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Structure and a Detailed Analysis of Various Simulation Results of CNTFET: A Review

[1]Himanshu Gautam, [2]Prateek Bindra
ITM University, Gurgaon, Haryana
[1]himanshugautam1908@gmail.com, [2]prateekbindra@itmindia.edu

Abstract: A detailed review on the Carbon Nanotube Filed Effect Transistors (CNTFETs) has been given. A little description about what are carbon nanotubes is also been covered. Various simulation results have also been included in this paper in order to provide better understanding about the carbon nanotubes field effect transistors.Characteristic Graphs of a C-CNTFET with n=10. m=11 (diameter=1.4246 nm) have been studied. Threshold voltage of CNTFETs vs n (for m=0) is also simulated. Equivalent high-frequency small-signal circuit model for a Nanotube transistor has also been analyzed. Also current voltage relationship of the CNTFET with respect to gate oxide thickness and dielectric constant has been analyzed.

Keywords –chirality. CNTFETs, graphene, HSPICE, MOSFETs, Nano-ribbon, quantum capacitance.

Introduction

Technological advancement means reducing the size of devices. MOSFETs have technology sizes less than 30nm. These devices with such less size are commonly available in the market now. But when we think to shrink their sizes more and more, it becomes a bit difficult task. We confront problems related to fabrication technology and device performance. So in order to tackle this problem, many solutions have been proposed by experts all over the world.

One such solution is carbon nanotube field effect transistors. A carbon Nanotube filed effect transistor does not have a channel made of silicon, but instead it has a Carbon Nanotube (which could be single nanotube or a nanotube array). Nanotubes are inert in nature (chemically) and could transport very high electric current.

Now let us focus a little on carbon nanotube. These are grapheme strips rolled up into tubular shapes. There are Single Walled Carbon Nanotube (SWCNT) and Multi Walled Carbon Nanotube (MWCNT).

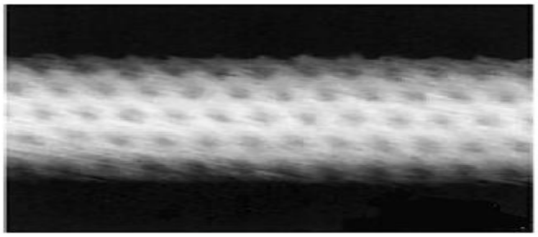


Figure 1: Microscopic Image of a carbon nanotube [7]

Chirality of a CNT is the angle difference between the graphene strip's orientation and the axis of the resulting nanotube.Chirality of the CNTs affects their semiconducting behavior.

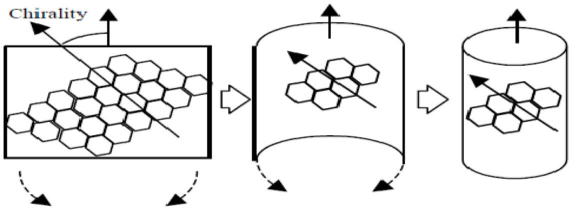


Figure 2: Chirality of a CNTFET [7]

The expression used for bandgap energy [15] is:

$$E_{gap} = 2 Y_{o\ c-c} / d \quad (1)$$

where E_{gap} is the bandgap, γ_o is the carbon to carbon distance and d is the diameter of the nanotube. As the diameter of the nanotube becomes larger, its band-gap becomes smaller and conduction of the carbon nanotube increases. Scattering caused by defects and lattice vibrations that lead to resistance effect the electrical transport inside the CNTs.

The Carbon Nanotube Field Effect Transistor have several advantages [5] like they have high ratio of on current to off current, their threshold voltage is also superior, they also have a higher value of transconductance, low power devise could also be built with them and they could even be used to build low-resistance high strength interconnections.

