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Efficient Electromagnetic Shielding Properties and Applications of Two-dimensional Materials and Their Derivatives

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Abstract:

With the rapid development of electronic devices and wireless communication technologies, the problem of electromagnetic interference has become increasingly serious, and the development of efficient, lightweight and corrosion-resistant electromagnetic shielding materials has become a current research hotspot. This paper reviews the latest research progress of two-dimensional materials and their derivatives in the field of electromagnetic shielding, focusing on the structural properties, preparation methods, and electromagnetic shielding performance of graphene and its composites, MXene (e.g., Ti3C2Tx) and CrxTey ultrathin films. It is shown that graphene is an ideal filler for electromagnetic shielding by virtue of its excellent electrical conductivity, mechanical strength and thermal conductivity. MXene materials are capable of preparing lightweight, high-strength and long-life electromagnetic shielding materials due to their excellent electrical conductivity, multifunctionality and composite ability with other materials. CrxTey ultra-thin films exhibit unique magnetoelectric properties and high chemical stability while maintaining good electromagnetic shielding properties, making them suitable for use in harsh environments. This paper summarizes the prospects and challenges of the application of these materials in aerospace and electronic devices, and provides references and suggestions for future research directions.

Keywords: Two-dimensional materials; electromagnetic shielding; electromagnetic interference; MXene; CrxTey ultrathin films

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1. Introduction

Electromagnetic interference is a kind of electromagnetic radiation noise that affects the normal operation of electronic equipment. With the increasing number of electronic components in science and industry, the electromagnetic interference that occurs between or within such electronic and electrical equipment is becoming more and more serious, and at the same time, exposure to a large amount of electromagnetic radiation also seriously affects people's health. Therefore, how to block or attenuate the external environment of electromagnetic radiation and shielding of internal electromagnetic leakage, while eliminating the threat of electromagnetic radiation on the safety of personnel, has become a new problem in the aerospace field as well as other fields.

At the present stage, the design optimization of structure and circuit is used to inhibit and shield the interference source, propagation medium or interfered object, in which the characteristics of shielding materials are used to make the electromagnetic wave reflected, scattered, and absorbed on the surface or inside the shielding material, which becomes an effective and reliable means. Their Such as metal materials and ferromagnetic composites, due to their excellent electromagnetic shielding and conductive properties, so as common electromagnetic shielding materials appear in daily life or production. However, the more common shielding materials still exist in the quality of large, easy to be corroded, and other shortcomings. The structural properties and special electronic properties of two-dimensional materials and their composites, and three-dimensional structure formed by multi-layer stacking of two-dimensional materials, can enhance the electromagnetic wave in the material inside the multiple reflection loss and absorption loss. Therefore, two-dimensional materials have a strong and effective shielding and absorption ability in the direction of electromagnetic shielding and have a lighter quality than traditional shielding materials. At the same time, two-dimensional materials have high anti-permeability performance, which can play a great role in the field of corrosion resistance [1]. Therefore, there is a great potential for application, making 2D materials and their complexes the material of choice for the study of electromagnetic shielding, e.g.. Raghvendra Singh Yadav et al. combined ZnFe2O4 nanoparticles and reduced graphene oxide, with polyurethane resins as the matrix to body, prepared nanocomposites with relatively high electromagnetic wave absorption while providing special benefits such as light weight and corrosion resistance [2].

Firstly, this paper provides a comprehensive review of the structural properties and electromagnetic shielding performance of 2D materials and their composites. And then it summarizes their new advances in the direction of electromagnetic shielding. Lastly the paper also looks forward to new applications and challenges in a number of fields.

2. Two-dimensional Materials for Efficient Electromagnetic Shielding

2.1 Graphene and Its Composite Materials

2.1.1 Surface morphology and structure

Graphene has low density, lightweight, high electrical conductivity, electron mobility as high as 2×10 5 cm2 / (V-s), high thermal conductivity at room temperature of 5300W/(m-K), high surface area of 2630m2/g, high strength of Young's modulus up to 1TPa, strong hydrophobicity and other characteristics, as well as a unique two-dimensional lamellar structure, so that the electromagnetic wave to form a number of reflective loss as well as multiple absorption loss. Graphene is an ideal conductive filler for filled electromagnetic shielding coatings. At the same time, the dielectric constant of graphene changes with frequency, and can exhibit a negative dielectric constant at certain frequencies, a characteristic that has potential applications in the field of electromagnetic shielding and sensors [3].

