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Carbon Nanotube Field Effect Transistor as Non-Volatile Memory- A Review

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***Abstract: Carbon nanotubes (CNTs) are amongst the most explored one-dimensional nanostructures and have attracted tremendous interest from fundamental science and technological perspectives. Carbon nanotubes are one of the most inventive inventions in the field of nanotechnology, and they are the important materials in the nanoelectronics. Since its discovery in 1991, numerous research works have been drawn to it due to its enormous production. Carbon nanotubes (CNTs) have attracted much attention because of their unique electrical properties and their potential for a variety of applications. CNTs are also promising material as field effect transistors for future nanoelectronics and show hysteresis in the curve of the drain current versus gate voltage which makes CNTs possible for a non-volatile memory application. This paper highlighted on properties of CNTs and its applications as memory devices in electronics*.**

Keywords: Nanotechnology, carbon nanotubes, SWCNTs, MWCNTs, CNTFETS, Non-volatile memory.

I. INTRODUCTION

Carbon Nanotubes (CNTs) are hollow cylinders composed of one or more concentric layers of carbon atoms in a honeycomb lattice arrangement. They are basically rolled-up sheet of graphene, which are mono-atomic layer of graphite. Carbon nanotubes formed by the arc discharge of carbon electrodes and are not made by literally graphene sheets into cylinders. Sumio Iijima of NEC first observed carbon nanotubes (CNTs) in 1991[1] in electron microscope images of the soot produced by discharges between carbon electrodes. Those nanotubes consisted of several sheets of graphite (which is composed of multiple layers of carbon atoms) rolled into cylinders with one cylinder inside another, a form now referred to as multiwalled nanotubes. In 1993, Iijima [1,2] and Don Bethune [3]of IBM independently found that by adding small amounts of catalytic metals to the carbon electrodes, they could produce CNTs consisting of a single atomic layer of carbon's graphite structure-a configuration now called single-walled carbon nanotubes (SWCNTs). If the cylinder axis is the x-axis the resulting tube is called a Zigzag tube. If the cylinder axis is the y-axis the resulting tube is called an armchair CNT and if the cylinder axis is neither the x nor the y axis the resulting nanotube is called a chiral CNT. The basis vectors $a_1 = a(\sqrt{3}, 0)$ and $a_2 = a(\sqrt{3}/2, 3/2)$ generate the graphene lattice, where a = 0.142 nm is the carbon–carbon bond length. In cutting the rectangular strip, one defines a circumferential vector $C = na_1 + ma_2$, from which the CNT radius can be obtained [3]. Thus, CNT can be characterized by the dual index(n, m). When the circumferential vector lies purely along one of the two basis vectors $(n, 0)$, the CNT is said to be of the 'zigzag' type. Second, when the circumferential vector is along the direction exactly between the two basis vectors ($n = m$), the CNT is said to be of 'armchair' type. When a nanotube has arbitrary chirality (n, m), where $m \neq n$ is called chiral nanotube.

