Chapter

# Carbon Nanotubes: Synthesis, Properties and Applications

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## Abstract

Recent discoveries of salient carbon nanoforms have paved tremendous interest among research and also toward their discrete applications in scientific fields. Various generation methods for carbon nanotubes (CNTs) involve chemical deposition of vapor, discharge using electric arc and laser ablation mechanism which were driven by functionalization, chemical addition, doping, and filing such that in-depth characterization and manipulation of CNTs were possible. The in-built elasticity, electromechanical, chemical, and optical properties of CNTs have a notable impact on its stability and reactivity. Perhaps, the flexibility along with its determined strength makes them to validate its potential application in diverse fields which enables that these CNTs will definitely procure a prominent role in nanotechnology.

**Keywords:** nanotechnology, nanotubes, synthesis, electromechanical, nanosensor

## 1. Introduction

Carbon materials can be grouped into three classifications based on their period of advancement: classical carbons, nano ones and new carbons. Cracking carbons incorporate engineered graphite squares principally utilized as anodes, carbon blacks, what are more, enacted carbons, for which creation systems were created before [1] the 1960s. During the 1960s, carbon materials not quite the same as these great carbons were designed: carbon filaments from different forerunners, including fume developed carbon filaments; pyrolytic carbons delivered by means of concoction fume testimony forms; glasslike carbons with high hardness and gas impermeability; high-thickness isotropic carbons created by isostatic squeezing; intercalation mixes with various functionalities, for example, high electrical conductivity; and precious stone like carbons as straightforward carbon sheets. These recently evolved carbon materials are grouped as new carbons [2]. Since the 1990s, different fullerenes with shut shell structure, carbon nanotubes with nanometer distances across, and graphene pieces of just a couple molecules' thickness has stood out from nanotechnology; these are ordered as nanocarbons.

On the off chance that these carbon materials are considered from the perspective of their surface, be that as it may, they might be ordered into two gatherings: nano-textured and nano-sized carbons [3]. Most carbon materials in the new carbon classification are delegated nano-textured carbon, in light of the fact that their nano texture is controlled by means of various procedures in their creation, notwithstanding the basic control. Then again, fullerenes, carbon nanotubes, and graphene can be delegated nano-sized carbon, the shell size of fullerenes, breadth of carbon nanotubes, and thickness of graphene, drops are on the nanometer scale [4]. Carbon blacks in great carbon are made out of nano-sized particles, yet they are not typically named nanocarbons since they have different applications as a mass, not as individual nano-sized particles [5].

Carbon, a basic chemical substance containing 6 as atomic number with 6 electrons tend to occupy s and p orbitals. It can able to undergo hybridization through three different forms such as $sp/sp^2$ or $sp^3$ means. Recent inventions of compact structured carbon materials such as fullerene [6], graphene [7], and carbon nanotubes [8] have envisaged prompt enquiries into this emerging field. Various physical properties of carbon nanotubes were mostly derived from base material (graphene). Such graphene involves the dense packing arrangement of carbon atoms in a regular $sp^2$ pattern bonded to honeycomb based atomic scale structure and especially this pattern is most suitable as a primary structure for other $sp^2$ materials [9]. Based on theoretical judgment, this CNT is explicitly distinct in the cylinder form fabricated of swirled up graphene thick sheet, which can delineate itself to single or multiple well. The single well nanotubes were known as single walled carbon tubes which were investigated during 1993 whereas multi-walled ones were found during 1991 itself [10].

CNTs have outstanding mechanical, thermal, electrical, and optical properties that are being used exclusively or in mix to deliver keen sensors or on the other hand multifunctional materials [11, 12]. They have high angle proportions that are perfect for long and persistent detecting. Their high surface region, for example, can be misused for storing materials to make half breed useful materials or functionalized to make cathodes for an assortment of uses [13]. CNTs are additionally known to display ballistic conductivity because of insignificant electron dispersing in their 1D structure with mean free-ways of the request of several microns [14, 15].

Mechanical strain may cause reproducible changes in the electrical properties of CNT filaments, making it conceivable to misuse them as electromechanical sensors [16, 17]. The partner changes incorporate inductance, capacitance, and obstruction which can be associated to the strain. Of incredible significance is that CNT filaments are receptive to elastic, compressive, flexural, and torsional strain [18].

The working standards of sensors produced using a CNT plainly visible get together incorporate difference in their electrical resistivity or obstruction because of mechanical strain known as piezoresistivity, change of their inductance and capacitance because of mechanical strain, change of their electrical resistivity because of variety in temperature known as thermoresistivity [19], change of their electrical obstruction because of variety in an attractive field known as magnetoresistance [20], and change in their electrical opposition with change of their mechanical thunderous recurrence because of variety of temperature, weight, mass, and strain [11]. The adjustment in conductance or obstruction is substantially more predominant than other variety in electrical properties. This is somewhat in light of the fact that charge transporters are handily isolated under simultaneous deformation prompting an expansion in obstruction. For extremely little strains, the total deformation has demonstrated to be flexible and the conductive system is completely recouped when the strain is evacuated, prompting an abatement in opposition [21]. Thus, the presented chapter highlights the synthesis details, associated properties and current applications of carbon nanotubes.

## 2. Discussion

### 2.1 Synthesis of carbon nanotubes

There are many methods to synthesize CNTs, but these three methods are most important and commonly used methods. They are as follows.

### *2.1.1 Chemical vapor deposition method*

**Chemical vapor deposition (CVD):** CVD is a technique in which the vaporized reactants react chemically and forms a nanomaterial product that is deposited on the substrate **Figure 1**.

**Sources for carbon:** The precursor for carbon nanotubes are hydrocarbon gases such as acetylene, ethylene, methane, etc. [22].

**Substrate used:** Substrates are materials on which the CNTS are grown. The commonly used substrates in CVD method are zeolite, silica, silicon plate coated with iron particles, etc.

**Catalyst used:** To produce single-walled carbon nanotubes metal catalyst nanoparticles such as iron, cobalt, nickel, molybdenum, iron-molybdenum alloys, etc. are used.

**Sources for CVD used:** Based on the heating source, the CVD can be:

- Thermal activated CVD which is heated by IR radiation, RF heater, etc.
- Photo assisted CVD which is heated by Arc lamps, $CO_2$ laser, Argon ion laser, Nd:YAG laser, etc.
- Plasma assisted CVD which is heated by microwave radiation, etc.

**Conditions maintained:** The following conditions are maintained inside the furnace.

- Temperature: 500–900°C.
- Inert gas atmosphere: Argon gas.

