



GLOBAL JOURNAL OF RESEARCHES IN ENGINEERING: F
ELECTRICAL AND ELECTRONICS ENGINEERING
Volume 17 Issue 2 Version 1.0 Year 2017
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

Performance Analysis of Enhanced Carbon Nanotube Field Effect Transistor (CNTFET) using Zirconia as Gate Dielectric

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GJRE-F Classification: FOR Code: 090699



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Abstract- The Carbon Nanotube Field Effect Transistor (CNTFET) is one of the most rising devices among the emerging technologies to extend and/or complement the traditional Silicon MOSFET as it is showing high efficiency and wide range of applications in many different fields of science and technology. Carbon Nanotube Field Effect Transistors have been explored and proposed to be the upcoming more efficient and suitable candidates for the integrated circuit (NGIC) devices of next generation. In this study, firstly, the Density of State (DOS) with different types of nanotubes considering the chirality have been reviewed. Then we have studied the carbon nanotube field effect transistor by replacing the traditional gate insulator with a material that has much higher dielectric constant. Carbon Nanotube Field Effect Transistor has been analyzed with the bandgap of 1.0882eV in this research and ZrO₂ (Zirconia) has been taken as the gate dielectric. We have also analyzed quantum capacitance, transconductance and mobile charge behavior at different drain voltage. Finally, the output characteristics of proposed model has been given.

Keywords: carbon nanotube, CNT field effect transistor, CNT DOS, Gate Dielectric.

I. INTRODUCTION

Carbon Nanotubes are sheets of graphite rolled in the shape of a tube. Depending on chirality they can be either metallic or semiconducting. Carbon Nanotubes were discovered by Iijima at the NEC Fundamental Research Laboratory while he used a high resolution transmission electron microscope (TEM) to observe byproducts of carbon which had been generated by an arc between two carbon electrodes (Iijima, 1991). After that momentous development has been achieved by understanding the characteristics and searching possible applications of these on semiconductor technology. They have high elastic modulus, small weight and are predicted to be the strongest fibers. Carbon Nanotube's strength and flexibility are their unique properties. The fascinating electronic properties of them depend drastically on both the diameter and the chirality of the hexagonal carbon lattice along the tube (Mintmire *et al.*, 1992;

Hamada *et al.*, 1992; Saito *et al.*, 1992). Because of its excellent conductivity and high dielectric properties, CNTs play a vital role in different nano electronic devices such as transistors, digital logic devices, memory components, etc (Heinze *et al.*, 2002).

The fundamental strategy for improving the performance of VLSIs is scaling down of electronic devices. According to the ITRS the gate length of MOSFETs will be less than 16 nm in 2016 (ITRS, 2003). If this continues then the MOSFETs will reach its limiting size very soon. Thus the semiconductor industry is searching for different materials to integrate with the current silicon-based technology and in the long run, possibly replace it if required. In this regard the carbon nanotube field effect transistor (CNTFET) will be the most promising alternatives for its unique properties. It was demonstrated long before in 1998 (Tans *et al.*, 1998). Carbon nanotube field-effect transistors offer high mobility for ballistic transport, high mechanical and thermal stability with high resistance to electro migration, attracting strong interest as alternative high device technologies for the future nano electronics applications (Avouris *et al.*, 2007). Recently, a carbon nanotube transistor, which integrates ultra-short channel, thin high-k top gate insulator and excellent Pd source-drain contact is demonstrated using a self-align technique (Javey *et al.*, 2008).

This paper proposes CNTFET with ZrO₂ as gate oxide which is also one of the most promising devices. This paper has been devised into main two sections. In the first section, the mobility of CNTs has been discussed with analyzing the Density of State (DOS) of different types of nanotubes and in the second part, the proposed CNTFET device modeling has been described with its parameters, along with simulation results.

