Applications of Graphene In Different Fields

Dongze Luan*

College of Engineering, Northeastern University, 02115 Boston, USA

Abstract. Graphene is the single layer of carbon atoms, which shows extraordinary electrical, mechanical, thermal, and optical capabilities. This research summarizes recent advances in applying graphene for energy storage, environmental engineering, and electronic devices. The two common synthetization approaches of graphene, top-down and bottom-up are illustrated. Graphene enhances lithium-ion batteries and supercapacitors as electrode materials due to its excellent physical and chemical properties such as high surface area and conductivity. The preparation methods of the graphene used in electrodes are shared. It removes both inorganic and organic pollutants from water through adsorption. As a printed 3D scaffold, graphene effectively absorbs gaseous pollutants. Graphene nanostructures improve the sensitivity of the biosensors: fluorescence sensors, electrochemical sensors, the surface plasmon resonance (SPR) sensors, the surface enhanced Raman scattering sensors. Highly conducting graphene paper can replace metals in flexible antennas. Graphene-metal nanocomposites transfer heat efficiently and cool electronics when dispersed in fluids. The multifunctionality and sustainability of graphene materials hold promise for next-generation technologies.

1 Introduction

In modern society, when talking about famous new materials, graphene is always mentioned. Since graphene was first isolated and characterized in 2004, it attracted an immense amount of study and research. Graphene has become one of the most widely studied materials, since it has remarkable chemical and physical properties. Graphene is a single carbon atoms layer that is arranged in a hexagonal lattice structure. Graphene is sp2 hybridized. The electrons in out-of-plane bonds, as well as the electrons in sigma bonds. Graphene can be found in many different forms, and these different forms of graphene have shown outstanding applications in different fields [1], such as biosensors and biomedical imaging.

Graphene has intrinsic electron mobility of up to 200,000 cm2/Vs, making it one of the most conductive materials known [1]. Its high electrical conductivity arises from its delocalized pi electrons that can move freely across the sheets. The highest specific surface area is 2630 m2/g in theory for a single side of the graphene, providing abundant surface sites for reactions and interactions [1]. Additionally, graphene displays excellent mechanical strength, where the Young's modulus can be up to 1 TPa. It can sustain high levels of strain without cracking. Graphene has an extremely high thermal conductivity, and is optically transparent, absorbing only 2.3% of incident light [1]. Other notable properties include its impermeability to gases and ability to conduct heat better than diamonds.

There are two main approaches for synthesizing graphene. The first approach is the bottom-up method. Bottom-up graphene formation is accomplished by applying specialized processes to break the chemical bonds of carbon-containing compounds and deposit carbon atoms on the substrate [2]. Chemical vapor deposition, epitaxial growth, and plasma synthesis are all common bottom-up techniques [2, 3]. One advantage of bottom-up methods is the ability to control the graphene growth process so that the thickness and quality are guaranteed. This makes the bottom-up approach suitable for synthesizing graphene for precise devices. However, bottom-up synthesis currently faces challenges in scalable and sustainable manufacturing due to the complex, energy-intensive, and hazardous operational conditions required [2]. Further research into greener and more efficient bottom-up techniques will be key to enabling large-scale graphene production while minimizing environmental impacts.

The other approach is the top-down approach. Graphite is made of multiple layers of graphene. The layers are bonded together due to the van der Waals forces. Top-down is to overcome the intermolecular force and exfoliate individual graphene sheets from multiple layers. Common top-down techniques include chemical redox force exfoliation, Hummers method, electrochemical exfoliation, mechanical exfoliation, etc [2, 3]. Despite top-down graphene can contain defects and lacks precise control over layer number, it offers advantages in scalability, cost, and simplicity compared to bottom-up growth. Compared to bottom-up, top-down methods are energy efficient, operationally straightforward, and can be applied for large-scale graphene production [2]. This makes top-down graphene suitable for applications like capacitors, and batteries

* Corresponding author: luan.d@northeastern.edu

Further research needs to be done to minimize the defects.

