Simulations of enhanced CNTFET with HfO$_2$ gate dielectric

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Abstract- Carbon Nanotube is one of the rising technologies within nano science, which is showing high efficiency and wide range of applications in many different fields of science and technology. The Carbon Nanotube Field Effect Transistors (CNTFETs) have been explored and proposed to be the rising candidate for the next generation of integrated circuit (NGIC) devices. In this paper first the Carbon Nanotube and density of state (DOS) with different types of nanotubes considering energy gap have been reviewed. We have then studied the carbon nanotube field effect transistor. In this research CNTFET is analyzed where the bandgap is 0.94eV with HfO$_2$ as gate dielectric. Finally the simulation of proposed model is given.

Index Terms- Carbon Nanotube, Carbon Nanotube Field Effect Transistor, CNT DOS

I. INTRODUCTION

As the discovery of carbon nanotubes by Iijima in 1991 at the NEC Fundamental Research Laboratory in Tsukuba, Japan [1], momentous development has been achieved for understanding the characteristics and searching possible applications on relevant technology. Carbon nanotubes have small bandgap compare to other traditional semiconductor technologies. Nanotubes have a small weight and high elastic modulus, and they are predicted to be the strongest fibers that can be made. CNTs high strength and high flexibility are unique properties. They also have fascinating electronic properties. The electronic properties depend drastically on both the diameter and the chirality of the hexagonal carbon lattice along the tube [2–4]. CNTs can play a vital role in nano electronic devices such as transistors, memory components, digital logic devices etc. because of its excellent conductivity and high dielectric properties [5].

Scaling down of electronic devices has been the fundamental strategy for improving the performance of VLSIs. The ITRS suggests that in 2016 the gate length of MOSFETs will be less than 16nm [6].Though this roadmap still continues, MOSFETs will soon reach its limiting size For this reason, the semiconductor industry is searching for different materials to integrate with the current silicon-based technology and in the long run, possibly replace it. The carbon nanotube field effect transistor (CNTFET) is the most promising alternatives due to its properties. It was demonstrated in 1998 [7]. Carbon nanotube field-effect transistors offer high mobility for ballistic transport, high mechanical and thermal stability, and high resistance to electro migration, attracting strong interest as alternative device technologies for future nano electronics applications [8].Recently, a carbon nanotube transistor, which integrates ultra-short channel, thin high-κ top gate insulator, excellent Pd source drain contacts is demonstrated using a self-align technique [9].

This paper propose CNTFET which is one of the most promising device. This paper has been devised into main two sections, first in section II the mobility of CNTs are discussed with analyzing the density of state (DOS) of different types of nanotubes. In second part, from section IV, the proposed CNTFET device modeling has been described with its parameters, along with simulation results in section V. We conclude the paper in section VI.

