Optimization of DMG-CNTFET Photo Detector for Different Illumination Conditions by Nano Scale Size and Doping Through Self-consistent Poisson-Schrodinger Equations

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Optimization of DMG-CNTFET Photo detector for different illumination conditions by nano scale size and doping through Self-Consistent Poisson- Schrodinger Equations

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ABSTRACT:
In this paper, we propose a nano scale Dual Material Gate Carbon Nanotube field-effect transistor (DMG-CNTFET) photo detector based on self-consistent 2D Poisson and Schrodinger equation. The main advantage of the proposed device is the improved performance due to dual material gate consisting of two laterally contacting Molybdenum and Titanium metals (M1,M2) with two different work functions (ΦM1, ΦM2). The 2D-Poisson equation is solved through finite difference method in open boundary for dark and illuminated condition. The Schrodinger equation is solved through non-equilibrium green function. The proposed DMG-CNTFET photo detector overcomes the problem of maximum thickness in gate oxide and gate size by nano-scaled sizing and highly doped source and drain. The gain and cutoff frequency of the device are increased due to the reduced work function and the drain conductance. The characteristics of the proposed transistor are validated through various parameters such as drain current, transfer, sub threshold swing, trans-conductance, gain and cutoff frequency. From the simulation results, the proposed DMG-CNTFET photo detector provides better performance of trans conductance, gain and cutoff frequency. These device characteristics are the key parameters in the design and fabrication of various electronic circuitry and design and hence the relative performance improvement is achievable.

Key words: Self-Consistent Poisson- Schrodinger Equations, DMG-CNTFET, quantum transport, Green function, Photo detector.

1. INTRODUCTION

A CNTFET photo detector with terminals at nanoscale level is proposed in this paper. The reason for such a device include high mobility of electron achieved through the arrangement of atoms on carbon surface. The surface of a CNT is made up of cylindrically rolled up graphene sheet and it forms a hallow cylinder. In CNT devices, gate voltage is applied in the CNT, and oxide interface, for potential in the charge based model devices . However, single wall carbon nanotube (SWCNT) device consist of unique optical property and used in development of optoelectronic devices. CNTFET devices are used in various applications such as CMOS, OEIC receivers and sensors based on the semiconducting property of CNT. The planar CNTFET simulated through Schrödinger equation, with Non-equilibrium Green’s Function (NEGF) and poison equation. In CNTFET
device simulation, Poisson equation improves the numerical convergence. CNTFET device as a photo detector provides the minimum cut off frequency and gain, due to various parameter such as chiral vectors, gate oxide thickness, dielectric constant, doping concentration and length in the source and drain.

In existing CNTFET devices, more leakage current and short channel effect is induced in the gate region of devices, due to the larger diameter of carbon nano tube. Furthermore, sub-threshold voltage increases due to increase in the length of source and drain. In CNTFET based photo detector device, leakage current in solar cell will flow opposite to the current generated from the photocell, and stray current form electrode will be flowing before cell voltage on, and leads to the minimum light current. These leakages current also reduces the operation speed of the photocells. Moreover, short- channel effect will be formed in the transistor and leads to generate hot electrons in the photocells. Moreover, surface scattering will affect the efficiency of the phototransistors.

