

# Analysis of the Operational Characteristics of CNTFET

Akshay Verma<sup>1</sup>, Harshul Gupta<sup>2</sup>, Nitin Chaturvedi<sup>3</sup>

<sup>1,2,3</sup>Birla Institute of Technology and Science, Pilani, Rajasthan, India

**Abstract:** Since the last few decades the silicon- based technology has escalated remarkably. The reason behind the exceptional advancement of the CMOS devices is acknowledged due to its potential of being scaled down to increasingly compact sizes. However, the excessive scaling of CMOS devices to the Nano ranges have resulted in several non-idealities affecting the I/V characteristics and increased short channel effects thereby not only affecting the reliability of the device but also its performance expectations. For this reason, the semiconductor industry is seeking out for incorporating different materials and devices with the current silicon-based technology which in the long run, could possibly substitute it. Recent studies in the field of Nano technology and Nano electronics have led to an increased emphasis on Carbon Nanotube Field Effect Transistor (CNTFET) as a suitable replacement for the current CMOS technology for designing the circuits. This paper gives an insight to the advantages and the operational characteristics of the CNTFET devices as compared to the existing CMOS technology.

**Keywords:** Chirality, CNT, CNTFET, I-V characteristics, Number of tubes, Threshold Voltage.

## Introduction

Aggressive scaling of CMOS technology has resulted into increased shorts channels effects which includes rise in leakage current and surface scattering, high power density and a lesser gate control. Some of these constraints can be overcome up to a certain range and can also help in facilitating the scaling down of device size by using a different material for the channel instead of using the Si. Therefore the Field Effect transistors using Carbon Nano Tubes (CNT) as a substitute for the Si as a channel material is getting more and more significance these days because of their improved I/V characteristics and higher electron mobility.

To ensure the efficient performance of CNTFETs as an important constituent of Nanoelectronic devices optimized size and chirality factor (n, m) values are needed to be determined. The traditional CMOS technology starts showing certain limitations if the scaling goes down below 60nm.

In this paper, we use Stanford University Model of the CNTFET, replacing Si as the channel material of the FET with Carbon Nano Tubes (CNT) and also compare and evaluate the effect of physical properties of CNTFET like number of tubes and chirality factor on its electrical properties. We also determined the I/V characteristics of CNTFET. Finally, we compared the projected performance of a silicon MOSFET with a carbon nanotubes based FET.

## Carbon NanoTube

Carbon nanotubes (CNTs) are allotropes of carbon that belong to the fullerene structural family. They have a cylindrical Nano structure with their walls made up of graphene. The metallic or semiconducting nature of the carbon Nano tube (CNT) depends upon its chiral angle (roll-up vector or chirality vector).

Considering the indices (n, m) the tube may be metallic if:

$$n = m \text{ or } n-m = 3I$$

Where I is an integer, or is semiconducting otherwise.

The diameter of an ideal nanotube can be calculated from its (n, m) indices as follows:

$$D_{\text{CNT}} = \frac{a\sqrt{3(n^2 + m^2 + nm)}}{\pi}$$

Where a = 0.142 nm, is the interatomic distance between carbon atom and its neighbour.

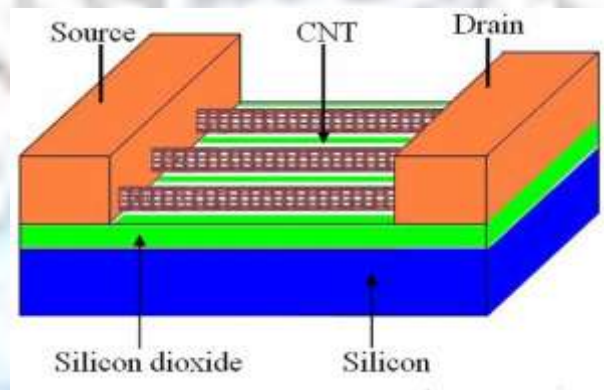
The chiral angle  $\theta$  is given by:

$$\theta = \tan^{-1}(\sqrt{3}\frac{n}{2m+n})$$

The chirality and diameter of carbon nanotubes directly affects its band-gap. Since only forward and back scattering is allowed in carbon nanotubes the mean free path travelled by electrons is long (in order of micrometers). Because of which, CNT shows quasi ballistic transport even at relatively low electric field and long lengths. The inert nature of carbon nanotubes because of its  $sp^2$  hybrid configuration which leads to an increase in its current carrying capacity.

