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The Application Research and Development of Graphene-like Materials

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Abstract. Graphene-like materials, as a new generation of two-dimensional nanomaterials, have become a research hotspot in the fields of materials science, nanotechnology and engineering applications due to their unique atomic layered structure and outstanding physical, chemical and electrical properties. They not only show great potential in electronic devices, energy storage, sensors, catalysis and biomedicine, etc. Moreover, due to its adjustable band gap structure, high specific surface area, excellent carrier mobility and outstanding environmental stability, it even surpasses the performance of traditional graphene in specific applications. At present, the synthesis methods of such materials mainly include mechanical exfoliation, chemical vapor deposition (CVD), liquid-phase exfoliation and solvothermal method, etc. Among them, although the CVD method can prepare high-quality films, the cost is relatively high, while the liquid-phase exfoliation method is more suitable for large-scale production but may introduce structural defects. Therefore, how to optimize the synthesis process to achieve high purity, low defect and controllable preparation remains the core challenge of current research. At the application level, graphene materials have demonstrated significant advantages. For instance, molybdenum disulfide (MoS_2) has become an ideal material for high-performance transistors due to its tunable bandgap characteristics. MXenes have shone brightly in the fields of flexible electronics and electromagnetic shielding with their ultra-high electrical conductivity. In the energy sector, This type of material is promoting the development of next-generation efficient energy storage technologies by enhancing the energy storage density and cycle stability of lithium-ion batteries and supercapacitors. Despite this, its industrialization still faces key bottlenecks such as scalability, cost control and environmental compatibility. In the future, it is necessary to develop green synthesis technologies through interdisciplinary collaboration, optimize device integration processes, and deeply explore the structure-performance relationship to fully unleash the full potential of such revolutionary materials and contribute to the breakthrough development of sustainable high-tech industries.

Keywords: graphene-like materials, nanomaterials, electronics, energy storage, sensors

1. Introduction

The discovery of graphene has ushered in a new era in the research of two-dimensional materials. In 2004, Novoselov et al. successfully prepared monolayer graphene for the first time through

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mechanical exfoliation [1]. The room-temperature quantum Hall effect and ultra-high carrier mobility characteristics it exhibits have completely changed people's understanding of material properties. Subsequent studies have shown that this two-dimensional material with a single atomic layer thickness possesses extraordinary mechanical strength, stronger electrical conductivity and greater flexibility [2]. Theoretical calculations further confirm that its carrier mobility can reach more than 100 times that of silicon materials [3].This study aims to address these issues by exploring advanced synthesis methods, such as chemical vapor deposition (CVD), mechanical exfoliation, liquid-phase exfoliation, electrochemical synthesis, and solvent-thermal synthesis. By optimizing these techniques, we seek to enhance the quality, scalability, and environmental friendliness of graphene-like materials. The research also delves into the application of these materials in electronics, semiconductors, energy storage, and sensors, highlighting their potential to revolutionize these fields. Through a comprehensive investigation, this study contributes to the advancement of sustainable high-tech industries and the transition from laboratory research to commercial implementation

2. Properties of graphene-like materials

2.1. Material properties

Two-dimensional materials exhibit extraordinary properties, making various technological applications possible. Materials such as graphene have excellent electrical conductivity (up to 10 ^ 26 S/m), mechanical strength (elastic modulus of 1 TPa), and thermal conductivity (exceeding 3000 W/mK), making them ideal materials for advanced electronic devices. Transition metal disulfide compounds such as molybdenum disulfide (MoS2) are particularly valuable as tunable semiconductors, and their band gap can be adjusted between 1.2 and 1.9 eV.

Hexagonal boron nitride (h-BN) is an excellent insulating material in electronic applications, with a wide band gap of 6 eV and excellent thermal conductivity (10 times greater than that of copper). The smooth surface of its atoms minimizes electron scattering, making it particularly valuable in the thermal management of high-power devices using GaN or SiC semiconductors. The efficiency of their second harmonic generation is 2-3 orders of magnitude higher than that of bulk materials. These characteristics have promoted the development of ultrathin lasers and quantum light sources.

The structural characteristics of two-dimensional materials have a great influence on their functions. The theoretical surface area of these materials exceeds 2600 m^2/g, with almost 100% surface atoms involved. The edge positions exhibit unique electronic states, performing exceptionally well in catalytic and sensing applications. These characteristics make an efficient CO_2 reduction process and sensitive DNA detection capabilities possible. Researchers can precisely design the properties of materials through various methods: van der Waals heterostructure engineering is used for band structure modification, defect engineering for controlling surface reactivity, and phase engineering for manipulating material properties. These advanced material design strategies support the development of professional solutions for aerospace, energy and biomedical applications, accelerating the transition from laboratory research to commercial implementation.

2.2. Synthesis method

The synthesis of graphene-like materials, which involves multiple techniques, employs methods that each have unique advantages and limitations. Chemical vapor deposition (CVD), which is

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widely regarded as the most effective method, produces high-quality, large-area films that exhibit precisely controlled thickness and uniformity.

The advantage of this technology lies in its suitability for industrial-scale applications. Chemical vapor deposition (CVD) is currently the most promising technology for the industrial preparation of graphene-like materials. Li et al. achieved the preparation of centimeter-level high-quality graphene by optimizing the CVD parameters on the copper foil, with the carrier mobility exceeding 4000 $cm^2/V \cdot s$ [4]. The Bae team further developed the roll-to-roll CVD process and successfully produced 30-inch graphene transparent electrodes, verifying the scalability of this technology [5]. However, for two-dimensional materials such as MoS 2, the CVD method still faces the problem of grain boundary defects [6], and the uniformity of the thin film needs to be improved through substrate selection and post-processing process optimization [7].

