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Simulated Time Dependent Characteristics of MODFET under Backside Illumination

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Abstract: The time dependent characteristics of n-A1GaAs/GaAs Modulation Doped Field Effect Transistors (MODFET) under backside optical illumination is investigated and the transient behaviour of the device have been simulated. A device structure with fiber inserted into the substrate up to GaAs layer is considered for direct illumination into the GaAs layer. Partial depletion of the active region is considered. The excess carriers due to photo generation are obtained by solving the time dependent continuity equation. The energy levels are modified due to generation of carriers. The offset voltage, sheet concentration and time dependent I-V characteristics have been simulated and discussed. The time dependent I-V characteristics is compared with available theoretical data at a particular gate source voltage under illuminated condition.

Key words: Two dimensional electron gas, MODFET, photovoltage, time dependent characteristics

INTRODUCTION

A strong interest has been created in the study of optical effect in high speed devices due to their application in fiber optical communication and optical integration.

In general OPtical Field Effect Transistors (OPFET) can be used as a radio frequency switch,gain control for amplifiers, for locking and frequency modulation, oscillator tuning, mixing, phase shifting etc. (Simons and Bhasin, 1986). Although some investigators have carried out both experimental and analytical studies on the effect of illumination and time dependent characteristics in GaAs Metal Semiconductor Field Transistor (MESFET) and A1GaAs/GaAs MODFET (Simons and Bhasin, 1986; Singh *et al*., 1986; Simons, 1987; Desallers *et al*., 1991; Pal *et al*., 1994), which show that there is significant effect of induced light on the electrical parameters of the device. Still there is lack of theoretical and experimental work describing the transient behaviour of MODFET due to backside illumination. Since MODFET shows better performance than MESFET in terms of frequency and noise, it is desirable to investigate the time dependent characteristics of MODFET under backside illumination

Initial work in optically controlling MODFET was done with frontside illumination of the device and the shadowing effects of the contact metal limited the responsivity and the quantum efficiency (Simons and Bhasin, 1986; Simons, 1987).

These shadowing effects were overcome by the ELO process demonstrated by Paul *et al.* (1993, 1994). A detailed analysis considering all effects resulting from optical illumination on MODFETs is a very complex task. However, by making some assumptions, a simplified analysis considering the relevant photo-effects can be made (Desallers, 1990).

In this study, we have simulated the time dependent characteristics of the device MODFET assuming that the optical radiation falls directly on the GaAs layer from its backside. We have calculated the time dependent sheet concentration of Two Dimentional Electron Gas (2DEG) under dark and illumination. Also the offset voltage of the device and the current versus time characteristics have been simulated and presented. The I-V characteristics have been compared under dark and illuminated condition with the available theoretical data (Pal *et al*., 1994) .The theory is presented below.

THEORY

Figure 1 shows the n-AlGaAs/GaAs Modulation Doped Field Effect Transistor with radiation falling on 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. The heterojunction is made of AlGaAs/GaAs. The GaAs considered here is undoped.

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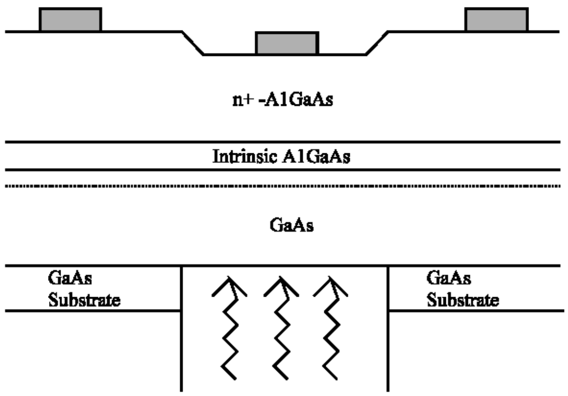

Fig. 1: AlGaAs/GaAs MODFET under backside optical Illumination

In this study, we assumed that the optical radiation falls directly on the GaAs layer from its backside to eliminate shadowing effect of the metals. The attenuation effect of the substrate is eliminated by inserting an optical fiber in the substrate region, so that the fiber touches the GaAs layer. This allows the optical radiation to create free electron-hole pairs in the GaAs layer, heterojunction regions and the neutral and depletion regions of AlGaAs (George and Hauser, 1990). The excess free electrons move toward the heterojunction interface and the holes move either toward the surface or substrate. A photo voltage is developed from the heterojunction, which drags the electrons into the interface enhancing the sheet concentration of the 2-DEG. Partial depletion of the device is considered so that the analysis is valid even at low temperature.