The characteristic study of CNTFET have been done at various levels with varying methods. Some important characteristic studies include the study of on-off and drain current using the FETtoy simulator with different dielectric materials such as SiO$_2$, ZrO$_2$ and HfO$_2$ [1]. The I-V and ON-to-OFF current of Dual Gate characteristics of CNTFET are compared with the DG-MOSFET [2]. The CNTs based transistor performs better than Si-MOSFET transistor due to gate thickness and spacing variations [3]. In Dual Gate Schottky-Barrier CNTFET device, decrease of leakage current and increase in the ratio of ON-OFF current and cutoff frequency are obtained, due to the work function in the device [4]. In CNTFET device, the doping structure of drain and source improves the cutoff frequency, sub-threshold swing and on/off ratio according to gate voltage [5]. In CNTFET device, stepwise doping profile of channel structure improves the ON-Current in device and decreases leakage current [6]. Photovoltaic effect and the monochromatic efficiency of the device under the light illumination are calculated[7]. Dual Metal Surround Gate Junction Transistor (DMSGJLT) device shows an increase in gain and decrease in channel effect and leakage current because of increase in mobility of electron in channel [8]. The Structures of various CNTFET reviews show that the thin gate oxide increases the saturation current, trans conductance, voltage gain and decreases the leakage current and short channel effect [9]. Carbon nano tubes with density of state and various type of nanotube has the relation with the energy gap [10]. In Graphene NanoRibon Field Effect Transistor (GNRFET), gate control ability on the channel, variation of the sub threshold leakage current, better drive current and maintaining sub threshold swing within the theoretical limits are obtained [11]. Modeling of Silicon On Insulator Metal Oxide Semiconductor Field Effect Transistor (SOI-MOSFET) photo detector is studied for the effect of illumination, current-voltage characteristics [12]. The Intrinsic and extrinsic device properties of CNTFET are investigated for the 9 nm Gate Length [13]. The CNT’s band gap design for fast switching is implemented [14]. The quantum simulation of DMG-CNTFET characteristics such as subthreshold swing, Drain-Induced Barrier Lowering (DIBL) and hot-carrier effect are compared with the conventional CNTFET [15]. The characteristics of Linearly Doped CNTFET (LD-CNTFET), Lightly Doped Drain and Source CNTFET (LDDS-CNTFET) is compared for channel length. LDDS-CNTFET has shorter channel length with same Off-state characteristic of the LD-CNTFET [16]. The characteristics of Dual Gate (DG-CNTFET) are obtained for effective controlling of ambipolar conduction, which is inherent to schottky barrier [17]. The Coaxial structure CNTFET with azimuthal symmetry is analyzed through Schrodinger solution, and solved with scattering matrix method [18]. The Coaxial CNTFET is studied using non-equilibrium green function method and analyzed for current voltage characteristics [19]. The VI characteristics of nano structures is analyzed in quantum transport and electrostatic environment [20]. The static and dynamic characteristic of CNTFET
for the capability of ballastistic transport is analyzed through coupled poisson and Schrodinger equations [21]. In CNTFET, the source and drain regions are varied in the doping density and length in 2D full quantum simulation environment and studied its characteristics such as drain conductance and sub-threshold swing [22]. In CNTFET, the different gate oxide thickness and carbon nanotube diameter are studied for the scaling issues during trancandance characteristic analyses [23]. CNTFET of analog RF application is developed through carbon nanotube model, analyzed for the DC shape and small signal characteristics [24]. The dual-gate Semiconductor Nano Thin Film Transistor (SNTFT) structure with a high-dielectric-constant HfO\textsubscript{X} material as the back gate oxide is compared with single SNTFT for various parameters such as Threshold voltage, charge carrier mobility, and transconductance [25]. Dual Gate Carbon Nanotube Ion Sensitive Field Effect Transistor (DG-CNTISFET) has high-\(\kappa\) dielectric material HfO\textsubscript{2} (\(\kappa\sim25\)) as the top gate insulator and a low-\(\kappa\) dielectric material ZnO (\(\kappa\sim1.5\)) as the bottom gate insulator for measuring pH value and the device analyzed for the drift rate and hysteresis [26]. The three HfO\textsubscript{2} gate dielectric thickness on the top surface of gate is used in the Double gate amorphous indium-gallium zinc oxide Ion Sensitive Field Effect Transistor (ISFET) device for pH sensing [27]. Nano sheet gate-all-round transistor is designed using sub stack and improves the RF performance through the cut-off-frequency. The spacing and number of stack in the device improves the performance of the transistor for RF applications [28]. In quantum environment simulation, Junction Less Carbon Nanotube Field Effect Transistor (JLCNTFET) is designed with linearly graded binary metal alloy gate and the device improves the intrinsic delay and on-state to off-state current ratio [29]. In quantum simulation, double gate Junction Less Graphene Nano Ribbon Field Effect Transistor (JL-GNRFET) is designed to study the short-channel effects. The design performed through solving Schrodinger equation using the mode space non-equilibrium greens function coupled with poison equation in ballistic limit [30]. The nano scale junction less carbon nano tube tunneling DETS using dual material source gate is designed with 5-nm coaxial gate length and improves the leakage current, sub threshold and switching characters [31].

This paper is a 2-D quantum simulation of DMG-CNTFET photo detector. The simulation has been done by the self-consistent solution of 2-D Poisson equations and Schrodinger equations. The Poisson equation uses finite difference method. And Schrodinger equations use green function with boundary conditions. The methods provide high performance of electrical and quantum properties of the proposed detector. The other parameters of the device are calculated and the outputs of the above are plotted.

