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Highlight

Ultrathin conformal EMI shielding via embedded-MXene-in-metal heterostructure films

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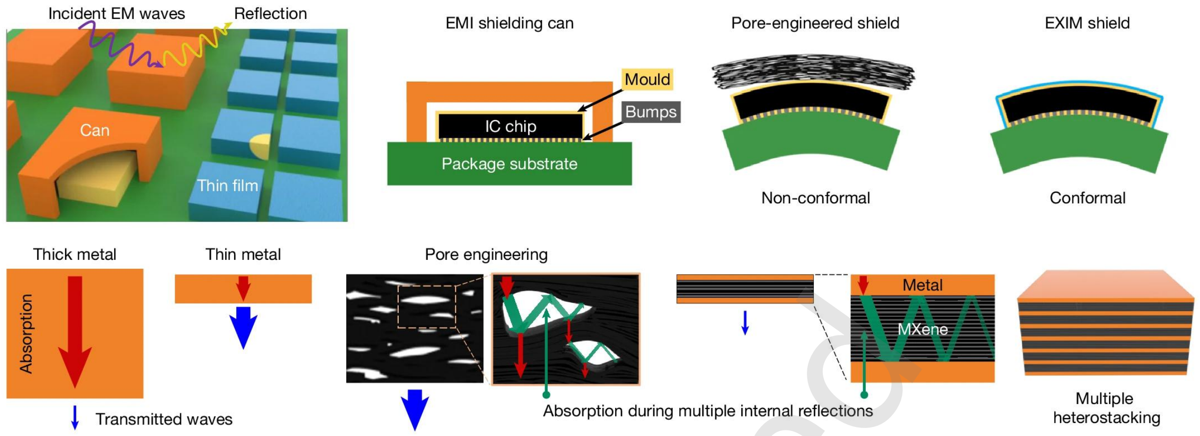

This manuscript highlights a transformative EXIM heterostructure thin film published in 2025 Nature, which achieves ultrathin, conformal, high-performance EMI shielding by leveraging polarization and ohmic loss at metal-MXene heterointerfaces to break the classic thickness-shielding effectiveness trade-off.

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Abstract: Conventional metal electromagnetic interference (EMI) shielding cans suffer from low conformability, thickness- performance trade- offs, and incompatibility with advanced packaging processes. MXene nanosheets demonstrate significant potential for EMI shielding; however, they suffer from low environmental stability and bottlenecks related to film thickness. In 2025, Kang et al. published a work in Nature that overcomes thickness limitation through an embedded-MXene-in-metal shielding non-porous ultrathin structure, achieving remarkable shielding effectiveness of 70 dB and 80 dB at respective thickness of 1 μm and 1.9 μm in the X-band. The work resolves the longstanding thickness-performance dilemma in EMI shielding and provides conformal protection for USB 3.0 flash drives and flexible Schottky diodes.

The rapid evolution of 5G/6G communications, wearable electronics, and integrated circuits imposes stringent demands on electromagnetic interference (EMI) shielding. Traditional bulky metal shielding cans are ill-suited for miniaturized and irregular chip surfaces. Conversely, porous MXene-based materials often suffer from low conformability, structural heterogeneity, and limited process compatibility (Figure 1) [1,2]. Despite achieving high shielding effectiveness (SE) in recent MXene composites, significant challenges remain, such as oxidation instability, thickness-dependent performance, and hurdles in scalable manufacturing [3,4].

In 2025, Kang et al. proposed an embedded-MXene-in-metal (EXIM) heterostructure employing non-porous MXene thin films and alternating high-conductivity metal layers [5]. This design achieves ultrathin, conformal, and high-performance EMI shielding, effectively eliminating the reliance on conventional porous engineering and overcoming the long-standing thickness-performance trade-off in thin-film EMI shields. The innovation of the EXIM architecture utilizes the conductivity mismatch at metal-MXene heterointerfaces to serve as electromagnetic wave confinement barriers. Unlike traditional pore-scattering mechanisms, the energy dissipation is driven by substantial polarization loss, stemming from interfacial dipoles and ohmic effects. This ultrathin, pore-free EXIM design achieves exceptional SE while preserving its nanoscale layered architecture. Furthermore, the architecture exhibits outstanding flexibility and mechanical durability. Particularly, a 1-μm-thick EXIM film achieves an SE of approximately 70 dB, while a 1.9-μm-thick film reaches nearly 80 dB in the X-band. Both values exceed the 60 dB benchmark for military-grade EMI shielding. Notably, SE is more dependent on the number of metal-MXene heterointerfaces than on the total thickness of the film, marking a significant departure from conventional material design principles [6,7]. To address environmental instability, a compact, self-passivating Cr-Al oxide capping layer is incorporated to effectively prevent oxygen and moisture ingress into the MXene layers. Even after aging for 420 hours at 105°C, or for 48 hours at 85°C with 85% relative humidity, the shielding performance remains consistent. By introducing this self-passivating layer, the proposed design successfully overcomes the longstanding reliability limitations inherent to MXene-based shielding materials.

