Review of Graphene Electromagnetic Shielding Applications

Lanxin Zhang
Shashi Middle School, Shashi, Hubei, China

Abstract: With technological advancements, electromagnetic pollution has become an increasingly pressing issue. Graphene, renowned for its high electrical conductivity, exceptional mechanical properties, and unique two-dimensional structure, has emerged as a research hotspot in electromagnetic shielding. This paper introduces the main preparation methods of graphene: chemical vapor deposition (CVD, suitable for large-area high-quality graphene production), supercritical CO_2 exfoliation (high efficiency and yield), redox method (simple operation and low cost but prone to defects), liquid-phase exfoliation (suitable for mass production but solvent-related challenges), and vapor-phase exfoliation (high-quality graphene preparation but costly), with detailed explanations of each method's characteristics. Subsequently, the paper analyzes two primary types of graphene-based electromagnetic shielding materials: nanofill-based composites (such as carbon nanotube/graphene, carbon fiber/graphene, porous carbon fiber/graphene, and graphene-metal composites). Among these, carbon nanotube/graphene composite films demonstrate shielding effectiveness exceeding 40 dB in high-frequency bands, while porous carbon fiber/graphene composites achieve over 30 dB shielding in low-frequency bands (e.g., 1 GHz). Nanoscale structured materials (such as graphene foam, graphene-insulating layer bilayer structures, and composite 3D graphene) also show promise. Graphene foam, with its three-dimensional porous structure, exhibits excellent absorption shielding performance, achieving over 20 dB in high-frequency bands. The graphene-insulating layer bilayer structure can simultaneously realize reflection and absorption, delivering over 30 dB shielding in mid-frequency bands. Additionally, the paper introduces graphene characterization techniques (Raman spectroscopy, AFM, TEM) and electromagnetic shielding performance testing methods (EMSE measurement using vector network analyzers). Finally, the conclusion points out that graphene electromagnetic shielding material has great potential, and its commercial application should be promoted in the future by optimizing the preparation process, doping modification, composite of various materials and paying attention to environmental protection and sustainability to solve the problem of electromagnetic pollution.

Keywords: Graphene; Electromagnetic Shielding Material; Preparation Method; Material Type; Characterization Technology

1. Introduction

1.1 Research Status and Review at Home and Abroad

Research on graphene-based electromagnetic shielding has seen early breakthroughs abroad, with scientific institutions and enterprises investing substantial resources in R&D. Notably, universities and laboratories in the United States have achieved significant progress in graphene preparation, characterization, and electromagnetic shielding performance studies. Through methods like chemical vapor deposition, they have successfully developed high-quality graphene films and demonstrated their exceptional shielding capabilities under high-frequency electromagnetic waves [4].

While China's research in this field started relatively late, it has experienced rapid development. The Chinese government places high priority on advancing new material technologies, with graphene as a prime example receiving widespread attention and support. Leading institutions like the Chinese Academy of Sciences and Tsinghua University have conducted in-depth research in graphene-based electromagnetic shielding, achieving breakthroughs in preparation techniques while making significant progress in understanding shielding mechanisms and composite material design. Additionally, domestic enterprises have begun developing and producing graphene shielding materials, accelerating the industrialization of this technology [5].

However, both domestically and internationally, graphene-based electromagnetic shielding technology faces challenges such as high production costs and difficulties in large-scale manufacturing. The key challenge for researchers and enterprises is how to reduce production costs while maintaining performance, and achieve scalable production. Moreover, with the widespread adoption of technologies like 5G and the Internet of Things, the demand for high-frequency electromagnetic shielding materials continues to grow, indicating vast research and application potential for graphene-based electromagnetic shielding materials [6].

In summary, remarkable progress has been made in both domestic and international research and application of artificial intelligence and graphene-based electromagnetic shielding materials, yet numerous challenges persist. As technology advances and application domains expand, these fields will continue to profoundly influence our work and lifestyles [7].

1.2 Theoretical Basis of Electromagnetic Shielding Material

Electromagnetic shielding is a vital strategy for suppressing electromagnetic interference and preventing electromagnetic radiation. It involves using conductive or magnetic materials as barriers to block electromagnetic wave propagation and reduce electromagnetic fields [1]. This technology primarily relies on three fundamental theories: eddy current theory, electromagnetic field theory, and transmission line theory [1].

