SYNTHESIS, CHARACTERIZATION AND PROCESSING OF NEW MATERIALS FOR INNOVATIVE APPLICATIONS
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MXene and dielectric polymer matrix: Energy storage applications

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ABSTRACT

Two-dimensional (2D) transition-metal carbides, nitrides, and carbonitrides, collectively called MXenes, represent an expanding class of functional materials with more than a dozen compositions synthesized. Their high electrical conductivity, tunable surface chemistry, and distinctive layered morphology show significant potential in energy storage, electromagnetic interference (EMI) shielding, electrocatalysis, plasmonics, and composite reinforcement. MXenes follow the general formula Mn+1XnTx, where M denotes an early transition metal, X represents carbon and/or nitrogen, and Tx corresponds to surface terminations such as –O, –OH, or –F. Prototypical examples include Ti_2CTx, Ti_3C_2Tx, and Nb_4C_3Tx. This review evaluates recent literature on MXene synthesis, structural configurations, and physicochemical properties. Comparative assessment of representative MXene phases is performed to explain the composition–structure–property relationships within the [MX]nM stacking framework. Recent findings demonstrate that MXenes exhibit high charge transport capability, active surface sites, and interlayer architectures conducive to ion intercalation and catalytic reactions. The combined effect between MXene surface terminations, structural anisotropy, and electronic characteristics enables targeted applications, redefining their status as promising next-generation functional materials. Major challenges include susceptibility to oxidation, batch-to-batch synthesis variability, and limited understanding of long-term environmental stability. This review aims to combine current advancements, identify unresolved scientific challenges and propose future strategies for optimizing MXenes for high-performance energy, catalytic, and composite technologies.

KEY WORDS

Mxene; Dielectric polymer; Electromagnetic interference (EMI) shielding; Metal carbides; Carbonitrides

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Introduction

Since the discovery of Ti_3C_2 in 2011, the class of two-dimensional (2D) transition-metal carbides, carbonitrides, and nitrides together known as MXenes has undergone substantial expansion and scientific scrutiny. Their layered architecture, high electronic conductivity, and chemically versatile surface terminations have set MXenes as an important platform within the broader landscape of emerging functional materials. This instant growth parallels the increasing demand for advanced materials capable of supporting next-generation electronic technologies.

In recent years, wearable and flexible electronics have faced accelerated development, encompassing foldable displays, smart textiles, and real-time biosensing devices. These systems require energy-storage technologies that combine mechanical flexibility with robust electrochemical performance [1]. Conventional storage devices are often structurally rigid, restricting their integration into deformable platforms. This encounter significant interest in flexible energy-storage systems, particularly flexible supercapacitors, where MXenes have demonstrated considerable promise owing to their high conductivity, hydrophilicity, and tunable interlayer spacing [2].

Approximately twenty distinct MXenes have been experimentally synthesized, while theoretical studies calculate the feasibility of many additional compositions. Advances in solid-solution engineering, surface termination control, and multi–transition-metal stacking continue to expand the MXene design space, enabling tailored property modulation. Their broad chemical compliance supports applications across lubrication, catalysis, energy storage, EMI shielding, water treatment, sensing, optical modulation, and composite reinforcement [3]. Moreover, MXenes shows attractive electronic, optical, plasmonic, and thermoelectric properties, featuring their potential as multifunctional materials for flexible and high-performance technological systems [4].

MXene Synthesis

MXenes are synthesized through selective etching of MAX phases, where A-element layers are removed from the stacked Mn+1Xn structures composed of transition-metal carbides or nitrides. These precursors usually possess a hexagonal close-packed framework. Due to the higher chemical reactivity of M–A bonds relative to M–X bonds, controlled and highly precise etching is necessary to obtain well-defined MXene layers with the desired structural and surface characteristics [5].

