Review Article

Graphene: A Multifunctional Nanomaterial with Versatile Applications

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Graphene is a 2D material of high quality obtained from a single atom with unique electronic properties. Graphene has the potential to improve the efficiency, versatility, and durability of a wide range of materials and their applications, but its commercial exploitation will require further study. Due to its flatness and semiconductivity in addition to its high surface area, high mechanical rigidity, high thermal stability, superior thermal conductivity, and electrical conductivity, good biocompatibility, and easy functionalization, graphene is the best candidate for multifunctional applications which opened up new possibilities for potential devices and systems. Every type of graphene material is found to exhibit different and unique tunable properties. Graphene is the best candidate in making nanocomposite-based electrochemical sensors. Graphene is among the best electronic materials, but synthesizing a single sheet of graphene has received less attention. The objective of this chapter is to bring awareness to readers on the synthesis, properties, and applications of graphene. The limitations of the current knowledge base and prospective research directions related to graphene materials have also been illustrated.

1. Introduction

Graphene has received a lot of attention as a multifunctional material in the recent years which is possibly due to its extraordinary properties such as high current density, chemical stability, ballistic transport, optical property, high thermal conductivity, and superior hydrophobicity at the nanoscale. A method known as micromechanical cleavage was used to remove the first graphene from graphite. This method appears to be very simple and made it possible to make superior quality graphene crystallites, which led to a slew of new experiments [1–4]. Intrinsic graphene material is a semimetal or zero gap semiconductor with excellent opacity for an atomic monolayer low absorption ratio of 2.3% of visible light due to its peculiar electronic properties. It has also been explored that the resistivity of the graphene sheet is superior to that of platinum, the lowest resistivity material known at room temperature. The electrical properties of graphene nanoribbons (GNRs) with zigzag or armchair configurations differ; zigzag GNRs exhibit metallic nature, whereas armchairs behave as either metallic or semiconductor. The energy band gap of armchair GNRs' was found to vary inversely with their width [5, 6].

The unique electrical properties possessed by graphene have been utilized in applications related to electronics such as transistors, field emitters, integrated circuit modules, transparent conducting electrodes, and electrochemical and biosensors. Many types of graphene materials such as single

and multilayer graphene, graphene oxide (GO), reduced graphene oxide (rGO), and graphene quantum dots (GQDs) have been applied for the fabrication of varieties of electrochemical and biosensor applications. Since graphene exhibits a high electron (or hole) mobility and low Johnson noise, it can be used as a field effect transistor tube (FET). Because of its 2D structure, its entire volume is exposed to the environment, making it very effective at detecting adsorbed molecules. In addition, graphene also finds applications in touch screens, displays, organic photovoltaic cells, and organic light-emitting diodes (OLEDs) [6]. The majority of the abovementioned intriguing applications have created a great demand for a single-layer graphene decorated on a suitable substrate, which is extremely difficult to monitor and has yet to be achieved. Many reports on graphene synthesis are available, with the majority of them relying on mechanical exfoliation from graphite, thermal graphitization of a SiC surface, and more recently, chemical vapor deposition [7–13]. This chapter starts with a brief description of the significant properties of graphene, followed by a review on the synthesis technologies, as well as their feasibility and possible applications in fields such as field emission, energy, electronics, photocatalysis, and sensors. The superior properties of modified graphene materials, such as higher surface area and availability of functional groups at the surface compared to CNTs, make them apply for enormous electrochemical sensor arrays.

2. Properties of Graphene

Graphene is a type of carbon nanomaterial that is considered advanced. It is a two-dimensional solitary carbon atom sheet. Figure 1 shows how carbon atoms are arranged in a hexagonal network. This historical material was synthesised in the year 2004 using the scotch tape peeling method [14]. Graphene can also be visualized as a single layer of carbon atoms arranged in the form of a hexagonal 3D lattice, as previously described. The versatile atomic structure of graphene can be used to create other carbon-based materials/nanomaterials. The sheet can also be twisted into fullerenes, nanotubes, and graphite by stacking it [15].