II. CARBON NANOTUBE

Carbon is an element with symbol C. Its atomic number is 6 (1s²2s²2p²). Carbon is a group 14 element that resides above silicon on the periodic table. It is nonmetallic and tetravalent making four electrons available to form covalent chemical bonds. Carbon has four electrons in its valance shell like silicon (1s²2s²2p⁶3s²3p²) and germanium (1s²2s²2p⁶3s²3p⁶3d¹⁰4s²4p²). There are several allotropes of carbon like graphite, diamond and amorphous carbon (Carbon materials

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research group, University of Kentucky). When carbon atoms are arranged in crystalline structures composed of benzene like rings, they form several allotropes that contain totally exceptional electronic properties.

The physical properties of carbon vary widely with the allotropic form (List of thermal conductivities, Wikipedia). Diamond, carbon nanotubes and graphene have the highest thermal conductivity of all known materials (e.g., diamond: $900\text{--}2300 \text{ Wm}^{-1}\text{K}^{-1}$, carbon nanotube: $3180\text{--}3500 \text{ Wm}^{-1}\text{K}^{-1}$) (Faisal and Ali, 2015) under normal conditions.

Carbon Nanotubes (CNTs) are an allotrope of carbon. Carbon nanotubes have many forms, differing in length, thickness and in the type of helicity and number of layers. It can be categorized into Single Walled Carbon Nanotube (SWCNT) and Multi Walled Carbon Nanotube (MWCNT) shown in Fig. 1 and 2. The carbon nanotubes have diameters from less than 1nm to 50 nm. These possess excellent mechanical and transport properties too.

The rolled graphene (CNT) can be explained by a coordinate of indices (n, m), which is known as Chiral Vector. It represents whether CNT is metallic or semiconducting and diameter of CNT. The table shown below describes "Chirality of carbon nanotube. The diameter of carbon nanotube is given by:

$$d = \frac{\sqrt{3}a_{c-c}}{\pi} \sqrt{m^2 + mn + n^2} \quad (1)$$

Where:

$a_{c-c} = 0.142 \text{ nm}$ is the carbon-carbon bond length

Figure 3 and 4 shows the Density of State (DOS) of different types of nanotubes. The simulated end states are within the energy gap of semiconducting carbon nanotubes, implying that the end states are a 1-D analogy with conventional surface states. Since the band gaps of carbon nanotubes are small, CNTs are either metallic or semi conductive. The energy band structures of carbon atom provide an occupied energy level in the band gap depending upon the density of states and types of CNT. The (10, 0) nanotube acts as semi conducting material since it has energy gap between conduction and valence band whereas the (8, 8) nanotube acts as conducting material as the valance and conduction bands are overlapping.

