

Chapter 13

Carbon Nanotubes and Graphene

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1. Introduction

Nanotechnology has changed modern science by allowing materials to be controlled at the smallest levels, such as atoms and molecules. Two important examples of these materials are carbon nanotubes and graphene. Both are made from carbon and have very strong chemical, electrical, physical, and mechanical properties. Because of these features, they are used in many areas like medicine, energy storage, electronics, environmental science, and biotechnology (Baughman et al., 2002; Geim & Novoselov, 2007).

Carbon can be found in several different forms, called allotropes. Some examples are graphene, graphite, diamond, fullerenes, and carbon nanotubes. The way the carbon atoms are arranged in each allotrope gives them special qualities, like being very strong, light, and good at conducting electricity and heat. Because of these properties, materials like graphene and carbon nanotubes are important for making new technologies (Baughman et al., 2002; Geim & Novoselov, 2007), as shown in Figure 1.

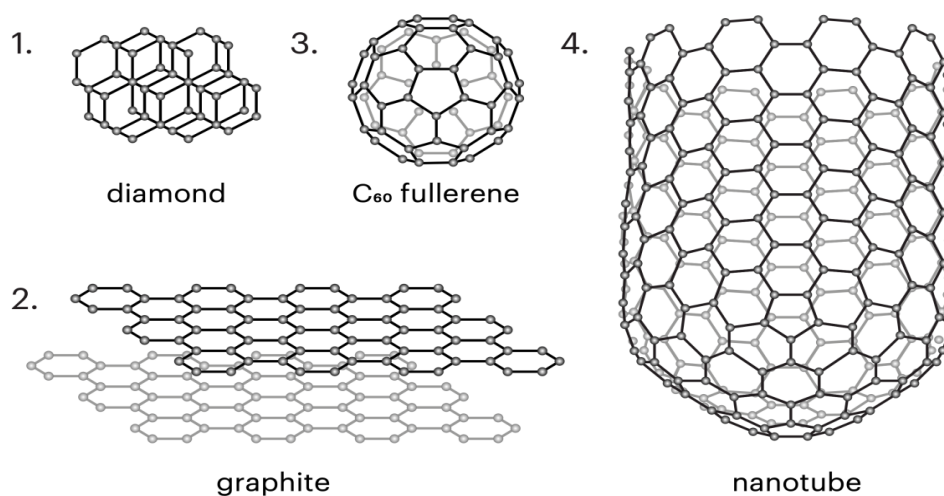


Figure 1. Different allotropes of carbon

Carbon nanotubes and graphene are both forms of carbon that are closely linked. Carbon nanotubes are made by rolling up sheets of graphene, which gives them a tube-like shape. Graphene itself is a single layer of carbon atoms arranged in a flat, honeycomb pattern. Both materials have SP² hybridization, which means they conduct electricity well and are very strong. Since their discovery, carbon nanotubes and graphene have been important topics in nanotechnology research. Scientists and engineers are looking at how they can be used in areas such as nanoelectronics, drug delivery, biosensors, tissue engineering, flexible electronics, water purification, and renewable energy. Their strength and sensitivity make them useful for both medical and industrial uses (Castro Neto et al., 2009; Dresselhaus et al., 2004).

Even though carbon nanotubes and graphene have many possible uses, there are still some challenges. These include concerns about toxicity, high production costs, problems with the materials sticking together, and difficulties in making them on a large scale. Researchers are working to improve how these materials are made, make them safer, and find better ways to use them in different industries (Figure 2).

This chapter discusses the properties, synthesis, structure, uses, benefits, and the challenges linked to carbon nanotubes and graphene.

