Recent advances in MXene for terahertz applications*

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Since first synthesized in 2011, MXenes have attracted extensive attention in many scientific fields as a new two-dimensional (2D) material because of the unique physical and chemical properties. Over the past decade, in particular, MXenes have obtained numerous exciting achievements in the field of terahertz applications. In this review, we first briefly introduce the MXene materials, such as the basic structure and main fabrication processes of MXenes. Then, we summarize the recent applications of MXene materials in various terahertz research areas, including terahertz modulation, terahertz absorption, terahertz shielding, terahertz communication, terahertz detection and terahertz generation, in which the representative results are presented. Finally, we give an outlook on the future research directions of MXene materials and their potential applications.

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In 2004, two-dimensional (2D) materials emerged for the first time as a new research field. With advances in technology, more and more new materials are being synthesized[1]. MXene materials were first discovered in 2011, since then, MXenes have had an important place in many 2D materials. The crystal structure of MXenes and graphene is very different, because graphene belongs to the class of carbon, while MXene is a short form for many transition metals, carbon, nitrogen, and carbon-nitrogen compounds. MXene is the general name of a family of materials, and it is extremely rich in MXene individuals. According to the general formula of MXene materials, it is the combination of a large number of different elements. The coordination of different transition elements with C, N, or C/N and the regulation of surface functional groups greatly enrich the types of MXenes. Among 2D materials, MXenes have the highest electrical conductivity, more than ten times that of reduced graphene oxide (rGO) films[2]. In addition, MXenes have excellent hydrophilicity and dispersion stability, so it can form stable dispersions in a variety of solvents without additives or surfactants. The preparation technology of MXenes is very flexible and can be prepared by low-cost methods. MXenes not only have excellent terahertz properties, but also exhibit exciting terahertz absorption, terahertz shielding, and terahertz modulation properties when combined with other substrate materials. Since MXenes have the best electrical conductivity among all 2D materials, many research results have shown that MXenes can be used as a transparent conductive layer[3-5]. MXenes also have good photoelectric performance and can be combined with other materials with good photoelectric performance to make photodetectors. Because of its unique photoelectric performance, MXenes are also used to prepare high-performance polymer light-emitting diode (LED) and are considered to be excellent electrode material. With its ultra-high conductivity and surface-active groups, MXenes are also used in strain, electrochemical and gas sensor research.

In the above, we briefly mentioned the properties of MXene materials and applications. Although MXenes have been a bright spot in many fields, MXenes are still in their infancy in one important area: terahertz. This paper introduces the applications of MXene materials in many fields of terahertz, analyzes the relevant mechanism, and gives representative references as evidence, but before this, please allow us to introduce what terahertz is.

Before they received their official name in the mid-to-late 1980s, terahertz waves were known as far

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infrared rays, but scientists had been researching them for more than a century[6]. Terahertz waves are electromagnetic waves with wavelengths between 30 μm and 3 mm, and frequencies between 0.1 terahertz and 10 terahertz[7,8], and cycles of oscillation between 0.1 ps and 10 ps[9,10]. As shown in Fig.1, it lies at the cross-range between electronics and photonics or between classical theory at the macro level and quantum theory at the micro level. Its frequency is higher than that of microwaves and lower than that of infrared waves[11]; the energy is in the transition zone between electron and photon. The terahertz wave has several characteristic properties, such as typical pulse width on the order of picosecond, which can successfully decrease the interference from background noise in the far-infrared region. With a wide frequency band range, terahertz waves are excellent for evaluating the absorption spectra of materials. In addition, because their photons have lower energy, they are less harmful to the substance being studied. As a source of radiation with numerous advantages, the terahertz wave is a useful tool for human understanding of nature. With the development of numerous new materials and technologies, terahertz waves can now be generated continuously and shine brilliantly in many fields.

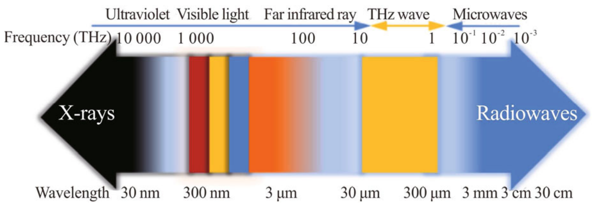

Fig.1 Frequency spectrum of electromagnetic waves

In this paper, we first introduce the basic structure, photoelectric properties and preparation technology of MXene materials. Subsequently, the recent applications of MXene materials in terahertz research areas are introduced, and the mechanisms of MXene materials in several terahertz application directions are analyzed, and the corresponding research results are given as the basis. Finally, we summarize this paper and make summary and outlook. We think our work will inspire further investigation.

MXene is a general term for a large family of newly discovered 2D early transition metal carbides and/or nitrides[12,13]. MXenes are synthesized mainly by etching the A layers from the MAX phases[14,15]. The MAX phases are a ternary carbide or nitride[16], its chemical expression can be expressed as $M_{n+1}AX_n$, where M are early transition metals, A are group IIIA or IVA elements, X are C and/or N (N=1, 2, 3). The MAX phase has a layered hexagonal structure, in which the $M_{n+1}X_n$ element and layer A are alternately stacked[17], as shown in Fig.2(a).

$Ti_3C_2T_x$ is one of the best-studied MXenes. It has individual physicochemical properties, it has a conductivity of 15 000 S/cm, moreover, it also disperses well in various solvents. NAGUIB et al synthesized the first $Ti_3C_2T_x$ MXene by immersing Ti_3AlC_2 powder in 50% concentrated hydrofluoric acid (HF) for 2 h at room temperature (RT)[17,18], and its typical structure is shown in Fig.2(b). The body of the 2D material consists of five individual atomic layers, and there are strong covalent bonds between the layers. The surface of MXenes is naturally chemically capped, this natural surface termination usually includes the functional groups O, OH and F[19], as further research[20], Cl-terminals and Br-terminals have extended the types of surface terminators of MXenes[21].

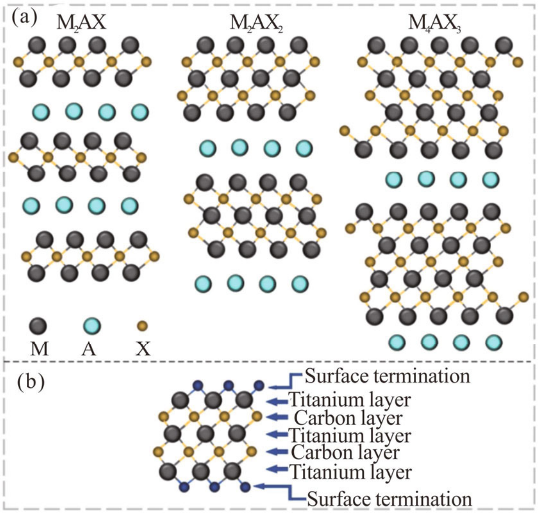

Fig.2 (a) Schematic representation of the layered structure of several MXene phases; (b) Schematic diagram of the crystal structure of $Ti_3C_2T_x$, showing the layered alternating structure of titanium and carbon atoms, and the surface terminating atoms at each end respectively

MXenes have high compositional diversity[22], various surface functionalization possibilities, and flexible thickness controllability[23], so it covers all kinds of properties of metals, semiconductors and insulators[24]. MXenes have a large family of materials, and materials with different elemental constituents exhibit different photoelectric properties. The nature and orientation of the end groups will also affect the properties of MXene materials, such as electronic and optical properties[25]. Different surface terminators will make MXene materials have obvious differences in light absorption performance, the O-terminal MXenes have outstanding metallicity, this property can significantly improve the terahertz absorption performance, the terahertz absorption performance of the OH-terminal MXenes is seven to eight times lower, and the performance of the F-terminal MXenes is significantly reduced by two orders of magnitude.

The optical nonlinearity of MXene is also an object of concern to researchers, including the absorption, scattering and refractive index of MXene. As reported by JIANG et al, $Ti_3C_2T_x$ thin sheets with fewer layers exhibit optical nonlinearity under laser irradiation at 800 nm, 1 064 nm, 1 550 nm and 1 800 nm, with outstanding saturation absorption response and nonlinear refractive index comparable to that of the precursor materials of 2D graphene[26]. According to ZHANG et al, Ti_2C MXene has a large nonlinear absorption efficiency and excellent third-order nonlinear characteristics, which can be used as a high-performance broadband saturation absorber and as a mode-locking device in lasers[27]. The MXene material family represented by $Ti_3C_2T_x$ and Ti_2C has great potential to become 2D nonlinear optical materials.