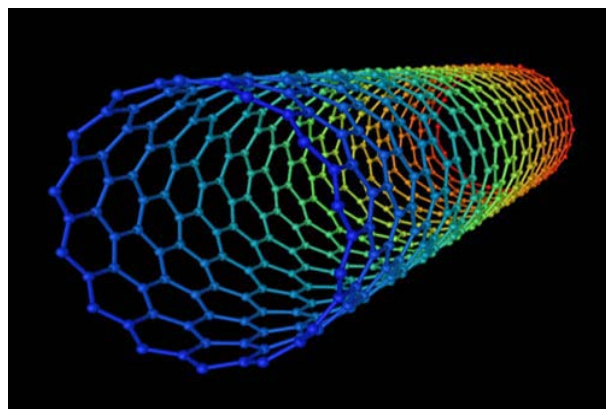


Fig. 1: Single walled carbon nanotube

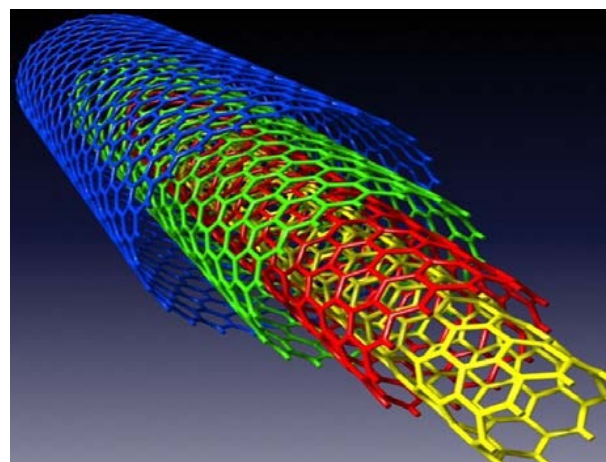


Fig. 2: Multi walled carbon nanotube

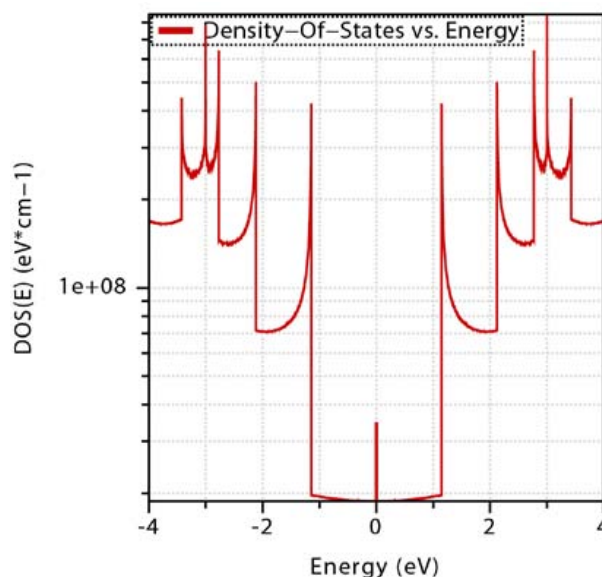


Fig. 3: DOS vs. Energy for (8, 8)

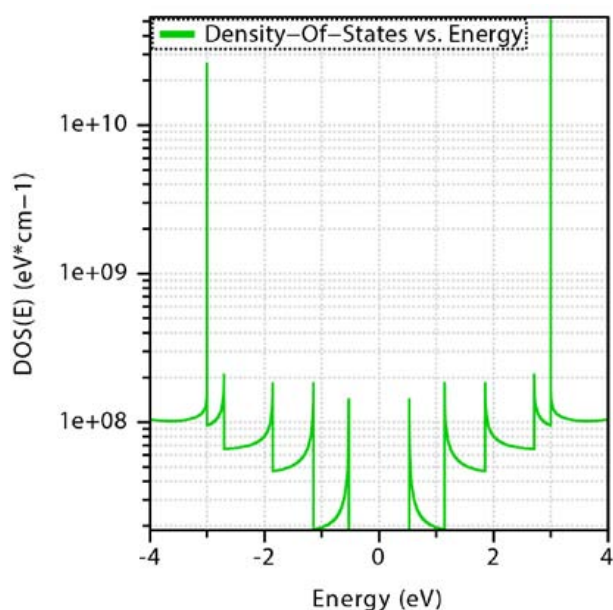


Fig. 4: DOS vs. Energy for (10, 0)

III. CARBON NANOTUBE FIELD EFFECT TRANSISTOR

A Carbon Nanotube Field-Effect Transistor (CNTFET) indicates a field-effect transistor which handles a single carbon nanotube or an array of carbon nanotubes as the channel material rather than silicon in the conventional MOSFET structure. CNTFET is a three-terminal (three to six layers) device consisting of a semiconducting nanotube bringing two contacts (source and drain) and acting as a carrier channel which is turned on or off electrically via the third contact (gate). According to the fabrication geometry, there are many types of CNTFET devices such as Back-gated CNTFET, Top-gated CNTFET, Wrap-around gate CNTFET, Suspended CNTFET etc. (Wind *et al.*, 2002; Chen *et al.*, 2008; Farmer and Gordan, 2006; Cao *et al.*, 2005). These are divided broadly in two categories: Planar CNTFET and Coaxial CNTFET which are shown in Fig. 5. CNTFETs show different characteristics compared to MOSFETs in their theoretical experiments. In a planar gate structure, the p-CNTFET produces ~1500 A/m of the on-current per unit width at a gate overdrive of 0.6 V while p-MOSFET produces ~500 A/m at the same gate voltage (Cao *et al.*, 2005). This on-current advantage comes from the high gate capacitance and modified channel transport. Since an effective gate capacitance per unit width of CNTFET is about double that of p-MOSFET, the compatibility with high gate dielectrics becomes a superior advantage for CNTFETs (Sahoo and Mishra, 2009).