The conducting properties of graphene are also significantly influenced by the symmetry orientation of 2pz orbitals [16–18]. Acoustic phonons are the reason for the thermal conductivity of solitary layer graphene under ambient conditions [19]. This thermal conductivity occurs due to the absence of a crystal defect and the suppression of the Umklapp processes [20]. These factors contribute to the future importance of graphene in the production of nanoelectric devices [21]. At the microscopic level, graphene crystals are normally well preserved and very stable [22]. These properties of graphene lead to its excellent heat conduction (Figure 2). They are regarded as a high-strength material in terms of mechanical properties. The yield power of graphene is 42 N/m. They have a mechanical strain of about 25% [24]. Mechanical stress measurements can also be used to monitor their mechanical thickness [21, 25]. As previously mentioned, graphene is made of one atom thick two-dimensional layer of carbon. These features, along with
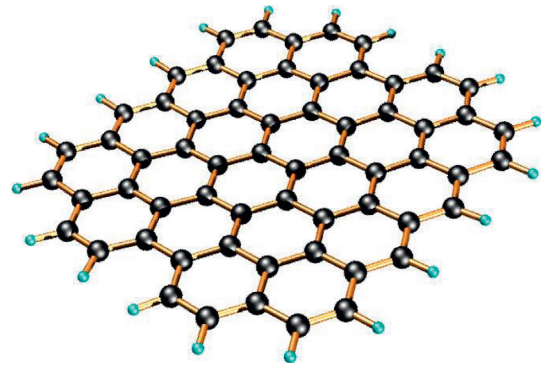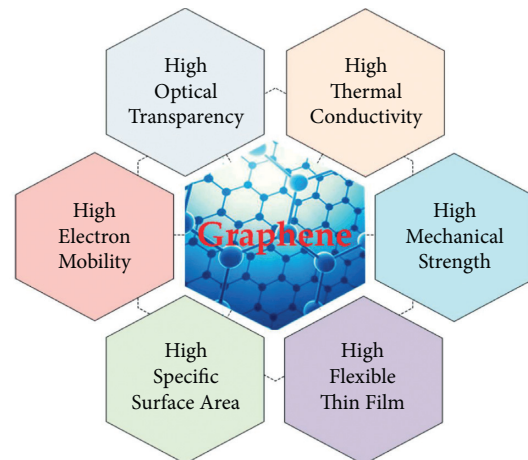

Figure 1: The structure of graphene.

Figure 2: Properties of graphene [23].

the fact that they are a component of sp2, distinguish them from carbon materials. The presence of a large surface area is one of these properties [26–28]. Graphene is also fully transparent; in terms of physical properties, it is thinner million times than a sheet of paper. In terms of thickness, it can be understood that a million sheets of paper are equal to 1 mm of graphene.

