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Advances in Improving Graphene Properties Based on Chemical and Biological Modification Methods

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Abstract: Graphene, a two-dimensional carbon nanomaterial with a single atomic layer, has piqued the interest of materials scientists for its remarkable mechanical strength, high thermal conductivity, and electron mobility. Electronic gadgets, composite materials, energy storage, and biomedicine have all exhibited significant interest in graphene since its initial successful synthesis through mechanical peeling in 2004 due to its unique features. Nevertheless, there are still challenges to using pure graphene due to its poor dispersibility, environmental stability, and electrical characteristics. In recent years, the introduction of specific functional groups or doping elements through chemical and biological modification has become a key method to improve the properties of graphene, including REDOX method, surface functional group modification, and biological macromolecular modification strategies. These modification methods significantly improve the hydrophicity, conductivity and biocompatibility of graphene and broaden its application prospects in flexible electronics, composite materials and energy storage devices. Therefore, the study provides a comprehensive overview of the most important functionalized modification approaches for graphene and assesses the benefits and drawbacks of using them in various industries. Research has shown that rational functional modification of graphene's physical and chemical characteristics can significantly enhance its potential for use in emerging electronic devices and energy storage systems.

Keywords: Graphene Functionalization, Material Modification, Flexible Electronics, Energy Storage System

1. Introduction

Graphene is a two-dimensional material composed of a single layer of carbon atoms arranged in a hexagonal lattice, garnering extensive attention due to its exceptional physical and chemical properties. These properties include an ultra-high electron mobility (exceeding 200,000 cm2/V·s), excellent thermal conductivity (up to 5000 W/m · K), and remarkable mechanical strength (approximately 200 times stronger than steel). As early as 1947, physicist Philip R. Wallace theoretically predicted the existence of two-dimensional carbon materials and their electronic properties. Using mechanical exfoliation, Andre Geim and Konstantin Novoselov isolated single-layer graphene for the first time in 2004, a milestone in graphene research. Since then, graphene's unique features have been studied for use in electronic devices, composite materials, sensors, and energy storage [1]. For instance, graphene, as the channel material for field-effect transistors (FETs),

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can significantly enhance device switching speed and current density. Its high thermal conductivity also makes it an ideal candidate for heat dissipation applications. However, chemical inertness, weak hydrophilicity, and incompatibility with other materials make pristine graphene difficult to use. To boost graphene's dispersion, stability, and electrical properties, functionalization techniques add chemical groups or doping elements. In recent years, various functionalization strategies have been proposed and widely adopted, including REDOX methods, surface functional group modification, and biomolecular functionalization. These approaches not only enhance graphene's properties but also expand its applicability across different fields [2]. By reviewing and analyzing the existing literature, the paper seeks to summarize recent advances in graphene functionalization techniques, evaluate their advantages and challenges in applications such as electronic devices, composite materials, and energy storage, and provide insights into potential future research directions.

2. Overview of the Modification of Graphene Functionalization

As a two-dimensional material with excellent physical and chemical properties, graphene is widely used in electronic devices, composite materials, and biosensing. Its unique properties make functional modification an important way to improve the application value of graphene [3]. Functionalizing graphene allows for substantial improvements in electrical conductivity, thermal conductivity, and mechanical strength, making it more suitable for a variety of applications. Chemical and biological modifications are the two basic types of functional modifications. Graphene can have its qualities enhanced by adding certain chemical groups or doping elements, a process known as chemical modification. To improve its dispersion and stability, graphene can have polar functional groups like hydroxyl, carboxyl, or epoxy added to its surface. This improves its interaction with polar solvents, which is useful in electronic devices [4]. In addition, the application of N-doped graphene technology can improve the charge carrier concentration of graphene and enhance its conductivity in field effect transistors (FETs). Biomodification exploits the action of biomolecules or organisms to give graphene specific biocompatibility and functionality. Proteins, nucleic acids, and polysaccharides are among the most frequently modified biological components. The sensitivity and selectivity of the sensor can be raised by immobilizing proteins, DNA fragments or polysaccharides on the surface of graphene hence enhancing their recognition of particular biomolecules [5]. For instance, graphene-antibody pairing allows for rapid detection of tumor markers, which aids in early cancer detection. When it comes to increasing graphene's characteristics and broadening its application range, functional modification technology is crucial. To attain a broader range of practical uses for functionalized graphene, future research should concentrate on improving modification methods and solving the problems of cost and environmental compatibility.

