Future Molecular Science

Smart Electromagnetic Interference Shielding Materials: From Static Protection to Dynamic and Adaptive Electromagnetic Regulation

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Abstract

The rapid development of 5G/6G communications, artificial intelligence, and aerospace technologies has created increasingly dynamic electromagnetic environments, challenging conventional static electromagnetic interference (EMI) shielding materials. Smart EMI shielding materials provide a promising approach to adaptive electromagnetic protection by dynamically regulating electromagnetic transmission, reflection, and dissipation in response to external stimuli. This Perspective discusses recent progress in mechanically, thermally, and electrically regulated EMI shielding materials, with emphasis on their underlying mechanisms and limitations. Despite these advances, most reported systems rely on predefined stimulus–response relationships and remain unable to adapt autonomously to changing environments. Future opportunities lie in integrating multiple stimuli, environmental adaptation, artificial intelligence, bioinspired architectures, and programmable structures to achieve more precise and versatile electromagnetic regulation. Such developments could shift EMI shielding from passive protection with fixed attenuation toward adaptive electromagnetic management for next-generation communication, electronic, and aerospace technologies.

1 Introduction

The rapid development of 5G/6G communications, artificial intelligence-enabled electronics, aerospace technologies, and advanced radar systems has dramatically increased the complexity of electromagnetic interference (EMI).[1-3] Unlike conventional electromagnetic environments dominated by continuous signals within limited frequency ranges, modern electronic systems are exposed to broadband, multi-source, time-varying, and strongly coupled electromagnetic radiation.[4-6] Such increasingly complex electromagnetic environments not only compromise signal integrity and data security but also induce crosstalk, false triggering, and even functional failure of electronic devices, posing substantial risks to safety-critical applications, including aerospace, healthcare electronics, and defense systems.[7] Consequently, high-performance EMI shielding materials have become indispensable for mitigating electromagnetic pollution and ensuring the reliable operation of next-generation electronic infrastructures.

Conductive EMI shielding materials have long served as the cornerstone of electromagnetic protection.[8-10] Their shielding capability primarily relies on constructing continuous conductive networks using metals or highly conductive fillers, such as metal foils, graphene, carbon nanotubes (CNTs), MXenes, and polymer-based conductive composites, to reflect incident electromagnetic waves.[11-13] These materials generally exhibit excellent shielding effectiveness under relatively simple electromagnetic conditions while benefiting from mature fabrication technologies and scalable manufacturing.[14] However, their shielding mechanism is inherently dominated by reflection, whereby most incident electromagnetic energy is reflected at the material surface rather than dissipated within the material, inevitably leading to undesirable secondary electromagnetic pollution.[15] To address this limitation, increasing attention has been devoted to structural loss-dominated shielding materials through multi-interface polarization, micro-/nanostructural engineering, and hierarchical conductive network design.[16] Representative strategies, including porous architectures, hollow structures, multilayer interfaces, and heterogeneous functional fillers, prolong electromagnetic wave propagation paths and enhance interfacial scattering and energy dissipation, thereby effectively improving electromagnetic attenuation while suppressing excessive reflection.[17-20]

Despite these significant advances, existing EMI shielding materials remain fundamentally static systems, whose electromagnetic responses are predetermined once fabricated.[21,22] Their shielding performance is therefore fixed and highly dependent on specific frequency bands, making them incapable of adapting to frequency shifts, dynamic communication channels, or rapidly evolving electromagnetic environments.[23] Such intrinsic

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limitations have become increasingly incompatible with the demands of modern intelligent electronic systems, where electromagnetic conditions continuously change over time and space.[24,25]

Looking forward, the development of EMI shielding materials should move beyond the conventional pursuit of higher shielding effectiveness toward smart materials capable of dynamically regulating electromagnetic behavior.[26] Against this backdrop, smart EMI shielding materials have emerged as a promising next-generation strategy. In this Perspective, smart EMI shielding materials are defined as materials whose shielding performance can be dynamically and reversibly regulated by external stimuli. Unlike conventional multifunctional materials, structural tunability or functional integration alone does not qualify a material as a smart EMI shielding material unless it enables stimulus-driven, reversible regulation of shielding performance. By actively manipulating the transmission, impedance matching, and dissipation of electromagnetic energy in response to external stimuli, these materials enable dynamically adjustable shielding performance and provide new opportunities for precise electromagnetic management in increasingly complex electromagnetic environments.

