ISSN: 2996 - 2498

Research Article

Environmental Science and Climate Research

Carbon Nanotubes: Methods, Achievements, Challenges, and Future Directions

Renaissa Ghosh*

Department of Electrical and Computer Engineering Rutgers University-New Brunswick Piscataway, NJ, USA

***Corresponding Author**
Renaissa Ghosh, Department of Electrical and Computer Engineering Rutgers University-New Brunswick Piscataway, NJ, USA.

Submitted: 2024, Oct 04; **Accepted**: 2024, Nov 29; **Published**: 2024, Dec 23

Citation: Ghosh, R. (2024). Carbon Nanotubes: Methods, Achievements, Challenges, and Future Directions. *Env Sci Climate Res, 2*(1), 01-05.

Abstract

Carbon nanotubes (CNTs), nanoscale hollow tubes of carbon atoms with their unique characteristics, have been revolutionizing the technology world because their unique structural and electrical properties make them ideal for a wide variety of nanotechnology-based applications [1]. This article gives a synopsis of three prevalent methods of CNT synthesis. The field of nanotechnology and nanoscience promote their investigation forward to produce CNTs with acceptable parameters for future applications. Therefore, new approaches to their synthesis need to be developed and optimized. Throughout this paper, the history, the types, the structure, and the distinct well-developed synthesis methods for preparing CNTs will be reviewed, including arc discharge, laser ablation, and chemical vapor deposition (CVD).

Keywords: Carbon Nanotubes, Nanotechnology, Fabrication, Arc Discharge, Laser Ablation, CVD, Nanoelectronic Applications, Biomedical Applications

1. Introduction

Carbon nanotubes (CNTs) are cylindrical molecules that consist of a hexagonal arrangement of carbon atoms and can be formed by rolling up a single layer of carbon atoms (graphene). They can be constructed in two primary forms: single-walled CNT (SWCNT) with a single tube of graphene whose diameter is less than 1 nm and multi-walled CNT (MWCNT) with many concentrically interlinked nanotubes of graphene, with diameters reaching more than 100 nm. Therefore, the diameter of CNTs varies from a few nanometers for SWCNTs to several tens of nanometers for MWCNTs. However, the lengths of the CNTs are mainly in the micron range. Furthermore, the structural, electrical, thermal, and mechanical properties of CNTs are genuinely remarkable as CNTs have high thermal conductivity, a high electrical conductivity, a minimal, high aspect ratio conductive and additive for all types of plastics, a high elasticity (˜18% elongation to failure), a very high tensile strength, high flexibility (can be bent considerably without damage), and a low thermal expansion coefficient. In addition, CNTs are good electron field emitters [2,3]. These properties make CNTs highly desirable for nanoelectronic applications, thus creating a massive demand for reliable and straightforward synthesis methods for the material. Today, there are numerous techniques for CNT synthesis. Throughout this paper, we aim to overview three of them, including arc discharge, laser ablation, and CVD.

2. Arc Discharge

The arc discharge method between graphite electrodes is first used to produce C60 fullerenes, nanostructured allotropes of carbon made of twenty hexagons and twelve pentagons. This technique was the first recognized method of synthesizing CNTs and is the oldest and among the best practices to produce high-quality CNTs. However, this technique has a complex combination of components that needs more purification to separate CNTs from the carbon and the residual catalysts ending with a tarnished product. This method makes CNTs travel through the vaporization of two carbon rods located at both ends that contains low pressure and inert gas [4]. The discharge evaporates the surface of one of the carbon electrodes and produces a tiny rod-shaped deposit on the opposing electrode. The massive production and collection of CNTs depend on the consistency of the plasma arc and the temperature of the deposit increasing on the carbon electrode.

HiPco method, an extensive carbon nanomaterial research for about two decades, is a type of arc discharge method that is synthesized using a high-pressure carbon monoxide (CO) process. It was developed at Rice University to produce high-quality SWCNTs from gas-phase reactions of iron pentacarbonyl ($Fe(CO)_5$) with high-pressure carbon dioxide (CO_2) gas at relatively high pressures (10-100 atm). People use $Fe(CO)_5$ to make iron nanoparticles that provide a nucleation surface for CO transformation into carbon during the evolution of CNTs.This synthesis method produces high-quality materials in slightly small quantities that cannot be distributed in the amounts needed for exchange.