3. Synthesis of Graphene

The graphene synthesis process is determined by the size and purity of the final product. Until the end of 1970s, several methods for synthesizing thin graphitic films were used [29–31] (Figure 3). In 1975, chemical deposition was used to create smaller graphite layers. However, since it was difficult to classify the material at the time and it was not needed for many applications, this material was not classified as graphene. Other aspects of the materials, such as their electronic properties, were not studied at the time [32]. Ruoff et al. investigated the possibility of isolating thin graphite flakes on SiO2 substrates in 1990s. In this work, researchers used highly oriented pyrolytic graphite to rub the patterned island [33]. The inquiry was unable to obtain detailed information on the material's electrical property characterization. Kim et al. used the same approach in their investigation in the year 2005, and the electrical characteristics of graphene was
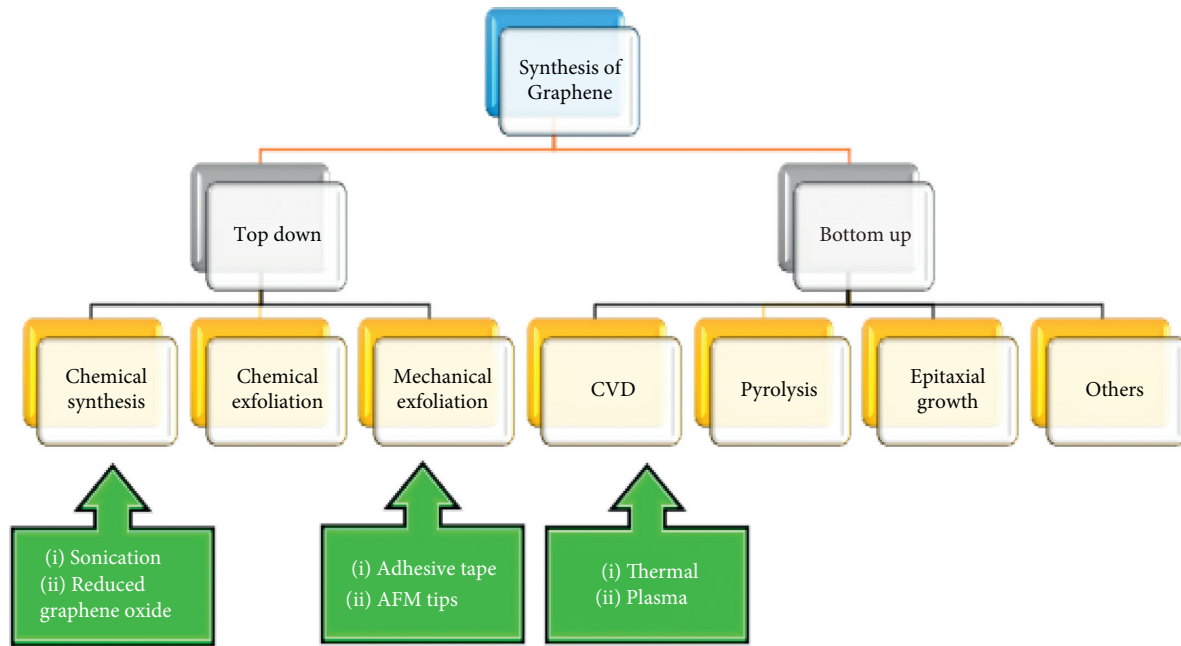
FIGURE 3: A schematic on various synthetic methods for graphene.

captured in their findings [32]. Geim et al. [34] conducted an investigation that resulted in a ground-breaking finding. Their research focused on the decoration of graphene on a SiO$_2$ substrate as well as the measurement of electrical properties. Since 2015, a variety of methods for producing graphitic films and graphene layers have been used. Graphene was discovered to be a two-dimensional crystal in an experiment performed in 2004. A decade ago, mechanical exfoliation of graphite produced the first type of graphene in the form of flakes [35]. Although the graphene generated using these methods is of superior quality, there are practical challenges in scaling up the mass production due to the need for a fabrication process to break down wafer scale graphene. Mechanical exfoliation, chemical exfoliation [36], chemical synthesis [8, 12], and thermal chemical vapor deposition (CVD) [37–40] are all methods that have been used in the past. Other techniques include unzipping nanotubes [41, 42] and microwave synthesis. Mechanical exfoliation with a cantilever has been shown to produce layered graphene in recent studies [43–48]. The graphene thickness ranged from 10 nm to 30 nm, which is comparable to a 30-layer graphene. In the chemical exfoliation process, solution dispersed graphite is exfoliated by introducing strong alkali ions into the layers of the graphite [49]. Breakdown of graphite oxide, diffusion in a solution, and the use of hydrazine are all part of the chemical synthesis of graphene. Separate processes are also involved in the amalgamation of nanotubes. The thermal CVD method has been shown to be the best method for producing graphene. PECVD or enhanced CVD is a process that involves plasma-assisted development. Many of these approaches have advantages and disadvantages. The use of a mechanical exfoliation technique will aid in the fabrication of single and fewer layers of graphene. The generation of same structure of graphene with this technique would be the key challenge [50–54].