In the past two decades, researchers and investigators have found that graphene is able to be applied in numerous fields because of the properties mentioned above. As a result, this research will analyze the application of graphene in the various fields, such as energy storage, electronic devices, engineering materials, and environmental engineering are investigated and summarized in this review study.

2 Energy storage

2.1 Lithium-ion battery (LIB)

The LIB is a popular type of energy storage device because of their lack of memory effect, high amount of energy storage ability, and low self-discharge [2]. Because of its exceptional features, graphene is a good material for the LIB. These unique characteristics make graphene act as an ideal electrode material. Graphene is well-suited as an anode material. Graphene sheets' high surface area gives an abundance of sites for lithium storage via surface adsorption or intercalation between its layered structure. Graphene has a potential specific capacity of 744 mAh/g, allowing lithium ions to attach on both sides of the single-layer graphene sheets [3]. Its high electrical conductivity facilitates rapid electron transport during charging and discharging. Graphene can accommodate the strain induced by lithium insertion and desertion, enhancing the battery's cyclability. Moreover, the highly porous structure of graphene enables thorough infiltration of electrolytes into the electrode. This full penetration of electrolytes facilitated by the high porosity further improves battery performance [2].

There are some different approaches for incorporating graphene into LIB electrodes. The graphene power can be directly mixed with the active material when preparing the electrode slurry. However, this method is expensive and cannot guarantee the evenly graphene dispersion. Good graphene dispersion is critical for enhancing LIB properties like cycle life, capacity, and rate performance. The solution to this problem is using the graphene produced by the exfoliation method. The exfoliated graphene disperses stably and evenly, and it's not easily aggregation. The exfoliated graphene slurry route saves dispersion costs and prevents aggregation of graphene pieces compared to dispersing graphene powder. The graphene can also be prepared by liquid phase method and then mix with the electrode slurry. It's a more simplified process. The time taken is short as well. The other process disperses graphene powder by ultrasonication before mixing into slurries, but it takes more time and risks. This method will cause non-uniform dispersion as well [3]. Overall, graphene dispersions from liquid exfoliation integrate more effectively into battery slurries than powders, enabling performance improvements. The following sections describe applying exfoliation-produced graphene dispersions in the LIB.

Graphene also has a good performance when used as a cathode. The two-dimensional planar structure and delocalized pi electrons of graphene enable it to form interconnected conductive networks with electrochemically active materials. This reduces the internal resistance and facilitates electron transport through the cathode, leading to decreased polarization and higher power output. Additionally, the robust mechanical properties of graphene sheets help accommodate the strain induced during battery cycling, enhancing cycling stability. Graphene's surface oxygen groups can undergo reversible redox reactions with lithium ions for fast charging/discharging Incorporation of graphene can decrease internal impedance, improve conductivity, and increase the durability of cathode materials in lithium-ion batteries [3]. Overall, graphene has the potential to be an exciting material for the development of new LIB.

2.2 Supercapacitor

Supercapacitors are one type of energy storage device that consists of an electrolyte, two electrodes, and a separator. They store charge electrostatically, without electron transfer between the electrodes and electrolyte. Since the supercapacitor also has electrodes in it. Graphene would be suitable material for the electrode for the same reasons as the lithium-ion battery. Graphene is recognized as an ideal substrate to support semiconductor fabrication due to its remarkable properties. Graphene-semiconductor composites are increasingly applied in energy and environmental applications. Graphene can enhance the photocatalytic performance of semiconductors by increasing reactant adsorption, light absorption range, and intensity, acting as a photosensitizer, and facilitating electron transfer [4].

The development of porous nanoelectrode materials can be used to greatly improve the energy density of supercapacitors. For example, porous three-dimensional graphene with a large surface area of 3100 m2/g could be an ideal material to use to improve supercapacitor performance [5]. The activated 3D graphene contained small pores from 1-10 nm and had excellent electrical conductivity around 500 S/m [5].