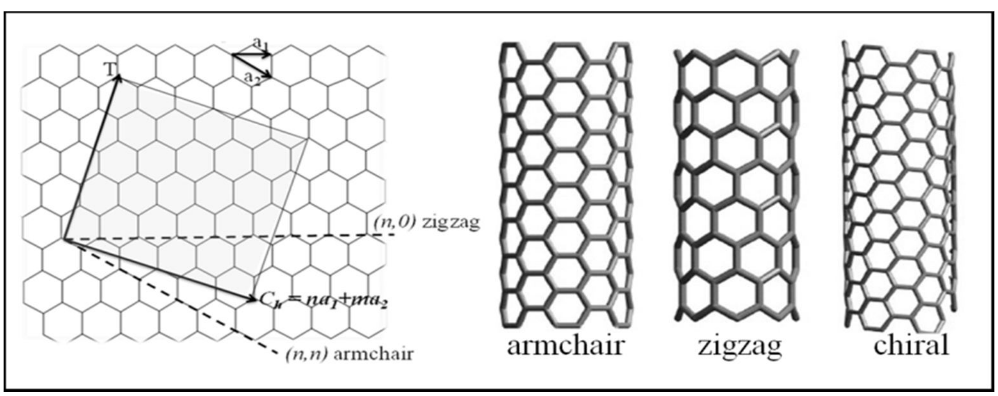

Fig. 1 Different types of CNTs on the basis of their chiral vectors

Multiwalled Nanotubes (MWCNTs) and Single-walled Nanotubes were observed by Iijima in 1991 and 1993 respectively. Nanotubes have a diameter of 1-2 nanometers (1 nm = 1 billionth of a meter) and a length of several micrometers. One of the amazing properties of carbon nanotubes is that they come in two flavors-metallic or semiconducting. Because of their extremely small diameter, quantum mechanical effects determine the electronic structure of a carbon nanotube. This means that the quantization conditions along the nanotube perimeter determine whether a nanotube acts as a metal or a semiconductor. Nanotubes do not have surface dangling bonds [4], as silicon does, and so there is no need to mainly use silicon dioxide (SiO_2) as the gate insulator. SWCNTs typically have a diameter of 1-2 nm and a length of several micrometers. The large aspect ratio makes the nanotubes nearly ideal one-dimensional (1-D) objects, and as such the SWCNTs are expected to have all the unique properties predicted for these low-dimensional structures [5]-[8]. The first CNT-FETs devices were fabricated in 1998 [9], [10]. In these a single SWCNT was used to bridge two metal electrodes on silicon substrate. The SWCNT played the role of the "channel," while the two metal electrodes functioned as the "source" and "drain" electrodes. Avouris *et al* showed [4] the output and the transfer characteristics of such CNTFETs.

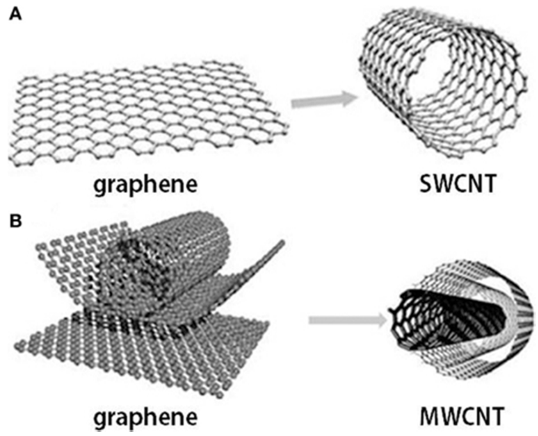

Fig.2 Structure of A) Single walled Carbon Nanotube (SWCNT) and B) Multiwalled Carbon Nanotube (MWCNT) from graphene sheets

II. CARBON NANOTUBE FIELD EFFECT TRANSISTOR

In recent years, a significant interest in carbon nanotube-based devices have been witnessed, including field-effect transistors (FETs) [9], [10] room-temperature single-electron transistors, [11] electron field emitters [12]-[13]. The performance of one group of devices, carbon nanotube-based field-effect transistors (CNTFETs), has improved steadily since the first successful batch of CNTFETs was reported in 1998. Most recently, there have been several reports of the observation of memory effects in various CNTFETs. Currently, one of the widely used nonvolatile semiconductor memories is the metal-oxide-semiconductor (MOS) transistor that has a floating gate between the channel and the control gate. Information is represented by storing charges on the floating gate. The information can be read by using the transistor because different amounts of charges on the floating gate shift the threshold voltage of the transistor differently. Most recently the single-walled carbon nanotube-based field effect transistors with good memory effect were reported by Fuhrer *et al.,* Wang *et al,* Radosavljevic *et al* [14]-[18]. Other crystalline or amorphous insulators with higher dielectric constants can be used instead. This implies that one can get higher performance in CNTFETs without having to use ultrathin SiO_2 gate insulating films. In addition, CNTFETs may make new applications possible. For example, semiconducting SWCNTs, unlike silicon, are direct-gap materials and, as such, they directly absorb and emit light, thus possibly enabling a future optoelectronics technology based on SWCNTs. A CNTFET is the analogue of silicon MOSFET in which SWCNTs replace the silicon channel. Depending upon the arrangement of the carbon atoms nanotube can be metallic or semiconducting. Nanotubes are held together by the C-C bonds and thus they are very strong resulting in extremely high mechanical stability. As individual molecules, nanotubes are 100 times stronger-than-steel and one-sixth its weight. They also have very high thermal conductivity and stiffness. CNTs are stiffest known fibers and exhibit the highest tensile strength of any known material. Some carbon nanotubes can be extremely efficient conductors of electricity. CNTs can carry very high current densities (much higher than typical metals), at 109A/cm^2or more, without melting. For comparison, copper is generally limited to 106A/cm^2 due to heating. Scientists at Rice University are developing a new type of wire made of carbon nanotubes that conducts electricity much better than copper, and could transform the electrical power grid.

