

Three dimensional modeling and simulation of a nano MISFET photodetector

M. KABEER^a, K. GOWRI, V. RAJAMANI^{*}

Department of Electronics and Communication Engineering, P.S.N.A. College of Engineering and Technology, Dindigul – 624 622, Tamil Nadu, India

^aDepartment of Information Technology, B.S. Abdur Rahuman Crescent College of Engg., Chennai, Tamilnadu, India

This paper deals with three dimensional numerical modeling of an optically controlled nano MISFET photodetector for OEIC photoreceiver design. The field dependent mobility of the carriers in the surface potential is considered for modeling. The exact potential profile of the device under illuminated condition has been computed numerically by solving 3D Poisson's equation using boundary value problems. The electric field profile along the length, width and thickness of the channel and mobility of the carriers have also been studied extensively under illuminated condition to have an in depth analysis. The photocurrent of the nano MISFET under illuminated condition has also been calculated and presented. The transfer characteristics of the MISFET has been studied numerically and presented in this paper. The results show that the device characteristics are strongly influenced by incident optical radiation. The switching speed has also increased under illuminated conditions because of the higher electron mobility and shorter transit time. The model enables one to estimate various parameters which determine the potential use of this device for photo detection in OEIC photoreceivers.

(Received July 23, 2007; accepted August 22, 2007)

Keywords: Numerical 3D modeling, MISFET, Photodetector, Photocurrent, OEIC receivers

1. Introduction

1.1 InP MISFET as photodetector

The semiconductors of choice for high-speed electronic and optoelectronic applications are comprised of group III-V compounds such as indium phosphide (InP) and gallium arsenide (GaAs). The bulk physical properties of III-V semiconductors are, in many cases, far superior for electronic and photonic applications than those of the most commonly used semiconductor, silicon.

A large number of works has been reported over past decades concerning the use of Field Effect Transistors in optically controlled applications including amplification, oscillations and optical detection. Commercially available FETs do not have the desired photo sensitivity for the proposed applications. The optically gated FET structures have been found to have better sensitivity as compared to their conventional counter part. In view of this, MISFET is considered for its potential use as high speed photodetector.

The basic requirements of optoelectronic integrated circuits (OEICs) are compatibility of the materials for the constituent electronic and optical devices and planarity. Investigation of integrated circuits is currently being carried out by many workers mainly using GaAs. However, most of IC's reported so far have employed MESFET's, being in contrast to Si-MOS IC's, since metal-insulator-GaAs MIS structures cannot be used to form n-channel at the semiconductor surface at present due to large number of interface states [1]. In spite of the successful operation of MESFET IC's, IC's with

MISFET's are still favorable as having large tolerance in applicable logic swings, threshold voltage control, and design of circuits. Especially, enhancement-mode MISFET's are highly desirable for low power logic applications. The photosensitivity of metal-insulator-semiconductor (MIS) structures has opened up the possibility of their use as infrared photodetectors, optically variable reactors (OVRs) and optical CCDs for solid-state imaging [2-5]. The basic MIS configuration can also be used to realize optically gated MISFET photodetectors [6-8]. A number of studies have been carried out to examine the potential of the MIS configuration for such optoelectronic applications. The initial investigations in this area were confined to conventional MOS devices. Successful development of heterogate MIS structures stimulated further research in this area with prime emphasis on photosensitivity. A number of novel MIS-based devices were proposed, studied and tested subsequently [3-8]. The results of preliminary investigations are quite encouraging. It has been found that the basic MIS component can be used as a potential photosensing element for developing many optoelectronic systems.

High electron mobility with high carrier peak and saturation velocities makes InP a desirable material for high speed insulated-gate field-effect transistors. High breakdown field, good thermal conductivity, and a low ionization coefficient make InP equally attractive for solid-state microwave power applications [9, 10]. Insulated gates are preferable to Schottky gates since larger operating voltages and higher output powers are more readily obtained.