In this paper, Numerical modeling of DMG-CNTFET photo detector is proposed. The prime focus is in the design for obtaining the device characteristics under dark and illuminated conditions. The detector is simulated with finite difference method for obtaining the solution from Poisson equation. Furthermore, proposed DMG-CNTFET device is modelled based on the Non-equilibrium green function and solves the Schrodinger equation, which provides high performance of electrical and quantum properties in the proposed detector. The contributions of the proposed device are in the following area.

(i) The proposed DMG-CNTFET based photo detectors has high on current/off current ratio. The results obtained also exhibit that the voltage gain is inversely proportional to the leakage current and the short channel effect is reduced. The reduction is obtained through the HfO\textsubscript{2} high dielectric material which is specific to the proposed Dual material Gate-CNTFET.
(ii) DGM-CNTFET applies zigzag(n=13,m=0) semiconducting CNT. The carbon atom density, HfO$_2$ gate oxide thickness, choice of high dielectric constant, nano scale reduction of source and drain length, doping concentration of source and drain proposed in the DGM-CNTFET photo detector result in excellent gain, quantum efficiency, trans conductance and cut off frequency.

(iii) The proposed DMG-CNTFET photo device limits the sub-threshold voltage which is achieved by the reduced diameter in the CNT (1.02nm) and the length of the source and drain (20nm) each.

(iv) In terms of the use of the advancements achieved through the proposed device especially in the receiver part of detector section optimizes performance in optical fiber communications.

2. PROPOSED MODEL OF DMG-CNTFET

The structure of the proposed DMG-CNTFET is shown in Fig.1. A schematic view of the proposed DMG-CNTFET is shown in Fig.2. The simulation parameters of the proposed structure have been listed in Table 1. Numerical computation has been carried out for the nano scale DMG-CNTFET. The parameters used for the calculation are as given in the Table 1. The programs are written using Matlab2017.

Table 1: DMG-CNTFET Device Parameter With Corresponding Input Values

| PARAMETER                     | VALUES            |
|-------------------------------|-------------------|
| Zigzag vector (n,m)           | (13,0)            |
| Diameter of the CNT (d$_{cnt}$) | 1.02nm            |
| Length of the gate (Lg)       | 20nm              |
| Channel length (Lc)           | 20nm              |
| Source length                 | 20nm              |
| Drain length                  | 20nm              |
| Source and drain doping density (N$_s$/N$_d$) | 1.2 x 10$^7$cm$^{-1}$ |
| Band gap Eg                   | 0.8631eV          |
| Gate work function material 1 ($\phi_{gM1}$) | 4.7ev |
| Gate work function material 2 ($\phi_{gM2}$) | 4.4ev |
| Dielectric constant (k)       | 16                |
| Gate oxide thickness (t$_{ox}$) | 1.6nm            |
| Gate voltage (Vg)             | 1V                |
| Thermal Voltage ($V_T$)       | 0.2V              |
| Planck’s constant (h)         | 6.626 x 10$^{-34}$ |
| Built-in potential (V$_{bi}$) | 0.6V              |

![Fig.1. Structure of dual material gate CNTFET](image_url)
Semiconductor type CNT is used in constructing the proposed DMG-CNTFET with the zigzag $(n = 13, m = 0)$. The diameter of CNT ($d_{cnt}$) is 1.02nm. The band gap is calculated by using the formula $E_g = \frac{2\times a_{cc} \times \Upsilon}{d_{cnt}}$ and the Band gap is 0.8631eV. The CNT is embedded in the cylindrical gate insulator HfO$_2$. The thickness of the gate oxide insulating layer ($t_{ox}$) is 20nm and dielectric constant ($k$) is 16. The device dimensions for the structures include gate length ($L_g$), channel length ($L_c$), source length ($L_s$) and drain length ($L_d$) of 20nm each. Moreover, the length of the undoped or intrinsic CNT channel is 20 nm. And the n-doped CNT extensions each of 20 nm are at the source and drain end. The doping density of n$^+$ Source and n$^+$ drain is $1.2 \times 10^7$ cm$^{-1}$. The above doping concentration is compared with the carbon atom density of $(4n/3a_{cc})$ in CNTFET, which is $\sim 122$nm$^{-1}$. The cylindrical gate contact material consists of two laterally contacting Molybdenum and Titanium metals (M1,M2) with two different work functions ($\phi_{gM1}$, $\phi_{gM2}$). These materials are of equal lengths of 5nm as shown in Fig.2. If work function is $\phi_{gM1} > \phi_{gM2}$, then $\phi_{gM1} = 4.7$ev, $\phi_{gM2} = 4.4$ev. $V_g$ is the gate-controlled voltage, $V_d$ and $V_s$ are the drain source voltage applied to the CNTFET. The prime focus of the proposed DMG-CNTFET device is characterized under illumination, when light is applied on the device.

