MXene aerogel: An advanced aerogel material

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Abstract. As a novel aerogel material, MXene aerogels have garnered significant attention in materials science due to their unique structure and exceptional properties. This paper briefly describes the fundamental characteristics and limitations of traditional aerogels, elucidates the research background and significance of MXene, and introduces fabrication methods for MXene aerogels including sol-gel and chemical vapor deposition (CVD) techniques. The study elaborates on the structural characteristics and physicochemical properties of MXene aerogels, explores their application domains in energy storage, electromagnetic shielding, and environmental remediation, and proposes future prospects for MXene-based materials development. This systematic review provides theoretical guidance and technical references for advancing the research and practical implementation of MXene aerogel materials.

Keywords: MXene, Aerogel, Electromagnetic Interference Shielding, Energy Storage, Environmental Purification.

1. Introduction

Aerogel was first proposed by S. S. KISTLER [1]. As a unique porous material, it has an extremely low density [2] high porosity and low thermal conductivity[3]. Adjustable mechanical properties and strong compounding ability [4, 5]. Of these, densities can typically be as low as: $3 \times 10^{-3} g/cm^3$ [6], which makes it one of the solid materials with the lowest density in the world. The porosity of aerogel can be more than 90% [7], and the pore size is generally between several nanometers and several hundred nanometers [8]; It has resulted in its extremely high specific surface area, and the specific surface area of some aerogels can even exceed 1000 m^2/g [9]. This unique nanopore structure endows the aerogel with excellent adsorption capacity, superior thermal insulation performance, and good acoustic transparency. However, traditional aerogels also have problems such as poor thermal stability, brittle texture, high cost, and weak molding ability [10].

MXene is a type of two-dimensional material composed of transition metal carbides, nitrides, or carbonitrides, with excellent electrical conductivity, thermal conductivity, high specific surface area, unique layered nanostructure, strong anti-electromagnetic interference ability, good solution dispersibility, rich surface chemical properties, and excellent mechanical flexibility [11, 12]. The combination of MXene and aerogel provides a new opportunity for the development of aerogel materials. The formation of MXene aerogel by combining MXene with aerogel technology not only retains the lightweight and porous characteristics of aerogel materials, but also enhances its conductivity and stability [13]. At the same time, the mechanical properties of the aerogel have been improved. offering new opportunities in energy storage [14], electromagnetic interference shielding[15, 16], environmental purification [17], and other fields.In recent years, MXene-based aerogels have attracted much attention due to their superior properties in many aspects such as mechanics, conductivity and catalysis. Although MXene has excellent performance, there are still many problems that need to be overcome. Due to the high electrical conductivity of MXene, the EMW reflection it causes will produce secondary electromagnetic radiation pollution. Reducing electromagnetic wave reflection without reducing the EMI shielding efficiency is a problem in the development of MXene aerogels [18]. Therefore, in-depth study of the preparation methods of

MXene aerogels and exploration of the properties of MXene aerogels have important research significance for promoting the development of aerogel materials and the research and development of future high-performance composite materials.

2. Structure and properties

2.1. Specific surface area and pore structure

The specific surface area and pore structure of MXene aerogels are crucial to their performance. MXene aerogels typically exhibit a porosity of over 80%. This high porosity not only facilitates lightweight and low-density properties but also provides channels for molecular and ion transport. [19]

MXene aerogel, due to its unique two-dimensional sheet-like structure, can form a highly ordered porous network, and its specific surface area often reaches several tens of square meters per gram. In 2023, Zheng's team reported a Ti3C2Tx MXene aerogel. After appropriate chemical treatment and freeze-drying, the specific surface area of this aerogel can exceed 400 m^2/g [20], This greatly exceeds the specific surface area of traditional aerogels. The characteristic of this high specific surface area endows MXene aerogels with excellent adsorption performance and catalytic potential.

MXene aerogel exhibits a multi-level pore structure. This structure can effectively enhance the molecular sieve effect and available surface area of the material. In 2024, Wang's team directly synthesized a double-network structure aerogel micro-nano fiber/MXene aerogel through simultaneous electrospinning and electrospraying. The average pore size of this aerogel is approximately between 30 and 60 nm, which enables MXene aerogel to be widely used in gas adsorption and energy storage devices [21].

2.2. Stability and conductivity

The conductivity and stability of MXene aerogels are critical determinants of their application performance. While the unique layered structure confers exceptional electrical conductivity, environmental stability (particularly oxidative degradation under humid and oxygen-containing conditions) remains a limiting factor for practical implementation. Surface modification strategies (e.g., functional group engineering) and structural optimizations (e.g., three-dimensional network reinforcement) can significantly enhance stability, offering a pivotal pathway to broaden the utility of MXene aerogels in complex environments.