These excess carriers generated are calculated by solving the time dependent continuity equations for electrons and holes. The Poisson's equation is used for solving the electric field and voltage.

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 and are represented by

$$J_n(x,t) = qv_x n(x,t) + qD_n\frac{\partial n(x,t)}{\partial x} \tag{3}$$

and

$$J_p(x,t) = qv_x p(x,t) - qD_p\frac{\partial p(x,t)}{\partial x} \tag{4}$$

In the above equation, G_n and G_p are the volume generation rates and

$$U_n = \frac{n(x,t)}{\tau_n} \text{ and } U_p = \frac{p(x,t)}{\tau_p}$$

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 Eq. (1) becomes

$$n(x,t) = \alpha\phi\tau_n e^{-\alpha(x+d)}\left(1 - e^{-\frac{t}{\tau_m}}\right) \tag{5}$$

where

$$\frac{1}{\tau_m} = \frac{1}{\tau_n} + \alpha v_x + \alpha^2 D_n \tag{6}$$

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

$$n(x,t) = \alpha\phi\tau_n e^{-\alpha(x+d)} e^{-\frac{t}{\tau_m}} \tag{7}$$

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

$$p(x,t) = \alpha\phi\tau_p e^{-\alpha(x+d)}\left(1 - e^{-\frac{t}{\tau_{rp}}}\right) \tag{8}$$

and when the light is turned off

$$p(x,t) = \alpha\phi\tau_p e^{-\alpha(x+d)} e^{-\frac{t}{\tau_{rp}}} \tag{9}$$

where

$$\frac{1}{\tau_{rp}} = \frac{1}{\tau_p} + \alpha v_x + \alpha^2 D_p \tag{10}$$

POISSONS 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:

$$\frac{\partial^2\psi}{dx^2} = -\frac{q}{\varepsilon}(N_D^+ - n_t(x)) \tag{11}$$

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 and is given by

$$n(x) = De^{\sqrt{A}x} - Ee^{\sqrt{A}(x)} + n_{n0}e^{-\sqrt{A}(d_1-x)} + \frac{B}{(\alpha^2 - A)}e^{\alpha x} + \frac{B^1}{(A^1 - \alpha)}e^{\alpha x} - \frac{C}{A} \quad (12)$$

where the constants A, B, C, D, E and B^1 are explained in the Appendix

Considering Fermi-Dirac integral approximation (George and Hauser, 1990), Eq. (11) may be written as:

$$\frac{\partial^2\psi}{dx^2} = -\frac{q}{\varepsilon}(N_D^+ - n)\left[\frac{N_D}{1+2\exp\left(\frac{qV_G - E_{D0} + q\psi}{kT}\right)} - \frac{N_C\exp\left(\frac{-E_{C0} - q\psi - qV_G}{kT}\right)}{1+0.27\exp\left(\frac{E_{C0} - q\psi - qV_G}{kT}\right)}\right] \quad (13)$$

By using the transformation

$$\frac{\partial^2\psi}{dx^2} = \frac{\partial}{d\psi}\left(\frac{\partial\psi}{dx}\right)\frac{\partial\psi}{dx} \quad (14)$$

the electric field at the gate semiconductor interface is given by

$$E^2(-d) = \left\{E^2(0) + \frac{2q}{\varepsilon}\left(\frac{N_C kT}{0.27q}\left(\ln\left(1+0.27\exp\frac{q\psi(-d)+qV_G-E_{C0}}{kT}\right) - \ln\left(1+0.27\exp\frac{q\psi(0)+qV_G-E_{C0}}{kT}\right)\right)\right) + \frac{2q}{\varepsilon}\left(\frac{N_C kT}{q}\left(\ln\left(\exp\frac{-q\psi(-d)}{kT} + 2\exp\frac{qV_G - E_{D0}}{kT}\right) - \ln\left(\exp\frac{-q\psi(0)}{kT} + 2\exp\frac{qV_G - E_{D0}}{kT}\right)\right)\right)\right\} \quad (15)$$