Photo detector is the first element of the photo receiver circuit which interprets the information contained in the optical signal. In general the optical signal is generally weakened and distorted when it emerges from the end of the fiber. To overcome this problem, the photo detector must meet very high performance requirements like, a high response or sensitivity in the emission wave length range of the optical source being used, a minimum addition of noise to the system, a fast response speed to handle the sufficient data rate, insensitive to variations in temperature and to be compatible with the physical dimensions of the optical fiber. Optical receivers use conventional photodetectors in discrete form in conjunction with other signal processing units realized with discrete active component MISFET. The speed of such photodetectors is seriously limited by the parasitic inductances and capacitances introduced by the interconnections of various stages. The overall performance of the optical receiver can be greatly improved by monolithically integrating the electronic and other optoelectronic components in the same chip known as OEIC. The optically gated MISFET structure has been found to have better sensitivity and act as a high speed photodetector for their possible use in optical receivers of future generation optical communication systems. The theoretical models developed by many researchers showed that the device characteristics were strongly influenced by incident optical radiation [11-13].

Yamaguchi *et al* [8] demonstrated the operation of an enhancement mode MISFET as a new high gain photodetector. The light was focused on the semi-transparent metal gate to increase the photosensitivity. It was shown that the photocurrent gain in the order of 10^3 can be obtained under application of gate bias. It was explained that the amplification is due to the increase in the surface channel conductivity via the development of an electron quasi-Fermi level shift towards the conductive-band edge under illumination.

Chakrabarti *et al* [11] developed a semi-numerical model of a novel hetero-gate MISFET to determine the optically controlled characteristics of the device under steady illumination. It was found that at a constant drain voltage and the gate voltage the saturation drain current, transconductance and drain conductance of the device can be controlled by incident optical illumination. It was also reported that the photocurrent decreases with increase in the gate voltage above the threshold voltage. This is because, below the strong inversion region, the increase in the drain current due to the photo generation is negligible. A three dimensional numerical modeling of nano MISFET was reported and studied the electrical characteristics by solving the 3D Poisson's equation numerically recently [14]. The potential profile, electric field profile and mobility of the nano MISFET were also studied. The drain current and the transconductance were also calculated by applying electric field and mobility of the carriers.

In this paper, we have developed 3D numerical model of an InP MISFET as photodetector for the OEIC applications. The 3D Poisson's equation has been solved numerically to obtain various device parameters such as

field profile, mobility of the carriers, potential profile photocurrent, transconductance and responsivity under the illuminated condition.

1.2 Theoretical three dimensional numerical modeling of nano MISFET photodetector

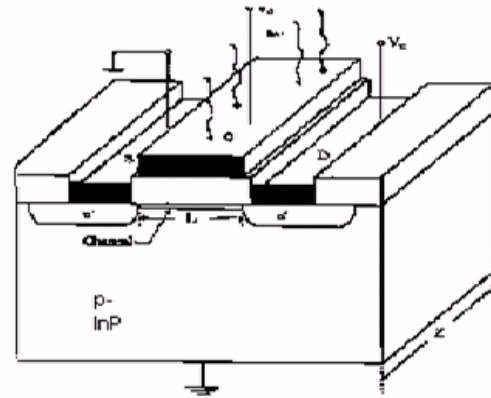


Fig. 1. Schematic diagram of an InP- Al_2O_3 NANO MISFET Photodetector under consideration.

The effect of illumination on the basic MIS (Metal-Insulator-Semiconductor) structure as well as MISFET (Metal Insulator Semiconductor Field Effect Transistor) has drawn considerable attention because of their enormous potential for their use in optical imaging and detection. The photosensitivity of MISFET largely depends on the optical response of the basic MIS configuration.

When optical signal applied on a semiconductor, carriers are generated either by band-to-band transitions (intrinsic) or by transitions involving forbidden gap energy levels (extrinsic), resulting in an increase in channel conductivity. For the intrinsic semiconductor, the increase of conductivity under illumination is mainly due to the increase in the number of carriers. For the extrinsic semiconductor, photo excitation may occur between a band edge and an energy level in the energy gap. Photo conductivity can take place by the absorption of photons of energy equal to or greater than the energy separation of the band gap levels and the conduction or valence band.