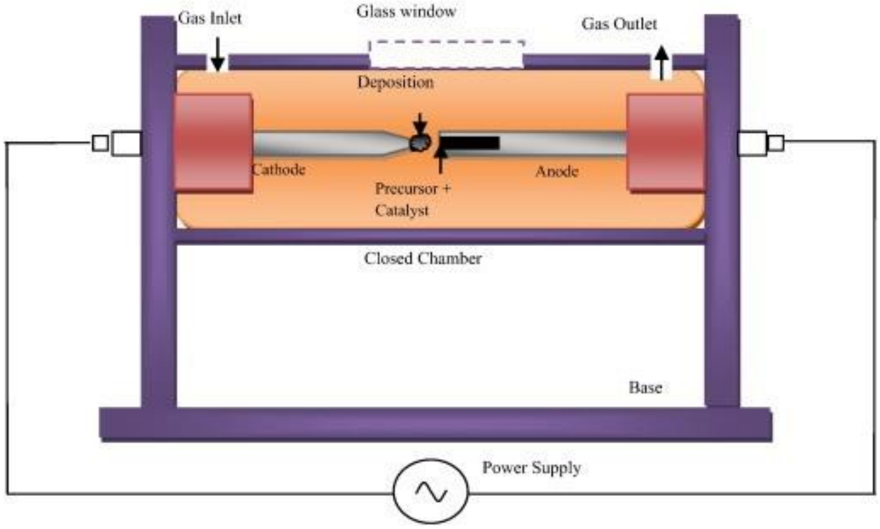

Figure 1: Schematic of an Arc Discharge Setup [4].

3. Laser Ablation

The laser ablation technique uses a pulsed laser to vaporize carbon from graphite at high temperatures [5]. Both MWCNTs and SWCNTs are made throughout this technique. Metal particles, such as catalysts, must be added to the graphite to grow SWCNTs, whose diameter ranges about 1.0 - 1.6 nm. This process is compared with the arc discharge technique. Several distinct factors affect the quantity and quality of produced CNTs. They include the number and type of catalysts, laser power and wavelength, temperature, pressure, type of noble gas, and the fluid dynamics of carbon. The laser is focused mainly on carbon consisting of 1.2 atomic % Co/Ni and 98.8 atomic % graphite composite placed in a 1200°C quartz tube furnace under the argon atmosphere with a pressure of about 500 torrs. Argon brings the steam from the chamber wall to the cooling collector located downstream throughout this technological process. The CNTs collect from vaporized carbon and sediment on the flow tube walls. Like the arc discharge method, laser ablation CNTs were purer (up to 90% purity) and had a narrower distribution of diameters than those made throughout the arc discharge process due to the temperature variation, catalyst composition, and laser parameters.

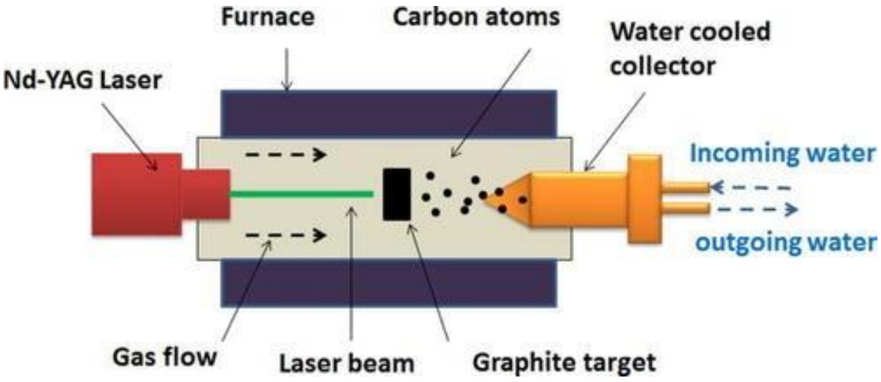

Figure 2: Schematic Diagram of Laser Ablation Method [5].

4. Chemical Vapor Deposition (CVD)

The chemical vapor deposition (CVD) method can be produced by collecting carbon sources (usually hydrocarbon gas that includes methane (CH_4), CO, and acetylene (C_2H_2)) at high temperatures (˜720°C) through a quartz tubular reactor in an oven with energy sources, such as a microwave plasma or any hot filaments, to transfer energy to a gaseous carbon molecule [6]. First, the hydrocarbons are broken to transform into hydrogen carbon bonds at high temperatures, producing pure carbon molecules. Then the carbon diffuses toward the substrate, which is heated and coated with metal catalyst particles (nickel, cobalt, iron, or a combination), where it holds together. CNTs are formed if the parameters are properly maintained. The advantages of CVD processing include low power input, lower temperature range, relatively high purity, and, most importantly, the possibility to scale up this processing. In addition, relying on the temperature, this technique produces both MWCNTs and SWCNTs in which the production of SWCNTs occur at higher temperatures than MWCNTs.

