

Ultrahigh elastic modulus and tensile strength of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ MXene by dual transition metal bonding

Ting Su^{1,2,3,§}, Chao Rong^{1,2,3,§}, Hao Wu^{1,2,3}, Xiaoyuan Wang^{1,2,3}, Bowei Zhang^{1,2,3}, Yabin Yan^{1,2,3}, and Fu-Zhen Xuan^{1,2,3}

¹ Shanghai Key Laboratory of Intelligent Sensing and Detection Technology, East China University of Science and Technology, Shanghai 200237, China

² Key Laboratory of Pressure Systems and Safety of Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

³ School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China

[§] Ting Su and Chao Rong contributed equally to this work.

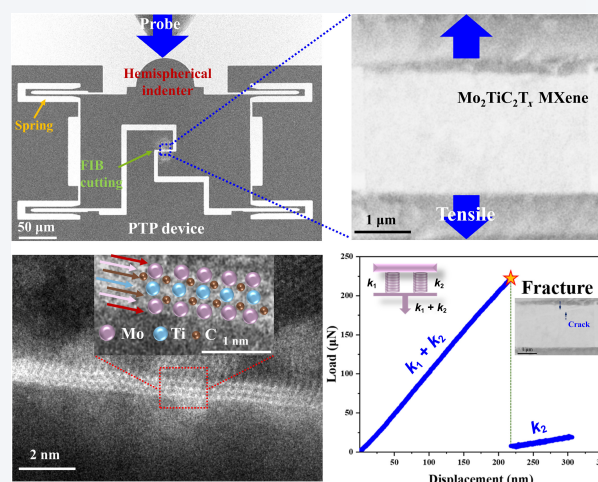
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ABSTRACT: Two-dimensional (2D) transition metal carbides or nitrides (MXenes) provide a versatile class of materials with tunable surface chemistry and distinctive mechanical and electronic functionalities. Among them, $\text{Mo}_2\text{TiC}_2\text{T}_x$, a representative dual transition metal MXene, is distinguished by its electrochemical activity and energy storage capability. Since the reliability of such devices is closely linked to the mechanical response of their smallest structural units, a clear understanding of the intrinsic mechanical properties and fracture behavior of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ is required. Here, using a push-to-pull (PTP) device inside a scanning electron microscope (SEM), we directly measure a Young's modulus of 563.09 ± 11.27 GPa for freestanding monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$, consistent with density functional theory (DFT) predictions for dual transition metal MXenes. DFT calculations further track bond-length evolution and charge-density redistribution during uniaxial tension, clarifying the microscopic origin of the exceptional stiffness and strength. This work elucidates the physical origin of the enhanced mechanical properties of bimetallic MXenes, demonstrates their potential in advanced energy and functional material systems, and provides key experimental and theoretical insights for improving structural reliability and failure prediction in other 2D materials.

KEYWORDS: dual transition metal MXenes, $\text{Mo}_2\text{TiC}_2\text{T}_x$, *in situ* mechanical test, mechanical properties

1 Introduction

Two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides (MXenes), with their high electrical conductivity, good dispersion stability, and tunable surface chemistries, have shown broad potential in electrochemical energy storage [1, 2],



catalysis [3, 4], flexible electronic devices [5, 6], and electromagnetic shielding [7, 8]. $\text{Ti}_3\text{C}_2\text{T}_x$, which was synthesized earlier than other MXenes [9], remains the most extensively investigated member of the family [10–13]. Research on $\text{Ti}_3\text{C}_2\text{T}_x$ has established the foundation for subsequent understanding of MXene structures and properties. During the fabrication and operation of flexible devices, $\text{Ti}_3\text{C}_2\text{T}_x$ is inevitably subjected to stretching, bending, and compression. These mechanical loads readily trigger crack initiation, interlayer sliding, and progressive structural degradation, which in turn limit device performance and reliability [14–16]. To overcome these limitations, increasing attention has been directed toward Mo-based MXenes [17–22], particularly the out-of-plane ordered dual transition metal $\text{Mo}_2\text{TiC}_2\text{T}_x$ [19, 22, 23]. By breaking the single metal symmetry inherent to conventional MXenes [24],

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✉ Address correspondence to Yabin Yan, yanyabin@ecust.edu.cn; Bowei Zhang, boweiz@ecust.edu.cn; Xiaoyuan Wang, wangxiaoyuan@ecust.edu.cn; Fu-Zhen Xuan, fzxuan@ecust.edu.cn

$\text{Mo}_2\text{TiC}_2\text{T}_x$ offers higher energy storage capacity together with enhanced electrochemical activity and improved mechanical tunability [23]. Despite these anticipated advantages in energy storage and flexible electronics, the intrinsic mechanical properties of $\text{Mo}_2\text{TiC}_2\text{T}_x$ have not yet been experimentally established. Quantifying these properties is essential for assessing their structural stability and long-term reliability. At present, experimental data describing the mechanical behavior of $\text{Mo}_2\text{TiC}_2\text{T}_x$ remain unavailable. For 2D materials, direct mechanical measurements based on push-to-pull (PTP) have been shown to provide robust access to intrinsic mechanical properties [13, 25–27].

Monolayer MXene nanosheets are commonly obtained through solution-based etching and subsequent delamination processes [13]. However, isolating a large area and high quality monolayer from suspension remains challenging. Their atomic scale thickness further complicates transfer procedures as well as *in situ* mechanical testing [28]. As a consequence, experimental studies on the mechanical properties of MXenes remain limited and have been reported for only a small number of MXenes. For instance, the elastic modulus of monolayer $\text{Nb}_3\text{C}_3\text{T}_x$ [29] was measured by atomic force microscopy (AFM), whereas multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ and Ti_2CT_x [30] were characterized using a PTP device to avoid structural perturbations and highly nonuniform stress fields induced by the AFM probe during MXene measurements. In our previous work, the Young's modulus of monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ was directly measured using a PTP device to be 484 ± 13 GPa [13]. This value shows closer agreement with the theoretical prediction of 502 GPa [31] than the modulus obtained from AFM-based in-plane measurements, which yielded 333 ± 30 GPa [11]. At present, the mechanical properties of monolayer Ti-based single transition metal MXenes have been systematically explored through both experiments and theoretical predictions. By comparison, the mechanical behavior of monolayer Mo-based dual transition metal MXenes remains far less explored. $\text{Mo}_2\text{TiC}_2\text{T}_x$, as a representative dual transition metal MXene, exhibits enhanced electrochemical stability and energy storage performance relative to conventional Ti-based MXenes, and has therefore been proposed as a candidate electrode material under high load and repeated cycling conditions [22]. Nevertheless, such electrodes are susceptible to cracking during bending or mechanical deformation, which imposes stricter requirements on their intrinsic mechanical properties. Consequently, a systematic investigation of the intrinsic mechanical properties of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheets, starting from the fundamental structural unit, is essential for elucidating their mechanical response and fracture mechanisms.