### Carbon Nanotube Field Effect Transistor

Carbon nanotubes Field effect transistors are the kind of FETs that instead of using silicon as the semiconducting channel use carbon nanotube. The electrical properties of the carbon nanotubes mentioned above makes it a suitable candidate for the replacement of existing technology. As the technology advances demand for reducing the supply voltage increases in the field of VLSI designing thereby increasing the demand for low power and low voltage consuming devices. So, it is necessary to develop some new structures for the various integrated circuits available. The high output impedance and low threshold voltage of the CNTFET increases the importance of replacing the MOSFET with CNTFET for making these devices.



The threshold voltage of CNT channel is approximately equal to the half of the band-gap and varies inversely with diameter.

$$V_{th} = E_g/2e = a \frac{V\pi}{\sqrt{3} e D_{cnt}}$$

Where  $a=2.49 \text{ \AA}$  is the carbon to carbon atom distance and  $V_\pi = 3.033 \text{ eV}$  is carbon  $\pi$ - $\pi$  bond energy.

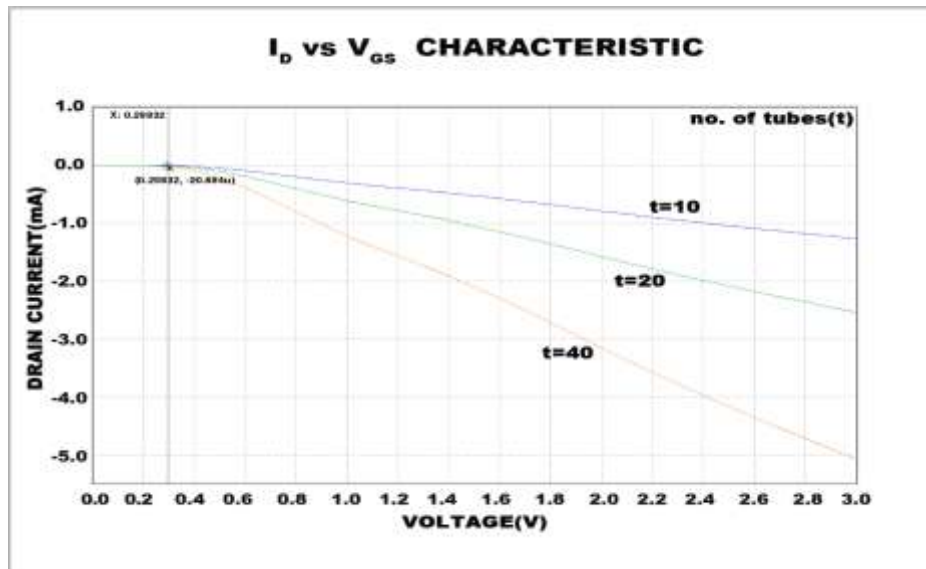
Since the potential of the Carbon Nanotubes as a replacement for the silicon has been identified, efforts are being made to further optimize and improve the efficiency and the feasibility of these devices. Several methods have been devised for achieving this. Some of these are listed below:

- Reduction in the contact resistance between CNTs and metal electrodes: When the CNTs come in contact with the metal electrodes weak Van Der Waals forces start interacting between them causing an increase in the contact resistance. In order to reduce it the devices are fabricated by annealing at a high temperature of around  $800^\circ\text{C}$ .
- Escalation in the tuning efficiency of gate voltage to CNT channels: This can be achieved by using the top-gate structure, decreasing the thickness of gate insulator and by adopting the high-k gate insulator.
- Reducing the length of the CNT channel: As the length of the channel increases the scattering of the carrier particles also increases thereby reducing their mobility. Therefore the length of the channel should be small.

