Current Researches on Novel Applications of Carbon Nanotubes

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Abstract: Nanostructured materials are of extraordinary intrigued within the vitality capacity and change field due to their great mechanical and electrical properties. Carbon nanotubes are substances which have been shown those properties. They are an interesting nanostructure that has promising possibilities for future applications. CNTs have different allotropes such as fullerenes, CNTs and graphene. They have been subjects of wide investigate intrigued due to their potential for novel applications spread over the logical range. Graphene to a great extent considered the essential of all carbon allotropes can be formed to make 0D fullerene or rolled to create 1D CNTs. CNTs come in numerous shapes which shift by diameter and by the course of action of their hexagonal clusters within the grid. These contrasts result in the changes to the thickness of electronic states and give each sort of CNTs one of a kind of electrical and basic properties. Progresses in synthesis and decontamination have given analysts get to higher quality materials which has empowered distant better and improved understanding of their properties and their guarantee for future electronic applications.

Keywords: Carbon Nanotubes, Cnts, Single-Walled Carbon Nanotubes, Double-Walled Carbon Nanotubes, Multi-Walled Carbon Nanotubes

1. Introduction

CNTs are one dimensional nano-materials, which have a wide range of applications due to their unique properties. The revelation of the fullerenes in 1985 (Kroto, Heath, O'Brien, Curl, & Smalley, 1985) and the investigate that was taken after gave modern experiences into the properties of sp^2 hybridized carbon allotropes. CNTs were first discovered by the Japanese scientist S. Iijima in 1991. After his study many researches and scientists have contributed in the development of this promising carbon allotrope. These studies show the unique characteristic such as electronic, mechanical and optical due to their physical properties such aspect ratio and electronic properties. Carbon nanotubes are basically rolled up graphene sheets with one to several layers (Subramoney, 1997). Based on the number of layers' carbon nanotubes are classified into three types.

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1.1 Single-Walled Carbon Nanotubes (SWCNTs)

Single-walled carbon nanotubes (SWCNTs) are the simplest carbon nanotubes which consist of only one honeycomb layer of graphene sheet in a cylindrical shape with approximately 1-3 nm (Subramoney, 1997). SWCNTs are prepared in different methods such as laser ablation, chemical vapor deposition (CVD), arc discharge, gas-phase catalytic growth and pyrolysis (Haddon, 2002).

SWCNTs consist of different shapes which have great impact on their electronic properties. There are three shapes of SWCNTs such as zigzag, armchair and chiral carbon nanotube (Saito, Fujita, Dresselhaus, & Dresselhaus, 1992b). Both of the achiral carbon nanotubes have similar mirror image with their original shapes. On the other hand, there is a chiral structure whose mirror image is nonsymmetrical with its original structure. Figure 1.a demonstrates different types of SWCNTs. Based on the shape and size the carbon nanotubes can be conductor or semiconductor (A. Lu & Pan, 2004). Some theoretical works show that the armchair nanotubes are the only metal behavior carbon nanotubes. Whereas, other carbon nanotubes possess semiconductor properties (Hároz et al., 2013).

1.2 Double-Walled Carbon Nanotubes (DWCNTs)

Double-walled carbon nanotubes (DWCNTs) are coaxial nanostructures composed of precisely two single-walled carbon nanotubes, one settled in another (Figure 1.b). This special structure offers focal points and openings for amplifying our information and application of the carbon nano materials family (Yang, 2017). Both layers are connected by Van der Waals interactions which are weak bonds. These structures have pulled in much consideration since they are perfect framework investigate the impact of the interlayer interaction on the physical properties, and for the future work will be great significance (Popov, 2020). A theoretical study shows that the transport properties of specific DWCNTs which appear a sensational variety in conductance corresponding to variety of chirality of inward and external dividers. The external wall also plays a part of assurance on inward divider (Wu et al., 2015).

A theoretical work on electronic structure of DWCNTs shows that the electronic band hole of the DWCNTs depends on the inter-wall remove as it were for metallic semiconductor arrangements and on the natural properties of the constituent tubes in all other combinations (Wu et al., 2015). It can be stated that, the calculated band crevice for most of the metallic-metallic DWCNTs was less than semiconductor metallic, metallic-semiconductor, and semiconductor-semiconductor arrangements. Metallic-semiconductor DWCNTs were found to be alluring for band hole tuning applications since of their reliance on inter-wall separate, opening up the plausibility of utilizing such frameworks in electronic gadget applications, such as transistors. Other applications incorporate the utilize of DWCNTs in plainly visible carbon nanotube conducting wires, for which metallic-metallic and semiconducting-metallic zigzag-zigzag DWCNTs were found to be the foremost alluring setups due to their little band crevices (Soto et al., 2015).

