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Research Article

Flexible $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ van der Waals heterostructure films for bias-free dual-mode sensing and EMI shielding

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Abstract: Developing flexible electronics that integrate multimodal sensing, bias-free signal generation, and electromagnetic interference (EMI) shielding is critical for wearable health monitoring, artificial intelligence, and human-computer interaction. Semiconducting $\text{Mo}_2\text{TiC}_2\text{T}_x$ MXene films show promise for flexible thermoelectrics and EMI shielding, but their relatively low electrical conductivity restricts both the power factor (PF) and the overall EMI shielding effectiveness (SE). Here, we report a van der Waals heterostructure film of $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$, fabricated via intercalation-exfoliation followed by vacuum-assisted filtration. The heterointerface engineering simultaneously enhances thermoelectric performance and EMI shielding. The electrical conductivity reaches 878.3 S cm^{-1} (~23-fold enhancement), and the PF reaches $14.4 \mu\text{W m}^{-1} \text{ K}^{-2}$ (~4-fold), while the EMI SE improves from 14.1 to 40.6 dB. The film enables dual-mode sensing free from crosstalk, temperature detection via the Seebeck effect and pressure sensing via piezoresistive response, as well as maintaining stable signal fidelity under external EMI. Furthermore, the film exhibits photothermoelectric and Joule-heating responses. Integrated with a wireless acquisition module for signal readout and transmission, the sensor enables real-time transmission of temperature and pressure signals. This work provides a strategy for designing flexible heterostructures that synergistically combine bias-free signal generation, multimodal sensing, EMI resilience, and multi-stimulus responsiveness for next-generation smart electronics.

Keywords: two-dimensional, thermoelectric, sensor, electromagnetic interference shielding, flexible electronic device

1 Introduction

Flexible sensors have attracted widespread attention in fields such as wearable health

monitoring, electronic skin, and intelligent human-computer interaction because of their excellent flexibility, conformability, and sensitivity to various external stimuli [1,2]. However, most existing sensors rely on a single sensing mechanism (e.g., capacitive, resistive, triboelectric, or piezoelectric) [3], which is insufficient for multimodal sensing and high adaptability in complex environments. In addition, reliance on external batteries and vulnerability to electromagnetic interference (EMI) compromise operational stability and signal accuracy [4–7]. This is a critical gap, as sensors in complex electromagnetic environments are highly susceptible to external interference [8]. Such interference can induce spurious signals, alter the intrinsic response of the sensing material, or even completely overwhelm the weak electrical outputs typically generated by electronics without external bias. Therefore, developing flexible electronic devices that integrate bias-free signal generation, multimodal sensing, and EMI shielding performance is of great significance.

Thermoelectric (TE) materials can directly convert a temperature gradient into a potential difference via the Seebeck effect without external energy. Their conversion performance is governed by parameters such as electrical conductivity (σ), Seebeck coefficient (S), and thermal conductivity (κ), and is quantified by the figure of merit $zT = S^2\sigma T/\kappa$. The power factor ($PF = S^2\sigma$) is the comprehensive indicator of the electrical part. Optimizing zT requires coordinated regulation of carrier and phonon transport. Compared with conventional power supply methods, TE devices contain no moving parts and offer advantages including simple structure, continuous operation, high

stability, and ease of miniaturization and integration. These features make TE materials promising candidates for bias-free sensing [9–12]. Traditional TE materials primarily include sulfides, tellurides, metal alloys, and organic conductive polymers. Sulfides, tellurides, and metal alloys such as Bi_2Te_3 and PbTe , and their solid solutions, exhibit high S and favorable PF . However, they are brittle, costly, and difficult to process, limiting their use in miniaturized, flexible wearable devices [13–15]. Organic conductive polymers offer excellent flexibility and processability, yet their conductivity and PF are generally low, hindering high-efficiency TE conversion [16].

Two-dimensional (2D) materials such as MXenes and transition-metal dichalcogenides (TMDs) have attracted significant attention in TE and EMI shielding [17–19]. MXenes are a class of 2D transition metal carbides, nitrides, or carbonitrides. They feature a highly layered structure, excellent electrical conductivity, and abundant surface functional groups. Their interlayer spacing can be tuned via surface terminal groups or chemical doping to optimize carrier transport and electronic state distribution [20,21]. Typical MXene materials, such as $\text{Ti}_3\text{C}_2\text{T}_x$, have been extensively studied for flexible electronics, EMI shielding, and energy conversion applications [22–24]. However, our group preliminary research further confirms that its low intrinsic Seebeck coefficient is a key factor limiting its thermoelectric applications [25,26]. More recently, metallic MXene compositions such as $\text{Mo}_2\text{TiC}_2\text{T}_x$ have emerged as a research hotspot [27]. Their multiple metal layered structure (Mo and Ti) endows richer electronic states and tunable interlayer spacing, offering unique advantages for TE

performance optimization and interface engineering [28]. Compared with $\text{Ti}_3\text{C}_2\text{T}_x$ $\text{Mo}_2\text{TiC}_2\text{T}_x$ typically exhibits a higher S but relatively lower σ [29]. These transport characteristics offer new opportunities for constructing multilayer heterointerfaces and for achieving synergistic regulation of PF and EMI SE.

TMDs are typically composed of a transition-metal layer sandwiched between two chalcogen (S, Se, Te) layers held by weak van der Waals (vdW) forces. They combine tunable band structures, high carrier mobility, and exceptional interface engineering capabilities. Typical TMDs include MoS_2 , WS_2 , MoSe_2 , and TaS_2 [30]. Among these, MoS_2 and WS_2 have been extensively studied due to their excellent semiconducting properties and high stability [31]. TaS_2 offers unique advantages for EMI shielding applications owing to its high σ [30]. By combining it with MXene, the high S and interfacial structure-regulation capabilities of MXene can be fully exploited, while also leveraging the high σ and electromagnetic wave-absorption advantages of TMDs. Constructing multilayer heterointerfaces and alternating layered structures not only enhances interfacial scattering and electromagnetic wave attenuation but also modulates electron state distribution [32], expecting to achieve synergistic optimization of the TE performance, EMI SE and multimodal sensing ability.

This work fabricated $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ heterostructure films via an intercalation-exfoliation method combined with vacuum-assisted filtration. Through interfacial engineering, the heterointerface generates significant charge accumulation. This effect introduces interfacial

polarization loss and enhances electromagnetic wave dissipation at the interface. The final total shielding effectiveness reaches 40.6 dB, enhanced by 3 times. The heterostructure also significantly optimizes electrical transport properties, achieving a maximum PF of $14.39 \mu\text{W m}^{-1} \text{K}^{-2}$, enhanced by fourfold. Furthermore, it demonstrates dual-mode sensing capability. The heterostructure resistance changes under tactile and stress stimuli, while the Seebeck voltage tracks temperature and respiration-induced thermal fluctuations. The sensor maintains stable signal fidelity even under external EMI. This multimodal response and electromagnetic interference immunity enable the device to acquire information such as human motion, contact pressure, body surface temperature, and respiratory status, potentially supporting multi-parameter flexible sensing applications such as electronic skin, wearable health monitoring, and intelligent human-computer interaction. Furthermore, this material system expands the functional dimensions of traditional flexible thermoelectric materials through the synergistic coupling of thermoelectric conversion, multimodal sensing, and electromagnetic protection, and provides a new design strategy for constructing multifunctional flexible composite materials that combine energy conversion, information sensing, and environmental adaptability.

2 Experimental methods

2.1. Preparation of $\text{Mo}_2\text{TiC}_2\text{T}_x$ and TaS_2 powder

To synthesize $\text{Mo}_2\text{TiC}_2\text{T}_x$, 1 g of $\text{Mo}_2\text{TiAlC}_2$ powder (Macklin, 200 mesh, 98%) was first introduced stepwise into 20 mL of a hydrofluoric acid (45%) solution under stirring. The reaction was then maintained at 55 °C for 48 h. Upon completion of etching, the mixture underwent repeated washing with deionized water (30 mL) to eliminate residual acidic species and impurities. The collected suspension was subsequently centrifuged at 3500 rpm for 5 min, after which the supernatant was removed. Finally, the obtained solid was freeze dried overnight to yield $\text{Mo}_2\text{TiC}_2\text{T}_x$ powder.

TaS_2 powders were synthesized by a solid-state reaction method. First, Ta (Aladdin, 99.9%) and S (Aladdin, 99.5%) powders were weighed according to the stoichiometric ratio, then ground and mixed in a mortar for 30 minutes to ensure a homogeneous mixture. Next, the mixed powder was transferred to a vacuum-sealed quartz tube and placed in a muffle furnace for heating. The temperature was gradually increased from room temperature to 950 °C over 8 hours, and held at this temperature for 24 hours to promote the reaction. Finally, the sample was cooled naturally to room temperature, and ground to fine TaS_2 powder.

2.2. Preparation of $\text{Mo}_2\text{TiC}_2\text{T}_x$ and TaS_2 nanosheet aqueous dispersion

For the preparation of the $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet dispersion, 0.2 g of dried multilayer MXene powder was dispersed into 0.2 g of 40 wt% tetrabutylammonium hydroxide (TBAOH) solution for intercalation and stirred at room temperature for 12 hours. The resulting mixture was washed twice,

and the precipitate was re-dispersed in deionized water, followed by ultrasonic treatment for 1 hour. The mixture was then centrifuged at 3000 rpm for 5 minutes, and the supernatant was carefully collected to obtain the $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet aqueous dispersion.

TaS_2 nanosheets were exfoliated by an alkaline ion intercalation method. First, TaS_2 (0.1g) powder was mixed with lithium hydroxide solution (LiOH , 1 mL, 2 M) in a centrifuge tube and allowed to react at 25 °C for 12 hours. The mixture was then washed 3 times with deionized (DI) water and centrifuged at 12,000 rpm for 15 minutes until the pH of the supernatant reached ~ 7 . The obtained expanded sediment was diluted with 80 mL of DI water and ultrasonically treated in an ice bath for 1 hour. Finally, the aqueous dispersion of TaS_2 nanosheets with a concentration of ~ 1.25 mg/mL was obtained by centrifugal separation.