### Simulation Results

We used HSPICE to obtain the operational characteristics of the CNTFET at different device parameters. We used Stanford University CNTFET Model Package v221. This model has a minimum possible channel length of 10nm and a width of 4nm. For simulating the MOSFET circuits we used TSMC SPICE MODELBSIM3 (V3.2) with the minimum channel length of 32nm.

The following graph shows the effect of variation in the number CNTs in a NCNTFET on its I/V characteristics.



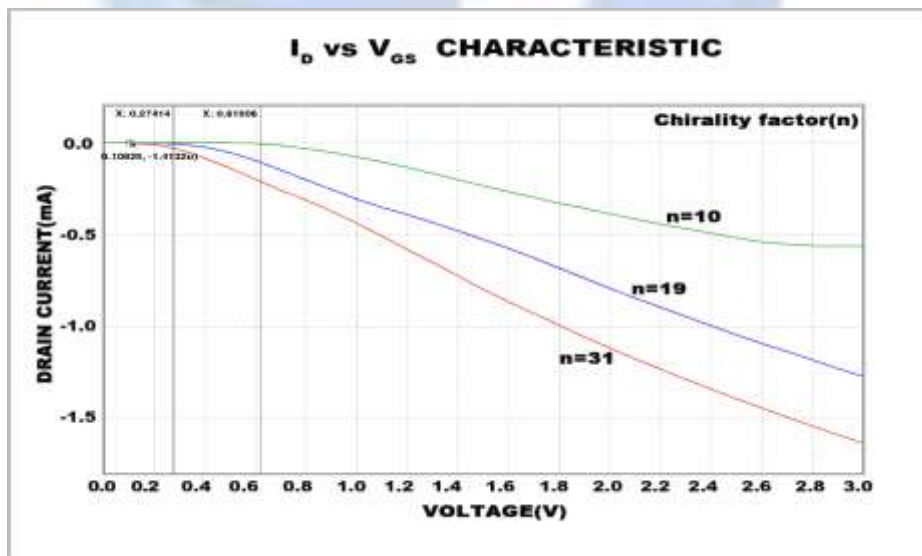
The above graph shows that as the number of tubes increases in a CNTFET:

- The drain current( $I_D$ ) also increases
- The threshold voltage approximately remains the same

As the number of Carbon Nano Tubes connected between source and drain increases, the area available for the electrons to move from source to drain also increases thereby increasing the channel current. However since the voltage across each of the tube is same there is not much change in the value of threshold voltage.

$$I_D \propto \text{number of tubes}$$

The following graph shows the effect of the variation in the chirality factor ( $n, m$ ) in a NCNTFET on its  $I/V$  characteristics



The above graph shows that as the chirality factor increases in a CNTFET

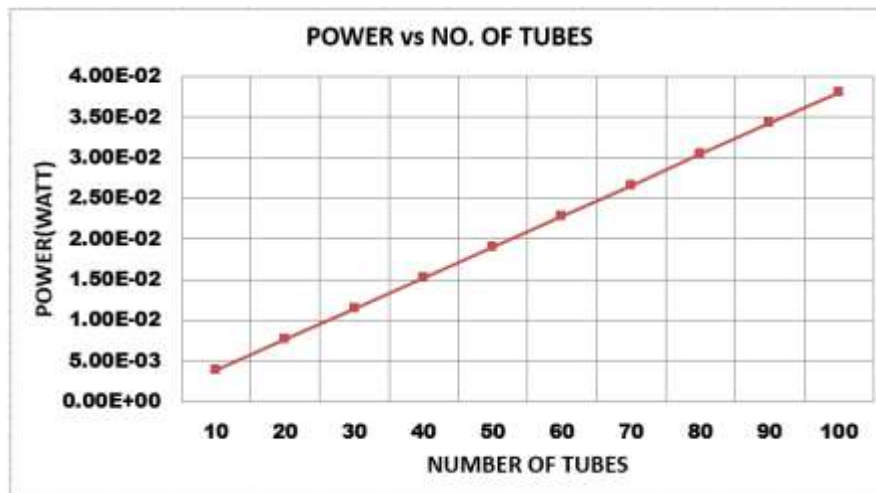
- The drain current( $I_D$ ) also increases
- The threshold voltage ( $V_{th}$ ) decreases