1.3 Multi-Walled Carbon Nanotubes (MWCNTs)

Multi-walled carbon nanotubes (MWCNTs) are a collection of several coaxial SWCNTs sheets. A graphitic plane space makes a separation between the sheets of SWCNTs. The distance between the SWCNTs in the MWCNTs is approximately 0.34 nm near the inner-wall of the graphite distances. While the diameter of each sheet of SWCNTs in MWCNTs starts from 2 to 25 nm in terms of size (Saito, Fujita, Dresselhaus, & Dresselhaus, 1992a). MWCNTs was the first observation of CNTs by

Iijima of the NEC Laboratory in Japan in 1991 (Dresselhaus & Avouris, 2001). MWCNTs have been found to be self-assembly connected as they grow and the bond that connected the single tubules is Van der Waals force (Bierdel et al., 2007). MWCNTs have high electrical conduction, especially when they are doped with other elements. Interestingly, the outer layer is more conductive in comparison with the inter layers. The most inter layer has no conductivity (Ando, Zhao, Shimoyama, Sakai, & Kaneto, 1999).

The length of MWCNTs is much bigger than their diameter which is 100 times higher than the aspect ratio. In addition to the aspect ratio straightness of the tubes and engagement degree are other factors that have great impact on the application of MWCNTs (Guo et al., 2014). This allotrope of CNTs can be extended easily when they are subjected with thermoplastic or thermoset materials as a composite. The reason behind this incredible characteristic is the possession of MWCNTs with great tensile strength (Gangu, Maddila, & Jonnalagadda, 2019). MWCNTs are resistant to temperature of higher than 600 ºC. However, catalysts can enhance the rate of their decomposition. The level of defects and purity put a great impact to their thermal stability. MWCNTs are chemically stable due to their bonding with sp2 hybridization. This property makes them to be analogous to graphite and fullerene. On the other hand, their strength and composite dispersibility can be raised by their functionalization with different active groups (Yang, Li, Zhu, Wang, & Descorme, 2008).

Despite the above advantages of MWCNTs, some drawbacks are observed in terms of dispersion, purity and defects. MWCNTs have more dispersion in comparison with SWCNTs in different solutions and polymers (Barus et al., 2010). The final yield is strongly relying on the quality of dispersions. The existence of residual metallic catalyst is a considerable problem in the processes of MWCNTs, which has great impact on the quality of the product. The number of layers in MWCNTs demonstrates a great role in the numbers of the defects. The use of MWCNTs is contributed mainly on their high aspect ratio (Lu et al., 2011).

MWCNTs like other nanostructure materials can be characterized by applying instrumental techniques such as AFM, SEM and TEM in order to determine their diameter, length and the number of layers. Additionally, the residual mass, the temperature of onset of oxidation and maximum oxidation rate of MWCNTs can be analyzed with thermo-gravimetric analysis (TGA) (Huynh et al., 2020).

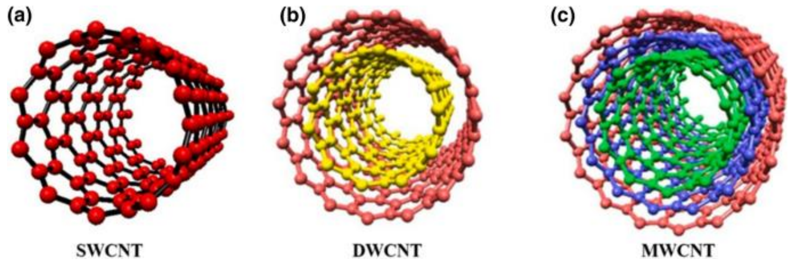

Figure 1: Structure of (a) SWCNT, (b) DWCNT, and (c) MWCNT (Shen, Brozena, & Wang, 2011).

2. Physical Properties of Carbon Nanotubes

Recently practical investigations indicate that the carbon nanotubes have the stiffest structure in comparison with other materials (Adohi, Mdarhri, Prunier, Haidar, & Brosseau, 2010). CNTs are one dimensional nanoparticle which is a simple structure. The simplicity in the structure of CNTs leads to spectacular electrical, mechanical, optical (An, Feng, & Lu, 2011), magnetic and electronic properties (Shtogun & Woods, 2009). SWCNTs are mostly investigated due to their elementary composition in comparison with other CNTs and this causes the SWCNTs to be compared easily between theoretical and practical data (Okpalugo, Papakonstantinou, Murphy, McLaughlin, & Brown, 2005).

CNTs allegedly have greatly wide surface areas, large aspect ratios, and strikingly tall mechanical strength. The tensile strength of CNTs is 100 times more noteworthy than that of steel, and the electrical and thermal conductivities approach those of copper (Ebbesen et al., 1996). These one of a kind properties make CNTs great candidates as fillers completely different polymers and ceramics to realize alluring buyer items (Chang et al., 2005). It has too been anticipated that CNT-based field-effect transistors (FETs) will before long supplant their silicon-based analog partners (Wepasnick, Smith, Bitter, & Howard Fairbrother, 2010). CNTs are moreover great consolidating specialists due to their special electrical, mechanical and thermal properties.