MXenes have very high electrical conductivity, ranging from less than 1 S/cm to thousands of S/cm, depending largely on their synthesis and layering methods. For example, HF-etched $Ti_3C_2T_x$ has a low conductivity of 2 S/cm[28], but LiF+HCl-etched $Ti_3C_2T_x$ can achieve a conductivity of 1 500 S/cm[29,30]. The combination of metallic conductivity and rich surface chemistry allows MXene to be used to build conductive networks in composites, offering significant conductivity and polarization loss.

It has been shown that MXene and its composites can be produced in different ways depending on the application scenario. The following is some typical techniques for fabricating MXene materials for terahertz applications[31-33]. MXene is synthesized by etching the A layer of the MAX phase. FENG et al prepared water-based dispersions of $Ti_3C_2T_x$ MXene thin sheets by selectively etching Al atomic layers from the Ti_3AlC_2 MAX phase using a mixture of HCL/LiF solution. First, $Ti_3C_2T_x$ MXene flakes were prepared by the MILD method, ultrasonic centrifugation was then used to peel and obtain stable MXene sheets, ethyl acetate was then used to cause the MXene sheet to automatically form a film at the surface of the liquid. Finally, the SiO_2 substrate was used to lift the film below, and the film was transferred from the surface of the liquid to the bottom. After natural drying in the air, multi-layer MXene film was obtained through the repeated transfer process, as shown in Fig.3(a). The preparation of MXene membranes can also be achieved in other ways.

$Ti_3C_2T_x$ is not the only member of the MXene family. LIU et al prepared Ti_2C powder by etching Ti_2AlC[34], first, sodium fluoride was mixed with hydrochloric acid to obtain the etching solution, Ti_2AlC was soaked in the etching solution and stirred, stored at 60 °C for 24 h, and then washed, centrifuged, and dried to obtain Ti_2C powder. The Ti_2C powder obtained by the above method was further exfoliated by intercalation. The Ti_2C powder was mixed with DMSO and $NH_3{\cdot}H_2O$, etc. After stirring, washing, and drying, the further exfoliated Ti_2C powder was successfully obtained.

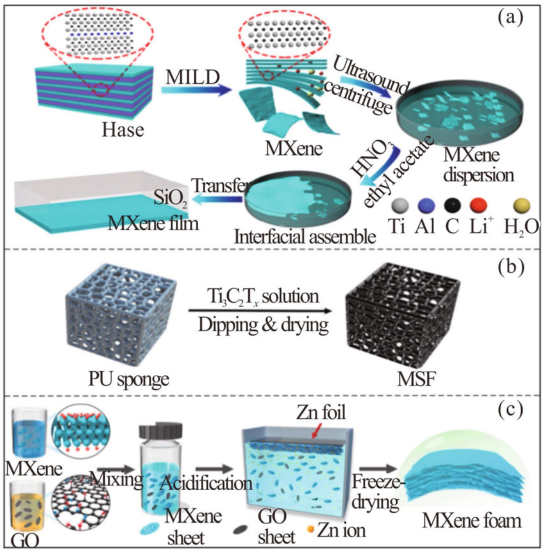

Fig.3 (a) Diagram of the MAX phase being assembled and transferred to a liquid surface after being stripped[31]; (b) Diagram of growing MXene film and wing in porous foam[32]; (c) Diagram of the technological process caused by ionic diffusion[33]

Above, we listed the preparation technology of MXene thin films, when MXenes are used for terahertz absorption and shielding, porous materials are used as the substrate, and the terahertz performance can be optimized by controlling the mass load of MXene. Here we list several preparation techniques of MXenes in composite materials. SHUI et al selectively etched the Al layer of the Ti_3AlC_2 MAX phase to obtain multiple layers of $Ti_3C_2T_x$ and then prepared $Ti_3C_2T_x$-MXene colloidal solution by delamination in deionized water. The $Ti_3C_2T_x$ thin sheets were filled into common polyurethane (PU) sponge foam by dipping coating method, the number of dipping and/or the concentration of MXene solution can easily adjust the filling amount of $Ti_3C_2T_x$ sheets in the MSF sample, and a flexible thin $Ti_3C_2T_x$ sponge composite has been successfully prepared. The sample preparation diagram is shown in Fig.3(b). LIN et al synthesized MXene foam with lightweight, foldable, high conductivity and stability by ion diffusion-induced gel synthesis, as shown in Fig.3(c). Ti_3AlC_2 powder was first etched and then exfoliated[35], $Ti_3C_2T_x$ MXene was synthesized, a stable MXene/graphene oxide (GO) mixed dispersion was formed by gentle ultrasonic treatment and agitation. After acidizing the dispersion with HCl, in order to gelate the dispersion surface, a zinc sheet is placed on the surface of the dispersion, the hydrogel will attach itself to the zinc sheet, and the hydrogel will separate from the zinc sheet when it is soaked in hydrochloric acid solution for a period of time, after dialysis in ultra-pure water, the independent hydrated MXene hydrogel was obtained. Finally, it is frozen and dried. By replacing the substrate with other metals in the same way, separate MXene foams of different metal species can be prepared.

Since the discovery of the first MXene material in 2011, researchers have discovered the enormous application potential of MXene in many fields[36]. With the continuous development of terahertz technology, MXene is certainly not absent. Fig.4 shows the research process for terahertz application of MXene in recent years. In the following chapters, we will introduce and analyze the research progress of MXene in various terahertz application fields[37-41], and introduce the relevant working mechanism of MXene in different research directions according to the ideas shown in Fig.5.

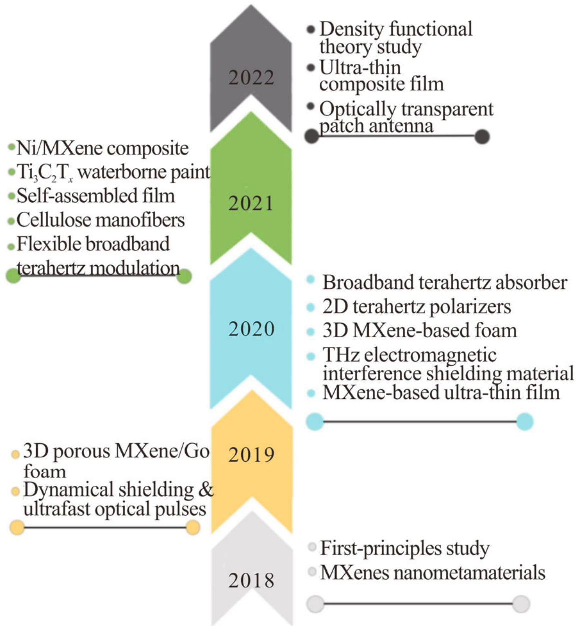

Fig.4 Research timeline of MXene in terahertz applications

The effect of modulating terahertz waves can be produced when the negative refractive index or dielectric constant of a terahertz material changes, the terahertz modulation performance of the material is affected by the carrier concentration, different external fields will change the carrier concentration of the material, thus changing the terahertz modulation performance of the material[42]. The working principle of terahertz modulation can be divided into all-optical[43], electro-optical[44], magneto-optical[45], and mechanical, etc. The effect of the material on terahertz modulation can be changed by changing the conductivity of the material[46], and the terahertz modulation experiment can be either reflection modulation or transmission modulation[47]. When studying the terahertz modulation performance of MXene thin films, the stack number of thin films and the concentration of dispersion can be used as independent variables.

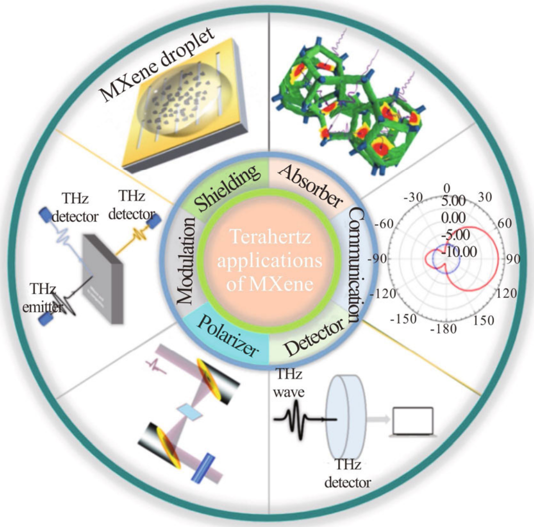

Fig.5 Research timeline of MXene in terahertz application: terahertz shieding[37]; terahertz absorber[32]; terahertz communicatin[38]; terahertz detector[39]; terahertz polarizer[40]; terahertz modulation[41]

A self-assembled, optically transparent MXene film was reported by FENG et al. The thin layer conductivity of the MXene film can be changed by adjusting the number of stacked MXene layers or the concentration of the dispersion[31], which can alter the impedance of the SiO_2/MXene/air interface and produce a significant modulation of the terahertz reflection. With relative reflections of 27% and 406%, respectively, it is demonstrated that MXene thin films have effective terahertz modulation from anti-reflection to enhanced reflection. First, the process for creating thin films of self-assembled MXene is described. The terahertz reflection properties of *n*-layer MXene thin films were subsequently evaluated. The first pulse Er1 of the reflected terahertz signal from the air/SiO_2 interface and the second pulse Er2 of the reflected terahertz signal from the air/SiO_2/MXene interface were defined in Fig.6(a). It was discovered that MXene film had the best terahertz anti-reflection effect when the number of layers was 2 and the equal was 30°, as shown in Fig.6(b). MXene film demonstrated a clear reflection enhancement effect on terahertz when 8 layers. Similarly, when the number of layers is replaced by the concentration of MXene dispersion, the frequency domain amplitude and relative amplitude reflection of Er2 are highly dependent on the dispersion concentration.