where the boundary conditions are

$$\psi(0) = -\frac{\Delta E_C}{q} - V_{OFF} - \frac{qn_S d}{\varepsilon}$$

$$\psi(-d) = \phi_b$$

$$E(0) = \frac{qn_S}{\varepsilon}$$

where, ϕ_b is the metal semiconductor work function difference, ΔE_C is the conduction band edge discontinuity between AlGaAs and GaAs materials and n_s is the sheet concentration of 2-DEG at the heterojunction. The offset voltage V_{OFF} is expressed as:

$$V_{on} = \phi_b + \frac{1}{q}(\Delta E_{F1} - \Delta E_C) - V_P - V_{PN} - V_{PGN} \quad (16)$$

when light is turned on and

$$V_{of} = \phi_b + \frac{1}{q}(\Delta E_{F1} - \Delta E_C) - V_P - V_{PF} - V_{PGF} \quad (17)$$

when light is turned off. where

$$V_P = \frac{qN_D d_d^2}{2\varepsilon_2} \quad (18)$$

and it 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

$$V_{PN,F} = \frac{KT}{q}\ln\left(\frac{qv_x P(x,t)}{J_S}\right) \quad (19)$$

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

$$V_{PGN} = \left[\frac{q}{\varepsilon_2}\frac{\phi e^{-\alpha d}}{\alpha}\right]\left[\tau_n\left(1 - e^{-\frac{t}{\tau_m}}\right) - \tau_p\left(1 - e^{-\frac{t}{\tau_{rp}}}\right)\right] \quad (20)$$

when light is turned on and

$$V_{PGF} = \left[\frac{q}{\varepsilon_2}\frac{\phi e^{-\alpha d}}{\alpha}\right]\left[\tau_n e^{-\frac{t}{\tau_m}} - \tau_p e^{-\frac{t}{\tau_{rp}}}\right] \quad (21)$$

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

The total charge in 2DEG is thus obtained as

$$Q_T = \varepsilon E\,(-d) \quad (22)$$

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

CURRENT VOLTAGE CHARACTERISTICS

The current voltage characteristics is obtained using the relation

$$I_D = Q_T Z v\,(y) \quad (23)$$

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, $v(y) = v_S(1-e^{(-\mu E/v_S)})$, where $E = -\frac{dV}{dy}$ is considered (Mitra *et al.*, 1998). Equation (19) covers both low field and high field region. Integrating from y=0 to y=L, 'L' being the gate length, yields

$$\int_{V(0)}^{V(L)} \frac{dV}{\ln\left(1-\frac{I_D}{Q_T Z v_S}\right)} = -\frac{v_S}{\mu}L \qquad (24)$$

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

$$V_D = I_D\left(R_D + R_S^{1}\right) - \frac{v_S L}{\mu}\ln\left(1-\frac{I_D}{Q_T Z v_S}\right) \qquad (25)$$

Eq. (25) represents the current-voltage (I-V) relation for the MODFET under optically illuminated condition.

RESULTS AND DISCUSSION

An analytical simulation have been carried out for an n-AlGaAs/GaAs MODFET, considering the optical effect. The dimensions and other basic parameters used in the calculation are given in Table 1.

Figure 2 and 3 shows the plot of offset voltage of the device against time at different radiation flux density under three different conditions. (i) When the light is turned on at a reference time t = 0. (ii) When the light is turned off at a reference time t = 0. (iii) at dark. It is observed that when the light is just turned on at a reference time t = 0, a depletion device in the dark condition goes to enhancement due to illumination and the off-set voltage increases with time and reaches the steady state value around 10 ps. The offset voltage also increases with radiation flux density and reason is that the photovoltage developed across the heterojunction increases with the increase in flux density in a logarithmic fashion. For the turned off case it is observed that when the light is first turned off, the offset voltage decreases linearly with time and moves from enhancement towards depletion at its dark values. The time required to reach the dark value is more than 240 ps. This is because in the turned off case, the photovoltage varies linearly with time dominates the decrease in the offset voltage with time. However in the turned on case, it is the optical relaxation time which determines the nature of variation of the offset voltage. That is why, the time required for attaining steady state value is much less in turned on case compared to the turned off case. Figure 4 and 5 shows the plot of sheet concentration of 2DEG with time when light is turned on and turned off.In the turned on case, the values reach the steady state value at around 10 ps and increases with increase in the flux density. For turned off case, it decreases linearly with time and reach the dark value at