Fig. 1 shows the Schematic diagram of an InP- Al_2O_3 MISFET structure under consideration. Application of a large positive voltage on the metal gate causes strong inversion to occur in the semiconductor at the interface. When an optical radiation of suitable wavelength is incident on the surface of the semi transparent metal gate, a part of the total incident optical power is transmitted through the insulation layer into the semiconductor where it is absorbed. Absorption of this radiation results in the generation of excess electron-hole pairs.

The goal of the modeling process is to make sure that all the parameters that are needed for the characterization of the device are completely and accurately represented. It

involves the proper identification of parameters and accurately defining a method to find them. Modeling is probably the most intensive and time consuming part of the development process.

A three dimensional modeling of InP MISFET photodetector is described for the calculation of various parameters like potential profile, electric field profile, mobility profile, drain characteristics, transfer characteristics and drain resistance under dark and illuminated conditions. The modeling procedure starts with solving the three dimensional Poisson's equation.

The 3-D Poisson's equations [14] in the space charge region of the device at the drain end in the n-channel MISFET under illuminated and dark conditions are written as,

$$\frac{\partial^2 \psi(x, y, z)}{\partial x^2} + \frac{\partial^2 \psi(x, y, z)}{\partial y^2} + \frac{\partial^2 \psi(x, y, z)}{\partial z^2} = \frac{-q(N_a + \Delta n)}{\epsilon_s} \quad (1a)$$

$$\frac{\partial^2 \psi(x, y, z)}{\partial x^2} + \frac{\partial^2 \psi(x, y, z)}{\partial y^2} + \frac{\partial^2 \psi(x, y, z)}{\partial z^2} = \frac{-qN_a}{\epsilon_s} \quad (1b)$$

where, $\Psi(x, y, z)$ is the surface potential at a particular point (x, y, z) , N_a is the doping concentration, Δn is the excess carriers generated per unit volume in the semiconductor due to the absorption of incident optical power density and ϵ_s is the permittivity of the semiconductor.

The boundary conditions to solve the Poisson's equation are given below.

Boundary conditions with respect to the thickness of the oxide layer are given by

$$\psi(0, y, z) = V_{gf} - V_{fb}^b \quad (2a)$$

$$\psi(t_s, y, z) = V_{gb} - V_{fb}^b \quad (2b)$$

Boundary conditions with respect to the length of the channel are

$$\psi(x, 0, z) = V_{bi} + V_{op} \quad (3a)$$

$$\psi(x, L_{eff}, z) = V_{bi} + V_{ds} + V_{op} \quad (3b)$$

Boundary conditions with respect to the width of the channel are written as

$$\psi(x, y, 0) = V_{gf} - V_{fb}^b \quad (4a)$$

$$\psi(x, y, W) = V_{gf} - V_{fb}^b \quad (4b)$$

Where,

V_g^f = applied potential to the front gate

V_{fb}^f = flat band voltage to the front gate

V_{fb}^b = flat band voltage to the back gate

V_{bi} = built in potential

V_{ds} = drain to Source voltage

V_{op} = photo induced voltage

The excess carriers generated per unit volume (Δn) in the semiconductor due to the absorption of incident optical power density is given by,

$$\Delta n = \frac{\sqrt{1 + \frac{4\tau P_{opt}(1-R_m)(1-R_s)(1-R_i)(1-e^{-\alpha W_m})}{W_m h \gamma n_i}} - 1}{\frac{2P_{opt}(1-R_m)(1-R_s)(1-R_i)(1-e^{-\alpha W_m})}{W_m h \gamma n_i}} \quad (5)$$

where, W_m is the maximum width of the depletion layer and is given by

$$W_m = [4\epsilon_s \ln(N_a / n_i) / q\beta N_a]^{1/2} \quad (6)$$

where, N_a is the acceptor concentration.

