

# Exploring Carbon Nanotubes in Nanotechnology: Functional Properties, Surface Modifications, and Biomedical Innovations

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## Abstract

Significant progress has been made in nanotechnology in recent years, especially in the creation of sensors with a broad range of uses. Among these, carbon nanotubes (CNTs) are cylindrical structures composed of carbon, with diameters in the nanometer range. CNTs originate from graphite sheets, where the graphite layers resemble a rolled-up, continuous, and robust hexagonal mesh. These hexagons have carbon atoms at their vertices. The fabrication of CNTs typically involves three primary methods: chemical vapor deposition, electric arc discharge, and laser ablation. CNTs exhibit several exceptional properties, including high elasticity, excellent thermal conductivity, low density, and chemical inertness. These attributes have made CNTs highly valuable in various fields, including nanotechnology, electronics, optics, and materials science. In addition to their use in sensing, water treatment, and drug delivery, CNTs can be functionalized to enhance their solubility and biocompatibility. Functionalization allows for the attachment of active molecules, making CNTs suitable for integration into biological systems. By modifying the surface of CNTs, it is possible to adsorb or attach molecules or antigens that can be specifically targeted to desired cell populations for therapeutic or immune recognition purposes. Examining Carbon Nanotubes in Nanotechnology: Applications, Surface Alterations, and Functional Features. Additionally, the antibacterial and antifungal properties of CNTs will be discussed.

**Keywords:** Carbon nanotubes (CNTs), nanotechnology, functionalization, medical diagnostics, drug delivery

## INTRODUCTION

Nanotechnology has emerged as a cutting-edge and expansive field of research, gaining prominence across the globe as a highly advanced manufacturing technology. This discipline focuses on creating materials at the nanometer scale through various chemical and physical methods. Among the most significant advancements in nanotechnology is the development of nanostructured materials,

which form the foundation of this field. Nanomaterials, characterized by dimensions below 100 nm, offer a unique array of magnetic, electronic, mechanical, and optical properties. Among these, nanotubes stand out as particularly promising. While other nanotubes, such as those based on boron and molybdenum, have been widely reported, carbon nanotubes (CNTs) have garnered the most attention due to their importance.

CNTs consist of one or several concentric layers resembling graphite, with diameters ranging from 0.4 nm to tens of nanometers.

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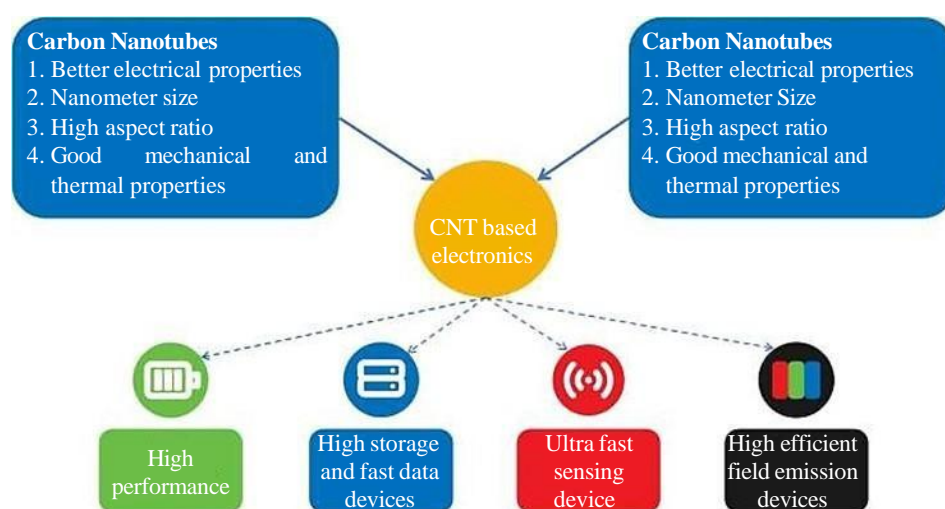
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The discovery of CNTs dates back to 1991, when Iijima first observed them experimentally using transmission electron microscopy (TEM), followed by subsequent reports detailing the conditions for large-scale synthesis. Structurally, CNTs are essentially graphite sheets rolled into cylindrical forms, with lengths in the micrometer range and diameters around 100 nm. CNTs are often considered derivatives of both carbon fibers and fullerenes, with molecules composed of 60 carbon atoms arranged into unique, enclosed tubular structures.