Table 1: Parameter values used for calculation

Symbol	Name	Value
Z	Gate width	100 μm, 145 μm
L	Gate length	1 μm
N_D	Donar concentration	1.0×10^{18} m^{-3}
N_A	Acceptor concentration	3.0×10^{20} m^{-3}
vs	Saturated velocity	2×10^{7} cm sec^{-1}
ϵ_1	Permittivity of GaAs	13.2 ϵ_0 F cm^{-1}
ϵ_2	Permittivity of AlGaAs	12.1 ϵ_0 F cm^{-1}
ϵ_0	Permittivity of vaccum	8.854×10^{-12}F m^{-1}
μ	Low field mobility	6800cm^2 vs^{-1}
h	Plancks constant	6.6×10^{-34} J-s
q	Electron charge	1.6×10^{-19}C
d_s	Spacer thickness	60 A°
d_d	Active layer thickness	525A°
d^1	Width of the well	80A°

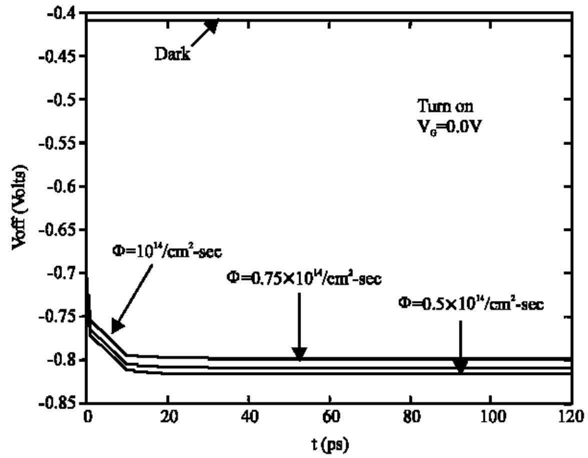

Fig. 2: V_{off} versus time when light is turned on

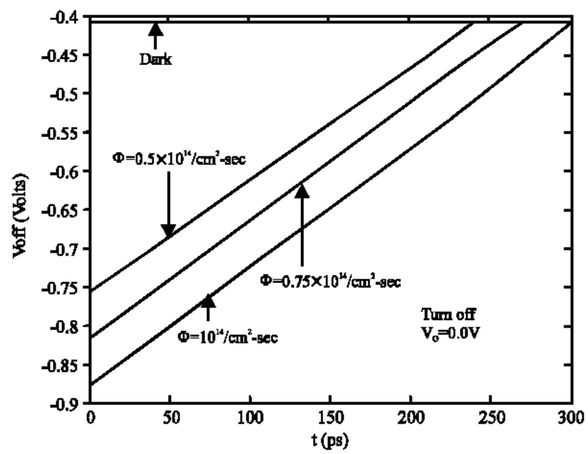

Fig. 3: V_{off} versus time when light is turned off

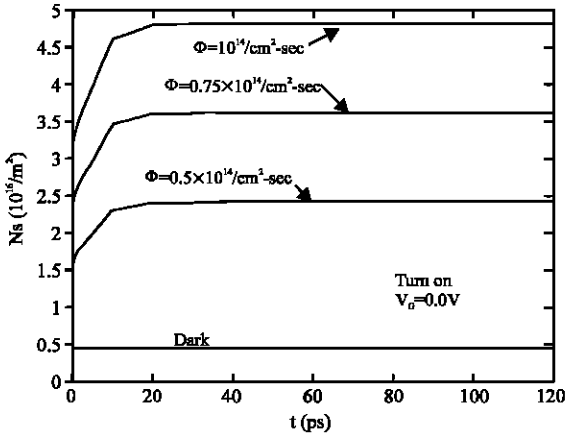

Fig. 4: Sheet concentration versus time when light is turned on