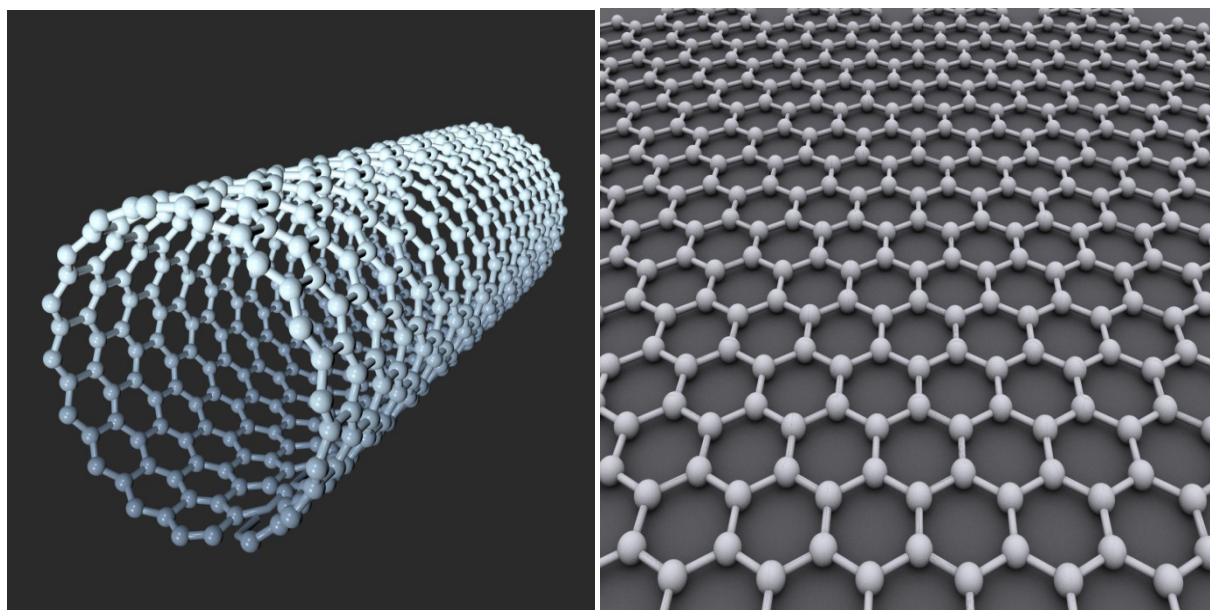


Figure 2. (a) Carbon nanotubes and (b) Graphene

2. Carbon Nanotubes (CNTs)

2.1. Structure and Types of Carbon Nanotubes

Carbon nanotubes (CNTs) are tiny cylinders made from carbon atoms that are connected in a hexagonal pattern. They are formed when a sheet of graphene is rolled up into a tube, with diameters measured in nanometers and lengths that can be as long as several micrometers. The discovery of carbon nanotubes was first made by Sumio Iijima in 1991. Since then, they have gained a lot of attention because they have strong mechanical strength, good electrical conductivity, and unique chemical properties (Iijima, 1991).

The structure of carbon nanotubes is similar to graphite and graphene. The way the carbon atoms are arranged in the tube is called chirality, and this affects whether the nanotube acts like a metal or a semiconductor. Carbon nanotubes are also much longer than they are wide, which is called a high aspect ratio. Besides their electrical and chemical features, they are flexible, strong,

and elastic. This means they can bend or stretch without breaking, which is important for many uses (Dresselhaus et al., 2001).

There are two main types of carbon nanotubes: Single-Walled Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs).

2.1.1. Single-Walled Carbon Nanotubes (SWCNTs)

Single-walled carbon nanotubes (SWCNTs) are made up of carbon atoms arranged in a single graphene layer that rolls into a cylinder. Their diameter is usually between 0.4 and 2 nanometers, and their length can reach several micrometers or even centimeters in some cases. Electrons travel along the tube, and the way the atoms are arranged and the size of the tube affect how well they conduct electricity. Because of these properties, SWCNTs are used in nano electronics, transistors, and sensors. Depending on their structure, they can act as either metals or semiconductors (Castro Neto et al., 2009).