The carbon nanotubes have diameters ranging from less than 1 nm to 50 nm. These carbon fibers have excellent mechanical and transport properties. The table shown below describes its properties. [16]

Table 1: Properties of the carbon nanotubes

Specific Density	1.3-2
E (TPa)	1
Strength (GPa)	10-60
Strain at Break (%)	10
Thermal Conductivity (W/mk)	>3000
Electrical Conductivity (mho/m)	10^6-10^7

The diameter (dcnt) and threshold voltage (V_{th})[5] for a SWCNT could be given as follows:

$$dcnt = \{3^{0.5} a_0 (n^2 + m^2 + nm)^{0.5}\} / (3 e*dcnt) \qquad (2)$$

$$V_{th} = E_g / 2c = (3^{0.5}\ a\ V_{\pi}) / 3\ e * dcnt \qquad (3)$$

where m, n are chiral vectors. E_g is bandgap.

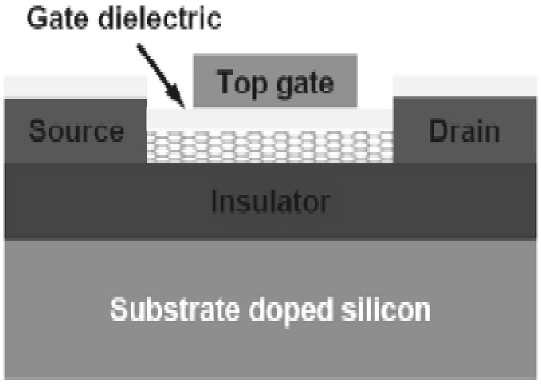


Figure 3: A 2-D schematic of a CNFET.

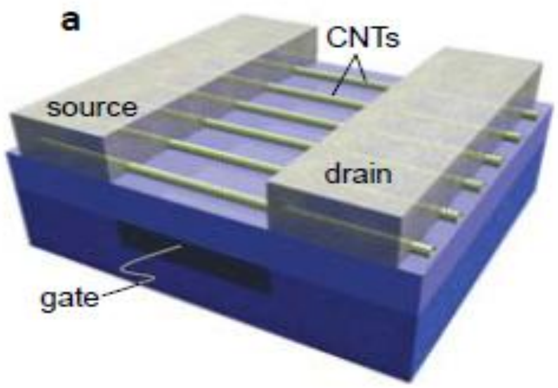
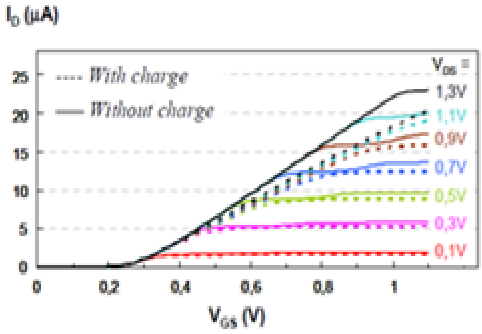


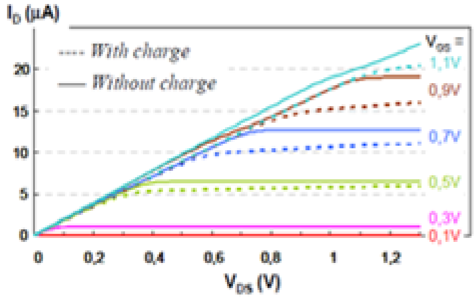
Figure 4: Schematic of a CNTFET with multiple CNTs as parallel channels [14] [2]

Drain Current Analysis

A high K dielectric conventional CNTFET is being taken and its simulation has been done in order to get its output and transfer characteristics.



(a)



(b)

Figure 5: Characteristic Graphs of a C-CNTFET with n=10. m=11 (diameter=1.4246 nm) [1]

(a): Drain current vs gate bias with drain bias as a parameter.
(b): Drain current vs source-drain bias with gate bias as a parameter.
Our drain current also varies with channel length. This could be seen in the graph given below where we have observed drain (saturation) current for various values of channel length. Here this observation is made for various values of gate voltages. This is clearly visible from the graph that with increase in gate voltage the saturation current is also increasing.