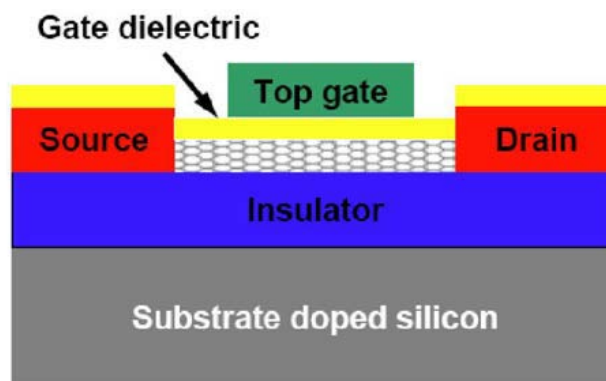


Fig. 5: Planar CNTFET

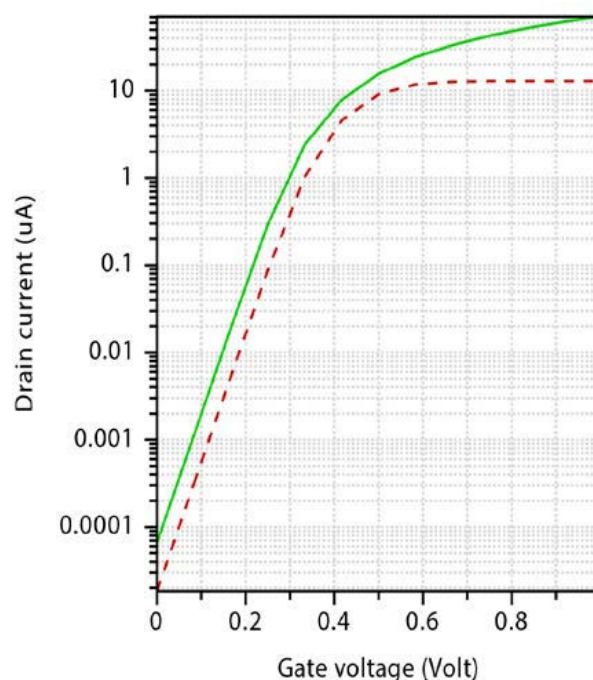


Fig. 6: I-V characteristics of proposed CNTFET (Solid line)

IV. MODELLING OF CNTFET

The proposed device is formed with a (10, 0) CNT. So the channel diameter = 0.782885 nm. For gate insulation ZrO_2 ($k = 25$) is used. Energy gap for a nanotube is given by:

$$E_g = \frac{2a\gamma_c}{\text{channel diameter}} \quad (2)$$

Where:

γ = The nearest neighbor-hopping parameter ($\gamma = 2.5$ – 3.2)

Using $\gamma = 3$, the energy gap is 1.0882 eV. The parameters used in the proposed model and calculations are given in Table 3.

Table 1: Properties of carbon nanotube

Material	Young's modulus (GPa)	Tensile strength (GPa)	Electrical conductivity (mho/m)
Single wall nanotube	~1050	150.000	~10 ⁷
Multi wall nanotube	~1200	150.000	~10 ⁶
Steel	208	0.400	~10 ⁵
Wood	16	0.008	~10 ⁻⁴

Table 2: CNT classifications

Type of CNTs	Values of m and n	State
Armchair	m=n	Metallic
Zigzag	m=0	Semiconducting
Semiconducting or Chiral	n-m≠3×integer	Semiconducting (large bandgap)
Quasi-Semiconducting	n-m=3×integer	Semiconducting (small bandgap)