Energy Storage Capability of 2D Carbides

Batteries with Mxenes

M_2X MXenes are anticipated to demonstrate higher gravimetric capacities than other MXene compositions due to the strong M–X bonding, which inhibits structural disruption and upholds ion transport primarily through the MXene layers [6]. For example, Ti_2CTx shows a Li^+ uptake approximately 50% greater than synthesized Ti_3C_2Tx. Oxygen terminations generally yield superior electrochemical performance, whereas –OH and –F

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terminations are associated with lowered capacity and slower Li-ion diffusion. Studies on Ti_3C_2Tx have shown that the oxidation state of Ti varies continuously during charge–discharge processes; however, further decreases in potential do not induce additional changes in oxidation state [7, 8]. Instead, owing to their high electrical conductivity and 2D architecture, MXenes likely enable the reversible formation of an additional lithium layer, thereby enhancing capacity. Moreover, the ability of MXene interlayers to accommodate ions of varying radii broadens their applicability to non-lithium energy-storage systems. For Na^+ and other larger ions, the formation of a supplementary metal layer has been theoretically predicted to result in approximately doubled capacity [9].

MXene-based electrochemical capacitors

MXenes readily accommodate protons, the smallest cations, enabling efficient access to electrochemically active sites. They also exhibit excellent cycling stability; for example, Ti_3C_2Tx electrodes show no measurable capacitance loss even after 10,000 charge–discharge cycles [10]. In dielectric terms, ε_0 denotes the vacuum permittivity (8.85×10^{-12} F/m), while ε_r represents the relative permittivity of a material, reflecting its ability to store energy under an applied electric field. Polymers containing polar functional groups, such as PVA, can intercalate between Ti_3C_2Tx layers, preventing restacking and significantly enhancing the mechanical robustness of MXene films without compromising their electrochemical behavior [11]. Under cathodic (negative) potentials, MXenes demonstrate outstanding performance; however, application of positive potentials in aqueous electrolytes can induce irreversible oxidation, leading to increased resistance and reduced capacitance [12].

Applications of MXenes Beyond Energy Storage

The extensive chemical versatility and structural diversity of MXenes enable a wide range of potential applications across multiple technological domains. Among these, energy storage remains the most thoroughly investigated field, where MXenes have demonstrated exceptional performance. Nevertheless, their unique electronic, mechanical, and surface characteristics suggest that MXenes may surpass conventional materials in several additional application areas.

Polymer-based dielectrics with improved permittivity for energy storage

Polymer-based dielectric materials are emerging as promising alternatives to conventional ceramic and inorganic dielectrics, offering advantages such as enhanced mechanical flexibility, cost-effective and scalable processing, and favorable chemical stability. To be viable for advanced electronic applications, these materials must satisfy stringent criteria, including electrical, thermal, and environmental stability, low moisture uptake, high breakdown strength, minimal leakage current, low dielectric constant, low loss tangent, high glass transition temperature, and reduced surface roughness. However, a key limitation of polymer dielectrics remains their relatively moderate thermal stability, which constrains their performance and restricts their broader practical implementation [13].

Dielectric materials

When a metal body is exposed to an external electric field, free electrons redistribute to generate internal electric forces that counteract the applied field until the field within the conductor is effectively nullified [14]. This process results in the conduction of charge. In contrast, dielectric materials do not possess free charge carriers; instead, they permit the propagation of electric field lines by undergoing polarization. The term “insulator” generally refers to a material’s resistance to electrical conduction under strong electric fields, whereas “dielectric” describes its behavior under varying or moderate electric fields.

Dielectric materials play a critical role in modern electronic and power systems, particularly in the storage and regulation of electrical energy. In dielectric capacitors, energy is stored in the form of an electric field generated by the polarized alignment of electrons within atoms or molecules. Capacitance density, defined as capacitance per unit area, depends strongly on the dielectric layer thickness [15, 16].

The dielectric constant, κ, is expressed as the ratio of the electric field in vacuum (E_0) to the electric field within the dielectric (E):

$$k = E_0/E$$

Because E_0 is always greater than or equal to E, the dielectric constant is never less than 1. Here, ε_0 represents the vacuum permittivity (8.85×10^{-12} F/m), and ε_r denotes the relative permittivity of a material, which reflects its ability to store energy in an applied electric field.