2.3. Preparation of composite film

Directly mixed MTay ($\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$) film with a mass ratio of 1:y ($y = 0, 0.25, 0.5$ and 0.75) composite films were prepared by a one-step filtration method. Briefly, a mixed colloidal dispersion of $\text{Mo}_2\text{TiC}_2\text{T}_x$ and TaS_2 nanosheets was vacuum-filtered, and the resulting MTa film was dried at 30 °C under vacuum. For comparison, composite films with a sandwich structure were prepared by stepwise vacuum filtration. The specific steps are as follows: first, a layer of $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet aqueous dispersion was filtered onto a substrate; then, a layer of TaS_2 nanosheet aqueous dispersion was filtered onto the $\text{Mo}_2\text{TiC}_2\text{T}_x$ layer; finally, another layer of $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheet aqueous

dispersion was filtered on top of the TaS₂ layer. The as-prepared film was dried in a vacuum at 60 °C to obtain the MTM (Mo₂TiC₂T_x/TaS₂/Mo₂TiC₂T_x) film. The TMT (TaS₂/Mo₂TiC₂T_x/TaS₂) film was prepared by a similar procedure. The nominal mass ratios of the three layers in the MTM and TMT films were 0.5 : 0.75 : 0.5 and 0.375 : 1 : 0.375, respectively. These ratios were chosen so that the overall Mo₂TiC₂T_x/TaS₂ mass ratio in both sandwich films equals 1 : 0.75, ensuring direct comparability with the directly mixed MTa_{0.75} film.

2.4. Characterization

X-ray diffraction (XRD) measurements were performed on a Rigaku SmartLab system with CuK_α radiation ($\lambda = 0.1541$ nm) under ambient conditions for phase identification and crystal structure analysis. The cross-sectional morphology (SEM) was observed by scanning electron microscope (Hitachi Regulus 8100). X-ray photoelectron spectroscopy with Al K_α radiation was employed to determine elemental composition and chemical states (Thermo Fisher Scientific K-Alpha). Electrical conductivity, carrier concentration and Hall carrier mobility were obtained using a CH-100 Hall effect measurement system (CH-Magnetoelectricity Technology). The Seebeck coefficient was measured at room temperature using a PTM-3 (JouleYacht, Wuhan China). Flexibility was assessed by bending the films on glass tubes with different radii while recording conductivity variations. The resistance and voltage signals of the sensors were measured using a Keithley 6500 digital multimeter. Joule heating was recorded via infrared thermal imaging (UNI-T

UTi120S). Atomic Force Microscopy (AFM) and Kelvin Probe Force Microscopy (KPFM) measurements were performed on an Oxford Instruments Cypher atomic force microscope. Sample preparation involved spin-coating a $\text{Mo}_2\text{TiC}_2\text{T}_x$ dispersion onto a silicon substrate, followed by spin-coating a TaS_2 dispersion onto the surface to form the $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ interface. Tensile tests were performed using a DR-509A tensile testing machine (Dongguan Dongri Instrument Co., Ltd., China).

2.5. Calculations

Spin-polarized density functional theory (DFT) calculations were performed to investigate the electronic structure of $\text{Mo}_2\text{TiC}_2\text{T}_x$, TaS_2 , and $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ using the Vienna Ab initio Simulation Package (VASP) [33], which implements the projector-augmented wave (PAW) method [34,35]. Valence electrons behavior was describe using Kohn-Sham wave functions, which were expanded in a plane wave basis set with a kinetic energy cutoff of 520 eV [36]. The generalized gradient approximation (GGA) [37] was employed to account for electron exchange and correlation interactions, while vdW interactions were included using Grimme's DFT-D3 method [38] to model dispersive forces. Convergence criteria were set to ensure a total energy tolerance within 0.000001 eV and forces on each atom below 0.05 eV $\text{\AA}^{-1}$. The Python Materials Genomics (Pymatgen) [39] and Atomic Simulation Environment (ASE) [40] libraries were used for crystal structure construction and input file generation. The Materials Project database was used as the source for the

computational parameters of the bulk structures [41], and the VASP code is employed to analyze the work function and charge density difference [42].

3 Results and discussion

3.1. Synthesis and microstructures

The synthesis of $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ films is illustrated in Fig. 1(a). TaS_2 powder was prepared by solid-state reaction. Its XRD pattern matched that of the PDF card (PDF #80-0685) (Fig. S1 in the Electronic Supplementary Material (ESM)) [43], indicating a typical 2H- TaS_2 crystal structure. After treatment with LiOH , Li^+ ions are considered to enter the interlayer space of TaS_2 [44], weakening the vdW interactions between adjacent layers and promoting the expansion of the interlayer space. Subsequently, the liquid-phase shearing effect induced by ultrasonic treatment gradually exfoliated bulk TaS_2 into few-layer or monolayer TaS_2 nanosheets [45]. Simultaneously, the adsorption of $-\text{OH}^-$ on the nanosheet surface introduces electrostatic repulsion, improving dispersion stability and inhibiting aggregation. Compared to dark gray or black bulk TaS_2 , the exfoliated TaS_2 nanosheet dispersion exhibits a distinctly yellow color (Fig. S2 in the ESM) [30], due to changes in the altered light absorption and scattering behavior [46].

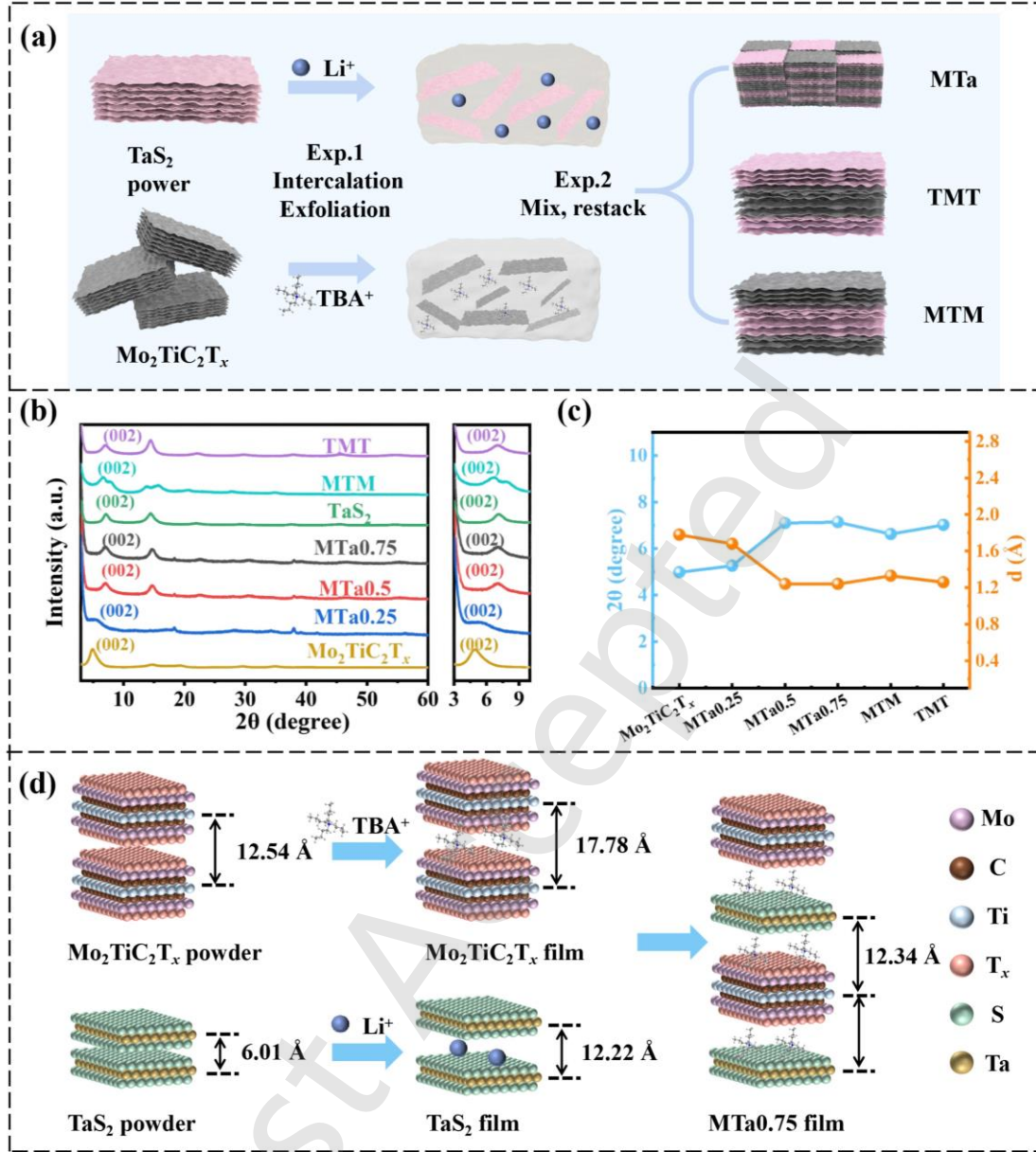


Fig. 1. (a) Schematic illustration of the fabrication process for three types of composite films via vacuum-assisted filtration: MTa (mixed $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ with varying mass ratios), TMT ($\text{TaS}_2/\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ sandwich structure), and MTM ($\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2/\text{Mo}_2\text{TiC}_2\text{T}_x$ sandwich structure). (b) XRD patterns of pristine $\text{Mo}_2\text{TiC}_2\text{T}_x$ (M), TaS_2 , and composite films MTa0.25, MTa0.5, MTa0.75, MTM, and TMT. (c) Relationship between the interlayer spacing and the corresponding 2θ angle for the films shown in (b). (d) Schematic representation of the structural evolution from the initial bulk $\text{Mo}_2\text{TiC}_2\text{T}_x$ and TaS_2 powders, through the intercalated phases (Li^+ or TBA^+ intercalation), to the final exfoliated nanosheets and the assembled MTa composite film, illustrating the expansion of interlayer spacing and the subsequent restacking process.

Concurrently, the Al atomic layer within $\text{Mo}_2\text{TiAlC}_2$ powder was preferentially etched with HF, inducing a characteristic shift in the (0 0 2) peak from 9.46° to 7.04° , corresponding to an interlayer expansion from 0.93 to 1.25 nm (Fig. S1 in the ESM). The structural transformation also arises from the introduction of groups such as $-\text{O}^-$ and $-\text{OH}^-$ [47]. Subsequent intercalation by TBA^+ ions, ultrasonication, and centrifugation yielded a dark red colloidal suspension of $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheets (Fig. S3 in the ESM). Compared to the multilayer $\text{Mo}_2\text{TiC}_2\text{T}_x$ powder, the (0 0 2) peak of the deposited $\text{Mo}_2\text{TiC}_2\text{T}_x$ film shifted to a lower angle, indicating a further increase in interlayer spacing (Fig. S1) [48]. The MTay ($\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$) film with a mass ratio of 1: y ($y = 0, 0.25, 0.5$ and 0.75) was prepared by uniformly mixing and vacuum-assisted filtration of the aqueous dispersion of TaS_2 and $\text{Mo}_2\text{TiC}_2\text{T}_x$ nanosheets. XRD results (Figs. 1(b)–(c)) revealed that as the TaS_2 content increases, the (0 0 2) diffraction peak gradually shifted toward higher angles. This change is due to the introduction of TaS_2 , which alters the stacking mode and layered arrangement of $\text{Mo}_2\text{TiC}_2\text{T}_x$ sheets, leading to a rearrangement of the layered structure [49,50]. The interlayer spacing of the MTa0.75 film slightly decreased to ~ 1.23 nm (Fig. 1(d)).