Changing the conductivity of materials is not the only way to produce terahertz modulation. The terahertz properties of materials are sensitive to strain. The changes in terahertz transmission or reflection caused by material stretching or deformation can be used not only in terahertz modulation, but also in sensing field. The sample can be placed in the terahertz time domain-spectroscopy system

(THz-TDS), the sample's tensile degree can be adjusted to obtain the corresponding terahertz time-domain spectrum, and then the terahertz spectrum can be obtained to study the terahertz modulation performance of MXene material under various strains.

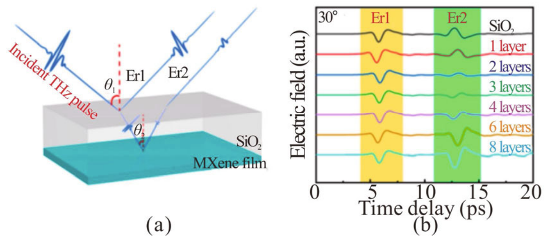

Fig.6 Self-assembled, optically transparent MXene film[31]: (a) Diagram of reflection of terahertz waves by two interfaces; (b) Diagram of variation of terahertz reflection time domain signal of sample with the number of MXene layers when terahertz wave incidence angle is 30°

LIU et al reported a flexible broadband terahertz modulation material, this material is strain sensitive, it is proved that the terahertz transmittance of MXene can be affected by external force[48], and the electrical conductivity decreases with the increase of tensile degree, thus resulting in the increase of terahertz signal transmission with the increase of stretch degree, when the material tension reaches 163%, and the modulation depth of the signal is 98%. MXene samples were prepared by spinning coating sintering and hot evaporation, and the sample was placed in the THz-TDS system, as shown in Fig.7(a). The stretching degree of the sample was adjusted to obtain the terahertz time-domain spectra of the sample with different stretching degrees. The terahertz time-domain spectrum and frequency domain spectrum obtained by Fourier transform of the sample are shown in Fig.7(b)—(e). Similar experimental results are obtained with poly vinyl acetate (PVAc) and sponge as the basis, the terahertz transmission power increases with the increase of the tensile degree of the sample significantly, the modulating factor (MF) was introduced to assess the terahertz wave modulation capability, and the experiment shows that MF is proportional to the tensile strength.

In order to further explain the terahertz modulation mechanism of the material, the change of the conductivity with the degree of strain was calculated, and the real part $\sigma_r(\omega)$ and imaginary part $\sigma_i(\omega)$ of the electrical conductivity of the thin film with the terahertz frequency under different degrees of tension were obtained, as shown in Fig.8(a) and (b). For the purpose of making TDS compute more precise, electrical characterization was processed, and the *I-V* graph of different materials in different stretch levels was given, as shown in Fig.8(c). The relationship between resistance, conductivity, and stretch level is deduced. As shown in Fig.8(d), the resistance of the sample increased with the increase of stretch level, while the conductivity decreased with the increase of stretch degree. FENG et al prepared $Ti_3C_2T_x$ MXene/waterborne polyurethane (WPU) by vacuum-assisted filtration, and also used flexible tensile method to study the terahertz modulation performance of MXene material, achieving more than 90% terahertz dynamic tuning[49].

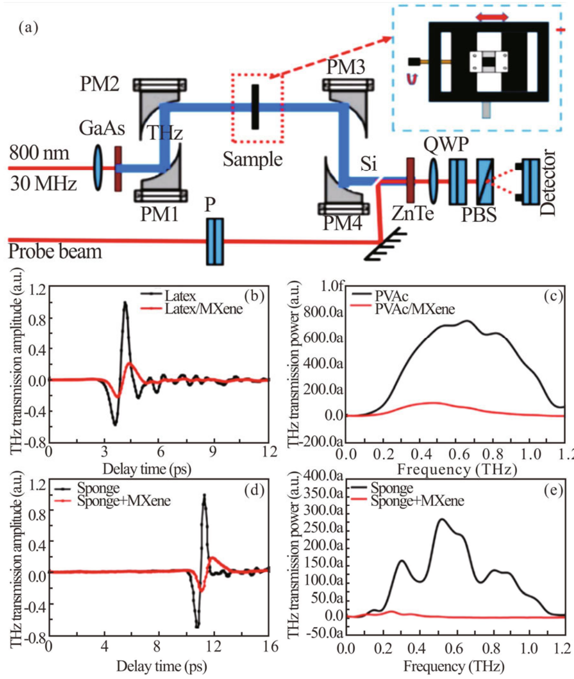

Fig.7 Terahertz properties of aflexible broadband terahertz modulation material[48]: (a) Schematic diagram of a terahertz strain sensitivity experimental facility for testing MXene in THz-TDS; (b) Terahertz time-domain spectrum on PVAc substrates; (c) Terahertz frequency-domain spectrum on PVAc substrates; (d) Terahertz time-domain and (e) frequency-domain spectra when replacing the base with sponge

The above describes the representative research results of MXenes in the field of terahertz modulation, which confirms that the thickness and degree of deformation of materials are important factors to change the depth of terahertz modulation of materials, and also explains the principle of terahertz modulation through these methods. In the future, researchers can work towards achieving more flexible and convenient dynamic terahertz modulation, and should explore more factors influencing terahertz modulation effect of MXenes.

Terahertz waves have now become a powerful tool, and terahertz absorbing materials with high absorption strengths (>99%) are also urgently needed in the field of terahertz absorption. The incident power produced by the electromagnetic wave can be split into three components when it enters lossy material: the reflected, absorbed, and transmitted power[50]. Currently, MXenes have been shown to have excellent terahertz absorption performance. MXenes can be made into a coating that effectively absorbs and shields terahertz waves generated by the device when the coating is brushed onto the surface of the device emitting terahertz waves. It could also be combined with other materials to create a new structure and absorb terahertz waves.

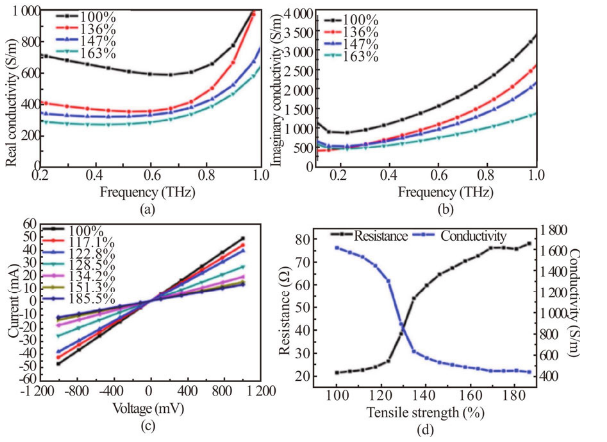

Fig.8 Electrical properties of the sample[48]: (a) The relationship between the real part of the conductivity and the THz frequency with different stretch levels of the sample; (b) The relationship between the imaginary part of the conductivity and the THz frequency with different stretch levels of the sample; (c) *I-V* graph for electrical properties of samples at different stretch levels; (d) The relationship between the resistance and conductivity of the sample with respect to the stretch level

To improve the terahertz absorptivity of materials, increasing the transport path of terahertz waves in the absorbing materials has proved to be an excellent method. Many excellent research results have already been obtained on this method. For example, MXene materials are injected into porous substrates, it can grow thin films in the pores, or construct multi-layered absorptive materials with sandwich structure, so that terahertz waves can be reflected repeatedly inside the material, and their energy will be lower and lower, so as to realize the absorption of terahertz waves. The terahertz transmission and reflection curves of samples, as well as the electrical conductivity and reflection loss (RL) value of materials, are typically obtained through experiments when examining the terahertz absorption properties of materials. In both theoretical research and practical application, terahertz wave absorption and shielding of materials are related. Therefore, the electromagnetic interference (EMI) shielding capacity of materials frequently reflects their ability to absorb terahertz waves. There have been some excellent research findings recently regarding the terahertz absorption performance of MXene. The following will outline the recent developments in terahertz absorption of MXenes from a variety of angles.