Single-walled carbon nanotubes are useful in biosensing and molecular detection because they are very sensitive to chemicals. Producing pure SWCNTs is challenging and costly. The manufacturing process usually results in a mix of metallic and semiconducting tubes, as well as impurities like amorphous carbon. As a result, extra steps are needed to purify and separate them for most uses (Liu et al., 2009).

2.1.2. Characteristics of SWCNTs

- Consist of a single cylindrical graphene layer
- Diameter ranges between 0.4–2 nm
- Excellent electrical conductivity
- High flexibility and elasticity
- Suitable for nanoelectronic devices and sensors
- Higher purity requirements during synthesis

2.1.3. Multi-Walled Carbon Nanotubes (MWCNTs)

In multi-walled carbon nanotubes (MWCNTs), multiple concentric graphene cylinders are arranged one inside another, forming a nested tubular structure. The spaces between the layers are similar to the interlayer spacing found in graphite. The diameter of MWCNTs can range from approximately 2 to 200 nm, and they possess exceptional mechanical strength and durability compared with single-walled carbon nanotubes (Jorio et al., 2008).

2.1.4. Characteristics of MWCNTs

MWCNTs are made up of several concentric layers of graphene, which are arranged inside each other to form a tube-like structure.

The diameter of multi-walled carbon nanotubes usually falls between 2 and 200 nanometers.

These nanotubes have higher mechanical strength and better thermal stability compared to single-walled carbon nanotubes.

They are also more chemically stable than single-walled carbon nanotubes, which makes them suitable for a wider range of applications.

In addition, MWCNTs are generally easier and less costly to produce than single-walled carbon nanotubes.

Because of these properties, they are commonly used in composite materials and various industrial products.

3. Synthesis of Carbon Nanotubes

Several chemical and physical methods are used for the synthesis of carbon nanotubes. The choice of synthesis technique is influenced by factors such as the desired diameter, purity, and structural quality of the produced nanotubes (Zhu et al., 2010).

3.1. Arc Discharge Method

One of the earliest synthesis methods used for the production of carbon nanotubes is the arc-discharge method. In this method, a high electric current is passed between two graphite electrodes. The electrodes are placed in an environment containing inert gases such as helium or argon. As the current passes between the two electrodes, carbon atoms are vaporized from the graphite electrodes. When the carbon vapor cools and condenses, nanotubes are formed, particularly around the cathode deposit. This procedure can produce highly crystalline carbon nanotubes with relatively few structural defects (Jorio et al., 2008), as shown in **Figure 3a**.

3.2. Advantages

This method is known for producing carbon nanotubes of high quality.

It also generates nanotubes that have good crystallinity.

The arc discharge method can be used to produce both single-walled and multi-walled carbon nanotubes.

3.3. Limitations

However, this process requires very high temperatures and consumes a lot of energy.

It also produces impurities, including amorphous carbon and metal particles, which need to be removed.

As a result, additional purification steps are necessary to obtain pure carbon nanotubes.

3.4. Laser ablation method

In this technique, a high-powered laser beam is used to vaporize graphite containing metal catalysts inside a reactor. Upon cooling, the vaporized carbon atoms condense and form carbon nanotubes. This method can be used to produce nanotubes with controlled diameters; however, it is not considered cost-effective because it requires high energy consumption and sophisticated laser systems. The method can produce highly pure carbon nanotubes and provides good control over nanotube diameter and structural quality (Hirsch, 2002; Stankovich et al., 2006) as shown in Figure 3b.

3.5. Advantages

This method is able to produce carbon nanotubes with a high level of purity.

It also offers excellent control over the diameter of the nanotubes produced.

The laser ablation method results in nanotubes with high structural quality.

3.6. Limitation

However, this technique requires expensive equipment and has high operational costs, and it is not suitable for large-scale production.