2 Strategies for Smart EMI Shielding Materials

Driven by increasingly complex electromagnetic environments, EMI shielding is shifting from passive protection toward dynamic regulation.[27-29] Smart EMI shielding materials can respond to external stimuli such as mechanical force, temperature, and electric fields, enabling reversible changes in conductive networks, magnetic components, and multiscale interfaces. These structural and physicochemical changes alter the electromagnetic parameters and wave propagation behavior of the materials, thereby providing dynamic control over shielding performance.[30,31] Based on the applied stimulus and the corresponding regulation mechanism, current smart EMI shielding strategies can be divided into mechanically, thermally, and electrically driven systems (Figure 1).

3 Force-driven Switch

Force-driven regulation is an effective approach to dynamically tuning EMI shielding performance by mechanically altering the internal structure of shielding materials.[32-34] Compression, stretching, bending, and rotation can change the contact between conductive components, pore structure, and filler orientation, resulting in changes in electrical conductivity and electromagnetic propagation.[35,36] The shielding response is therefore closely related to the structural evolution induced by mechanical deformation.

Compression is particularly effective for porous shielding materials because the conductive network can be readily reconstructed through changes in the distance and contact between conductive components. In carbon aerogels and graphene-based foams, compression reduces the pore size and inter-filler distance, increasing conductive contacts within the network.[37]

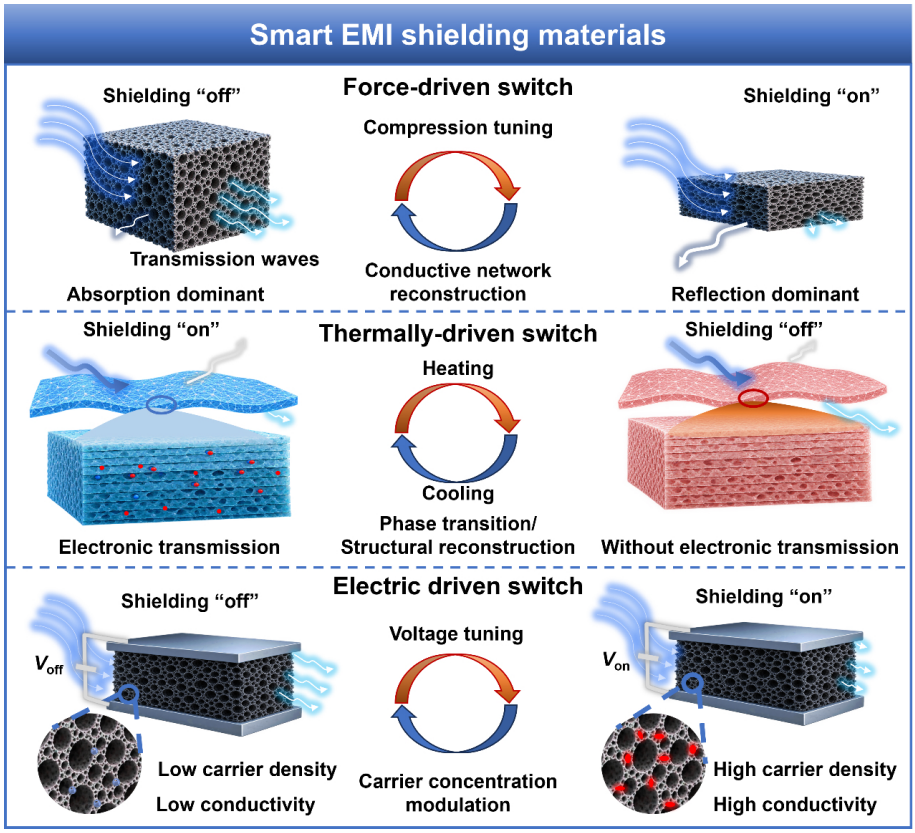

Figure 1 Schematic illustration of the adjustable mechanism of smart EMI shielding materials.

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The reduced pore dimensions can also increase the probability of multiple scattering and interfacial polarization, which contributes to electromagnetic attenuation. As a result, the shielding effectiveness can be reversibly tuned over a range of 58–80 dB by varying the compression strain, enabling transitions between relatively weak and strong shielding states (Figure 2a–2c).[38] In these systems, the extent of shielding is determined by the combined effects of network connectivity and the porous architecture, rather than by conductivity alone.

Mechanical rotation provides another means of regulating shielding through the anisotropic structure of the material. In carbon nanotube textiles and wood-derived composites, the orientation of conductive pathways relative to the incident electromagnetic field determines the electrical anisotropy and consequently affects electromagnetic propagation through the material. Changing the orientation or rotation angle can therefore produce distinct shielding responses, with the shielding effectiveness reversibly tunable from 18 to 42 dB and instantaneously adjusted during rotation (Figure 2d–2e).[39] This type of regulation is different from compression-induced switching, as the primary variable is the spatial orientation of the conductive network rather than its overall connectivity. It thus provides a means of controlling the direction-dependent electromagnetic response of anisotropic shielding materials.