The applications of MXene are flexible and diverse, and in combination with other materials, they show exciting properties. GO is a 2D material with a layered structure. When MXenes and GO are fused, the terahertz absorption properties of GO will be significantly enhanced. Of course, MXenes have been shown not only to fuse with GO but also to use PU as a substrate. Previous studies have shown that when the filling content of MXene in the foam substrate increases continuously, the new material after fusion will show a nonlinear increase in terahertz absorption performance, which is because MXene will first wrap on the substrate skeleton, then grow in the pores, and then break to form an eclosion state. In this section, the research progress of terahertz absorption properties of MXene/porous structural materials based on the above content will be introduced.

MA et al reported an ultralight compressible three-dimensional (3D) porous MXene/GO foam (MGOF). Its high RL, tunable, and wide-band terahertz absorption properties are described in Ref.[51]. There are a lot of micro and nano pores in GO, and these pores can make the electromagnetic wave incoming into GO be reflected and scattered continuously[52]. By fusing MXene with GO, a new substance known as MGOF is created that can improve the terahertz absorption properties of the original GO. The production process of MGOF was shown in Fig.9.

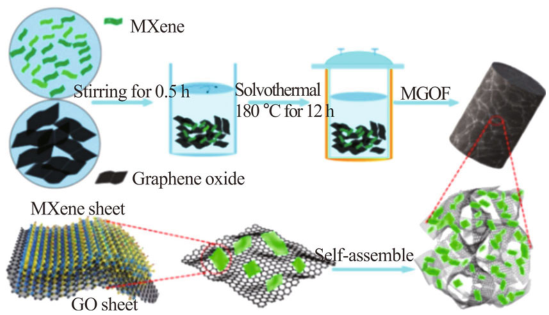

Fig.9 MGOF preparation process[51]

According to the THz-TDS system, the addition of MXene has a great influence on the GO foam. It significantly improves the absorption performance compared to pure GO foam. Average absorption intensity (AAI) is also proportional to the bandwidth terahertz absorption capacity of material. In the range of qualified bandwidth, when the sample thickness is different, combined with the average RL, it is clear that the optimal ratio of MXene to GO is 1: 5. The material mixed with MXene and GO not only has better terahertz absorption performance, but also has good compressibility. In this paper, the influence of the compression amount of MGOF on the absorption capacity of terahertz was studied. Compression can result in the high-density gradient pore structure of MGOF, which will increase the multi-scale scattering and refraction of electromagnetic waves. In addition, the oriented and compressed porous structure facilitates lateral scattering, so compression can improve the terahertz absorption capacity of MGOF. Interestingly, as the thickness of original MGOF 1: 5 varies from 1 mm to 4 mm, its terahertz absorption performance gradually approaches that of compressed MGOF. When the thickness increases to 4 mm, no matter how the compression ratio changes, MGOF can fully weaken terahertz waves entering the material. The continuous compression test also proves that the material has good durability.

SHUI et al reported a flexible thin $Ti_3C_2T_x$ sponge composite used as a wideband THz absorber, named $Ti_3C_2T_x$ MXene sponge foam (MSF)[32]. Using the open structure based on macroporous sponges[53], it can easily satisfy the impedance matching with free space and significantly decrease the reflection of terahertz wave[54]. The absorption rate of terahertz in the absorber with a thickness of only 2 mm is more than 99.99%. MSF is made by dipping $Ti_3C_2T_x$ sheet into commonly used PU sponge foam. After drying, the $Ti_3C_2T_x$ wafer exists in the whole sponge. Three typical filling states of $Ti_3C_2T_x$ wafer in MSF are wrapped on the framework, forming a film above the holes and attching to the framework. The terahertz transmission and reflection spectra of the sample were measured by THz-TDS[55]. The terahertz absorption performance of MSF was measured by three parameters, including the filling amount of $Ti_3C_2T_x$, the thickness of the PU sponge, and the hole size. The transmitted THz signal of MSF quickly decreased with the increase of $Ti_3C_2T_x$ wafer filling. Importantly, for all MSF samples, the terahertz reflected signal was always kept in an extremely low range. When the $Ti_3C_2T_x$ is filled with 10.5 mg, the sample achieves almost 100% terahertz absorption. The absorption rate of terahertz waves is not completely proportional to the aperture size, but the optimal absorption rate is obtained when the aperture is 50 ppi. However, the influence of the thickness of the sample on the absorption rate of terahertz is not obvious.

According to the analysis, the content of $Ti_3C_2T_x$ is the main factor affecting the terahertz absorption capacity of MSF. When the load of $Ti_3C_2T_x$ reaches the "threshold", MSF will always obtain the maximum terahertz absorption regardless of thickness and aperture. The existence of a "threshold" helps the manufacturing process because it is not necessary to precisely control the optimal load value of $Ti_3C_2T_x$, as shown in Fig.10(a). The absorption performance is represented by EMI SE_A. With the increase of MXene content, the terahertz absorption performance of MSF does not linearly increase. The mass load of $Ti_3C_2T_x$ in EMI SE_A and MSF can be divided into six sections, from partial encapsulation to complete encapsulation, then the growth of wing-like MXene film, and finally the formation of continuous film, and then due to insufficient mechanical strength, the film began to fracture, and then the mass load was further increased, the growth and fracture repeated, and finally the stable absorption was achieved. The absorption principle of MSF for terahertz waves is shown in Fig.10(b).

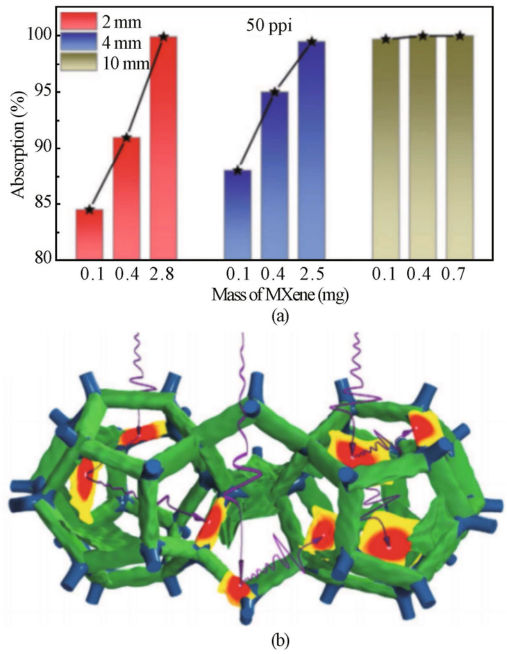

Fig.10 Terahertz properties and principles of MSF[32]: (a) When the thickness of MSF varies between 2 mm, 4 mm, and 10 mm, the terahertz absorption capacity of MSF varies with the content of MXene; (b) Schematic diagram of terahertz wave absorption principle for MSF

LUO et al reported MSF with a similar structure as described above, and super high terahertz absorption efficiency of 99.6% is achieved in the frequency range of 0.3—1.2 THz[56]. The application of MSF has been expanded by spraying a mixture of silane coupling agent (SCA) and silica particles to enable superior liquid removal, self-cleaning, and corrosion resistance. Again, using polyurethane sponge (PUS) as a base, BAI et al reported a Ni/MXene decorated PUS. The sample has a 99% terahertz absorption capacity and an EMI SE_A of 69.8 dB when the thickness is 8 mm[57]. FEI et al also introduced polarization loss into MXene and prepared a 3D crosslinked $Ti_3C_2T_x$ aerogel (CMXene). Experiments show that CMXene has an effective bandwidth of 0.2~1.4THz and a reflection loss of 27.3dB[58].

As described above, MXene terahertz absorbers based on porous materials show excellent terahertz absorption properties. However, if the absorbent material can be made into a thin film, its application value can be significantly improved. It has been proved that MXene/rGO composite film (MGF) can achieve excellent terahertz absorption/shielding performance. This composite film with a 3D macroporous structure can also realize multiple reflections and loss of terahertz waves in its interior, so as to achieve significant absorption of terahertz waves. The following will introduce the representative MGF with 5-layer sandwich structure, and explain its research status.