3 Environmental engineering

3.1 Waste water treatment

Graphene is able to be utilized as a sorbent for waste water treatment. Graphene can remove the inorganic pollutants like heavy metals from the water. Wastewater from landfills, industries, and agriculture can contain toxic heavy metals like silver, zinc, and mercury that harm ecosystems and human health. Graphene oxide fabricated from agricultural wastes efficiently adsorbed Cu^{2+} and Pb^{2+} ions, with added ethylenediamine tetraacetic acid improving removal by 20-80% [6]. Graphene oxide synthesized using rice straw, black liquor, sawdust, and sugarcane bagasse achieved 85% removal of Ni^{2+} ions [6]. Kinetic studies found these bio-

derived graphene oxides followed pseudo-second order adsorption behavior. Waste-derived graphene oxide-polyaniline anodes in benthic microbial fuel cells simultaneously generated energy while removing 55-65% of Cd(II) and Pb(II). Reduced graphene oxide from algal biomass strains also effectively adsorbed over 90% of Cu and Pb ions [6]. In addition, the graphene can eliminate the organic pollutants, like dyes, from water and also pharmaceutical pollutants. One drawback is because of the van der Waal forces, the graphene layers accumulate in the water. This will weaken the absorption capacity. The solution to this problem is to transfer the 2D graphene into 3D. Also, adsorption efficiency can be affected by the physical and chemical properties of the adsorbent. Furthermore, 3D printing provides significant advantages in terms of increasing adsorbent mechanical strength [7].

3.2 Air pollution treatment

Since 3D graphene has super absorption capacity, it can be used as an air pollution treatment material. You produced a graphene scaffold using 3D printing [8]. The graphene scaffolds allow gas molecules to quickly diffuse to the inner graphene surface. Here is an example. The resistance of the freestanding platform may respond in real time to H_2O and NO_2, with relative resistance increases of up to 2% and 2.5% for 100 ppm H_2O and 100 ppm NO_2 [8]. In industrial production, the optimized graphene linked scaffold offers significant promise for sensing humidity and oxidizing contaminating gases. Some other forms of graphene, for example, the reduced graphene oxide, can act as a sorbent to absorb lots of polluted gas like toluene and nitric oxide.

4 Electronic devices

4.1 Biomedical sensors

Graphene nanostructures like GO, rGO, and GQDs have been incorporated into optical and electrochemical biosensors due to their excellent electrical and optical properties. They improve sensor sensitivity, allowing the detection of different biomarkers down to picomolar concentrations in clinical samples [9]. In fluorescent biosensors, the fluorescence resonance energy transfer between the donor and the acceptor. The unique optical properties make graphene-based nanostructures suitable for fluorescence-based biosensing applications. Their interaction with target biomolecules can result in detectable changes in fluorescent signals. Graphene nanomaterials have been utilized as both donors and acceptors in fluorescence resonance energy transfer systems. As fluorescence resonance energy transfer donors, graphene nanostructures exhibit strong energy transfer within 6-10 nm and have broad emission spectra that overlap with acceptor absorption bands [9]. This enables their fluorescence to be quenched in the presence of analytes. Graphene quantum dots can act as fluorophores and fluorescence resonance energy transfer donors due to their natural photostability and brightness. GQDs functionalized with aptamers or doped with nitrogen detect cancer biomarkers like EpCAM protein and metal ions like Hg^{2+} with high sensitivity [9]. Alternatively, as acceptors, graphene nanomaterials can effectively quench fluorescent probes up to 30 nm distance, enabling high sensitivity fluorescence detection of biomarkers [9]. In this case, the labelled probes are quenched on the graphene surface until displaced by specific binding with target biomolecules, recovering the fluorescence.