There are two main types of CNTs, classified based on the number of graphene layers they contain. The single graphene layer that makes up single-walled carbon nanotubes (SWCNTs) typically has a diameter of between 0.4 and 2 nm and is frequently arranged into bundles that are hexagonally packed. On the other hand, numerous concentric cylinders of graphene sheets, with diameters varying from 1 to 3 nm, make up multi-walled carbon nanotubes (MWCNTs) [1–3].



**Figure 1.** Role of Carbon Nanotubes.

The arc discharge method employs high temperatures ( $>3000^{\circ}\text{C}$ ) to evaporate carbon atoms in a plasma, producing both SWCNTs and MWCNTs. While the synthesis of MWCNTs does not necessarily require a catalytic agent, the production of SWCNTs requires the presence of catalysts such as cobalt, yttrium, nickel, or iron. The CVD method involves the decomposition of hydrocarbons like methane or ethylene in the presence of catalysts, whereas the laser ablation method uses laser vaporization of graphite in a furnace heated to around  $1200^{\circ}\text{C}$ . High graphite purity ensures a high conversion ratio and purity in the resulting products, making this process desirable for biomaterial applications, where purity is a key concern. Additionally, macroscopic processing is used to further refine the characteristics of CNTs, such as length and alignment Figure 1.

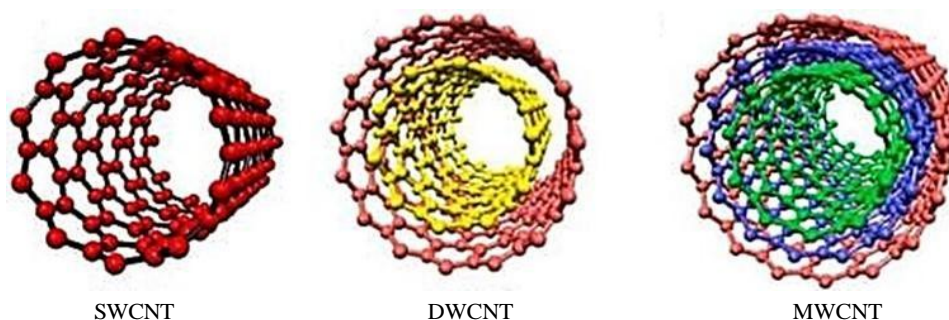
MWCNTs were first discovered by Iijima through the arc discharge method, the earliest technique used to produce carbon fibers. A notable advancement in CNT synthesis was achieved by Khan et al. (2016) through in situ emulsion polymerization, which enabled the successful formation of CNT composites in a colloidal system with poly(styrene) (PS), resulting in nanostructured brushes. In this process, CNTs were first functionalized with oleic acid, followed by silanization with (3-aminopropyl) triethoxysilane, to introduce cross-linking properties [4–6].

CNTs exhibit exceptional chemical and physical properties, including high tensile strength, ultra-lightweight nature, unique electronic structures, and high chemical and thermal stability. Due to these impressive attributes, CNTs have become a focal point of research across various scientific domains. Among carbon-based nanomaterials, CNTs are the most widely explored for numerous applications.

Notable uses include their roles in biomolecule transport, drug delivery to targeted organs, and as biosensors for diagnostic purposes.

### Types of Carbon Nanotubes (CNTs)

Structurally, an SWCNT is a seamless cylindrical tube composed of a single layer of graphene, rolled from edge to edge. SWCNTs typically have a diameter of around 1 nm, with lengths that can extend up to 1 mm. However, the production of SWCNTs is more expensive compared to MWCNTs.



**Figure 2.** Types of carbon nanotubes.

The interplanar spacing between these concentric cylinders is approximately 0.32 nm to 0.35 nm, which closely matches the interlayer distance in graphite. Due to better adhesion on substrates, MWCNTs are more commonly used in electronic applications compared to SWCNTs, as SWCNTs often have poor adhesion. MWCNTs offer more active sites at the tube ends, attributed to their additional concentric layers, which improves substrate adhesion [7].