LI et al reported an ultrathin wideband MGF with 3D polyporous structure, and rGO stands for graphene[59]. The maximum RL value of MGF with 5-layer sandwich structure is 57.7 dB, the ultrathin thickness is 0.148 mm, and the effective bandwidth covers 0.37—2.0 THz. The terahertz absorption performance of MGF samples was measured by terahertz imaging system, as shown in Fig.11(a). By comparing the absorption curves of MGF with different interlayers, it can be seen that the optimal number of MGF layers is five. Meanwhile, the 5-layer MGF also has better-qualified bandwidth than other layers. Sandwich MGF induces more obvious dielectric loss through interfacial polarization between MXene and rGO/polyvinylpyrrolidone (PVP) slices as well as continuous scattering and reflection within the sandwich structure, thus rapidly dissipating electromagnetic waves entering the material. In this study, hollow MXene ($Ti_3C_2T_x$) film with CNTs (MCF) (CNT: carbon nanotubes) was prepared and its terahertz absorption and reflection properties were investigated. The results show that although the sandwich MCF has efficient absorption, the AAI, maximum absorption, and effective bandwidth are lower than the MGF, as shown in Fig.11(b). Therefore, the sandwich MGF has significantly higher absorption and wider effective bandwidth.

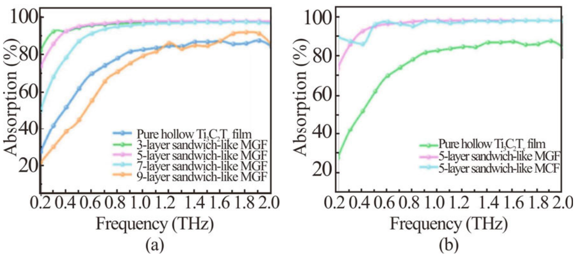

Fig.11 Terahertz performance of ultrathin wideband MGF with 3D polyporous structure[59]: (a) Terahertz absorption performance of MGF samples with different interlayers; (b) Absorption comparison between the sandwich MCF and MGF

Attenuation loss, multilayer structure, and quarter-wavelength resonance theory all contribute to the high terahertz absorbability of MGF. After incorporating rGO/PVP as an interval layer between $Ti_3C_2T_x$/polymethyl methacrylate (PMMA) hybrid spheres, a thin layer of graphene is sandwiched between a large number of $Ti_3C_2T_x$ hollow spheres, which act as a channel for terahertz waves to reflect between layers within the material, thus achieving effective electromagnetic energy conversion and attenuation. It should be noted that the terahertz absorption characteristics of MGF are related to the number of interlayered MGF layers, but not to the thickness. Taking R to represent the wavelength of 1 THz, the thickness of 5-layer sandwich MGF is 0.148 mm, which is half of the wavelength of 1 THz, and $\lambda/2$ is a positive multiple of $\lambda/4$, which satisfies the quarter-wavelength resonance theory[60]. In order to in-depth explore the influence of electrical conductivity on the electromagnetic characteristics of MGF, different samples were surveyed. The 5-layer sandwich structure MGF can increase the electrical loss and further enhance the terahertz absorption performance.

We have described the excellent performance of MXenes fusion with porous materials in the field of terahertz absorption, and relevant studies have confirmed its great application value. However, the above form of terahertz absorption materials still has application limitations. Next, we will explore another MXene-based terahertz absorption material, namely MXene water-based coatings. The advantage of water-based coatings is that they can be applied to device surfaces in any shape, especially when applied to irregular surfaces, and water-based MXene coatings show considerable flexibility while retaining strong terahertz wave shielding/absorption capabilities. The content of MXene has a certain correlation with the viscosity of water-based coatings, and the thickness of coatings also has a significant correlation with its shielding effect.

WAN et al reported a MXene water-based paint (MWP)[61]. It has a powerful terahertz EMI shielding/absorption performance and can expediently adhere to many substrates. The 38.3-μm-thick MWP on quartz shows a 64.9 dB EMI shielding value, and the MWP-coated sponge foam achieves an excellent reflection loss of 32.8 dB. The preparation process of $Ti_3C_2T_x$ dispersant and water-based coating is shown in Fig.12(a). Using X-ray photoelectron spectroscopy (XPS) analysis, it is concluded that the C and N triple bonds are critical for providing adequate adhesion strength. To determine the effect of material thickness on terahertz shielding properties, coating 30 wt% MWP on quartz substrate of different thicknesses, terahertz TDS experiment was performed to obtain EMI SE and RL[62], as shown in Fig.12(b) and (c). Compared with similar studies, the material properties of this study are shown in Fig.12(d).

In the above research content, the researchers conducted an in-depth study on the application of MXenes in the field of terahertz, and explored the practical value of relevant research, so that it can be applied to different terahertz absorption application scenarios. These research results laid a solid foundation for the next exploration. However, if a sponge or foam substrate is used to grow MXene in its void, the shielding effect may be worse when the thickness of the shielding material is very thin, but the successful exploration of MXene film composite materials with millimeter thickness can make the shielding layer be considerably thinner, which effectively reduces the overall volume of the device, while retaining efficient terahertz shielding capability.

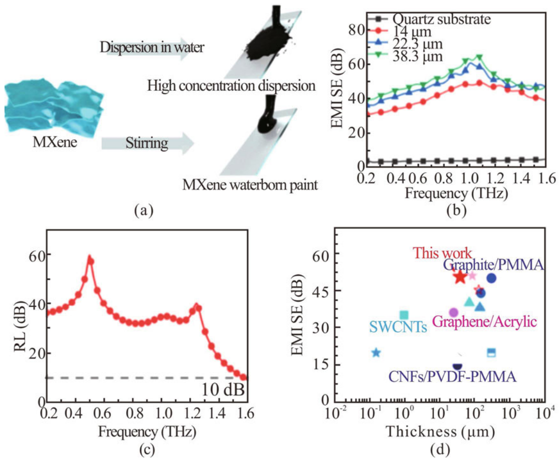

Fig.12 Preparation method terahertz properties of NMP[61]: (a) Preparation diagram of MXene water dispersion and MXene waterborne paint; (b) EMI SE graph of samples with different thicknesses; (c) RL values graph using porous sponges as base materials; (d) Comparison with similar studies

Terahertz technology is widely used, so it is essential to protect the devices and their surroundings from the EMI that is frequently produced by these terahertz devices[63]. According to studies, the primary mechanism of high shielding effectiveness is absorption. In order to create a consortium with a porous structure, MXenes are typically combined with foam substrate materials, and the shielding characteristics of the sample will change significantly as the mass load of MXene in the complex material changes. Researchers have created a variety of shielding materials based on the characteristics of MXene to ensure that MXene-based terahertz shielding materials can be widely used, and these materials have useful qualities like lightweight, stress resistance, and easy coating. $Ti_3C_2T_z$ films have been shown to perform better than carbon nanostructures and their composites in EMI shielding, with performance equal to copper and silver, while being much lighter. The research described below explores the terahertz shielding properties of MXene materials and points the way to practical applications of MXene-terahertz shielding materials.

Absorption-based terahertz shielding is an important method in terahertz shielding of MXenes. In the past, some EMI shielding techniques used reflection, which caused electromagnetic waves to reflect. This likely increased the negative effects of EMI, and terahertz shielding based on absorption can solve this problem. Researchers have developed a series of preparation technologies so that terahertz shielding materials based on MXene can be flexibly used for EMI shielding, which provides the theoretical and experimental basis for the widespread use of MXenes in terahertz shielding. Due to its extremely high terahertz absorption properties, MXenes can produce an excellent terahertz shielding effect when combined with porous materials. The following will provide an overview of the representative research developments of absorption-dominated MXene terahertz shielding materials.

LI et al reported an ultrathin wideband MGF with 3D macroporous structure. The total shielding effectiveness (SE_T) of 5-layer MGF reaches 54.2 dB at 1.4 THz. When terahertz waves reach the surface of the materials, reflection (SE_R), absorption (SE_A), and internal shielding (SE_I) are three shielding modes, and the three together constitute the total shielding efficiency (SE_T). The SE_A value of 5-layer MGF is significantly greater than its SE_R, and its variation trend is basically in line with that of SE_T, so absorption plays a leading role in the total electromagnetic shielding efficiency and is the main mechanism for generating high shielding efficiency. The special structure combined with MXene and rGO/PVP can form a conductive network inside the material, which has excellent absorption and scattering ability of electromagnetic waves. When the thickness of MGF is 0.148 nm, the material exhibits excellent electromagnetic characteristics and wide absorption bandwidth.

LIN et al synthesized a composite material with high terahertz shielding properties by ion diffusion-induced gel method[33], which is a highly stable composite of MXene and foam structural materials[64]. A small amount of GO modification can make the 3D MXene structure more robust[65,66], as shown in Fig.13(a). The method described in this paper has good versatility. Independent MXene foams containing different metals can be prepared by using different metal substrates. It has been proved that Al, GO, Fe, and Ni can induce gelation. In general, the conductivity and thickness of the material jointly determine the shielding performance. However, the formation of porous structures can overcome the adverse effects of reduced conductivity by increasing thickness, resulting in a significant reduction in density and improved shielding capability. The terahertz shielding mechanism of the sample is shown in Fig.13(b).