$G_{op}(y)$ is the excess carrier generation rate at ant point y in the semiconductor and is given by

$$G_{op}(y) = \frac{P_{opt}}{h\gamma} (1-R_m)(1-R_i)(1-R_s) \alpha e^{-\alpha y} \quad (7)$$

where p_{opt} is the incident optical power density, h is the Planck's constant, γ is the operating frequency, α is the absorption coefficient of the semiconductor at the operating wavelength, R_m , R_i , and R_s are the reflection coefficient at the metal gate entrance, gate-insulator interface and the insulator-semiconductor interface respectively.

The mean lifetime of the minority carriers in the illuminated condition, τ_1 can be written as

$$\tau_1 = (n_i / n_i + \Delta n) \tau \quad (8)$$

where, τ is the lifetime of the carriers for the intrinsic semiconductor.

2.2 Electric field profile

In order to obtain electric field profile equations under dark and illuminated conditions (11a), (11b) and (11c) are solved respectively for the corresponding profiles in x, y and z directions.

$$E_x = \frac{\psi(i+1, j, l) - \psi(i-1, j, l)}{\frac{2L}{m_x}} \quad (10a)$$

$$E_y = \frac{\psi(i, j+1, l) - \psi(i, j-1, l)}{\frac{2W}{m_y}} \quad (10b)$$

$$E_z = \frac{\psi(i, j, l+1) - \psi(i, j, l-1)}{\frac{2t_s}{m_z}} \quad (10c)$$

where m_x , m_y and m_z are the separation of the grid line along the x and y directions, $\psi(i, j, l)$ is the surface potential at a particular point and l , w and t_s are the gate length, device width and oxide thickness respectively.

The field dependent mobility of charge carriers is given by,

$$\mu_x = E_x \xi_{ox} \xi_{si} \quad (11a)$$

$$\mu_y = E_y \xi_{ox} \xi_{si} \quad (11b)$$

$$\mu_z = E_z \xi_{ox} \xi_{si} \quad (11c)$$

where, μ_x , μ_y and μ_z denote the mobility of charge carrier in x , y and z directions respectively and E_x , E_y and E_z are the corresponding Electric fields.

The drain to source current I_{dsop} can be written considering its continuity equation as,

$$I_{dsop} = \frac{\epsilon_{ox}}{d_{ox}} Z \mu_x (V_{gs} - V_{th} - V_{op}(x)) E_x \quad (12)$$

where, ξ_{ox} and d_{ox} are permittivity and thickness of oxide layer respectively. μ_x and E_x denotes the mobility and electric field along the length of the channel respectively. Here, V_{gs} denotes the gate to source voltage and V_{th} denotes the threshold voltage of the device. $V_{op}(x)$ is the surface potential along the length of the channel under illuminated condition and z is the width of the channel.

The transconductance g_{mop} is given by,

$$g_{mop} \left\{ V_{gs}(i) \right\} \Big|_{V_{ds, const}} = \frac{I_{dsop}(i+1) - I_{dsop}(i-1)}{V_{gs}(i+1) - V_{gs}(i-1)} \quad (13)$$

As defined by (13), the transconductance is the ratio between the drain current under illuminated condition and the gate voltage keeping the drain voltage constant. Moreover, the transconductance is inversely proportional to the gate voltage. Therefore, when the gate voltage increases, the transconductance decreases.

The drain resistance r_{dop} and the responsivity of the device have been obtained from (14) as given below.

$$r_{dop} \left\{ V_{ds}(i) \right\} \Big|_{V_{gs, const}} = \frac{V_{dsop}(i+1) - V_{dsop}(i-1)}{I_{dsop}(i+1) - I_{dsop}(i-1)} \quad (14)$$

$$R(\lambda) = \frac{I_{ph}}{P_{opt}} \quad (15)$$

where λ is the operating wavelength, I_{ph} is the photo response current (the difference between the drain current in the illuminated condition to that in the dark condition).