2.1 Mechanical Properties

Due to their special mechanical characteristic, Graphite is widely utilized in different industrial products. However, in microscopic level the researches have faced with obstacles due to their enormous anisotropy which gives weakness in crack propagation initiation. As long as modulus is inversed with tensile strength, carbon nanotubes as nanomaterial made of graphite cannot be investigated easily (Bajpai, Yadav, Tiwari, Rastogi, & Deva, 2015).

There are some important parameters to study the mechanical properties of CNTs such as tensile strength and Young's modulus. In spite of difficulties to measure in nano-scale level, the mechanical properties of the carbon nanotubes can be measured with the help of atomic force microscope (AFM) both qualitatively and quantitatively. However, there is a problem with AFM, when the beam is sent over the nanotube it inters empty area where no nanotubes exist. Alternatively, the nanotube is covered on an alumina substrate with a high filtration. With this method the nanotube layer covers all the empty space on the substrate. The interaction force between the wall and the nanotube fastens the attraction between the substrate and the tubes. After that the AFM is utilized to the sample in order to analyze the amount of deflected beam. Finally, the diameter and length of the nanotubes can be determined (Ando et al., 1999).

Theoretical research has been done with the aid of an observational force-constant model for single and multi-wall nanotubes. In this study the elastic moduli are appeared to be heartless to points of interest of the structure such as the helicity, the tube radius and the number of walls. The tensile Young's modulus and the torsion shear modulus calculated are comparable to that of the precious stone, whereas the bulk modulus is littler (Lu, 1997).

Both practical and theoretical studied indicates the CNTs potentiality and their suitability for a wide range of technological applications due to their flexibility and convenient mechanical properties.

2.2 Electronic Properties

Graphene can be considered as zero-band gap or a metal. The reason behind this is that the Fermi energy has zero density of states, which take a great role in determining the electrical properties of the nanotubes. The conductivity of CNTs is strongly dependent on the chirality and the diameter of their tubes (Ajayan, 1999) (see Figure 2).

The hexagonal bonding in carbon atoms in CNTs decides on the shape of electronic band structure. Since a carbon atom possesses six electrons in its outer shell, three of them are bonded with sp2 molecular orbitals and all others are hybridized with pi-band. The CNTs can be metal or semiconductor due to the existence of an even numbers of electrons in the two carbon atoms of the unit cell of the graphene (Zhang et al., 2015).

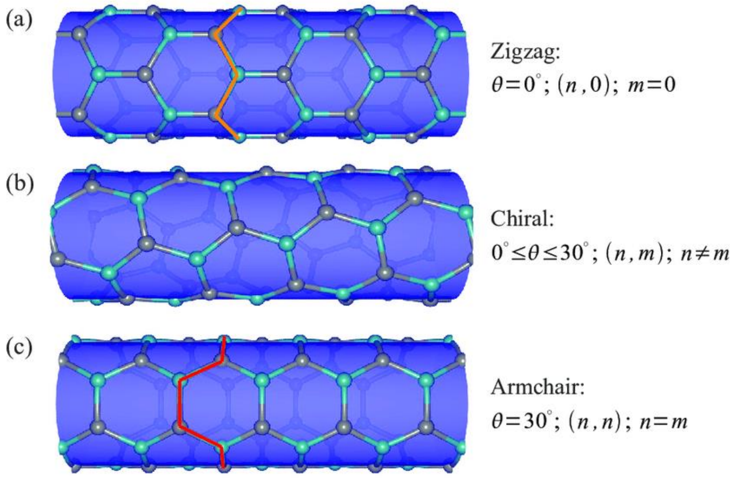

Figure 2: The formation of CNTs lattice in different shapes: (a) Zigzag, (b) Chiral and (c) Armchair which is represented with its angles (Mamalis, Vogtländer, & Markopoulos, 2004).

The conductivity can be determined through the arrangement of the graphite sheets, in which the integer numbers (armchairs) as (0,0), (1,1) and so on… behaves like metals. Whereas, others behave as non-metal/semiconductor. The conductivity of semiconductor CNTs is carried out by the holes which belong to P-type semiconductors. Generally, one- third of the CNTs are considered to be metals, while the others two-third of the graphene nanotubes are semiconductors (Saito et al., 1992b). In order to apply the carbon nanotubes in a variety of electronic instruments, it is considered to combine their metallic and semiconductor types as hetero-junctions. For this reason the manipulation of various sides of the graphene tubule can be done to control their physical and chemical properties (Valentini et al., 2003).

2.3 Thermal Properties of CNTs

Due to the significance and wide applications of CNTs it's worthwhile to study their thermal properties in addition to the mechanical and electronic properties. CNTs possess small sizes this unique property leads to changes in their thermal property in comparison with their essential material, graphite. The functionalized CNTs can double the thermal conductivity, which can be applied in industry for thermal management applications (Ibrahim, 2013). The number of phonon-active modes, boundary surface scattering, and the length of the free path for the phonons are factors which have great impact on thermal properties of CNTs (Yu, Shi, Yao, Li, & Majumdar, 2005). The existence of impurities, the diameter and length of the tubes, atomic organization, the number of defect and surface morphology of the CNTs are other factor which influence the thermal properties of the CNTs (Maeda & Horie, 1999).