3. SIMULATION OF DMG-CNTFET DEVICE

The cross sectional view of coaxial DMG-CNTFET is shown in Fig.2. Potential is symmetric and charge density is developed in the walls of the tube structure. The two dimensional poisson equation on the z direction is as in Eq.(1).

$$\frac{\partial^2 V_j(\rho,z_j)}{\partial \rho^2} + \frac{1}{\rho} \frac{\partial V_j(\rho,z_j)}{\partial \rho} + \frac{\partial^2 V_j(\rho,z_j)}{\partial z^2} = - \frac{qQ(\rho,z_j)}{\epsilon}$$

(1)
where \( \rho \) is the Radial parameter, \( z \) is the co-ordinate along the channel, \( V(\rho, z) \) is the surface potential of the CNTFET, \( \varepsilon_{\text{si}} \) is the permittivity of the device, \( Q(\rho, z) \) is the net charge density distribution which includes dopant density as well. The DMG-CNTFET structure is azimuthally symmetric. For Azimuthal symmetry, Poisson equation in Eq.(1) is defined to be two-dimensional. This helps in better analysis of the electrical properties of the device. The boundary conditions for the proposed DMG-CNTFET structure is given in below equations

\[
\begin{align*}
V(d_{\text{CNT}}, z) &= V_{\text{gs}} - \left( \frac{\phi_{gM1} - \phi_{gM2}}{q} \right) \\
V(\rho, 0) &= V_{\text{bi}} - \frac{\phi_s}{q} \\
V(\rho, L_{\text{CNT}}) &= V_{\text{ds}} - \frac{\phi_d}{q} \\
\frac{\partial V(0, z)}{\partial \rho} &= 0
\end{align*}
\]

Where \( d_{\text{CNT}} \) is the diameter of the CNT, \( V_{\text{gs}} \) is the gate source voltage. \( \phi_{gM1} \) is the work function of the gate contact material M1 and \( \phi_{gM2} \) is the work function of gate contact material M2. \( q \) is the electron charge and \( \phi_s \) is the work function of the source contact material. \( V_{\text{bi}} \) is the Built-in potential and \( \phi_d \) is the work function of drain contact material.

The retarded Green’s function of the DMG-CNTFET can be expressed as [7]

\[
G(E) = \left[ (E + i\tau - eU)I - H - \varepsilon_s - \varepsilon_d - \varepsilon_{\text{ph}} \right]^{-1}
\]  

Where \( E \) is the energy and \( \tau \) is an infinitesimal broadening. \( e \) is the electron charge, \( U \) is the electrostatic potential and \( I \) is the identity matrix. \( \varepsilon_s \) and \( \varepsilon_d \) are the self energies of source and drain end metal contacts respectively. \( H \) is the Hamiltonian matrix of the CNT. The mode-space treatment of electron transport is used in Hamiltonian matrix.

The Hamiltonian matrix for the qth mode is

\[
H = \begin{bmatrix}
U_1 & b_{2q} & \cdots & \cdots & \cdots \\
b_{2q} & U_2 & t & \cdots & \cdots \\
\cdots & b_{2q} & U_3 & \cdots & \cdots \\
& \vdots & \ddots & \vdots & \vdots & \ddots \\
& & \ddots & \ddots & \ddots & \ddots \\
& & & \ddots & t & \cdots \\
& & & \cdots & \cdots & \cdots & U_N
\end{bmatrix}
\]  

(3)

The values are, \( b_{2q} = 2t\cos\left(\frac{\pi q}{N}\right) \), \( t = 3\text{eV} \) which is the nearest neighbor hopping parameter. \( U_i \) (\( i = 1, 2, 3, \ldots, N \)) is the electrostatic potential at the \( i \)th carbon ring. \( q \) is the angular quantum and \( N \) is the total number of carbon rings along the DMG-CNTFET device. For the study of the carrier transport of a zigzag \((n,0)\) nanotube it is relevant when only one or few modes are considered. The diagonal elements \( U_i \) correspond to the on-site electrostatic potential along the tube surface obtained by solving the Poisson equation(1) [36].