In the $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2/\text{Mo}_2\text{TiC}_2\text{T}_x$ (MTM) sandwich structure film with only two heterogeneous interfaces, characteristic XRD diffraction peaks from both TaS_2 and $\text{Mo}_2\text{TiC}_2\text{T}_x$ are observed. This indicates that both components retain their respective crystal structures in the MTM sandwich film, without significant crystal phase reconstruction or new phase formation. In contrast,

in $\text{TaS}_2/\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ (TMT), the diffraction signal from the intermediate MXene layer was not clearly detected. This phenomenon may be related to the strong diffraction response of the high-atomic-number Ta element in the TaS_2 layer [51].

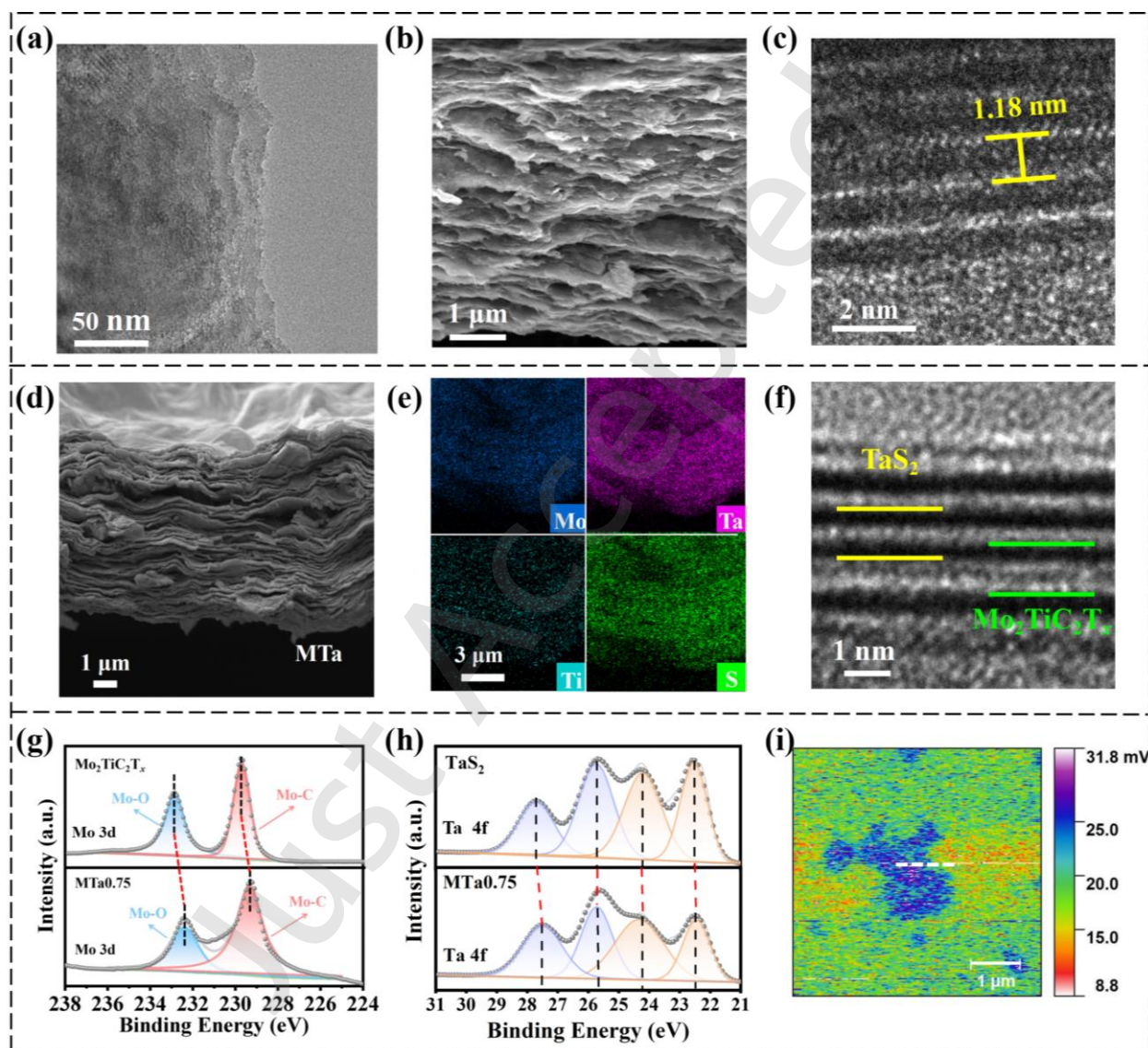


Fig. 2. (a) TEM image of pristine $\text{Mo}_2\text{TiC}_2\text{T}_x$ powder. (b)–(c) Cross-sectional SEM (b) and TEM (c) of TaS_2 film. (d) Cross-sectional SEM image and (e) corresponding EDS maps of the $\text{MTa}_{0.75}$ film. (f) TEM image of the $\text{MTa}_{0.75}$ film. (g) High-resolution XPS spectra of Mo 3d for M and $\text{MTa}_{0.75}$. (h) High-resolution XPS spectra of Ta 4f for TaS_2 and $\text{MTa}_{0.75}$. (i) KPFM contact potential difference (CPD) distribution map of the MTa film.

The $\text{Mo}_2\text{TiC}_2\text{T}_x$ powder exhibits a typical layered structure with relatively uniform elemental distribution (Fig. 2(a) and Fig. S4 in the ESM). However, trace amounts of Al were still detected by EDS (Fig. S4 in the ESM), suggesting the possible presence of a small amount of incompletely removed Al in the precursor. SEM and TEM images of the TaS_2 film show a distinct layered stacking characteristic with an interlayer spacing of ~ 1.2 nm (Figs. 2(b)–(c)). As shown by the cross-sectional morphology of the MTa0.75 film (Fig. 2(d)), $\text{Mo}_2\text{TiC}_2\text{T}_x$ and TaS_2 nanosheets overlap and form a layered structure, indicating that the two 2D components achieved close interlayer contact during vacuum filtration-assisted self-assembly [52]. EDS analysis revealed uniform elemental distribution of the two components (Fig. 2(e)). Furthermore, TEM images further revealed the formation of an ordered layered heterostructure between $\text{Mo}_2\text{TiC}_2\text{T}_x$ and TaS_2 nanosheets, exhibiting an interlayer spacing of 1.2 nm (Fig. 2(f)). Cross-sectional TEM and EDS analyses reveal wavy heterogeneous interfaces and distinct elemental distributions in MTM and TMT films (Figs. S5 and S6 in the ESM).

The XPS spectra of $\text{Mo}_2\text{TiC}_2\text{T}_x$, TaS_2 and MTa0.75 films are shown in Fig. S7 in the ESM and Figs. 2(g)–(h), respectively. The MTa0.75 film exhibits clear Mo 3d and Ta 4f peaks, indicating the successful construction of the $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ heterostructure (Fig. S7 in the ESM). As shown in Fig. 2(g), in the Mo 3d spectrum of $\text{Mo}_2\text{TiC}_2\text{T}_x$, characteristic peaks appear at 229.78 eV and 232.94 eV, respectively, attributing to Mo_2C carbides and Mo-O component [53]. Compared with $\text{Mo}_2\text{TiC}_2\text{T}_x$, the

characteristic peaks of the Mo 3d region in the MTa0.75 film shifted towards lower binding energies. The proportion of Mo–O peak area decreased, while the relative proportion of Mo₂C carbides increased. Figure 2(h) shows that the Ta 4f XPS spectrum of the TaS₂ film exhibits a set of characteristic peaks at 22.56 and 24.26 eV, corresponding to the 4f_{7/2} and 4f_{5/2} states of Ta⁴⁺, respectively. Another set of bimodal peaks at 25.79 and 27.71 eV can be attributed to the Ta 4f_{7/2} and Ta 4f_{5/2} signals of the Ta⁵⁺ respectively, indicating slight surface oxidation of the TaS₂ nanosheets. This phenomenon may stem from the increased specific surface area on the nanosheets after exfoliation, making them more susceptible to surface oxidation [54]. XPS primarily reflects chemical state information within a few nanometers of the material surface, whereas XRD characterizes the average crystal structure of the sample bulk phase. Therefore, although small amounts of surface oxide species can be detected by XPS, they are insufficient to produce resolvable diffraction peaks in the XRD pattern. The Ta 4f peak of the MTa0.75 film shifts towards a lower binding energy direction compared to pure TaS₂. This may be related to electronic interactions at the Mo₂TiC₂T_x/TaS₂ interface, indicating that the two components are not simply physically stacked, but rather exhibit a certain degree of interfacial coupling [55]. KPFM characterization further reveals the potential distribution at the MTa heterointerface. As shown in Fig. 2(i), a distinct CPD difference is observed between the Mo₂TiC₂T_x and TaS₂ regions; line-scan results across the interface indicate an average CPD difference of approximately 20.9 mV between the two sides, signifying a localized variation in

surface potential near the interface (Fig. S8 in the ESM). Work functions and charge density difference calculated by DFT (section 3.5), a work-function gap of 0.24 eV between TaS₂ and Mo₂TiC₂T_x, indicating a tendency for electrons to transfer from TaS₂ to Mo₂TiC₂T_x upon contact. These results further confirm interfacial electronic coupling between Mo₂TiC₂T_x and TaS₂, accompanied by interfacial charge redistribution.