The EMI shielding effect of block MXene-based films and Zn^{2+} MXene-based foam under different MXene contents is shown in Fig.13(c) and (d). The surface reflection signal of the sample was detected by the THz-TDS system in reflection mode, the Zn^{2+} MXene IV foam exhibited low surface reflection of terahertz waves with a wide frequency bandwidth (0.86—2.0 THz) RL value. Experimental results show that Zn^{2+} MXen-based foam has an excellent terahertz shielding effect of 51 dB at a small thickness of 85 μm, and the surface reflection is much lower than its film counterpart.

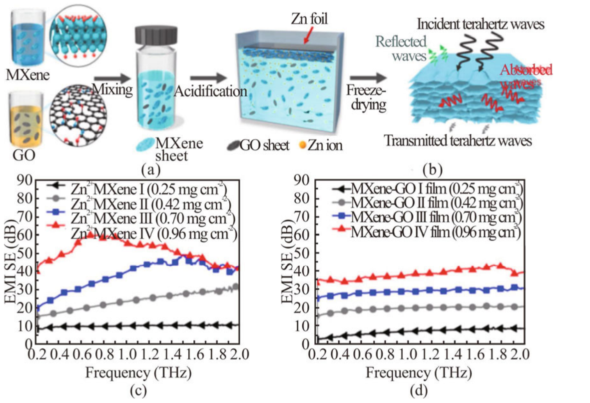

Fig.13 Preparation techniques and terahertz properties of composite materials[33]: (a) Schematic of the ion-diffusion-induced gelation process; (b) Terahertz shielding principle of samples; EMI shielding performance of (c) bulk MXene-based films and (d) the Zn^{2+} MXene-based foams

Among the current MXene shielding materials, hydrogel material is a special kind. With its unique property, it can be adhered to the surface of any shape device like gum and can be easily bonded into one after being flat and broken. While having interesting and flexible features, it also has excellent terahertz shielding performance. ZHU et al reported a hydrogel-type shielding material incorporating MXene and poly(acrylic acid)[67]. Due to the combination of porous structure, medium conductivity and internal water-rich environment, the shielding properties of hydrogels are characterized by absorption dominance[68]. It has high EMI SE of 45.3 dB and wide effective absorption bandwidth (0.2—2.0 THz), RL of 23.2 dB. MXene composite hydrogel can be pinch-shaped into any shape, and has ideal shape change and rapid self-healing ability[69], it can adapt to any complex surface and recover quickly from severe damage, ensuring its reliability as a high-performance EMI shielding material for applications in complex environments[70], as shown in Fig.14(a). The terahertz shielding principle of the sample is shown in Fig.14(b). In order to explore the EMI shielding performance of MXene composite hydrogel, its electrical properties were first studied. The higher the content of MXenes, the higher the conductivity of the sample[71]. Terahertz time-domain spectroscopy shows that when the content of MXene in the sample exceeds 8.5 wt%, incident terahertz electromagnetic waves are almost completely shielded. Excessive MXene will inevitably increase more reflection, which will enhance EMI SE but reduce the absorption performance. The terahertz EMI shielding and absorption properties of MXene composite hydrogel, foam and pure polyacrylic acid-amorphous calcium carbonate (PAA-ACC) hydrogel were compared, as shown in Fig.14(d). PAA-ACC hydrogel is insulated, but it still shows a medium EMI SE value of 12.6 dB and a strong electromagnetic absorption capacity. According to the above results, the MEI shielding mechanism of samples is dominated by absorption. With the porous structure of the sample surface and the appropriate conductance to optimize the impedance matching, the electromagnetic wave can enter the sample without obvious reflection, and then reflect and lose inside the sample. The comparison between the results of this study and those of the same type is shown in Fig.14(c).

ZOU et al reported a conforming hydrogel prepared using PEDOT: PSS and nanosheets, which achieved absorption-based terahertz shielding properties at frequencies of 2—10 THz, facilitating the development of organic hydrogels in terahertz applications[72].

ZOU et al reported a polyacrylonitrile/$Ti_3C_2T_x$ MXene/silver nanoparticles fiber film[73]. It is verified that the terahertz shielding properties of the composites change significantly when the AgNPs content and thickness change. The EMI SE value of the sample increased with the increase of AgNPs content, and the thickness of the sample is also positively correlated with the terahertz shielding properties. Compared with the shielding material based on the reflection mechanism, the terahertz absorbing material has lower reflectivity and transmittance, which can effectively eliminate the terahertz radiation in the environment. The electromagnetic shielding mechanism of the sample is shown in Fig.15. The shielding principle is similar to that of the mixed material of MXene and GO with porous structure.

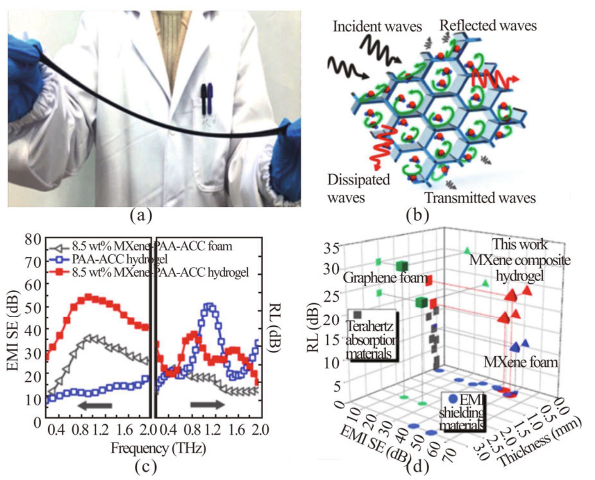

Fig.14 Terahertz shielding principle and properties of hydrogel shielding materials incorporating MXene and polyacrylic acid[67]: (a) Photographs showing the stretchability and processability of the MXene composite hydrogel; (b) Schematic diagram of the terahertz shielding principle of the sample; (c) Comparison of terahertz shielding and absorption properties; (d) Terahertz properties of MXene hydrogels compared with reference samples

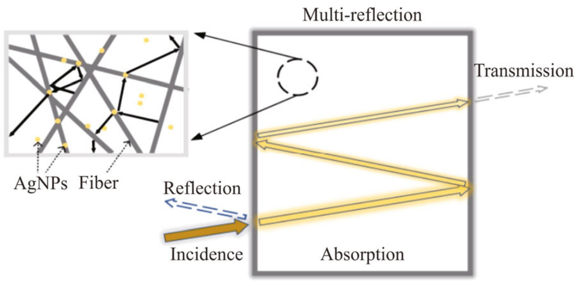

Fig.15 Schematic diagram of the terahertz shielding principle of the sample

ZOU et al also reported a single-layer MXene sheet capable of better reflecting MXene absorption properties[74]. In this study, MXene films with different thicknesses were prepared on polyimide plastic by spin coating method, in order to better analyze the absorption effect of terahertz band, and the films prepared by spin coating method were compared with those prepared by vacuum filtration method. The EMI SE value of MXene film with single spin coating is about 3 dB. When the sample thickness of MXene film with spin coating is 25 μm, and the EMI SE value of MXene film can reach 70 dB at 0.3—0.7 THz.

Most of the current research results are based on other materials to study the effect of MXene filling amount on the terahertz shielding properties of composites, there are relatively few reports of work on MXene-based composites, and the research into polymer composites based on MXene that are used for THz shielding is still in its early stages.

HUSSAIN et al reported terahertz shielding of flexible $Ti_3C_2T_x$/multi-walled carbon nanotubes (MWCNT)/polyvinyl alcohol (PVA) polymer composite films[75]. First, the sample material was prepared step by step, as shown in Fig.16. Then, the EMI shielding efficiency, absorption coefficient, and conductivity of composite films in the frequency range of 0.1—2.0 THz were measured by THz-TDS. With the increase of MXene content and the addition of MWCNT, the electromagnetic shielding effect is enhanced and the conductivity of the sample increases. The absorption coefficients of PVA and composite films in the frequency domain of 0.1—2.0 THz and the shielding efficiency of the original PVA and MXene/PVA composite films at different MXene contents and different MXene/MWCNT/PVA films (1.5 wt% MWCNT) were also investigated. Adding MWCNT and MXene in PVA matrix to construct the bridge structure significantly enhanced the conductivity and EMI SE in the terahertz range.

