

# Stretchable MXene-based humidity sensor arrays with high sensitivity and rapid response for proximity-sensing electronic skin

Zhijian Sun, Hao Xing, Jiashu Huang, Mingqi Zhang, Junqi Sun, and Desheng Kong  

State Key Laboratory of Analytical Chemistry for Life Science, College of Engineering and Applied Sciences, and Jiangsu Key Laboratory of Functional Materials, Nanjing University, Nanjing 210021, China

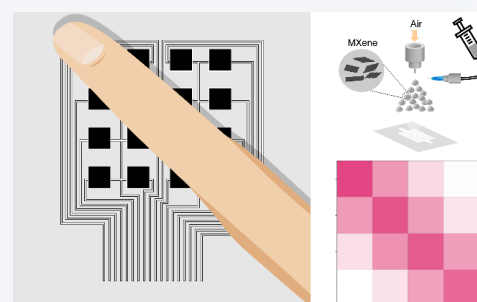


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**ABSTRACT:** Stretchable electronic skins for touchless human-machine interfaces require accurate humidity sensing that is fully decoupled from mechanical strain interference. However, pristine two-dimensional (2D)  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene films suffer from restacking-induced sluggish kinetics and strain-induced resistance crosstalk. Herein, we report highly sensitive, rapid-response, and electromechanically isolated MXene-based humidity sensor arrays for proximity-sensing electronic skins. To enhance water molecule transport, MXene nanosheets are modified via alkaline intercalation to expand the interlayer spacing, followed by *in situ* polymerization of polydopamine (PDA) nanoparticles. The hydrophilic PDA

aggregates act as hygroscopic spacers, modulating electron tunneling via moisture-induced swelling to achieve a high relative sensitivity of 0.707%/RH and rapid response/recovery times (1.2 s/2.3 s). To eliminate mechanical interference, the active composite is integrated onto a heterogeneous substrate consisting of glass-microfiber-reinforced stiff islands embedded in a compliant elastomer matrix. This architecture isolates the active film from strain-induced variations up to 300% strain. Utilizing liquid metal interconnects and a gas-permeable electrospun encapsulation, the fabricated  $4 \times 4$  sensor array demonstrates high-fidelity spatial moisture mapping and non-contact gesture recognition even under 50% biaxial strain, offering a robust platform for advanced interactive robotics and personalized healthcare.

**KEYWORDS:** humidity sensor, stretchable electronics, MXene, electronic skin



## 1 Introduction

Stretchable electronics constitute a transformative technological frontier that transcends the intrinsic limitations of rigid, wafer-based systems [1–3]. As a primary platform for mimicking biological tactile perception, electronic skin (e-skin) has become indispensable for next-generation robotics and personalized healthcare [4, 5]. Unlike conventional flexible devices restricted to simple bending, emerging e-skins can endure complex, multi-axis deformations, including stretching, twisting, and folding, to conform intimately to the dynamic, irregular contours of arbitrary biological and robotic structures [6, 7]. A key requirement for these systems is the maintenance of reliable signal transduction under substantial mechanical deformation, enabling continuous, unconstrained monitoring in practical scenarios [8, 9].

Among the diverse sensing modalities integrated into e-skin, humidity sensing holds a critical position due to its dual relevance

to environmental perception and physiological diagnostics [10, 11]. Measured humidity offers a non-invasive window into metabolic and respiratory states, allowing real-time tracking of skin moisture evaporation, thermoregulation, and breathing patterns [12–14]. Beyond health monitoring, assembling humidity sensors into discrete arrays provides a promising platform for touchless interaction [15, 16]. By detecting localized moisture gradients around the human body, these sensors enable hygienic, non-contact gesture recognition and spatial mapping, endowing e-skins with a sophisticated level of perceptual intelligence that can rival or even surpass human somatosensory capabilities [17, 18].