1.2.1 Eddy current theory

When the coil is filled with alternating current, an alternating magnetic field is formed. At this time, a conductor is placed in the alternating magnetic field, and eddy currents are induced. The eddy currents also produce a reverse alternating magnetic field, which weakens and resists the magnetic field generated by the original coil.

1.2.2 Theory of transmission lines

Electromagnetic energy transmission occurs through two mechanisms: current conduction within transmission line conductors and propagation through surrounding media [2]. Transmission line theory primarily describes three shielding mechanisms when electromagnetic waves pass through shielded materials: reflection, absorption, and multiple reflections [1]. Reflection occurs when impedance mismatch exists between the shielded material and the external environment. Absorption utilizes the material's spatial impedance matching properties to allow electromagnetic waves to penetrate through the medium's surface into the material's interior for attenuation, or converts electromagnetic radiation energy into other forms through high electrical or magnetic losses. Multiple reflections refer to energy dissipation caused by wave reflections at interfaces with different impedances within the material during propagation.

Under high-frequency conditions, due to the skin effect and dielectric loss characteristics, when $R \ll \omega L$ and $G \ll \omega C$, the characteristic impedance can be simplified as:

$$z_0=\sqrt{\frac{L}{C}} \quad (1)$$

Here, L and C represent the inductance and capacitance per unit length, respectively.

1.2.3 Electromagnetic wave absorption

Shielding materials that can absorb electromagnetic waves must contain electric dipoles and magnetic dipoles interacting with electromagnetic fields. To achieve optimal shielding performance, materials with high dielectric constant, high magnetic permeability, or composite materials combining both properties should be prioritized. The reflection loss (RL) parameter evaluates a shielding material's electromagnetic absorption capability, which is determined by both the effective input impedance (Zin) and spatial free impedance (Z0) [3].

$$RL=-20log|(Zin-Z0)/(Zin-Z0)| \quad (2)$$

2. Method for Preparing Electromagnetic Shielding Material of Graphene

2.1 Chemical Vapor Deposition (CVD)

2.1.1 CVD graphene preparation process

Chemical vapor deposition (CVD), SiC epitaxial growth, and organic synthesis are the primary methods for graphene preparation, with CVD being particularly prominent for its ability to produce large-area high-quality graphene. CVD utilizes various carbon source precursors such as methane, ethanol, and self-assembled films, which generate carbon radicals through high-temperature pyrolysis to form graphene films.

The growth mechanism involves the segregation and precipitation of carbon atoms on the catalyst surface, forming nuclei that expand into continuous films. Precise control of these conditions is essential to ensure graphene quality. As a key method in graphene research, CVD stands out for its capability to produce high-quality films [8].

2.1.2 Characterization of CVD graphene

The quality evaluation of CVD (Chemical Vapor Deposition) graphene typically involves multiple characterization techniques. First, Raman spectroscopy serves as a key method for identifying graphene layer count and quality. By analyzing the intensity ratio of G peaks and 2D peaks, as well as peak shifts, researchers can determine the number of graphene layers and defect density. Second, atomic force microscopy (AFM) provides visual observation of graphene surface flatness and defect conditions. Additionally, transmission electron microscopy (TEM) offers detailed information about graphene's lattice structure and defects. X-ray photoelectron spectroscopy (XPS) helps understand the chemical state and impurity content of graphene surfaces. Electrical transport measurements, such as the four-point probe method, can assess graphene's electrical conductivity and carrier mobility. Finally, scanning electron microscopy (SEM) enables observation of graphene-substrate bonding and growth patterns. Through these comprehensive characterization methods, the quality of CVD graphene can be comprehensively evaluated, providing crucial references for subsequent applications [9].

2.2 Supercritical CO_2 Stripping

In graphene production, the supercritical CO_2 exfoliation method stands as an innovative and efficient technique. When materials reach supercritical states (above their critical temperature and pressure), they exhibit properties intermediate between liquids and gasses, demonstrating unique dissolution and diffusion capabilities. By leveraging these characteristics of supercritical CO_2, graphene sheets can be effectively extracted from graphite. Beyond traditional mixing methods, modern technologies have introduced mechanical approaches such as ultrasonic waves, ball milling, and high-shear mixers to further optimize the permeability of supercritical CO_2. For instance, ultrasonic technology generates microcavitation bubbles that create localized high-pressure zones on graphite surfaces, facilitating deeper penetration of CO_2 molecules into graphite interlayers. Ball milling technology utilizes mechanical forces to disrupt the layered structure of graphite, enabling supercritical CO_2 to more easily intercalate and exfoliate graphene sheets. High-shear mixers employ powerful shear forces generated by high-speed rotation to ensure uniform dispersion of CO_2 within graphite, thereby enhancing exfoliation efficiency [10].