3. Graphene Modification

3.1. Chemical Modification

The REDOX method is a widely utilized and effective approach for modifying graphene, allowing for the introduction of various oxygen-containing functional groups on the graphene surface, including hydroxyl (-OH), carboxyl (-COOH), and epoxy (-O-), thereby enhancing the hydrophilicity and reactivity of graphene. The procedure comprises two primary phases: oxidation and reduction [6]. The oxidation step can be carried out by the Hummers method. We first mix the natural graphite powder with sulfuric acid to form a uniform slurry. Potassium permanganate was gradually introduced to the slurry, and the reaction was stirred under low temperature conditions to ensure complete interaction of the oxidant with the graphite layers. Hydrogen peroxide or distilled water can be added to halt the oxidation reaction and purify the reaction product to yield graphene oxide (GO).

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In this process, the layered structure of graphite is broken and a large number of oxygen-containing functional groups are generated, which are mainly concentrated at the edges and defect sites of graphene. The introduction of these functional groups enables GO to exhibit good hydrophilicity and reactivity. However, its electrical conductivity is poor, so it needs to be further reduced to restore part of the electrical conductivity. Common reduction methods include chemical reduction and thermal reduction. Chemical reduction involves the reduction of specific oxygen-containing functional groups in GO using chemical reducing agents, including hydrazine hydrate, ammonaborane, or ascorbic acid, to produce reduced graphene oxide (rGO). rGO can be synthesized by dispersing GO in water, introducing a hydrazine hydrate solution, and maintaining the reaction under stirring for several hours at the optimal temperature. And the thermal reduction principle involves heating GO to elevated temperatures (300-1000 ℃) in an inert gas atmosphere (e.g., argon or nitrogen) to eliminate oxygenated functional groups, resulting in rGO [7].

3.2. Biological Modification

Biomodification involves adding biocompatibility or functionality to graphene by utilizing the impacts of biomolecules or organisms. Biomacromolecule modification allows us to accomplish this. Some common ways for modifying macromolecules are: Immobilizing proteins (e.g., enzymes, antibodies, receptors) onto graphene surfaces enables biosensing, catalysis, medication delivery, and other potential uses for protein modification. Because of its ability to undergo protein changes, graphene can now detect and respond with certain biomolecules. Graphene can be modified to serve purposes in genetic testing, medication delivery, and molecular recognition by adding bits of DNA or RNA. Graphene can be made more sensitive and selective by modifying it with nucleic acids. Graphene can be modified by adding polysaccharides (such chitosan or alginate) to make it more biocompatible, increase its affinity for living things, and make it more stable and dispersible in water. To identify tumor markers, viral proteins, and infections, for instance, biomodified graphene can be used in the bloodstream. These sensors may detect diseases rapidly and correctly by combining graphene with specific enzymes, antibodies, or DNA probes; this helps accomplish early diagnosis and avoid the repercussions of being too late [8].

4. Performance and Applications of Functionalized Graphene

4.1. Characteristics of Functionalization Modification

Functionalization modification significantly enhances various properties of graphene. For example, introducing polar functional groups on the surface of graphene can improve its dispersion in solvents, effectively preventing agglomeration. Specifically, the Hummers method is used to oxidize graphene into GO, resulting in the introduction of various polar functional groups, including hydroxyl, carboxyl, and epoxy groups on its surface [9]. This modification significantly improves its interaction with polar solvents such as water, facilitating stable dispersion of graphene oxide in aqueous environments. This material not only exhibits excellent dispersion properties but also retains high electrical conductivity, making it suitable for a wide range of applications. Moreover, unfunctionalized graphene often lacks sufficient selectivity toward specific biomolecules or target substances in detection applications, making it prone to responding to nonspecific molecules, which can compromise the accuracy of detection results. Functionalization modification addresses this issue by immobilizing biomolecules such as antibodies, enzymes, and DNA probes onto the surface of graphene, significantly enhancing its ability to recognize specific targets. This modification approach greatly improves the selectivity and reliability of graphene, providing strong support for applications such as biosensing and molecular detection.