2.4 Optical Properties

Carbon nanotubes is a kind of material that possesses strange and exiting optical properties which entirely significant for curious material scientists. Similar to other properties, optical properties of

CNTs is considered as anisotropy (Zhang et al., 2013). The reason behind this unique characteristic of the CNTs is due to their special geometry, particularly when they interact with a beam of light. This phenomenon is for the CNTs can be proved through absorption, fluorescence and Raman spectra. With the aid of optical investigation, the electronic and geometrical structures of CNTs can be found. In other words, the optical and electronic properties of carbon nanotubes can be manipulated by changing their structures (X. Wan, Dong, & Xing, 1998). SWCNTs have optical properties similar to conducting polymer due to the effect of helical structure with metallic. On the other hand, the MWCNTs behave like graphite, which are not affected by helicity and geometry of the nanotubes. The diameter is considered to be the only factor that affects the optical properties of the MWCNTs (Popov, 2004).

Due to the limitation of information about the optical properties of CNTs in comparison with other properties, they are less applied in optical science (Misewich et al., 2003), bolometers (Itkis, Borondics, Yu, & Haddon, 2006) and optoelectronic memory (Star, Lu, Bradley, & Grüner, 2004) are almost only technologies which have utilized CNTs in their constructions. However, separated from coordinate applications, the optical properties of carbon nanotubes can be exceptionally valuable in their fabrication and application to other areas. Spectroscopic strategies offer the plausibility of fast and non-destructive characterization of moderately expansive sums of carbon nanotubes, producing nutty gritty estimations of non-tubular carbon substance, tube sort and chirality, structural defects, and numerous other properties that are important to those other applications (Wan et al., 1998).

2.5 Physical and Chemical Adsorption

The tabulate carbons are widely utilized in the applications which are depended on adsorption process. The physical and chemical properties of CNTs have great impact on the adsorption of the most of materials on them. The possession of surface area and porous are key factors for high quality of CNTs and have great impact in the adsorption of other materials on them. The defects; basal, in which the graphene plane is parallel to the surface, and edge, in which the graphene plane is perpendicular to the surface of adsorption. Due to high densities of unpaired electrons, the defects adjacent with the tubes play a vital role in the CNTs reactivity (Shanmugharaj et al., 2007).

3. Synthesis of Carbon Nanotubes

In order to produce the desired CNTs with specific properties the way of preparation of the nanotube is exceptionally significant to control the synthesis method. The reason behind this is that properties of the nanotubes is strongly depended on the structure and the structure of the CNTs, such as diameter and the length, is the most important factor that shapes their properties. Arc-discharge method, Chemical vaporize deposition (CVD) and the laser ablation method are the most widely used methods for the preparation of the CNTs (Awasthi, Srivastava, & Srivastava, 2005).

3.1 Arc-Discharge Method

Arc-discharge method is the first approach was applied for the preparation of CNTs comparative to the preparation of fullerene in 1991 by the discovery of the nanotubes (Iijima, 1991). In the Arc-discharge method a DC current is applied to a two carbon tools with about 1 mm distance and connected to electrodes of anode and cathod poles, the carbon nanotubes are grown on the negative electrode (Figure 3) (Yoshinori Ando & Zhao, 2006). The prossess is carried out in enclosed chamber full of helium or argon with a high temperature (Ibrahim, 2013).

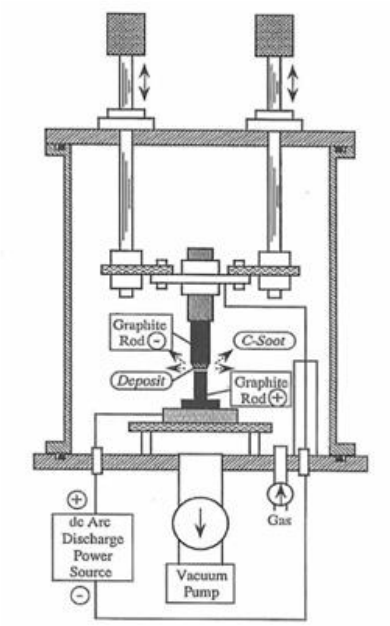

Figure 3: A schematic picture of Arc discharge device which is used for the preparation of CNTs (Yoshinori Ando & Zhao, 2006)

3.2 Laser Ablation Method

Laser ablation is another technique which is used to synthesize CNTs. Laser ablation is the method of evacuating fabric from a strong surface by lighting it with a laser pillar. The removal handle takes put in a vacuum chamber-either in vacuum or within the nearness of a few foundation gases. Within the case of oxide movies, oxygen is the foremost common foundation gas (Prasek et al., 2011). In this method a beam of laser is applied to bombard the aimed graphite in a controlled temperature. This process is carried out in an evacuated tube (see Figure 4). Then the temperature of the system is raised to 1200ºC. The targeted graphite is vaporized before focusing the laser beam on it (Ibrahim, 2013).