We have seen above that the chirality vector of the Carbon Nanotube is directly proportional to its diameter ( $D_{CNT}$ ). So as we increase the chirality vector it leads to an increase in the tube diameter which in turn increases the area available for the flow of electrons from source to drain thereby increasing the channel current and since the threshold voltage is inversely proportional to diameter of the CNT, it decreases with an increase in chirality vector.

$$I_d \propto \text{chirality factor}$$

$$V_{th} \propto 1/\text{chirality factor}$$

The following graph demonstrates the relationship between the power consumption in a NCNTFET vs the number of tubes present in it.



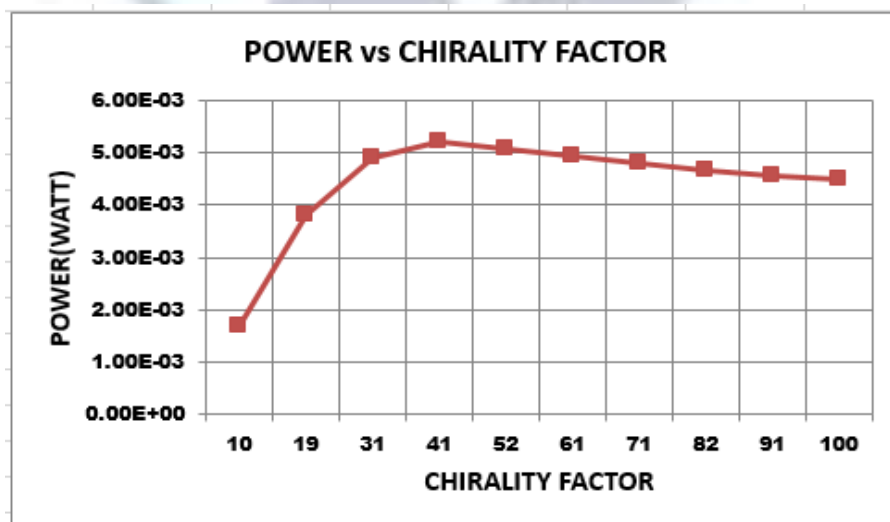
The above graph shows that :

- As the number of CNTs used to make the channel of a CNTFET increases the power dissipation also increases.
- The power increases approximately linearly with increases in the number of CNTs in a CNTFET.

As mentioned above, the increase in the number of the CNTs leads to an increase in the amount of the current flowing in the circuit thereby increasing the net power consumption.

$$\text{Power} \propto \text{number of tubes}$$

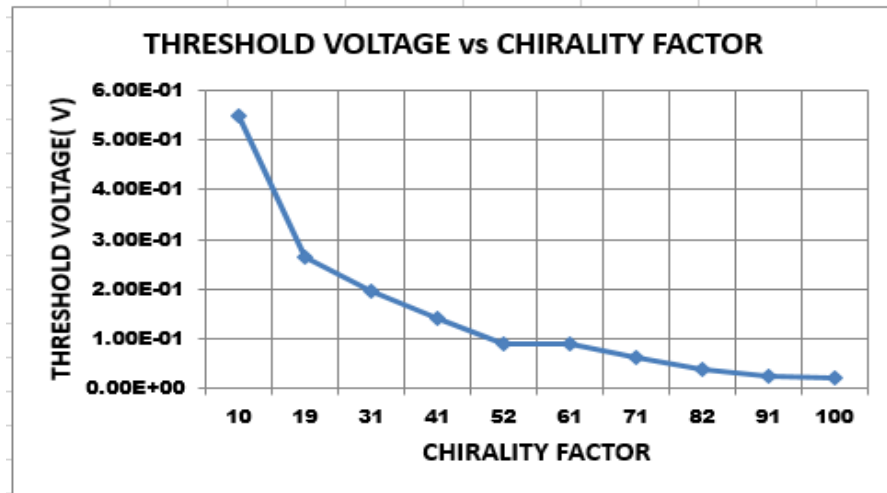
The following graph shows the dependence of the power dissipation of a NCNTFET on its chirality factor