3. Computational techniques

The 3D Poisson's equations (1a, 1b) are solved using Liebmann's iterative method to determine the surface potential at illuminated and dark conditions for a fixed value of gate voltage and assumed value of the drain voltage. The numerically estimated value of the surface potential is utilized to determine the electric field and mobility in all the three directions. The drain current has been calculated from equation (12). The voltage profile and the electric field distribution in the channel have been estimated for accurate calculation of the drain to source current. The voltage profile in the channel is obtained by calculating the differential change in the voltage across the channel and is assumed to be very small (1mV) at the source end and low field mobility has been used to begin the numerical computation from the source end.

In order to obtain the channel voltage profile, the 3D Poisson's equations (9a and 9b) are numerically solved by considering the entire channel to be divided into a large number of elementary strips within the device boundary. As outcome of this process, we obtain the potential at every point in the channel and its variation along the length and width of the channel as well.

$$\psi(i, j, l) = \psi(i-1, j, l) + \psi(i+1, j, l) + \psi(i, j-1, l) + \psi(i, j+1, l) + \psi(i, j, l-1) + \psi(i, j, l+1) - ((q(Na + \Delta n) / \epsilon_{si}) / 6) \quad (9a)$$

$$\psi(i, j, l) = \psi(i-1, j, l) + \psi(i+1, j, l) + \psi(i, j-1, l) + \psi(i, j+1, l) + \psi(i, j, l-1) + \psi(i, j, l+1) - ((qNa / \epsilon_{si}) / 6) \quad (9b)$$

The potential at the surface end of the gate is the sum of built-in voltage and applied drain voltage. The effective gate voltage at the semiconductor-insulator interface is the difference between V_G and V_{FB} , where V_{FB} is the flat-band voltage of the device and an electric-field at the edge of the depletion region is zero.

4. Results and discussion

Fig. 2 shows the distribution of potential along the length of the channel that is estimated using (9a) and (9b). It is seen from the figure that the surface potential decreases linearly near the source end and increases linearly near the drain end. The potential increases near the drain because of the applied positive bias at the drain side. It is observed that the surface potential under illuminated condition is slightly higher than that of the potential under dark condition due to the excess generated electron hole pairs.

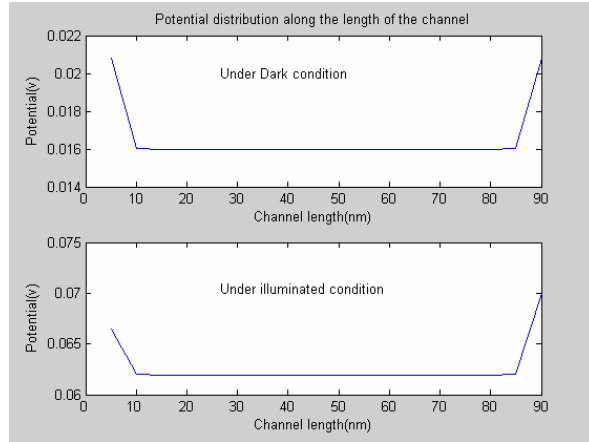


Fig . 2. Potential distribution along the length of the channel under dark and illuminated conditions.

The potential profile along the channel and width of the device under both dark and illuminated conditions in a three dimensional figure is shown in Fig.3. The device exhibits the similar kind of characteristics along the length and width of the channel. In both cases it can be seen that the potential reaches abruptly higher near the drain end due to the high electric field near the drain end which causes a rapid conduction. The effect of potential under illuminated condition is also observed.

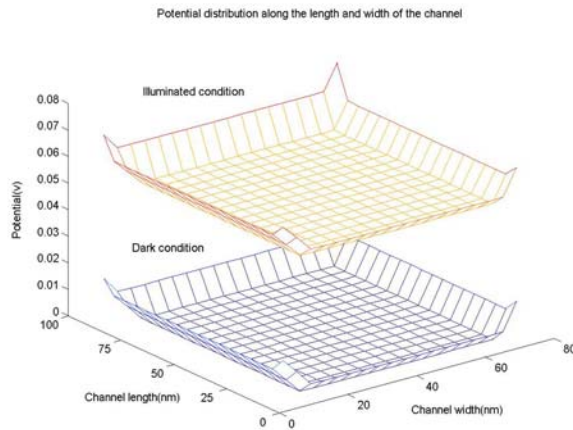


Fig .3. Variation of potential distribution along the length and width of the channel.