Dr. Richard Smalley and co-operators at Rice University, who is applied this method for the first time on various metals before the discovery of carbon nanotubes. After the discovery of the CNTs they substituted metals with graphite in order to synthesis Multi-walled carbon nanotubes (Guo, Nikolaev, Rinzler et al., 1995). Then they had used different metals with graphite as a composite to create single-walled carbon nanotubes (Guo, Nikolaev, Thess, Colbert, & Smalley, 1995). The quality of the carbon nanotubes obtained from the laser ablation method is strongly depended on the quality of laser beam, energy fluency, oscillation wavelength and the chemical composition of the aimed material (Chrzanowska et al., 2015). The advantage of the laser ablation is the almost high purity of the produced CNTs which is approximately 70%, which is much high and their composition is more graphitized in comparison than the synthesized CNTs in the arc discharge. However, the amount of the produced CNTs is small in the laser ablation method. This method is also more costly than Arc discharge and other methods (Szabó et al., 2010).

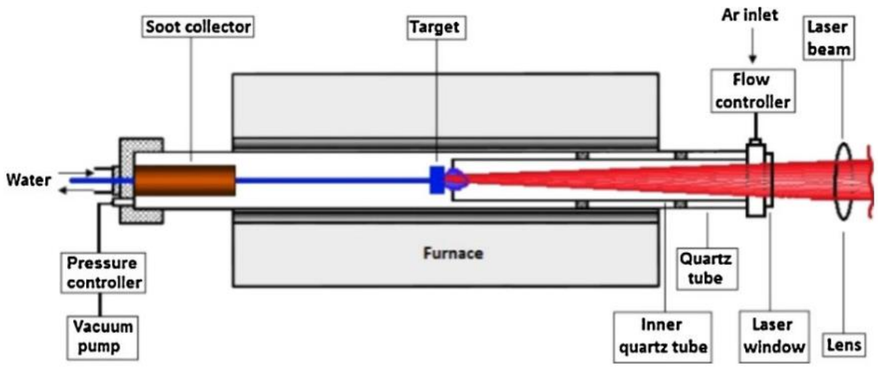

Figure 4: A schematic draw of Reactor for the production of carbon nanotube by the laser ablation method (Chrzanowska et al., 2015)

3.3 Chemical Vapor Deposition Method

Chemical Vapor Deposition (CVD) is a vapor process of coating solid materials on the surface of a heated substrate (An et al., 2011). During the process a chemical reaction in vapor state takes place to vaporize the solid substance into gaseous state after that it adsorbed on the surface of the substrate. The temperature and pressure of the system in the CVD process have to be controlled and a source of carbon, such as hydrocarbon, and an energy source is required (Ibrahim, 2013) (See Figure 5).

Several substances can be synthesized with CVD such as carbon, silicon, nitrides and many others, on the surface of a substrate, which is commonly transition metals are used (Wu & Chen, 2008), with different geometrical structures (2-dimensional, holes, 3-dimensional) during processes like coating, powders nanostructures, etc. The process starts with heating the substrate to about (500-900ºC). Then a hydrocarbon gas as a carbon source; methane, ethylene, etc. is added to a gas such as nitrogen. After that the gas mixtures are inserted into the chamber reactor to start producing carbon nanotubes. The hydrocarbon gas starts to decompose in the atmospheric pressure and the mentioned temperature. As a result, the product of carbon nanotube is deposited on the substrate (Xie et al., 1999). Many factors have effect on the quality of the produced CNTs. Physical effects such as temperature, pressure and rate of flow of the gases and other factors are the structure of the chamber reactor, carbon source, substrate composition and many mores (Jeon, Matsuo, & Maruyama, 2019).

Nowadays CVD is most widely applied to the synthesis of CNTs. This is because the product is produced in large quantities, is consistent, and costs less than using other techniques. The speed of the deposition is considerably high, which aids in reducing time consuming. On the other hand, some problems are being observed such as the high temperature applied. In addition, the CNTs could be deposited on the substrate which requires potential work to remove it, sometimes an acid is used to remove it which perhaps damage some of the synthesized CNTs (Szabó et al., 2010).

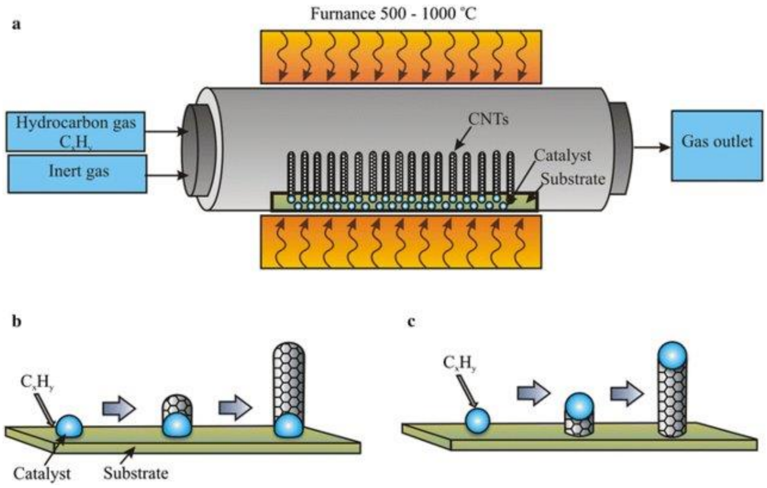

Figure 5: (a) Schematic representation of CVD procedure. (b) base-growth mechanism model of CNT; (c) tip-growth mechanism model of CNT (An et al., 2011)

4. Applications

Due to the spectacular properties, carbon nanotubes have a wide range of applications in several fields such as solar cell, medicine and drug delivery, energy and hydrogen energy, as chemicals, electronics, composite materials, environment, sensors and many other applications.

