Science Arena Publications
Specialty Journal of Electronic and Computer Sciences
ISSN: 2412-7485
Available online at www.sciarena.com
2019, Vol, 5 (2): 53-57

A Review of the Carbon Nanotube Field Effect Transistors

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Abstract: *Field Effect Transistors based on Carbon Nanotube (CNTFET) are promising Nano-scaled devices for implementing high performance very dense and low power circuits. A CNTFET refers to a FET that utilizes a single CNT or an array of CNT's as the channel material instead of bulk silicon in the traditional MOSFET structure. In this paper, the review of CNTFETs is presented. The structure, operation and the characteristics of different types of CNTFET's have been discussed. The operation, dc characteristics of CNTFETs have been presented and analysis of the performance of various characteristics.*

Keywords: *Field Effect Transistor, Carbon Nanotube, Source-Drain Current.*

INTRODUCTION

Silicon technology has experienced tremendous growth over the past few decades. The larger part of the success of the MOS transistor is due to the fact that they are scaled up with a much smaller dimension that results in high performance. For this reason, the semiconductor industry has recently been looking for different materials and tools to integrate with silicon technology, which is a carbon nanotube field effect transistor due to its superior electrical characteristics as a more successful option. The first CNTFET was created in 1998. In the same year, Ermarttel and his colleagues constructed field effect thyristors based on multi-wall and single-walled carbon nanotubes and analyzed their performance. Some of the advantages of CNTFETs include:

- One-dimensional carbon nanotube, which greatly reduces the probability of dispersion, and works in a ballistic environment.
- Nanotubes necessarily conduct conduction at its outer surface. Where all chemical bonds are saturated and stable. In other words, there are no Dangling bonds that create interconnect modes.
- Shakti barrier in Connection Nanotube- Metal is an active keying element in an intrinsic nanotube device.

Several research works have been reported regarding to the use of carbon nanotubes for the detection of biomolecules, … (Pantarotto et al., 2003; O'Connor et al., 2004). The detection mechanism is mainly based on the antigen-antibody interaction. SWCNTs have all their carbon atoms at the surface; therefore, they trend to interact with other compounds including proteins. This article first examines different types of CNTFETs, one of the successful tools for replacing Si-MOSFET in the near future, which is organized as follows. Section 2 describes the methods of Synthesis of carbon nanotubes. Advantages of carbon nanotubes and Type of CNT discussed in Sections 3 & 4. Devices based on Carbon Nanotube Field effect transistors and CNTFET types are discussed in Section 5. CHARCTERISTICS OF CNTFETs in section 6 & a brief comparison between Si-MOSFET and CNTFET in Section 7 presents and finally concludes with the conclusion.

Synthesis of carbon nanotubes

Three methods are usually employed to synthesize CNTs. They involve arch-discharge, laser ablation and chemical vapor deposition (CVD). CVD method employs a carbon source (carbon monoxide, acetylene, methane, etc) which is decomposed in an oven by heating at temperatures in the range of 500 to 1100º. The carbon released by the decomposition of the gas, is deposited onto the surface of the catalyst particles (usually Ni, Fe and Co) which act as seeds to nucleate the growth of CNT. Depending on the operating conditions (temperature, catalyst, flow rate of gases, size of the particles) SWCNTs or MWCNTs can be obtained. Usually, SWCNTs are synthesized at higher temperatures (800-1100 ºC) than MWCNTs. CVD allows continuous fabrication, and may be the most favorable method for scale up and production (Poole, C.P. and Owens, F.J. 2003). Nevertheless, the control of the size of the catalyst particles in order to produce tubes with high purity and low diameter is still a challenge.

Advantages of carbon nanotubes

- Biocompatible, Non-biodegradable and non-immunogenic nature.
- Highly elastic nature and have the possibility of intracellular delivery.
- May exhibit minimum cytotoxicity.
- Ultra-light weight and do not break down during processing.
- CNTs are able to enter cells by spontaneous mechanism due to its tubular and Nano needle shape.

Type of CNT

The carbon nanotubes are of two types namely:

- Single walled carbon nanotubes (SWCNTs)
- Multiple walled carbon nanotubes (MWCNTs)