3.2. Thermoelectric performance

As shown in Figs. 3(a)–(b), the variation in TaS₂ content significantly affects the carrier transport behavior of the Mo₂TiC₂T_x-based composite films. The pristine Mo₂TiC₂T_x film exhibits a low carrier mobility (μ) of only 0.11 cm² V⁻¹ s⁻¹. With increasing TaS₂ content, the μ of the MTa film gradually increases, reaching a maximum of 0.80 cm² V⁻¹ s⁻¹ in MTa1. This change is considered not only determined by a weighted average of each intrinsic mobility, but also related to the interfacial coupling of Mo₂TiC₂T_x and TaS₂ nanosheets. The MTa film, prepared by a mixing method, consists of few-layer, even monolayer, Mo₂TiC₂T_x and TaS₂ nanosheets that alternate and are in extensive contact, with TaS₂ bridging adjacent Mo₂TiC₂T_x nanosheets. This architecture maximizes interfacial coupling and minimizes contact impedance and interfacial scattering during carrier transport, giving MTa the highest mobility among the three films [56]. In contrast, TMT and MTM are micron-thick layer-by-layer stacks with interlayer planar interfaces, so interlayer coupling is weaker than in MTa [57]. Since TaS₂ has a much higher intrinsic mobility than Mo₂TiC₂T_x, all TaS₂-containing films

exceed pristine M. TMT outperforms MTM because the high-mobility TaS₂ layers dominate its conducting channel more strongly, whereas in MTM the thicker Mo₂TiC₂T_x layers and their larger interlayer spacing (~1.78 vs. ~1.22 nm) amplify interlayer separation effects and lower mobility [58]; both nevertheless remain below MTa due to weaker interlayer coupling [58]. Meanwhile, the carrier concentration (n) of the composite film increases with increasing TaS₂ content. It tends to stabilize after $y \geq 0.5$, indicating that the regulatory effect of TaS₂ on n gradually reaches saturation.

According to Formula (1):

$$\sigma = n \mu e \quad (1),$$

the n and μ determine σ jointly. Since the n of the thin film remains relatively stable after $y \geq 0.5$, the further increase in σ in MTa mainly comes from the improvement in μ . The TMT and MTM sandwich structures exhibit a clear layer sequence, but TaS₂ and Mo₂TiC₂T_x exist as relatively thick independent layers. The heterogeneous contacts are mainly concentrated at the macroscopic interlayer interfaces, making carrier transport across layers more susceptible to limitations imposed by interfacial contact resistance and potential barriers. Therefore, MTa exhibits higher σ than TMT and MTM. As shown in Fig. 3(c), the σ of the MTa0.75 film reaches 878.3 S cm⁻¹, which is enhanced by ~23 times. Therefore, the high mobility and excellent conductivity exhibited by MTa are not only attributed to the conductive bridge, but may also be related to the regulatory effect of the Mo₂TiC₂T_x/TaS₂ heterointerface on electron transport behavior.

To further understand the intrinsic electronic origin of the optimized carrier transport, we calculated the band structures of pristine $\text{Mo}_2\text{TiC}_2\text{T}_x$, TaS_2 and their heterostructure (Fig. S9 in the ESM). Both $\text{Mo}_2\text{TiC}_2\text{T}_x$ and TaS_2 exhibit metallic character, with multiple bands crossing the Fermi level without a detectable band gap. After constructing the $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ heterostructure, the band folding and enriched electronic states near E_f originate from interlayer orbital coupling. This modification of band structure facilitates carrier transport across the heterointerface, consistent with the enhanced mobility and electrical conductivity observed in the MTa composite films.

As shown in Fig. 3(d), the absolute value of the Seebeck coefficient ($|S|$) of the composite thin film gradually decreases with increasing TaS_2 content, and then basically stabilizes after MTa0.5. This change is partly due to the low $|S|$ of TaS_2 ($10.8 \mu\text{V K}^{-1}$). As the TaS_2 content increases, its contribution to the overall electrical transport gradually strengthens, thus decreasing the overall $|S|$. On the other hand, according to the single parabolic band model, S can be expressed by Formula (2):

$$S = \frac{8\pi^2 k_B^2}{3eh^2} m^* T \left(\frac{\pi}{3n} \right)^{2/3} \quad (2),$$

where k_B denotes the Boltzmann constant, h is Planck constant, m^* represents the effective mass of the carrier, and T is the absolute temperature. This relationship shows that an increase in n usually decreases $|S|$. Combined with Hall test results, the decrease in $|S|$ in the low TaS_2 content range is mainly related to the increase in n ; when y reaches 0.5, both n and $|S|$ tend to stabilize. Although the introduction of TaS_2 reduces $|S|$, the improvement in σ is more significant. Ultimately, the PF of the

MTa0.75 film reached $14.39 \mu\text{W m}^{-1} \text{K}^{-2}$, representing a ~ 4 fold increase compared to the pristine $\text{Mo}_2\text{TiC}_2\text{T}_x$ film. Upon further increasing the TaS_2 content, the electrical conductivity of MTA1 film rose to 996.68 S cm^{-1} , but the $|S|$ dropped to $11.1 \mu\text{V K}^{-1}$, resulting in a decrease in the power factor to $12.28 \mu\text{W m}^{-1} \text{K}^{-2}$. This indicates that MTA0.75 has an optimal compositional ratio.

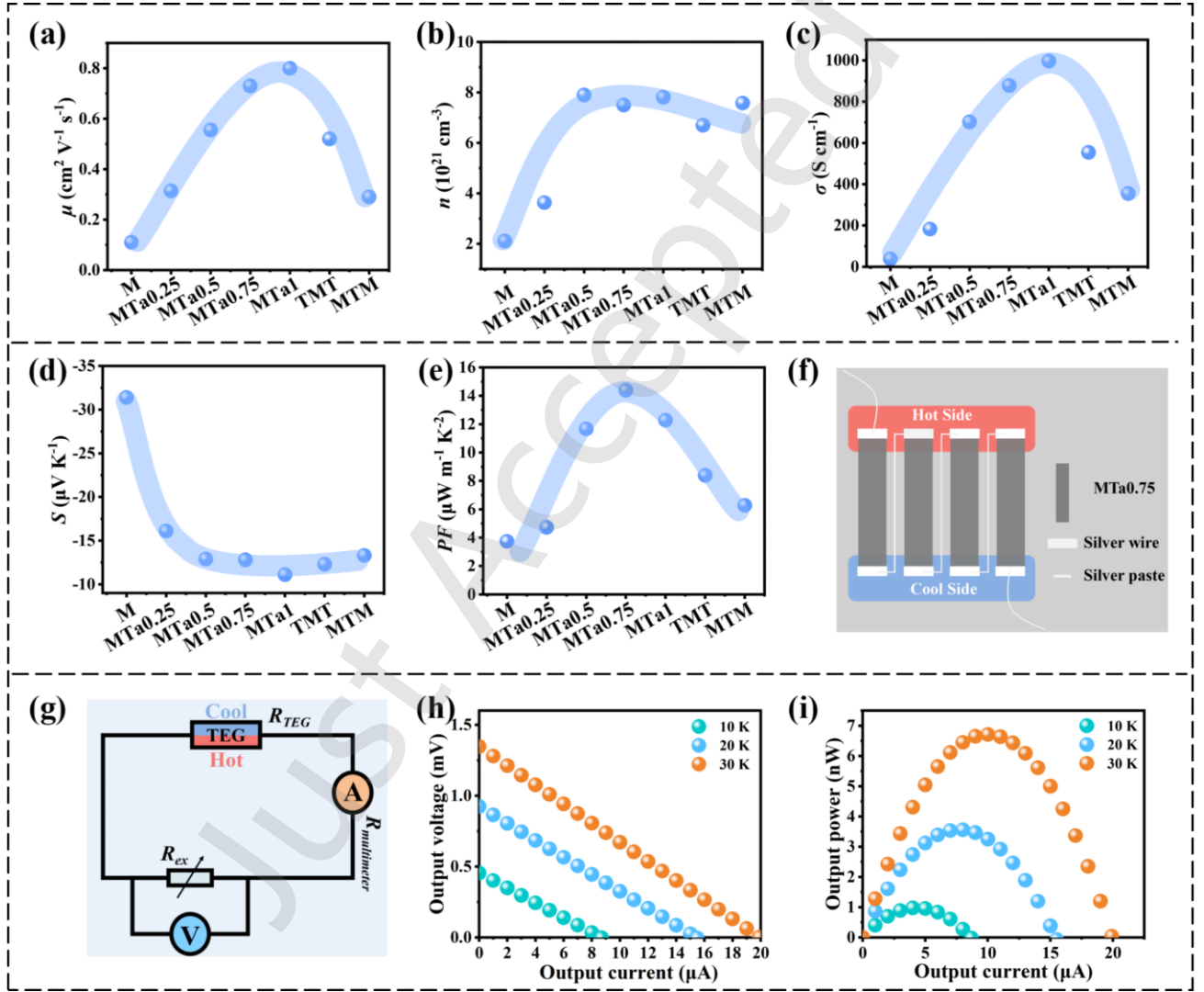


Fig. 3. (a) Carrier mobility (μ), (b) carrier concentration (n), (c) electrical conductivity (σ), (d) Seebeck coefficient (S) and (e) Power factor (PF) of M, MTa0.25, MTa0.5, MTa0.75, MTa1, TMT, and MTM films. (f) Schematic diagram of a thermoelectric generator (TEG) fabricated using four pieces of MTa0.75 film. (g) Schematic diagram of the measurement circuit for the TEG device. (h) Output voltage (V) as a function of current (I) under temperature differences (ΔT) of 10 to 30 K. (i) Output power (P) as a function of I under the same ΔT values.

Figure 3(f) schematically shows a flexible four-legged TE generator (TEG) made of MTa0.75 film. A variable resistor is then integrated to form a circuit (Fig. 3(g)). Figure 3(g) shows the circuit configuration constructed with a variable resistor. The electrical behavior of the TEG under open-circuit conditions is given in Fig. 3(h). With ΔT varying between 10 and 30 K, the device output voltage increases from 0.45 to 1.35 mV, and the output power (P) is calculated as:

$$P = \left(\frac{V_{oc}}{R_{in} + R_{Load}} \right)^2 R_{Load} \quad (3),$$

where R_{Load} and R_{in} correspond to the load resistance and internal resistance, respectively, and V_{oc} represents the open-circuit voltage. As illustrated in Fig. 3(i), the maximum output power (P_{max}) increases from 0.98 to 6.71 nW when the temperature difference (ΔT) is rises from 10 to 30 K.