\( \varepsilon_{\text{ph}} \) is the self-energy due to the electron-photon coupling.

\[
\varepsilon_{\text{ph}} = -\left(\frac{1}{2}\right)\Gamma_{\text{ph}}
\]  

(4)

Here \( \Gamma_{\text{ph}} \) is broadening function due to electron-photon coupling.
\[ \Gamma_{ph} = \varepsilon_{ph}^{in}(E) + \varepsilon_{ph}^{out}(E) \]  

\( \varepsilon_{ph}^{in} \) and \( \varepsilon_{ph}^{out} \) are the in and out-scattering functions for contact coupling, which are defined by [7]

\[ \varepsilon_{ph}^{in}(E) = (N + 1)\alpha \sum_{ij} M_{ij} G_{ij}^n(E + \hbar \mu) + N\alpha \sum_{ij} M_{ij} G_{ij}^n(E - \hbar \mu) \]  

\[ \varepsilon_{ph}^{out}(E) = (N + 1)\alpha \sum_{ij} M_{ij} G_{ij}^p(E - \hbar \mu) + N\alpha \sum_{ij} M_{ij} G_{ij}^p(E + \hbar \mu) \]

In the above equation \( j \) is the layer number of the grid slice. \( M_{lm} = \pm \delta_{l \pm 1, m} \) and \( \alpha = \frac{e^2 a^2 \gamma^2 F}{2\hbar \mu c \varepsilon_0} \) given that \( e \) is the electron charge, \( a \) is the thickness of the grid slice, \( \gamma \) is the coupling strength of adjacent carbon atom, \( c \) is the speed of the light, \( \varepsilon_0 \) is the permittivity of vacuum and \( \hbar \mu \) is the photon energy.

The electron and hole correlation functions are given by

\[ G^n(E) = G(E) \left[ \Gamma_S(E) f_S(E) + \Gamma_D(E) f_D(E) + \varepsilon_{ph}^{in}(E) \right] G^+(E) \]  

\[ G^p(E) = G(E) \left[ \Gamma_S(E)[1 - f_S(E)] + \Gamma_D(E)[1 - f_D(E)] + \varepsilon_{ph}^{out}(E) \right] G^+(E) \]

Where \( f_{S,D} \) is the Fermi-Dirac function of the source and drain end metal, \( \Gamma_{S,D} \) is the broadening function of the source and drain metal terminal contacts.

Then \( Q \) is charge density and it is calculated by

\[ Q(\rho = d_{CNT}, z_j) = N_d^+ - N_a^- + \frac{4}{\sqrt{2}} \int_{-\infty}^{E_{m(j)}^+} \frac{G^p_j(E)}{2\pi} dE - \frac{4}{\sqrt{2}} \int_{E_{m(j)}^-}^{0} \frac{G^n_j(E)}{2\pi} dE \]  

When the radial parameter \( \rho \) is not equal to the diameter of the CNT then the above value equals to zero \( (\rho \neq d_{CNT}, z) = 0 \). Values of the parameters in the equation above are, \( \rho \) which is equal to radius of carbon nano tube. \( N_d^+ \) is the donar concentration and \( N_a^- \) is acceptor concentration through out the tube. \( E_{m(j)} \) is the mid-gap energy value and \( j \) is the layer number of the grid slice. Here, it is assumed that the induced charge and the dopants are uniformly distributed over the CNT surface.

In simulation of the device under dark condition, at bias voltage, the self-consistent poisson equation iteratively solves Eq.(2). The values of \( U, H \) and \( Q(\rho, z_j) \) are obtained from Eq.(1,8,9,10) with \( \varepsilon_{ph} = 0 \). The initial value of the electrostatic potential \( U \) is taken from Eq.(1) with \( Q = 0 \). Once self-consistency is achieved, Green function \( G(E) \) is obtained by Eq.(2), \( G^n(E) \) and \( G^p(E) \) under dark condition are given by Eq.(8,19). And \( h \) is the Planck’s constant.

The current under dark condition can be calculated from

\[ I = \left( \frac{4e}{2\pi \hbar} \right) \int_{-\infty}^{\infty} Tr \left[ H_{j,j+1} G_{j,j+1}^n(E) - H_{j+1,j} G_{j+1,j}^n(E) \right] dE \]  

Calculation of the current under illumination using the self-consistent poisson equation iteratively is calculated by Eq.(1,2) and (4-7). The values of \( \varepsilon_{ph} \) and \( G(E) \) are obtained. The initial values are taken from Eq.(6) and (7) using the values of \( G^n(E) \) and \( G^p(E) \) obtained from dark condition. With the value obtained for self-consistency the corresponding values for \( \varepsilon_{ph}, G^n(E) \) and \( G^p(E) \) under illumination can be obtained. Then the photocurrent is calculated by Eq.(11). The entire procedure above is repeated for a series of bias voltages to generate the I-V characteristics in dark and illuminated condition.