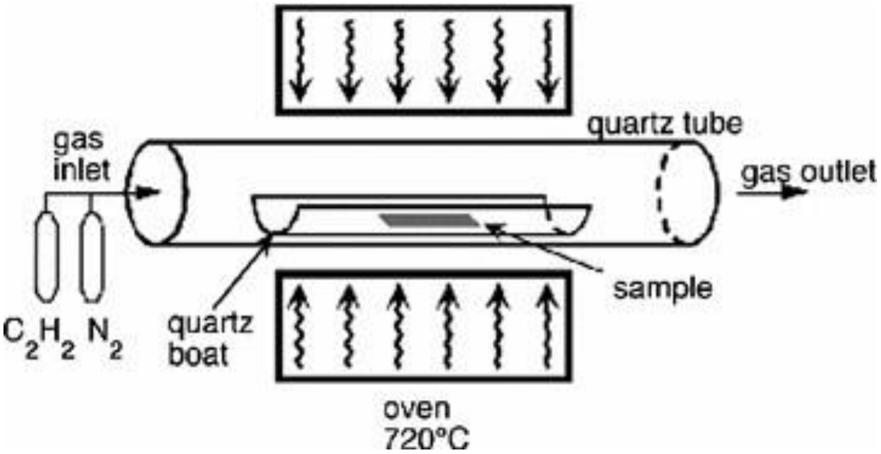

Figure 3: Hot-wall Thermal CVD Experimental Setup. The Chamber Reactor is Heated by an Electrical Furnace During the Hot-Wall CVD Process. [6]

5. Achievements and Key Challenges in CNT Synthesis

CNTs offer vital opportunities in science and nanotechnology but also pose a challenge for further work in this field. The goal is to produce large and perfect ultra-long graphene fibers. If this idea can be achieved, it will open vast new possibilities, like using space elevators. The path of direct growth of nanowires into systematized structures on surfaces is an encouraging route to nanoscale problems and create nanoscale devices with advanced electrical, electromechanical, and chemical functions. By achieving control in CNT growth will help to open new opportunities in the elementary science and real-life applications. The future goal for growth in synthesizing CNTs is to produce as perfect as possible CNTs by simple and efficient methods, secure control over the CNT chirality and diameter, and control the growth of a semiconducting or metallic nanowire from and to any desired sites. Modifying CNTs by physical or chemical means should be feasible to produce sensitive and selective chemical sensors that can be used for practical applications. The goal is to reduce the chance of catalyst deactivation. In 2020, a Japanese lab successfully manufactured CNTs of over 15 cm in length, which is almost seven times longer than any previous ones, by using the chemical vapor deposition, which was able to keep the catalyst active for about 26 hours.

This event was done by adding a layer of gadolinium to a conventional iron aluminum oxide catalyst coated on a silicon substrate, using a lowering chamber temperature and aluminum vapor. Building a single molecule fiber of any significant length is challenging. The strength of manufacturing CNTs depends on creating a continuous perfect lattice of carbon atoms. At the same time, some have got CNTs of 50 cm; it has been a struggle to get bigger bundles of tubes, called forests, to get a length larger than 2 cm. This issue happens because the catalyst involved is deactivated during the growth process, thus ending the growth of the CNTs. The long-term goal is to create individual CNTs lighter than aluminum and more conductive of electricity than copper but creating yarn of CNTs that could match copper is still a challenge because of the high price. In addition, CNTs among vapor debris require much more work to separate the CNTs from their byproducts. High wettability, high shear forces are among the key challenges. OCSiAl manufactures compatible products with a wide range of applications.

6. Applications

The unique properties of CNTs make it a very desirable material to work within a wide range of noticeable applications in many different aspects of biomedical fields, such as nanoporous membrane systems and probing the various surfaces of semiconducting materials. In addition, they are also beneficial in nanotechnology, medicine, construction, manufacturing, electronics, peripheral hardware, software, etc., as displayed in figure 4 [7].