Two-dimensional (2D) transition metal carbides, commonly termed MXenes, stand out as premier candidates for humidity transducers owing to their metallic conductivity, excellent solution processability, and abundant surface hydrophilic groups [19, 20]. The delamination of bulk-phase crystals has facilitated the high-yield production of MXenes in colloidal dispersions [21]. However, pristine MXene nanosheets are prone to thermodynamically driven restacking into compact, multilayered structures via van der Waals forces and hydrogen bonding [22]. This restacking severely impedes the diffusion of water molecules into MXene films, resulting in

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 Address correspondence to [dskong@nju.edu.cn](mailto:dskong@nju.edu.cn)



compromised sensitivity and sluggish response dynamics [23, 24]. To mitigate this issue, alkaline treatment has been used to expand interlayer spacing through ion intercalation [25]. Alternatively, introducing polymeric spacers or small molecules has proven effective in preventing nanosheet aggregation and tuning surface hydrophilicity [26]. Although these approaches can improve sensitivity, certain additives may inadvertently degrade response speed due to sluggish desorption kinetics [27]. Conversely, engineering MXenes into three-dimensional (3D) porous architectures—such as aerogels or electrospun nanofiber networks—can enable rapid vapor transport [14]. However, these bulky structures present significant challenges for high-density, low-profile integration into e-skin devices.

Beyond these mass-transport limitations, MXene-based functional films suffer from severe mechanical fragility, tending to fracture under moderate tensile strain [28–30]. While this pronounced piezoresistive behavior has been widely harnessed for strain sensors [31–33]. It introduces catastrophic signal crosstalk in humidity-sensing applications. In dynamic wearable environments, resistance variations triggered by mechanical stretching are often indistinguishable from those induced by humidity fluctuations, rendering accurate, quantitative moisture detection nearly impossible. Consequently, developing a robust structural or material architecture that completely decouples the humidity signal from mechanical interference is essential for next-generation stretchable e-skins.

To address these collective challenges, we report the development of stretchable, highly sensitive, and rapid-response MXene-based humidity sensor arrays designed for proximity-sensing electronic skins. Herein,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanosheets are subjected to a two-step modification consisting of alkaline intercalation followed by *in situ* oxidative self-polymerization of polydopamine (PDA) nanoparticles. The alkalization process expands the interlayer gallery spacing to accelerate water molecule diffusion. The decorated PDA nanoparticles further act as hygroscopic spacers between MXene sheets that, upon swelling, induce substantial tunneling resistance changes. This optimized formulation yields an optimal relative sensitivity of 0.707 %RH and ultra-fast response/recovery time (1.2 s/2.3 s). To decouple the humidity signal from mechanical interference, the sensor is integrated onto a structurally engineered heterogeneous substrate consisting of glass-microfiber-reinforced stiff islands embedded within a compliant soft elastomer matrix. This strain-isolation architecture effectively confines applied mechanical deformation to the soft elastomer matrix, shielding the active MXene film from strain-induced resistance variations up to 300% global strain. Leveraging this robust electromechanical decoupling, we successfully fabricate a  $4 \times 4$  sensor array integrated with liquid metal (LM) electrical interconnects. The resulting electronic skin demonstrates high-fidelity spatial moisture mapping and non-contact gesture recognition, irrespective of large mechanical deformation up to 50% biaxial strain. Our findings underscore the vast potential of this humidity sensing e-skin for next-generation interactive robotics and smart systems.

## 2 Experimental

### 2.1 Materials

Titanium aluminum carbide ( $\text{Ti}_3\text{AlC}_3$ , 400 mesh) was purchased

from 11 Technology Co., Ltd. Lithium fluoride (LiF, 99.99%) was obtained from Anhui Zesheng Technology Co., Ltd. Hydrochloric acid (HCl), ethanol, tris(hydroxymethyl)-aminomethane (Tris), sodium hydroxide (NaOH), N,N-dimethylformamide (DMF), and cyclohexane were purchased from Shanghai Macklin Reagents Co., Ltd. Dopamine hydrochloride was supplied from Shanghai Aladdin Biochemical Technology Co., Ltd. Toluene was obtained from Nanjing Chemical Reagents Co., Ltd. Gallium (Ga), indium (In), and tin (Sn) were all purchased from Dongguan WoChang Co., Ltd. Styrene-ethylene-butylene-styrene elastomer (SEBS, G1652) was acquired from Asahi Kasei Corporation. Styrene-isoprene-styrene elastomer (SIS, D113) was obtained from Kraton, Inc. Fumed  $\text{SiO}_2$  nanoparticles (Aerosil 200) were acquired from Evonik Industries. Glass microfibers (200 mesh) were purchased from Fuhua Mineral Materials Co., Ltd. To prepare the ternary eutectic liquid metal, Ga, In, and Sn powders were mixed at a weight ratio of 68.5:21.5:10 and magnetically stirred at 80 °C for 2 h inside an argon-filled glovebox. All materials were used as received without further purification.