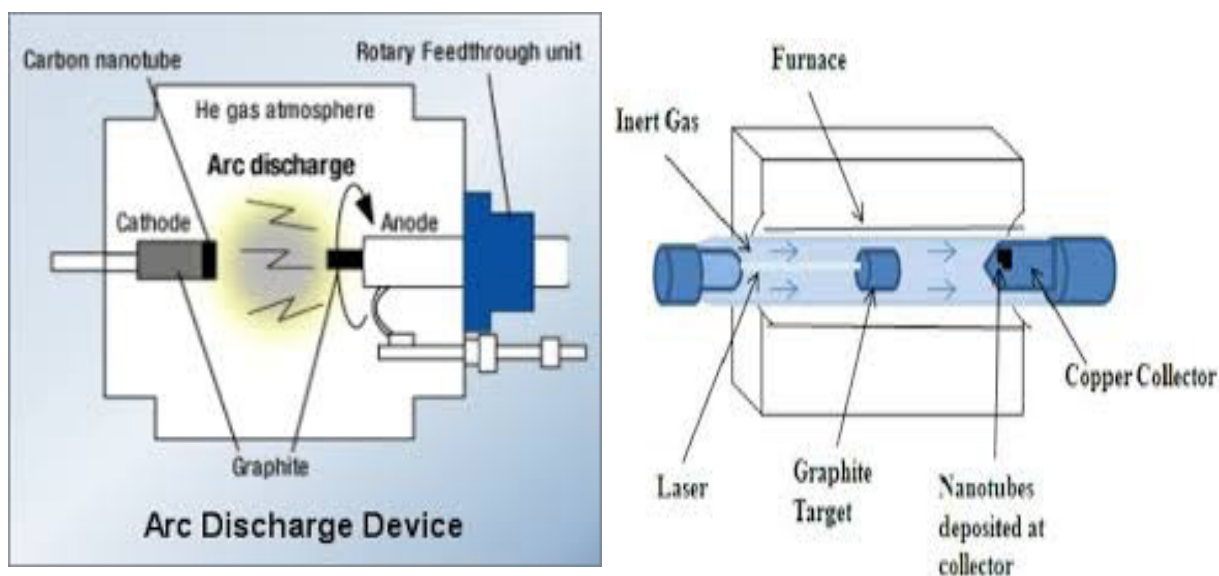


Figure 3. Synthesis of carbon nanotubes: (a) Arc discharge method (b) laser ablation method

3.7. Chemical vapour deposition (CVD)

Chemical vapor deposition (CVD) is the main method used to produce carbon nanotubes in industry. In this process, gases like ethylene, acetylene, or methane are broken down at high temperatures with the help of metal catalysts such as nickel, cobalt, or iron. The carbon from these gases collects on the catalyst and forms carbon nanotubes. CVD is widely used because it allows for large-scale production and gives good control over how the nanotubes are made. It is also suitable for industrial use (Stankovich et al., 2006), as shown in Figure 4.

3.8. Advantages

This method is good for making large amounts of carbon nanotubes. It also helps control the length, diameter, alignment, and density of the nanotubes. Another benefit is that it is cost effective.

3.9. Limitations

However, sometimes this method can lead to defects in the structure of the nanotubes or make it harder to purify them.