In this work, high-quality and large-area monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheets were prepared and transferred onto PTP devices using an improved dry transfer technique. Direct *in situ* tensile experiments were then carried out inside a scanning electron microscope (SEM), enabling reliable mechanical testing under well-controlled conditions. The Young's modulus, ultimate tensile strain, and tensile strength of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ were quantitatively determined, providing the first experimental measurement of its intrinsic mechanical properties. In combination with density functional theory (DFT) based first principles calculations, the microscopic mechanisms underlying the superior mechanical performance of this dual transition metal MXene were further examined. These results offer essential experimental data and theoretical insight for assessing the structural stability of $\text{Mo}_2\text{TiC}_2\text{T}_x$

under mechanical loading in flexible electronic devices and energy storage systems, and provide key mechanical parameters for the design of reliable MXene-based functional devices.

2 Results

2.1 The transfer of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$

In this study, a dry transfer technique was employed to place a monolayer of $\text{Mo}_2\text{TiC}_2\text{T}_x$ onto a PTP device. Briefly, a suspension containing monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ was drop cast onto a 400 mesh copper grid without a carbon support film and dried under vacuum, resulting in the monolayer nanosheets resting on the copper grid as shown in Fig. S1(a) in the Electronic Supplementary Material (ESM). One edge of the nanosheet was first cut using a focused ion beam (FIB) operated at 30 kV and 1 pA. A micromanipulator was then carefully advanced to contact the nanosheet edge, followed by ion beam-induced platinum (Pt) deposition to firmly attach the nanosheet to the micromanipulator, as illustrated in Fig. S1(b) in the ESM. Subsequently, the remaining three edges of the nanosheet were cut under the same beam conditions, allowing the nanosheet to be lifted from the grid as shown in Fig. S1(c) in the ESM. The nanosheet was then transferred to the $2.5\ \mu\text{m}$ tensile region of the PTP device in Fig. S1(d) in the ESM. After Pt deposition was used to secure the nanosheet to the device, the connection between the nanosheet and the micromanipulator was removed, and the manipulator was retracted as shown in Fig. S1(e) in the ESM. The enlarged dashed circle indicates a schematic view of the monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ structure. Although Pt residues may remain on the $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet after deposition, the deposited Pt particles are sparse and discontinuous, rather than forming a continuous load-bearing layer on the monolayer nanosheet. Therefore, their contribution to the measured mechanical response is negligible. Previous PTP-based tensile testing of monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene also showed that Pt deposition does not exert a significant influence on the measured mechanical properties [13, 32].

2.2 Characterization of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$

As shown in Fig. 1(a), a SEM image illustrates a monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet fixed onto the tensile region of a PTP nanomechanical device by ion beam-induced Pt deposition, enabling *in situ* tensile testing. During the experiment, a probe applies force to the hemispherical loading pad, which is converted by the PTP device into in-plane tensile loading on the $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet. Figure 1(b) shows a $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet with a length of $2.5\ \mu\text{m}$ and a width of $4.0\ \mu\text{m}$, where the blue arrows indicate the tensile loading direction. The entire deformation process was monitored and recorded in real time, as shown in Movie S1 in the ESM. The thickness of the monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ is a critical parameter for the interpretation of *in situ* mechanical testing results. AFM measurements confirm the monolayer nature of $\text{Mo}_2\text{TiC}_2\text{T}_x$, as shown in Fig. S2 in the ESM. However, AFM-based thickness determination for 2D materials is subject to inherent limitations. For example, although the theoretical thickness of graphene is 0.335 nm, AFM measurements often report values ranging from 0.4 to 1.7 nm [33] depending on imaging mode, tip-sample interactions, surface adsorbates, and interfacial trapped species. To avoid uncertainties associated with these effects, studies of 2D material mechanics commonly adopt nominal thickness values

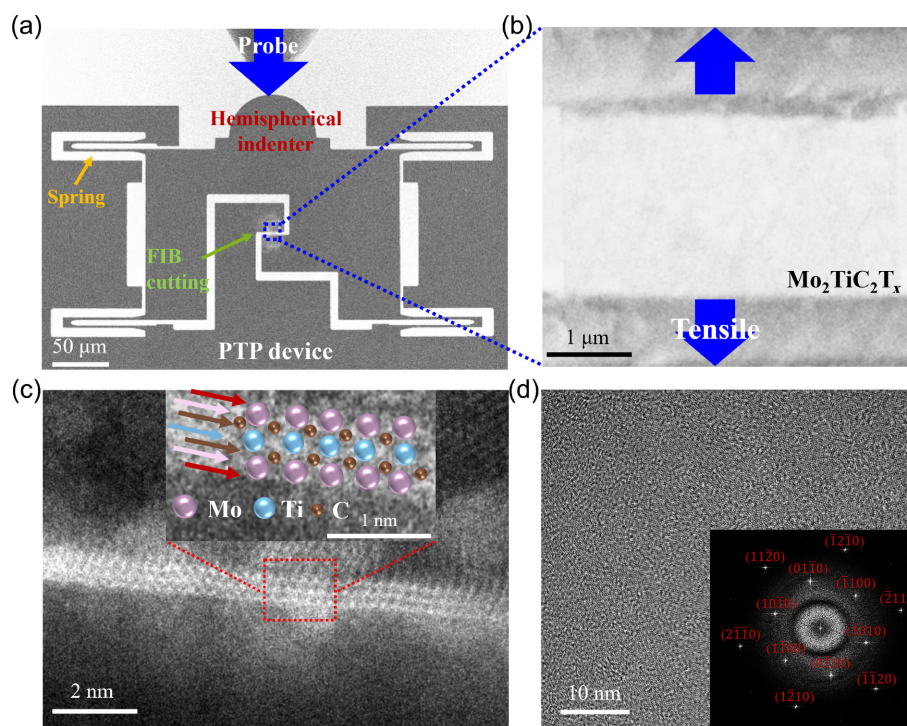


Figure 1 Experimental procedure and characterization of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$. (a) Schematic illustration showing how the PTP device converts the compressive force applied by a hemispherical probe into tensile loading on monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$. (b) Enlarged view of the blue region in (a), revealing a monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet patterned into a rectangular tensile region by FIB cutting. The blue arrows indicate the tensile loading direction. (c) Cross-sectional STEM image of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ acquired along the fractured edge of the tested specimen. The enlarged red region reveals the Mo-C-Ti-C-Mo atomic stacking sequence, confirming the monolayer structure. Surface terminations, such as O and F atoms marked by red arrows, are distributed on the surfaces of $\text{Mo}_2\text{TiC}_2\text{T}_x$. (d) TEM image of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ and the corresponding SAED pattern.

rather than AFM-derived heights [11, 13, 29, 34, 35]. For monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$, the nominal thickness was estimated to be approximately 1.03 nm by combining the bare crystal height obtained from high-resolution scanning transmission electron microscopy (STEM), DFT structural modeling, and the thickness contribution from surface terminations, following the nominal-thickness treatment commonly adopted for monolayer MXenes [13]. This value was further supported by cross-sectional STEM characterization along the fractured edge of the tested specimen and was subsequently used to evaluate the mechanical properties of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$. As presented in Fig. 1(c), the fracture-edge cross-section of the suspended $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet was characterized after tensile testing using STEM. The enlarged region clearly reveals the Mo-C-Ti-C-Mo atomic stacking sequence, confirming the monolayer structure of the tested nanosheet.