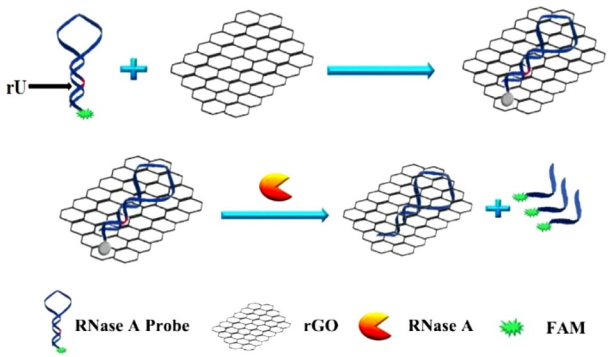

Fig. 1. RNA interacts with reduced graphene oxide [9, https://doi.org/10.1016/j.aiepr.2023.03.001]

Graphene and its derivatives are suitable for electrochemical biosensors, which enables sensitive detection of targets. Some techniques utilize graphene prepared through non-chemical routes to preserve optimal conduction properties. Graphene materials are often incorporated as sensitive films on sensor electrodes, especially the working electrode, to enhance biomolecule immobilization and energy conversion by increasing active surface area. The large surface area also provides more sites for electrocatalysis. Graphene-coated electrodes can further amplify signals through interactions with metallic nanoparticles or heteroatom dopants. Depositing metal nanoparticles like gold and palladium onto graphene can improve electron transfer for electroanalysis [9]. Nanocomposites of rGO-metal NPs detect antibiotics and prostate cancer biomarkers at pg/mL levels in biofluids. Graphene nanosheets detect DNA via in-situ deposition of silver NPs which enhance electrochemical signals. Doped rGO with enhanced surface area provides label-free detection of cancer biomarkers at fg/mL in serum [9], as shown in Fig. 1.

The surface plasmon resonance (SPR) sensors and the surface enhanced Raman scattering (SERS) Sensors are the application of graphene as well. Graphene functionalization of gold SPR chips improves sensitivity. The large surface area amplifies signals enabling the detection of microRNAs, small molecules, and cancer biomarkers down to the fM range in serum. Graphene-gold nanoparticle composites enhance SPR signal for multiplex detection [9]. The tunable optical properties of graphene augment SPR measurements. Graphene interacts with Raman probes and metal NPs to amplify SERS response. GO-gold NP composites detect cardiac biomarkers at pg/mL levels in serum [9]. GO reduces SERS signals for indirect detection of cancer biomarkers at fg/mL [9]. Graphene layers improve SERS uniformity,

chemical enhancement, and reuse, detecting metal ions at pM levels.

4.2 Antennas in electronic devices

Antennas in electronic devices are made of different metals. The key property that the antenna should have is electrical conductivity. Graphene, its different forms, or graphene metal combination can be utilized as antennas. The graphene material has a distinct structure that enables higher charge mobilities, resulting in faster electrical rates in the THz frequency range. Unlike metal-based antennas, this property enables the generation of specialized electromagnetic radiation [10]. Graphene can be reassembled in thick and flexible layers to form graphene paper, which can be applied to the antennas. The G-paper was produced by compressing graphene nanoplatelets into continuous, flexible layers. The electrical conductivity of 4.2 x 10^5 S/m achieved is comparable to monocrystalline graphite [11]. The graphene antennas showed excellent stability during 1 million bending cycles, significantly outperforming commercial metallic antennas which degraded rapidly. The self-resonance frequency and inductance peak of the graphene antenna remained almost unchanged [11]. The antennas also showed long-term durability and could be fabricated on various substrates. The feasibility of graphene as a replacement for metals in consumer electronic antennas was demonstrated.

4.3 Cooling or heat generation electronic devices

Besides graphene itself and its oxidized derivatives, graphene can form nanocomposite materials. By adding graphene oxide to aluminum isopropoxide in propanol, heating to form an intermediate product, and then annealing at 280°C, graphene-encased alumina nanocomposites can be synthesized [12]. And the results from transmission electron microscopy characterization showed the graphene nanoplatelets uniformly coating the alumina nanoparticles in a core-shell structure [12]. The graphene-encased alumina nanofluid displayed significantly better cooling capacity compared to water. The nanofluid's performance for cooling can be simulated using an electronics system [11]. The core temperature decreased with increasing nanofluid concentration and flow rate. At 0.2 vol% loading, the temperature dropped 11% compared to water [12]. And the experiment shows that the graphene-alumina nanocomposite's synergistic actions produced a nanofluid with good heat transfer capabilities and dispersion stability around neutral pH. As a result, the graphene-alumina nanofluid is a good heat transfer material in cooling or heating electronic devices.