The sub threshold swing \( S \) is the measure of gate control on the Channel in the CNTFET which
is expressed as [15]

\[ S = \frac{\partial V_{gs}}{\partial \log I_{ds}} \]  \hspace{1cm} (12)

In DMG-CNTFET, the potential at the top of the barrier is controlled by gate, source and drain capacitance. In the proposed DMG-CNTFET device, the gate source capacitance associates with gate dielectrics Hfo\(_2\) and nanotube. The High current and cut off frequency under illumination are provided by the modified channel transport and gate source capacitance.

The transconductance of DMG-CNTFET is represented in Eq.(13)

\[ g_m = \frac{dI_d}{dV_g} \]  \hspace{1cm} (13)

Where \( dI_d \) is the differential drain current and \( dV_g \) is differential gate voltage. \( g_m \) is the transconductance. The gate capacitance of DMG-CNTFET is represented as in Eq.(14)

\[ C_g = \frac{\partial Q_g}{\partial V_g} \]  \hspace{1cm} (14)

Where \( \partial Q_g \) is the differential total charge on the channel or gate length and \( \partial V_g \) is the gate voltage in volts. The \( C_g \) is the gate capacitance. For low dimensional gates, the gate charge can limit the channel charge, and the transfer characteristics of the device become dependent on the gate electronic density of states. The dependence of gate capacitance on \( V_{gs} \) corresponds to the integrated electronic density of states. The cut-off frequency of the DMG-CNTFET device is derived from the Eq.(15)

\[ f_T = \frac{1}{2\pi} \frac{g_m}{C_g} \]  \hspace{1cm} (15)

In the above equation \( f_T \) is the cut-off frequency of the device. \( g_m \) is the transconductance of the device and \( C_g \) is the gate capacitance. The intrinsic gain of the DMG-CNTFET is calculated using the Eq.(16)

\[ gain \ (A_v) = \frac{g_m}{g_d} \]  \hspace{1cm} (16)

Where \( g_m \) is trans conductance and \( g_d \) is the drain conductance of the DMG-CNTFET.
4. RESULT AND DISCUSSION

The DMG-CNTFET device is simulated at Zigzag (13,0), $V_{gs} = 1$V, $d_{cnt} = 1.02$nm, $t_{ox} = 20$nm. The fixed optical power intensity ($P_{opt}$) is $100$W/cm$^2$, wavelength $\lambda = 633$nm in the room temperature (300K) under dark and illumination conditions with the photon energy of 1.5eV. The Fig.3 shows the output characteristic of the DMG-CNTFET with and without illumination. The current under dark condition shows a strong dependence on the gate voltage and the minimum leakage current is obtained. DMG-CNTFET has maximum drain current ($I_d$) of 40μA under the dark condition. Under the illuminated condition photogenerated electron-hole pairs are induced in the DMG-CNTFET. The photo current ($I_{ph}$) is 45 μA. In DMG-CNTFET, the discontinuity of the electric field at the interface of the two gate metals increases the electric field in the vicinity of the source. This results in high average velocity of carrier under M1 gate in the channel. Also, the reduction of electron velocity near the drain end of DMG-CNTFET results from decreasing the electric field near the drain in the DMG-CNTFET. Consequently, the drain conductance of the device decreases.

Fig.3 shows the transfer characteristics of drain current of DMG-CNTFET device under dark and illuminated conditions at gate source voltage is $1$V, $P_{opt}=100$W/cm$^2$, $d_{cnt}=1.02$nm, $\lambda=633$nm.