X-ray diffraction (XRD, Fig. S3 in the ESM) and X-ray photoelectron spectroscopy (XPS, Fig. S4 in the ESM) were employed to assess the synthesis of $\text{Mo}_2\text{TiC}_2\text{T}_x$. The precursor MAX phase $\text{Mo}_2\text{TiAlC}_2$ shown in Fig. S3(a) in the ESM is fully converted into the MXene $\text{Mo}_2\text{TiC}_2\text{T}_x$ after etching, as evidenced in Fig. S3(c) in the ESM. Figure S3(b) in the ESM presents the XRD pattern of the $\text{Mo}_2\text{TiAlC}_2$ MAX phase, while Fig. S3(d) in the ESM shows the corresponding pattern of $\text{Mo}_2\text{TiC}_2\text{T}_x$. The disappearance of characteristic MAX phase reflections together with the emergence of a strong low-angle (002) peak indicates successful removal of the Al layers and the formation of a layered MXene structure with enlarged interlayer spacing. No residual peaks associated with the precursor phase are detected in the XRD pattern of $\text{Mo}_2\text{TiC}_2\text{T}_x$, confirming the complete transformation from $\text{Mo}_2\text{TiAlC}_2$ to the MXene phase. XPS spectra shown in Fig. S4 in the ESM clearly

reveal the presence of Mo-C and Ti-C bonding in $\text{Mo}_2\text{TiC}_2\text{T}_x$, consistent with its typical layered carbide structure. In addition, the spectra in Figs. S4(c) and S4(d) in the ESM confirm the abundance of surface termination groups on the MXene. Suspended $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheets were further characterized by TEM. As shown in Fig. 1(d), the corresponding selected-area electron diffraction (SAED) pattern exhibits a single set of hexagonal diffraction spots, confirming the crystalline nature and hexagonal carbide structure of $\text{Mo}_2\text{TiC}_2\text{T}_x$ and indicating the high structural quality of the nanosheets. Previous studies have demonstrated by TEM and SAED that the single-crystalline nature and crystal structure of MXene nanosheets remain unchanged, suggesting that Pt deposition does not introduce a substantive effect on their intrinsic mechanical properties [13].

2.3 In situ tensile test of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$

To investigate the mechanical properties of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$, *in situ* uniaxial tensile experiments were conducted inside a Carl Zeiss CrossBeam 340 SEM. Prior to testing, a Bruker Hysitron PI 88 picoindenter was aligned with the hemispherical loading head of the PTP device, and the driving parameters of the flat punch probe were calibrated in air. Tensile loading was applied under displacement control at a rate of 10 nm/s through the PI 88 probe, during which the PTP device converted the applied compression into uniaxial tension on the monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$. Load-displacement data were recorded by the probe sensor, and *in situ* tensile videos were acquired at an accelerating voltage of 2 kV. The tensile strain of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ was determined by tracking sample deformation in the recorded *in situ* videos. Representative scanning electron microscopy snapshots taken

before loading and immediately prior to fracture are shown in Figs. 2(a) and 2(b), respectively, from which a maximum engineering strain of 5.54% was obtained. As shown in Fig. 2(c), monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ underwent catastrophic failure with typical brittle fracture characteristics. A distinct crack can be observed in the suspended tensile region, as indicated by the arrows. Notably, fracture did not occur in the Pt-deposited clamping regions, and no obvious crack branching was observed. The corresponding load–displacement curve is presented in Fig. 2(d), where the slope represents the stiffness of the system. Before fracture, the linear loading region represents the combined stiffness of the monolayer nanosheet and the PTP device. After fracture of the monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet, the applied load drops sharply, and the subsequent loading response is dominated by deformation of the PTP device alone. Therefore, the slope of the post-fracture linear region corresponds to the calibrated stiffness of the PTP device, which is approximately 150 N/m. Accordingly, the intrinsic tensile stiffness of the monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet was obtained by subtracting the calibrated PTP stiffness from the total measured stiffness. Under the continuum assumption, a stress-based description is more appropriate than a strain-based description for most regions of the specimen [13, 26], consistent with previous reports.

To verify the reliability of the measurements, two additional monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ samples were tested. The dimensions, Young's modulus, ultimate tensile strain, and tensile strength of all measured samples are summarized in Table S1 in the ESM. Although only three successful tensile tests were obtained due to the substantial experimental challenges associated with transferring and testing freestanding monolayer MXene nanosheets, the measured

mechanical properties show limited scatter among independent samples. Statistical analysis gives a Young's modulus of 563.09 ± 11.27 GPa, an ultimate tensile strain of $5.24\% \pm 0.26\%$, and a tensile strength of 29.52 ± 1.38 GPa. The corresponding 95% confidence intervals, calculated using Student's *t*-distribution for $n = 3$, are 563.09 ± 28.00 GPa, $5.24\% \pm 0.64\%$, and 29.52 ± 3.42 GPa, respectively.

3 Discussion

A comparison of the Young's modulus of $\text{Mo}_2\text{TiC}_2\text{T}_x$ with other experimentally measured representative MXenes is presented in Fig. 3(a). The comparison includes multilayer Ti_2CT_x and $\text{Ti}_3\text{C}_2\text{T}_x$ tested by PTP devices, monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ measured by both PTP and AFM, and monolayer $\text{Nb}_4\text{C}_3\text{T}_x$ characterized by AFM. The results indicate that the experimentally determined effective Young's modulus of $\text{Mo}_2\text{TiC}_2\text{T}_x$ exceeds those reported for previously studied monolayer or multilayer single transition metal MXenes. Specifically, AFM measurements report an in-plane elastic modulus of 333 ± 30 GPa for monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ [11]. Similarly, monolayer $\text{Nb}_4\text{C}_3\text{T}_x$ exhibits a Young's modulus of 386 ± 13 GPa as determined by AFM [29]. Considering the local stress perturbation and surface height nonuniformity introduced by AFM probes, PTP measurements yield a higher elastic modulus of 484 ± 13 GPa for monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ [13]. In addition, PTP testing shows that the Young's modulus of multilayer MXenes remains nearly constant with increasing layer number, with values of 217.75 GPa for Ti_2CT_x and 204.92 GPa for $\text{Ti}_3\text{C}_2\text{T}_x$ [30], indicating a limited influence of layer number on in-plane stiffness. By comparison, $\text{Mo}_2\text{TiC}_2\text{T}_x$ exhibits an elastic modulus of 563.09 ± 11.27 GPa, representing the