### *2.1.2 Procedure for synthesis of CNTs by thermal CVD method*

CNTs are synthesized by thermal CVD method by using hydrocarbon gas as carbon source. In this method, a quartz tube is placed inside a furnace maintained at high temperature (500–900°C) heated by RF heater. A crucible containing the substrate coated with catalyst nanoparticles is placed inside quartz tube filled with inert gas

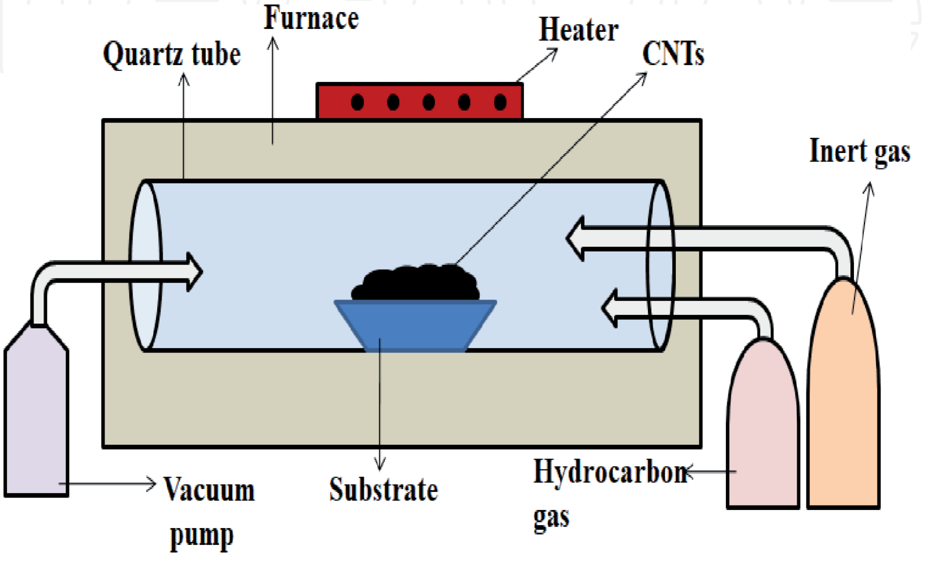


**Figure 1.**
*CVD method.*

such as argon gas. The hydrocarbon gas (carbon source) is pumped into the quartz tube which undergoes pyrolysis reaction and forms vapor carbon atoms. These carbon atoms bind to the substrate and join to eachother by Vanderwaal force of attraction and grow as multi-walled carbon nanotubes (MWCNTs) on the substrate [23]. To synthesize single-walled carbon nanotubes catalyst nanoparticles of Fe, Co, Ni are used. The obtained CNTs are further purified to get the pure form of CNTs.

*2.1.3 Electric arc discharge method*

Carbon nanotubes are synthesized by electric arc discharge method which is also called Plasma Arcing method.

*2.1.3.1 Description*

**Electrodes:** Pure graphite rods (both positive and negative electrode). The positive electrode is adjustable from outside to maintain the gap between the two electrodes.

**Diameter of electrodes:** 5–20 μm.

**Gap between electrodes:** 1 mm.

**Current:** 50–120 amperes.

**Voltage:** 20–25 V.

**Inert gas pressure:** 100–500 torr (No CNT formed below 100 torr). Inert gas is used for cooling and condensation of atoms to form the CNTs. Inert gas determines the structure of carbons to be present in CNTS. Commonly used inert gas is helium gas.

**Temperature:** 3000–3500°C.

**Reactor:** It contains a quartz chamber which is connected to vacuum pump and a diffusion pump to inert gas supply. Initially the chamber is made vacuum by the vacuum pump and then the chamber is filled with helium gas by the diffusion pump [24].

*2.1.4 Procedure for synthesis of CNTs by Electric arc discharge method*

In this method, a potential of 20–25 V is applied across the pure graphite electrodes separated by 1 mm distance and maintained at 500 torr pressure of flowing helium gas filled inside the quartz chamber **Figure 2**. When the electrodes are made to strike each other under these conditions it produces an electric arc. The energy produced in the arc is transferred to the anode which ionizes the carbon atoms of pure graphite anode and produces $C^+$ ions and forms plasma (Plasma is atoms or

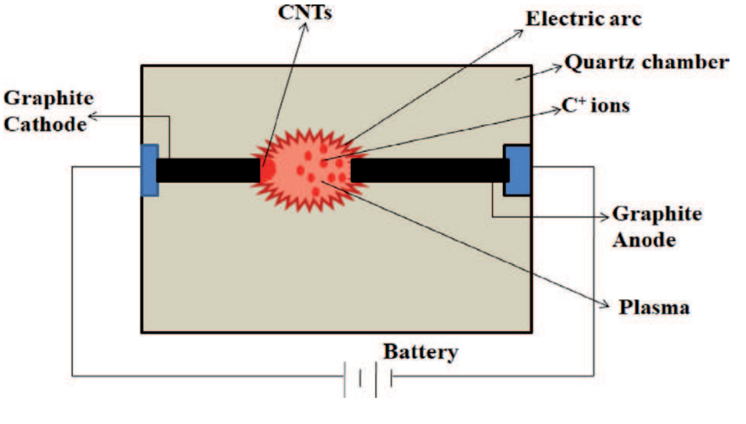


**Figure 2.**
*Electric arc method.*

molecules in vapor state at high temperature). These positively charged carbon ions moves towards cathode, gets reduced and deposited and grow as CNTs on the cathode. As the CNTs grow, the length of the anode decreases, but the electrodes are adjusted and always maintain a gap of 1 mm between the two electrodes. If proper cooling of electrodes are achieved uniform deposition of CNTs are formed on the cathode which is achieved by inert gas maintained at proper pressure [25]. By this method multi-walled carbon nanotubes are synthesized and to synthesize single-walled carbon nanotubes catalyst nanoparticles of Fe, Co, and Ni are incorporated in the central portion of the positive electrode. The obtained CNTs are further purified to get the pure form of CNTs.

### *2.1.5 Laser ablation method*

**Physical vapor deposition (PVD):** PVD is a technique by which a material can be vaporized into gaseous form and then deposited on the surface of a substrate.

**Target source:** The most common carbon source target used is solid graphite which is irradiated by laser source and vaporized into vapor carbon atoms.

**Laser source:** Laser source used for vaporization of target material into target vapor atoms can be continuous laser source such as $CO_2$ laser or pulsed laser source such as Nd:YAG laser (Neodymium doped Yttrium Aluminum Garnet, Nd:$Y_3Al_5O_{12}$) .