A specific subtype of MWCNT is the double-walled carbon nanotube (DWCNT), which contains just two concentric graphene cylinders with an interlayer Distances. The structures of SWCNTs, DWCNTs, and MWCNTs are depicted in Figure 2.

### Properties of CNTs Electrical Properties of CNTs

Carbon nanotubes (CNTs) are extensively used in electronics due to their exceptional current density and specific capacitance. For instance, the specific capacitance of a CNT sheet electrode with a 25.4- $\mu\text{m}$  thickness ranges between 39.2 and 90.4 F/g. Their electrical conductivity, resistivity, and capacitance can be tuned by functionalizing them with specific chemical groups. Doping CNTs with gold nanoparticles creates covalent bonds on the fiber surface, enhancing conductivity.

Electrical properties such as conductivity and resistivity also depend on factors like chirality, temperature, defects, and the surrounding environment. Multi-walled carbon nanotubes (MWCNTs), in comparison, typically exhibit higher electrical conduction than SWCNTs. Pure SWCNTs have a reported electrical resistivity of about 0.34  $\Omega$  cm, while commercially produced SWCNTs (via chemical vapor deposition, CVD) show a resistivity ranging from 1  $\Omega$  cm to 7  $\Omega$  cm. This variation can be attributed to impurities and defects introduced during the manufacturing process [8].

### Mechanical Properties of Carbon Nanotubes (CNTs)

The mechanical properties of CNTs can vary due to several factors, including the method of production, the number of defects, the structure, diameter, and symmetry of the nanotubes. Studies comparing the strength of arc-grown and catalyst-grown MWCNTs have shown that arc-grown MWCNTs possess higher strength due to fewer defects compared to those produced through catalytic methods. However, producing defect-free, ideal CNTs on a large scale remains impractical, which is why standardized values for CNT moduli are not readily available. The covalent bonding within CNTs significantly contributes to their overall strength.

It has been observed that MWCNTs can withstand greater bending angles without compromising their structure. For instance, MWCNTs with larger diameters have demonstrated bending strengths of  $14.2 \pm 0.8$  GPa. In earlier studies, measuring the strength or Young's modulus of CNTs was challenging due to their small size. However, the use of transmission electron microscopy (TEM) eventually allowed researchers to measure the Young's modulus of both SWCNTs and MWCNTs. The highest recorded

Young's modulus for MWCNTs was 4.15 TPa, while for SWCNTs, it was around 1.3 TPa. However, this method often produced significant measurement errors.

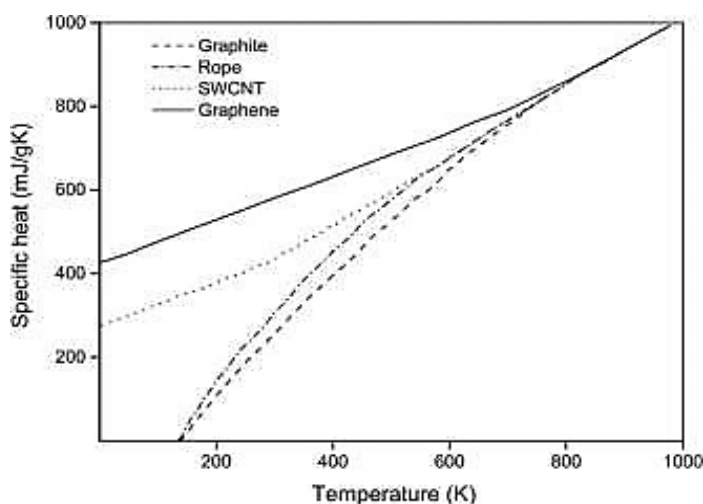
Atomic force microscopy (AFM) later provided a more reliable approach to measure the mechanical properties of CNTs. In this method, a Si<sub>3</sub>N<sub>4</sub> AFM tip applied pressure on CNTs, and load-displacement curves were used to determine the Young's modulus directly. MWCNTs with diameters between 26 and 76 nm recorded a Young's modulus of  $1.28 \pm 0.59$  TPa, while SWCNTs exhibited values close to 1 TPa. Despite these advances, theoretical simulations and experimental results have sometimes yielded varying results. Many researchers prefer studying SWCNTs due to their lower defect rates, which contribute to greater strength [9].