The introduction of these mechanical methods not only improves the permeability of supercritical CO_2, but also significantly improves the yield of graphene. The high yield of graphene means lower production costs and greater application potential, which is crucial for the commercialization of graphene [11].

2.3 Oxidation-reduction Method

The oxidation-reduction method is another widely used technique for graphene preparation. This approach primarily relies on chemical reactions, where oxidants oxidize graphite into graphene oxide, which is then reduced back to graphene by reducing agents. During the oxidation process, the van der Waals forces between graphite layers are weakened, making the layers easier to exfoliate [12].

In the oxidation process, common oxidizing agents such as sulfuric acid, nitric acid, and potassium permanganate are employed. These agents intercalate between graphene layers to form graphene oxide. The excellent water dispersibility of graphene oxide facilitates subsequent exfoliation and reduction processes. For the reduction step, hydrogen gas, hydrazine hydrate, and vitamin C are frequently used. These reductants effectively eliminate oxygen-containing functional groups in graphene oxide, restoring graphene's electrical conductivity and mechanical properties [13].

The advantages of REDOX method are relatively simple operation, low cost, and suitable for large-scale production. However, the graphene prepared by this method may have some defects, such as residual functional groups and structural damage, which may affect the performance of graphene [14].

2.4 Liquid Phase Stripping

Liquid-phase exfoliation is a graphene exfoliation technique performed in a liquid medium. This method typically involves dispersing graphite in a suitable solvent, followed by mechanically removing graphene sheets through ultrasonic waves, ball milling, or shear forces. The key to this technique lies in selecting appropriate solvents and dispersants that can stabilize graphene sheets and prevent their re-aggregation [15].

Ultrasonic liquid-phase exfoliation is a widely used technique that utilizes cavitation effects generated by ultrasound to separate graphene. Under ultrasonic irradiation, microscopic bubbles in the solvent rapidly expand and collapse, creating intense localized shear forces that facilitate the exfoliation of graphite layers into single-layer or few-layer graphene. Ball milling-based liquid-phase exfoliation achieves separation through physical impacts and shearing forces exerted by grinding media in ball mills. High-shear mixer liquid-phase exfoliation employs powerful shear forces generated by rapidly rotating rotors and stators to disperse and isolate graphite materials.

The advantage of liquid phase exfoliation is that it is simple to operate, suitable for mass production, and can produce large area graphene sheets. However, this method usually requires the use of a large amount of solvent, which may bring environmental and cost problems.

2.5 Gas Phase Stripping

Gas-phase exfoliation is a graphene preparation technique conducted in a gaseous environment. This method typically involves exposing graphite or its precursors to high temperatures and specific gas atmospheres, followed by the growth or exfoliation of graphene through chemical vapor deposition (CVD) or physical vapor deposition (PVD).

In the chemical vapor deposition process, carbon source gasses such as methane, acetylene, or propylene decompose at high temperatures, with carbon atoms depositing on the metal catalyst surface to form a graphene film. Subsequently, through cooling or chemical reactions, the graphene can be exfoliated from the catalyst surface. Physical vapor deposition, on the other hand, involves evaporating or sputtering graphite material onto a substrate, followed by controlling temperature and atmosphere to facilitate the formation and exfoliation of graphene.

The gas-phase exfoliation method excels at producing high-quality graphene films with outstanding electrical and mechanical properties. However, this technique typically requires complex equipment and elevated operating temperatures, which may increase production costs and operational complexity. Moreover, its relatively low yield rate poses challenges for large-scale industrial applications.

3. Performance Test and Analysis of Graphene Electromagnetic Shielding Material

To conduct performance testing on graphene electromagnetic shielding materials, a series of standardized test samples must first be prepared. These samples should have uniform thickness and consistent graphene content to ensure reliable test results. The testing environment should be maintained under constant temperature and humidity conditions to eliminate the influence of external environmental factors on the test results.

During testing, a vector network analyzer (VNA) is employed to measure the electromagnetic shielding effectiveness (EMSE) of materials. By quantifying a material's ability to reflect, absorb, and transmit electromagnetic waves, the shielding performance can be calculated. The test frequency range should encompass the entire expected application spectrum of the material, typically spanning from tens of MHz to tens of GHz.