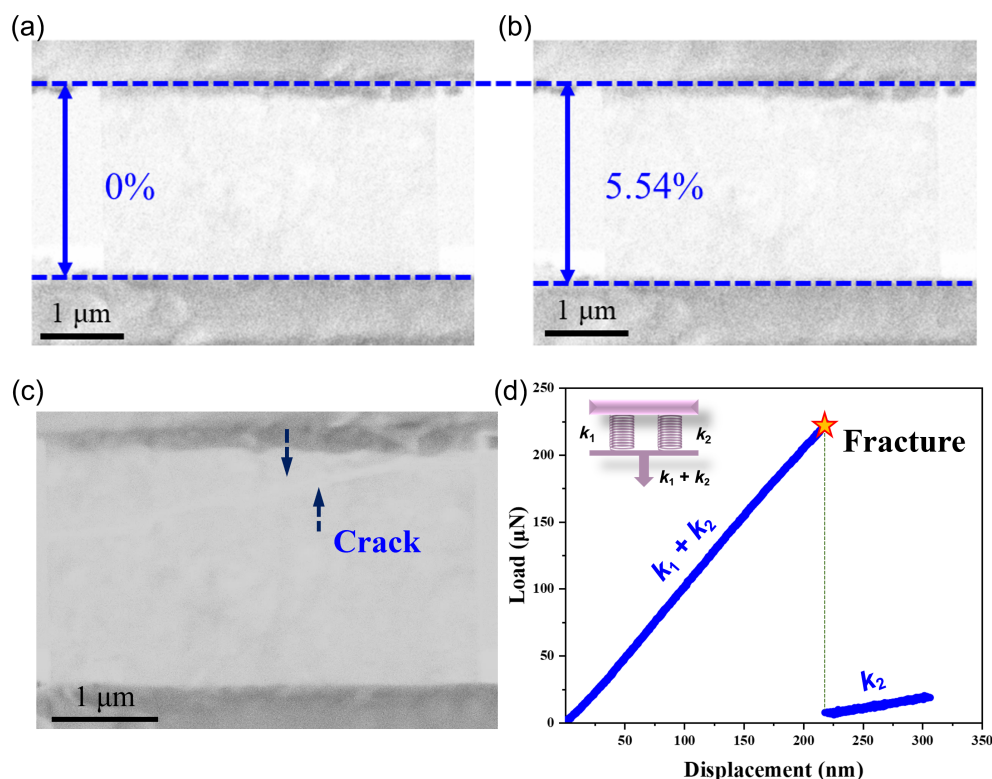


Figure 2 Tensile fracture of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheets. (a) Scanning electron microscopy image showing the $\text{Mo}_2\text{TiC}_2\text{T}_x$ specimen fully taut at 0% strain. (b) SEM image acquired immediately before tensile failure, indicating a peak strain of 5.54%. (c) Brittle fracture of the $\text{Mo}_2\text{TiC}_2\text{T}_x$ after failure, showing that the fracture occurred in the suspended tensile region rather than in the Pt-deposited clamping regions. (d) Measured load–displacement curve of the monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet. The corresponding calculated mechanical parameters are summarized in Table S1 in the ESM (sample 1).

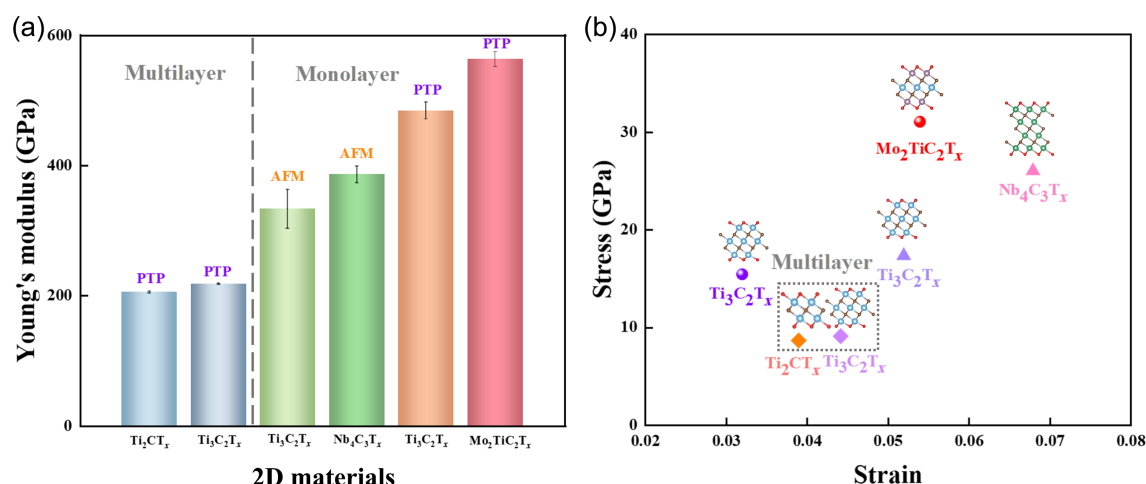


Figure 3 Comparison of the mechanical performance of monolayer $Mo_2TiC_2T_x$ with other experimentally measured MXenes. (a) Young's modulus of monolayer $Mo_2TiC_2T_x$ compared with other MXenes measured by AFM indentation or PTP tensile testing, including multilayer Ti_3CT_x and $Ti_3C_2T_x$ (PTP), monolayer $Ti_3C_2T_x$ (PTP and AFM), and monolayer $Nb_4C_3T_x$ (AFM). Monolayer $Mo_2TiC_2T_x$ exhibits the highest experimentally measured modulus among MXenes. (b) Ultimate tensile strain and fracture strength of monolayer $Mo_2TiC_2T_x$ compared with other MXenes characterized by AFM or PTP. Monolayer $Mo_2TiC_2T_x$ demonstrates the highest fracture strength reported for MXenes to date.

highest experimentally reported value among MXenes to date. Figure 3(b) further compares the ultimate tensile strain and fracture strength of $Mo_2TiC_2T_x$ with those of other MXene materials. Monolayer $Mo_2TiC_2T_x$ displays a fracture strength of 31.03 GPa, exceeding that of commonly studied single transition metal MXenes. For example, multilayer Ti_3CT_x measured using a PTP device shows a fracture strength of 8.6 GPa [30], monolayer $Ti_3C_2T_x$ measured by PTP reaches 15.4 GPa [13], $Ti_3C_2T_x$ measured by AFM reaches 17.3 GPa [11], and $Nb_4C_3T_x$ reaches 26 GPa [29]. Remarkably, $Mo_2TiC_2T_x$ sustains a tensile strain of about 5.54% before catastrophic failure, suggesting an appreciable failure strain among MXene materials while retaining a brittle fracture mode.