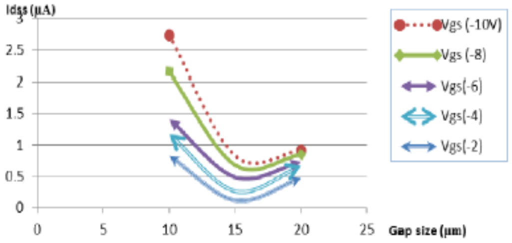


Figure 6: Variation of saturation current due to channel length [18]

Threshold Voltage Analysis

The threshold voltage of a CNTFET can be changed by varying its diameter while for CMOS requires adjustments for each MOSFET in order to attain different threshold voltages [10]. Simulations have been done to obtain the values of the threshold voltage at various chirality vectors [7].

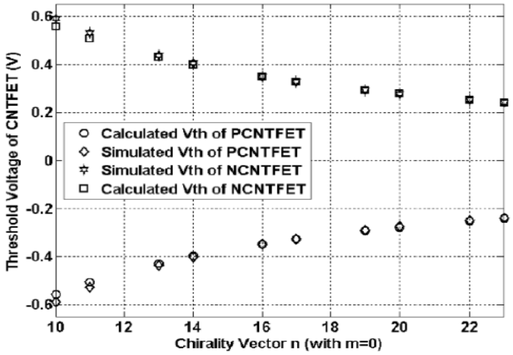


Figure 7: Threshold voltage of CNTFETs vs n (for m=0) [7].

If we consider both the chiral vectors (i.e. m and n) then after several simulations on HSPICE we could observe decrease in the value of threshold voltage as we increase the value of the chiral vector.

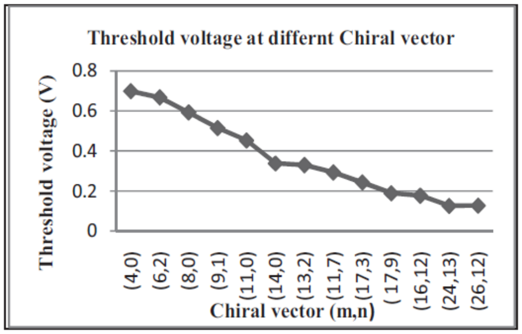


Figure 8: Threshold voltage versus chiral vector (m,n). [17]

Effect of Temperature on Threshold Voltage

This threshold voltage of CNTFET is also almost temperature independent. This could be concluded from the table shown below. Here in this table, a CNTFET has been observed for both positive and negative values of temperature. [17]

Table 2: Effect of Temperature on CNTFET

Temperature (°C)	Threshold Voltage (V)
-10	0.221
-20	0.229
-30	0.238
-40	0.243
-50	0.249
-60	0.256
27	0.210
47	0.210
67	0.210
87	0.210
107	0.202
127	0.198
147	0.194
167	0.191
187	0.187
207	0.180
227	0.164

HF Small Signal Circuit Model of CNTFET

An equivalent high-frequency small-signal circuit model for a nanotube transistor has been developed and shown below [11].

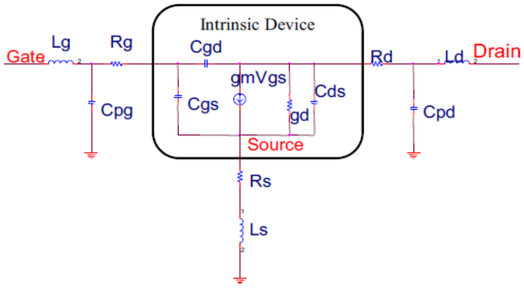


Figure 9: Equivalent high-frequency small-signal circuit model for a Nanotube transistor [11].

The behavior of a CNT field effect transistor could be optimized by using covalent functionalization. By covalent functionalization we mean to convert sp2-bonds to sp3-bonds which results in a reorganization of the remaining π-electron system. This results in a change of the electronic band structure including a change in the band gap and band curvature [6].