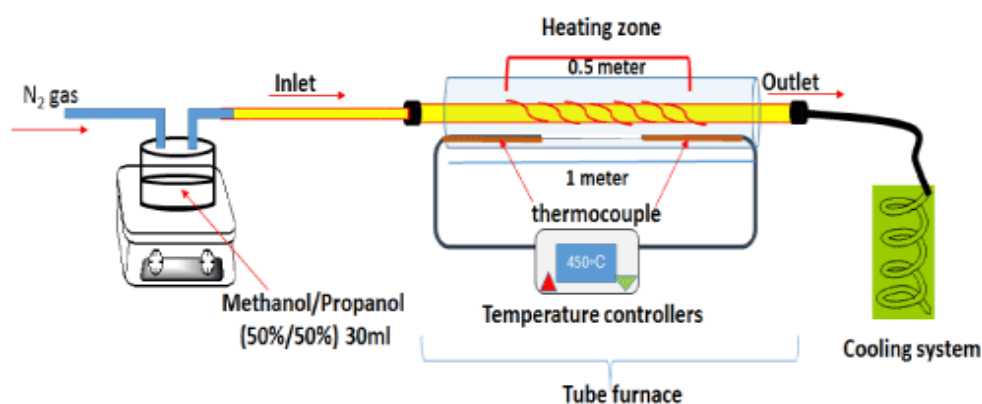


Figure 4. Synthesis of carbon nanotubes by chemical vapour deposition

Properties of carbon nanotubes: Carbon nanotubes possess a unique combination of chemical, thermal, electrical, mechanical, and physical properties. They are among the strongest known materials and exhibit exceptionally high tensile strength, which can be considerably greater than that of steel. Electrons can travel efficiently along carbon nanotubes, giving them excellent electrical conductivity. CNTs also have high thermal conductivity and can transfer heat efficiently. Under harsh environmental conditions, they show good chemical stability and corrosion resistance. In addition, their high surface area makes them highly effective for adsorption and facilitates interactions with other molecules, increasing their potential for various technological and industrial applications (Avouris et al., 2007).

4. Graphene

Graphene: Graphene is a two-dimensional sheet of carbon atoms arranged in a hexagonal honeycomb lattice. In 2004, graphene was successfully isolated by Andre Geim and Konstantin Novoselov. Their pioneering work on graphene was subsequently recognized with the Nobel Prize in Physics in 2010 (Geim, 2009).

4.1. Methods of graphene synthesis

4.1.1. Mechanical exfoliation

In this technique, adhesive tape is used to separate graphene layers from graphite, producing high-quality graphene. This approach, commonly known as mechanical exfoliation, is useful for

obtaining graphene with excellent structural quality but is not suitable for large-scale production (Figure 5a)

4.1.2. Chemical vapour deposition (CVD)

In this method, hydrocarbon gases are decomposed at high temperatures, resulting in the formation of a graphene layer on metal substrates such as copper. Chemical vapor deposition provides an approach for producing graphene over relatively large areas and is therefore more suitable for scalable production than mechanical exfoliation (Geim, 2009), as shown in Figure 5b).

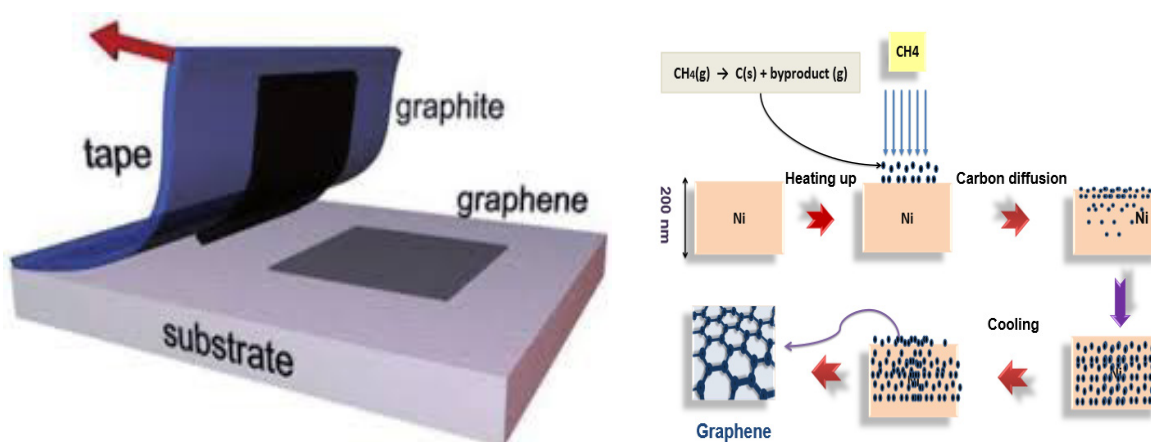


Figure 5. Synthesis of Graphene by (a) mechanical exfoliation and (b) chemical vapour deposition