Stretching can further be used to continuously regulate shielding performance in flexible conductive composites.[40-42] Tensile deformation increases the separation between conductive domains and can partially disrupt the conductive network. Upon releasing the strain, the conductive pathways can be re-

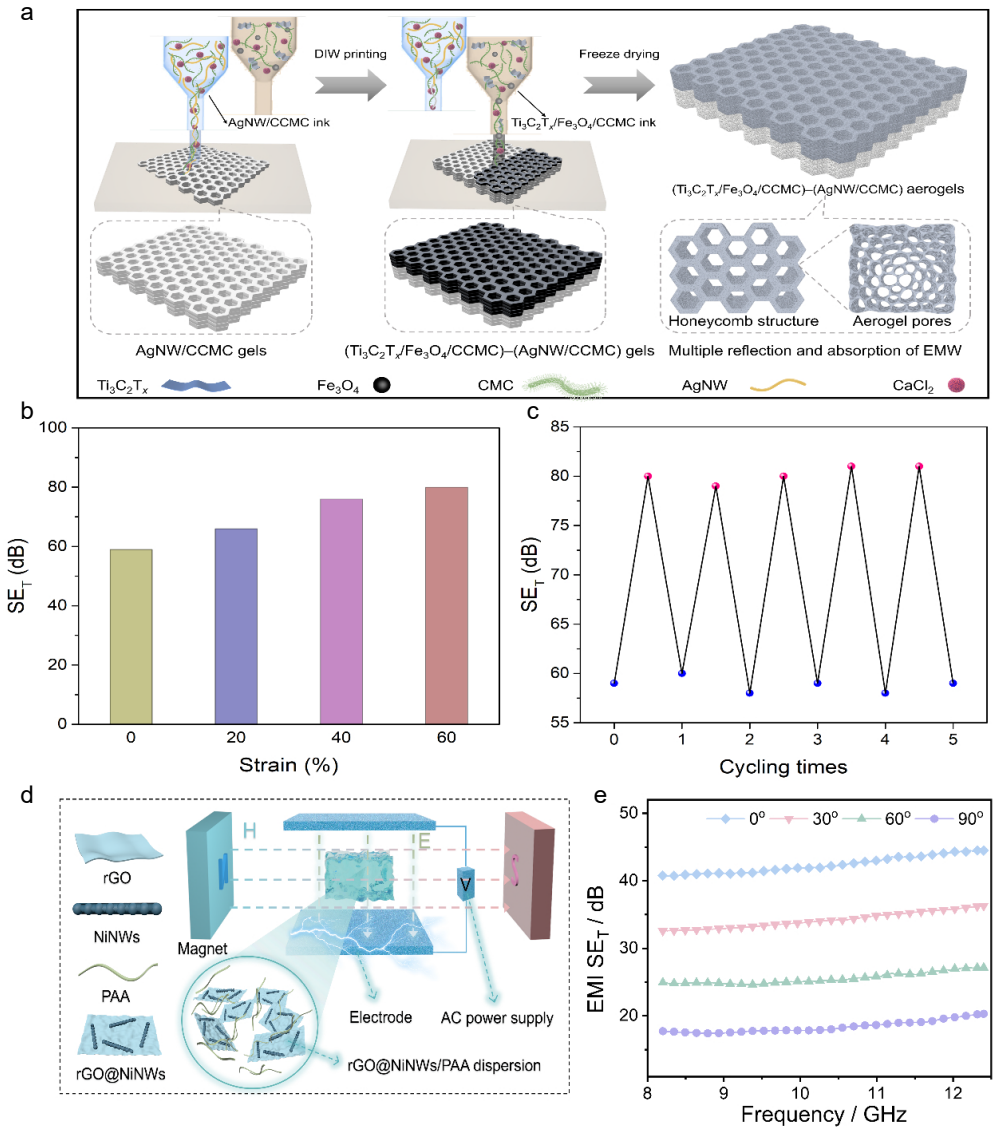

Figure 2 **Force-driven smart switchable EMI shielding material.** a, Schematic illustration for fabricating $(Ti_3C_2T_x/Fe_3O_4/CCMC)$–(AgNW/CCMC) aerogels. b, Total shielding effectiveness (SE_T) value of the aerogel with different strains. c, SE_T value of the aerogel under repeated application of 60% compressive strain. Adapted with permission. Copyright 2025, Wiley.[38] d, Schematic illustration for preparation of rGO@NiNWs/PI aerogels. e, SE_T of rGO@NiNWs/PI aerogels at various angles between the rGO's oriented direction and the alternating electric field of incident EMWs. Adapted with permission. Copyright 2026, Wiley.[39]

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established, depending on the structure and interactions within the network. The associated changes in electrical conductivity affect electromagnetic attenuation and can lead to continuous variation in shielding effectiveness. In some systems, deformation also changes the relative contributions of reflection and absorption, allowing the electromagnetic response to be adjusted over a range of strain rather than through a simple on/off transition. Such behavior is particularly relevant to flexible shielding materials that undergo deformation during service.