- **Single-wall carbon nanotubes (SWCNTs)**

CNTs, discovered by Iijima, S. can be described as a graphene sheet rolled up into a nanoscale-tube. A single sheet generates single-walled carbon nanotubes (SWCNTs). SWCNTs have a minimum diameter of about 0.4 nm to 2 nm and lengths up to 1.5 cm have been reported. The atomic structure of a SWCNT is conventionally described by a pair of integers (n,m) denoting the relative position $C_h = n a1 + m a2$ of the pair of atoms on a graphene strip which, when rolled onto each other, form a tube (a1 and a2 are unit vectors of the hexagonal honeycomb lattice). The chiral vector C_h uniquely defines a particular (n,m) tube, as well as its chiral angle (Θ), which is the angle between C_h and a1. It can vary between 0 and 30º, which allow obtaining three possible configurations of CNTs. Armchair nanotubes formed when n = m and the chiral angle is 30°. Zigzag nanotubes formed when either n or m is zero and the chiral angle is 0°. All other nanotubes, with chiral angles intermediate between 0° and 30°, are known as chiral nanotubes. A few published reports on measurements of the SWCNTs show that the armchair tubes are metallic, the zigzag tubes are semiconducting and chiral tubes are semiconducting or metallic, depending on the diameter of the tube and on the wrapping angle. Both, diameter of the tube and the wrapping angle at the same time depend on the indices n and m. In general, if $n - m = 3q$, where q is an integer, the nanotube is metallic, whereas for $n - m \neq 3q$ it is semiconducting.

- **Multiple walled carbon nanotubes (MWCNTs)**

MWCNTs consist of several coaxial cylinders, each made of a single grapheme sheet surrounding a hollow core. MWCNTs have diameters from 10 to 200 nm and lengths up to hundreds of microns with an adjacent shell separation of 0.34 nm. They usually display a metallic character. The images of the SWCNT and MWCNT are shown in Figure 1.

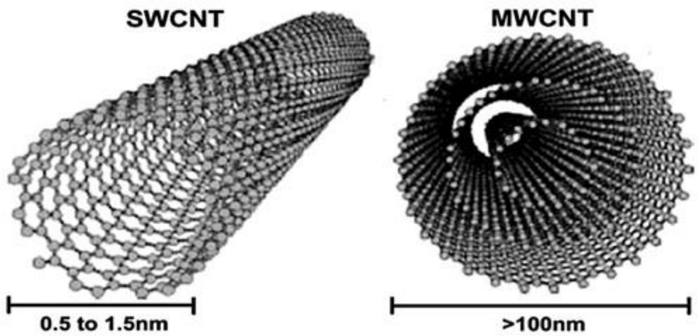

Fig 1. The imagesof the SWCNT and MWCNT.

Devices based on Carbon Nanotube Field effect transistors (CNTFETs)

The development of CNTFETs was independently reported by the Avouris group at IBM (Martel et al., 1998) in 1998. They are electronic devices that use CNTs as conducting channels and display high sensitivity towards local chemical environments (Kauffman and Star, 2008). The structure of a FET consists of two metal electrodes called source and drain connected to the conducting channel. Moreover, a third electrode called gate is often used. The gate can be used to electrostatically induce charges onto the tube. In semiconducting CNTs, a negative bias on the gate induces positive charges (holes) and a positive bias induces negative charges (electrons). Based on the conducting channel two types of CNTFETs can be obtained. The first one is based on a single wall carbon nanotube (back gate CNTFET), as shown in Figure 2. The back gate controls the amount of charge in the channel through a vertical electric field that induces electrons or holes in the nanotubes. The second type is based on a network of CNTs in which the device operation depends on the density of the nanotubes. Although they are less sensitive than FETs based on a single nanotube, offer better reproducibility and manufacturability (Gruner, 2006). In these devices each CNT has its own threshold voltage and on–off ratio due to natural variations in CNT synthesis. Thus, the electronic characteristics of the devices depend on the sum of individual CNT thresholds and on–off ratios. CNTFETs can be operated in two gate configurations. The first one, involve CNTFETs back-gated.In this configuration the capacitor is a SiO2 layer located between the ***n*** or ***p*** doped Si substrate and the CNTs. The carbon nanotubes are connected to the source and drain electrodes. The third electrode "gate" is the so-called back-gate electrode since it is placed at the back of the device producing the final structure of a transistor. The second type of configuration include CNTFETs electrolyte gated. These CNTFETs behaved as p-type FETs with an I (on)/I (off) ratio~10^5. The second type of configuration include CNTFETs electrolyte gated. In this configuration a reference electrode (usually Pt) is placed in contact with a solution containing the analyte which at the same time is in contact with the SWCNTs. The electrostatic potential difference between the solution and the CNTs is controlled through a gate voltage and the potential at the metal-liquid interface.

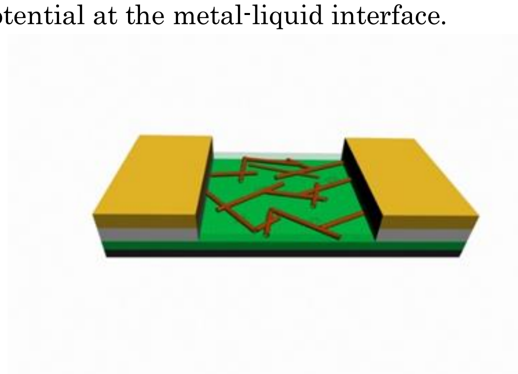

Fig 2. The shematic of the Back gate Field effect transistor.