**Substrate used:** The substrate used in this method is the water cooled copper collector on which the vaporized carbon atoms deposit and grow as CNTs.

**Inert gas atmosphere:** Argon gas is commonly used as inert gas which flows at a constant flow rate towards the water cooled copper collector.

### *2.1.6 Procedure for synthesis of CNTs by Laser Ablation method*

Laser Ablation method is a Physical Vapor Deposition method in which graphite target is vaporized by laser source **Figure 3**. In this method the graphite target is placed at the center of quartz chamber filled with argon gas and maintained at 1200°C. The graphite target is vaporized by either continuous laser source or pulsed laser source. The vaporized target atoms (carbon) are sweeped toward cooled copper collector by the flow of argon gas. The carbon atoms are deposited and grown as CNTs on cooled copper collector. In case of continuous laser beam, the carbon atoms are continuously vaporized whereas in case of pulsed laser beam the amount of CNTs produced can be monitored as each shot of pulsed laser beam is directly proportional to the amount of carbon atoms vaporized [26]. By this method multi-walled carbon nanotubes are synthesized and to synthesize single-walled carbon

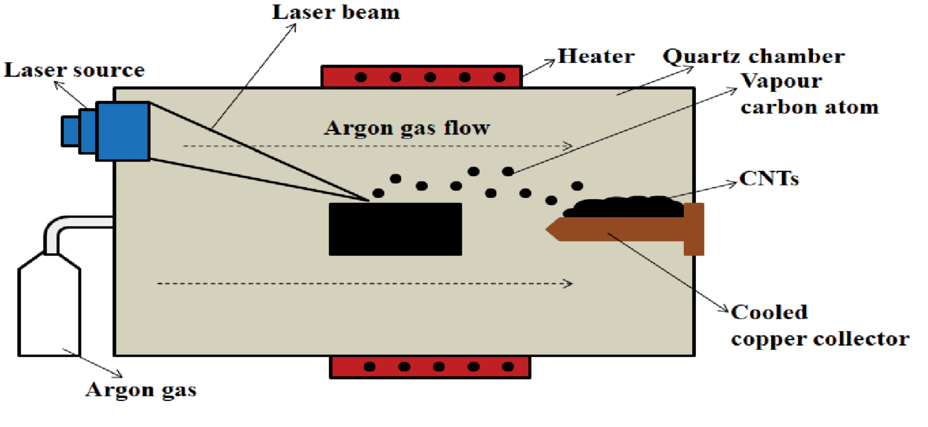


**Figure 3.**
*Laser ablation method—schematic representation.*

nanotubes catalyst nanoparticles of Fe, Co, Ni are used. The obtained CNTs are further purified to get the pure form of CNTs.

*2.1.6.1 Procedure for pulsed laser deposition method*

Pulsed Laser deposition is a thin film deposition technique in which the target material is vaporized by pulsed laser beam and vaporized target atoms are made to deposit on substrates **Figure 4**. The furnace contains a target at bottom and substrate mounted on the top. A pulsed laser beam from Nd:YAG laser source is made to strike the target to produce vaporized target atoms called the plume (plume is vaporized atoms at high temperature) [27]. The plume moves towards the substrate and it is deposited and grown as CNTs. Each shot of laser is directly related to the amount of material ablated, thus deposition rate can be controlled and calibrated.

*2.1.6.2 Purification of CNTs*

The synthesized CNTs can be separated from the amorphous carbon, carbon nanoparticles, residual catalyst and other impurities by various methods. The conventional methods of purification are not very successful but methods like gas phase, liquid phase and intercalation methods show good results.

**Gas phase purification of CNTs:** In this method the CNTs are subjected to a high temperature oxidation followed by repeated extractions with nitric acid and hydrochloric acid. This procedure makes the synthesized CNTs purer and high stability with fewer amounts of residual catalyst and other non CNTs forms.

**Liquid phase purification of CNTs**: A series of steps are followed in the liquid phase purification of synthesized CNTs. They are:

- Preliminary filtration to remove bulk graphite particles.
- Dissolution in both organic solvents and concentrated acids to remove the fullerenes and catalyst, respectively.
- Centrifugal separation of CNTs (Solid part) from the solution (containing impurities).

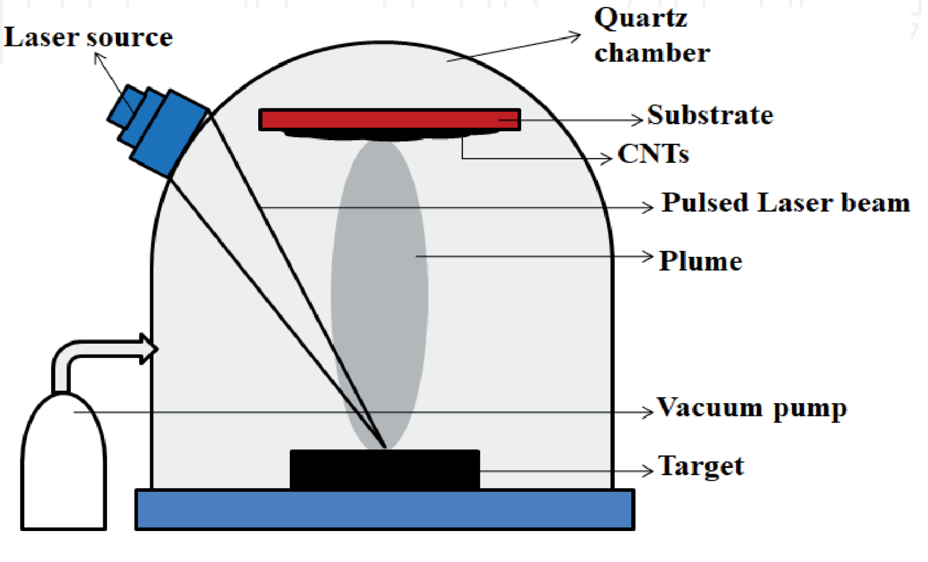


**Figure 4.**
*Pulsed laser ablation method—Schematic representation.*

- Microfiltration.
- Chromatography to isolate multi-walled carbon nanotubes, single-walled carbon nanotubes, etc.

**Intercalation purification of CNTs:** In this method the nanoparticle impurities present are oxidized by metallic copper which acts as oxidation catalyst formed from the reduction of copper chloride added during the process. This process introduces intercalate residues and damage CNTs during oxidation process.

