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RESEARCH

2D MATERIALS

High-strength scalable MXene films through bridging-induced densification

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MXenes are a growing family of two-dimensional transition metal carbides and/or nitrides that are densely stacked into macroscopically layered films and have been considered for applications such as flexible electromagnetic interference (EMI) shielding materials. However, the mechanical and electrical reliabilities of titanium carbide MXene films are affected by voids in their structure. We applied sequential bridging of hydrogen and covalent bonding agents to induce the densification of MXene films and removal of the voids, leading to highly compact MXene films. The obtained MXene films show high tensile strength, in combination with high toughness, electrical conductivity, and EMI shielding capability. Our high-performance MXene films are scalable, providing an avenue for assembling other two-dimensional platelets into high-performance films.

Layered titanium carbide ($Ti_3C_2T_x$) materials known as MXenes (1) are of interest for flexible electrode (2, 3) and electromagnetic interference (EMI) shielding (4, 5) and are also useful because of their metallic electrical conductivity (6) and mechanical properties (7, 8). A prerequisite for realizing these uses is the assembly of the MXene platelets into high-performance macroscopic films. Interlayer interaction, alignment, and compactness are three pivotal structural factors for the high-performance assembly of two-dimensional (2D) platelets (9, 10).

It has been shown that the abundant surface functional groups (where T_x can be –F, =O, or –OH) are useful for designing interactions between MXene platelets through hydrogen (11, 12), ionic (13, 14), and covalent bonding (15). For example, strong MXene–polyvinyl alcohol films were fabricated by hydrogen bonding (11). Aluminum ions were used to reinforce MXene films through ionic bonding (13). Adjacent MXene platelets were covalently cross-linked to enhance the stiffness of MXene films (15). Hydrogen and ionic bonding were also combined to promote the tensile strength of MXene films to 436 MPa (16). However, alignment and compactness are usually ignored in assembling MXene films, limiting improvements in their mechanical and electrical properties.

Polydopamine can be used to bridge the MXene platelets into aligned MXene films (17), improving both tensile strength and electrical conductivity. Additionally, a blade-coating method was demonstrated to improve the alignment, tensile strength, and electrical

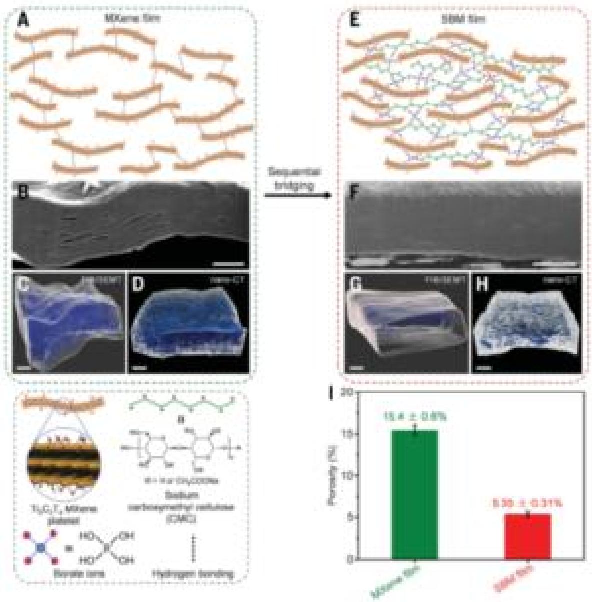

Fig. 1. Structural characterization of SBM films. (**A** and **E**) Structural models of MXene (A) and SBM (E) films. (**B** and **F**) SEM images of cross-sections cut by an FIB for MXene (B) and SBM (F) films. (**C** and **G**) 3D-reconstructed void microstructure derived from FIB/SEMT for MXene (C) and SBM (G) films. Note that the serial section derived from FIB/SEMT is not perpendicular to the film surface. (**D** and **H**) 3D-reconstructed void microstructure derived from nano-CT for MXene (D) and SBM (H) films. Scale bars, 2 μm. (**I**) Porosities of MXene and SBM films derived from density measurements.