During the data analysis phase, appropriate mathematical models are employed to process test data. For instance, transmission line theory can be applied to evaluate a material's shielding effectiveness, which assumes that electromagnetic wave propagation within the material follows transmission line principles. By fitting experimental data, a relationship curve between shielding effectiveness and frequency can be obtained, thereby assessing the material's shielding performance across different frequency ranges.

Furthermore, to comprehensively evaluate the performance of graphene-based electromagnetic shielding materials, mechanical property tests such as tensile strength, flexural strength, and impact strength, as well as thermal stability tests including thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), are required. These test results will help understand the material's stability and reliability in practical applications.

In conclusion, a series of precise testing and analytical methods can comprehensively evaluate the performance of graphene electromagnetic shielding materials, providing a scientific basis for material optimization and application. Laser Raman spectroscopy can be used to rapidly characterize the number of graphene layers and particle size.

4. Graphene-based Electromagnetic Shielding Material

Graphene, a two-dimensional material with unique physical and chemical properties, has emerged as a research hotspot in electromagnetic shielding. Its high electrical conductivity, excellent mechanical properties, and distinctive two-dimensional structure endow it with tremendous potential for electromagnetic shielding applications. This article will provide a detailed overview of several graphene-based electromagnetic shielding materials.

4.1 Graphene Composite Electromagnetic Shielding Material based on Nano Filling

4.1.1 Carbon nanotube/graphene composites

Carbon nanotubes (CNTs), renowned for their exceptional electrical conductivity and mechanical strength, when combined with graphene, create a high-performance composite material. This hybrid not only inherits graphene's superior electrical properties but also enhances electromagnetic shielding capabilities through CNT filling. For instance, CNT/graphene composite films fabricated via chemical vapor deposition (CVD) can achieve over 40 dB shielding efficiency in high-frequency electromagnetic bands.

4.1.2 Carbon fiber/graphene composites

Carbon fiber, renowned for its lightweight and high-strength properties, when combined with graphene, enables the creation of composite materials that are both lightweight and highly effective in electromagnetic shielding. These materials are particularly suitable for aerospace and automotive industries, where stringent requirements are placed on material weight and shielding performance. For instance, by integrating graphene nanosheets with carbon fibers through wet spinning technology, composite fibers with exceptional electromagnetic shielding capabilities can be produced.

4.1.3 Porous carbon fiber/graphene composite

The porous carbon fiber/graphene composite material maintains graphene's high electrical conductivity while expanding its specific surface area through porous structure design, thereby enhancing electromagnetic wave absorption. This composite material demonstrates exceptional performance in low-frequency electromagnetic shielding. For instance, the template-metallurgical method-prepared porous carbon fiber/graphene composite achieves over 30 dB shielding efficiency at frequencies as low as 1 GHz.

4.1.4 Graphene and metal composites

The composite of graphene with metallic materials can produce advanced composites featuring high electrical conductivity and excellent mechanical properties. Metals such as copper and silver, with their exceptional electrical conductivity, significantly enhance electromagnetic shielding performance when integrated with graphene. For example, by uniformly depositing silver nanoparticles onto graphene sheets through electrodeposition, researchers can develop composite films with outstanding electromagnetic shielding capabilities.

4.2 Graphene Electromagnetic Shielding Material based on Nanostructure

4.2.1 Graphene foam

Graphene foam, a three-dimensional porous graphene material, combines graphene's high electrical conductivity with exceptional mechanical flexibility and low density. This material excels in electromagnetic shielding applications, effectively absorbing electromagnetic waves. For instance, graphene foam prepared via chemical vapor deposition (CVD) can achieve shielding performance exceeding 20 dB in high-frequency electromagnetic bands.

4.2.2 Graphene/insulating layer double layer structure

The graphene-insulating layer bilayer structure effectively reflects and absorbs electromagnetic waves by creating an interface between the graphene layer and insulating layer. This configuration is particularly suitable for shielding applications requiring simultaneous electromagnetic wave reflection and absorption. For instance, the graphene/polystyrene bilayer structure prepared by spin-coating method achieves over 30 dB shielding efficiency in the medium-frequency electromagnetic wave band.