4.1 CNTs in Solar Cells

Due to their high ability to absorb UV/Vis light, CNTs are applied in Photovoltaic cells. The cells are consisting of semiconducting materials. They convert light into electrical energy. Numerous studies have been conducted in this field showing the CNTs' potential. An investigation has been on making SWNT hybrid solar cell to enhance its efficiency. These hybrids are created by mixing SWNTs with photo-excitable electron donors to rise the number of electrons generated. It has been observed that the interaction between the photo-excited porphyrin and SWNT at the surface of the CNTs produces electro-hole pairs. Experimental observation of this phenomenon has shown an increase in the capacity of the cells in a reasonable rate (Guldi et al., 2005). Another reason for the applicability of CNTs in solar cell is the difference in optical transmittance, which shows the semiconducting properties of the CNTs, SWCNTs in particular. This property makes the single tubes to participate in transferring the charges between the photovoltaic layers (Jeon et al., 2019).

4.2 CNTs in Electronic Devices

CNTs are a significant participant in electronic industries. They are applied in transistors, electron guns, thin films, antennas, brushers, computers, smart phones and many other devices. Several researches have been conducted in applying CNTs in electronic equipment. A research has shown that CNTs can improve the electrical properties of the electric motors through the orientation of the magnetic fields of some kinds of polymers (Kim et al., 2010). Another research in transistors has been done based on the single-walled carbon nanotubes. In this research, some field-effect transistors with three terminal switching instruments have been fabricated. The device included a semiconducting SWCNT connected to two metal electrodes. The nanotube can be converted between conduction behavior to insulation one, after the application of an electrical source (Tans, Verschueren, & Dekker, 1998). This research was conducted in ambient condition which was different with a previously work in low temperature (Tans et al., 1997). Many other investigations have been reported on the applications of CNTs in the electronic field.

4.3 CNTs in Medicine

The application of CNTs in the medical field is the most rapid and applicable in comparison with other fields due to the direct needs for human safety, easily penetrating cell membrane. Owing to unique characteristics such as high aspect ratio, electrical conductivity and mechanical power; CNTs have been deeply utilized in immunes of human body. They are mostly used in nanosensors, biosensors and bioelectronics because of the high electrical conductivity (Polizu, Savadogo, Poulin, & Yahia, 2006). In addition, the possession of wide surface area which helps in adsorbing greater amount of drugs, CNTs are intensively utilized in medicine and pharmaceutical cases (He et al., 2013). They are of great concern for recognizing biomolecules and transferring the therapeutic pharmaceuticals to the target position as a substitution to the previously drug deliveries. They are non-toxic and can aid in the dissociation of the used drug which can be more effective and cure the patients with high rate consumption (Polizu et al., 2006).

Despite the mentioned advantages, CNTs have some drawbacks when they are applied in medicine and pharmacology. Firstly, the high surface area could carry more than required amount of drug to the target organ, which can cause a harmful consequence in the human body. Secondly, some physical and chemical factors can affect the distribution and the rate of reactions of the nanotubes (Eatemadi et al., 2014). Thirdly, flawless CNTs, being metallic in their nature, are insoluble and they frame expansive bundles or ropes in numerous solvents, including water and most solvents, so they cannot be utilized specifically in biomedical applications. Much work has been done to prepare them for utilization in pharmaceuticals. Lastly, the CNTs are mostly heterogeneous in their structure which may be an issue for an era of reproducible comes about that permits assessment of the natural movement relating to particular structures. Up to date, huge endeavors have been put into the surface functionalization of CNTs for utilization in medication. This incorporates various compelling strategies for covalent or noncovalent adjustment of CNTs to scatter them into fluid arrangements and to connect useful particles for therapeutic applications. It is proposed that considerations are required to create the strategies for the era of CNTs with homogeneous measures, which is exceptionally imperative for future clinical applications of CNT-based therapeutics (Shao, Arghya, Yiyong, Rodes, & Prakash, 2013).