The chemical synthesis technique is carried out at low temperatures, making it easier to fabricate graphene on various substrates at room temperatures; however, most of the times, the graphene formed under these conditions is not uniform and dispersed. Graphene synthesis can also be achieved by reduced graphene oxides (RGOs) which results in a graphite oxide reduction process that is in adequate. This raises more concerns about its electrical properties. Thermal chemical vapor deposition is also suitable for fabricating large-area devices [55–58]. The thermal graphitization of SiC results in the development of epitaxial graphene, which is another method for graphene synthesis. However, the main disadvantage of this method is that it is carried out at high temperatures. This distinguishes the thermal CVD method because it creates a constant layer of catalyzed carbon atoms. After that, the atoms can be fixed to the metal surface. Graphene is made using a variety of techniques (Table 1).

Table 1 presents the synthetic methods for various forms of graphene such as nanosheets, aerogel, quantum dots [69], and nanoribbons.

4. Applications of Graphene

Graphene has been applied for multifunctional applications in the recent years (Figure 4). The following sections details the various applications of graphene, with an emphasis on its use in energy storage and conversion devices.

4.1. Electrochemical Sensors. The qualitative and quantitative detection of trace targets is possible with graphene. Because of the large pores, analyte transport is increased, which aids in the identification of binding targets. As graphene can be functionalized for the direct sensing systems and useful biological moieties can be detected at lower concentrations,

TABLE 1: Diverse approaches for the synthesis of graphene with their applications.

| Methods	Precursor	Morphology	Applications	Reference
Chemical vapor deposition (CVD)	Cu foil	Monolayer	Hydrogen sensing	[59]
Ultrasonic synthesis	Graphene oxide	Quantum dots	Sensing of alkaline phosphatase	[60]
Electrochemical reduction	Graphene oxide	Nanosheet	Electrocatalysis of dopamine	[61]
Electron-beam irradiation	1,3,6-Trinitropyrene	Quantum dots	Cell imaging	[62]
Suzuki coupling reaction	Polymers	Nanoribbons	Thin-film transistor	[23]
Green synthesis	Corn powder	Quantum dots	Photocatalysis	[63]
Sol-gel	Graphene oxide	Aerogel	Electrical conductivity	[64]
Exfoliation approach	Graphite	Nanosheet	Electrochemical sensing of H_2O_2	[65]
CVD	Cu foil	Quantum dots	Phototransistor application	[66]
Lithography	Graphite	Nanoribbons	Field effect transistor	[67]
Arc discharge method	Graphite	Nanosheet	Electrical properties	[68]
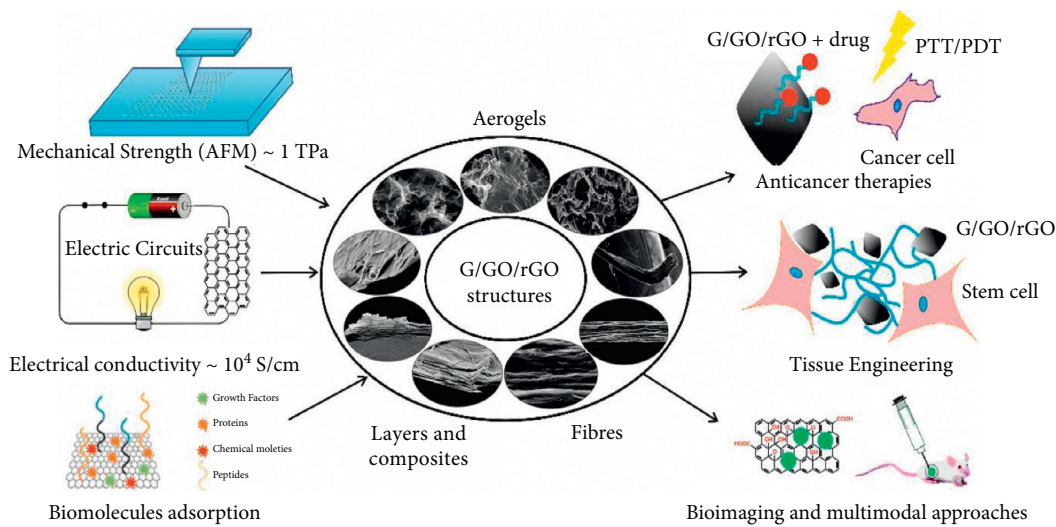
FIGURE 4: Multifunctional applications of graphene/graphene structure [62].