These studies demonstrate that mechanical deformation can regulate EMI shielding through several distinct structural mechanisms, including conductive-network reconstruction, pore-structure evolution, and orientation-dependent transport. The resulting changes in electromagnetic response depend strongly on the initial architecture and the reversibility of the structural changes. A large shielding modulation generally requires substantial structural rearrangement, whereas repeated deformation may cause network damage, interfacial slippage, or mechanical fatigue. In addition, force-driven regulation requires an external mechanical input and is therefore less suitable when continuous or autonomous switching is required. Future development should consequently focus on reducing the deformation required for effective electromagnetic modulation, while improving the reversibility and durability of the underlying conductive network.

4 Thermally Driven Switch

Thermally driven regulation provides a non-contact route for tuning EMI shielding performance.[43,44] Temperature changes can modify the electronic state, phase structure, or morphology of a shielding material, which in turn affects its electrical transport and electromagnetic response.[45] Compared with mechanical deformation, thermal stimulation does not require direct physical contact or macroscopic deformation of the shielding layer, making it suitable for systems in which the operating temperature can be readily controlled or naturally varies during service.[46]

One important class of thermally responsive materials relies on reversible phase transitions. Vanadium dioxide (VO_2) is a representative example, undergoing a reversible transition between an insulating monoclinic phase and a metallic tetragonal phase with increasing temperature.[47] The associated changes in electrical conductivity and dielectric properties alter the interaction between the material and incident electromagnetic waves, allowing its EMI shielding effectiveness (SE) to be tuned from 19 to 54 dB over a temperature range of 25–80 °C (Figure 3a–3d).[48] The transition temperature and electromagnetic response can be further modified through compositional and interfacial engineering. For example, heterostructure construction and elemental doping have been used to adjust the phase-transition characteristics and interfacial electromagnetic interactions, providing additional control over the temperature-dependent shielding behavior.[49]

Thermal regulation can also be achieved without relying on an electronic phase transition. In thermally expandable or contractive systems, temperature changes induce changes in volume, phase state, or the spatial arrangement of conductive components. Ionic liquids, liquid metals, and liquid crystal elastomers provide representative examples in which thermal stimulation can drive changes in conductive pathways or macroscopic structure.[50] Such structural changes alter the electrical connectivity and electromagnetic propagation within the material, resulting in a temperature-dependent shielding response, with ΔSE reaching 16 dB over a temperature range of 25–45 °C (Figure 3e–3g).[51] Phase-transition hydrogels represent another emerging platform in which temperature-induced changes in the polymer network and conductive pathways can be used to switch the shielding state. In addition, incorporating conductive and magnetic components into thermally responsive structures introduces multiple electromagnetic loss processes and provides further possibilities for controlling electromagnetic attenuation.[52]

The main advantage of thermal regulation lies in its non-contact operation and compatibility with materials that undergo intrinsic thermal transitions during service. However, the electromagnetic response is closely tied to the kinetics and reversibility of the underlying thermal process. A narrow transition temperature range restricts the usable operating window, whereas thermal hysteresis can lead to different shielding states during heating and cooling. Heat transfer through polymer matrices and porous structures can also limit the response rate, particularly for relatively thick shielding layers. These factors make it difficult to simultaneously obtain a broad operating temperature range, rapid switching, and stable cycling. Further progress will require better control of transition temperatures and hysteresis, together with improved heat-transfer characteristics and structural stability.

5 Electrically Driven Switch

Electrical regulation provides a direct means of changing the electromagnetic response of conductive and electroactive materials through an applied voltage or electric field.[53,54] Depending on the material and device configuration, electrical stimulation can modify carrier concentration, charge distribution, ion concentration, or dielectric properties, leading to changes in electrical transport and electromagnetic attenuation.[55] Unlike mechanically driven systems, electrical regulation does not require macroscopic deformation, while its response can be controlled by the applied voltage and therefore integrated with electronic control systems.