4.4 CNTs as Gas Storage and Energy Storage

CNTs can be used as storage of gases or energy in several technologies and fields:

4.4.1 Gas Storages

Recently gases have been used as an alternate to fuel liquid resources. However, the transportation of the gases from one place to another place requires to be liquefied to make it easier for movement. The liquefaction process of the gases leads to losing the potentials to a high ratio, which has economical drawbacks and have to be solved. Carbon nanotubes can be used for the storage of the gases. CNTs, particularly SWCNTs (Liu et al., 1999), are mostly suitable for storage of H2. Because they possess vacant cylindrical size and high surface area, which lead to high adsorption capacity (Park & Lee, 2009) and can help to reserve gases without liquefying. Thus, the potential of the carried gas can be conserved and the amount of lost decreased to a high rate (Dillon et al., 1997).

In spite of some advantageous of utilizing CNTs as gas storage, few controversies have been revealed. The existence of impurities, which comes from CNTs, is an obstacle that leads to uptake of the process of gas storage (Züttel et al., 2002). Theoretical investigations have been conducted that during the process of storage chemical adsorptions take place between the molecules of the surface of the CNTs and the molecules of the proposed stored gas. As a result, some amount of the gas will be consumed (Gordon & Saeger, 1999). However, these barriers to some extend are solvable via reducing the impurities of the CNTs, which can be done by applying convenient methods of synthesis and preparation such as chemical vapor deposition (Ibrahim, 2013). In addition, providing suitable physical conditions can help from protect from chemical adsorption of gases by the CNTs substrate (Darkrim, Malbrunot, & Tartaglia, 2002).

Hydrogen gas is not the only gas to be stored in CNTs. There are some other gases can be stored in carbon nanotubes. A theoretical study has been conducted using functional theory to investigate the storage of methane in the SWCNTs. This study reveals that an isolated SWCNT has higher efficiency to store methane than an idealized SWCNT. The study also shows that the internal surface of the SWCNTs can store more gas molecules than the external surface (Tanaka, El-Merraoui, Steele, & Kaneko, 2002). The storage of other gases such as helium (He), nitrogen dioxide (NO2) and some other gases are revealed (Vasylenko, Tokarchuk, & Jurga, 2015).

4.4.2 Energy Storage

Based on their spectacular properties, CNTs are considered as an efficient candidate for the progression of energy storage. They are applied in several energy storage devices such as supercapacitors, actuators, batteries and many other electrical devices. Studies have shown that applying the CNTs as energy storage can improve the performance of electrochemical cells. It was determined that the variation of the lithium diffusion coefficient DLi with the activities of Li-ion in MWNTs electrodes was inversed (Amin, Kumar, & Belharouak, 2020).

CNTs can be embedded to capacitors to enhance their performance to store energy to the devices that require great amount of power. Research in an electronics laboratory at Massachusetts Institute of Technology (MIT) has been done in order to enhance supercapacitors by applying CNTs. In this research CNTs have been used as an alternative to activated charcoal. Due to possessing nano-sized hollows inside the CNTs improvements have been observed (Kasuya et al., 1996).

Batteries are another industry that widely used CNTs in their components owing to the carbon nanotubes electronic properties. The lithium-ion batteries are the most embedded CNTs, which can be used to substitute with classical carbon black to take part in their anode electrodes. Researches have shown considerable capacity improvement, longer life and electronic movement; particularly when CNTs with high metallic properties are used; in the lithium ion batteries due to the continual charging and discharging (De las Casas & Li, 2012).

Furthermore, CNTs are applied to the cathode electrode of the lithium-ion batteries. In this process MWCNTs are mixed with some active substances and a kind of polymer. Consequently, enhancement in the charge capacity and life cycle of the batteries has been observed due to improvement in electrical and mechanical properties of batteries after the addition of CNTs (Susantyoko et al., 2018).

4.5 CNTs as Gas Sensors

CNTs are widely used to detect gases due to the possession of high sensitivity, selectivity and fast response. Basically, the suitability of CNTs in detecting gases is due to their spectacular electronic structure and electrical resistance. Researches show that SWCNTs are highly sensitive when they interact with other substances considerable variations in electrical conductivity, density of states and some other parameters have been observed. The adsorption of gases leads to changes in electrical properties which can convert the nanotube into metal from semiconducting property (Collins, Bradley, Ishigami, & Zettl, 2000). In addition, MWCNTs are also reported of great beneficial for the detection of gases such as NH3, CO2, CO and H2O gas (Varghese et al., 2001).

Moreover, the structure of the CNTs is another factor that aids to be a convenient substance for sensing gases. The extreme diameter and the hollow shape of the CNTs make these nanomaterials to be highly sensitive to environment, because the entire surface of the Nano tubular interacts with the environmental gases. Therefore, a small change in the environments directly influences the electronic and electrical properties of the CNTs. As a result, variations can be observed in the electrical conductivity (Piloto, 2016).

Numerous investigations have appeared that in spite of the fact that CNTs are vigorous and dormant structures, their electrical properties are amazingly delicate to the impacts of charge exchange and chemical doping by different particles. The electronic structures of target particles close the semiconducting nanotubes cause quantifiable changes to the nanotubes' electrical conductivity (Zhang, Mubeen, Myung, & Deshusses, 2008).

