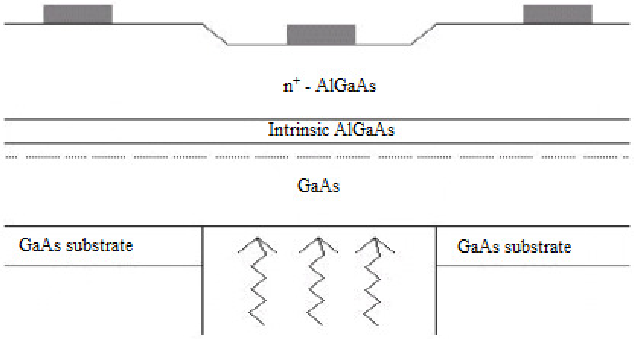

Figure 1. AlGaAs/GaAs MODFET with improved absorption under backside optical illumination.

As a result, the GaAs layer, heterojunction regions, and the neutral and depletion regions of AlGaAs can all produce free electron-hole pairs when exposed to optical radiation [2]. While the holes travel either toward the surface or the substrate, the extra free electrons move in the direction of the heterojunction interface. The heterojunction produces a photovoltage that pulls electrons toward the interface and increases the 2-DEG sheet concentration. The device's partial depletion is taken into account so that the analysis is still accurate at low temperatures. These excess carriers generated are calculated by solving the time dependent continuity equations for electrons and holes. The electric field and voltage are solved using the Poisson's equation. The time dependent continuity equations for excess electrons and holes generated in the neutral and depletion regions of the device are:

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_n(x,t)}{\partial x} + G_n - U_n \, , \tag{1}$$

for electrons and

$$\frac{\partial p(x,t)}{\partial x} = -\frac{1}{q}\frac{\partial J_p(x,t)}{\partial x} + G_p - U_p \, , \tag{2}$$

for holes, where J_n (x, t) and J_p (x, t) are the electron and hole current densities. In the above equation, G_n and G_p are the volume generation rates and U_n and U_p are the recombination rates, D_n and D_p are the diffusion coefficients and n (x, t) and p (x, t) are the electron and hole concentrations, v_x is the carrier saturated velocity along vertical x-direction, assumed the same for both electrons and holes. When light is just turned on at t = 0 the boundary condition is n (y =-d, t) = 0.In this case the solution of equation (1) becomes

$$n(x,t) = \alpha\phi\tau_n \exp[-\alpha(x+d)\left[1-\exp\left(\frac{\tau}{\tau_{rn}}\right)\right], \tag{3}$$

where

$$\frac{1}{\tau_{rn}} = \frac{1}{\tau_n} + \alpha v_x + \alpha^2 D_n \tag{4}$$

being defined as the optical relaxation time. When light is just turn off at t = 0, the boundary condition becomes n (y = -d, t) = $\alpha\varphi\tau_n$ and the solution of equation (1) is obtained as:

$$n(x,t) = \alpha\phi\tau_n \exp[-\alpha(x+d)\exp\left(-\frac{\tau}{\tau_{rn}}\right). \tag{5}$$

Similarly for holes, when the light is turned on the solution of equation (2) is obtained as:

$$p(x,t) = \alpha\phi\tau_p \exp[-\alpha(x+d)\left[1-\exp\left(-\frac{\tau}{\tau_{rp}}\right)\right] \tag{6}$$

and when the light is turned off

$$p(x,t) = \alpha\phi\tau_p \exp[-\alpha(x+d)\exp\left(-\frac{\tau}{\tau_{rp}}\right) \tag{7}$$

where

$$\frac{1}{\tau_{rp}} = \frac{1}{\tau_p} + \alpha v_x + \alpha^2 D_p \, . \tag{8}$$

3. Poisson’s equation and the total charge

To simulate the current characteristics, we need to determine the relation between 2-DEG electron concentration n_s and the gate voltage V_g. Considering the partial depletion of the AlGaAs layer, the Poissons equation is represented as:

$$\frac{\partial^2\psi}{\partial x^2} = -\frac{q}{\varepsilon}(N_D^+ - n_t(x)) \, , \tag{9}$$

where N_d is the doped layer concentration and n_t (x) is the number of excess electrons due to photogeneration both in the depleted and neutral region of AlGaAs. The photo generated electron density in the depleted and neutral region has been derived by solving the steady state continuity equation.

The electric field E(-d) at the gate semiconductor interface is obtained. The offset voltage V_{OFF} is expressed as:

$$V_{on} = \phi_b + \frac{1}{q}(\Delta E_{F1} - \Delta E_C) - V_P - V_{PN} - V_{PGN} \, , \tag{10}$$

when light is turned on and

$$V_{of} = \phi_b + \frac{1}{q}(\Delta E_{F1} - \Delta E_C) - V_P - V_{PF} - V_{PGF} \, , \tag{11}$$

when light is turned off. Here V_p is the pinch off voltage of the device. V_{PN} and V_{PF} are the photovoltages across the heterojunction due to excess holes generated in the active region, when the light is turned on and turned off respectively and is given by