It is worth noting that the combination of solution-based synthesis and delamination of monolayer $Mo_2TiC_2T_x$ nanosheets with a precise micromanipulator-assisted transfer inside a SEM effectively overcomes long-standing challenges associated with sample preparation and transfer in *in situ* mechanical testing of solution processable 2D materials. This approach enables reliable experimental determination of the intrinsic mechanical properties of monolayer dual transition metal MXene $Mo_2TiC_2T_x$, which has not been previously accessible. Given that MXenes can be produced at scale as dispersible 2D nanosheets and are already widely used in conductive coatings and polymer composites, the intrinsic mechanical properties of individual nanosheets play a critical role in governing the macroscopic performance of these materials. The higher effective Young's modulus measured for $Mo_2TiC_2T_x$ establishes a new experimental benchmark among MXenes and suggests its suitability for applications where structural integrity is required. Together with its previously reported electrochemical stability, high electrical conductivity, and favorable energy storage characteristics [36], $Mo_2TiC_2T_x$ emerges as a mechanically robust candidate for flexible energy storage systems, including supercapacitors [37] and memory-related devices [23], where lightweight design, mechanical reliability, and deformation tolerance are essential.

The experimentally measured elastic modulus is consistent with the value of 594.6 GPa obtained from first principles DFT calculations for $Mo_2TiC_2T_x$, as summarized in Table 1. Among the commonly considered termination configurations, O-terminated

MXenes represent the most stable form [38]. At the first-principles level, elastic constants are primarily governed by bond stiffness, and the strong metal-oxygen interactions in O-terminated MXenes are therefore favorable for enhancing in-plane stiffness [39]. The monolayer thickness adopted in the calculations is 7.62 Å, which agrees well with previously reported DFT results [38, 39]. To further evaluate the mechanical performance of $Mo_2TiC_2T_x$ among dual transition metal MXenes, we calculated the elastic properties of a series of dual transition metal MXenes, including $Mo_2TiC_2T_x$, $Cr_2TiC_2T_x$, $V_2TiC_2T_x$, $Nb_2TiC_2T_x$, and $Ta_2TiC_2T_x$. The optimized structures are shown in Fig. S5 in the ESM, and the calculated structural parameters and Young's moduli are summarized in Table S2 in the ESM. As shown in Fig. S6 in the ESM, $Mo_2TiC_2T_x$ exhibits a higher calculated three-dimensional (3D) Young's modulus than $Ta_2TiC_2T_x$, $Nb_2TiC_2T_x$, $V_2TiC_2T_x$, and $Cr_2TiC_2T_x$, demonstrating its superior stiffness among the investigated dual transition metal MXenes.

To clarify the origin of the high Young's modulus and tensile strength of monolayer $Mo_2TiC_2T_x$, the atomic-scale fracture edges were examined by STEM. As shown in Figs. 4(a) and 4(b), the fractured region retains continuous and well-aligned atomic rows, indicating that lattice order is largely preserved after failure. Consistently, DFT evolution of the $Mo_2TiC_2T_x$ framework under large strain reveals a continuous structural backbone, with deformation mainly manifested as relative displacement between surface terminations and the metal layers, rather than collapse of the primary lattice (Fig. 4(c)). The uniaxial stress-strain response in Fig. S7(a) in the ESM shows no abrupt instability over a wide strain range, reflecting sustained stiffness and effective load bearing at high strain. Analysis of bond length evolution in Fig. S7(b) in the ESM further reveals differentiated load sharing among distinct bonds. The Mo-C, Ti-C, and Mo1-O1(2) bonds elongate monotonically and accommodate the majority of tensile deformation, whereas the Mo-Ti distance remains nearly

Table 1 DFT results of elastic constants of monolayer $Mo_2TiC_2T_x$

	C_{11} (GPa)	C_{12} (GPa)	Poisson's ratio	Young's modulus (GPa)
$Mo_2TiC_2T_x$	663.3	213.4	0.32	594.6

unchanged, indicating its role as a rigid structural scaffold. Correspondingly, crystal orbital Hamilton population (COHP) analysis shows a clear reduction in the negative of the integrated crystal orbital Hamilton population ($-ICOHP$) of Mo–O1(2) at 18% strain (Figs. S8(b) and S8(d) in the ESM) compared with the unstrained state (Figs. S8(a) and S8(c) in the ESM), indicating progressive weakening of Mo–O bonding contributions during tension. Projected density of states (PDOS) analysis further reveals that, in the occupied energy region below the Fermi level, $Mo_2TiC_2T_x$ (Figs. S9(a) and S9(b) in the ESM) exhibits more continuous and broader overlap between Mo-d states and O-p and C-p states than $Ti_3C_2T_x$ (Figs. S9(c) and S9(d) in the ESM), indicating stronger p-d hybridization. Combined with the more spatially extended and polarizable nature of Mo-d orbitals, these results suggest that load bearing is no longer governed solely by Ti-d-C-p backbone coupling, but instead supported by a reinforced hybridized network involving Mo-d and O-p and C-p states. Moreover, the 2D charge density distribution on the (001) plane in Fig. 4(d), which shows pronounced and continuous charge accumulation around oxygen and adjacent surface metal atoms even at 18% strain, indicates persistent covalent interactions that underpin the high stiffness and strain tolerance of monolayer $Mo_2TiC_2T_x$.

In summary, the Mo/Ti-C backbone serves as the primary load-

bearing pathway with high bond stiffness, while strong p-d bonding introduced by O termination further promotes load redistribution. This synergistic bonding network enables the framework to remain continuous under large strain and delays the onset of structural instability, providing a microscopic basis for the mechanical reliability of $Mo_2TiC_2T_x$ in flexible devices and structural reinforcement applications. Consistent with this interpretation, previous studies have reported that the incorporation of only 2 wt.% $Mo_2TiC_2T_x$ can enhance the elongation of Mo-based alloys by a factor of 2.3 to 2.7 and increase fracture toughness by approximately 2.4 times [40], highlighting the potential of $Mo_2TiC_2T_x$ as a lightweight reinforcement strategy.

4 Conclusions

In summary, this work employs a PTP device inside a SEM to experimentally determine the intrinsic mechanical properties of monolayer $Mo_2TiC_2T_x$ for the first time. The measured Young's modulus reaches 563.09 ± 11.27 GPa, accompanied by an ultimate tensile strain of $5.24\% \pm 0.26\%$ and a tensile strength of 29.52 ± 1.38 GPa. These results provide the first experimental mechanical data for a dual transition metal MXene and establish the highest experimentally reported stiffness among MXene systems to date. The combination of high tensile strength and