II. CARBON NANOTUBE

Carbon is an element with symbol C and atomic number 6 ($1s^2 2s^2 2p^2$).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. Like silicon ($1s^2 2s^2 2p^6 3s^2 3p^2$) and germanium ($1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$), carbon has four electrons in its valance shell. There are several allotropes of carbon like graphite, diamond, and amorphous carbon [10].When carbon atoms are arranged in crystalline structures composed of benzene like rings, they form several allotropes that contains exceptional electronic properties. The physical properties of carbon vary widely with the allotropic form. Under normal conditions, diamond, carbon nanotubes, and graphene have the highest thermal conductivities of all known materials(e.g. diamond: 900–2300 W$\cdot$m$^{-1}\cdot$K^{-1} ,carbon nanotube: 3180-3500 W$\cdot$m$^{-1}\cdot$K^{-1}) [11]. 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 Figure 1.The carbon nanotubes have diameters from less than 1nm to 50 nm. These have excellent mechanical and transport properties too.
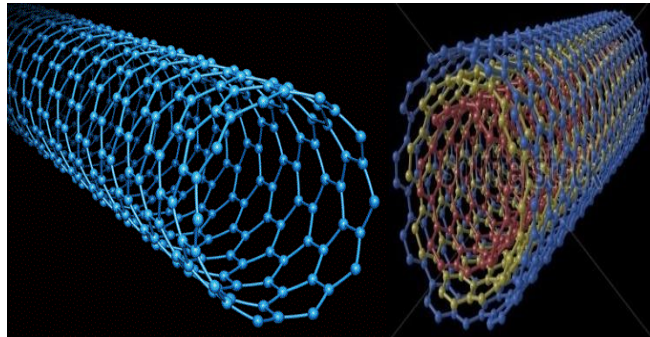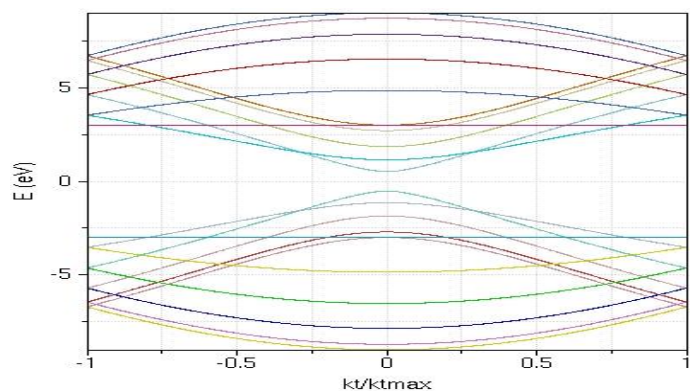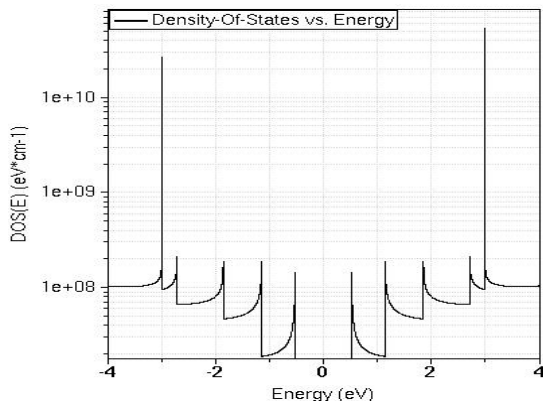
Table I: Properties of carbon nanotube [12]

Specific Density	1.3-2
Young's Modulus(TPa)	~1
Tensile Strength(GPa)	10-60
Electrical Conductivity(mho/m)	10^6-10^7

Figure 1: SWCNT and MWCNT [13]

In another way the rolled graphene (CNT) is 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, $d = \frac{\sqrt{3}\, a_{c-c}}{\pi} \sqrt{m^2 + mn + n^2}$ where a_{c-c} =0.142nm is the carbon-carbon bond length [14].

Table II: Types of CNTs according to m and n values

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)

Figure 2 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. The band gaps of carbon nanotubes are small, so CNTs are either metallic or semi conductive. The energy band structures of carbon atom provides 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. The (8, 8) nanotube act as conducting material as the valance and conduction bands are overlapping.
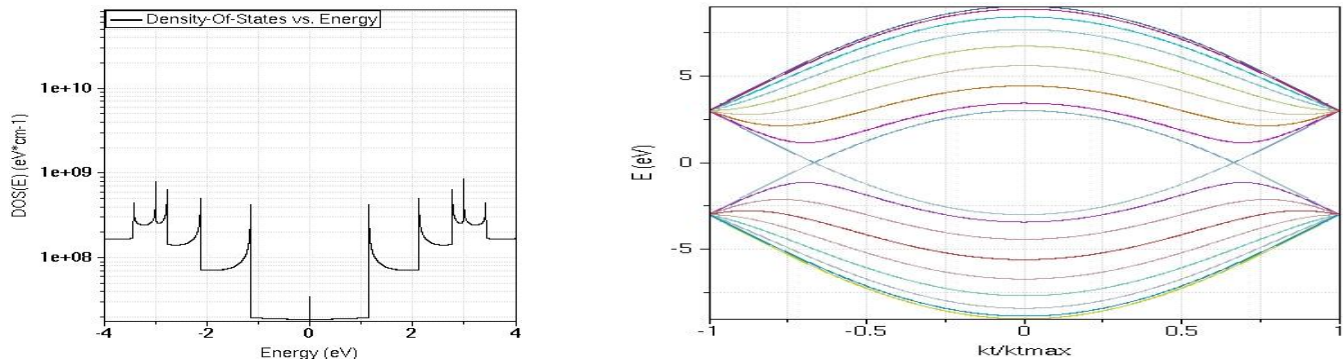
Figure 2: DOS vs Energy for (10,0) and (8,8)