The aforementioned information introduces the development in terahertz shielding research for MXene materials, with absorption serving as the primary mechanism. Of course, more effective techniques have been discovered in recent EMI shielding of MXenes research, and the terahertz shielding performance of MXenes can be controlled by an optical pulse, which is a mechanism akin to terahertz modulation. The method of combining MXenes with terahertz nanomaterial to realize the shielding has also made certain research achievements, which will be discussed in the following.

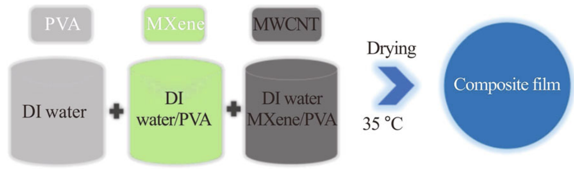

Fig.16 Preparation process of the composite membrane

CHOI et al reported a MXene thin film covering a nanogap antenna array[37]. It is experimentally confirmed that the antenna covered by MXene shows a great reduction in terahertz transmission. First, a stable supernatant of MXene colloidal solution at a concentration of 30 mg/mL was prepared, and the colloidal solution was then dripped onto a silicon substrate and a nanogap antenna array, the drip-cast sheet formed a completely covered uniform film, as shown in Fig.17(a). Terahertz transmission curves of different slit antennas covered by MXene are shown in Fig.17(b). The MXene membrane blocks terahertz waves between 0—2 THz. When the thickness of the MXene thin film increases to 65 nm (150 nm wide antenna) and 200 nm (500 nm wide antenna), the basic resonance of the nanoantenna at 1 THz disappears, as shown in Fig.17(c). With the further increase of MXene membrane thickness, terahertz transmission is completely blocked in the whole frequency range.

The terahertz shielding previously introduced mostly uses absorption as the main shielding mechanism, but most of them change the filling amount of MXene in the shielding material or change the thickness of coating to achieve different shielding efficiencies. If the terahertz wave transparency of MXene can be controlled by optical pulses, and the terahertz shielding efficiency of the material can be adjusted, the MXene shielding material can have higher flexibility and practicability.

LI et al reported a method to control the EMI shielding degree of $Ti_3C_2T_y$ MXene using optical pulses, and it was demonstrated that ultrafast pulses of light with wavelengths across the visible range (400 nm and 800 nm) can cause instantaneous broadband terahertz transparency lasting nanoseconds in MXene[76]. To investigate the effect of photo excitation on terahertz conductivity, an optically pumped terahertz probe measurement was performed. The experiment proves that EMI SE can be manipulated in terahertz range by optical excitation, both 800 nm and 400 nm optical pulses enhance terahertz pulse transmission. The frequency resolution transient changes of EMI SE at different times after excitation with 800 nm pulse are shown in Fig.18(a). The THz-TDS and optical (800 nm) pumped terahertz probe spectral measurements were performed at 95 K, and the decrease in EMI SE caused by optical excitation and its relaxation kinetics were found to be insensitive to temperature changes from 290 K to 95 K, as shown in Fig.18(b).

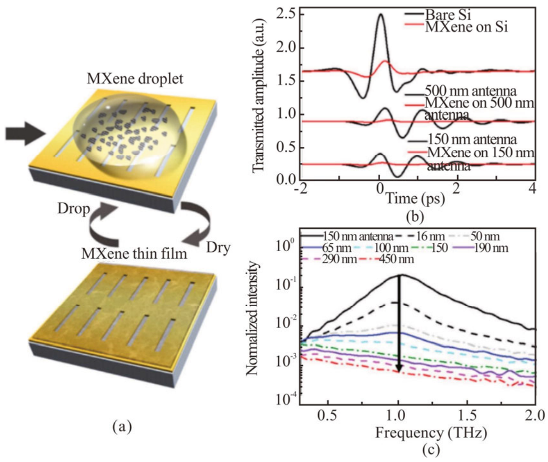

Fig.17 Sample schematic and terahertz performance[37]: (a) A thin film formed by dripping MXene colloidal solution onto an antenna array; (b) Terahertz transmission performance of bare silicon and different width antennas before and after attachment of MXene thin films; (c) Normalized transmission spectra of 150 nm wide antenna attached with MXene thin films of different thicknesses

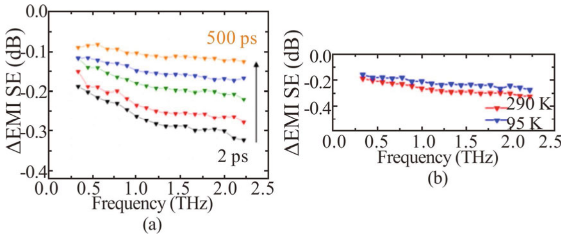

Fig.18 Terahertz shielding performance of $Ti_3C_2T_y$ MXene[76]: (a) Photo-induced change in EMI SE at different times; (b) Change in EMI SE 2 ps after photo excitation at 290 K and 95 K with 800 nm, 950 μJ/cm^2 pulse

The research of MXene in terahertz shielding direction is closely related to its research in terahertz absorption direction. As can be seen from the above, terahertz absorption is an important mechanism for MXene terahertz shielding materials, but for MXene composites with foam or sponge as a substrate, it is still possible to continue to explore how to apply to complex devices or device surfaces. The appearance of MXene composite hydrogels and composite films makes the shielding material be better and more flexible to cover the surface of irregular devices and equipment. At the end of this chapter, we also introduce how to dynamically adjust the terahertz shielding efficiency of MXene shielding materials, which makes the application of MXene in terahertz shielding direction more flexible and suitable for more application scenarios.

In the field of communication, the upper limit of information transmission often depends on the frequency of electromagnetic wave[77]. With the rapid development of communication technology, the research and development of 6G technology is imminent. The application of terahertz band in the field of communication is the key to solving the next generation of high-speed communication technology. In addition to the above areas proved to be promising, and MXene has also made some research achievements in the field of terahertz communication.

ANAND et al reported a terahertz communication TA_4C_3-MXene-based optical transparent patch antenna and analyzed its performance[38]. Terahertz antennas are necessary to fulfill the future transreceiver system requirements in indoor and inter satellite communications[78]. An optical transparent microstrip patch antenna based on Ta_4C_3-MXene was designed on 800 GHz polyimide substrate[79]. Ta_4C_3, one of the MXene materials used in the study, has higher electrical conductivity than any other 2D material[80], including graphene, metal sulfides, and hydroxides[81]. Impedance matching between patch antenna and microstrip line in working frequency band is analyzed by using voltage standing wave ratio (VSWR) and return loss. The relationship between VSWR and antenna frequency is shown in Fig.19(a). In the resonant band of the antenna, the radiation efficiency ranges from 89.6% to 90.7%. Thus, 2D MXene materials are the most suitable for the design of optically transparent antenna. At 800 GHz, the electric and magnetic fields of XMene antenna are shown in Fig.19(b). It can be seen that the main lobe of the antenna has a high directivity in the working frequency band, and the back lobe is negligible (less than −5 dB).

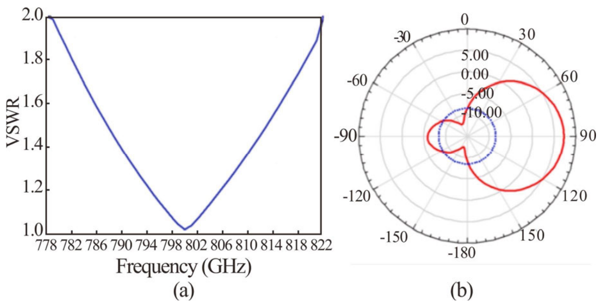

Fig.19 Performance of terahertz communication optical transparent patch antenna based on TA4C3-MXene[38]: (a) Frequency versus VSWR of the antenna; (b) The E (solid line) and H (dashed line) far-field radiation patterns of the antenna at 800 GHz

In the next two sections, the research progress of MXene in terahertz detection and terahertz polarizer will be introduced. MXene has more room for advancement in the field of terahertz detection and terahertz polarizer than terahertz absorption and terahertz shielding.

JHON et al reported a first-principles study of the MXene terahertz detector, and MXenes have extremely high photo-thermal conversion efficiency[39]. In order to verify MXene's great potential in terahertz detection applications, systematic density functional theory (DFT) was performed for the electronic band structure, terahertz optical properties and thermoelectric figure of merit (ZT) of monolayers and/or stacked $Ti_3C_2T_x$ (T_x: -F, -O or -OH), it was found that excellent terahertz optical absorption occurred in this 2D material regardless of stacking. The thermoelectric properties of stacked Ti_3C_2 with surface terminals of -O and -OH were investigated by constructing a device system consisting of channel and electrode regions, and then examining phonon and electron transport. The ZT of stacked Ti_3C_2 sheets at Fermi level is 4.56×10^{-4}. This ZT value is significantly lower than that of commercial thermoelectric materials and can be used for terahertz detection applications.