Interestingly, the interaction response of the CNTs is different for different gases. With some gases the exposure leads to the increase of electrical conductance, whereas with some others cause the reduce in electrical resistance of the CNTs. For example, some studies show that the interaction of NO2 with CNTs sensors has a considerable decrease in electrical resistance (Kong et al., 2000), other gases such as NH3, H2O, C6H6, ethanol, and oxygen cause the rise of electrical resistance (Collins et al., 2000).

Nevertheless, carbon nanotube sensors do not show responses to some gases in a normal condition such as H2 and CO. The gases have no obvious impact on the conductance of the sensors in ambient temperature. Alternatively, with the increase in temperature the detection of both gases can be possible (Han et al., 2020). In addition, some other solutions can lead to increase in the sensitivity of CNTs, where SWCNTs or MWCNTs, during their interaction with the gases. The chemical process such as functionalization which sometimes can show effects even at room temperature (Tavakkoli, Akhond, Ghorbankhani, & Absalan, 2020). The process of functionalization is the addition of metals, organic active groups; such as carboxylic and hydroxyl group, ionic liquids and many others to achieve the properties which are required. Covalent and non-covalent are the two ways to functionalize the carbon nanotubes due to the nature of carbon bonds in the carbon nanotube structure, which is sp2 (Karousis, Tagmatarchis, & Tasis, 2010).

Furthermore, H2S is another gas that is required frequent detection in air. H2S gas is poisonous, inconvenient small and erosive. There are many resources of H2S such as petroleum refinery process, sewage cleansing factory, natural gas treatment (Sayago et al., 2005). The concentration of H2S in air when reaches above 150 ppm, needs to be treated due to the extreme hazardous and toxicity (Wang & Yeow, 2009). Therefore, it is of great significant to construct instruments such as sensors to detect H2S with high sensitivity and many other properties. In order to, measure the gas with ultimate precision and to determine the lowest concentration as possible. There are numerous devices that have been invented for the detection of H2S such as gold as a metal sensor and metal oxides such as tin oxide. As was previously satated, the detection of gases depended on the variation of the sensors resistivity when they interact with each other. The conventional gas sensors show drawbacks such as lower sensitivity, selectivity and long-time response and recovery (Mubeen et al., 2010).

CNTs, as 1-dimentional nanostructures, have been substituted due to their enormous characteristics. They have been used due to their small size and remarkable sensitivity to even the smallest changes in the environment's electricity when exposed to other materials in a gaseous form.

The electronic and electrical properties of CNTs at room temperature change as a result of electrodeposition with various metals, such as platinum(Q. Wan, Zhang, & Gui, 2015), palladium (Kong, Chapline, & Dai, 2001), and gold (Mubeen et al., 2010), due to direct interaction of CNTs with some gases, particularly H2S. Few theoretical and computational studies have also been conducted as a result of the inability to effectively detect H2S at the atomic scale. Recently Salmankhani et al. (2020) have applied different theoretical methods by utilizing different substances to adsorption of the sensors to detect H2S (Salmankhani et al., 2020). In this study some metal oxides and graphene have been used as substrates with and without decoration Ni for doping. The results have shown that the doped graphene sheets with Ni, formed chemical adsorption more convenient than the metal oxides with and without doping and graphene without Ni, formed physical adsorption. As the carbon nanotubes have made of rolled graphene sheets, therefore, it can be an optimistic approach to be applied into carbon nanotubes. While, carbon nanotubes are a rolled graphene, this process of decoration can be more suitable for nanotubes than graphene due to high surface area particularly in SWCNs whish more sensitive and more surface interactions are existing. On the other hand, in a study by Srivastava et al., (Srivastava, Suman, Shrivastava, & Srivastava, 2019) has applied density functional theory as a theoretical approach to investigate the adsorption of H2S on SWCNT as a substrate alone and a SWCNT doped with Boron and Nitrogen. In this study different parameters have been applied to analyze the electronic variations, chemical and physical consequences. Surprisingly, the results demonstrated the higher response of pristine CNT than the doped ones in terms of time response, sensitivity and selectivity for the detection of the H2S as a gas sensor. The existence H2S molecule on the pristine SWCNT leads to the dramatic reduction in conductivity up to zero. Whereas for the two others doped CNTs with boron and nitrogen some fluctuations in conductivity have been noticed.

5. Conclusion

CNTs are the cylindrical graphene sheets in one, two and multiple layers called single-walled, double-walled and multi-walled carbon nanotubes. They have fascinating physicochemical properties which have been the case of numerous studies by the scientist and engineers. CNTs have shown variations in their electronic structure, conductance, and mechanical properties whenever they have applied to different fields and areas. Due to their sensitivity, selectivity, short-time response and recovery they have been applied to detect gases as sensors. Many gases have been detected using CNTs such as CO2, H2 and H2S. The detection of H2S is of great concern due to the toxicity of the gas. The adsorption and analysis of gases via applying CNTs as substrate sometimes leads to non-effective results. Therefore, researchers have utilized different methods such functionalization with active groups and doping with some metals, transition metals in particular.

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