$$V_{PN,F} = \frac{KT}{q}\ln\left(\frac{q v_x P(x,t)}{J_S}\right). \tag{12}$$

Here, V_{PGN} and V_{PGF} are the voltages developed due to photogenerated carriers in the active region and are given as:

$$V_{PGN} = \left[\frac{q}{\varepsilon_2}\frac{\phi.\exp(-\alpha d)}{\alpha}\right]\left[\tau_n\left(1-\exp\left(\frac{t}{\tau_{rn}}\right)\right) - \left(1-\exp\left(\frac{-t}{\tau_{rp}}\right)\right)\right], \tag{13}$$

when light is turned on and

$$V_{PGF} = \left[\frac{q}{\varepsilon_2}\frac{\phi.\exp(-\alpha d)}{\alpha}\right]\left[\tau_n \exp\left(\frac{-t}{\tau_{rn}}\right) - \tau_p \exp\left(\frac{t}{\tau_{rp}}\right)\right], \tag{14}$$

when light is turned off, respectively. These parameters vary with time.

The total charge in 2DEG is thus obtained as:

$$Q_T = \varepsilon E(-d) \, . \tag{15}$$

The total charge includes charge due to surface, bulk and the charge due to photo generation.

The current voltage characteristics are obtained using the relation:

$$I_D = Q_T Z v(y)\,, \qquad (16)$$

where Q_T is the total Charge in the 2-DEG in the quantum well, Z is the gate width and $v(y)$ is the velocity of electrons at any point y. The realistic velocity field relation

$$v(y) = v_s\left[1-\exp\left(-\frac{\mu_E}{v_s}\right)\right] \qquad (17)$$

where $E = -dV/dy$ is considered (Mitra et al. 1998). Equation (17) covers both low field and high field region. Integrating from $y = 0$ to $y = L$‘; L’ being the gate length, yields

$$\int_{V(0)}^{V(L)} \frac{dV}{\ln\left(1-\frac{I_D}{Q_T Z v_s}\right)} = -\frac{v_s L}{\mu}\,, \qquad (18)$$

where $V(0) = I_D R_S^{'}$, and $V(L) = V_D - I_D R_D$, $R_S^{'}$ and R_D and being the source and drain parasitic resistances. Thus

$$V_D = I_D(R_D + R_S^{'}) - \frac{v_s L}{\mu}\ln\left(1-\frac{I_D}{Q_T Z v_s}\right). \qquad (19)$$

Equation (25) represents the current –voltage (*I*-*V*) relation for the MODFET under optically illuminated condition

4. Results and Discussion

For an n-AlGaAs/GaAs MODFET, an analytical simulation was performed while taking the optical effect into account. Table 1 lists the dimensions and other fundamental variables that were used in the calculation.

Table 1. Parameter values used for calculation.

Symbol	Name	Value
Z	Gate width	145 mm
L	Gate length	1 mm
N_D	Donor concentration	1.0×10^{18} m^{-3}
N_A	Acceptor concentration	3.0×10^{20} m^{-3}
v_s	Saturated velocity	2.0×10^{7} cm s^{-1}
ε_1	Permittivity of GaAs	$13.2\varepsilon_0$ F cm^{-1}
ε_2	Permittivity of AlGaAs	$12.1\ \varepsilon_0$ F cm^{-1}
ε_0	Permittivity of vacuum	8.8×10^{-12} F m^{-1}
μ	Low field mobility	6800 cm^{2} V^{-1}s^{-1}
h	Plancks constant	6.6×10^{-34} Js
q	Electronic charge	1.6×10^{-19} C
d_s	Spacer thickness	60 Å
d_d	Active layer thickness	525 Å
d	Width of the well	80 Å

Drain current is plotted against time in Figures 2 and 3. when switching the light on and off at various gate voltages while it is in the saturation area (VDS = 1.0V). The drain current grows with gate voltages in the turn-on scenario and achieves the stable value at a time of about 10 ps. In the turn-off case, the drain current reaches the dark value at around 240 ps. The graphs indicate that the influence of backside lighting results in better absorption and significantly increases drain current. The device exhibits improved transient behaviour, it seems.

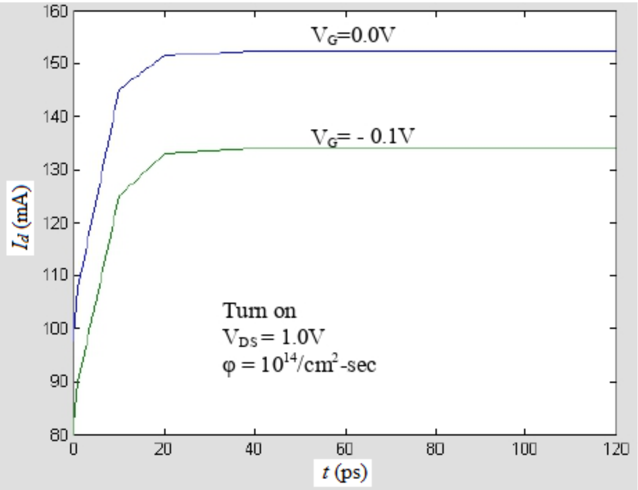

Figure 2. Drain current versus time when light is turned on.