3.3. Temperature, respiration and tactile sensor

Based on the Seebeck effect, the TE film can generate a voltage signal from a ΔT at room temperature, enabling temperature sensing. Figure 4(a) shows the variation in output voltage of a sensor consisting of a single MTa0.75 leg under different ΔT conditions (5 to 17 K). As the ΔT increases, the output voltage amplitude increases (Fig. S10 in the ESM). Figure 4(b) illustrates the non-contact temperature sensing capability. When a finger is placed at distances between 2 and 10 mm from the sensor, the output voltage is inversely proportional to the distance. Figure 4(c) shows the sensor output upon contact with hot water and ice water. Contact with hot water generates a positive voltage signal, while contact with ice water generates a negative signal.

A face mask integrated with a TE sensor was used to monitor human breathing patterns. One end of the sensor is exposed to the ambient air outside the mask, and the other end is placed inside the mask near the upper lip (Fig. 4(d) and Fig. S11 in the ESM). During respiration, the ΔT between the air inside and outside the mask generates a voltage signal. Figure 4(e) shows the respiratory rate monitoring results for a subject in different body positions. In a standing position, the respiratory cycle was 2.92 s, corresponding to a respiratory rate (RR) of 20.55 breaths per minute (bpm). Upon transitioning to a squatting position, the respiratory cycle shortened to 1.86 s (32.26 bpm). In a sitting position, the respiratory cycle was 2.09 s (28.75 bpm). To further assess the sensor reliability for respiratory monitoring in human, we conducted repeated tests on five individuals with diverse gender and body characteristics (Fig. S12 and Table S1 in the ESM). We obtained clear, continuous, and periodic respiratory signals from each subject across multiple states. Notably, the subject in Fig. 4 (e) is the same as in Fig. S12(a) in the ESM. Despite an interval of ~6 months between the two tests, the respiratory responses showed excellent reproducibility, indicating that the sensor maintains stable monitoring performance over time after packaging. The respiratory signals were also recorded in a completely resting state over ~10 minutes (Fig. 4(f)), showing a respiratory cycle of 3.57 s (16.8 bpm). Figure 4(g) displays the output voltage during repeated finger-contact for 1200 seconds, with only slight signal fluctuations.

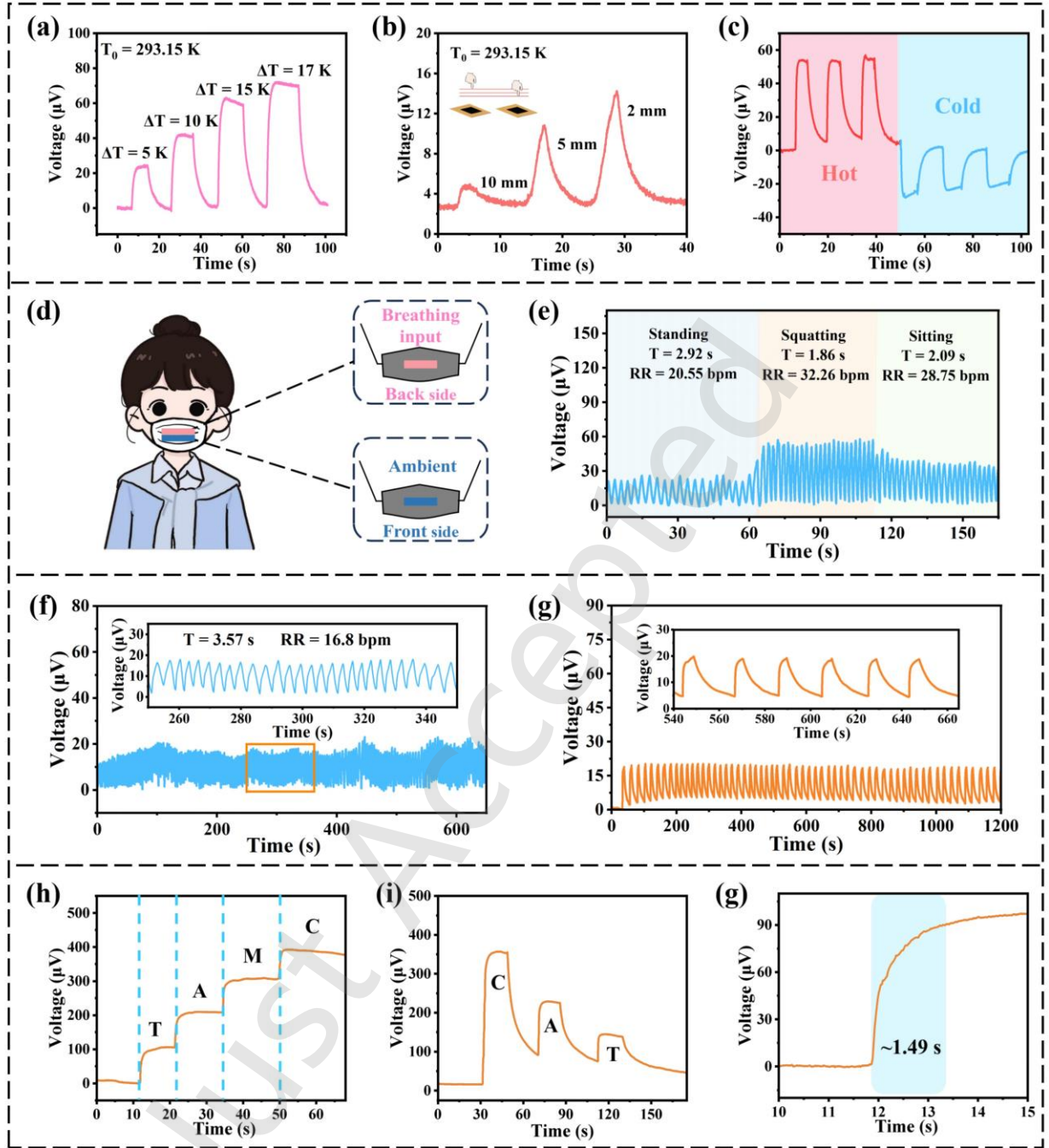


Fig. 4. (a) Output voltage of the MTa0.75 sensor under temperature differences of 5 to 17 K. (b) Output voltage as a function of finger-to-sensor distance (2–10 mm) for non-contact temperature sensing. (c) Output voltage signals when the sensor is sequentially contacted with hot water and ice water. (d) Schematic illustration of the smart mask with an integrated respiration sensor. (e) Respiratory signals of a subject in different body postures. (f) Respiration sensor signal over ~ 10 min at rest. (g) Touch sensor signal during repeated finger contacts over 1200 s. (h) Output voltage generated by touches with one, two, three, and four fingers. (i) Sequence of finger touches forming the word “CAT” (four-finger, two-finger, one-finger). (j) Response time of the sensor to a single finger touch, measured as ~ 1.49 s.

Four MTa0.75 thermoelectric legs were connected electronically in series and thermally in parallel to construct a flexible thermoelectric sensor, as schematically illustrated in Fig. 3(f). When different numbers of fingers are placed on the sensor surface, the output voltage changes accordingly (Fig. 4(h) and S13 in the ESM). The voltage signal from a single finger touch was defined as the letter “T”, and the signals from two, three, and four fingers as “A”, “M”, and “C”, respectively. Using these symbols, sequences of touches can form words. Figure 4(i) shows the word “CAT” generated via sequential finger contact (four, two and one fingers). Figure 4(j) presents the sensor response time upon finger contact, measured at ~1.49 s.

3.4. Pressure sensor

The MTa0.75 thin films can also be used for constructing piezoresistive sensors through multilayer stacking. Specifically, 10 layers of MTa0.75 thin films were stacked. Under external pressure or bending, the contact area and contact resistance between adjacent films change, thereby altering the device resistance and enabling piezoresistive sensing. Figure S14 in the ESM shows a physical image of the sensor after it has been encapsulated with ordinary office tape, and illustrates the structural evolution of the 10-layer stacked film under compressive load. The compression process consists of two stages: compression between adjacent layers, and compression of nanopores between MXene and TaS₂ nanosheets. Under external force, the contact area between adjacent MTa0.75 films increases, reducing the interlayer contact resistance. Simultaneously, local voids

between the layers are compressed, gradually increasing the number of conductive pathways, which alters the device resistance and produces a piezoresistive response [59].