III.   CARBON NANOTUBE FIELD EFFECT TRANSISTOR

A carbon nanotube field-effect transistor (CNTFET) indicates to a field-effect transistor that handles a single carbon nanotube or an array of carbon nanotubes as the channel material rather 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 fabrication geometry there are many type of CNTFET devices such as Back-gated CNTFET, Top-gated CNTFET, Wrap-around gate CNTFET and Suspended CNTFET etc. [15-18].These are divided broadly in two categories: Planner CNTFET and Coaxial CNTFET shown in Figure 3. 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 [19] .This on-current advantage contains 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 [20].

Figure 3: Carbon Nanotube Field Effect Transistor: Planner, Coaxial

IV.   MODELLING OF CNTFET

The proposed device is formed with a (10,0) CNT. So the channel diameter =0.782885nm.For gate insulation HfO_2 (k=15) is used. Energy gap for a nanotube is given by

$$E_g = \frac{2 \times a_{c-c} \times \gamma}{channel\ diameter}$$

(1)

Where γ is the nearest neighbor-hopping parameter (γ=2.5-3.2)

Using γ=2.6, the energy gap is 0.94384eV.The parameters used in proposed model and calculations are given in Table III.

Table III: Proposed parameters

Energy Gap	0.94eV	Gate oxide thickness	1.6nm
CNT diameter	0.78nm	Gate Dielectric(HfO_2)	15

Using Landauer's formula [21], conductance can be represented by

$$G = \frac{2Te^2}{h}$$

(2)

Where e 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

$$T = \text{trace } [\Gamma_S \, G_0^r \, \Gamma_D \, G_0^a]$$

(3)

$G_0^r \, G_0^a$ 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. Finally the current is found using the Landauer Bouttiker expression

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

(4)

T is the transmission probability across the source/drain; f_S and f_d are the source/drain Fermi-Dirac distribution functions consistent potential.

V.   SIMULATIONS

Hafnia (HfO_2) adopts the same structure as zirconia (ZrO_2, K=~25). Unlike TiO_2(k=40), which features six-coordinate Titanium in all phases, zirconia and HfO_2 consists of seven-coordinate metal centers[22]. Hafnium-based oxides were introduced by Intel in 2007 as a replacement for silicon oxide as a gate insulator in field-effect transistors [23].We simulate the I-V Characteristics of CNTFET using HfO_2 as gate insulator for proposed model. The drain current reaches around 60.1µA at the gate voltage of 1V (drain voltage fixed to 1V).At a gate voltage of 1.5V drain current reaches around 112 µA. So the high-K gate insulator and bigger CNT diameter allows higher drain current.
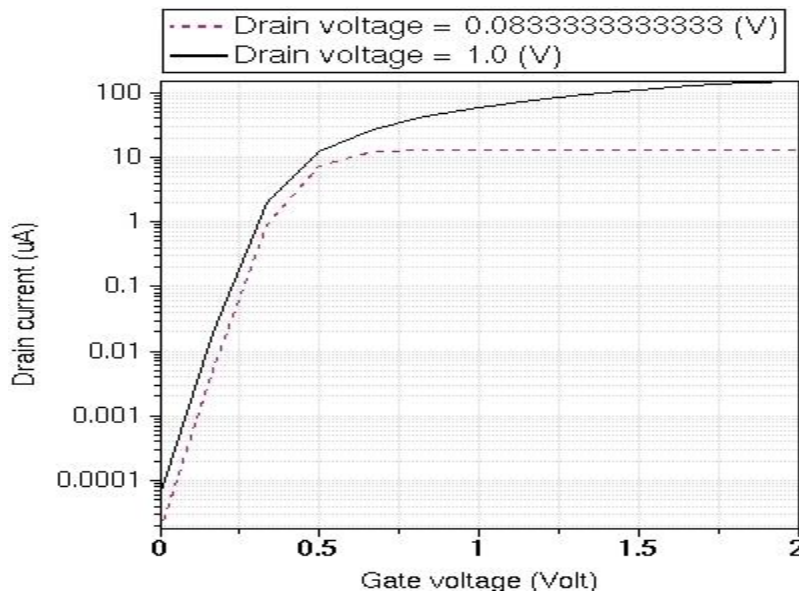