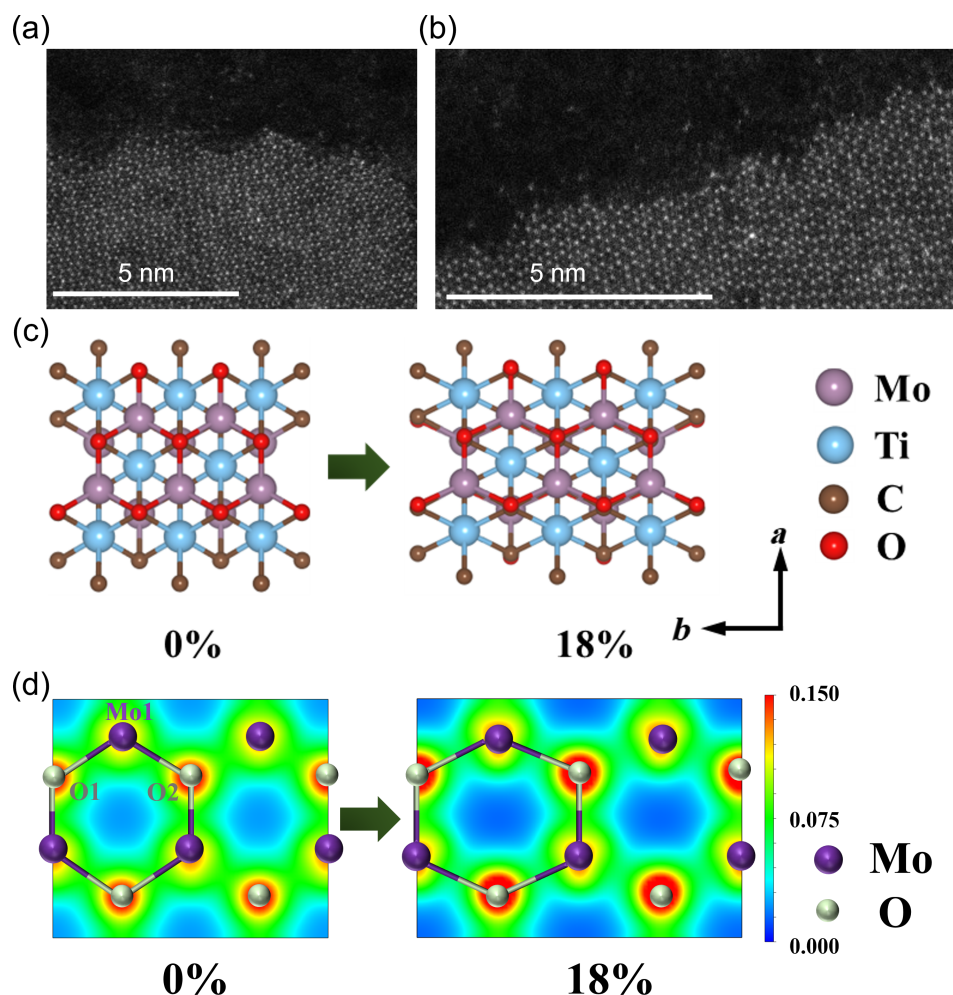


Figure 4 Fracture characteristics, structural evolution, and electronic mechanism analysis of monolayer $Mo_2TiC_2T_x$. (a) and (b) Atomic-scale STEM images of the fracture edges of monolayer $Mo_2TiC_2T_x$, showing that the lattice arrangement in the fractured region remains highly ordered. (c) DFT results over strains from 0% to 18%, revealing the structural stability of the MXene framework under tensile deformation. (d) Charge density distributions on the (001) plane at 0% and 18% strain.

appreciable ultimate tensile strain before brittle fracture indicates that monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ achieves a favorable balance between stiffness and elastic deformability among MXene materials. First-principles calculations further elucidate the evolution of bond lengths and charge density during tensile fracture of monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$, offering mechanistic insight that informs structural modulation, electrode design, and performance enhancement under high stress conditions. Collectively, these findings suggest that $\text{Mo}_2\text{TiC}_2\text{T}_x$ is a promising candidate for applications requiring mechanical reliability in next-generation electronic and optical functional materials.

5 Methods

5.1 DFT method

All first-principles calculations were performed within the framework of DFT using the Vienna *ab initio* simulation package (VASP). The projector augmented-wave (PAW) method was employed to describe the electron-ion interactions, with the Perdew–Burke–Ernzerhof (PBE) functional under the generalized gradient approximation (GGA). The plane-wave cutoff energy was set to 500 eV. For structural optimization, a Monkhorst–Pack k -point mesh of $12 \times 12 \times 1$ was adopted. To eliminate spurious interactions arising from periodic boundary conditions, a vacuum layer of 20 Å was introduced along the z -direction. The convergence criterion for self-consistent electronic iterations was set to 1×10^{-5} eV, while the force convergence threshold was 0.015 eV/Å, ensuring full relaxation of both lattice vectors and atomic positions.

5.2 Sample preparation for tensile tests

Monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ was prepared via selective etching and subsequent delamination of $\text{Mo}_2\text{TiAlC}_2$ powders (Fig. S10 in the ESM). Briefly, 40 mL of 49% hydrofluoric acid (HF) was added to a PTFE-lined reaction vessel. $\text{Mo}_2\text{TiAlC}_2$ powder (2 g) was gradually introduced into the HF solution in small portions to avoid rapid exothermic reactions. The mixture was then stirred at 500 rpm and maintained at 60 °C in an oil bath for 48 h. After etching, the resulting suspension was collected and centrifuged at 8500 rpm for 5 min, repeated 7–8 times, until a viscous sediment was obtained. The supernatant was discarded, and the sediment was re-dispersed in 50 mL of 30 wt.% tetramethylammonium hydroxide (TMAOH) solution, followed by manual shaking and subsequent transfer into a 100 mL beaker. The suspension was stirred at room temperature for 24 h under sealed conditions. To remove the residual TMAOH, the suspension was centrifuged twice at 8500 rpm for 5 min. Finally, the delamination process was achieved by centrifugation at 3500 rpm for 30 min, and the supernatant containing monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ was collected as a stable colloidal suspension.

5.3 In situ SEM tensile testing

In situ tensile experiments on monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheets were conducted inside a Carl Zeiss CrossBeam 340 SEM chamber, where real-time tensile deformation was recorded at a low accelerating voltage of 2 kV. Before testing, the PTP device was mounted on the recessed stage of an integrated 2D materials testing platform using conductive silver paste. A Bruker Hysitron PI 88 PicoIndenter (Fig. S11(a) in the ESM) was aligned with the semicircular indenter head of the PTP device (Fig. S11(b) in the

ESM), and the electrostatic comb-drive actuator was calibrated in air. Under displacement control at a rate of 10 nm/s, the PI 88 indenter applied compressive loading onto the PTP device, which was mechanically converted into uniaxial tensile loading of the $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet. The indenter transducer simultaneously recorded the load–displacement curve. The ultimate tensile strain was determined from the SEM tensile video, while the Young's modulus and tensile strength were calculated from the load–displacement data. Specifically, the stiffness of the monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet was obtained by subtracting the spring constant of the PTP device from the overall slope of the load–displacement curve. The 2D and 3D Young's modulus are calculated as follows: $E_{2D} = C \cdot \frac{l}{b}$, $E_{3D} = C \cdot \frac{l}{b \cdot h}$, where C , l , b , and h represent the tensile stiffness, length, width, and thickness of the $\text{Mo}_2\text{TiC}_2\text{T}_x$ within the tensile region, respectively. In this study, the sample length and width were measured to be 2.5 and 4.0 μm. Generally, the definition of thickness for 2D materials is not straightforward. Following the convention adopted for graphene, we employed a nominal thickness for monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$. Based on STEM imaging and DFT calculations, the thickness of a monolayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ was determined to be 1.03 nm. It is important to note that, due to the nanoscale thickness of the monolayer, assumptions regarding the stress and strain state must be made. During the tensile experiments, no necking was observed at the suspended edges of the nanosheet. The maximum tensile strain, $\epsilon = 5.54\%$, $\sigma = E_{3D} \cdot \epsilon$ was used in the tensile strength equation to calculate the ultimate tensile strength.