Table 3: Proposed parameters

Energy gap	1.0882 eV	Gate oxide thickness	1.6 nm
CNT diameter	0.78 nm	Gate dielectric (ZrO2)	25

Conductance between two leads source and drain is defined in terms of current and voltage: $I = GV$. Using Landauer formula (Nazarov and Blanter, 2009), conductance is expressed by the following equations:

$$G = \frac{2Te^2}{h} \quad (3)$$

where, q is the charge of electron and h is the Planck's constant. T is known as the transmission function in terms of energy that represents the probability of an electron injected at one end of a conductor will emit at the other end. T can be expressed as:

$$T = \text{trace} [T_s G_0^r \Gamma_D G_0^a] \quad (4)$$

G_0^r G_0^a represents the retarded and advanced Green's function of the nanotube and Γ_D , Γ_S are the coupling of the CNT to the source and the drain. The retarded Green's function is calculated by:

$$G_0^r = (E - H - \Sigma_S - \Sigma_D)^{-1} \quad (5)$$

where, E is Fermi energy, I is the identity matrix, H is the Hamiltonian of the nanotube. Σ_S , Σ_D is the self-energy terms at the source and drain coupling of the contacts are the calculated using the broadening function of the self-energy terms at the source and drain.

The nanotube behaves as the conducting channel in the CNTFET from the source to drain; it depends on the current density of the tube. The current density is a measure of the density of flow of an electric current per unit area across a section. The current density is an area density described by J . The current through an area A is simply the flux of the current density through that area as shown below:

$$I = \int J \cdot dA \quad (6)$$

Using the charge density within the device, the NEGF transport equation is solved iteratively with the poisson equation until self-consistent potential distribution is found. Finally the current is calculated using the Landauer Böttiker expression:

$$I_d = \frac{4d \int T(E) [f_s(E) - f_d(E)] dE}{h} \quad (7)$$

T is the transmission probability across the source/drain; f_s and f_d are the source/drain Fermi-Dirac distribution functions consistent potential; The equation is solved simultaneously to evaluate and characterize the performance of these devices.

V. SIMULATIONS

Hafnia (HfO_2) adopts the same structure as zirconia (ZrO_2 , $K \sim 25$). Unlike TiO_2 ($k = 40$), which features six-coordinate Titanium in all phases, zirconia and HfO_2 consists of seven- coordinate metal centers (Miikkulainen *et al.*, 2013; Faisal and Ali, 2012). Hafnium-based oxides were introduced by Intel in 2007 as a replacement for silicon oxide as a gate insulator in field-effect transistors (Source: INTEL). We simulate the I-V Characteristics of CNTFET using ZrO_2 as gate insulator for proposed model. The high-K gate insulator and bigger CNT diameter allows higher drain current.

Figure 7 shows the output characteristics of the proposed CNTFET. The channel allows the current to flow when the gate voltage is greater than 0.3 V. So the on current is 70 μA at $V_g = 2.0$ V and $V_d = 1.0$ V and the off current is 6.61e-05 μA at $V_g = 0\text{V}$ and $V_d = 1.0$ V.