The distribution of electric field along the length and width of the device under consideration under dark and illuminated conditions is depicted in the Fig. 4. It is seen that the electric field E_x is more dominant than field E_y . The electric field increases rapidly near the drain end as is seen in Fig 4. This is due to the fact that the carrier density near the drain end experiences a rapid decrease in surface concentration which calls for a rapid increase in the electric field to maintain the constant drain current. It is

seen that the electric field near the drain end in the illuminated condition is less compared to the value of the dark. As a result a high drain voltage is needed to attain saturation in the illuminated condition. It is well known that, when an optical signal is illuminated on the device more and more electron hole pairs are generated. As the charge carriers are more crowded under illuminated condition, their mobility gets reduced in all three directions. It can be seen from (11a, 11b and 11c) that the electric field is directly proportional to mobility. Therefore the field in all three directions gets reduced due to the decrease in mobility.

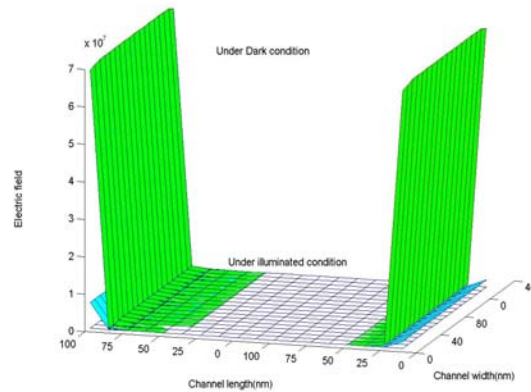


Fig. 4. Variation of electric field profile along the length and width of device.

Fig .5 shows the two dimensional view of electric field along the thickness of oxide layer. It can be seen that E_z rapidly decreases near the drain end as opposite to that of E_x . This is due to the fact as V_{gs} is applied, the electron acquires more energy to move along the length of the channel i.e., in x direction than along the other two directions. The electric field in Y- direction and Z- direction will follow the same characteristics.

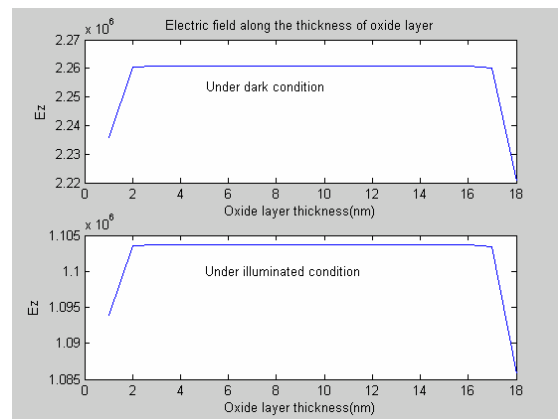


Fig.5. Variation of electric field along the thickness of the oxide layer.

The distributions of mobility in all the three directions are shown in Fig. 6 and Fig. 7 for both the dark and illuminated conditions. As mobility is directly proportional to electric field ($\mu = \xi E$), the shape of the mobility curves under x, y and z directions are similar to that of E_x , E_y and E_z .

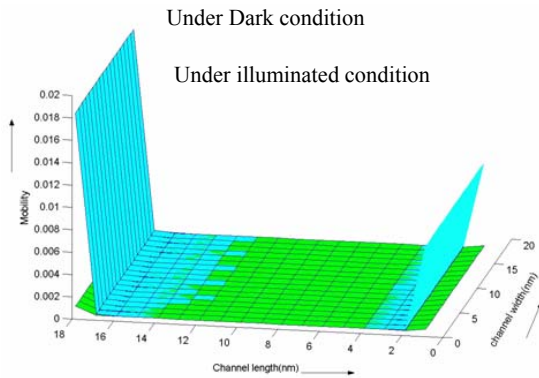


Fig. 6. Mobility distribution along the length and width of the channel.