Figure 4: I-V Characteristics of proposed CNTFET (solid black line)

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 .78nm diameter, with different drain voltage (figure 5,6). 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.
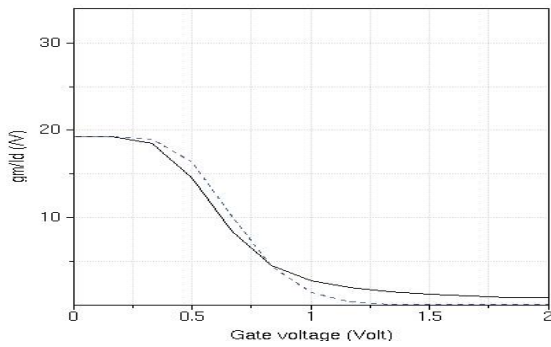
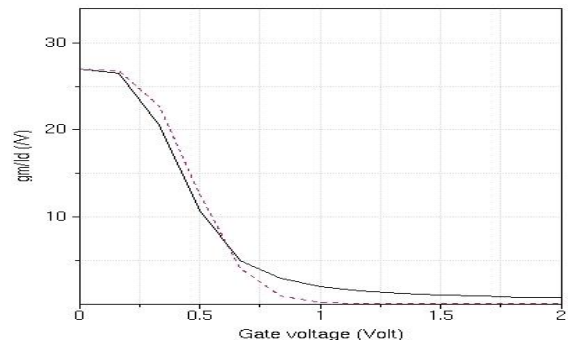Figure 5: Transconductance of CNTFET (V_D=0.5V)

Figure 6: Transconductance of CNTFET (V_D=0.7V)

Figure 6 shows the output characteristics of the proposed CNTFET. The channel allows the current to flow when the gate voltage is greater than 0.3V.So the on current is 154µA at V_g=2.0V and V_d=1.0V, and the off current is 6.61e-05 µA at V_g=0V and V_d=1.0V.Figure 7 shows average velocity versus the gate voltage at saturation. The average velocity starts decreases around 1.8V of gate voltage.
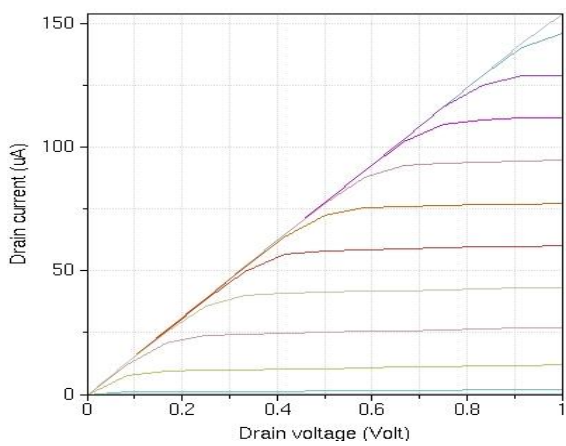