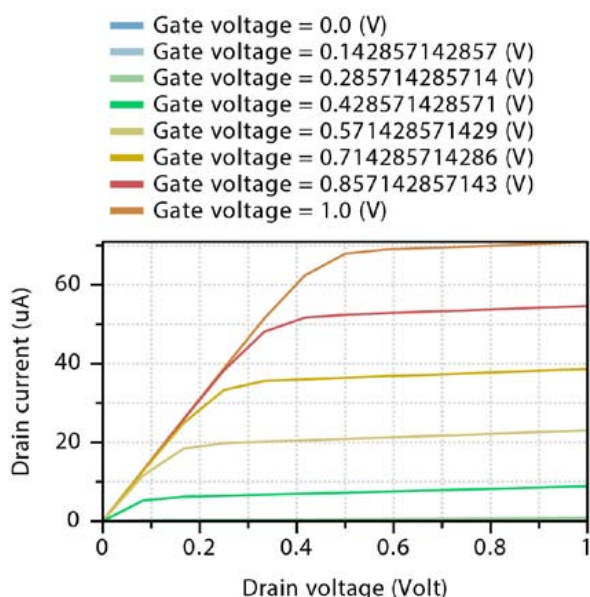


Fig. 7: I_d vs. V_d (Output characteristics) curve at different V_g

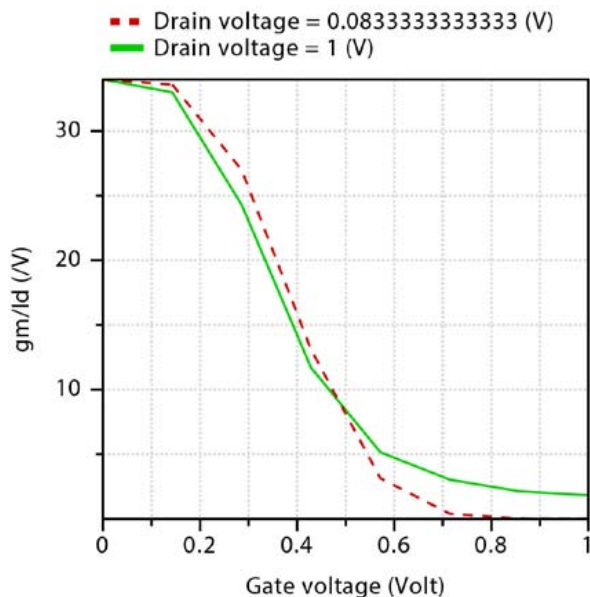


Fig. 8: Transconductance of CNTFET

In order to achieve a relatively large transconductance the CNT must have large channel diameter. The larger the transconductance, the greater the gain it will deliver. As the diameter gets smaller this reduces the carrier mobility, changing the transconductance. The transconductance behavior is obtained at 0.78 nm diameter, with different drain voltage (Fig. 8). The transconductance varies by a factor of 10/V depending on the amount of voltage applied to the gate. However, the increase of V_g will reduce the allowed voltage signal through the drain.