4.2. Properties of graphene

Graphene possesses exceptional mechanical strength and is extremely lightweight and thin. It is also an excellent electrical conductor because electrons can move rapidly through its two-dimensional structure. In addition, graphene exhibits excellent thermal conductivity, making it valuable for applications in advanced electronics, energy technologies, and other high-performance materials (Avouris et al., 2007; Geim, 2009), as shown in Table 1.

5. Summary

Carbon nanotubes and graphene are among the most important nanomaterials discovered in modern science. Both materials are composed of carbon atoms arranged in highly organized structures that provide exceptional mechanical strength, electrical conductivity, thermal stability, and chemical resistance. Carbon nanotubes are cylindrical structures formed by rolled graphene sheets and are classified into single-walled and multi-walled nanotubes. Various synthesis methods, including arc discharge, laser ablation, and chemical vapor deposition, are employed to produce CNTs with different structural characteristics and applications.

Carbon Nanotubes and Graphene

Table 1.

Comparison between carbon nanotubes and graphene

Property	Carbon Nanotubes (CNTs)	Graphene
Structure	Cylindrical tubes formed by rolling graphene sheets	Single layer of carbon atoms arranged in a two-dimensional honeycomb lattice
Dimensionality	One-dimensional (1D) nanomaterial	Two-dimensional (2D) nanomaterial
Discovery	Discovered by Sumio Iijima in 1991	Isolated by Andre Geim and Konstantin Novoselov in 2004
Composition	Carbon atoms arranged in rolled graphene sheets	Single layer of sp^2 -hybridized carbon atoms
Shape	Hollow cylindrical structure	Flat sheet-like structure
Diameter/Thickness	Diameter ranges from 0.4–100 nm depending on type	Thickness of one carbon atom (~ 0.34 nm)
Surface Area	Very high surface area	Extremely high specific surface area
Mechanical Strength	Extremely strong with high tensile strength	Approximately 200 times stronger than steel
Flexibility	Highly flexible and elastic	Highly flexible and bendable
Electrical Conductivity	Can be metallic or semiconducting depending on chirality	Excellent electrical conductor with high electron mobility
Thermal Conductivity	Excellent thermal conductivity	Superior thermal conductivity, among the highest known
Optical Transparency	Limited transparency	Nearly transparent (about 97.7% transparent)
Chemical Stability	Highly stable and corrosion resistant	Highly stable but can be chemically functionalized
Types	Single-Walled CNTs (SWCNTs) and Multi-Walled CNTs (MWCNTs)	Mainly exists as single-layer, bilayer, or few-layer graphene
Synthesis Methods	Arc discharge, laser ablation, chemical vapor deposition (CVD)	Mechanical exfoliation, CVD, chemical reduction, epitaxial growth
Major Electronic Applications	Transistors, conductive films, nanoelectronics, sensors	Flexible electronics, touchscreens, transparent electrodes, transistors

Graphene is a two-dimensional sheet of carbon atoms arranged in a honeycomb lattice and serves as a fundamental building block of several carbon allotropes. Its outstanding strength, flexibility, transparency, and electrical conductivity have made it one of the most extensively studied materials in nanotechnology. Both carbon nanotubes and graphene have found widespread applications in electronics, biomedical engineering, energy storage systems, environmental remediation, sensors, and advanced composite materials. Their unique properties have enabled the development of innovative technologies with improved performance and efficiency.

Despite challenges such as production costs, scalability, and potential toxicity concerns, ongoing research continues to unlock new possibilities for these materials. With further advancements in synthesis, functionalization, and application development, carbon nanotubes and graphene are expected to play a transformative role in future scientific and technological innovations.

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