Graphene composites are made by compositing graphene with other similar polymers, metals or ceramic materials, and their surface morphology depends on the dispersion of graphene, the type of matrix material and the composite method. By adding other substances, their physical, chemical, mechanical strength and other properties can be improved, resulting in a wider range of applications. For example, graphene-metal oxide composite electrodes can provide higher capacitance, while graphene-hydrogen composites have higher hydrogen storage capacity. Graphene nanosheet composites have excellent electrical and thermal conductivity while maintaining good electromagnetic shielding and thermal management properties, making them suitable for electromagnetic interference shielding and thermal management applications in highly integrated electronics [4].

2.1.2 Preparation method and properties

Graphene and its composites are currently prepared by a variety of methods, mainly including top-down and bottom-up strategies. Bottom-up (Top-Down) starts from a large-sized or lumpy material and gradually reduces it to the nanoscale by physical or chemical means. Examples include mechanical stripping, liquid phase stripping, and electrochemical stripping. Mechanical exfoliation method utilizes physical force to peel graphite layer by layer to obtain single layer or few layers of graphene; liquid phase exfoliation method is through ultrasonic oscillation in the liquid so as to peel graphite into nanoscale flakes; electrochemical exfoliation method utilizes electrochemical reaction to peel graphite into graphene. These methods have the advantages of simple process, low equipment requirements, and high purity graphene can be obtained directly, but there are also limitations that it is difficult to accurately control the size and morphology of the material, and the yield is relatively low and not suitable for large-scale production.

Bottom-Up methods, on the other hand, start from the basic units at the atomic, molecular, or nanoscale level, and gradually build up or form the desired nanomaterials or structures through chemical reactions. Typical methods include Chemical Vapor Deposition (CVD) and In-Situ Polymerization. In CVD, carbon-containing gases (e.g., methane) are decomposed at high temperatures and deposited layer by layer on the surface of a metal catalyst to form large-area, high-quality graphene films. In In-Situ Polymerization, graphene is added to a matrix material (e.g., polymer) during the polymerization reaction, forming a composite material simultaneously with the matrix. Being able to precisely control the structure, number of layers and size of graphene, it is suitable for the preparation of high-performance graphene and its composites, but at the same time the process is complex, requiring high temperature and precise reaction conditions, and usually at a higher cost.

Graphene and its composites exhibit a range of excellent properties due to its unique two-dimensional structure. Graphene itself has an ultra-high electrical conductivity of up to 200,000 cm^2/V-s, superb mechanical strength of up to 130 GPa in a single layer, as well as an excellent thermal conductivity of about 5,000 W/(m-K) and a light transmittance of up to 97.7%. These properties give graphene the potential for a wide range of applications in the fields of electronics, materials and thermal management. For example, graphene's high electrical conductivity makes it excellent for high-frequency electronics, while its extremely high elasticity and strength make it an ideal reinforcing material for high-strength composites.

Graphene composites can significantly enhance the comprehensive performance of composites by introducing graphene into the matrix material. The introduction of graphene enhances the mechanical properties of the material, making the composite material superior in strength and rigidity, while the electrical conductivity of the composite material is also significantly improved, which is suitable for high-performance batteries and supercapacitors and other fields. In terms of thermal management, the thermal conductivity of graphene composites has also been enhanced, effectively improving the heat dissipation performance of electronic devices. In addition, graphene's high light transmittance and tunable surface functionalization capabilities make the composites uniquely suited for applications in transparent conductive films and environmental resistance.

2.2 Ti3C2Tx MXene and its composite materials

2.2.1 Material characteristics

In addition to graphene, so far, the use of other two-dimensional materials and their composites also have good electromagnetic shielding performance and other properties. As a two-dimensional material of transition metal carbide or nitride, MXene has a sufficient number of functional groups on its surface, which can link and interact with other molecules through hydrogen bonding and van der Waals forces, and is a two-dimensional material of transition metal carbide or nitride, which can be well applied in polymers and composites. Among them, Ti3C2Tx has received wide attention as the most typical MXene material.