In 2023, Kim's team prepared a 3D MoS_2/MXene heterostructure aerogel by physically mixing MXene and MoS_2 and then freeze-drying. The MoS_2 catalytic layer significantly enhanced the gas detection sensitivity and stability of the MXene aerogel [22]. This provides a new idea for the stability improvement of MXene aerogels.

MXene aerogel exhibits excellent intrinsic electrical conductivity due to its two-dimensional layered structure and the interconnection network between conductive layers. Its electrical conductivity can be further regulated by optimizing the preparation parameters (such as freezing temperature, precursor concentration, and gelation rate).

In 2018, Zhao's team utilized the directional freezing - freeze-drying method to construct a Ti3C2Tx MXene/reduced graphene oxide hybrid aerogel [23]. Due to the internal framework of MXene layers and graphene sheets, the electrical conductivity of this aerogel is as high as 695.9 S m^{-1}.

2.3. Mechanical properties

MXene aerogels demonstrate exceptional mechanical properties—including high specific strength and compressive resistance—The MXene aerogel developed by the Jiang team even shows a reversible compressive strain of up to 95% [24]. This property is attributed to the three-dimensional interlocking network structure of MXene nanosheets. It not only endows the material with excellent mechanical bearing capacity through the hierarchical self-assembly effect, but also effectively suppresses the microcrack propagation caused by stress concentration through the topological stress dissipation mechanism, thereby significantly improving the macroscopic structural integrity.

The mechanical properties of MXene aerogels are synergistically regulated by their multi-level pore structure and the orientation of nanosheets. The pore structure gradient design and the sheet orientation engineering can be achieved through the sol-gel method combined with the freeze-drying process, which can directionally optimize its compressive modulus and resilience. Yu's team once prepared an ultralight three-layer gradient-structured MXene/reduced graphene oxide composite aerogel through freeze-drying and thermal annealing. This aerogel exhibits compressive resistance performance that can cycle 200 times under 80% strain [25]. Through the introduction of crosslinking agents or the design of multi-level pore structures, the toughness and fatigue resistance of MXene aerogels can be effectively enhanced. Combining the co-doping/in-situ polymerization modification strategy can improve its mechanical properties while maintaining the lightweight characteristics.

2.4. Antioxidant properties

MXene aerogel possesses excellent high-temperature oxidation resistance. Its anti-oxidation and corrosion mechanism derives from the physical diffusion barrier effect of the two-dimensional layered structure and the chemical passivation of surface terminal groups (-O/-OH). The closely packed MXene nanosheets can prevent the penetration of oxygen molecules, while the terminal functional groups reduce the oxidation activity through electron transfer, jointly ensuring the structural stability of the material in extreme environments.

The oxidation resistance of MXene aerogels can be significantly enhanced through surface engineering strategies. Yang's team (2023) developed a 3D macroporous $Ti_3C_2T_x$ MXene hybrid hydrogel system using L-cysteine as a dynamic crosslinker and L-ascorbic acid (VC) as a synergistic reducing agent, which formed an interpenetrating network architecture. This material demonstrated extraordinary cyclic durability (97.1% capacitance retention after 100,000 cycles) and environmental stability (merely 9.3% resistance increase after 60-day storage), providing an innovative solution for long-term oxidation protection of MXene-based materials [26].

2.5. Surface chemical activity

The surface chemical activity of MXene aerogels is one of the key factors for their excellent performance in multiple fields.

The surface of MXene aerogel is rich in active functional groups such as hydroxyl (-OH), which enables it to form a strong chemical bond with various metal ions or organic molecules in the solution. According to Wang's research, the adsorption capacity of MXene aerogel for Pb2+ is strong, and its maximum adsorption capacity can reach 230 mg/g, providing a new idea for the removal of heavy metals in the field of water treatment [27].

The surface of MXene aerogel is highly tunable. By changing the chemical etching conditions of MXene and the subsequent surface treatment processes, such as heat treatment and chemical modification, the surface chemical properties of MXene can be effectively adjusted. Chen carried out nitriding treatment on Ti3C2Tx MXene to increase the number of surface amino functional groups, which can improve the accessibility and reactivity of the active sites, thereby significantly improving the adsorption efficiency of amine compounds [28].