Two mechanisms have been explored in electrically responsive EMI shielding materials. The first involves the modulation of charge carriers in conductive materials. MXenes, graphene, and other two-dimensional conductors can exhibit changes in electrical transport when their carrier concentration or interfacial charge state is modified.[56,57] Such changes affect the conductivity and electromagnetic interaction of the shielding layer, providing a means of tuning the shielding response. The second mechanism involves electrochemical or dielectric regulation, in which ion intercalation, electric-double-layer formation, or voltage-induced changes in dielectric properties modify the electro-

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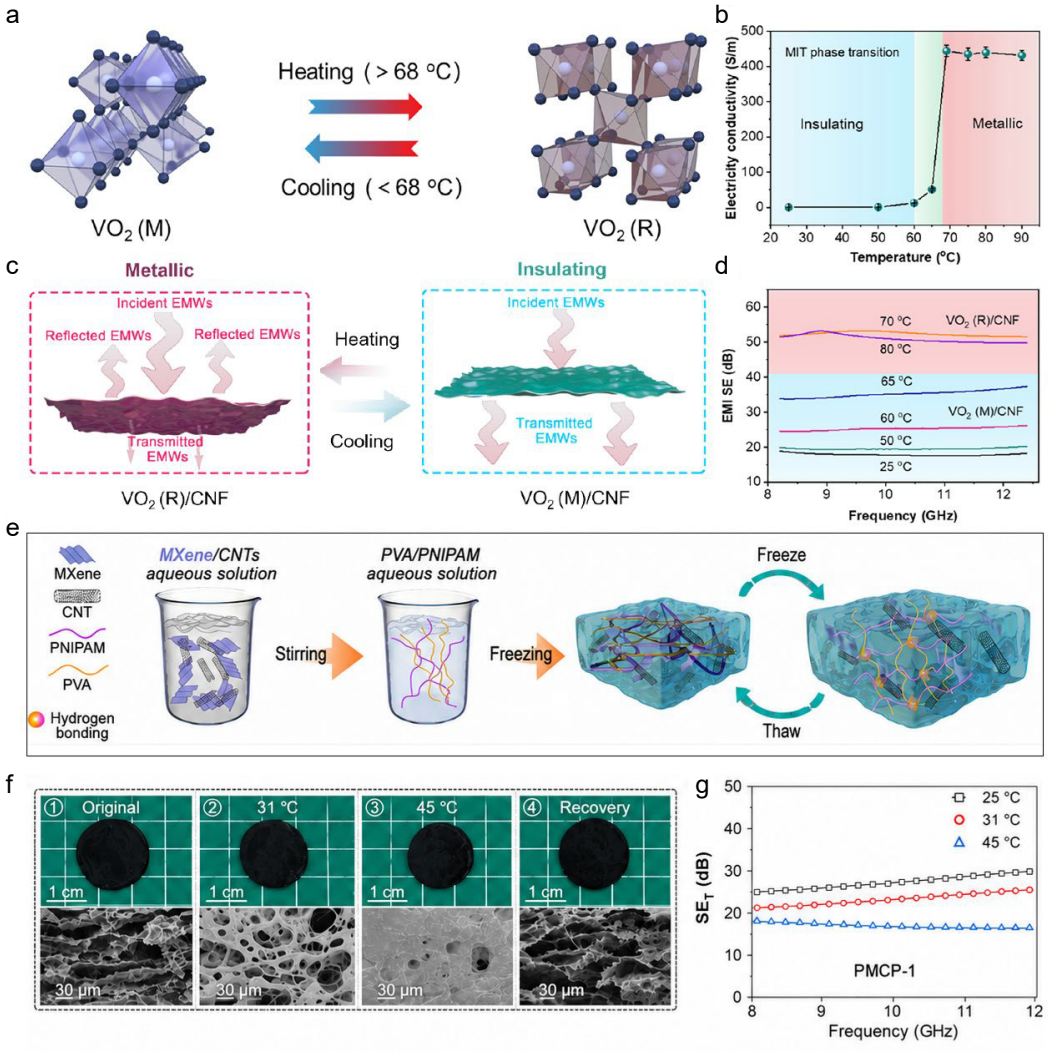