From a physical mechanism perspective, the microscopic origins of the exceptional EMI shielding performance were elucidated via multiscale simulations and advanced structural analyses. The substantial electrical conductivity contrast between metals (~380×10^3 S cm^{-1}) and MXene (~3.6×10^3 S cm^{-1}) establishes strong electromagnetic wave confinement at their interfaces. Within the MXene layers, these confined waves undergo multiple internal reflections and resonance-induced attenuation. Simultaneously, interfacial dipoles induced by adhesion promoters interact with electromagnetic fields, generating polarization loss. Additional energy dissipation arises from electron tunneling across van der Waals gaps and conductive networks, which contributes to further ohmic loss. This attenuation mechanism yields absorption-dominated shielding with minimal secondary electromagnetic pollution, making it ideal for protecting high-precision electronic systems. Notably, increasing the number of metal-MXene heterointerfaces enhanced the SE in a nearly linear manner. This finding offers a distinct engineering strategy for optimizing shielding performance while minimizing material volume.

In terms of fabrication, EXIM films are compatible with standard semiconductor manufacturing protocols, including physical vapor deposition and spray coating. These techniques facilitate uniform, large-area deposition at processing temperatures below 250°C. The resulting films exhibit exceptionally low flexural rigidity, which allows for conformal coverage over uneven chip surfaces without cracking or delamination. Furthermore, the films withstand severe mechanical deformations, including bending to a curvature of 1 mm^{-1} and tensile strains up to 1.5%, all without degradation in shielding performance. Collectively, these attributes ensure that the films meet the rigorous mechanical and flexibility requirements of next-generation wearable and flexible electronics.

The practical utility of EXIM films was demonstrated through conformal shielding applications on USB 3.0 flash drives and flexible ZnO Schottky diodes. On USB 3.0 flash drives, a 1-μm-thick EXIM film effectively mitigated EMI disrupting Bluetooth communication, thereby restoring stable audio transmission. Notably, it outperformed non-conformal aluminum foil shields, which required a significantly greater thickness of 16 μm to achieve comparable results. For flexible Schottky diodes exposed to electromagnetic noise from wireless charging modules, the film suppressed interference-induced current fluctuations from over 100 nA to below 5 nA. Consequently, the signal-to-noise ratio and operational stability improved by more than an order of magnitude compared to pure MXene shields of identical thickness. These findings demonstrate that EXIM films offer superior EMI shielding capabilities while preserving the mechanical integrity and functionality of flexible, miniaturized devices. Thus, they bridge the critical gap between high-performance shielding and the stringent demands of conformal packaging.

In summary, Kang et al. introduced a transformative architectural framework for ultrathin, conformal, and durable EMI shielding films, effectively resolving the long-standing trade-off between thickness and performance in microelectronic packaging. The EXIM film achieved unprecedented SE at minimal thicknesses and elucidated interface-driven electromagnetic attenuation mechanism based on electromagnetic wave-matter interactions in heterostructures. Furthermore, it demonstrated both scalable manufacturing and reliable device integration. Future adaptations of the EXIM concept could extend to diverse MXene chemistries, metallic systems, and multilayered architectures. Such expansions would enable broader operational frequency ranges, enhanced durability in extreme environments, and multifunctionality. Moreover, it offers a commercially viable solution for next-generation flexible electronics, wearables, and automotive or aerospace systems, paving the way for high-performance conformal shielding in the era of ubiquitous intelligence.

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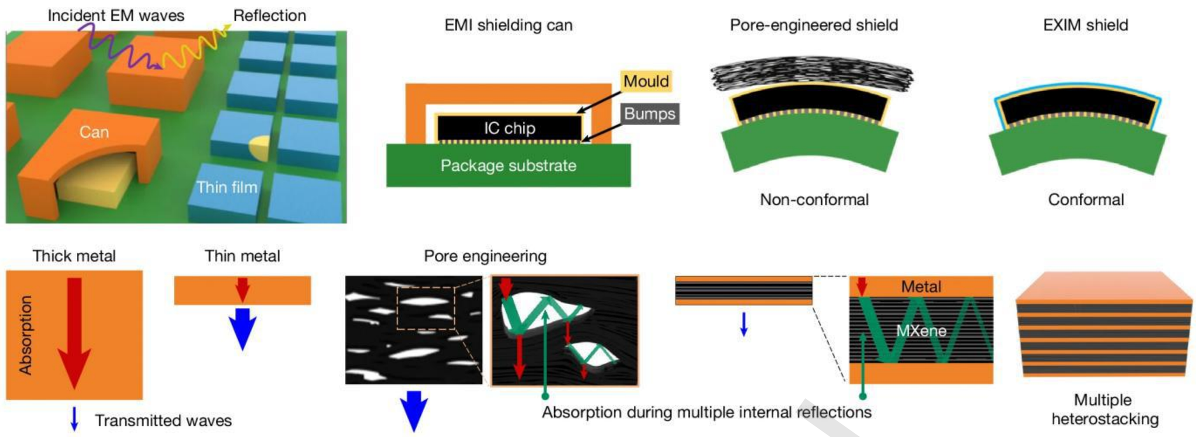

Figure 1. Schematics of the limitations of conventional strategies for conformal EMI shields and the key characteristics of EXIM shields. Traditional porous shielding relies on pore scattering for electromagnetic attenuation, while the pore-free EXIM shield realizes energy dissipation via interfacial polarization loss and ohmic loss. This absorption-dominated shielding mode produces nearly no secondary electromagnetic pollution and presents superior comprehensive performance. Reprinted with permission from Kang et al.[5], copyright 2025 Nature Spring Press.