### 2.2 Structure/properties of CNT

There are numerous mechanisms available to build up structures occluded with various characteristics. The $sp^2$ nature of carbon hybridization constructs a layered pattern of arrangement with weaker plane bonding of Vander Waals forces at the outside and strong forces at inner plane bounds. Few numbers of concentric cylinders were equipped with regular spacing of interlayers that are located around central hollow section and demonstrated as multi walled CNTs **Figure 5**. In general, the real time spacing of MWCNTs contain interlayer spacing in range of 0.35–0.40 nm. The inner diameter of multi-walled CNTs can even range from 0.40 nm to few nanometers [28]. Outer diameter can exist up to 25 nm. The tips on both sides were closed and protruding ends were capped using dome shaped half width fullerene molecules. Axial molecules can exist up to few centimeters. The primary function of half width fullerene molecules is to aid in shutting down the tubes at both the ends. Whereas SWCNT can exist up to 4 nm. Length is up to micrometer range. Such arrangement is organized in a hexagon shape so as to develop a crystal [29].

#### *2.2.1 Structure of SWCNT and MWCNT*

Based on wrapping mechanism, three different forms of SWCNTs include chiral, armchair, and zigzag pattern. The single walled structure is primarily characterized by a set of indices (n and m) which describes the vector mechanism of chiral and absolutely it impinges an impact on electrical tendency of both nanotubes **Figure 6**.

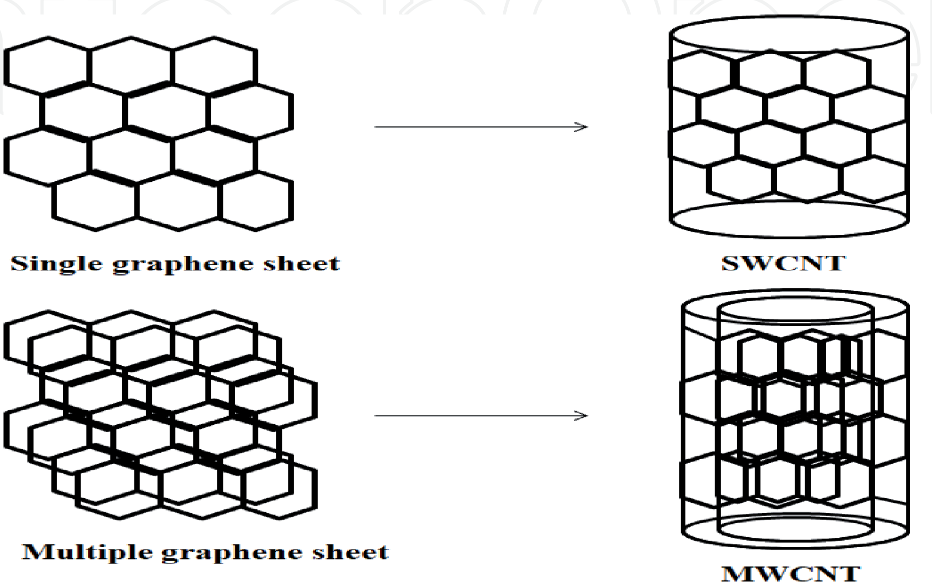


**Figure 5.**
*Graphene to CNT.*

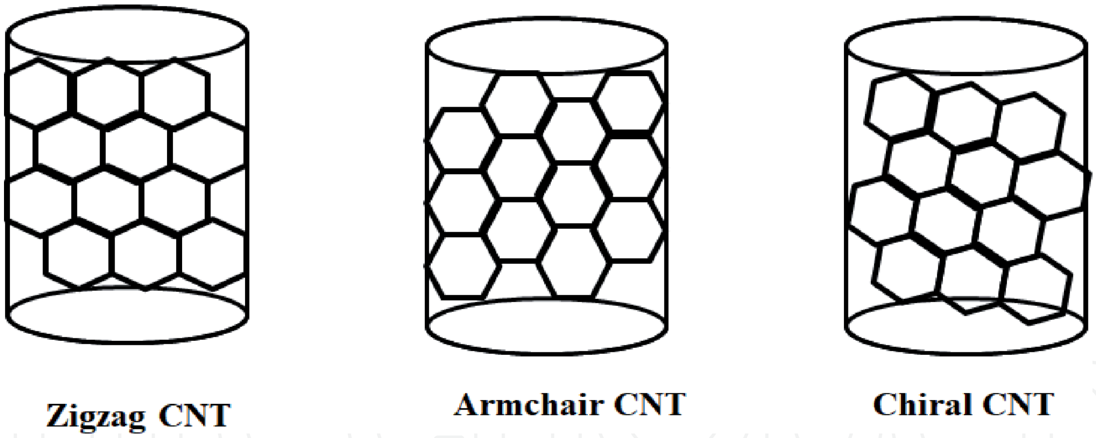


**Figure 6.**
*Different forms of SWCNTs.*

As a general predict, when n = m, these nanotubes are known as armchair ones and if m = 0, they are said to be zigzag and for other range as chiral pattern [30].

The vector value of chiral mechanism can be determined using $C = na_1 + ma_2$, where $a_1$ and $a_2$ represent the base vectors of graphite cell and also used to evaluate the tube radius and moreover this vector function also estimates the rolling direction of graphene sheet. Hence, the radius of carbon nanotube can be estimated using.

$$r = a\frac{m2 + mn + n2}{2\prod}$$

where a takes the lattice parameter in graphite sheet.

Whenever n – m = 3 times of any value, it indicates the carbon nanotube to be metallic or extremely conducting nature and if it is not so, it can be semi-metallic type or a semi-conductor. At most of the times, armchair type can be referred as metallic one whereas all other forms can be denoted as a semi-conductor. Various involved parameters and vector representations [31] can provide an impinging impact on structure of CNT as follows.

1. chiral vector = $na_1 + na_2 >> (n,m)$
2. Translational vector, $T = t_1a_1 + t_2a_2 >> (t_1, t_2)$
3. Chiral vector length, $L = a(n^2 + n.m + m^2)^{1/2}$ a is constant of lattice parameter.
4. angle of chiral vector = $(2n + m)/2^*(n^2 + n.m + m^2)^{1/2}$
5. radius = $L/2\prod$
6. Rotation angle, $\Psi = 2\prod/N$
7. vector of symmetry, $R = pa_1 + qa_2$

### *2.2.2 Formation of multi walled nanotubes*

Such MWCNTs can be developed via two distinct models such as Russian doll and Parchment type model. If the diameter of outer CNT exceeds the inner tube, such a model is prescribed as Russian type model whereas, wrapping of a single graphite sheet to many a fold around itself constitutes the simple Parchment model. Both multi walled and single walled CNTs possess similar properties. Due to multi-layered arrangement of multi walled nanotubes, the outer portion not only cover the inner tubes from certain chemical reactions when contaminate with ambient substances but also exhibit greater tensile characteristics, which would be a drawback of single walled CNTs [32].