Although mechanical exfoliation is limited to small-scale production due to its labor-intensive nature and low yield, it remains a highly cost-effective and straightforward method for obtaining high-purity monolayer graphene materials with minimal defects. This technique, often implemented through Scotch tape peeling or ball milling, provides researchers with pristine graphene samples ideal for fundamental studies and high-performance applications where quality outweighs quantity concerns. In contrast, liquid-phase exfoliation has emerged as a more scalable alternative that involves dispersing bulk layered materials in carefully selected solvents, followed by ultrasonic or shear exfoliation to produce 2D nanosheets. This solution-based approach offers several advantages, including the ability to control nanosheet concentration, size distribution, and thickness through centrifugation and other post-processing techniques. The resulting colloidal suspension can be further processed into functional inks for printed electronic products, or added to a polymer matrix to manufacture advanced composite materials. These graphene-based formulations have been widely applied in flexible electronic products, such as stretchable conductors and transparent electrodes, including energy storage systems for supercapacitors and lithium-ion batteries, where the formulations enhance mechanical and electrochemical properties. The scalability of liquid-phase exfoliation, combined with the compatibility of existing industrial processing technologies, provides significant assistance for commercial applications that require a large amount of two-dimensional materials.

These methods can also combine heteroatoms or functional groups to further enhance the performance of materials for target applications. Despite these advancements, challenges such as defect control, reproducibility and scalability still exist, so it is necessary to continue researching new synthesis strategies.

3. The application of graphene-like materials

3.1. Electronics and semiconductors

Integrating graphene-like materials into the electronics industry has ushered in a new era of equipment performance and functionality. For instance, graphene-based field-effect transistors (FETs) outperform silicon transistors in terms of carrier mobility and switching speed, making them promising candidates for the next generation of high-frequency and low-power electronic products. Furthermore, the bipolar nature of graphene makes it possible to design reconfigurable logic circuits, providing unprecedented flexibility for device architectures.

Transition metal disulfide compounds such as MoS_2 and WS_2 (TMDs) have become key materials for flexible and transparent electronic products. Their direct band gaps achieve effective light absorption and emission in a single-layer form, paving the way for ultra-thin photodetectors, light-

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emitting diodes (leds), and photovoltaic devices. In addition, the mechanical strength of these materials is highly suitable for use in wearable electronic products, where durability and flexibility play the most significant role.

3.2. Energy storage and batteries

Graphene-based materials are revolutionizing energy storage technology by addressing the key limitations of traditional systems. In lithium-ion batteries (LIBs), graphene-based electrodes exhibit enhanced charging capacity and cycling stability due to their high electrical conductivity and large surface area.

The advantages of graphene-reinforced supercapacitors include high energy and power density, successfully bridging the gap between traditional capacitors and batteries. The porous structure of graphene-based electrodes is conducive to rapid ion transport, achieving ultra-fast charging and discharging capabilities that surpass those of traditional energy storage devices. In addition, the combination of pseudo-capacitive materials (such as conductive polymers or metal oxides) with graphene can enhance the charge storage capacity and meet various application requirements. These system performance parameters exceed those of traditional solutions and are now being implemented in a wide range of applications, from portable electronic devices to large-scale grid energy storage systems.

3.3. Sensors and environmental applications

Graphene-based materials have good sensitivity and selectivity and are mostly applied in sensor technology. The advantage of sensors using graphene oxide (GO) as an effective component in detection over traditional sensors lies in their ability to identify trace elements that are usually unidentifiable, including gases, biomolecules, and heavy metals. The detection of these elements requires nanoscale accuracy. These advanced sensors, whose applications span multiple medical fields, enable real-time biomarker monitoring.

4. Challenges and limitations

4.1. Create challenges

Despite its great potential, the wide adoption of graphene-like materials is hindered by several manufacturing challenges. Scalability remains a key issue because many synthesis methods, such as CVD, require complex equipment and strict conditions, which limit the cost-effectiveness of large-scale production. Although mechanical stripping is simple, the amount of material produced is small and the quality is inconsistent, making it unsuitable for industrial applications.

Furthermore, developing standardized protocols for material synthesis and processing is crucial for ensuring repeatability and performance consistency across different applications.

4.2. Environmental and sustainability issues

The environmental impact of the production and processing of graphene-like materials is an area that is receiving increasing attention. For instance, the method used by Hummer to produce graphene oxide generates hazardous waste, thereby increasing costs.

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5. Conclusion

This study elucidates the transformative potential of graphene-based nanomaterials in driving next-generation technological and industrial advancements. Through systematic investigation of their structure-property relationships, multifunctional applications, and existing limitations, this work provides a critical assessment of both the opportunities and challenges within this rapidly evolving research domain. Key findings indicate that while graphene and its derivatives exhibit exceptional promise for disruptive innovations in flexible electronics (e.g., ultra-thin transistors, transparent conductive films), advanced energy systems (e.g., supercapacitors, Li-ion battery anodes), and ultrasensitive sensor platforms, several fundamental constraints impede their full-scale commercialization. Foremost among these are unresolved issues in scalable synthesis, interfacial engineering, and environmental sustainability across the material lifecycle.

As the field progresses, the rational design of graphene-based material systems is anticipated to play a pivotal role in enabling paradigm-shifting technologies. Their unique combination of mechanical robustness, quantum confinement effects, and tunable surface chemistry positions them as key enablers for sustainable advanced manufacturing and post-Moore's law nanoelectronics. Continued advancements in controlled synthesis and application-specific functionalization will be instrumental in transitioning these materials from laboratory curiosities to industrially viable solutions.

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