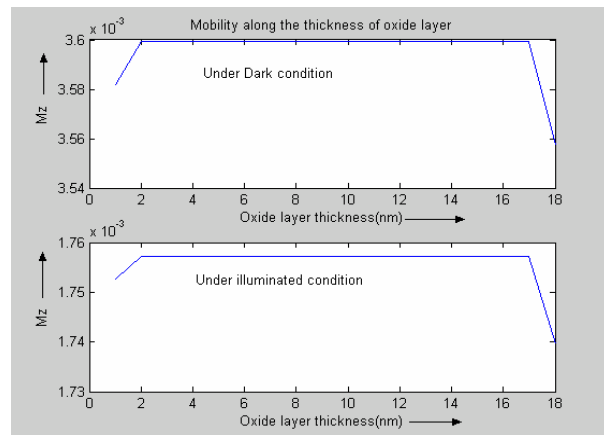


Fig. 7. Mobility distribution along the thickness of oxide layer.

The variations of the current for different applied gate-to-source voltages are depicted in Fig. 8 for the dark and illuminated conditions. It is seen that the for the applied gate-to-source voltage, the drain current increases significantly. When the applied gate voltage is further increased, drain current also increases. The channel width is mainly determined by applied gate to source voltage. The charge carriers pass through the channel and thereby conduction is said to take place. When drain voltage increases further, more charge carriers try to pass through the channel due to which drain current increases. But the charge carriers can utilize only the channel width that is created earlier. That is the reason the drain current saturates after a certain limit even if drain voltage is increased further. The current under illuminated

condition is higher and this is due to the generation of excess carrier under illumination.

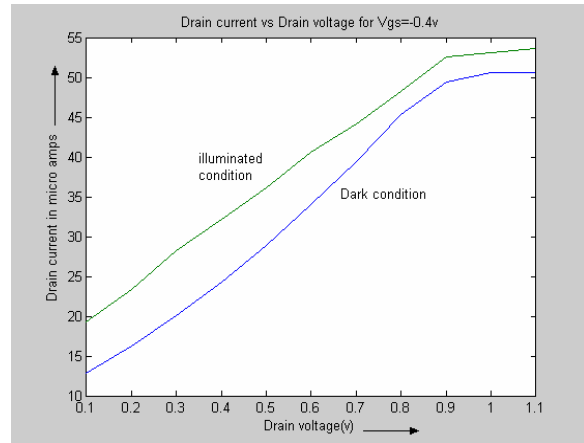


Fig. 8. Variation of the drain current with applied drain voltage.

The transfer characteristics of the MISFET photodetector are shown in Fig. 9 for different drain voltages. As the applied gate to source voltage increases, the drain current also increases linearly as shown in the figure for a fixed drain voltage. When the drain voltage increases further, the drain current also increases rapidly as shown in the Fig. 9. The effect of illumination also depicted in the same figure.

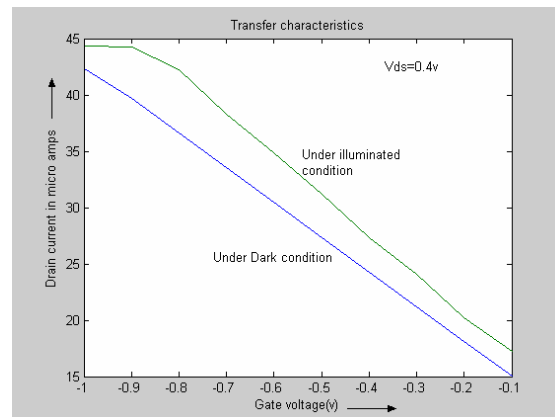


Fig. 9. Transfer characteristics of the MISFET photodetector.