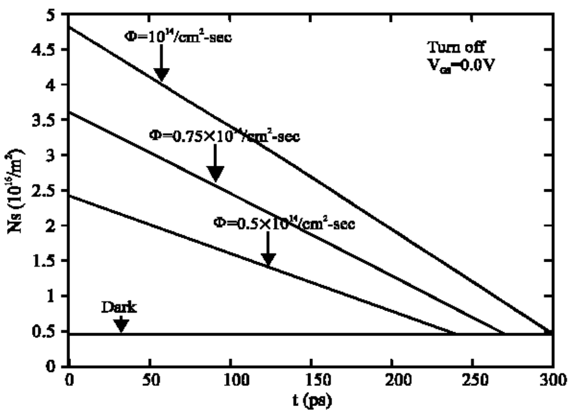

Fig. 5: Sheet concentration versus time when light is turned off

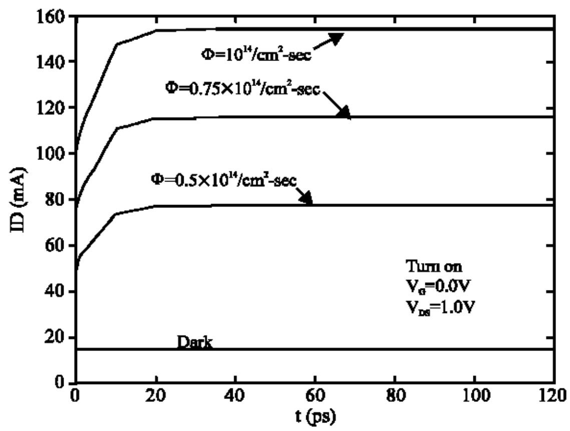

Fig. 6: Drain current versus time when light is turned on

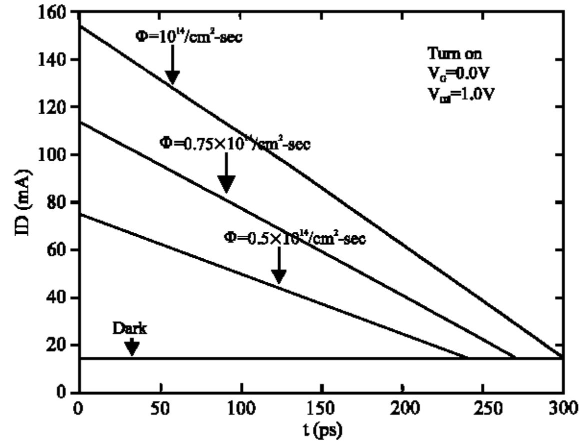

Fig. 7: Drain current versus time when light is turned off

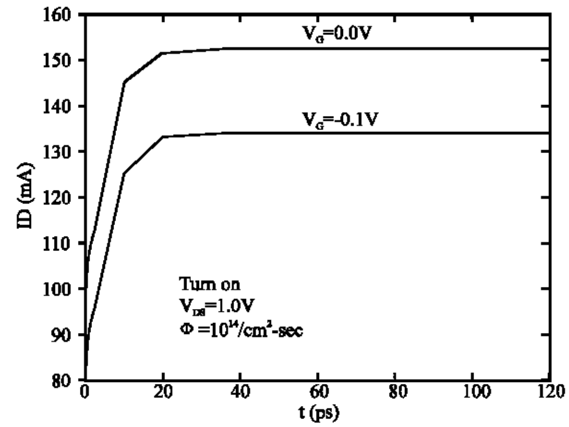

Fig. 8: Drain current versus time when light is turned on

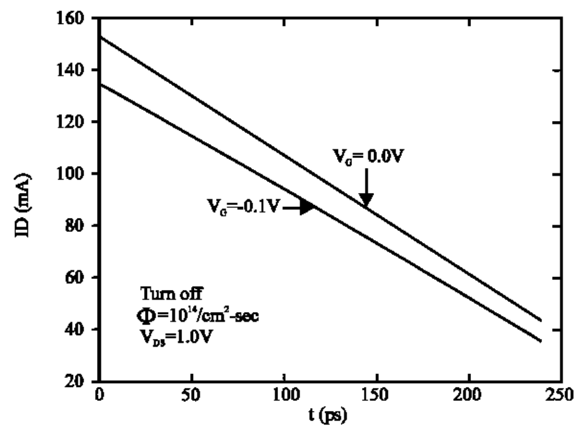

Fig. 9: Drain current versus time when light is turned off

around 240 ps. Figure 6 and 7 represents the plot of drain current against time. When light is turned on and turned off at three different flux densities and at a particular gate source voltage and drain source voltage. Similar to previous observation the current reaches the steady state value at a time 10 ps in the turned on case and at around 240 ps in the turn off case.