5 Conclusion

In conclusion, this review highlights the tremendous potential of graphene and its derivatives for diverse technological applications. The exceptional electrical, thermal, mechanical, and optical properties of graphene make it suitable for energy storage devices, water treatment systems, wearable biomedical sensors, flexible electronics, thermal management of devices, and more. While most applications are currently at the research stage, graphene shows strong promise to enhance performance and sustainability compared to conventional materials. Translation from lab prototypes to commercial technologies will require scalable and low-cost graphene production methods. However, lots of more research should have been done to test all the properties of graphene. This review article only summarized a tiny portion of graphene applications. Researchers in different fields should pay attention to this new material. It could be suitable for devices or products in any different fields. People still need more exploration of graphene. With continuous innovation in materials processing and device engineering, graphene could become ubiquitous in next-generation sustainable technologies and find widespread adoption. Realizing the full potential of graphene will rely on strong collaborations between materials scientists, chemists, physicists, engineers, and industrial manufacturers.

References

1. Santosh K. Tiwari, Sumata S, Andrzej H, Wang NN. “Graphene Research and Their Outputs: Status and Prospect.” Journal of Science: Advanced Materials and Devices, pp10-29, 2020.
2. Wen Y, Liu HM, Jiang XY. “Preparation of Graphene by Exfoliation and Its Application in Lithium-Ion Batteries.” Journal of Alloys and Compounds, vol 961,7 2023.
3. L. Syam Sundar, M. Amin Mir, M. Waqar Ashraf, Faramarz D. “Synthesis and Characterization of Graphene and Its Composites for Lithium-Ion Battery Applications: A Comprehensive Review.” Alexandria Engineering Journal, vol. 78, pp224-245, 2023.
4. Rashi. “Exploring the Methods of Synthesis, Functionalization, and Characterization of Graphene and Graphene Oxide for Supercapacitor Applications.” Ceramics International, vol 49, issue 1, pp 40-47, 2023.
5. Xiehong Cao, et al. “Three-Dimensional Graphene Materials: Preparation, Structures andApplication in Supercapacitors.” Energy & Environmental Science, 2014.
6. P. Kumari, S. R. Samadder. “Valorization of Carbonaceous Waste into Graphene Materials and Their Potential Application in Water & Wastewater Treatment: A Review.”Materials Today Chemistry, vol 22. 2022
7. Zhang HN, Liu XM, et al. “Additive Manufacturing of Three-Dimensional Graphene-Based Architectures and Its Application in Environmental Treatment: A Review.”Chemical Engineering Journal, vol 465, 2023.

8. Xiao Y, Yang JS, Wang MM, et al. "Interconnected Graphene Scaffolds for Functional Gas Sensors with Tunable Sensitivity." Journal of Materials Science & Technology, vol 58, pp 16-23, 2020.
9. Rebecca G, Haftom W, Li HY, et al. "Graphene-Based Nanostructures from Green Processes and Their Applications in Biomedical Sensors." Advanced Industrial andEngineering Polymer Research, 2023.
10. Murali krishna Ch a, et al. "A Micro-Scaled Graphene-Based Wideband (0.57–1.02 Thz) Patch Antenna for Terahertz Applications." Results in Optics, Elsevier, vol 12, 2023.
11. A. Scida, S. Haque, et al. "Application of graphene-based flexible antennas in consumer electronic devicese." Materialstoday, vol 21, pp223-230, 2023.
12. Vishnuprasad S, Haribabu K. "Synthesis of Graphene Encased Alumina and Its Application as Nanofluid for Cooling of Heat-Generating Electronic Devices." Powder Technology, vol 363, pp 665-675, 2020