2.2.2 Preparation methods and properties

MXene materials are currently mainly transformed by etching the original MAX phase with three-dimensional structure and separated by ultrasonic stripping method to produce MXene with two-dimensional structural properties.Aihu Feng et al. obtained Ti3C2Tx MXene material by etching and sintering Ti3AlC2 powder prepared by NH4HF2 with very little fluorine residue, and found that the Ti3C2Tx atomic layers have sufficient spacing between them for ion storage [5].

Wei Xin and his team used a mixture of LiF and HCl in Teflon to etch Ti3AlC2, and Ti3C2Tx nanosheets were separated by ultrasonic separation and centrifugation, and finally Ti3C2Tx nanosheets were intercalated and composited with cellulose nanofibers (CNFs), and AgNO3 solution was added gradually MXene-CNFs-Silver (MCS) composite films were obtained, and the structural strength and electromagnetic shielding effectiveness of the materials increased with the concentration of silver ions, and gradually rose to reach the peak and then decreased, reaching a maximum of 588.2 S/m, and an electromagnetic shielding effectiveness of 50.70 dB between 8-13 GHz [6]. Ti3C2Tx nanosheets were found to have the highest structural strength and electromagnetic shielding effectiveness of 50.70 dB between 8-13 GHz, due to the sufficient interlayer spacing as well as the carrying of functional groups. spacing and the functional groups carried

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by Ti3C2Tx nanosheets, the intercalation and intertwining with other materials further improve the bonding strength, as well as make the material mechanical properties more superior. The selection of suitable materials for composite with MXene not only enhances the electromagnetic properties of the composites, but also protects the MXene from further oxidation or corrosion.Lei Wang et al. In their experiments of compositing CNF/Ti3C2Tx aerogel/epoxy nanocomposites by assembly annealing with epoxy and CNF through directional freezing and freeze-drying techniques, the CNF/Ti3C2Tx aerogel/epoxy nanocomposites are also composited with Ti3AlC2 as the raw material. Ti3AlC2 as raw material, Ti3C2Tx nanosheets with typical face-centered hexagonal structure were exfoliated by ionic intercalation method through etching and ultrasonication, and finally, the composite came out with the electrical conductivity of 1672 S/m, the electromagnetic shielding effect of 74 dB between about 8-12 GHz, and the formation of a porous skeleton by the interaction of Ti3AlC2 nanosheets could be preserved [7].

For the composite of Ti3C2Tx nanosheets, Yunyi Zhu and his research team proposed to mix the prepared Ti3C2Tx nanosheets with two materials, poly acrylic acid (PAA) and CaCl2, and then gradually add Na2CO3 solution until a viscous precipitate was obtained and the solution became clear, which finally made the calcium ions combine with the carbonate to form an amorphous carbonate. The amorphous calcium carbonate (ACC) and PAA successfully embedded into the Ti3C2Tx nanosheets, and the composite material prepared has significant softness and ductility compared with the traditional electromagnetic shielding materials, which expands the scope of application, and at the same time the special self-repairing ability ensures that in the practical application of the life of the composite material. service life, in which the material obtained by adding 12 wt% concentration of PAA during the fabrication process, the final electromagnetic shielding effect also reached 52.8 dB between 0.2 - 2.0 THz due to the moderate electrical conductivity and microscopic porous structure [8].

The excellent electromagnetic shielding properties, mechanical properties, and thermal stability of MXene nanomaterials will greatly expand their applications. Although pure MXene exhibits significant electromagnetic shielding performance, the interaction between its own materials is weak, making it difficult to self-assemble or fully replace more refined metals and their composites. However, by combining MXene with other materials, it is possible to create materials with higher shielding performance compared to traditional electromagnetic shielding materials. These composites also offer better antioxidant or corrosion resistance, which improves their service life, reduces usage costs, and leads to broader applications [9].

2.3 D Layered CrxTey Ultrathin Films

2.3.1 Surface morphology and structure

The surface morphology and structure of CrxTey are represented by CrTe2 and Cr4Te5. The lattice structure of CrTe2 is a NiAs-type hexagonal structure consisting of three basic units of Cr-Te-Cr stacked along the c-axis, while Cr4Te5 has a framework of CrTe2 as the basic structure. While the lattice structure of Cr4Te5 has the framework of CrTe2 as the basic structure, with 3/5 proportion of the vacancies in the van der Waals gap occupied by Cr atoms [10].