For the semiconducting tubes, electronic properties can be controlled by doping like another semiconductor. Doping can be introduced chemically by inserting molecules inside the tube.

For the CNTs are currently considered as promising building blocks of a future nanoelectronic technology. This is not simply due to their small size but rather to their overall properties.

Due to its high strength, lightweight, high toughness, flexibility, high thermal conductivity good electric conductivity and chemical stability carbon nanotubes can be used to manufacture smaller transistors, Field Emission Display(replacing the traditional bulky CRT screen), Supercapacitors, gate electrodes of Field Effect Transistors, gas sensors, batteries, fuel cells, solar cells and single electron transistors. Semiconducting nanotube gate electrode FET has 100 times electrical conductivity than Si FET when voltage is applied and 1000 times higher operational frequency than current Complementary Metal Oxide Semiconductor. Some predict that nano-scale carbon transistor will replace Si transistors within the next decade.

III.MEMORY EFFECTS OF CNTFETs

The memory effects on SWNTs have been studied by several groups. Fuhrer *et al* (2002) constructed a high mobility semiconducting CNT transistor as charge storage device. A threshold voltage shift has been detected by the application of a gate voltage across SiO_2 dielectric between nanotube and Si substrate. The threshold voltage shift indicates that the electrons are injected into the oxide traps in the dielectric, like floating gate memory. Traps are populated by electrons injected from the nanotube channel. Due to the cylindrical geometry of the device, the electric field is much higher at the nanotube than at the Si/SiO_2 interface; for this reason, they suggested [17] the nanotubes as the source of charge injection. Since the tiny structure of the CNTFET, the memory effect of the CNTFET makes it potential for the ultra-small and ultrahigh density transistor memory.

Radosavljevic *et al* reported [18] an air-stable n-type CNTFET with a similar hysteresis phenomenon and the bit storage time of at least 16 hours at room temperature. Lee and coworkers [19] also discussed SWCNT transistor as charge storage memory device which was operated by injecting electron from nanotube. The hysteretic behavior of the drain current as a function of the gate voltage of CNTFETs are clearly demonstrated at room temperature by Yang *et al* [20] and Wang *et al* [17]. The threshold voltage shift increases with increasing the sweeping range of the gate voltage. The CNTFET memory effects show good charge retention capability with the data storage time of around 7 days at ambient condition [17].

Cui *et al* presented memory device by using semiconducting SWNTs. Charge storage was achieved by sweeping the gate voltage associated with a storage stability of at least 12 days at room temperature [21]. In 2002 Cui *et al* presented a SWCNT model where the SWCNT grown on a thin SiO_2 film. He discussed a hysteresis from the SWCNT bundles at room temperature. Data storage is achieved by sweeping gate voltages in the range of 3V associated with a threshold voltage shift of 1.25V.

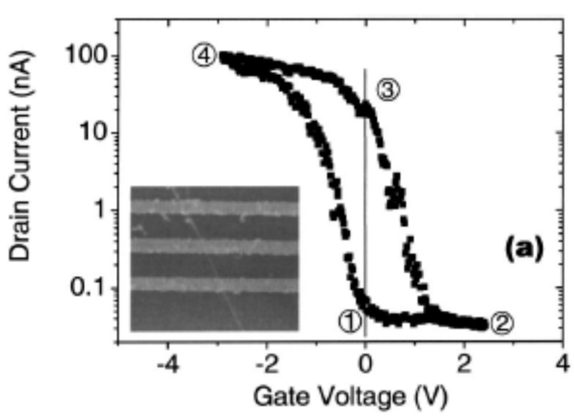

Fig 3 Memory effects observed at room temperature in individual SWCNT with a diameter of 2 nm. A threshold voltage shift of~1.25 V is observed upon sweeping the gate voltage along the points 1→2 →3→4→1 [17]

A significant threshold voltage shift, combined with a long charge retention time, is the prerequisite for memory devices. Wang and coworkers reported the fabrication of memory devices using 1.8 nm diameter SWNTs, employing a simple two-stage annealing process involving hydrogen and air treatment which resulted in good memory characteristics with a pronounced hysteresis which was stable for at least 14 days.