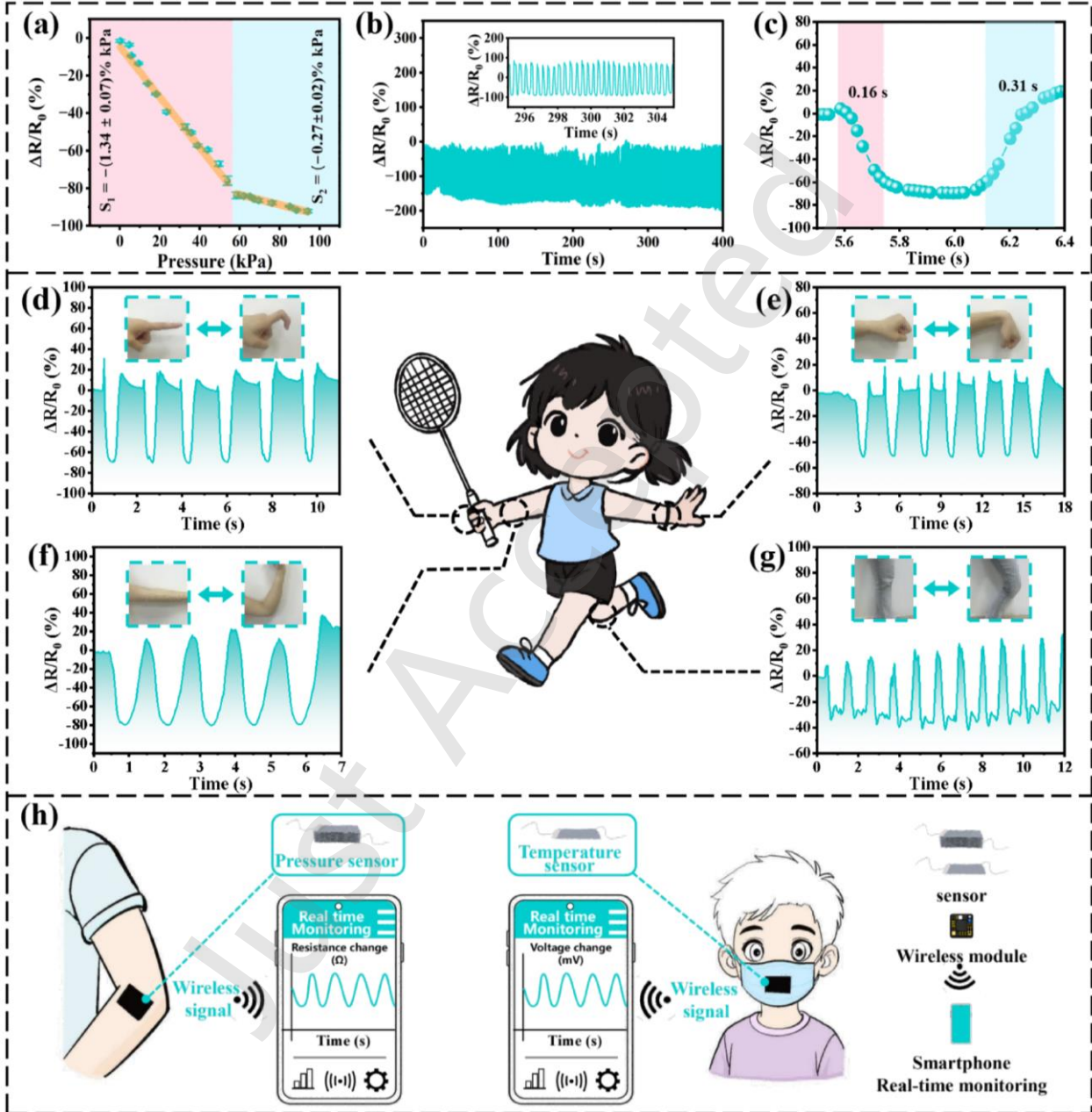


Fig. 5. (a) Change in resistance as a function of pressure. S_1 and S_2 denote the sensitivity coefficients in the pressure ranges of 0–60 kPa ($1.38\% \text{ kPa}^{-1}$) and 60–100 kPa ($0.26\% \text{ kPa}^{-1}$), respectively. (b) Normalized resistance change of the sensor after more than 1000 bending cycles. Inset: magnified view of selected cycles. (c) Single response and recovery time of the sensor during a bending cycle: 0.16 s and 0.31 s, respectively. (d–g) Resistance signals of the sensor integrated into (d) finger, (e) wrist, (f) elbow, and (g) knee joints for motion monitoring. (h) Schematic diagram of the sensor

connected to a wireless module, with integration into a mask and an elbow for wireless monitoring of breathing and elbow flexion.

Figure 5(a) shows the resistance changes in different pressure ranges (0~60 kPa and 60~100 kPa), exhibiting sensitivities of $-(1.34 \pm 0.07) \% \text{ kPa}^{-1}$ and $-(0.26 \pm 0.02) \% \text{ kPa}^{-1}$ respectively. After undergoing more than 1000 consecutive cycles at a bending angle of not less than 160° , the sensor output signal remained relatively stable with minimal attenuation (Fig. 5(b)). Furthermore, we compared this sensor sensitivity and cyclic stability with those of previously reported MXene-based flexible pressure sensors. As shown in Table S2 in the ESM, the sensitivity of our sensor ($1.34\% \text{ kPa}^{-1}$) is comparable to that of MXene@CS@PU sponge ($1.4\% \text{ kPa}^{-1}$) and MXene/PVA/DES ($1.09\% \text{ kPa}^{-1}$), while its cyclic stability (>1000 cycles) is comparable to F-Mene/MXene/TPU (1000 cycles). It should be noted that sensors with higher sensitivity, such as MXene@PDMS ($9 \% \text{ kPa}^{-1}$) and TPU/PDA/MXene ($3.02 \% \text{ kPa}^{-1}$), generally operate over a much narrower pressure range (0–3 kPa and 0.49–30 kPa, respectively), whereas our sensor maintains a stable response over a wider range (0–100 kPa). Furthermore, the sensor prepared in this study responds rapidly to a single bending stimulus, with response and recovery times of 0.16 s and 0.31 s, respectively (Fig. 5(c)).

The sensor was further integrated into fingers, wrist, elbow, and knee joints for real-time motion monitoring. Figures 5(d)–(g) show that movements of different joints result in regular changes in the sensor resistance signal. To further verify the practical application potential, the sensor was connected to a wireless acquisition module, enabling real-time wireless detection of temperature and

pressure signals (Fig. 5(h)). As shown in Videos S1–S2 and Figs. S15–S16 in the ESM, after integration into the wrist, the sensor accurately identifies joint movement across different bending angles and can also be used for respiratory monitoring. In a comparison experiment between finger pressing and pen cap pressing, finger pressing produced temperature responses, whereas pen did no obvious temperature signal (Video S3 and Fig. S17 in the ESM). Thus, this device can distinguish between thermal and mechanical stimuli, demonstrating good recognition capabilities and potential for wireless applications. Based on the above characterization results, the sensor maintains stable output even under repeated bending conditions, demonstrating good bending durability and surface conformation capability, making it suitable for pressure monitoring on non-flat surfaces such as human joints.

3.5. Electromagnetic shielding performance

Figure 6(a) shows the EMI shielding performance of the M, MTM, TMT, and MTa0.75 films in the frequency range of 8.2–12.4 GHz. According to classical Schelkunoff theory, the total shielding effectiveness (SE_T) characterizes a material overall attenuation capability for incident electromagnetic waves; a higher value indicates that less electromagnetic wave ultimately passes through the material. SE_T can be expressed as:

$$SE_T = SE_R + SE_A + SE_M \quad (4),$$

where SE_R , SE_A , and SE_M represent contributions from reflection, absorption, and multiple internal

reflections. When $SE_A \geq 10$ dB, the electromagnetic waves are sufficiently attenuated within the shielding material, and the contribution of SE_M becomes negligible [60]. Under this condition, SE_T can be simplified as:

$$SE_T \approx SE_R + SE_A \quad (5),$$

therefore, SE_T is primarily determined by SE_R and SE_A . If SE_A is significantly higher than SE_R , absorption loss plays a dominant role in the overall shielding effectiveness.

The MTa0.75 film exhibits the highest EMI shielding performance, with a SE_T of 40.6 dB, which is 2.8 times that of the pristine M film (14.1 dB). Figure 6(b) presents the average SE_R , SE_A , and SE_T values of the different films. Both SE_R and SE_A show an upward trend, indicating that both reflection and absorption contribute to the EMI performance [15]. In all samples, SE_R and SE_A increase simultaneously, and SE_T also improves significantly, indicating that the enhanced EMI shielding performance stems from synergistic improvements in both reflection and absorption losses. Moreover, the SE_A values of all samples are consistently higher than their corresponding SE_R values, confirming that absorption is the dominant contributor to the shielding performance. Figure 6(c) shows the SE_A/SE_T ratios of the different films. The SE_A/SE_T ratios for the M, MTM, TMT and MTa0.75 films are 69.5%, 69.8%, 63.4% and 63.4%, respectively. All ratios exceed 50%, further indicating that absorption loss dominates the overall shielding effectiveness.

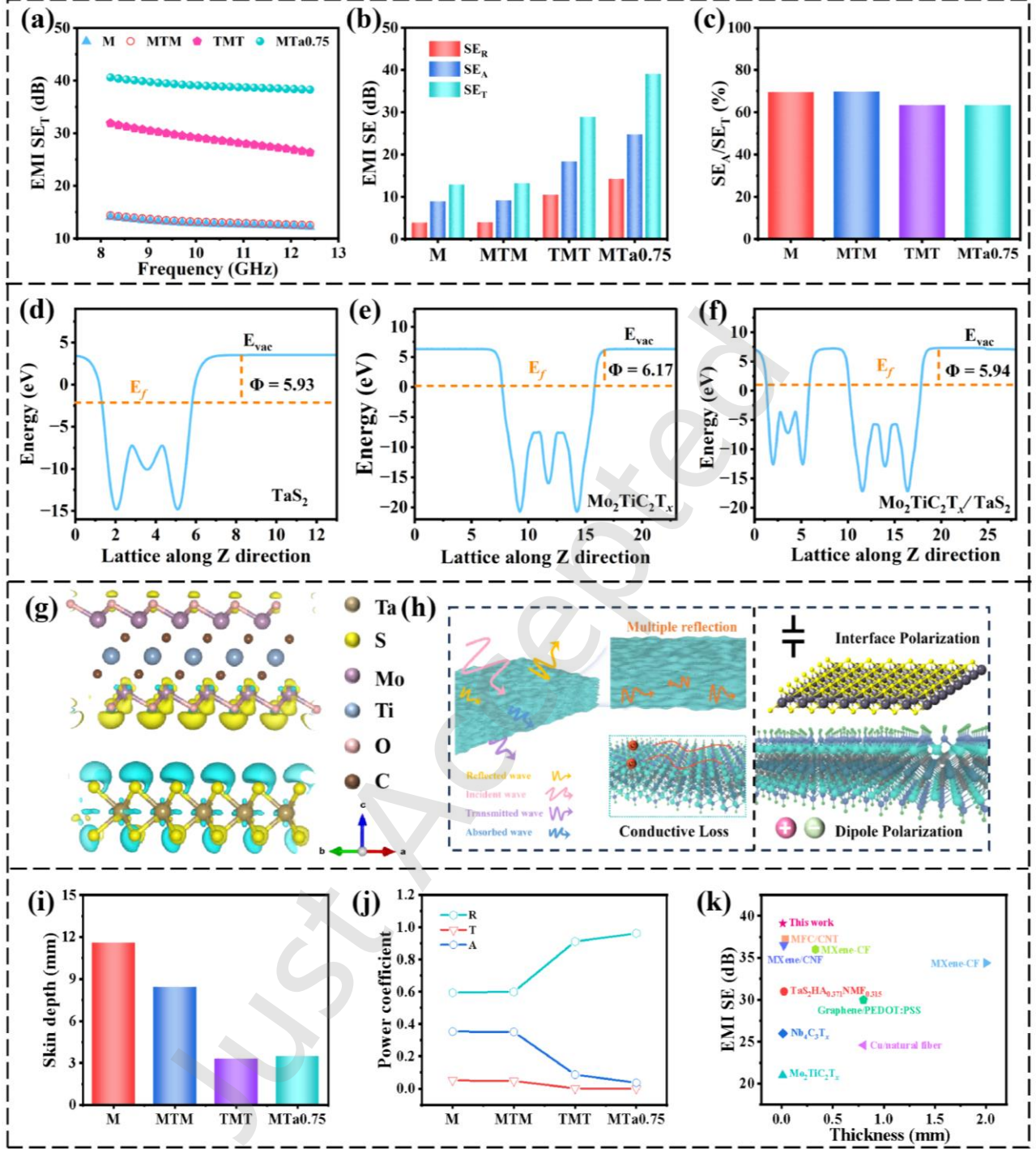


Fig. 6. (a) Total EMI shielding effectiveness (SE_T) in the frequency range of 8.2–12.4 GHz, (b) Average SE_T , SE_A , and SE_R values, (c) SE_A/SE_T ratios for M, MTM, TMT, and MTa0.75 films. (d–f) Calculated average electrostatic potential distributions for (d) TaS_2 , (e) $Mo_2TiC_2T_x$, and (f) the $Mo_2TiC_2T_x/TaS_2$ heterostructure. E_f : Fermi energy; E_{vac} : electrostatic potential in the vacuum region; Φ : work function. (g) Charge density difference at the $Mo_2TiC_2T_x/TaS_2$ interface. Cyan and yellow regions represent charge depletion and accumulation, respectively. (h) Schematic diagram of the EMI shielding mechanism. (i) Skin depth (δ) of the four films. (j) Reflectance (R), absorptance (A), and transmittance (T) of the films. (k) Comparison of EMI shielding effectiveness as a function of

thickness between this work and reported literature.