2.3.2 Preparation methods and properties

Both films were prepared by pulsed laser deposition on an Al2O3 substrate.X-ray diffraction results show that the films grow along the direction of the substrate crystal axis, possessing good crystallinity and out-of-plane weaving of the unitzeng stacked arrangement. Analyzed by AFM, the surface of CrxTey thin films has a uniform particle distribution with a square root surface roughness of about 1.5 nm and undulations at each point of no more than 2 nm, which results in relatively smooth sample surfaces of the films.

The preparation of CrxTey ultrathin films was carried out by pulsed laser deposition (PLD). The specific steps were divided into target preparation, deposition condition setting, laser pulse deposition, and annealing treatment, in four steps. Firstly, to create the basis for thin film growth, the cake-like CrTe2 and Cr4Te5 targets were synthesized and pressed by solid-phase reaction using extremely high-purity Te and Cr powders according to the stoichiometric ratios of 1:2 and 4:5 as a prerequisite. Secondly, to create an environment conducive to film growth, the reaction chamber is pumped to a vacuum of 1 × 10-4 Pa, the distance between the target and the substrate is set to 8 cm, and the temperature inside the chamber is raised to 500 °C. Then, the laser density on the target is adjusted to 1.7 Jcm-2, and the emission frequency is kept constant at 5 Hz, and the laser is adjusted so that the laser focal point falls on the surface of the target, and the tail of the emission falls on the substrate to achieve a good deposition effect. Good deposition effect, the control of laser energy and frequency in this step is important for the quality of the film. Finally, after deposition, the film is annealed at 600 degrees Celsius for 1 hour, and then removed when the film has cooled to room temperature, which helps to improve the overall quality of the film.

The pulsed laser deposition method not only ensures the precise chemical composition of the films, but also realizes the high-quality growth of the films by controlling the deposition and annealing conditions, which provides a good sample base for the subsequent magnetoelectric property study.

By measuring the variable-temperature magnetization intensity, it was found that the CrTe2 and Cr4Te5 films underwent obvious paramagnetic-ferromagnetic phase transitions at 198 K and 257 K, respectively. This result indicates that the films exhibit obvious ferromagnetism under low-temperature conditions and possess high Curie temperatures, which suggests that the films have the properties of electromagnetic shielding materials for applications. Hysteresis loops of the films at 5 K very low temperature between external magnetic fields of 2.0 T show that both are saturated at high magnetic fields, with saturation magnetization strengths of 38 emu/g and 47 emu/g, coercivity of 3000 Oe and 4000 Oe, and residual magnetization strengths of 15 emu/g and 28 emu/g, respectively, which are indicative of the excellent magnetic properties of the films. By measuring the evolution curve of resistivity versus temperature T, the resistivity of the films decreases continuously with temperature in the temperature range of 50-250 K, showing a clear metallic behavior. In the paramagnetic phase above the Curie temperature, the resistivity-temperature fit is closest to the ρ~T2 relation, i.e., it is dominated by the electron-magneton scattering mechanism at low temperatures. In the ferromagnetic phase below the Curie temperature, the resistivity-temperature fit is closest to the ρ~T5 relation, i.e., the electron-phonon scattering mechanism dominates at higher temperatures.

3. Electromagnetic shielding material applications and challenges

3.1 2D Materials in Aerospace Applications

MXene nanosheets combine excellent electrical conductivity and flexibility.The hydrophilicity of MXene films increases the resistivity of the samples when they are applied in humid environments. Therefore, the hydrophilicity of the MXene phase may affect the electromagnetic shielding performance of MXene films.Liu et al. converted MXene films into MXene foams with high electrical conductivity, ultra-high strength, and excellent hydrophobicity through a hydrazine-induced foaming process. Since the porous structure of the MXene foam effectively attenuates incident electromagnetic waves, the EMI shielding effectiveness of the lightweight MXene foam with the same mass (70 dB) is significantly higher than that of the unfoamed MXene film (53 dB) This MXene foam with hydrophobicity, flexibility, lightweight and excellent EMI shielding effectiveness. It has clear application prospects in aerospace and portable wearable smart electronics.