Gate Current Dependence on Gate Oxide and Dielectric Constant

Now we would observe the current-voltage characteristics of the CNTFETs while considering the effect on it because of oxide thickness and dielectric constant. We have considered non-ballistic conduction in both the cases. It has been realized that gate oxide thickness has maintained an inverse relationship with the drain current [12] while dielectric constant has maintained a positive relationship with the drain current [13].

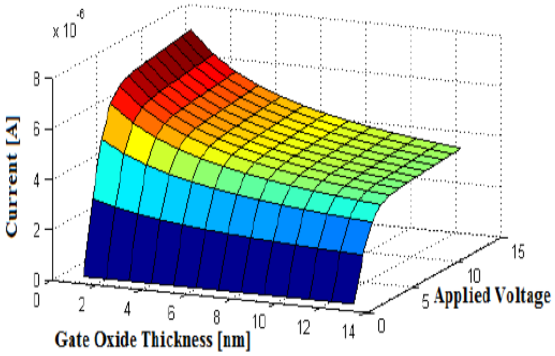


Figure 10: A 3-D view of CV relationship wrt gate oxide thickness [12].

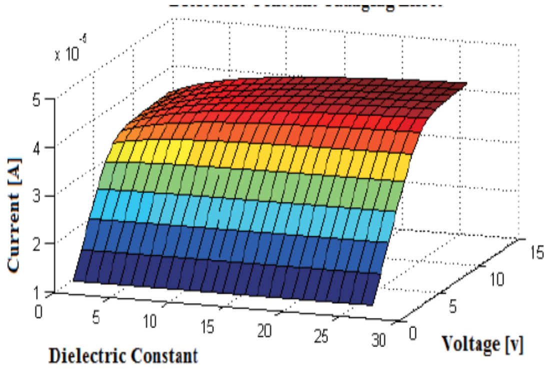


Figure 11: A 3-D view of CV relationship wrt dielectric constant [13].

Quantum Capacitance dependence on Gate Voltage for various Oxide Thicknesses

Above we have seen the current voltage characteristics of the CNFET with respect to the gate oxide thickness. Now we would observe how for various gate oxide thicknesses our quantum capacitance of the CNFET varies, which clearly shows a decreasing pattern. In case of MOSFET it increases.

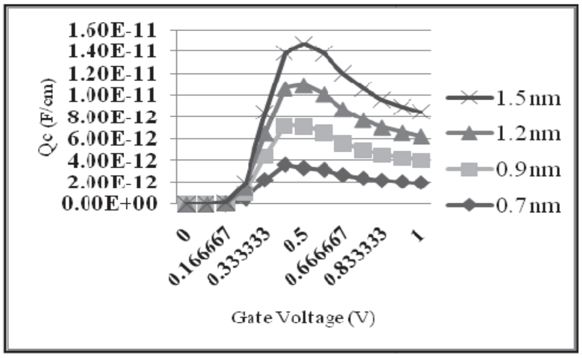


Figure 12: Quantum Capacitance versus gate voltage for various oxide thicknesses for a CNTFET [17]

Even ternary logic gates have been proposed using carbon nanotube field effect transistors [8]. This technique provides an excellent speed and low power consumption characteristics. In various realistic circuit applications, more than 90% of power reduction could be achieved with the use of these proposed ternary gates [8].

Conclusion

After doing a review on CNTFETs, it is clear that these could certainly be considered as future devices in place of silicon based MOSFETs. There are certain disadvantages of them like the carbon nanotube degrades when exposed to oxygen, issues related to reliability and difficulty in mass production. One possible solution to the problem of degradation of the carbon nanotube on exposure to the oxygen is that it could be coated with a certain material which repels oxygen. This would enhance the lifetime of CNTFETs from few days to a lifelong time. We could also increase its reliability by making it functional at high electric field and temperature gradients. Once these issues are resolved they would certainly become the back-bone of the electronics industry.

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