This absorption-dominated shielding characteristic is closely related to changes in the charge distribution after the formation of the $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ heterostructure [9]. Theoretical calculations of the electrostatic potential show that the work functions of TaS_2 and $\text{Mo}_2\text{TiC}_2\text{T}_x$ are ~ 5.93 , 6.17 eV respectively, while the work function of the $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ heterostructure is ~ 5.94 eV (Figs. 6(d)–(f)), indicating a change in electronic energy levels after recombination. Further analysis of the differential charge density (Fig. 6(g)) reveals a localized redistribution of charge near the $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ interface. This non-uniform charge distribution facilitates the formation of polarization centers at the heterojunction interface, enhancing interfacial polarization and dipole relaxation loss, thereby improving its ability to absorb electromagnetic waves [61]. In addition, the layered $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ structure extends the propagation path of electromagnetic waves within the film, causing multiple reflections and scatterings between adjacent layers and heterointerfaces, thereby enhancing the dissipation within the multiple interfacial structure (Fig. 6(h)).

Skin depth (δ) is defined as the characteristic distance over which an incident electromagnetic wave decays exponentially to $1/e$ ($\sim 36.8\%$) of its initial intensity, serving as an important parameter for evaluating the electromagnetic shielding ability of the material. The δ can be calculated by Formula (6) [62]:

$$\delta = 8.686 \times \left(\frac{d}{\text{SE}_A} \right) \quad (6),$$

where d is the film thickness. Figure 6(i) shows that the TMT and MTa0.75 films have lower δ values, indicating stronger attenuation capabilities against electromagnetic waves. Figure 6(j) further shows the reflectance (R), absorptance (A), and transmittance (T) of each sample. In particular, a 10 μm thick MTa0.75 film exhibits a reflectance as high as 0.96, indicating that the transmittance of electromagnetic waves through this material is extremely low, and the vast majority of incident electromagnetic waves are effectively blocked. This is primarily due to the high σ of the MTa0.75 film; higher σ increases the impedance mismatch between the material and free space, causing the film to surface reflect a portion of the incident electromagnetic waves. The above results further demonstrate that the MTa0.75 composite film can not only effectively block electromagnetic waves from passing through, but also attenuate those that enter the film, exhibiting highly efficient electromagnetic shielding dominated by absorption loss. Figure 6(k) compares the shielding performance of composite materials with different thicknesses [27,43,63–70]. Under similar thickness conditions, the MTa0.75 film still exhibits a higher EMI SE, indicating a significant advantage in EMI shielding performance.

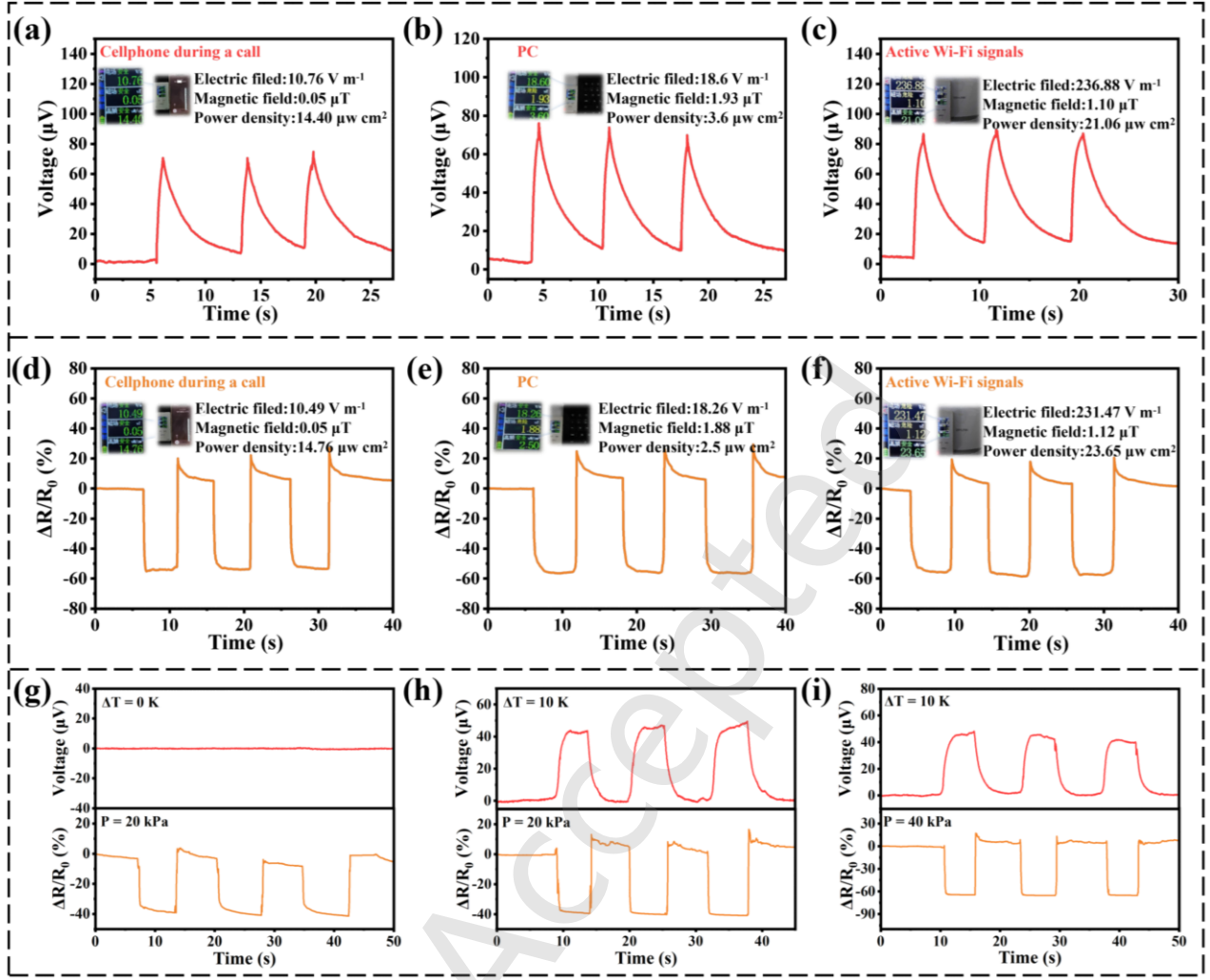


Fig. 7. (a–c) Output of the temperature sensor under different electromagnetic fields: (a) near a mobile phone during a call, (b) near a PC, (c) near an active Wi-Fi signal. (d–f) Output of the pressure sensor under the same interference conditions: (d) near a mobile phone during a call, (e) near a PC, (f) near an active Wi-Fi signal. (g–i) Output voltage and resistance changes of the stacked sensor under combined temperature and pressure stimuli: (g) $\Delta T = 0$ K, $P = 20$ kPa; (h) $\Delta T = 10$ K, $P = 20$ kPa; (i) $\Delta T = 10$ K, $P = 40$ kPa. The outputs remain stable and show no cross-interference.

3.6. Anti-interference and decoupled bimodal sensing

EMI shielding is essential for flexible sensors operating in everyday environments with various EMI sources. Figures 7(a)–(f) show the output of a sensor assembled from 10 stacked MTa0.75 interlayers under interference from mobile phone calls, personal computer (PC) electromagnetic

fields, and active Wi-Fi signals. Both the temperature and pressure sensors maintain stable output under these conditions. The temperature-pressure dual-parameter sensing performance of the MTa0.75 sensor was further evaluated. As shown in Figs. 7(g)–(i), the sensor responds stably to both temperature changes and pressure stimuli, with no significant cross-interference between the two signal types. This is because the temperature signal arises from the TE output, while the pressure signal originates from force-induced resistance change. Consequently, the MTa0.75 sensor can reliably output independent temperature and pressure signals, demonstrating effective signal decoupling and reliable dual-parameter sensing.

3.7. Flexibility, photothermoelectric performance and joule heat

Cyclic bending tests were conducted on the MTa0.75 film to evaluate its bending stability. After 100–500 bending cycles at a bending angle exceeding 160°, the S remained below 10% relative change (Fig. 8(a)). To further test flexibility, the MTa0.75 film was progressively bent over glass tubes with decreasing bending radii. The resistivity ratio (R_s/R_0 , R_s : film resistivity at bending state; R_0 : film resistivity at flat state) remained below the value and remained within a 10% variation until the bending radius reached 5 mm (Fig. 8(b)), indicating that the conductive channel is not seriously damaged even under large deformation. This flexibility is attributed to the vdW interactions between MXene and TaS₂ nanosheets.