to improve the efficiency of graphene in making better electrochemical sensor in terms of functionality and applicability, surface modification with suitable functional groups, molecules, biomolecules, or nanomaterials necessary in the fabrication of different electrochemical sensors, it was shown in some reports that the functionalization of graphene oxide can be accomplished via the formation of amide linkage between GO sheet edges and organic molecules, for example, *p*-amino thiophenol, polyethyleneimine, or imidazole under mild conditions [69].

4.2. Composite Materials. In composites, graphene is used as a functional element, which improves the composite's properties and efficiency. When graphene is mixed with composites that have strong elasticity, strength, and porosity, it has a positive effect. Compression increases the power of certain graphene. Under cross-linked conditions, this type of graphene exhibits high compression. These graphene materials are suitable for reinforcing polymer matrices because of their spongy composition. It means that graphene matrices have a high strength, hydrophobicity, and conductivity [70].

4.3. Energy Storage Devices. Graphene is really a great material for making energy storage systems. This is particularly true when they have been treated with metal oxide, resulting in minimal sheet restacking. The fact that graphene's interconnected networks are highly conductive adds to the appeal of graphene as an energy storage material. Other advantages of graphene as energy storage devices include their porous microstructure, electrochemical stability, and mechanical stability. These devices can be used in fuel cells, solar cells, batteries, and supercapacitors, among other applications. Graphene is commonly used as anodic and cathodic material in proton exchange membrane (PEM) fuel cells, in batteries such as Li batteries. Graphene finds application as electrode material in both double layer capacitors and pseudocapacitors in supercapacitors. It is also used as dye sensitizers in fuel cells [71].

4.4. Adsorbents. The surface area of three-dimensional graphene is very large. They are suitable for absorption events due to their characteristics. In contrast to other materials, graphene has a strong take-up for organic liquids and is also reusable. Graphene sheets have been shown to adsorb certain gases at the lower concentrations once again.

Also in the industry, graphene's functional group is also capable of reducing gas exposure for trapping and converting unwanted gases [72].

4.5. Drug Delivery. In the last few years, graphene has been widely investigated as a unique drug nanocarrier for the loading of a variety of treatments, including anticancer medications, antibiotics, poorly soluble pharmaceuticals, antibodies, genes, DNA, RNA, and peptides [73, 74]. Selected examples from this study will be provided to demonstrate the use of graphene for targeted, controlled, and stimulated drug delivery, including certain anticancer and gene therapy applications. Conjugating drug carriers with particular ligands that can recognize molecular markers on the cancer cell surface is a well-known technique for achieving effective tumor targeting. Peptides, folic acid, polysaccharides, transferring, and monoclonal antibodies are examples of targeting ligands that are being investigated using graphene as drug nanocarriers for cancer therapy [75, 76].

Wang et al. [77] synthesised a gold nanocluster and graphene nanocomposite and showed that it could inhibit HepG2 cells at high concentrations, transport DOX inside the cells, and induce karyopyknosis in a synergistic manner.

Iannazzo et al. proposed combining graphene quantum dots with biotin (GQD-BTN) to boost the anticancer effect of graphene quantum dots (GQD) [78]. DOX loaded on GQD-BTN was found to suppress A549 cell growth more effectively than DOX or GQD-BTN alone. GQD-BTN appears to transfer DOX more efficiently into cells than free DOX.