### 2.2 Synthesis and modification of MXene

$\text{Ti}_3\text{C}_2\text{T}_x$  MXene aqueous dispersions were synthesized via a modified minimally intensive layer delamination (MILD) approach. Briefly, 3.2 g of LiF was thoroughly dissolved in 40 mL of 9 M HCl. Subsequently, 2 g of  $\text{Ti}_3\text{AlC}_3$  powder was slowly added to the etching solution under continuous stirring at 200 rpm, and the reaction was maintained at 60 °C for 24 h. The resulting acidic mixture was repeatedly centrifuged and washed with deionized (DI) water until the supernatant reached a nearly neutral pH of ~ 6. The concentrated sediment was then collected and vigorously shaken to delaminate the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene flakes, followed by a final centrifugation step at 3500 rpm for 30 min to separate delaminated few-layer MXene flakes from unetched residues and multilayer aggregates. The supernatant was collected as a stable MXene colloidal dispersion with a typical concentration of ~ 2.0 mg/mL. For the alkalization treatment, 40 mL of the pristine MXene dispersion was mixed with an equal volume of 0.5 M NaOH solution and stirred at 400 rpm for 4 h at room temperature. The reacted dispersion was washed several times with DI water via centrifugation until the pH returned to neutral. Subsequent PDA decoration was achieved through *in situ* oxidative self-polymerization. First, 40 mL of the alkalized MXene dispersion was ultrasonicated for 2 min, mixed with a 10 mM Tris buffer solution (pH ~ 8.5), and kept under constant stirring for 2 h. Dopamine hydrochloride was then added to the mixture under ice-water bath cooling within a few minutes. Finally, free PDA particles and residual Tris were removed by washing with DI water several times, yielding a stable dispersion.

### 2.3 Material characterizations

Surface topography and film thickness were characterized using a confocal laser scanning microscope (VK-X1000, Keyence). Optical images were taken with a Fujifilm X-T10 camera. Morphological and microstructural evaluations were conducted using a field-emission scanning electron microscope (FE-SEM, Ultra5, Zeiss) and a transmission electron microscope (TEM, Talos F200S, Thermo Scientific). X-ray diffraction (XRD) patterns were recorded on a D8 ADVANCE diffractometer (Bruker). X-ray photoelectron spectroscopy (XPS) was performed on an ESCALAB 250Xi microprobe (Thermo Scientific). The hydrodynamic diameter and

zeta potential were monitored by a Zetasizer Pro dynamic light scattering (DLS) analyzer (Malvern Panalytical). Optical absorbance was recorded with an Infinite 200 Pro multifunctional microplate reader (Tecan Group). Contact angle was measured using an OCA 30 Goniometer (DataPhysics Instruments GmbH). Uniaxial tensile stress-strain curves were acquired using a universal testing machine (AGS-X, Shimadzu). Electrical resistance was measured using a Keithley 2110 digital multimeter. Tensile strain was applied using homemade motorized/manual linear stages. The relative humidity within the testing chamber was monitored using a commercial CENTER 314 digital hygrometer. Humidity sensing measurements were performed on a home-built humidity sensing test system (Fig. S1 in the Electronic Supplementary Material (ESM)). The rapid switching between low and high humidity is achieved by instantaneously altering the flow ratio of the dry carrier air (99.999%) and fully saturated wet air via a high-precision mixer valve. To achieve sharp RH transitions, two design optimizations were adopted: First, the effective headspace volume of the custom-sealed glass bottle was strictly confined to  $\sim 20$  mL; second, the transit gas tubing was shortened to facilitate rapid gas turnover. RH readouts inside the chamber were recorded via a CENTER 314 digital hygrometer.