Owing to the presence of $sp^2$ bonds available betwixt indigenous carbon atoms, CNTs possess higher tensile property compared to steel as well as Kevlar. such a bond exhibits more strength rather than $sp^3$ bonding of diamond. Hence, SWCNTs possess maximum tensile property which may be nearly 100 times as that of steel [33].

### *2.2.3 Elasticity property*

An amazing feature of CNTs is its elasticity. Under maximum force and high pressure by exposing it to greater compressive forces along axial direction, it can even bend, kink, twist and ultimately buckle without causing any damage to CNT. Thus nanocarbon tubes can retain its original geometric structure. But sometimes, elasticity tends to cope up with a limit and hence under the influence of stronger physical pressure forces, it can even undergo a temporary deformation to form the nanotube shape. Few defects may weaken its structure which includes the atomic defects or else rearrangement developed on the carbon bonds.

The elasticity property for both single walled and multi walled CNTs is examined by the term known as modulus of elasticity or elastic modulus. Such property of multi-walled CNTs can be analyzed using transmission electron microscopy (TEM). Using such an apparatus, the researchers examine and investigate the molecular vibrations owing to thermal forces created at both edges of tubes [34].

As the atomic bond strength is high, CNTs not only withstand elevated temperature levels but also act as excellent thermal conductors. Hence under vacuum atmospheric pressure ranges, they are able to withstand 2900°C and nearly 800°C at normal pressure conditions. But the prevailing tube temperature and ambient environment may have an impact on thermal conductivity of carbon nanotubes [35]. The prescribed physical properties were outlined in **Table 1**.

Various types of indigenous single walled CNTs obtained using chemical vapor deposition technique onto a supporting chemical agent are mostly of semi-conducting nature (I type). Such nanotube type depicts the impact of field transistor (FET) nature at atmospheric conditions and these have been recently attaining greater interest and also achieved extensive exploration towards their application as nano-electronic materials indulging logic circuit devices and electronic transistors. Such growing CNTs are seemed to be p-type containing doped holes with absolute hole depletion and reduced conductance values (100 kΩ to 1 MΩ) in specific to positive logic gate voltages. in the present context, it has been demonstrated that adsorption of molecular oxygen onto the CNTs is a contributing factor do drive the hole doping effect of SWCNTs. Oxygen removal can even lead to mere existence of semi-conducting nature. Instead, day by day investigations on CNTs reveals that the electrical properties of such carbon nanotubes are much sensitive to chemical doping impacts and charge transfer mechanism in spite of exhibiting extreme robustness [36].

The II type CNTs developed by CVD technique appears to be quasi metallic consisting smaller band gaps in the order of 10 meV. Such CNTs are not sensitive compared to semi-conducting type due to their electrostatic doping mechanism through gate potentials but exhibit a mere conductance dip occluded with that of smaller band gap. These CNTs origin towards a class of non-armchair single walled CNTs and band origin may be due to shift of $sp^2$ to $sp^3$ orbital hybridization which occurs prominently by the existence of non-flat hexagonal nature of tube walls. Quasi metallic types exhibit enhanced electrical conductivity at low temperature levels when subjected to temperature dependent experimental studies [37].

| Physical properties | Parameter | Range | References |
|---|---|---|---|
| Structure during equilibrium | Mean diameter | 1.3–1.5 nm | [31] |
| Density | Zig zag (16,0) | 1.33 g/cm$^3$ | [30] |
| | Armchair (10,9) | 1.32 g/cm$^3$ | [30] |
| | Chiral (12,5) | 1.41 g/cm$^3$ | [32] |
| Lattice parameter | Zig zag (16,0) | 16.53 nm | [32] |
| | Chiral (12,5) | 16.53 nm | [33] |
| | Arm chair (10,9) | 16.55 nm | [32] |
| Interlayer distance | Zig zag | 3.40 Å | [33] |
| | Chiral | 3.38 Å | [33] |
| | Arm chair | 3.37 Å | [34] |
| Elastic nature | Young's modulus | 1.0–1.27 TPa | [35] |
| | Tensile strength | About 100 GPa | [35] |
| Thermal property | Mean free path | Around 100 nm | [36] |
| | Thermal conductivity | Around 2000 W/m-K | [37] |
| Electrical behavior | Current density | 1015 A/m$^2$ | [38] |
| | Conductance | 13.0 (K.Ohms)$^{-1}$ | [38] |

**Table 1.**
*Physical properties of CNTs.*

Even quantum interfering impacts were also being observed: (1) phonon acts as the basic scattering mechanism existing in single walled CNTs at ambient conditions and (2) excellent levels of ohmic frequency contacts can be proliferated in the nanotubes with a probability of adequate transmission T = 1 and 3 electron transfer is explicitly phase coherent along with ballistic ability in CNTs at even low temperature levels. This also suggest a lengthy mean distance for ballistic electron transfer in super quality CVD developed SWCNTs [39].

### *2.2.4 Electromechanical properties*

Schematic pattern of growth has been extensively used to obtain suspended CNTs in single wall across certain trenches along with normal nanotubes which may be electrically wired up with relative easiness. By manipulating a suspended CNT using an AFM probe while measuring its electrical conductivity, the impact of mechanical deformation on electrical characteristics of CNT can be judged. The wide scope of CNTs based on nanoelectro-mechanic (NEM) devices are invented to explore twisting pattern of single nanowires, pure stretching levels and also due to their high frequency characteristics of resonance measurements. Operated NEMs switches and accessible memory devices have also been envisioned in nearby future. Powerful control and deterministic mode of synthesis of CNT will further explore exciting opportunities and greater possibilities of finding novel nanomaterials and other devices [38].

### *2.2.5 Chemical properties and species interaction*

SWCNTs are mostly inert in nature. The covalent attachment agglomerated the molecular species with fully bonded sp$^2$ hybridization onto sidewalls of CNT proves to be complex. The adsorbed molecules onto CNTs through the development of non-covalent forces has evidently turned to be facile and consequently lead to possible effects on their physical properties and also with their potential applications. Desorption of orientation molecules from single walled tubes can be achieved by heating the nanotubes to higher temperature levels [40].