MXene aerogels demonstrate exceptional surface reactivity in electrochemical applications. Their high conductivity and large specific surface area make them ideal candidates for efficient electrocatalysts and energy storage electrodes. Surface chemical functional groups (such as -O, -OH) significantly enhance the charge storage performance through pseudocapacitive redox reactions. The $Ti_3C_2T_x$ MXene/hydrogel composite electrode developed by Yang's team has a specific capacitance of up to 349 F/g, far exceeding the traditional activated carbon electrode (~150 F/g), providing a new strategy for the design of high-energy-density supercapacitors [26, 29].

3. Preparation method

3.1. Sol-Gel Method

The sol-gel method is a solution-based chemical synthesis technique that enables controllable material fabrication through a two-stage process of sol formation and gelation. Its core advantages lie in mild reaction conditions, low cost, and the flexible tunability of microstructural features (e.g., porosity, three-dimensional networks) via process parameter adjustments [30].

This method can achieve the precise design of the material's microstructure and properties through the flexible adjustment of process parameters.

In 2022, Zhou's team introduced tetraethyl orthosilicate (TEOS) into an aqueous solution of $Ti_3C_2T_x$ MXene. Hydrolysis and polymerization of TEOS generated SiO_2 nanoparticles, whose surface hydroxyl groups formed hydrogen bonds with oxygen-containing functional groups (-O/-OH) on MXene, resulting in a hybrid hydrogel. Freeze-drying of this hydrogel produced a hierarchically porous three-dimensional MXene/SiO_2 hybrid aerogel. This material exhibited a specific surface area of 572 $m^2\ g^{-1}$, along with high electrochemical performance (specific capacitance >300 F/g) and long-term cycling stability [31].

In 2021, Li's team prepared a kind of MXene aerogel fiber (MAF) with high conductivity through a dynamic sol-gel spinning strategy. This aerogel fiber not only has the unique high conductivity of MXene aerogel, but also has flexibility, electrical/optical responsiveness, and excellent photothermal conversion ability [32].

3.2. Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition (CVD) is a commonly used technique for preparing nano-composite functional materials. Wang's team elaborated on this method in detail in 2023. Taking Ti3C2Tx MXene as an example, using hydrofluoric acid to etch the Ti3C2T2 precursor and conducting the CVD process in an argon environment can obtain high-quality MXene materials. The CVD method has the advantage of precisely controlling the film composition, microstructure, and thickness by regulating the reaction conditions such as temperature, pressure, gas flow rate, and the selection of chemical precursors to obtain excellent material properties [33].

The MXene aerogel treated by Chemical Vapor Deposition (CVD) shows high cycle durability. In 2025, Zheng et al. designed a multifunctional cellulose-based aerogel assisted by MXene. The data indicate that after 100 cycles at 40% strain, this aerogel still exhibits an initial height close to 100% [34].The MXene materials prepared by the CVD method have molecular-level homogeneity, so they have a large reactive surface area and enhanced chemical reactivity. This property can be applied in fields such as environmental purification and energy storage.

3.3. Directional Freezing - Freeze-Drying Method

Directional freezing-freeze drying method is a process for preparing materials with specific porous structures such as aerogels. In this method, "directional freezing" means pouring the solution containing the components required for preparing the materials into a specific mold, and in a low-temperature environment, by controlling the cooling rate, etc., the solvent in the solution forms ice crystals in one direction along the temperature gradient. In this process, the solute is extruded to the liquid phase region in the ice crystals, and this step gives the material a specific microstructure. And "freeze drying" is after the directional freezing is completed, the obtained cryogel is transferred to a freeze-drying device such as a freeze dryer, and then through processes such as decompression and appropriate heating, the ice crystals in the cryogel are continuously sublimated, and finally an aerogel material with a highly porous and directional freezing microstructure is obtained. Compared with other methods, this method has the advantages of being environmentally friendly, having a controllable structure, and being simple to operate. The aerogel made also has stronger mechanical properties.

In 2021, Liang's team constructed a 3D $Ti_3C_2T_x$ MXene/reduced graphene oxide (RGO) aerogel anchored with magnetic Ni nanochains via directional freezing. The expulsion effect of ice crystal growth aligned the Ni/MXene/GO hybrids at the solidification front, forming a cell wall-like structure. This approach prevented the agglomeration of micro/nano-units in conventional aerogels and demonstrated favorable elasticity and mechanical properties [35].

4. Application field

4.1. Energy storage and conversion

MXene aerogel has excellent electrical conductivity, mechanical flexibility, and chemical stability, which enables it to show a broad application prospect in energy storage devices such as supercapacitors, lithium-ion batteries, and lithium-sulfur batteries.