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Pronounced hysteresis loops, which reflect memory effects, are clearly observed in the drain current versus the gate voltage, and the hysteresis loops were found to be reproducible. The memory effects are suggested to be originated from the charge traps in the underlying SiO_2 / Si substrate at room temperature. TEM observation indicated that the diameter of our SWNT was only 1.8 nm, such a small diameter SWNT can cause a highly localized electric field at the nanotube surface [15], [18]. Charges are therefore easily reversibly injected and removed from the SiO_2 dielectric by applying a bias voltage across the dielectric between the carbon nanotube and the substrate. This characteristic makes the CNTFETs possible to function as nonvolatile charge storage memories [15], [21]. In order to improve the memory performance, a CNTFET with a charge storage node is under construction. Our observation that a larger gate voltage sweep range leads to a larger threshold voltage shift might be due to an increase in the amount of charges stored in the dielectric with increasing injected charges from the SWNT channel.

In the roadmap of nonvolatile memories, besides the threshold voltage shifts, the charge storage stability (retention time) is another very important factor for their practical applications. However, little attention has been paid to this subject for the CNTFET memory to date. Wang et al measured [16] the retention time as shown in the figure below.

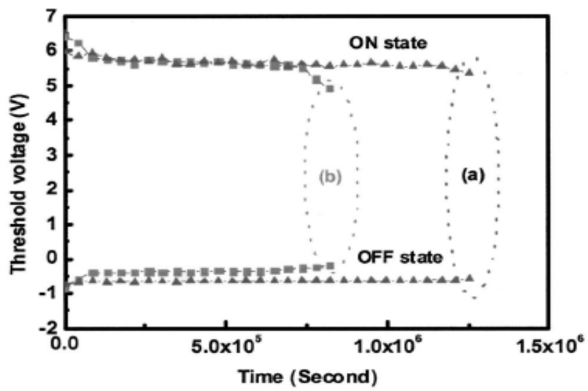

Fig 4 I_{ds}−V_g curves measured at the voltage sweeps of −4 to +4, −6 to +6 and −10 to +10 V with V_{ds}=1 V at room temperature, respectively. Pronounced hysteresis behavior was clearly observed [21]

Ganguly et al (2005) proposed [22] a CNT based nonvolatile memory structure where CNT played the role of a conducting channel and metal nanocrystal as charge storage nodes. The gate electrode regulates the charging and discharging of metal nanocrystals from the channel. The nanotube in these structures reduces the trap density and trap assisted leakage current than normal Si channel. He also showed high threshold voltage shift and large memory window.

So far, the function of the CNTs was the current channel, and the memory effect of the devices was attributed to the charges injected from the CNTs to the defects or charge traps in the dielectrics or the interface between the CNTs and the oxides. The CNTs were not used as the charge storage nodes. Up to now, there is no report on flash memory devices using CNTs as a floating gate. Lu et al (2006) proposed a memory device using CNT as a floating gate embedded in HfAlO high-k tunneling/control oxides and its memory effect has been observed [23] by studying C-V characteristic. The C-V hysteresis loops of the samples with and without CNTs have been shown by Lu et al. A clear hysteresis between subsequent forward and backward C-V curves can be observed for the sample containing CNTs. During the voltage sweep range of 3 to −3 V, a memory window width of 400 mV was observed.

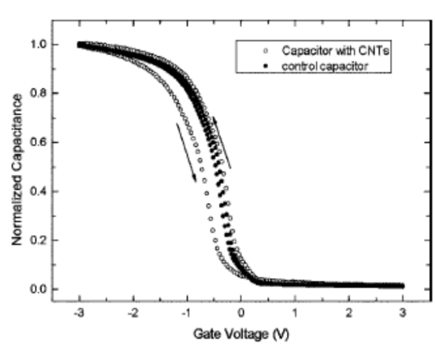

Fig 5 Typical C-V hysteresis characteristics of the CNT based MOS memory devices and the control sample [23]

IV. CONCLUSIONS

Based on the review in this paper, carbon nanotube field effect transistor has the potential to be used as the non-volatile memory in the field of nanotechnology. Generally, nanotubes are used as the channel between the source and the drain terminal of MOS structure but researchers are trying to use CNT as dielectric material in the gate stack which can be a replacement of high-k dielectric in the modern non-volatile memory device. It must be said that the excitement in this field arises due to the versatile properties of CNT. Nanotubes truly bridge the gap between the molecular and the macro-world, and are destined to be a star in future nanotechnology.