### Thermal Properties of Carbon Nanotubes (CNTs)

The thermal properties of CNTs are primarily influenced by the behavior of their acoustic phonons. The thermal conductivity of carbon nanotubes is largely determined by the mean free path of these phonons. As illustrated in Figure 4, the specific heat of SWCNTs at various temperatures may be compared to that of 2D graphene, 3D graphite, and 3D SWCNT rope.

Due to the one-dimensional cylindrical structure of CNTs, formed by rolling a two-dimensional graphene sheet, the phonon band structure in CNTs becomes stiffer.

The population of acoustic phonon modes results from the constant phonon density of states (PDOS) for isolated SWCNTs at low temperatures. As a result, temperature over 1 K and specific heat have a linear connection. Because there are more optical subbands when the temperature approaches 6 K, the specific heat rises more quickly.



**Figure 3.** The graph of specific heat vs. temperature of graphene, graphite, SWCNT rope and SWCNT.

The temperature dependence of specific heat below 1 K differs from that above 1 K. Below 1 K, the specific heat exhibits a distinct temperature-dependent trend due to the increased population of transverse phonons.

Once the temperature surpasses 1 K, the specific heat becomes linearly dependent on temperature due to the rising population of longitudinal and acoustic phonons, as illustrated in Figure 3.

The specific heat of graphene, 3D SWCNTs, and SWCNT ropes align and start to reflect the 3D graphite phonon structure at increasing temperatures.

This indicates that, at elevated temperatures, the thermal properties of SWCNTs closely resemble those of graphite.

### **Electronic Applications**

The uses of carbon nanotubes (CNTs) in energy storage, biosensing, field emission, nanoelectromechanical systems, data storage, and supercapacitors are examined in this work. An outline of CNTs' functions in various domains can be found in the sections that follow [10].

### **Field Emission Technology**

Field emission refers to the release of electrons from specific locations, and it has a range of applications, including as an electron source for scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM), transistors, and flat panel displays. Effective field emitters should have a small tip structure, low gate voltage, minimal sensitivity to current fluctuations, and high current density. CNTs are notable for their high current density, with values reaching up to  $10^6$  A/cm<sup>2</sup> before electro-migration begins. SWCNTs, in particular, have a low threshold voltage for field emission, ranging from 1 to 3 V/ $\mu$ m, compared to silicon tips, which have a threshold voltage starting at 50 V/ $\mu$ m [11].

CNTs use only 6% of the current required by conventional emission tips, making them more efficient. Additionally, CNTs outperform other carbon allotropes in field emission applications. MWCNTs 0.1 nm, smaller than that of MWCNTs grown in helium or SWCNTs. These CNTs are referred to as graphitic nanofibers or nanografibers due to their lack of a central cavity and exhibit higher current densities compared to conventional MWCNTs. CNTs are thus considered excellent candidates to replace traditional field emission materials due to their superior properties.

### **Field Emission Transistors**

Field emission transistors (FETs) are utilized in amplifiers, oscillators, current choppers, and limiters. MOSFETs operate based on the principle of altering electrical conduction in response to applied voltage.

CNT field-effect transistors (CNT-FETs) operate on a similar principle to MOSFETs but offer several advantages. CNT-FETs exhibit reduced quantum capacitance at higher voltages, whereas MOSFETs tend to degrade. Additionally, CNT-FETs are less affected by temperature fluctuations compared to MOSFETs. A typical production method for CNT-FETs, as described by Kilnke, involves functionalizing CNTs with hydroxamic acid, depositing the functionalized CNTs onto a pre-oxidized aluminum strip on a silicon substrate, and then annealing at 600°C to remove the functionalization and restore the CNT properties. Palladium leads are used as the source and drain. This process results in CNT-FETs with a very low gate voltage of  $\pm 0.5$  V and an on-to-off current ratio greater than  $10^5$ .