#### 2.4 Fabrication of flexible humidity sensors

A bilayer Cr/Ag (10 nm/100 nm) film was deposited onto PET substrates using a thermal evaporator. Interdigitated electrode geometries (Fig. S2 in the ESM) were precisely patterned by laser ablation using a 1064 nm fiber laser marking system (XM-FB30, Xianming Optoelectronic Equipment Co., Ltd.). The patterned substrates were then treated with oxygen plasma for 5 min to enhance their hydrophilicity. Finally, the targeted MXene dispersion was spray-coated onto the active area through a custom shadow mask and dried under ambient conditions.

#### 2.5 Fabrication of locally reinforced stretchable substrate

The preparation workflow of the locally reinforced heterogeneous substrates is illustrated schematically in Fig. S3 in the ESM. SEBS pellets were first fully dissolved in toluene to achieve 33 w/w%. Glass microfibers were then incorporated at a concentration of 14.1 wt.% relative to the total solution to enhance the mechanical properties. Subsequently, fumed  $\text{SiO}_2$  nanoparticles (1.9 wt.% of the total solution) were introduced to increase the viscosity and facilitate printing. The resulting slurry was thoroughly homogenized using a planetary mixer at 1000/1000 rpm (revolution/rotation) for 10 min. The slurry was then blade-coated through a patterned stainless-steel stencil onto a glass wafer previously treated with octadecyltrichlorosilane to provide a low-adhesion surface. After drying at 60 °C for 4 h, discrete stiff islands with a uniform thickness of  $\sim 200$   $\mu\text{m}$  were obtained. Concurrently, a soft elastomer ink was prepared by dissolving SIS pellets at 20 w/w % in a co-solvent mixture of cyclohexane and toluene (1:3 by weight). The SIS solution was drop-cast over the entire pattern-bearing glass wafer to completely encapsulate the pre-printed stiff islands. The locally reinforced stretchable substrate was obtained after drying through natural evaporation for 12 h.

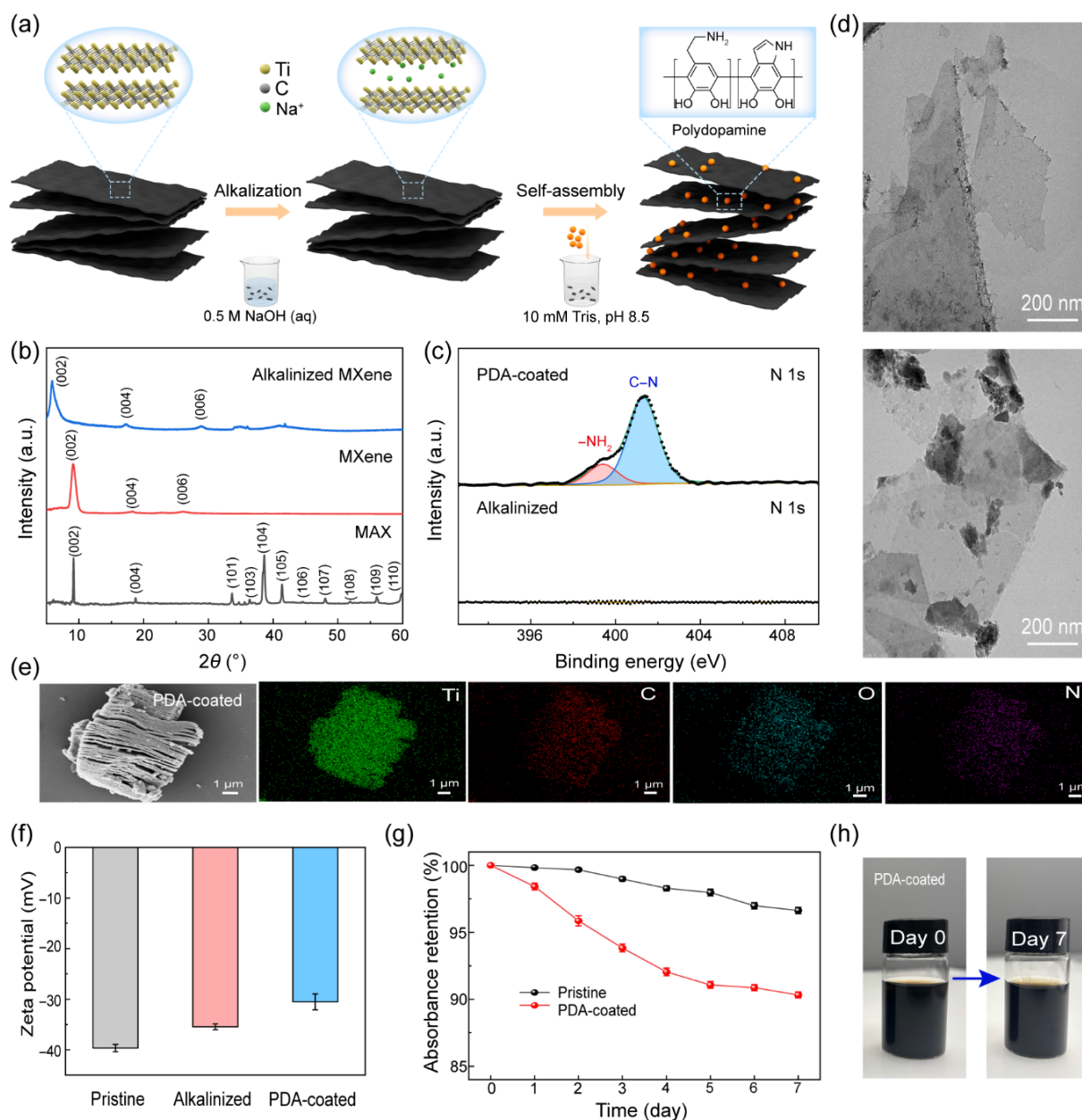
#### 2.6 Fabrication of the proximity-sensing electronic skin