MXene aerogels have garnered significant attention in supercapacitor applications due to their exceptional conductivity and structural tunability. Research demonstrates that MXene aerogels can markedly enhance the specific capacitance of supercapacitors (up to 483 F/g), while maintaining ~90% capacity retention after 10,000 charge-discharge cycles at a current density of 1 A/g, highlighting their high power density and cycling stability [36].These excellent properties are attributed to the multi-layered structure and tight interface of MXene, which provides channels for the rapid transport of ions, while the porous structure of the aerogel can alleviate the volume expansion of the material.

In lithium-ion batteries, MXene aerogel as an electrode material can effectively enhance the battery capacity and cycling stability. The research by Gao et al. indicates that the composite aerogel cathode of MXene and other nanomaterials can increase the charge-discharge capacity. At a current density of 0.5 C, the initial discharge capacity of the composite aerogel can reach 1220 mAh/g, and after 300 cycles, it can still maintain approximately 1100 mAh/g. This excellent performance is attributed to the characteristics of reversible lithium-ion intercalation/deintercalation in the MXene material and the high porosity of the aerogel, which can effectively alleviate the volume change of the material [37].

In lithium-sulfur batteries, MXene aerogel can be used as the carrier of the sulfur cathode to improve the utilization rate of sulfur and the cycling performance of the battery. The research shows that the high conductivity and rich surface chemical activity of MXene aerogel are conducive to the conversion of polysulfides and inhibit the "shuttle effect" of sulfides. Pei's research shows that the electrode with sulfur loaded on MXene aerogel exhibits a highly reversible specific capacity of 1042 mAh/g, excellent rate performance, and long-term cycling stability at a current density of 0.1 C [38].

Due to its unique structure and chemical properties, MXene aerogel shows great application potential in the field of energy storage and conversion. Future research can further explore the composite functionalization design of MXene aerogel and integrate it into various energy conversion systems to improve its practical value in practical applications.

4.2. Environmental purification

MXene aerogel has shown great potential in the field of environmental purification. Its unique structure and excellent physicochemical properties give it significant advantages in water treatment, air pollution control, and other environmental remediation applications.

MXene aerogel, with its high specific surface area and excellent adsorption capacity, has been extensively studied for the removal of heavy metal ions (e.g., Pb^{2+}, Cu^{2+}), dyes, and organic pollutants from water. For example, a research result by Gao in 2024 shows that the removal efficiency of MXene aerogel for V can reach more than 80% [39]. This is primarily attributed to the high specific surface area and nano-layered architecture of MXene aerogel, which endows it with the capability for efficient adsorption of heavy metal ions.

MXene aerogels demonstrate outstanding performance in organic pollutant removal. Their layered structure and abundant surface functional groups enable efficient adsorption of organic molecules such as toluene, phenol, and bilirubin. Zhang's research revealed a saturated adsorption capacity of

142.86 mg/g for bilirubin [40]. This is mainly attributed to its relatively high hydrophilicity and unique layered hydrophobic/hydrophilic framework, which enables MXene aerogels to capture organic pollutant molecules through hydrogen bonding and π-π interactions.

Chen et al.'s research demonstrates that MXene aerogels exhibit potential in electrochemical sensing applications. Their excellent conductivity, sensitivity, and reliability offer significant advantages for fabricating sensors capable of real-time monitoring of environmental pollutant concentrations [41].

MXene aerogel, with its excellent physical and chemical properties, provides a brand-new solution for environmental purification. Future research can further explore its application in large-scale environmental remediation, focusing on improving its regeneration ability, long-term stability, and adaptability under complex pollution conditions. Meanwhile, the development and industrial application prospects of the low-cost preparation technology of MXene aerogel also need to be deeply discussed to promote its wide application in the field of environmental protection.

5. Conclusion

MXene aerogels, with their low density, high electrical conductivity and surface chemical reactivity, exhibit significant potential in fields as energy storage, electromagnetic shielding and environmental purification. However, their practical application still faces challenges. For instance, the structural stability and electrical conductivity durability of MXene aerogels under extreme conditions such as thermal cycling and electrolyte corrosion need to be improved. Moreover, the current manufacturing process relies on expensive reagents and complex chemical etching procedures, which hinders their large-scale production. In the future, breakthroughs in stability improvement, precise performance control and low-cost manufacturing of MXene aerogels can be achieved through multi-dimensional structural design, cross-technology integration and full industrial chain optimization.

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