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4.2. Applications of Functionalized Graphene in Flexible Electronic Devices

Functionalized graphene is a crucial part of bendable electronics because of its great chemical stability, remarkable mechanical flexibility, and superb electrical characteristics. Improved compatibility with substrates and optimized device performance are two outcomes of functionalization's impact on graphene's surface characteristics. Transparent conductive films and flexible electrodes made of functionalized graphene are commonplace in touchscreens, flexible displays, and wearable electronics [10]. For instance, flexible substrates like polydimethylsiloxane (PDMS) are well-served by graphene that has been functionalized with polyethylene glycol (PEG), which exhibits outstanding electrical conductivity and flexibility. By enhancing its adhesion to flexible substrates, graphene can be enhanced using PEG, leading to better stability and reliability of devices. Flexible sensors also rely heavily on functionalized graphene. Its high sensitivity and rapid response capabilities enable applications in pressure sensing, strain sensing, and gas detection. Functionalized graphene, for instance, enables sensitive monitoring of minute pressure variations when utilized in flexible pressure sensors; this property is essential for health monitoring and HMI devices. Functionalized graphene sensors can measure pulse, blood pressure, and respiration rate in real time using biomolecules or chemicals. Another important application of functionalized graphene is as an electrode material for flexible batteries. Due to its excellent conductivity and chemical stability, functionalized graphene is used in the manufacturing of energy storage devices such as lithium-ion batteries and supercapacitors. Functionalization enhances the specific surface area and conductivity of graphene, thereby improving energy storage capacity and power density. These characteristics make it highly promising for use in wearable electronic devices, providing higher energy density and extended device lifespan.

4.3. Applications of Functionalized Graphene in Energy Storage Devices

Functionalized graphene has significant potential in energy storage systems like lithium-ion batteries and supercapacitors. And it has been extensively studied as an active material and conductive additive to improve battery and supercapacitor energy density, power density, and cycle stability due to its outstanding conductivity, high specific surface area, and mechanical qualities [11]. In Li-ion batteries, functionalized graphene can improve the performance of the battery by acting as a negative electrode material or as a conductive filler. It has been shown that the ability to embed and de-embed lithium ions can be significantly improved by introducing functional groups such as oxides or nitrates into the graphene structure. These modifications can improve the charging and discharging efficiency of lithium-ion batteries, and reduce the charging time. For example, nitrogen-doped graphene not only enhances the kinetic properties of lithium ions, but also improves the cycling stability of the electrodes, thus significantly extending the battery lifetime. In terms of supercapacitors, functionalized graphene is an ideal electrode material due to its high specific surface area and good conductivity. Through chemical or biological modification, the functional groups on the surface of graphene can enhance its interaction with the electrolyte and increase the electrochemical activity of the electrode. For example, surface functionalization of graphene with hydroxyl and carboxyl groups leads to a dramatic increase in power density and capacitance. In tests, functionalized graphene supercapacitors perform very well under rapid charging and discharging in terms of both energy storage capacity and cycle stability. In addition, composite electrode materials, which combine functionalized graphene with other materials, can significantly enhance the performance of batteries and supercapacitors. An example of a composite material that can improve the device's performance is functionalized graphene combined with conductive polymers or metal oxides. This combination increases the mechanical strength and conductivity of the electrodes. This composite material has great potential for commercial use due to its exceptional performance in applications requiring a high power density and energy density.

5. Conclusion

This study provides an overview of the latest developments in the functional modification of graphene, with a focus on its applications in flexible electronic devices and energy storage systems. The research demonstrates that through chemical and biological functionalization methods, graphene's dispersion, conductivity, hydrophilicity, and biocompatibility have been significantly improved, thus expanding its potential applications across various fields. Functionalized graphene has demonstrated excellent performance in transparent conductive films, flexible electrodes, pressure sensors, and supercapacitors, with particularly promising prospects in flexible electronics and energy storage devices. However, there are still some practical problems. Functionalization is costly and environmentally unfriendly, and cost reduction and environmental enhancement need to be addressed urgently. In addition, though the existing functionalization process is promising, the stability and long-term performance of graphene in complex environments still need to be further investigated. Large-scale synthesis of functionalized graphene still faces technical obstacles and requires process optimization and improved production efficiency. Improving the performance of graphene for flexible electronics, sensors, and energy storage, as well as creating more efficient and cost-effective ways to functionalize it to address environmental and economic issues, should be the focus of future research. Equally important is expanding functionalized graphene's use in biomedicine, especially in areas like early illness detection and precision medicine. As a result of these endeavors, functionalized graphene is anticipated to have a substantial impact in a wider range of domains, laying the groundwork for future technological developments both materially and technically.

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