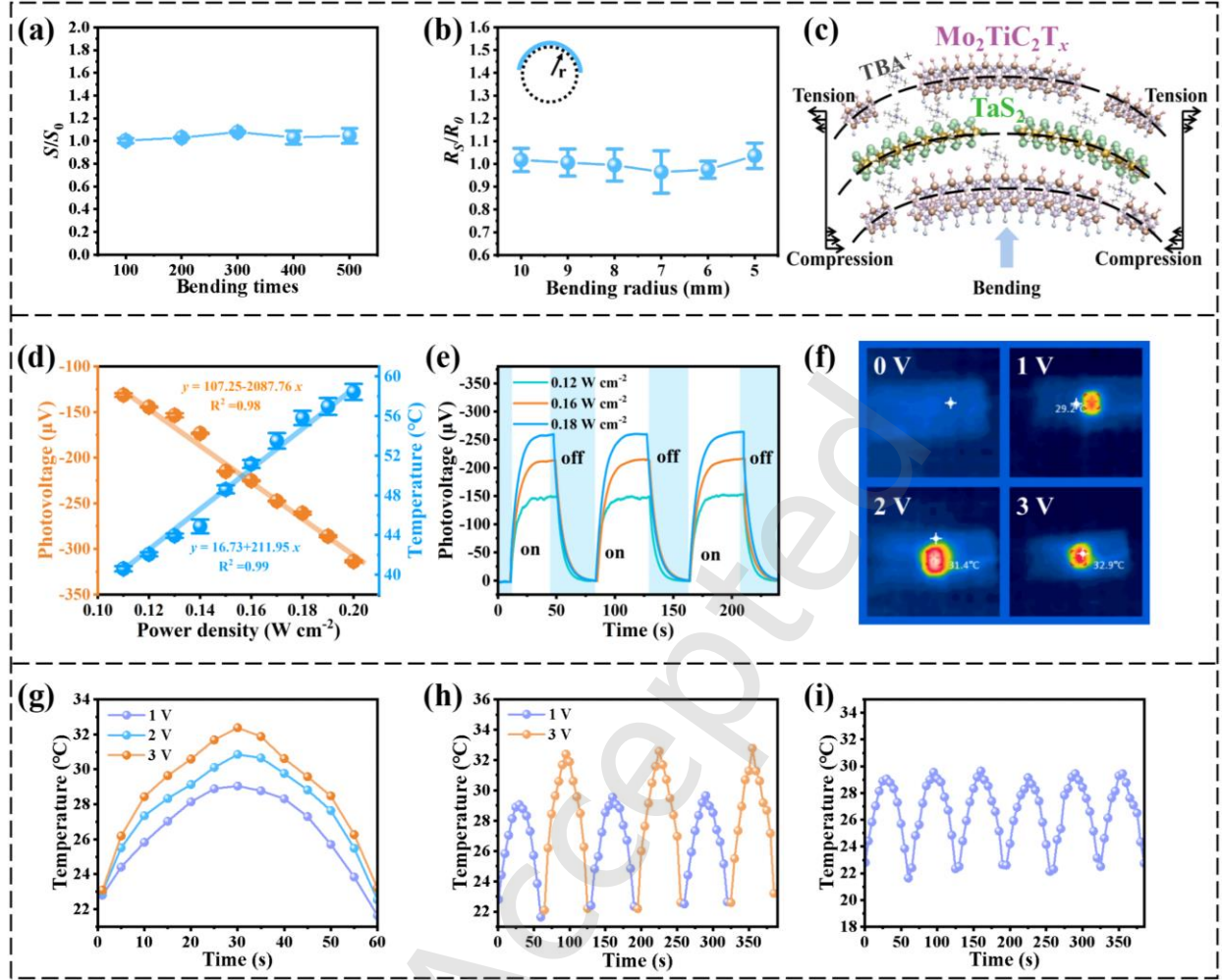


Fig. 8. (a) Relative change in Seebeck coefficient of the MTa0.75 film following 100–500 cycles of bending (bending angle $> 160^\circ$). (b) Dependence of the resistivity ratio (R_s/R_0) on bending radius. R_0 : resistivity in the flat state; R_s : resistivity in the bent state. (c) Schematic illustration of the flexibility mechanism based on vdW interactions between MXene and TaS₂ nanosheets. (d) Variation of output voltage and generated temperature with optical power density under 638 nm near-infrared laser irradiation. (e) Repetitive voltage response of the photothermoelectric device at four distinct optical powers levels. (f) Infrared thermographic images of the MTa0.75 film at applied voltages from 0–3 V. (g) Temperature evolution over time at different applied voltages (1 V, 2 V, 3 V). (h) Temperature response under alternating voltages from 1 V to 3 V. (i) Cyclic temperature performance over 6 cycles at 1 V.

The flexibility mechanism is schematically illustrated in Fig. 8(c). Under external forces such as bending, and compression, adjacent 2D nanosheets connected by vdW forces undergo reversible interlayer slip, local orientation rearrangement, and spacing adjustment, effectively releasing local

strain and promoting stress redistribution [71]. This excellent flexibility arises from the synergy between TBAOH intercalation and heterostructure mismatch. TBAOH treatment expands the $\text{Mo}_2\text{TiC}_2\text{T}_x$ interlayer spacing from 1.25 nm to 1.78 nm, weakening interlayer interactions and facilitating sliding [72,73]. Upon compositing with TaS_2 , the average interlayer spacing of the MTa film slightly decreases to ~ 1.23 nm. However, this modest reduction does not imply diminished flexibility. Instead, the newly formed $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ heterointerfaces, with weak vdW bonding and substantial lattice mismatch, offer much lower shear barriers for sliding than homogeneous MXene interfaces, serving as preferential slip planes for strain dissipation [74]. Moreover, the 1.23 nm spacing remains far larger than the pre-intercalation value (~ 0.93 nm), and the XRD average masks highly nonuniform local environments that provide additional strain-release channels. Meanwhile, the staggered lamellar structure extends crack paths and impedes continuous crack penetration [75]. These structural features enable MTa films to adapt more effectively to localized deformation during bending, consistent with the sensor stable electrical response across different bending radii and during long-term cyclic bending. However, good bending flexibility does not necessarily translate into high uniaxial tensile ductility. The maximum tensile stress of the MTa0.75 film is ~ 3.8 MPa, and the fracture strain is $\sim 0.58\%$ (Fig. S18 in the ESM). Therefore, it is more suitable for flexible applications such as bending, and pressure sensing, rather than scenarios involving large tensile deformation. In future work, combining highly elastic packaging with strain-relief structures such as

pleats and serpentine geometries could reduce the tensile strain on the MTa functional layer and further enhance device stretchability.

In addition, we evaluated the storage stability of the encapsulated devices. After assembling the MTa0.75 thin film into a device and encapsulating it with standard office tape, we stored the device in air at room temperature for 20 days, testing temperature and piezoresistive responses every five days. Temperature testing involved generating a temperature difference via finger contact, while piezoresistive testing recorded the resistance change as the elbow joint was flexed to $\sim 90^\circ$. As shown in Figure S19 in the ESM, the voltage and resistance responses remained essentially stable across the tested time points; minor fluctuations were primarily attributable to variations in finger temperature, contact conditions, and the elbow flexion angle.

Figure S20 in the ESM shows the setup for a photothermoelectric (PTE) experiment. A 638 nm near-infrared laser was used as the illumination source at one end of the device. The MTa0.75 film device exhibits different temperatures under different optical power levels. Based on the PTE effect, the film converts the temperature difference into output voltage (Fig. 8(d)). As the incident light power density increases, the temperature of the light-receiving region gradually rises, and the absolute value of output voltage increases. Both effects show approximately linear relationships with light power density, with R^2 values being 0.99 and 0.98, respectively. This result indicates that within the tested light power density range, the sensor photothermal–electric response shows strong power

dependence. Figure 8(e) shows the voltage response over multiple switching cycles; the response is stable and repeatable. This stable PTE response, which correlates with optical power density, enables the MTa0.75 film to directly convert incident light energy into a measurable voltage signal without an external power supply. Given the strong linearity between the output voltage and optical power density, the device allows for the quantitative detection of incident optical power based on voltage variations; meanwhile, its stable and repeatable switching response ensures reliability during continuous monitoring. Consequently, the MTa0.75 film holds significant application potential in areas such as flexible self-powered optical power sensors, real-time laser power monitoring, non-contact photothermal sensing, and optical safety warning systems.

Figures 8(f)–(i) illustrate the Joule heating behavior of an individual MTa0.75 film device, with temperature distributions captured by an infrared camera. As the applied voltage increases from 0 V to 3 V, the saturation temperature rises from room temperature to 32.9 °C (Fig. 8(f)) and reaches saturation within ~30 s (Fig. 8(g)). The heating and cooling processes under voltages from 1–3 V show stable and repeatable performance (Fig. 8(h)). Figure 8(i) presents the temperature consistency over six cycles, demonstrating excellent stability. These results indicate that MTa0.75 film devices have potential for use as wearable heaters.

4 Conclusions

Existing flexible sensors, which mostly rely on single sensing mechanisms, suffer from insufficient multimodal sensing capability, inadequate power supply, and electromagnetic interference issues. To address these challenges, we successfully fabricated $\text{Mo}_2\text{TiC}_2\text{T}_x/\text{TaS}_2$ heterostructure films via intercalation, exfoliation, and vacuum-assisted filtration. Due to significant charge accumulation at the heterojunction interface, the composite film not only optimizes carrier transport but also reduces interfacial polarization losses and enhances electromagnetic wave energy dissipation, leading to synergistic improvements in both electrical transport and EMI shielding properties. Specifically, the MTa0.75 film achieved a maximum electrical conductivity of 878.3 S cm^{-1} and a PF of $14.39 \text{ } \mu\text{W m}^{-1} \text{ K}^{-2}$, 3.85 times that of the pristine $\text{Mo}_2\text{TiC}_2\text{T}_x$ film. Its total EMI shielding effectiveness reached 40.6 dB, 2.8 times that of the pristine film. Besides excellent EMI shielding, the film enables multimodal sensing responses to respiration, stress, touch, and photothermal responses. This study demonstrates that constructing MXene-based heterojunctions is a promising route to boost EMI shielding and multifunctional sensing synergistically, and it integrates functionality, combining multimodal information sensing and electromagnetic interference resistance, and is expected to meet the collaborative needs of wearable health monitoring, electronic skin, and intelligent human-computer interaction for multi-parameter sensing and signal reliability, and provide new material design ideas for the construction of flexible sensor devices in complex electromagnetic environments.

Electronic Supplementary Material (ESM)

Supplementary material is available in the online version of this article at

<https://mc03.manuscriptcentral.com/jacer>

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Author contributions

Mengran Chen: Writing-original draft, Visualization, Validation, Data curation; Investigation; Formal analysis; Yuru Ji: Writing-original draft, Data curation, Investigation; Heng Liu: Methodology; Xuefei Zhang: Investigation; Jingzhang Zhang: Resources, Investigation; Jieyi Zhao: Validation, Investigation; Zhe Tang: Investigation; Jianhua Li: Validation; Peng-an Zong: Conceptualization, Writing-review & editing, Supervision, Funding acquisition; Chunlei Wan: Resources.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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