Figure 3 **Thermally-driven smart switchable EMI shielding material.** a, Schematic of the reversible phase transition between insulating monoclinic phase M and metallic tetragonal phase R. b, Electrical conductivity of VO_2/CNF composite film as a function of temperature. c, Schematic illustration of reversible characteristic of VO_2/CNF film, showing the transformation between the metallic and insulating states under heating and cooling. d, EMI SE of VO_2/CNF composite film at different temperatures. Adapted with permission. Copyright 2023, Elsevier B.V.[48] e, Schematic illustration of preparation process for PMCP hydrogel. f, Optical photographs of hydrogels and SEM images of the cross-section at different temperatures. g, SE_T of the 2 mm-thick PMCP hydrogels at different temperatures. Adapted with permission. Copyright 2025, Wiley.[51]

magnetic response of the material.[58] Electrochemically modulated MXene systems, for example, have demonstrated substantial changes in EMI shielding with applied potential, accompanied by changes in the structure and chemical state of the material. The EMI SE of V_2CT_x can be reversibly tuned over a range of approximately 6 dB, with a switching time of 10 s and remains stable over 500 cycles. By comparison, $Ti_3C_2T_x$ exhibits a reversible EMI SE modulation range of approximately 4 dB (Figure 4).[59] These results indicate that electrical stimulation can regulate shielding through changes in both charge transport and the internal state of the shielding material.

Electrical regulation is also attractive because the applied voltage can, in principle, be precisely controlled and readily incorporated into electrically driven devices. Electrically gated structures have therefore been investigated for dynamic electromagnetic modulation over different frequency ranges, while multilayer architectures and electrolyte-assisted gating provide additional control over the accessible electromagnetic response.[60,61] However, these systems generally require electrodes, electrolytes, dielectric layers, or other auxiliary components, which increases device complexity and places greater demands on interfacial stability and encapsulation. The response rate can also be affected by ion transport and electrochemical kinetics, particularly when the regulation mechanism involves ion migration or intercalation.[62] In addition, the mechanisms governing electromagnetic response are strongly frequency dependent, and a regulation strategy effective in one frequency range cannot necessarily be extended directly to broadband electromagnetic waves. Improving switching speed, reducing device complexity, and achieving stable and reversible regulation over broader frequency ranges therefore remain important issues for electrically driven EMI shielding. Repeated electrical switching may further affect the long-term stability of these materials. Depending on the regulation mechanism, ion redistribution, irreversible electrochemical reactions, or changes at electrode–material interfaces may lead to gradual variations in electrical conduc-

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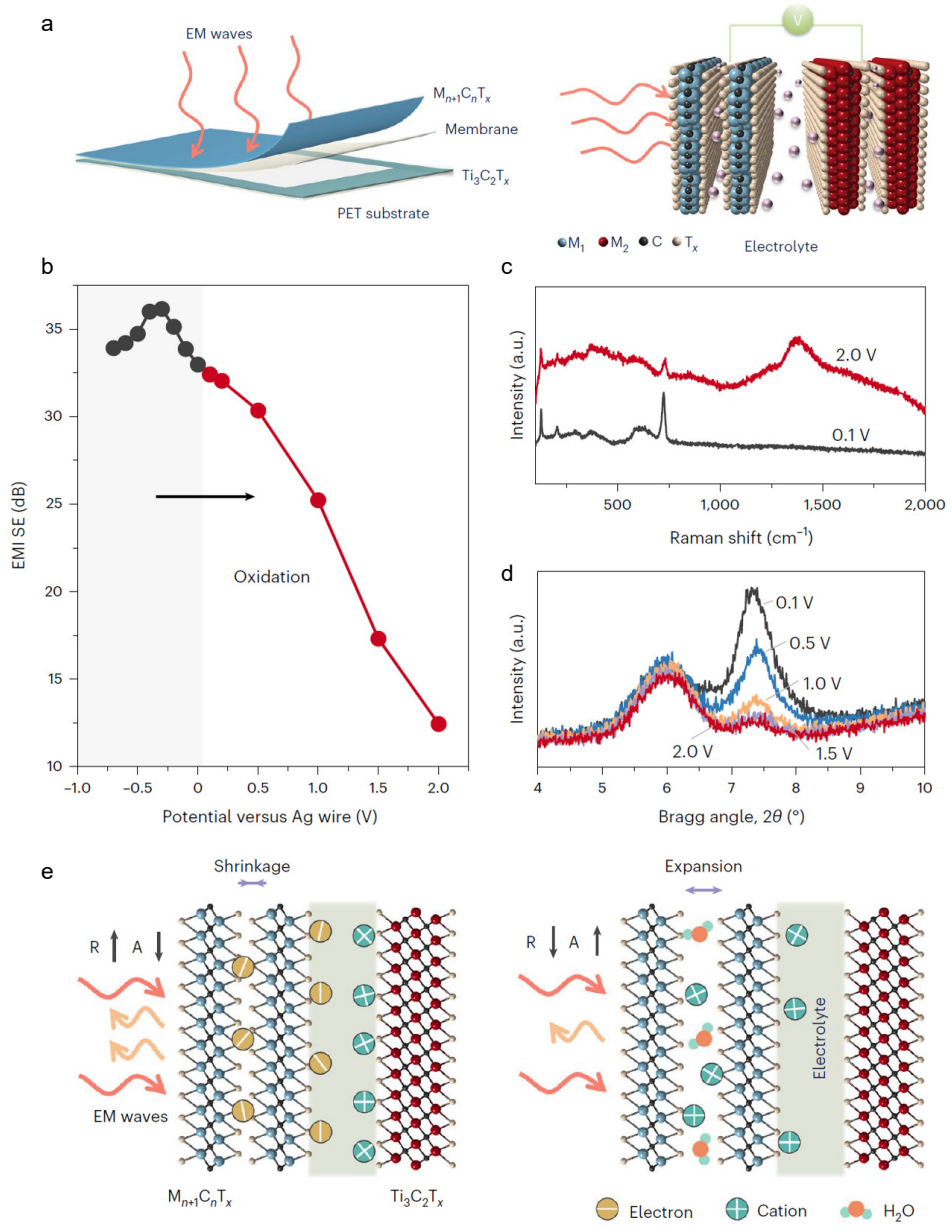