### **Biosensing Applications**

Commercially produced carbon nanotubes (CNTs) often contain impurities such as Al<sub>2</sub>O<sub>3</sub> and transition metal catalysts (Fe, Co, Ni), necessitating extensive purification before their use in biosensing applications. Once purified, CNTs are functionalized to suit the specific requirements of the biosensing environment. Surface modification and functionalization typically reduce the CNTs' electrical conductivity by altering the bonding characteristics.

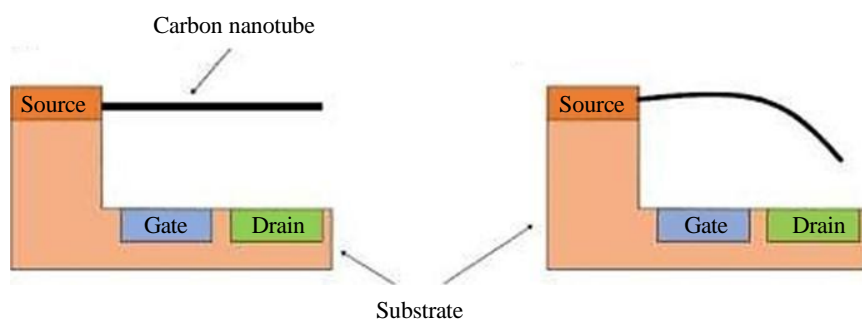
To minimize interactions with chemicals such as uric acid and ascorbic acid, CNTs are often coated with a semi-permeable material like Nafion. Functionalizing CNTs with amino acids enhances their covalent bonding in biological environments, which increases physical absorption. Additionally, CNTs exhibit fluorescence in the near-infrared region, which allows human cells and tissues to remain transparent to their fluorescence, making them suitable for biological imaging.

### Data Storage Devices

The development of compact and powerful data storage devices is crucial for advancing portable electronics. In contrast to conventional techniques, new technologies like phase-change memory (PRAM) and magneto-resistive random access memory (MRAM) are opening the door for speedier and non-volatile data storage options. Additionally, Nantero Inc. is developing nano-RAM (NRAM) technology, which is in the development stage and should hit the market shortly. It is anticipated that CNT-based data storage devices, which come in cantilevered, suspended, vertical, and telescopic formats, would have a bright future.

### CNT-Based Cantilevered Data Storage

CNTs with larger diameters are preferred due to adhesion issues with smaller diameter CNTs and metal electrodes.

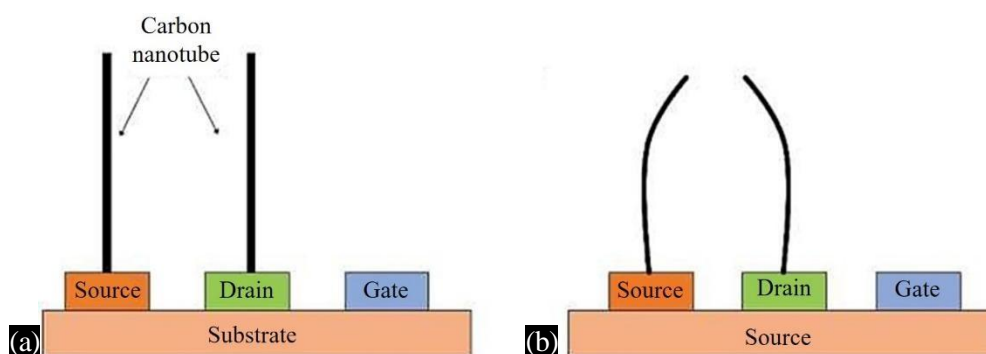


**Figure 4.** CNT-based data storage device.

Figure 4 The CNT electrode bends and makes an electrical connection with the drain when a voltage is supplied between the gate and the source (Figure 4b), resulting in a conducting condition. (1'). CNTs generally take some time to contact the drain, which induces phonon excitation and reduces the transition time between the non-conducting state (0') and the conducting state (1') by two orders of magnitude.