Dielectric polymers

In the microelectronics industry, a range of polymers including epoxies, benzocyclobutenes, and polyimides are widely employed as dielectric materials through various coating and deposition techniques. Polymer-based dielectrics present both advantages and limitations. Most polymers exhibit paraelectric behavior, maintaining stable capacitance over broad temperature and frequency ranges. They also possess favorable mechanical properties, ease of processing, high dielectric breakdown strength, and low dissipation factors. Representative dielectric polymers include polypropylene, polyisobutylene, polyvinyl alcohol, and polymethyl methacrylate (PMMA) [17].

Different types of dielectric polymers

Low-k dielectric materials:

The development of low-k dielectric materials generally follows two primary strategies: (a) incorporation of fluorine and/or carbon to reduce the electronic contribution to polarizability, thereby lowering the intrinsic dielectric response; and (b) reduction of ionic and orientational polarization by decreasing the density of polarizable groups or introducing additional free volume within the material [18].

Organic dielectric materials inherently exhibit lower k values than inorganic counterparts due to their reduced polarizability and greater hydrophobicity. Low-k dielectric polymers must satisfy stringent electrical requirements, including an appropriate dielectric constant range, low dissipation factor, minimal leakage current, reduced charge trapping, high dielectric breakdown strength, and long-term reliability [19, 20].

Chemically, these materials must demonstrate controlled reactivity, low humidity absorption, minimal water solubility, low gas permeability, high chemical purity, minimal metal corrosion, extended shelf-life, and compliance with environmental safety standards.

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Mechanically, desirable properties include uniform thickness, strong substrate adhesion, low internal stress, minimal shrinkage, crack resistance, and high tensile modulus [21].

Thermal performance criteria encompass high thermal conductivity, robust thermal stability, low thermal mass loss, and a low coefficient of thermal expansion. Collectively, these properties ensure that low-k dielectric polymers can meet the demands of advanced microelectronic and semiconductor applications.

High-k dielectric materials:

High-k dielectric materials are essential for numerous advanced electronic applications due to their ability to enhance charge storage and reduce device dimensions. However, their implementation is accompanied by several challenges. A major limitation is charge trapping within pre-existing defect sites in the dielectric film, which can lead to instability in threshold voltage and degrade the performance of high-k gate stacks [22].

Dielectric composites of polymers

A composite material consists of two or more distinct constituent phases combined to function as an integrated system, thereby leveraging the advantageous properties of each component. For example, low-k polymers exhibit excellent stability and low leakage currents but typically require higher operating voltages, whereas high-k ceramic materials provide enhanced permittivity yet often lack the mechanical and electrical stability required for low-voltage applications [23]. This complementary behavior has motivated the development of polymer–ceramic dielectric composites, particularly for ultrahigh-k systems that also demand linear mechanical performance, including strong interfacial adhesion.

Additionally, three-phase percolative composites and polymer–conductive filler systems have been engineered using a variety of conductive additives such as silver (Ag), aluminum (Al), nickel (Ni), and carbon black. These fillers can be incorporated to tailor dielectric behavior, adjust percolation thresholds, and optimize electrical or mechanical performance for advanced electronic and energy-storage applications.

Composite dielectric polymers for power storage

Polymer composites incorporating ceramic or other high-permittivity fillers have demonstrated strong potential for use in pulse power storage systems requiring elevated energy densities. Studies, including those reported in The Journal of Electrochemistry, indicate that such composites can be engineered to balance high dielectric performance with mechanical and electrical reliability [24]. Fillers are typically introduced to enhance the effective dielectric constant of the composite while preserving the inherently high breakdown strength of the polymer matrix. A critical design requirement is that any increase in dielectric constant must not be accompanied by greater dielectric loss, as excessive energy dissipation would undermine overall storage efficiency.

Dielectric polymer nanocomposites

Nanocomposite dielectrics that integrate nano-ceramic fillers with polymer matrices have emerged as promising candidates for advanced electronic and power applications. These materials combine the high dielectric permittivity of ceramic phases with the superior breakdown strength and mechanical flexibility of polymers. As filler particles are reduced to the nanoscale, interfacial phenomena increasingly dominate the composite's overall behavior. The large surface-area-to-volume ratio of nanoscale fillers significantly enhances interfacial interactions, thereby influencing dielectric response, charge transport, and mechanical properties.