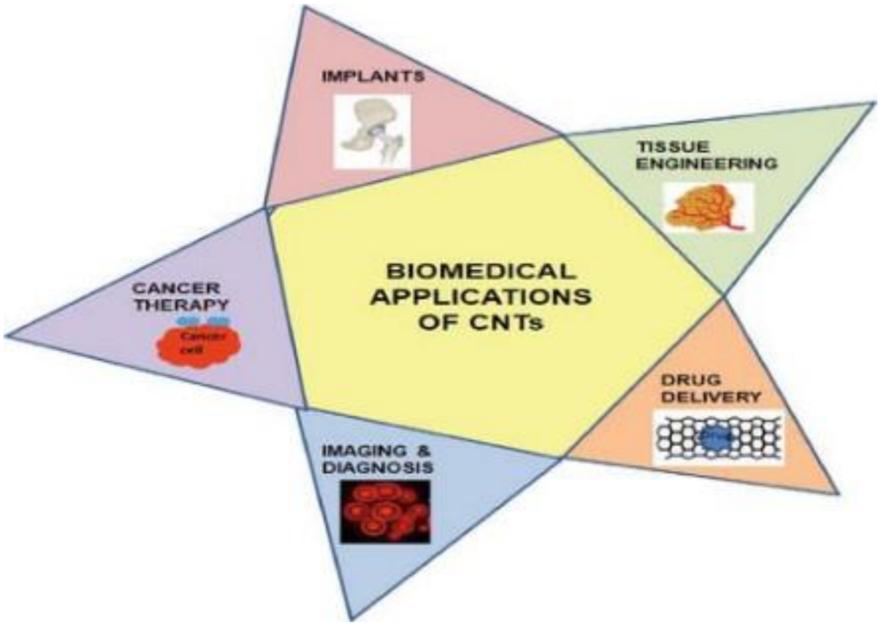

Figure 4: CNT Applications in Biomedical Field [7].

7. Future Directions

Most fibers today are woven with yarn. One wove together 1-mm long CNTs into a thread and then impregnated that with an epoxy resin to form a composite material having an outstanding tensile strength of 1.6 GPa [8,9]. These new CNTs may give us more muscular woven fibers in the future. CNT wires are being used in super lightweight airplanes and cars. As a means of composite structures for aircraft like the Boeing 787, this will help them survive lightning strikes and reduce fuel consumption. Because of their elasticity, capable of stretching to 18% and coming back to their original shape, this characteristic can be used in making wearable technology. Elon musk's company, Neuralink, creates neural interphase material, smaller wires, and the machines to implant them. Experimentation on adding CNTs to polyethylene makes production costs as low as possible. Product ultra-high purity: Scalable technology with a low purity (<1 weight % Fe) and a high Raman ratio of G/D > 100.

8. Conclusions

CNTs are one of the most noticeable discoveries in nanotechnology as CNTs are a member of the fullerenes structure family. The unique structural and electrical properties of CNTs make them different from amorphous carbon. Throughout this paper, the history, the types, the structure, and the three prevalent methods for synthesizing CNTs have been reviewed, including arc discharge, laser ablation, and CVD. It has been argued that currently, CVD provides the best option for synthesis due to its low-cost, low energy consumption, and considerable control of the reaction. CNTs can be found within various applications in electronics, biomedicine, nanotechnology, etc.

References

1. Bai, W., Chu, D., & He, Y. (2021). Bubble characteristic of carbon nanotubes growth process in a tapered fluidized bed reactor without a distributor. *Chemical Engineering Journal, 407,* 126792.
2. Karak, N. (2021). Sustainable epoxy thermosets and nanocomposites. (*No Title*).
3. Karak, N. (2021). Modification of Epoxies. In Sustainable Epoxy *Thermosets and Nanocomposites. American Chemical Society* 1385, 37-68.
4. Almarasy, A. A., Yamada, Y., Mashiyama, Y., Maruyama, H., Kimura, Y., & Fujimori, A. (2021). Activity Maintenance Characteristics and Protease Adsorption on Langmuir Monolayer of Organo-Modified Single-Walled Carbon Nanotubes. *ChemistrySelect, 6*(21), 5329-5337.
5. Lahoz, R., Naghilou, A., Kautek, W., & Bomati-Miguel, O. (2020). Study of the physicochemical surface alterations and incubation phenomena induced on iron targets by nanosecond pulsed laser ablation in liquids: effect on productivity and characteristics of the synthesized nanoscale zero-valent iron (nZVI) particles. *Applied Surface Science, 511*, 145438.
6. Abdulhafez, M., Lee, J., & Bedewy, M. (2020). In Situ Measurement of Carbon Nanotube Growth Kinetics in a Rapid Thermal Chemical Vapor Deposition Reactor With Multizone Infrared Heating. *Journal of Micro-and Nano-Manufacturing, 8*(1), 010902.
7. Xiang, L., Xia, F., Jin, W., Zeng, X., Liu, F., Liang, X., & Hu, Y. (2020). Carbon nanotube dual-material gate devices for flexible configurable multifunctional electronics. *Carbon, 161*, 656-664.
8. Xu, W., Cao, D., Moses, O. A., Sheng, B., Wu, C., Shou, H., ... & Song, L. (2021). Probing self-optimization of carbon

support in oxygen evolution reaction. *Nano Research, 14*(12), 4534-4540.

9. Yang, Y., Xiong, Y., Zeng, R., Lu, X., Krumov, M., Huang, X., ... & Abruña, H. D. (2021). Operando methods in electrocatalysis. *ACS Catalysis, 11*(3), 1136-1178.