Similarly, illumination of UV light at low photon intensity forces a drastic molecular desorption rate from SWCNTs at even ambient conditions whereas, wavelength governing measurements predict that photo-desorption process may occur due to sudden excitation of electrons occluded in the nanotubes and perhaps it is a non-thermal process. The excitation of electrons in specific by ∏ plasmons included in SWCNTs due to UV light results in electron/hole pair formation which occur through Landau damping. The studies portray that surface and photochemistry problems are much predominant to exhibit properties and to create molecular nano surface wires that possess ultrahigh surface distribution with each and every atom accommodating onto the surface. Therefore, surface science study can be evaluated at single wire level itself by incorporating both chemical and electrical properties of CNTs as thin probes [41].

#### *2.2.6 Optical properties*

Carbon nanotubes have helpful assimilation, photoluminescence (fluorescence), and Raman spectroscopy properties. Spectroscopic strategies offer the chance of speedy and non-dangerous portrayal of moderately a lot of carbon nanotubes. There is a solid interest for such portrayal from the mechanical perspective: various parameters of nanotube union can be changed, purposefully or accidentally, to modify the nanotube quality. As demonstrated as follows, optical assimilation, photoluminescence, and Raman spectroscopies permit brisk and solid portrayal of this "nanotube quality" as far as non-rounded carbon content, structure (chirality) of the delivered nanotubes, and auxiliary imperfections. These highlights decide about some other properties, for example, optical, mechanical, and electrical properties [42].

Carbon nanotubes are novel "one-dimensional frameworks" which can be imagined as moved single sheets of graphite (or all the more accurately graphene). This rolling should be possible at various points and ebbs and flows bringing about various nanotube properties. The width normally fluctuates in the range 0.4–40 nm (i.e., "just" ~100 times), yet the length can shift ~100,000,000,000 times, from 0.14 nm to 55.5 cm [43] The nanotube perspective proportion, or the length-to-breadth proportion, can be as high as 132,000,000:1 [44] which is unmatched by some other material. Thusly, all the properties of the carbon nanotubes comparative with those of common semiconductors are incredibly anisotropic (directionally reliant) and tunable.

#### *2.2.7 Outline information*

While mechanical, electrical, and electrochemical (supercapacitor) properties of the carbon nanotubes are entrenched and have quick applications, the down to earth utilization of optical properties is yet muddled. The previously mentioned tunability of properties is conceivably helpful in optics and photonics. Specifically, light-discharging diodes (LEDs) and photograph detectors dependent on a solitary nanotube have been created in the lab. Their exceptional element is not the effectiveness, which is yet moderately low, however the limited selectivity in the frequency of discharge and recognition of light and the chance of its adjusting through the nanotube structure. What's more, bolometer and optoelectronic memory gadgets have been acknowledged on groups of single-walled carbon nanotubes [45].

Crystallographic absconds additionally influence the cylinder's electrical properties. A typical outcome is brought down conductivity through the flawed space of the cylinder. An imperfection in easy chair type tubes (which can lead power) can make the encompassing area become semiconducting, and single monatomic opening incite attractive properties.

## 3. Applications

### 3.1 Biomedical field

The characteristic properties ascertained to CNTs are really enthusiastic. in the last decades, many research studies have proposed potential uses of CNTs and also have remarkably portrayed promising applications when such newly developed materials are joined together with typical scientific products, for example, nanorods production using such CNTs as reactive template materials.

Applications of CNTs encompass major fields and various disciplines, which include nanotechnology, medicine, construction, manufacturing, electronics, peripheral hardware, software and so on **Figure 7**. The mentioned applications can be considered: actuators, composites with maximum strength, energy storage as well as energy conversion equipment, media for $H_2$ storage, nanosensors and probes, electronic instruments and process catalysis. Anyway the forthcoming sections will highlight detailed applications of CNTs in biomedical field. There are three parameters which may act as barriers before using CNTs in the fields of biotechnology and biomedical based industry. These barriers have to be overcome: toxicity, pharmacology and functionalization perspectives of CNTs [46].

The most prominent barrier is toxic nature of CNTs. In general, the coexistence of maximum surface area rendered by CNT along with the intrinsic toxic nature of nano surface can become most important for the harmful impacts of aggregated nanoparticles. The toxic nature of CNTs can be influenced by the particle size of designed nanotubes. If the particles are less than a size of 100 nm, they are able to exhibit definite harmful effects such as enhanced potential hazard to the liver, lung, protein structure modification, escape from usual phagocytic powerful attacks, activation of immunological and inflammatory responses, and explicit redistribution strategy from their spot of tube deposition [47].

Another predominant barrier with CNT is the pharmacokinetics and biodistribution of aggregated nanoparticles which are in-turn influenced by distinct physicochemical attributes such as size, shape, aggregation capacity, chemical composition, solubility of surface and effective fictionalization. Previously made studies have demonstrated that CNTs of water soluble nature are much more biocompatible with the inbuilt human body fluids and also do not show any toxic ill-effects or abnormal mortality [48].

The most notable disadvantage of CNTs is the lack of aqueous solubility when exposed to any media and in order to eradicate such a problem, surface modification is introduced on the carbon nanotubes, that is, stable fictionalization of surface with suitable hydrophilic substituents and reaction chemistries which can improve both aqueous solubility as well as biocompatibility of CNT [49].

### 3.2 Artificial implant scopes

Nanomaterials portray their chosen probability and thrusted promise in the field of regenerative medicine due to their extraneous physical/chemical properties. In general, the rejected implant materials which may be the cause for post administration implant pain and in order to avoid such rejection, nanotubes were attached to amino acids and to proteins, thereby achieved a promising development. Both the single and multi-walled forms can be effectively utilized as implants which may be either artificial joints or else other implant materials without any kind of host rejection output response. Perhaps, due to its unique material properties such as maximum tensile strength, these can effectively act as implant materials for bone substitutes and if suitably filled with calcium, such implants can be shaped or arranged within the bone structure [50, 51].

It has also been invented that proliferation and cellular adhesion can increase with the availability of SW and MW carbon nanotube composites and hence, these can be essentially integrated into natural nanomaterials and synthetic type materials to fabricate suitable nanocomposites. The specific type of CNT accustomed to artificial implants was represented in **Table 2**.

### 3.3 Tissue engineering

The scope of tissue engineering lies in the substitution of damaged tissue using biological alternatives that can possibly replace/repair original and normal function. The recent advances in the emerging fields of material science have been promisingly supported in the growth of tissue engineering and regenerative medicine [54].