Nanocomposite materials consist of multiple constituents engineered to form nanoscale phases with distinct structural, chemical, and functional characteristics. They commonly involve organic matrices combined with inorganic nanoparticles, or vice versa, enabling tailored property enhancement unattainable in single-phase materials. Such nanocomposites offer a versatile platform for designing next-generation dielectric systems with improved energy density, stability, and performance [25].

Nanofillers

Nanofillers are defined as materials with at least one dimension below 100 nm. Their incorporation into polymer matrices enables nanocomposites to exhibit enhanced electrical, mechanical, magnetic, optical, and catalytic properties. Owing to their high surface-area-to-volume ratio, nanoparticles interact strongly with the surrounding matrix, producing large interfacial areas that improve stress transfer and functional performance. Examples such as carbon nanotube-based composites demonstrate significantly increased conductivity and modulus, while maintaining material ductility.

Modification of nanoparticles by organic coatings

Organic surface modification of nanoparticles can be achieved either by grafting short-chain molecules through covalent or strong hydrogen bonding interactions, or by polymerizing monomers directly onto the particle surface to form a polymer shell. These coatings enhance compatibility between the nanoparticles and polymer matrices by improving interfacial interactions and enabling controlled tuning of surface chemistry and adhesion strength.

Inorganic coatings

Inorganic surface coatings are applied to nanoparticles through methods such as sol–gel processing, precipitation, or physical adsorption of inorganic species onto the particle surface. These coatings enhance chemical stability, prevent oxidation, and improve compatibility with polymer matrices by providing a controlled and robust interfacial layer [26].

Nanodielectrics

Nanoscale fillers are incorporated into high-k dielectric composites to enable the fabrication of thinner dielectric films with enhanced specific capacitance. Such nanodielectrics combine the favorable processing simplicity and mechanical robustness of polymer matrices with the superior electrical, dielectric, and piezoelectric properties imparted by nanoscale constituents. This synergistic integration allows for improved performance in advanced electronic and energy-storage applications.

Dielectric elastomers

Dielectric elastomers are a class of highly flexible polymers capable of undergoing large, reversible deformations under mechanical or electrical stimuli. These materials typically possess dielectric constants in the range of 2–25 and include examples such as polyacrylates, polyurethanes, natural rubber, and chloroprene. Key performance attributes of dielectric elastomers include high strain capability, substantial actuation

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pressure, low density, high efficiency, and rapid mechanical response.

As polarizable insulating materials, dielectric elastomers can convert electrical energy into mechanical deformation when functioning as actuators, and conversely, transform mechanical input into electrical energy when operating in generator mode [27]. Their unique electromechanical coupling makes them suitable for a wide range of applications, including artificial muscles, conformal loudspeakers, tunable lenses, soft robotic systems, force and pressure sensors, active noise control components, and mechanical oscillators.

Table 1. Different features of some commonly used dielectric elastomers.

Dielectric elastomer	Dielectric constant	Electric field, V/um	Coupling efficiency %	Strain%	Young's modulus, MPa	Pressure, MPa	Elastic energy density, J/cm3
Silicone nusil CF19- 2186	2.8	235	54	32	1.0	1.36	0.22
Silicone DC HS3	2.8	72	64	41	0.125	0.13	0.026
Silicone DC Sylgard 186	2.8	144	54	32	0.7	0.51	0.082
Polyurethane Deerfield PT6100S	7.0	160	21	11	17	1.6	0.087
Fluorosilicone DC 730	6.9	80	48	28	0.5	0.39	0.055
Fluoroelastomer Lauren L143HC	12.7	32	15	8	2.5	0.11	0.0046
Isoprene natural Rubber	2.7	67	21	11	0.85	0.11	0.0059
SEBS161 Copolymer 5-30w% Midblock	1.7-2	133	80	Areal 180	0.007-0.163	-	0.151

Discussion

The convergence of MXene research with dielectric polymer and nanocomposite science presents a promising pathway for developing multifunctional materials capable of meeting the performance demands of advanced energy-storage and electronic systems. The dielectric behavior of polymer-based materials is strongly governed by chain morphology, molecular configuration, and interfacial interactions, all of which influence polarization mechanisms, breakdown strength, and long-term stability. Incorporation of nanoscale fillers can substantially enhance permittivity and energy density; however, these improvements are highly dependent on dispersion quality and the physicochemical characteristics of the filler–matrix interface [28, 29].