LI et al reported a 2D MXene $Ti_3C_2T_z$ nanosheet by simple rotary casting for the manufacture of terahertz polarizers[40]. $Ti_3C_2T_z$ nanosheets can be deposited on various substrates after solution treatment, which has the advantages of high performance[82], low cost, and manufacturing[83]. The THz-TDS system is used to test the MXene polarizer. The test method and the rotation mode of the polarizer are shown in Fig.20(a) and (b). The time-domain and frequency-domain terahertz waveforms of the sample are shown in Fig.20(c). Four sizes of linear gate MXene polarizer are introduced, namely K1 (w=10 μm, s=2 μm), K2 (w=30 μm, s=3 μm), K3 (w=10 μm, s=4 μm) and K4 (w=40 μm, s=5 μm), respectively, where w and s are MXene fringe width and gate slit width, respectively. The relationship between the peak value of the transmitted pulse of the four polarizers and the rotation angle θ of the polarizer is shown in Fig.20(d). The extinction ratio and insertion loss of four MXene polarizers are shown in Fig.20(e).

Very thin (about 30 nm), 10—20 μm wide stripes (consisting of overlapping nanosheets with a transverse size of 1—3 μm) coated with $Ti_3C_2T_z$ exhibit excellent polarization characteristics in the 0.3—2.0 THz spectrum, with an electric field ERs of up to 3 dB, corresponding to a power ERs of 6 dB. To further explore how the performance of the MXene polarizer can be improved by geometric optimization, finite-difference time-domain (FDTD) simulations were performed at frequency of 1 THz. By increasing the line thickness to 1.5—2 μm and optimizing the periodic scraping period and filling factor, the ER of the electric field will increase to >16 dB, or power of ER increased to >32 dB while keeping insertion loss low. The dynamic tunability of terahertz conductivity of $Ti_3C_2T_z$ was demonstrated by ultrafast optical pulses, opening the possibility of using MXene wire grids in high-speed terahertz modulators.

The research of MXene in terahertz communication, terahertz detection, and terahertz polarization direction is basically in the theoretical and preliminary stage, and it is expected that researchers will conduct more in-depth research in these directions.

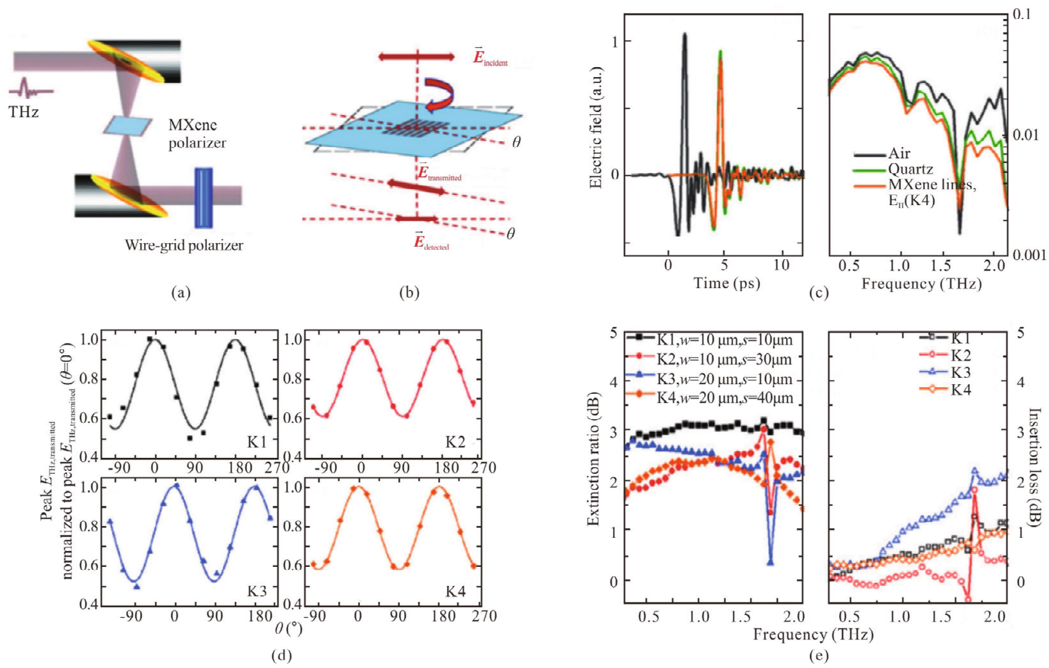

Fig.20 Two-dimensional MXene $Ti_3C_2T_z$ nanosheets for the manufacture of terahertz polarizers[40]: (a) Schematic of a terahertz time-domain spectra system for sample detection; (b) The rotation mode of the MXene polarizer sample; (c) Time-domain and frequency-domain terahertz transmission waveforms of the sample; (d) The relationship between the peak value of the emitted pulse and the rotation angle θ of the four polarizers; (e) Extinction ratio and insertion loss of four MXene polarizers

Here, the fundamental structure and characteristics of MXene materials are primarily introduced, and the research status of using MXene materials in terahertz applications, such as terahertz shielding, terahertz absorption, terahertz modulation, terahertz communication, terahertz detection, and terahertz generation, is presented.

By adjusting the number of stacked MXene layers/concentration of MXene dispersion, the thin layer conductivity of the film is changed, and the terahertz reflection giant modulation is effectively achieved. Mechanical stretching proved that the terahertz transmittance of MXene could be affected by external forces when the material tension reached 163%, the time-domain spectrum signal of terahertz was modulated by 98%, and the maximum modulation of the terahertz projection power spectrum reaches 281%.

According to the terahertz application research of MXene material, there is an inseparable link between the absorption capacity and the shielding capacity of the material. The terahertz absorption material based on MXene mainly achieves a better absorption effect by making terahertz waves repeatedly reflected and attenuated inside the material. With excellent characteristics, MXene can not only fill the pores of the foam base material, so that the conductive loss capacity of the material is significantly increased, and then efficiently attenuates terahertz waves. Meanwhile, the terahertz absorption film based on MXene can also take into account the characteristics of high absorption rate and thinness, and efficiently absorb terahertz waves through high dielectric loss.

Previous research on high-performance EMI shielding materials aims to improve the conductivity of materials. This design concept is helpful to reduce the thickness of shielding layer, but it will lead to strong reflection of electromagnetic waves, which cannot achieve reasonable EMI shielding. EMI shielding materials based on MXene materials mostly adopt absorption mechanism. Due to the electromagnetic wave absorption characteristics of porous materials, they show ultra-high EMI shielding performance and have been proven to be manufactured in a variety of forms, effectively attenuating and shielding terahertz waves in a variety of environments. In terahertz communication, terahertz detection, and terahertz generation, some research achievements have been made on MXene.

Although MXene has shown many advantages in terahertz applications and has accumulated certain research achievements, the properties and applications of MXene still need to be explored. We list some problems in the research of MXene materials in terahertz-related fields, and give suggestions for future efforts.

Suggestion 1: At present, MXene research in many areas of terahertz remains mostly in the laboratory stage.

Solution: With the continuous development of terahertz technology, and more and more application scenarios have been discovered, terahertz technology is no longer a "teraherz gap", but has become the top ten technologies that change the world. At the same time, the research of MXene in various fields of terahertz should be developed in the direction of practical application. Researchers should take advantage of the large number of materials in the MXene family, excellent performance, and high interest, follow the development of terahertz technology, and strive to put relevant research into engineering applications.

Suggestion 2: At this stage of research, the application of MXene in terahertz is not widely studied.

Solution: Terahertz applications cover a wide range of fields and are expected to become a key support for the next generation of communication technology, and the research of MXene for terahertz applications mainly focuses on terahertz absorption, terahertz shielding and terahertz modulation. Researchers should broaden their thinking, deepen the research on other applications of MXene in terahertz, such as terahertz communication, terahertz detection, and terahertz generation, and enrich the application scenarios of this kind of research.

Suggestion 3: MXene materials are diverse, but most of the relevant research has focused on $Ti_3C_2T_x$.

Solution: The MXene material family consists of many members. Many of these material members have their unique properties, such as high density, controllable surface end groups, excellent mechanical properties, high electrical conductivity, 2D layered structures, etc. It is hoped that researchers can study and explore further the role of other representative MXene materials for terahertz applications, such as Ti_2C, Ti_3C_2, etc.

In the future, it is hoped that MXene and its composites can achieve greater terahertz modulation depth, enabling more flexible and high-performance terahertz shielding. We also expect MXene materials to be used on a large scale in the terahertz research areas. We hope that this review will guide future research and exploration of MXene materials for terahertz applications.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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