Electronic Supplementary Material: Supplementary material (further details of sample preparation, structural characterization, mechanical testing, and DFT calculations) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908929>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interest in this work.

Author contribution statement

Y. B. Y., X. Y. W., B. W. Z., and F.-Z. X. conceived and planned the project. T. S., C. R., and H. W. conducted the experiments and simulations. T. S., X. Y. W., and Y. B. Y. wrote the paper. All authors discussed the results and commented on the manuscripts.

Use of AI statement

None.

References

- [1] Anasori, B.; Lukatskaya, M. R.; Gogotsi, Y. 2D metal carbides and nitrides (MXenes) for energy storage. *Nat. Rev. Mater.* **2017**, *2*, 16098.
- [2] Wu, Y. Q.; Sun, M. T. Recent progress of MXene as an energy storage material. *Nanoscale Horiz.* **2024**, *9*, 215–232.
- [3] He, L.; Zhuang, H. Z.; Fan, Q.; Yu, P.; Wang, S. C.; Pang, Y. F.; Chen, K.; Liang, K. Advances and challenges in MXene-based electrocatalysts: Unlocking the potential for sustainable energy conversion. *Mater. Horiz.* **2024**, *11*, 4239–4255.
- [4] Zhang, J. Q.; Zhao, Y. F.; Guo, X.; Chen, C.; Dong, C. L.; Liu, R. S.; Han, C. P.; Li, Y. D.; Gogotsi, Y.; Wang, G. X. Single platinum atoms immobilized on an MXene as an efficient catalyst for the hydrogen evolution reaction. *Nat. Catal.* **2018**, *1*, 985–992.
- [5] Seyedin, S.; Uzun, S.; Levitt, A.; Anasori, B.; Dion, G.; Gogotsi, Y.; Razal, J. M. MXene composite and coaxial fibers with high stretchability and conductivity for wearable strain sensing textiles. *Adv. Funct. Mater.* **2020**, *30*, 1910504.
- [6] Qin, R. Z.; Nong, J.; Wang, K. Q.; Liu, Y. S.; Zhou, S. B.; Hu, M. J.; Zhao, H. B.; Shan, G. C. Recent advances in flexible pressure sensors based on MXene materials. *Adv. Mater.* **2024**, *36*, 2312761.
- [7] Iqbal, A.; Kwon, J.; Hassan, T.; Park, S. W.; Lee, W. H.; Oh, J. M.; Hong, J.; Lee, J.; Naqvi, S. M.; Zafar, U. et al. Environmentally stable and highly crystalline MXenes for multispectral electromagnetic shielding up to millimeter waves. *Adv. Funct. Mater.* **2025**, *35*, 2409346.
- [8] Han, M. K.; Zhang, D. Z.; Shuck, C. E.; McBride, B.; Zhang, T.; Wang, R. C.; Shevchuk, K.; Gogotsi, Y. Electrochemically modulated interaction of MXenes with microwaves. *Nat. Nanotechnol.* **2023**, *18*, 373–379.
- [9] Naguib, M.; Kurtoglu, M.; Presser, V.; Lu, J. J.; Niu, J.; Heon, M.; Hultman, L.; Gogotsi, Y.; Barsoum, M. W. Two-dimensional nanocrystals produced by exfoliation of Ti_3AlC_2 . *Adv. Mater.* **2011**, *23*, 4248–4253.
- [10] Hart, J. L.; Hantanasirisakul, K.; Lang, A. C.; Anasori, B.; Pinto, D.; Pivak, Y.; van Ommen, J. T.; May, S. J.; Gogotsi, Y.; Taheri, M. L. Control of MXenes' electronic properties through termination and intercalation. *Nat. Commun.* **2019**, *10*, 522.
- [11] Lipatov, A.; Lu, H. D.; Alhabeb, M.; Anasori, B.; Gruverman, A.; Gogotsi, Y.; Sinitskii, A. Elastic properties of 2D $\text{Ti}_3\text{C}_2\text{T}_x$ MXene monolayers and bilayers. *Sci. Adv.* **2018**, *4*, eaat0491.
- [12] Firestein, K. L.; Von Treifeldt, J. E.; Kvashnin, D. G.; Fernando, J. F. S.; Zhang, C.; Kvashnin, A. G.; Podryabinkin, E. V.; Shapeev, A. V.; Sirivardana, D. P.; Sorokin, P. B. et al. Young's modulus and tensile strength of Ti_3C_2 MXene nanosheets as revealed by *in situ* TEM probing, AFM nanomechanical mapping, and theoretical calculations. *Nano Lett.* **2020**, *20*, 5900–5908.
- [13] Rong, C.; Su, T.; Li, Z. K.; Chu, T. S.; Zhu, M. L.; Yan, Y. B.; Zhang, B. W.; Xuan, F. Z. Elastic properties and tensile strength of 2D $\text{Ti}_3\text{C}_2\text{T}_x$ MXene monolayers. *Nat. Commun.* **2024**, *15*, 1566.
- [14] Wyatt, B. C.; Rosenkranz, A.; Anasori, B. 2D MXenes: Tunable mechanical and tribological properties. *Adv. Mater.* **2021**, *33*, 2007973.
- [15] Ma, R.; Chen, Z. T.; Zhao, D. N.; Zhang, X. J.; Zhuo, J. T.; Yin, Y. J.; Wang, X. F.; Yang, G. W.; Yi, F. $\text{Ti}_3\text{C}_2\text{T}_x$ MXene for electrode materials of supercapacitors. *J. Mater. Chem. A* **2021**, *9*, 11501–11529.
- [16] Mim, M.; Habib, K.; Farabi, S. N.; Ali, S. A.; Zaed, M. A.; Younas, M.; Rahman, S. MXene: A roadmap to sustainable energy management, synthesis routes, stabilization, and economic assessment. *ACS Omega* **2024**, *9*, 32350–32393.
- [17] Bibi, F.; Hanan, A.; Soomro, I. A.; Numan, A.; Khalid, M. Double transition metal MXene for enhanced electrochemical applications: Challenges and opportunities. *EcoMat* **2024**, *6*, e12485.
- [18] Kuznetsov, D. A.; Chen, Z. X.; Kumar, P. V.; Tsoukalou, A.; Kierzkowska, A.; Abdala, P. M.; Safonova, O. V.; Fedorov, A.; Müller, C. R. Single site cobalt substitution in 2D molybdenum carbide (MXene) enhances catalytic activity in the hydrogen evolution reaction. *J. Am. Chem. Soc.* **2019**, *141*, 17809–17816.
- [19] Ali, I.; Yousaf, M.; Sajid, I. H.; Hakim, M. W.; Rizwan, S. Reticulation of 1D/2D Mo_2TiC_2 MXene for excellent supercapacitor performance. *Mater. Today Chem.* **2023**, *34*, 101766.
- [20] Hanan, A.; Bibi, F.; Elsa, G.; Numan, A.; Walvekar, R.; Khalid, M. A comprehensive review of double transition metal MXene ($\text{Mo}_2\text{Ti}_3\text{C}_3\text{T}_x$) in energy storage, conversion, and harvesting. *Mater. Today Energy* **2025**, *51*, 101905.
- [21] Nawaz, T.; Ahmad, M.; Hussain, I.; Chen, X.; Abraham, B. M.; Zhuang, S. L.; Low, K. H.; Zhang, K. L.; He, J. Minimizing intersheet junction resistivity via Au_4Cu_2 nanocluster-based connectivity in Mo_2TiC_2 MXene for symmetric supercapacitor device. *Small Struct.* **2025**, *6*, 2400664.
- [22] Maughan, P. A.; Bouscarrat, L.; Seymour, V. R.; Shao, S. Q.; Haigh, S. J.; Dawson, R.; Tapia-Ruiz, N.; Bimbo, N. Pillared Mo_2TiC_2 MXene for high-power and long-life lithium and sodium-ion batteries. *Nanoscale Adv.* **2021**, *3*, 3145–3158.
- [23] Hakim, M. W.; Fatima, S.; Tahir, R.; Iqbal, M. Z.; Li, H.; Rizwan, S. Ni-intercalated $\text{Mo}_2\text{TiC}_2\text{T}_x$ free-standing MXene for excellent gravimetric capacitance prepared via electrostatic self-assembly. *J. Energy Storage* **2023**, *61*, 106662.
- [24] Anasori, B.; Xie, Y.; Beidaghi, M.; Lu, J.; Hosler, B. C.; Hultman, L.; Kent, P. R. C.; Gogotsi, Y.; Barsoum, M. W. Two-dimensional, ordered, double transition metals carbides (MXenes). *ACS Nano* **2015**, *9*, 9507–9516.
- [25] Su, T.; Rong, C.; Yan, Y. B.; Xuan, F. Z. Tensile mechanical properties and edge defect-driven degradation in bilayer graphene. *ACS Appl. Mater. Interfaces* **2025**, *17*, 48680–48689.
- [26] Cao, K.; Feng, S. Z.; Han, Y.; Gao, L. B.; Hue Ly, T.; Xu, Z. P.; Lu, Y. Elastic straining of free-standing monolayer graphene. *Nat. Commun.* **2020**, *11*, 284.
- [27] Han, Y.; Feng, S. Z.; Cao, K.; Wang, Y. J.; Gao, L. B.; Xu, Z. P.; Lu, Y. Large elastic deformation and defect tolerance of hexagonal boron nitride monolayers. *Cell Rep. Phys. Sci.* **2020**, *1*, 100172.
- [28] Su, T.; Rong, C.; Yu, T. H.; Hu, S.; He, P.; Zhang, B. W.; Yan, Y. B.; Xuan, F. Z. Progress and perspectives of high-quality mechanical properties testing and mechanisms for 2D materials. *Int. J. Extreme Manuf.* **2026**, *8*, 012002.
- [29] Lipatov, A.; Alhabeb, M.; Lu, H. D.; Zhao, S. S.; Loes, M. J.; Vorobeve, N. S.; Dall'Agnese, Y.; Gao, Y.; Gruverman, A.; Gogotsi, Y. et al. Electrical and elastic properties of individual single-layer $\text{Nb}_4\text{C}_3\text{T}_x$ MXene flakes. *Adv. Electron. Mater.* **2020**, *6*, 1901382.
- [30] Li, Y. X.; Wei, C. J.; Huang, S. H.; Ghasemi, A.; Gao, W.; Wu, C. L.; Mochalin, V. N. *In situ* tensile testing of nanometer-thick two-dimensional transition-metal carbide films: Implications for MXenes acting as nanoscale reinforcement agents. *ACS Appl. Nano Mater.* **2021**, *4*, 5058–5067.
- [31] Borysiuk, V. N.; Mochalin, V. N.; Gogotsi, Y. Molecular dynamic study of the mechanical properties of two-dimensional titanium carbides $\text{Ti}_{n+1}\text{C}_n$ (MXenes). *Nanotechnology* **2015**, *26*, 265705.
- [32] Rong, C.; Su, T.; Yu, T. H.; Wang, X. Y.; Chu, T. S.; Zhu, M. L.;