Figure 8 and 9 represents the plot of drain current against time. When light is turned on and turned off at different gate voltages in the saturation region (V_{DS}=1.0V). In the turn on case, the drain current increases with gate voltages and reaches the steady value at a time around 10 ps in the turn on case and in the case of turn off, it reaches the dark value at around 240 ps. It can be

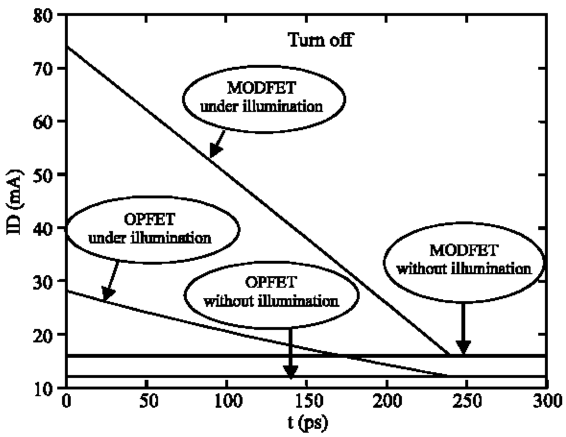

Fig. 10: Comparision of the current versus time characteristics under illumination and dark conditions

concluded from the the plots, the effect of backside illumination leads to improved absorption and increases the drain current considerably. A better transient behaviour of the device is observed. Figure 10 shows the comparision of current versus time characteristics of our result with the published theoretical data under illuminated condition. Since the experimental results are not available for the transient behaviour of MODFET, we have compared our results under illumination with the results of OPFET. A better result and a good agreement in the falling time is observed between our calculated results with those given by Pal *et al.* (1994).

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 offset voltage, sheet concentration of 2-DEG and the drain current versus time characteristics have been simulated and discussed. The sheet concentration of 2DEG with time has been calculated when the light is turned on and turned off. It is observed that offset voltage and 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, these parameters reduce with time and become equal to their corresponding dark values at around 240 ps, which is much higher than the turned on case. The reason pointed out is the photovoltage which varies linearly with time under the condition of turned off case and the optical relaxation time which dominates the behaviour under the condition of turned on. Results of current versus time characteristics is compared under illumination with the published data (Pal *et al.*, 1994) showing a better result and a good agreement.

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APPENDIX-A

Different constants in Eq. (12) is given below

$$A = \frac{1}{\tau_n D_n},\ A' = \frac{1}{v_x \tau_n},\ B = -\frac{\alpha\phi e^{-\alpha d}}{D_n},\ B' = \frac{\alpha\phi e^{-\alpha d}}{v_x}$$

$$C = \frac{R_S}{D_n a},\ d = d_d + d_1$$

$$D = \frac{\alpha\phi\tau_n\left(e^{\left(-\alpha d+\sqrt{A}d\right)} - 1\right) - \left(\frac{B}{\alpha^2 - A}\right)\left(e^{\sqrt{A}d} - e^{\alpha d}\right) + \frac{C}{A}\left(e^{\sqrt{A}d} - 1\right)}{\left(e^{\sqrt{A}d} - e^{-\sqrt{A}d}\right)}$$

$$E = \frac{\alpha\phi\tau_n\left(e^{\left(-\alpha d-\sqrt{A}d\right)} - 1\right) - \left(\frac{B}{\alpha^2 - A}\right)\left(e^{-\sqrt{A}d} - e^{\alpha d}\right) + \frac{C}{A}\left(e^{-\sqrt{A}d} - 1\right)}{\left(e^{-\sqrt{A}d} - e^{\sqrt{A}d}\right)}$$

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