CHARCTERISTICS OF CNTFET's

Bipolar property in the CNTFET structure means the passing of current by electrons in a range of gate voltage and by holes in another range of gate voltage (Kim et al., 2003). Figure 3 shows bipolar conductance in Back gate CNTFET with W=120, L=8 μm and 0.1 V drain source voltage. It means that by increasing source gate voltage from minus amount to about half of drain source voltage, the role of hole carriers in conducting the current decreases gradually, and by increasing voltage to more than half of drain source voltage, electrons function as major carriers in transmission of current (Masoumi et al., 2016).

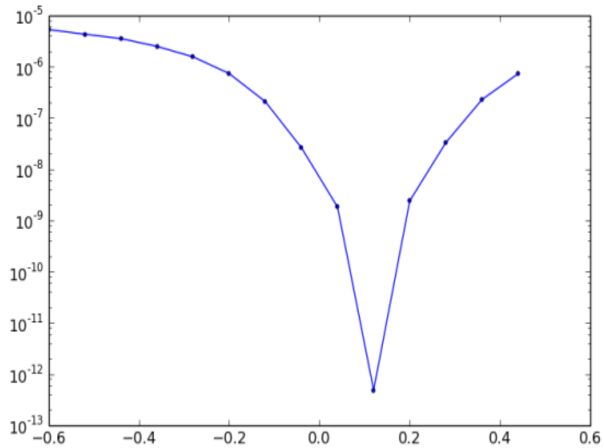

Fig 3. The transfer characteristics of a transistor with a width of 6 μm.

The drain I-V characteristics in back gate cntfet with chirality vector (16, 0), 20 nm channel length, 4 nm gate oxide thickness, insulated electrical insulation resistance of 3.9, 0 <V_DS < 0.5 V, and V_G = 0.5 V as shown in Fig 4. The saturation current at VGS = 0.5 V is around 1.6 μA.

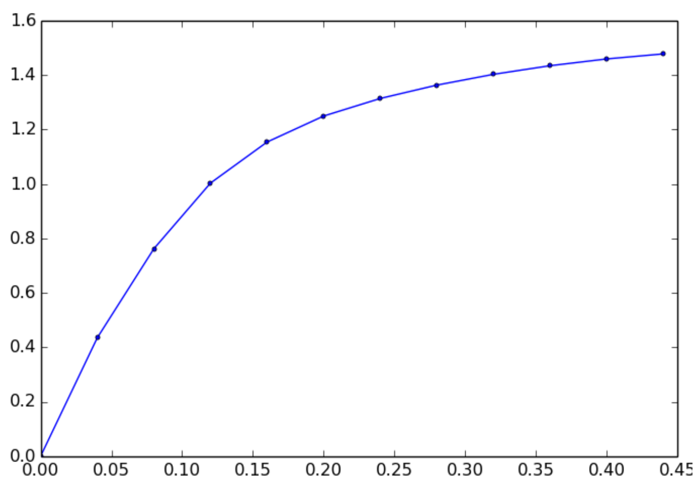

Fig 4. Drain current-voltage characteristics of back gate CNTFET.

Drain I-V characteristics exhibited dependence of saturation drain current on temperature. When CNTFET is cooled, drain saturation currents were lightly decreased.

Comparison between CNTFET and MOSFET

In this section we have given a brief comparison between the performance of CNTFET and MOSFET.

- In case of Si-MOSFET switching occurs by altering the channel resistivity but for CNTFET switching occurs by the modulation of contact resistance.
- CNTFET is capable of delivering three to four times higher drive currents than the Si MOSFETs at an overdrive of 1 V.
- CNTFET has about four times higher transconductance in comparison to MOSFET.
- The average carrier velocity in CNTFET is almost double that in MOSFET.

The on-current performance advantage of the CNTFET is either due to the high gate capacitance or due to the improved channel transport. The improved channel velocity for the CNTFET is due to the increased mobility and band structure of CNTFET.

Conclusion

The understanding of carbon nanotube transistor is evolving and the performance of the transistor is improving very rapidly. CNTFET devices present a bright future and promise to sustain FET scaling and Moore's Law should their practical and manufacturing problems be overcome. The I-V characteristics of back gated CNTFET are also described. This article basically provides insight into the types of existing CNTFETs. It also discusses some of the index curves for CNTFETs. Ultimately, the benefits of CNTFET is compared with Si-MOSFET. Increasing the thickness of the gate oxide directly reduces the current of on-off mode. The use of the CNT band gap as a channel for CNTFETs is great importance in the high on-off switching rates. The large band gap increases the off-current more than the on-current. Control over the diameter of the tubes is important, too, but it is not almost as important as completely or nearly completely eliminating metal nanotubes in a channel. In the case of structure of transistor without metal nanotubes in the channel, the nanotube with smaller diameter produces a better on/off current ratio. On the contrary, even if there is a small number of metal nanotubes in a channel, CNTs with larger diameter are desirable.

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