The transconductance with the applied gate to source voltage is depicted in Fig. 10 for the both dark and illuminated condition. Due to the applied voltage and excess carrier generation, photo voltage induced in the channel. The reduction in the transconductance of device is due to the photovoltage induced in the channel. This can be evident from the figure that the transconductance of the device under illuminated condition is lower than that of the dark condition.

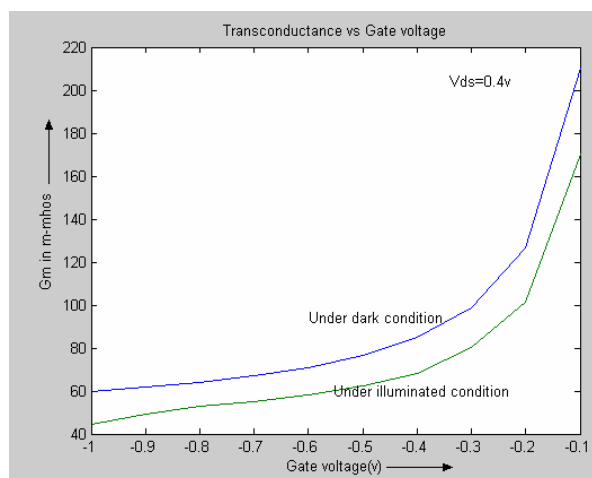


Fig. 10. Variation of the transconductance with gate voltage.

4. Conclusions

Photoresponse characteristics of a three dimensional numerical model of nano MISFET photodetector was presented for suitability in the OEIC receiver application. The effect of various internal device parameters such as electric field, mobility of the carriers in the presence of illumination, potential distribution of the carriers have also been studied extensively through numerical simulation. The drain current and transfer characteristics of the nano MISFET photodetector has also been calculated numerically. Transimpedance of the 3D photoMISFET has also been calculated. The circuit level parameters of the device under illuminated condition will be studied extensively. The performance of the device in OEIC application will also be analyzed.

Acknowledgment

The authors are grateful to the All India council for Technical Education (AICTE), New Delhi, India for providing research grants (0023/BOR/RPS/080/06/07) in the year 2006-2007.

References

- [1] H. Hasegawa, T. Sawada, IEEE Trans., Electron Dev. ED-27(6) 1055 (1980).
- [2] J. Grosvalet, C. Jund, IEEE Trans. Electron Devices, ED-14, 777 (1967).
- [3] A. Sher, Y. H. Tsuo, J. A. Moriarty, W. E. Miller, R. K. Crouch, J. Appl. Phys. **51**, 2137 (1980)
- [4] P. Chakrabarti, B. R. Abraham, A. Dhingra, A. Das, B. S. Sharan, V. Maheswari, IEEE Trans. Electron Devices, ED-39, 507 (1992).
- [5] B. B. Pal, S. S. Nelson, IEEE Trans. Electron Devices, ED-40, 1878 (1993).
- [6] K. Okamoto, I. Inoue, Solid-State Electron. **16**, 657 (1973).
- [7] P. Chakrabarti, S. Kumar, P. K. Rout, B. G. Rap-Pai, Proceedings of 3rd Asia Pacific Microwave conference, Tokyo, Japan, 575 (1990).
- [8] E. Yamaguchi, T. Kobayashi, Jpn. J. Appl. Phys. **21**, 104 (1982).
- [9] D. L. Lile, D. A. Collins, Thin solid films **56**, 225 (1979).
- [10] D. L. Lile, D. A. Collins, L. G. Meiners, L. Messick, Electron Lett. **14**, 657 (1978).
- [11] P. Chakrabarti, B. K. Mishra, Y. Pratap Reddy, S. Prakash, Phys. Stat. Sol., 277 (1995).
- [12] M. Armand et al., Electron. Lett. **19**, 433 (1983).
- [13] L. Messick, et al. Proc. IEDM, 767 (1986).
- [14] K. Gowri, P. Rajesh, V. Rajamani, Physica E : Low dimensional Systems and nanostructures **36**, 52 (2007).

*Corresponding author: rajavmani@rediffmail.com