Under low-power NIR laser irradiation, Yang et al. [79] observed that the PEGylated graphene nanosheets (GNS) themselves had ultrahigh in vivo tumor uptake and efficient photothermal treatment capabilities in mice. Following that, Markovic et al. [80] compared the photothermal anticancer activity of graphene nanoparticles and carbon nanotubes (CNT) and revealed that, despite its lower NIR-absorbing capacity, a suspension of polyvinylpyrrolidone-coated graphene sheets exposed to NIR radiation generated more heat than DNA or sodium dodecylbenzenesulfonate-solubilized single-wall CNTs under the same.

Pan et al. [81] used click chemistry to functionalize graphene sheets (GS) with poly (N-isopropylacrylamide) (PNIPAM). After 72 h at 37°C in water and PBS, the PNIPAM-GS had a greater ability to bind CPT with a high loading ratio of CPT.

Improved surface chemistry and graphene functionalization are necessary to accomplish effective goals. Furthermore, the unique features of graphene-based materials and their hybrids are likely to provide resources for enhanced gene delivery vector design in the future.

5. Future Perspective

Graphene's benefits are among the core merits of its use in a variety of energy storage and conversion applications. The recent technical advancements in the synthesis, characterization, and modern-day applications of these advanced materials were extensively investigated in this investigation. Today, 3D graphene structures have been developed that have shown to be as good as 2D graphene in terms of efficiency. The aim of this study was to find new ways to synthesize graphene in order to improve its quality and efficiency. CVD is one of these methods, and it often results in the formation of larger pore structures with good conductivity. Using this technique, the material's consistency is greatly improved. There are also increasing questions about the approach's scalability. The size and consistency of the precursor have an equal impact on the characteristics and efficiency of graphene. The quality and size of the precursor, the type of reducing agent, cross linkers, and pH, all of them play a role in the sponges' strength. Again, the strength of graphene sponges must be greatly enhanced in order to manufacture them on a large scale. Another interesting path for research in this field is to investigate the adoption of new techniques aimed at improving intersheet binding. These characteristics can be achieved by combining graphene sponges with elastic polymers.

Many research activities are currently being conducted to explore the futuristic application of graphene materials in a variety of multifunctional systems. This chapter looked at graphene's suitability for electrochemical and non-electrochemical applications. The advantages of graphene over other carbon allotropes were also discussed. Some of these advantages include a large surface area, ease of synthesis, high conductivity, solubility, and a low-cost material source. There has been a lot of technical progress, but there is still space for development in both electroanalytical and electrochemical sensors. Some of the material's problems, such as its ease of synthesis, must be tackled. The design and methodology used in the manufacture of graphene-based devices are also important for the material's potential advancement. Despite the challenges listed, graphene applications in electrochemical sensors remain the most promising future development of graphene.

6. Conclusions

The multifunctional graphene exhibits many numbers of benefits, even though it has several drawbacks. Further modification of graphene material is inevitable to explore its commercialization and compete with other prominent materials already on the market. Most of the graphene sponges considered in this study are still on a small scale, and despite being flexible and elastic, these sponges are easily damaged, leading researchers to label them as fragile when not treated properly. The future research on graphene materials should focus on the methods that can produce improved intersheet binding and composites that are flexible and tear resistant. This can be accomplished by using elastic polymers, as well as changing the fibrous material or optimizing the structure's crosslink agents. The size of the furnace, as well as defects in the sheets, reduces the scale of template growth techniques. More research can be done in order to create a furnace design that can support more

layers. For commercial applications, graphene sponges made by dry and self-assembly methods need a freeze-drying process. Other factors may also prevent the sponge structure from adhering. In future studies, the characterization of graphene precursors must be looked into further to make it easier to detect changes in binding forces, especially during compositing and sponge formation. The use of concentrated acid, as well as variable sheet sizes and functionality, limits the commercial processing of graphene. In the quest to commercialize graphene, regulated surface functionalization of graphene sheets obtained from the exfoliation of graphite must also be considered as an advanced research path. It is also necessary to look into the need for template support. In order to overcome the challenges, above-described features in terms of graphene sponge, further research will be needed. The use of three-dimensional graphene and graphene oxide in many applications is the future, so it must be critically considered in the future study.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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