Fig.4 shows the transfer characteristics of DMG-CNTFET in dark and illuminated conditions. The values are, Zigzag (13,0), $t_{ox}=20$nm, $k=16$. It also shows the transfer characteristics of CNTFET with different structural parameters in ballistic transport mode. In the proposed DMG-CNTFET, Hafnium-based Oxide (HfO$_2$) is replaced by Silicon Oxide (SiO$_2$) as a gate insulator. At $V_{ds}=0.9$v, the on current of DMG-CNTFET under dark condition is lower than the drain current under illuminated condition. With the proper selection of gate length and gate oxide thickness ($t_{ox}$), higher will be the subthreshold slope of the device. The Fig.5. shows the sub-threshold swing(SS) of DMG-CNTFET and it provides good control of the theoretical limit of the sub-threshold swing. Cylindrical gate comprises of two horizontally connecting metals with different work functions and lengths of these two metal gates are equal, which are of 10nm each. Work function in the proposed dual material gate CNTFET structure reduces sub-threshold swing and confirms good control of the structure on the short channel effects. Different materials are used in the gate metals M1 and M2. Metal M1 is Molybdenum and M2 is Titanium. The work function ($\phi_{gM1}$) of Molybdenum is 4.7ev and work function of Titanium ($\phi_{gM2}$) is 4.4ev. $\phi_{gM1}$ is always greater than $\phi_{gM2}$ which helps in lowering the sub-threshold swing. Furthermore, the sub threshold swing can be improved by decreasing the diameter of the CNT. The theoretical subthreshold swing is 60mv/decade at room temperature(300K). Subthreshold swing significantly increases under illumination. Fig.6 is the energy band diagram.
of CNTFET.

The Fig. 7 shows the transconductance ($g_m$) characteristics of the DMG-CNTFET. The values for calculation of the proposed DMG-CNTFET include energy band gap of 0.8631eV for zigzag (13,0) and the diameter ($d_{cnt}$) is 1.02nm. $V_{ds} = 1V$, fixed optical power intensity ($P_{opt}$) is 100W/cm$^2$. Wave length ($\lambda$) is 633nm, $t_{ox} = 20$nm and high dielectric constant $k = 16$. The transconductance characteristics are simulated under dark and illuminated conditions. When the CNT diameter is increased from 0.5nm to 1.5nm, more sub-bands participate in electron transport, increasing the channel conductance. This increase continues to increase the transconductance[23]. Therefore, average velocity of carriers and current increase under illumination with significant reduction in the drain conductance and increment in the transconductance of DMG-CNTFET. So the transconductance characteristic of DMG-CNTFET is $\approx 0.09$m mho which is greater than the value under dark condition.

Fig. 8 shows the drain conductance of DMG-CNTFET at $V_{ds} = 1V$, $V_{gs} = 0.9V$, $P_{opt} = 100W/cm^2$, $d_{cnt} = 1.02nm$ and $\lambda = 633nm$ under dark and illuminated conditions. The n$^+$ Source ($N_s$) and n$^+$ drain ($N_d$) doping density is $1.2 \times 10^7$ cm$^3$. The drain conductance ($g_d$) of CNTFET changes with source and drain doping densities and it has the worst value when $N_s = N_d = 2\times 10^7$ cm$^3$. The transconductance of the device is dependant on the source and drain doping densities[22]. The proposed DMG-CNTFET has dual material gate which decreases the drain conductance of the device as already discussed in Fig.3. At $V_{gs} = 0.9V$ the drain conductance
is $\sim 7.5 \times 10^{-4}$ S under illumination.

The Fig.9 shows the cut–off frequency of DMG-CNTFET with zigzag (13,0). It is compared with various gate voltage ($V_{gs}$) which varies from 0v to 0.8v., drain voltage $V_{ds}$ is 1V, incident optical power $P_{opt}$ is 100W/cm², wave length $\lambda = 633$nm, gate oxide thickness $(t_{ox})$ is 20nm, diameter of the nano tube $d_{cnt}$ is 1.01nm and channel length is 20nm. Higher gate voltage can lead to higher cutoff frequency for all the devices. This is because larger gate bias can reduce the source/intrinsic barrier height in channel, thus resulting in higher transconductance, which increases the cutoff frequency efficiently. The intrinsic cutoff frequency of CNTFET can reach up to a few THz[11]. The higher cut-off frequency of DMG-CNTFET is $\sim 5.2$THz under illumination.

![Fig.9 Cut off frequency of DMG-CNTFET device under dark and illumination conditions with $P_{opt}=100W/cm^2$, $d_{cnt}=1.02nm$, $\lambda=633$nm](image)

The Fig.10 shows the gain of DMG-CNTFET device under dark and illuminated conditions. The gain of DMG-CNTFET is obtained with drain source voltage $V_{ds} = 1$V, dielectric constant $k = 16$. Gate oxide thickness $t_{ox}$ is 20nm, fixed optical intensity $P_{opt} = 100W/cm^2$ and the wavelength, ($\lambda$) is 633nm. The photo-excited electrons contribute to increase of the current. Therefore, photo current gets increased which increases the photoconductive gain. In the proposed device, doping densities of source and drain regions are identical and fixed at $1.2 \times 10^7$ cm$^{-1}$. Source length of 20nm and drain length of 20nm is used for investigating the design optimization in terms of the drain conductance. From the Fig.10, gate source voltage is 1V, the gain of the DMG-CNTFET is 27.5 db which is increased under illumination.