Figure 4 **Electric-driven smart switchable EMI shielding material.** a, Schematic illustration of the shield and ion intercalation between MXene layers for tuning EMI shielding. b, Potential-dependent EMI SE of the MXene electrode in 1 M H_2SO_4, showing the decrease in electromagnetic protection by about 350 times from 0.1 V to 2 V. c, In situ Raman and d, X-ray diffraction analyses of the film oxidation process. e, Illustration of the mechanisms for electrochemically modulated EMI shielding. Adapted with permission. Copyright 2023, Springer Nature.[59]

tivity and shielding effectiveness. Evaluating cycling stability, switching reversibility, and shielding performance retention is therefore essential for assessing their long-term reliability and practical applicability.

Table 1 summarizes the key advantages and limitations of force-, thermal-, and electrically driven regulation strategies, highlighting their differences in regulation mechanisms, controllability, and practical implementation.

6 Conclusion and Outlook

Smart EMI shielding materials have demonstrated the feasibility of dynamically regulating electromagnetic shielding through mechanical, thermal, and electrical stimuli. Depending on the material system, these stimuli can modify conductive pathways, phase states, carrier transport, or interfacial polarization, thereby altering the electrical, dielectric, and magnetic properties that govern electromagnetic transmission, reflection, and absorption. This dynamic regulation provides a means of adapting shielding performance to changing operating conditions, beyond the fixed attenuation characteristics of conventional shielding materials. However, most reported systems remain based on predefined stimulus–response relationships, and the connections between stimulus, structural evolution, electromagnetic parameters, and shielding response are often established qualitatively. Quantitative understanding of modulation depth, response and

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recovery kinetics, energy consumption, and cycling stability remains limited. Establishing these relationships will be essential for rationally designing materials with predictable and reproducible electromagnetic switching behavior.

(1) An important direction is the regulation of shielding performance under multiple and coupled stimuli. In practical environments, temperature, mechanical deformation, humidity, and electromagnetic fields may vary concurrently, whereas most reported systems are designed to respond predominantly to one type of stimulus. Such coupling can simultaneously modify conductive connectivity, interfacial polarization, and dielectric or magnetic loss, making the resulting electromagnetic response difficult to predict. Simply combining several responsive components does not necessarily provide independent control, because interactions between their response mechanisms may introduce competing or synergistic effects. A more effective approach would be to spatially or hierarchically organize different responsive units so that individual stimuli act preferentially on specific structural or electromagnetic functions. This could provide separate or coordinated control of conductive transport, polarization, and dissipation, and consequently enable regulation of both shielding level and reflection–absorption balance under varying service conditions.

(2) Thermal regulation may offer an additional degree of freedom when the shielding response needs to be correlated with the thermal environment. Rather than treating temperature only as a stimulus for a global change in material state, the spatial and temporal characteristics of thermal regulation deserve greater attention. Localized heating, thermal gradients, and thermally confined responsive regions could enable different parts of a shielding structure to adopt different electromagnetic states, while the thermal history may determine the rate and reversibility of the transition. Such spatially selective regulation is particularly relevant to devices with nonuniform electromagnetic or thermal loads, where global switching may be unnecessary or even undesirable. Coupling thermal transport with the spatial distribution of electromagnetic attenuation could therefore provide a route to thermally regulated shielding with greater control over where and when the shielding state changes.