### Vertically Aligned CNT-Based Data Storage

Multi-walled CNTs (MWCNTs) are grown vertically by carefully controlled chemical vapor deposition (CVD) to align with source and drain electrodes in vertically aligned CNT-based data storage devices. The drain and gate are coupled to a voltage source, and the source is grounded [12].



**Figure 5.** CNT in Vertically Aligned Data Storage Device.

Figure 5 Applying voltage causes the drain and source to attract and establish an electrical contact (conducting state 1'). The stability of this contact depends on the length of the CNT; longer CNTs provide a more stable contact. It is possible to make volatile and non-volatile memory devices using this configuration. Furthermore, the source electrode becomes a CNT insulator-metal (CIM) capacitor by being coated with a metal Cr layer and a dielectric SiNx layer.

This setup allows charge storage in the CIM capacitor when voltage is applied to the drain electrode, and vice versa. The dielectric coating can be adjusted for higher storage capacity systems.

### **Suspended CNT-Based Data Storage Device**

The NRAM gadget from Nantero Inc. is based on suspended CNTs. The gate is positioned beneath the CNT and divided from it by a gap in this configuration, which suspends the CNT between the source and drain. The van der Waals force is important in this arrangement, as opposed to the cantilevered CNT design. The van der Waals force created by the oxide layer of the gate allows the CNT to come into contact with the gate when a voltage is put between the gate and the CNT (conducting state 1'), rendering the device non-volatile. To return to the original state, a pull-out voltage must be applied. Performance can be improved by reducing the gap between the CNT and the gate, increasing the CNT's length, and selecting an appropriate oxide layer.

Smaller diameter CNTs placed at smaller gaps reduce the transition time between states 0' and 1'.

### **Other Applications of Carbon Nanotubes (CNTs)**

Carbon nanotubes (CNTs) are being explored for a variety of innovative applications across different fields:

- *Lamps:* CNTs are used in field emission lamps (FEL) to achieve high efficiency at low power. By employing a metal mesh as the gate electrode and utilizing screen-printing techniques, CNT-based FELs offer stability and reduced vibration of the metal mesh. These lamps have demonstrated a lifetime of up to 8000 hours.
- *Supercapacitors:* The volumetric specific capacitance of CNT blocks is 107 F/cm<sup>3</sup>, making them ideal for supercapacitor construction due to their highly porous structure. A composite electrode made from CNT and RuO<sub>2</sub>·xH<sub>2</sub>O, after annealing and pressing to remove impurities, has shown a capacitance of around 720 F/g when 55–75% RuO<sub>2</sub>·xH<sub>2</sub>O is used. CNT-based supercapacitors thus excel in high-power applications.
- This technology promises high efficiency, portability, and reduced power consumption for X-ray machines.
- *Welding:* For nano-spot welding, CNTs are combined with copper solder to create a cost-effective and robust design. The setup, which requires only a few volts to initiate Cu migration, achieves a solder flow rate of 120 ag/s. Using a 1 wt.% CNT-AZ31 magnesium composite filler rod in gas tungsten arc welding has resulted in improved tensile strength and hardness (67±3.6) compared to non-reinforced AZ31 magnesium welds (53±4.5).
- *Diodes:* In the semiconductor industry, traditional p-n junction diodes may soon be replaced by CNT-based diodes. These diodes are created by connecting two nanotubes of different diameters end-to-end to form a Schottky barrier.
- *Emerging Applications:* NASA is exploring CNTs for mini electron probes to measure chemical properties in space environments. Additionally, CNT composites may serve as antistatic shields in future vehicles and are under investigation for use in photovoltaics.

### **CONCLUSION**

As the electronics industry continues to evolve, there is an increasing demand for miniaturization, which offers benefits such as enhanced portability, reduced raw material use, lower power consumption, and decreased electronic waste. Research on CNTs has significantly increased since 2010, suggesting a future where CNT-based electronics could lead to affordable, miniature, and

powerful products. This review has covered various applications of CNTs, including field emission transistors, data storage devices, and energy storage batteries, demonstrating their effectiveness in these areas.

Additionally, the biocompatibility of CNTs is a critical consideration, as their small size may lead to environmental and health issues.

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