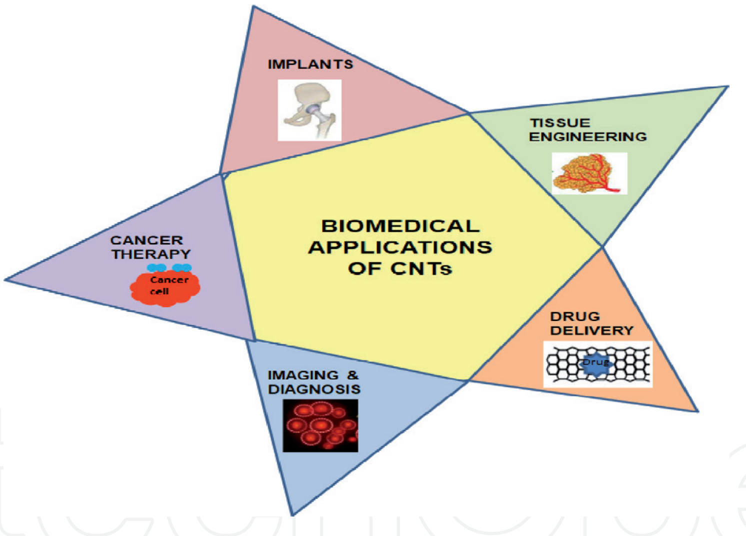


**Figure 7.**
*CNT applications in biomedical field.*

| Type of CNT | Background materials | Properties | References |
|---|---|---|---|
| SWCNT impregnated | Chitosan type | Enhancement in cell morphology and growth | [50] |
| SWCNT (pore type) | Membrane of polycarbonates | Increase cytoskeletal extensions | [51] |
| SWCNT | Sodium alginate | Elevate proliferation | [51] |
| MWCNT | Collagen type | Enhancement in cellular adhesion | [52] |
| MWCNT | Poly-acrylic acid type | Improves cellular discrimination | [53] |

**Table 2.**
*Nature of CNT in artificial implants application.*

CNTs can be recommended for use in the field of tissue engineering under four different perspectives. They are cell tracking/labeling, sensing cellular nature and mechanism, augmenting the mechanism and enhancing the tissue matrices. Cell tracking/labeling is the specific capacity to identify implanted cell structures and to record the noteworthy improvement of tissue growth in vivo as well noninvasively [52]. Labeling of transferred cells by implants not only permits the evaluation of engineered tissue viability but also promotes a deep understanding of migration, bio-distribution, movement pathways and relocation of implanted cells. The non-invasive techniques nowadays become more familiar than traditional techniques such as cytometry owing to more time consumption and practical challenges associated with handling of usage. Hence, CNTs can be more feasible as contrast imaging agents for optical resolution, magnetic resonance behavior and also for radio tracer simulating models [54].

One of the prominent applications of CNTs in the study of tissue engineering is its ability to bio-distribution measurement and also it can be systematically varied using radiotracers applicable to gamma scintigraphy. The proper design of engineered tissue structures enhances and promotes monitoring of cellular physiology that includes protein/metabolite secretion rate, enzyme and other cofactor interactions, cellular growth/mechanism and molecules/ions transport. Novel nanosensors will be effectively utilized in such a way to determine continuous monitoring associated towards the working performance of engineered tissues.

Numerous and popular features involved in the structure of CNTs envisage them to become key elements for nanosensing devices owing to its maximum surface area and DNA or protein immobilizing capacity along with electrical properties [53].

Moreover, these carbon nanotubes possess distinctive electronic structures make the invention of redox active proteins and also amino acids thereby rendering the cell monitoring activity in engineered tissue patterns. In another research, MWNTs were combined with that of platinum micro nanoparticles and also able to identify thiols such as prescribed amino acids which include glutathione and L-cysteine observations in rat.

The cell matrix predominates its function in tissue engineering. Even though, PLA and PLGA have been utilized for tissue engineering, they tend to adopt the inbuilt mechanical strength and cannot be just functionalized pertaining to controversial version of synthetic polymer compounds. Hence, CNTs have potential applications as tissue scaffolds and able to ascertain the structural reinforcement. The only demerit of CNTs is such that they are not biodegradable. When CNTs are dissolved in certain quantity of polymeric substance, rapid enhancement in mechanical strength has been promptly noted. If these MWNTs combine with chitosan material it may lead to advancement in properties whereas SWNT on blending with natural collagen improves the cell growth of smooth muscles [43].

### 3.4 Cancer cells tracing

Nanodevices have been investigated that has the effective potential to generate new techniques in cancer treatment, diagnosis as well as detection. The geometric structures of these nanomaterials may be very small (< 100 nm) such that the body will evacuate it rapidly so as to become more efficient either through detection or by imaging and thereby enter the damaged cells and organelles inside the body to have interaction with DNA or protein molecules. The possible detection of cervical cancer causing cells among human beings can be improved by carrying out modification on the graphene electrode using peptide form of nanotube folic acid [55].

As large quantity of cancer types is truly asymptotic throughout their initial stage and also due to absence of specific morphologic modifications among most of the neoplastic disorders in preliminary stage, possibly traditional cancer imaging and clinical methods such as X-ray, CT scan and even MRI scan does not require any kind of spatial resolution for such disease detection in initial stages. Imaging analysis using single walled CNTs have been explored for the past few decades. Coupling of radioisotopes with single walled CNTs along with imaging techniques based on radio nucleotides can progress advancement in tissue sensitivity, penetration as well as nano medium spatial resolution.

Many sophisticated protein biomarkers are available which are often overexpressed in the interior of cancer cells and they offer an entry mark for preliminary diagnosis, maintaining surveillance, prognosis, curative surgery techniques, advancement in disease monitoring therapy and finally detecting therapeutic response. Special categories of tumor biomarkers have been tremendously applied and also conceivably utilized in diagnosis and treatment of hepatocellular carcinoma, pancreatic, colorectal cancer, prostate cancer, ovarian tumor on epithelial cells which includes CA19-9 (carbohydrate antigen), carcinoembryonic antigen (CEA), alpha fetoprotein (AFP), human chorionic gonadotropin (hCG), carcinoma antigen 125 (CA125) and specific antigen to prostate (PSA) [27].

### 3.5 Gene and drug delivery applications

There are various interim obstacles associated with conventional application and administration of chemo-therapic agents which includes system toxicity, lack of proper sensitivity/selectivity, minimum solubility, poor cellular distribution, lagging of certain clinical procedures, and inefficiency of specific drugs to overcome the cellular barriers for achieving the treatment of multidrug resistive cancer disease. Scientists and research experts have conceptualized various drug handling/delivery systems to combat these terrific issues using silica nanomaterials, quantum dots, polymeric materials, dendrimers, liposomes, emulsions, micelles and even molecular conjugates [56, 57].