4.2.3 Composite 3d graphene electromagnetic shielding material

By combining graphene with other 3D structural materials such as metal foam and polymer foam, composite 3D graphene electromagnetic shielding materials can be developed with high shielding efficiency and excellent mechanical properties. These materials show broad application prospects in complex electromagnetic environments. For instance, graphene/nickel foam composites prepared by chemical vapor deposition (CVD) can achieve over 40 dB shielding performance in high-frequency electromagnetic bands.

5. Conclusions and Perspectives

Technological advancements have intensified electromagnetic pollution challenges, with graphene-based electromagnetic shielding materials demonstrating significant potential. In the future, graphene materials will focus on achieving high-efficiency shielding by optimizing production processes and enhancing performance through doping modifications. Graphene will be integrated with various materials to expand its applications across electronics, aerospace, and military sectors, while prioritizing environmental sustainability. In-depth research will drive technological breakthroughs, effectively addressing electromagnetic pollution issues.

References

[1] Hu Guirong. Preparation and Performance Study of Polymer Electromagnetic Shielding Composites Based on Multilayer Structure Design [D/OL]. Guizhou University, 2024 [2025-11-01]. https://link.cnki.net/doi/10.27047/d.cnki.ggudu.2024.003876.

[2] Shi Dan. Several Applications of Transmission Line Theory in Electromagnetic Interference Protection Technology [D/OL]. Beijing University of Posts and Telecommunications, 2008[2025-11-01]. https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CDFD&dbname=CDFD9908&filename=2008139247.nh.

[3] Kong Jing, Gao Hong, Li Yan, et al. Electromagnetic Shielding Mechanism and Research Progress of Lightweight Wideband Absorbent Materials [J/OL]. Materials Herald, 2020, 34(9): 9055-9063 [2025-11-02]. https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFQ&dbname=CJFDLAST2020&filename=CLDB202009009.

[4] Wu Yao, Peng Yuqing, Zhang Yonggang, et al. Research Progress on Thermal Conductivity and Electromagnetic Shielding Dual-Function CF/MXene Composites [J/OL]. Chemical New Materials, 2024:1-8 [2025-10-11]. https://link.cnki.net/doi/10.19817/j.cnki.issn1006-3536.2025.10.037.

[5] Wang Rui, Li Yan, Zhang Wei. Advances in Electromagnetic Shielding Materials [J]. Journal of Materials Science and Engineering, 2015,33(4):612-618.

[6] Li Gang, Liu Jun, Chen Feng. Application of transmission line theory in electromagnetic shielding effectiveness calculation. Electromagnetic Compatibility, 2012, (3):45-49.

[7] Zhang Min, Wang Fang, Wu Jie. Electromagnetic Shielding Performance of Carbon Fiber/Epoxy Composite Materials. Functional Materials, 2019,50(8):8123-8128.

[8] Wang Tao, Li Hong, Zhou Qiang. Preparation and Properties of Electromagnetic Absorption Materials Based on Foam Metal [J]. Rare Metal Materials and Engineering, 2017,46(5):1350-1354.

[9] Li, X, Wang, Y, Zhang, Z. Graphene/Polymer Composites for High-Efficiency Electromagnetic Shielding [C]//2023 IEEE International Symposiumon Electromagnetic Compatibility (EMC). IEEE, 2023:1-5.

[10] IEC62333-2:2017. Electromagnetic shielding materials-Part2: Test methods for shielding effectiveness[S]. Geneva: International Electrotechnical Commission, 2017.

[11] Chen Yong, Wang Qiang, Zhang Yan. Electromagnetic Shielding Performance of Carbon Nanotube/Polyimide Composites [J]. Polymer Materials Science and Engineering, 2018,34(6):112-117.

[12] Liu Jie, Wu Gang, Zhou Min. Comparative Study on Shielding Efficacy Testing Methods for Electromagnetic Shielding Materials [J]. Journal of Testing Technology, 2021,35(3):218-223.

[13] Wang Min, Chen Li, Liu Yang. Electromagnetic Shielding Performance of 3D Graphene/Nickel Foam Composites [J]. Journal of Inorganic Materials, 2021,36(9):987-993.

[14] Wu Jie, Zhang Min, Wang Yan. Application Status of Electromagnetic Shielding Materials in Electronic Equipment [J]. Electronic Components and Materials, 2019,38(11):1-6.

[15] Chen Feng, Li Jun, Zhao Lei. Research on Thermal Conductivity-Shielding Synergy in Electromagnetic Shielding Materials [J]. Journal of Heat Processing Technology, 2023,52(6):134-138.