CrxTey, a series of alloy films at room temperature still retains the long-range ferromagnetic order and unique stacking structure in the field of electromagnetic shielding excellence, and at room temperature in a humid environment to maintain a high degree of chemical stability, at 300 K to retain ferromagnetism, but also resistant to air corrosion, the Van der Waals gap in its Mn or Fe ions injected in order to effectively regulate the film's magneto-electric properties, which in turn promotes the effectiveness of electromagnetic shielding, can be effectively used as aerospace memory and intelligent electronic devices, portable wearable. It can effectively act as a protective film for aerospace memory and chips, reducing the load of transportation and avoiding the components from being subjected to excessive electromagnetic hazards.

Considering that aircrafts operate under harsh conditions, such as high temperature, high humidity and high salt, the complex and harsh environments expose the materials to corrosion, and the shielding performance will also be affected. After surface modification, multilayer graphene or graphene oxide is applied to the surface of metals and alloys to reduce structural defects and improve barrier and corrosion resistance.

3.2 Electromagnetic Shielding Fabric

Electromagnetic shielding fabrics are characterized by lightness, softness and high strength, and also have the advantages of controllable structure, flexible molding technology, washing resistance and low cost, which make them a highly applicable electromagnetic shielding material. However, considering the shielding effect and wearing comfort, the electromagnetic shielding fabrics on the market at present do not achieve the required effect.

Conductive polymer materials can also be combined with graphene oxide to improve the comfort of fabrics, and to overcome the problems of easy shedding and oxidization of electromagnetic shielding materials in fabrics made by a single method, and poor bonding with the substrate, which can improve the electromagnetic shielding effect of fabrics.

MXene has good metal conductivity but also has a large surface area, good solution processability and relatively low density, has a high thermal conductivity and strong heat resistance, and has excellent bactericidal properties, so it has broad application prospects. The use of conductive polymers improves the interfacial interaction between MXene and fabrics and the structural stability of fabrics.

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3.3 Challenges for 2D Materials and Electromagnetic Shielding Materials

Two-dimensional materials such as graphene and MXene show excellent performance in electromagnetic shielding, but their shielding efficiency, stability and durability still need to be further improved. For example, although graphene has high electrical and thermal conductivity, its stability and cost-effectiveness in large-scale applications still need to be improved.MXene material has good electrical conductivity and flexibility, but its hydrophilicity may lead to an increase in resistivity in humid environments, which affects the electromagnetic shielding performance. While satisfying efficient electromagnetic shielding, how to integrate other functions such as thermal management, mechanical strength, and optical transparency into the same material system to realize multifunctional integration is the key to enhance the value of material applications.

Most of the preparation processes of 2D materials are complex and relatively high in preparation cost, involving technologies such as chemical synthesis, physical stripping or chemical vapor deposition, which not only have high requirements on energy consumption but also have strict requirements on equipment and technology, which leads to difficulties in realizing large-scale production of 2D materials. In addition, the preparation process of composite materials, how to reduce the production cost, realize the uniform dispersion and good combination of 2D materials and matrix materials is also a technical difficulty.

In practical applications, 2D materials need to face various complex environments, such as high temperature, high humidity, corrosive media, etc., which puts forward higher requirements on the stability and durability of the materials. At the same time, considering the trend of environmental protection and sustainable development, the development of electromagnetic shielding materials in line with the concept of “green” and “carbon-neutral” to reduce the impact on the environment is also an important direction of current research.

4. Conclusion

This paper presents a review of the research progress of two-dimensional materials and their derivatives in the field of electromagnetic shielding, emphasizing the unique structural properties and electromagnetic shielding performance of such materials. Graphene and its composites show great potential in applications such as high-frequency electronic devices, thermal management, and EMI shielding by virtue of their ultra-high conductivity, strength, and lightweight advantages.MXene materials, on the other hand, with their good electrical conductivity and multifunctionality, can be used to obtain lightweight, high-strength, and long-life EMI shielding materials by compositing them with other materials, which are suitable for applications in harsh environments. Meanwhile, CrxTey ultra-thin-film materials have unique magneto-electric properties and excellent chemical stability, maintain ferromagnetism and corrosion resistance at room temperature, and are suitable for electromagnetic shielding in aerospace and high-end electronic devices. In conclusion, 2D materials and their derivatives demonstrate excellent performance and wide application prospects in the field of electromagnetic shielding, but their large-scale preparation and application in complex environments still face challenges, and future research needs to further optimize the materials in terms of their preparation process and performance to promote their practical applications in more fields.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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