The above graph shows that:

- The power dissipation of a CNTFET increases upto a certain value of its chirality factor, post which it starts decreasing and approximately becomes constant.

The following graph shows the dependence of the threshold voltage( $V_{th}$ ) of a NCNTFET on its chirality factor

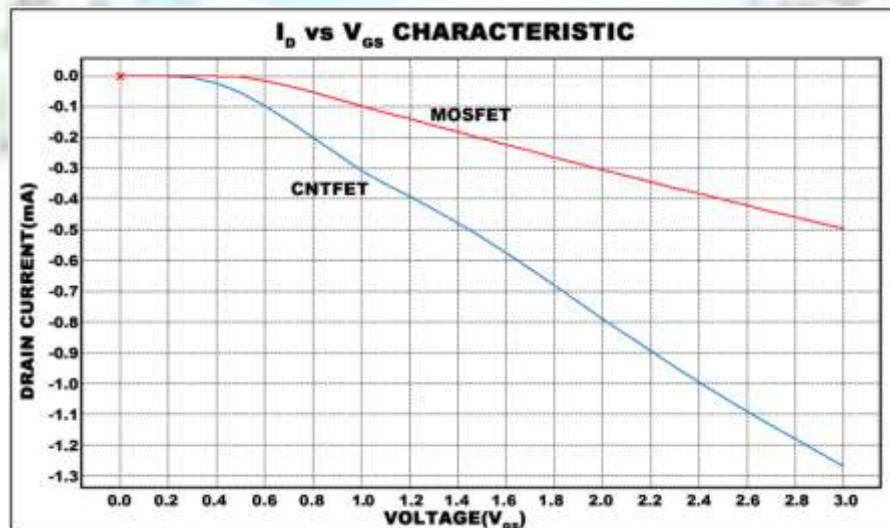


The above graph shows that:

- As the chirality factor increases the Threshold Voltage( $V_{th}$ ) decreases.
- The rate of declination of the Threshold Voltage ( $V_{th}$ ) decreases as the Chirality factor increases.

$$V_{th} \propto 1/\text{Chirality Factor}$$

The following graph shows the comparision between the I/V characteristics of the MOSFET and the CNTFET.



The above graph shows that:

- The Current flowing through the CNTFET is more than that in MOSFET for the same value of the voltage applied.
- The Threshold Voltage( $V_{th}$ ) of the MOSFET is higher than that of the CNTFET for the same input condions applied.
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$$I_{CNTFET} > I_{MOSFET}$$

$$V_{th}(\text{CNTFET}) < V_{th}(\text{MOSFET})$$

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### Conclusion

This paper gives an overview about the basics of the Carbon Nanotube Field Effect Transistor (CNTFET) followed by the advantages it offers in contrast to the existing CMOS technology. Although the industrial application of the CNTFETs has not been recognized because of the issues related to its design and fabrication, the theoretical and the experimental results have shown its good future in the semiconductor market. From the graph showing the variation of the power dissipation in a CNTFET with the number of tubes, we can make out that power dissipation increases by approximately 0.38mW for every unity increase in the number of tubes used to make the channel. The simulation results shows the Threshold Voltage ( $V_{th}$ ) of the CNTFET is about 43% less than that of a MOSFET whereas the current is about 2.7% more than that of the MOSFET.

The unwanted growth of the metallic tubes during the fabrication of the CNTs is holding CNTFETs from overpowering MOSFETs in the semiconductor market. However efforts are being carried out in this field so that CNTFETs successfully overpowers the existing CMOS technology.

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