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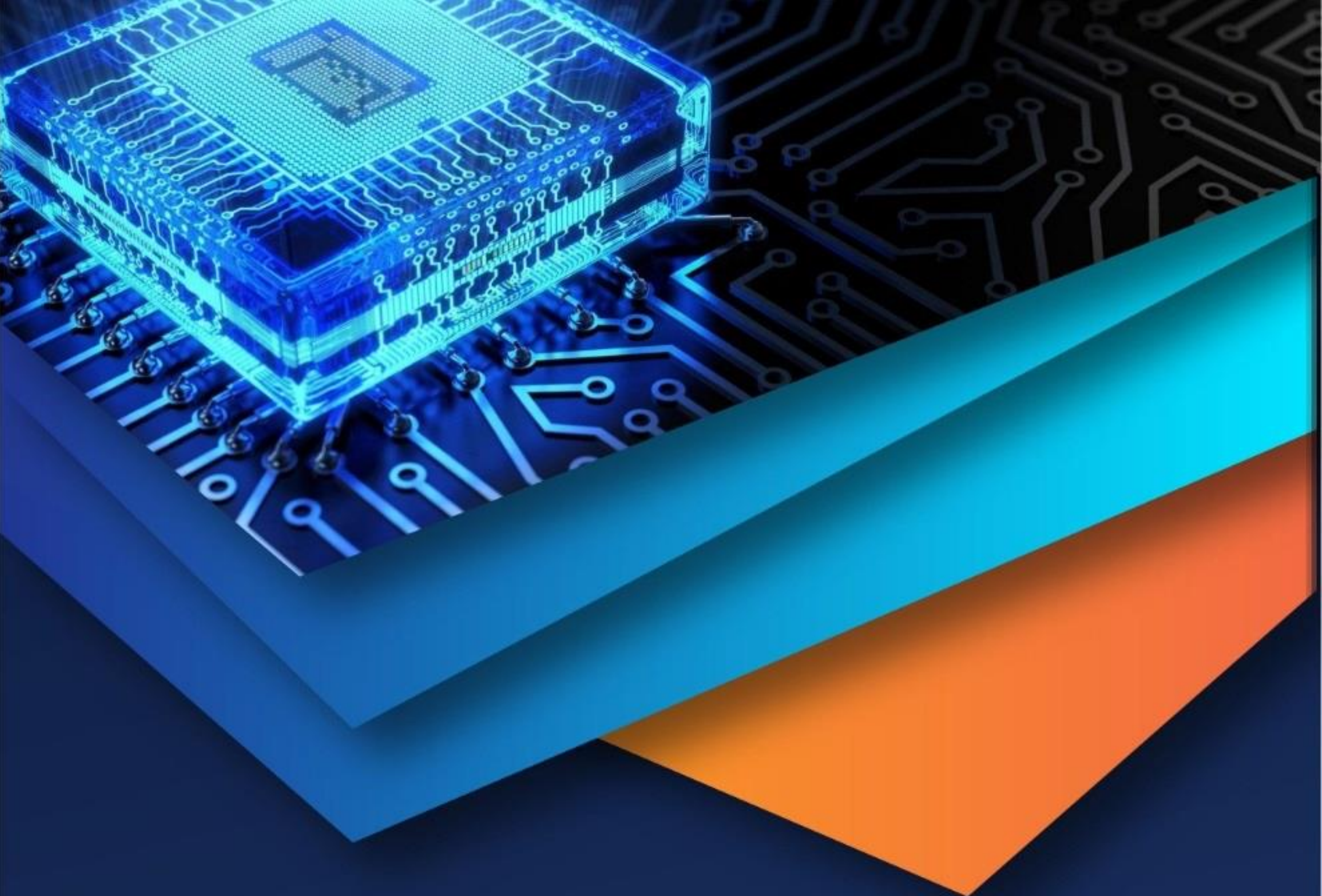

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