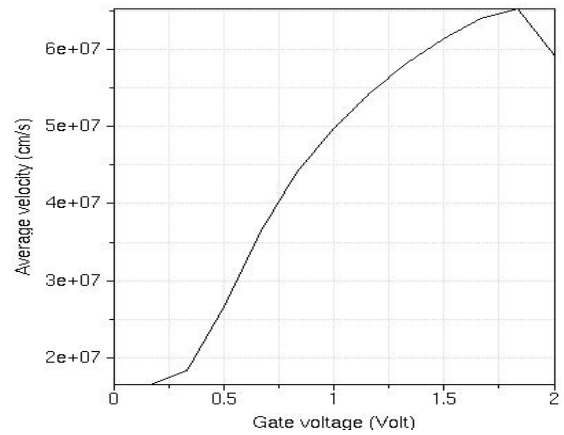Figure 6: I_d Vs V_d Curve at different V_g

Figure 7: Avg. Velocity Vs Gate voltage

Figure 8 shows the mobile charge behavior as a function of gate voltage. 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 0.5 or 1.75 volt (for proposed model).
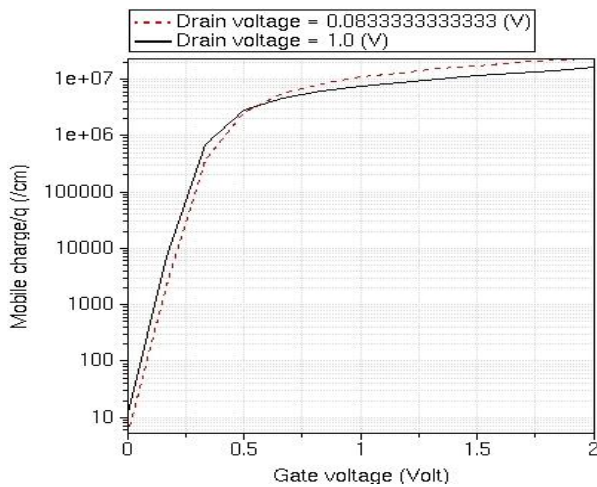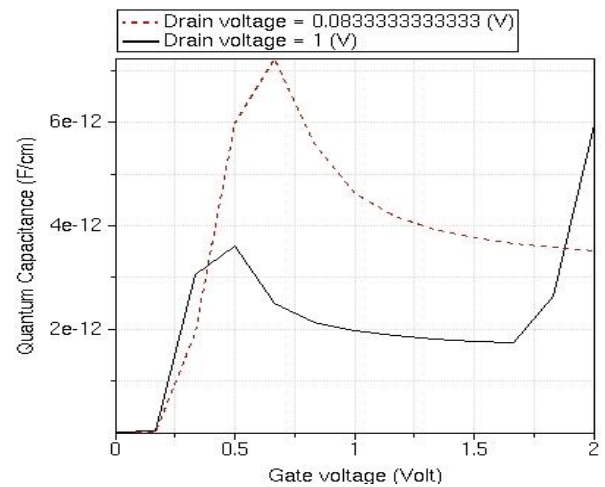

Figure 8: Mobile charge behavior

Figure 9: Quantum capacitance versus the gate voltage

VI. CONCLUSION

The proposed parameters and gate dielectric of CNTFET make the transistor a challenge to develop and to control the aspects of it such as maximum transconductance. We found two regions for maximum transconductance. Hafnia is used in optical coatings, and as a high-κ dielectric in DRAM capacitors and in advanced metal-oxide semiconductor devices. The advantage for proposed CNTFET is its high dielectric constant: the dielectric constant of HfO_2 is 4–6 times higher than that of SiO_2. In recent years, hafnium oxide (as well as doped and oxygen-deficient hafnium oxide) attracts additional interest as a possible candidate for resistive-switching memories [24].

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