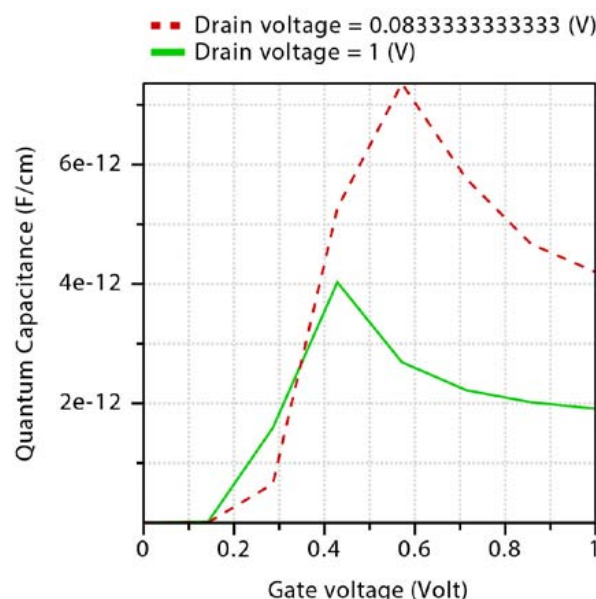


Fig. 9: Quantum capacitance vs. Gate voltage

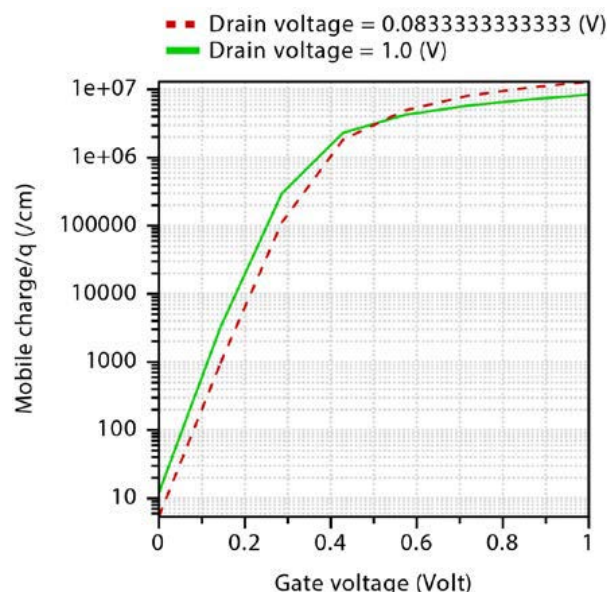


Fig. 10: Mobile charge behavior at gate voltage

Quantum capacitance is associated with the properties of channel material. As the density of state is finite in a semiconductor quantum well, the Fermi level needs to move up above the conduction band edge as the charge in the quantum well increases. This movement of Fermi level requires energy and this conceptually corresponds to quantum capacitance. Figure 9 shows the quantum capacitance versus the gate voltage at different drain voltages. It is clear that a higher quantum capacitance can be found at a gate voltage 0.42 or 0.57 volt (for proposed model).

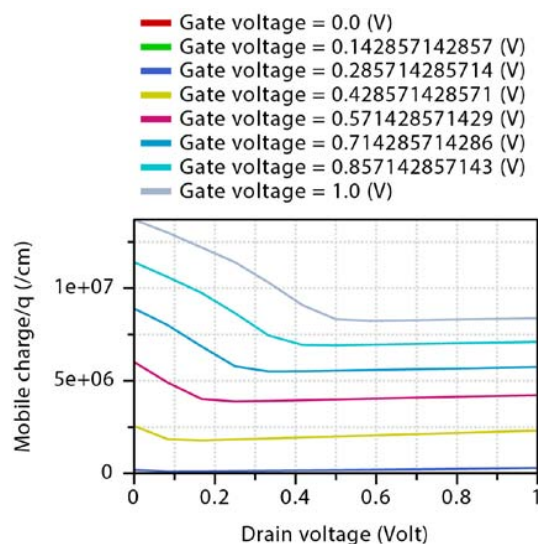


Fig. 11: Mobile charge behavior at drain voltage

As insulator thickness approaches the nanometer range, the insulator capacitance becomes comparable to the inversion layer capacitance, which means that the QC and the centroid capacitance start to affect the gate capacitance.

Figure 10 shows the mobile charge behavior as a function of gate voltage. It is noticed that increasing the drain voltage beyond a specific value has no longer an effect on the shape of the curves since the mobile charge remains constant. It is also observed that low drain voltage produces higher mobile charge and high drain voltage produces lower mobile charge. Also, it has been noticed that the mobile charge increases with the reduction in gate insulator thickness. Figure 11 shows the mobile charge behavior as a function of drain voltage.

VI. CONCLUSION

The proposed parameters and gate dielectric of CNTFET make the transistor a challenge to develop and control the aspects of it such maximum transconductance. We found two regions for maximum transconductance. Zirconia is used in optical coatings and in DRAM capacitors as a high- k dielectric and in advanced metal-oxide semiconductor devices. The advantage for proposed CNTFET is its high dielectric constant: The dielectric constant of ZrO_2 is 4-6 times higher than that of SiO_2 . In recent years, zirconium oxide (as well as doped and oxygen-deficient zirconium oxide) attracts additional interest as a possible candidate for resistive-switching memories (Lin, 2011).

VII. ACKNOWLEDGEMENT

The authors' would like to thank Dr. M. Tanseer Ali for his remarks and invaluable advises on different aspects of this work.

Funding Information

The authors have no support or funding to report.

Ethics

The authors' hereby declare, this work is their own contribution and hence there would not be any ethical issues related to this manuscript.

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