The responsivity, efficiency and directivity of proposed DMG-CNTFET device under illuminated condition is calculated with various gate voltages and the following parameters. $P_{opt}$ is the incident optical power delivered to the device and $\vartheta$ is the frequency of the illumination. $I_{ph}$ is the photo current, $I_d$ is the current under dark condition. Responsivity (R) of a photo detector is given as the ratio of the generated photocurrent ($I_{ph}$) to the amount of incident optical power intensity ($P_{opt}$) delivered to the device. The Responsivity is calculated using $R = \frac{I_{ph}}{P_{opt}}$. The Responsivity obtained is 73.32(mA/W). The quantum efficiency ($\alpha$) is calculated by using the formula $\alpha = \frac{I_{ph}/q}{P_{opt}/h\vartheta} \times 100$, where q is the charge of electrons, h is the planck’s constant. The efficiency of 55% is obtained. Directivity of the DMG-CNTFET is given by $D = \sqrt{\frac{A}{2eI_dR}}$. Where e is the elementary charge ($1.6 \times 10^{-19}$ Coulombs), R is the responsivity, $I_d$ is the dark current of the DMG-CNTFET. A is the active area of the detector.
The value obtained for directivity is $8 \times 10^6 \text{ (cmHz}^{1/2} / \text{W)}$ [32].

Comparison of diameter and directivity of proposed DMG-CNTFET and CNTFET devices are as shown in Table 2.

| Device Name       | Wave length (nm) | Responsivity (mA/W) | Diameter CNT ($d_{CNT}$) | Directivity (cmHz$^{1/2}$ /W) | Ref     |
|-------------------|------------------|----------------------|---------------------------|--------------------------------|---------|
| DMG-CNTFET        | 633              | 73.32                | 1.02nm                    | $8 \times 10^6$               | Our Work|
| Photo-CNTFET      | 437 - 633        | 121.48               | 0.8nm                     | -                             | [32]    |
| SWCNT array       | 785              | 65.8                 | 1-2nm                     | $10.9 \times 10^6$            | [33]    |
| Single SWCNT      | 780-980          | 0.1                  | 0.8nm                     | -                             | [34]    |

Comparison of the performance of DMG-CNTFET and various CNTFETs under dark and illuminated conditions are as shown in Table 3.

| Different CNTFET | Optical Incident Power ($P_{inc}$) | Wave Length (nm) | Dark Condition (Current) | Illumination Condition (Current) | Ref     |
|------------------|-----------------------------------|------------------|--------------------------|---------------------------------|---------|
| DMG-CNTFET       | 100W/cm$^2$                        | 633              | 40 µA                    | 45 µA                           | Our work|
| Photo-CNTFET     | 1.0mW                             | 633              | 10 µA                    | 50 µA                           | [32]    |
| SWCNT array      | 1.57kW                            | 785              | 10nA                     | 21nA                            | [33]    |
| Single SWCNT     | 0.1mW                             | 1.5µm            | $8 \times 10^{-13}$ A    | $8.0 \times 10^{-12}$ A         | [34]    |

5. CONCLUSION

The electrical and illumination properties of the proposed Dual Material Gate Carbon Nanotube Field-Effect Transistor (DMG-CNTFET) are analyzed. The numerical analysis for the DMG-CNTFET device is based on the solution of two-dimensional Poisson equation with boundary conditions. And the Schrodinger equations are solved with boundary conditions using Green function. The simulated results of proposed DMG-CNTFET shows decrease in sub threshold swing. This is due to the dual material gate and high dielectric constant HfO$_2$. The transconductance, gain, cut off frequency and directivity of DMG-CNTFET are increased. Efficiency of 55% is obtained. Preservation of the optoelectronic properties of the nanotube is a base expectation in such analysis. Fabrication of such devices with coaxial gates and ultrathin gate dielectrics is possible [1,35]. The DMG-CNTFET device is more suitable for ULSI applications such as OEIC receiver and high frequency applications.

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