As discussed above **Table 3**, CNTs possess specific features such as ultrapure/maximum surface distribution, which essentially provoke them to act as a promising tool for drug delivery, nucleic acids and peptides. The selective drug or desired gene can be effectively coupled with tips and walls of carbon nanotubes and can easily trace out specific cancer causing receptors that are available on the cell structure and thereby such CNTs can even over cross the cell membrane of mammals through the mechanism of endocytosis or other plausible procedures. Thus, it can recognize the therapeutic drugs/genes much more reliably and safely in the affected cells that are reluctantly inaccessible during previous procedures.

Recent discoveries of research experts paved the way to invent novel and efficient single walled CNT based drug delivery tool for targeting tumor which comprises of targeting ligands for tumor, drugs for anticancer treatment and also functionalized single walled CNTs. If such system has an interaction with cancer causing cells, it can provoke the receptor assisted endocytosis by identifying specific receptors to cancer cells onto the affected cell surface and perhaps specifically and efficiently release the active chemotherapeutic agents [58]. The release of drugs using CNTs were highlighted in **Table 3**.

### 3.6 Sensor-based biomedical applications

In cardiology field, the CNTs are used for artificial valves to heart blocks, pacemakers, etc. These CNTs may be involved either as individual or in combined form to synthesize smart sensors and various multi-functional materials. They possess maximum aspect ratios that make the CNT to be extremely ideal for operating longer duration and of course continuous sensing. Their greater surface distribution shall be definitely exploited for providing material deposition in order to generate hybrid variety of functional materials or better functionalized to formulate different electrodes for certain applications [59].

CNTs are much prone to promote its ballistic conductivity which may occur owing to minimum scattering of electrons in their one dimensional solid structure containing mean free paths in the measurable range of tens to microns. The exerted mechanical stress/strain can even aid few reproducible changes acquainted with the electrical properties involved in CNT fibers, thereby felicitating it extremely viable to act as electro mechanical sensor devices. The occluded changes are noted as capacitance, inductance and electric resistance which can be directly correlated to the impact of strain **Figure 8**. Moreover, such CNTs are hugely responsive to compressive, flexural, tensile /torsional strain [60, 61].

The working mechanism of sensors derived from a simple CNT macroscopic assembly inculcate the change of their electrical resistance or resistivity resulting from mechanical strain is said to be piezo-resistivity, change of its inductance/capacitance via mechanical strain, variation of its electrical resistivity with a plausible variation with temperature is said to be thermo resistivity and a magnetoresistance may result due to variation in electrical resistance which may be due to varying magnetic field is known as magnetoresistance [62].

| Nucleic acid/ drug-CNT type | Cell/tissue | Properties |
|---|---|---|
| Doxorubicin—SWCNT | Colon cancer | Efficient take up of cancer causing cells and then transfers to nucleus |
| Radionuclide-SWCNT | Burkitt lymphocytes | Targeted tumor both in vitro/in vivo |
| siRNA-SWCNT | Human neuro cells | Improves the working of siRNA assisted gastrin peptide receptor |
| Toxic siRNA—MWCNT | Human lung system | Inhibits discrete tumor growth |
| Cisplatin—SWCNT | Neuro Carcinoma | Tumor development—drastic recession |
| Paclitaxel—SWCNT | Breast cancer | Improved efficacy in treatment with minimal effects |

**Table 3.**
*Release of drugs from CNTs.*

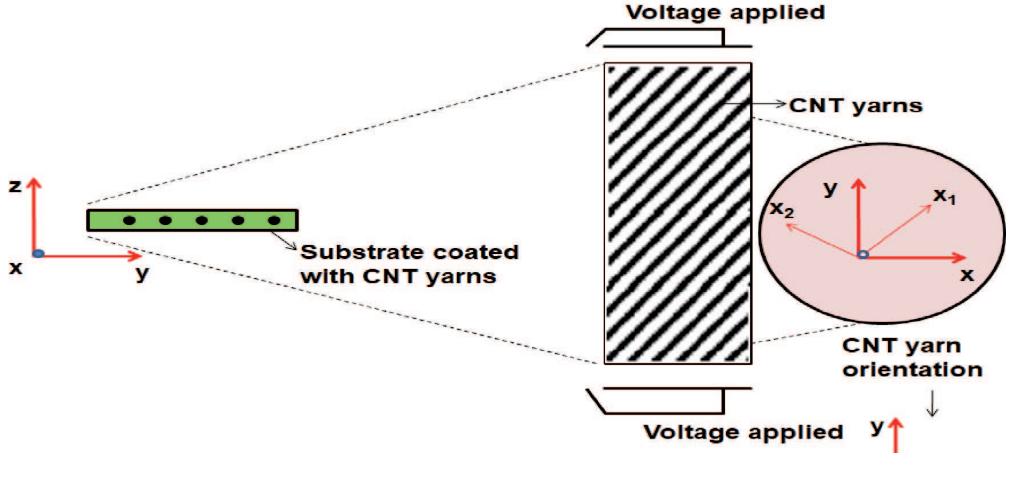


**Figure 8.**
*Nanosensor schematic representation.*

Even electrical resistance change can occur owing to variation in mechanical resonance frequency thereby resulting change in temperature, mass, pressure and strain. In contrast, the simultaneous change in electrical conductance/resistance is most predominant than any other mild variation accustomed in electrical properties. This happens partially due to selective and simple separation of charge carriers under the influence of temporary/permanent deformation which may lead to certain elevation in resistance. For every minute strain effects, the deformation is shown to be extremely elastic and the electrically conductive mechanism can be completely withdrawn due to its associated strain removal and thereby leads to a deduction in resistance [63]. However, plastic deformation has been proved to be much different. Though the resistance approaches zero due to strain removal and hence hysteresis curve has been fully observed. The various sensors involved with such CNT fiber yawns were strain type, pressure sensor devices, chemical sensors, and even mass sensors.

## 4. Conclusion

Nanomaterials provide an enriched knowledge on distinct probability and also definitely sound well in biomedical regenerative therapy for its uniqueness owing to its excellent physical as well as chemical properties. Thus, CNT both in modified and purified type have a definite potential of establishing promising applications in wide sectors of scientific fields. Perhaps, the prompt impregnation of other substituents in carbon nanoforms would confirm its strong perspective for their enhancing biomedical applications and in general medicine. Still then, there exist questions on unsolved issues whereas proximate homogeneity of the selected nanomaterial contains extensive distribution of nanotubes radius, unlike its geometric structures, classification of nanotubes, trace inclusion of residual elements, and a marked sensitivity to different species and other toxic gases.

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