- Yan, Y. B.; Zhang, B. W.; Xuan, F. Z. Shear properties and stable wrinkle resistance in 2D $\text{Ti}_3\text{C}_2\text{T}_x$ MXene monolayers. *Nat. Commun.* **2026**, *17*, 2411.
- [33] Shearer, C. J.; Slattery, A. D.; Stapleton, A. J.; Shapter, J. G.; Gibson, C. T. Accurate thickness measurement of graphene. *Nanotechnology* **2016**, *27*, 125704.
- [34] Jiao, M. D.; Wang, L.; Wang, C. Y.; Zhang, Q.; Ye, S. Y.; Wang, F. Y. Molecular dynamics simulations on deformation and fracture of bilayer graphene with different stacking pattern under tension. *Phys. Lett. A* **2016**, *380*, 609–613.
- [35] Arshad, M. U.; Gan, Y. X.; Wei, C. J.; Li, J. L.; Wu, C. L.; Naraghi, M. Fracture toughness characteristics of stacked bilayer graphene via far-field displacement measurements. *Small* **2023**, *19*, 2302499.
- [36] Kim, H.; Anasori, B.; Gogotsi, Y.; Alshareef, H. N. Thermoelectric properties of two-dimensional molybdenum-based MXenes. *Chem. Mater.* **2017**, *29*, 6472–6479.
- [37] Chowdhury, D.; Moolayadukkam, S.; Datta, P.; Puri, I. K. $\text{Ti}_3\text{C}_2\text{T}_x$ and $\text{Mo}_2\text{TiC}_2\text{T}_x$ MXene-based biocompatible supercapacitors for implantable medical devices. *J. Mater. Chem. B* **2025**, *13*, 7269–7279.
- [38] Li, L. H. Lattice dynamics and electronic structures of $\text{Ti}_3\text{C}_2\text{O}_2$ and $\text{Mo}_2\text{TiC}_2\text{O}_2$ (MXenes): The effect of Mo substitution. *Comput. Mater. Sci.* **2016**, *124*, 8–14.
- [39] Soomro, I. A.; Zhao, D.; Hinsch, J. J.; Allen, O.; Han, F. X.; Zhou, M.; Wang, L.; Liu, P. R.; Zhang, L.; Wang, Y. Superexchange interaction in double transition metal MXenes: A pathway to superior mechanical and thermal performance. *Small* **2025**, *21*, e07185.
- [40] Chen, X.; Li, R.; Li, B.; Wang, J.; Wang, T.; Yan, F. X.; Zhang, G. J. Achieving ultra-high ductility and fracture toughness in molybdenum via Mo_2TiC_2 MXene addition. *Mater. Sci. Eng. A* **2021**, *818*, 141422.



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