MXenes offer distinct advantages due to their layered structure, tunable surface terminations, and high electronic conductivity. Their ability to intercalate ions of various radii +and maintain excellent cycling stability makes them suitable candidates for flexible supercapacitors, embedded capacitors, and electromechanical components. Nonetheless, challenges such as oxidation susceptibility, variability in surface terminations, and processing limitations constrain their widespread technological adoption. Improved synthesis control, stabilization strategies, and interface engineering will be essential for enhancing MXene compatibility within dielectric systems.

In polymer nanocomposites, balancing increased permittivity with maintained breakdown strength remains a technical challenge, particularly near the percolation threshold of conductive fillers. Approaches such as multilayer architectures, core–shell filler designs, and targeted surface modifications have demonstrated potential for improving dielectric performance while minimizing losses.

Overall, synergistic integration of MXenes with polymer dielectrics holds significant potential for producing materials with high permittivity , enhanced mechanical robustness, and improved energy-storage capabilities. Continued research on scalable manufacturing, interfacial optimization, and long-term reliability will be critical for translating these advancements into practical device technologies [30].

Challenges and Future Perspectives

The long-term advancement of embedded capacitor materials is contingent upon overcoming several critical scientific and technological challenges. One major requirement is the design of ceramic–polymer nanocomposites incorporating high-k fillers, as well as conductive polymer composites engineered to operate near the percolation threshold without crossing into conductive regimes. Achieving this balance is essential for maximizing dielectric permittivity while maintaining low dielectric loss and high breakdown strength.

Microstructural refinement remains a central focus for future research. Enhancing polymer chain organization, minimizing structural defects, and precisely controlling filler dispersion are expected to significantly improve dielectric behavior and device reliability. Concurrently, the development and integration of inherently high-k polymer matrices could elevate composite dielectric constants while preserving desirable mechanical and thermal characteristics.

Interfacial engineering will continue to be a decisive factor in optimizing dielectric composites. Modification of filler surfaces—through functionalization, core–shell architectures, or tailored coupling chemistries—can improve compatibility with the polymer matrix, facilitate uniform dispersion, and reduce interfacial polarization effects. Such approaches are essential for mitigating dielectric depletion zones and ensuring uniform electric field distribution within the composite.

Looking forward, the convergence of advanced material synthesis techniques, predictive computational modeling, and scalable processing strategies will be crucial for translating laboratory-scale innovations into practical embedded capacitor systems. Progress in these areas will enable the development of

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high-performance, miniaturized, and durable dielectric components required for next-generation electronic and energy-storage technologies.

Conclusions

The dielectric performance of polymer composites is strongly governed by the morphology, microstructure, and chain configuration of the polymer matrix. Several key challenges and considerations remain in advancing these materials for high-performance dielectric applications. First, the design of polymers with tailored substitution patterns and controlled microstructures remains a major scientific and engineering obstacle. Pure polymer systems must simultaneously achieve appropriate permittivity, low dielectric loss, and high breakdown strength. Because energy-storage performance is closely correlated with filler concentration, systematic studies on composites combining non-ferroelectric polymers with inorganic fillers are essential for the development of next-generation capacitor dielectrics. Second, the physicochemical properties of nanoparticles exert substantial influence on the final dielectric behavior of polymer nanocomposites. However, the complexity of polymer–nanoparticle interactions limit the predictive capability of existing theoretical models, particularly when nanometer-scale components are incorporated. Third, core–shell filler architectures represent an effective approach for enhancing interfacial adhesion and promoting uniform dispersion of inorganic fillers within polymer matrices. Appropriate surface modification strategies can further strengthen polymer–filler compatibility and improve dielectric stability. Finally, multilayer composite architecture offers a promising pathway for achieving high-k performance through rational structural design. Optimizing functional layering and filler arrangement within these architectures will be essential for advancing dielectric materials with superior energy-storage capabilities and reliability.

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