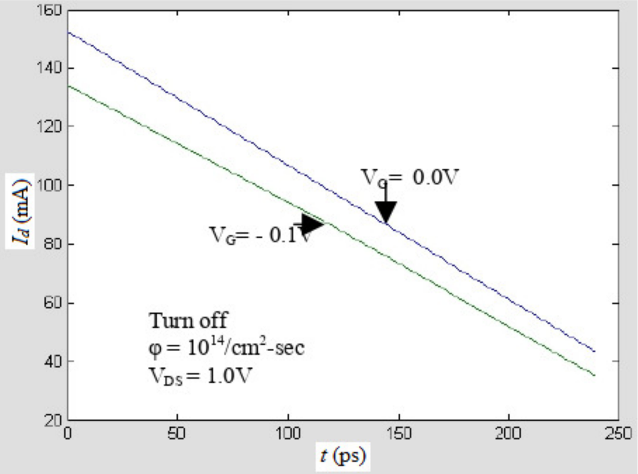

Figure 3. Drain current versus time when light is turned off.

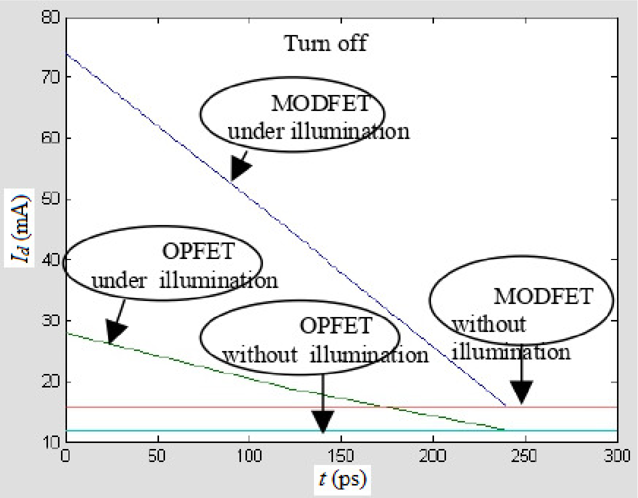

Figure 4. Comparison of the current versus time characteristics under illumination and dark conditions.

Figure 4 compares the current against time features of our result with the theoretical data that has been published under lit conditions. We contrasted our results under illumination with the results of OPFET because experimental results for the MODFET's transient behaviour are not yet available. Our estimated results and those provided in Ref. [7] show a superior outcome and good agreement in the declining time.

5. Conclusions

The effect of backside optical illumination on the time dependent characteristics of n-AlGaAs/GaAs MODFET with partial depletion of the active layer has been simulated. The drain current versus time characteristics have been simulated and discussed. It is observed the drain source current increases sharply with time and reach the steady state value around 10 ps, when the light is turned on at a reference time $t = 0$. When the light is turned off at $t = 0$, it reduces with time and become equal to its dark values at around 240 ps, which is much higher than the turned on case. The rationale given is the photovoltage, which under turned-off conditions changes linearly with time, and the optical relaxation time, which controls behaviour under turned-on conditions. When results of current versus time features are compared with published data [7-9] under light, the results are better and there is better agreement.

References

[1] B.B. Pal, S.N. chattopadhyay, S. Mishra, S. Singh, R.U. Khan, Time dependent analysis of an ion-implanted GaAs OPFET, *IEEE Trans. Elect. Device* **41** (1994) 491-498.

[2] R.N. Simons, Microwave performance of an optically controlled AlGaAs/GaAs high electron mobility transistor and GaAs MESFET, *IEEE Trans. Microwave Theor. Tech.* **35** (1987) 1444-1455.

[3] H. Mitra, B. Pal, S. Singh, R.U. Khan, Optical effect in InAlAs/AnGaAs/InP MODFET, *IEEE Trans. Elect. Devices* **45** (1998) 68-77.

[4] R.N. Simons, K.B. Bhasin, Analysis of optically controlled microwave/mm-wave device structures, *IEEE Trans. Microwave Th. Tech* MTT-**34** (1985) 1349-1355.

[5] A.A. Desallers, Optical effects of hemts microwave and optical, *Microwave Opt. Tech. Lett.* **3** (1990) 350-354.

[6] V.K. Singh, S.N. Chattopadhyay, B.B. Pal, Optically controlled characteristics in an ion-implanted silicon MESFET, *Solid State Electron*. **29** (1986) 707-711.

[7] S.K. Aggarwal, R. Gupta, S. Haldar, M. Gupta, R.S. Gupta, A physics based analytical model for buried p-layer non-self aligned SiC MESFET for the saturation region, *Solid State Electron*. **49** (2005) 1206-1212.

[8] H. Mitra; B.B. Pal; S. Singh; R.U. Khan, Optical effect in InAlAs/InGaAs/InP MODFET, *IEEE Trans. Electron Dev*ices **45** (1998) 68-77.

[9] V. Kannan, P.E. Sankarnarayanan, S.K. Srivatsa, Simulated time dependent characteristics of MODFET under backside illumination, *Info. Tech. J.* **5** (2006) 661-667.