(3) The transition from externally triggered switching to self-adaptive regulation represents a further development of smart EMI shielding. In current systems, the shielding state is generally determined by a prescribed external stimulus rather than autonomously adjusted according to the surrounding electromagnetic environment. A self-adaptive system would require a coupling between environmental sensing and reversible modulation of electromagnetic properties. Changes in electromagnetic intensity, temperature, deformation, or other service conditions could provide input signals, while reconstruction of conductive pathways, phase evolution, or carrier redistribution could generate the corresponding shielding response. Practical implementation, however, requires reliable integration of sensing, shielding regulation, and feedback control. Key challenges include minimizing electromagnetic interference between sensing and regulation, maintaining reliable feedback under varying operating conditions, and ensuring stable and reproducible shielding responses during repeated operation. Integration of sensing, responsive materials, and control elements within a common architecture may provide a basis for maintaining an appropriate shielding state as the service environment changes.

(4) The increasing complexity of material composition and architecture also provides an opportunity for data-driven design of dynamic shielding systems. The shielding response is governed by interdependent variables, including filler content and distribution, network connectivity, pore structure, thickness, electrical conductivity, dielectric and magnetic properties, and stimulus conditions. For dynamic systems, these variables need to be correlated not only with shielding effectiveness but also with frequency-dependent reflection and absorption, modulation amplitude, response and recovery time, and cycling stability. Establishing consistent datasets containing both structural descriptors and electromagnetic responses would enable machine-learning methods to identify relationships that are difficult to establish through conventional parameter-by-parameter experiments. For example, machine-learning models could predict frequency-dependent shielding effectiveness and modulation amplitude under different stimulus conditions based on material composition, network architecture, thickness, and electrical properties. Conversely, data-driven inverse-design approaches could identify suitable material compositions and structural configurations to achieve predefined shielding modulation ranges at target frequencies. Combined with electromag-

Table 1 **Comparison of representative strategies for dynamically regulating EMI shielding performance.**

Regulation strategy	Main mechanism	Advantages	Limitations
Mechanical regulation	Reconstruction of conductive networks, pore structures, or filler orientation	Direct regulation, suitable for flexible and deformable materials	Requires mechanical input, repeated deformation may cause fatigue or structural damage
Thermal regulation	Phase transitions, thermal expansion, or temperature-dependent changes in conductivity	Non-contact regulation, can utilize environmental or externally supplied heat	Limited by heat-transfer rates, thermal hysteresis, and operating temperature windows
Electrical regulation	Carrier modulation, charge redistribution, or electrochemical processes	Precise electrical control, compatible with electronic control systems	May require electrodes or electrolytes, affected by electrochemical kinetics and interfacial stability

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netic simulations, experimental validation, and iterative optimization, these approaches could reduce empirical trial-and-error and provide a more quantitative basis for designing smart EMI shielding materials with tailored dynamic responses.

(5) Programmable architectures provide another route to controlling electromagnetic behavior through structural rather than solely compositional changes. Reconfigurable conductive networks, periodic grids, and metasurface-inspired architectures can modify current distribution, electromagnetic coupling, and impedance through changes in geometry or spatial arrangement. This structural degree of freedom could extend dynamic shielding from modulation of shielding effectiveness to control of frequency-dependent, polarization-dependent, or direction-dependent attenuation, while also providing opportunities to regulate the relative contributions of reflection and absorption. The central issue is to couple such electromagnetic functions with reversible structural changes while retaining mechanical integrity and fabrication compatibility. In this regard, deformable conductive networks and shape-changing polymer composites provide promising platforms. However, repeated reconfiguration may compromise structural integrity and lead to variations in electromagnetic performance. Establishing quantitative relationships between structural parameters, deformation states, and frequency-dependent shielding responses, while ensuring mechanical stability and reproducible performance over repeated cycles, remains essential for predictable electromagnetic regulation.

Overall, the development of smart EMI shielding materials is shifting the focus from achieving a fixed shielding effectiveness toward controlling electromagnetic transmission and dissipation under changing conditions. A possible development trajectory is from single-stimulus switching to coordinated regulation under multiple stimuli and, ultimately, to adaptive control of the shielding state according to the service environment. Progress along this trajectory will require advances in responsive materials, hierarchical structural design, electromagnetic modeling, and sensing and feedback technologies. At the same time, the performance of dynamic shielding materials should be evaluated using parameters beyond a single shielding-effectiveness value, including modulation range, response and recovery kinetics, energy consumption, operating bandwidth, reflection–absorption characteristics, and long-term cycling stability. These considerations will provide a more complete basis for assessing dynamic shielding systems and may facilitate their integration into communication electronics, flexible devices, and aerospace platforms operating under variable electromagnetic and environmental conditions.

Competing Interests

The authors declare no competing financial or non-financial interests.

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