A bilayer Cr/Cu (10 nm/100 nm) film was deposited onto the locally reinforced stretchable substrate by thermal evaporation. Interdigital electrodes and electrical interconnects were defined via

selective laser ablation. Care was taken to ensure that all interdigitated electrodes rested precisely on stiff islands. The liquid metal was then coated onto the metallic templates via a previously established selective wetting technique. Subsequently, the PDA-modified MXene dispersion was spray-deposited onto the active sensing regions through a registered shadow mask. To ensure uniformity (Fig. S4 in the ESM), the atomizing spray nozzle was mounted on a computer-controlled two-dimensional translational stage. The nozzle was positioned 17 cm above the substrate, and a constant pressure of 0.9 MPa was applied. The ink dispersion was fed by a syringe pump at a fixed rate of 0.23 mm/min. The target film thickness was achieved by controlling the deposition time. Finally, a thin, gas-permeable SIS fibrous membrane was directly electrospun onto the device to serve as a protective, gas-permeable encapsulation layer. The precursor solution was prepared by dissolving SIS pellets at 29 wt.% in a toluene/DMF mixed solvent (8:2 by weight) under continuous stirring at 70 °C. Electrospinning was performed at a high voltage of 12 kV, a feed rate of 3.0 mL/h, and a collector-to-needle distance of 15 cm.

### 3 Results and discussion

$\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanosheets are synthesized top-down by delaminating  $\text{Ti}_3\text{AlC}_2$  MAX phase powders via a mild (MILD) etching method [34]. Selective removal of the Al layers from MAX phase powders yields  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene with the characteristic accordion-like morphology, as shown in Fig. S5 in the ESM. Figure 1(a) schematically illustrates the sequential modifications of the MXene dispersion via solution reactions. The MXene is then alkalized by treatment in 0.5 M NaOH solution for 4 h. Subsequently, the alkalized nanosheets are decorated with PDA via *in situ* oxidative self-polymerization of dopamine [35]. X-ray diffraction (XRD) is employed to track the structural evolution during the synthesis steps, as shown in Fig. 1(b). The  $\text{Ti}_3\text{AlC}_2$  MAX phase powders are confirmed by a series of characteristic crystalline peaks [36]. After etching, the Al(104) peak disappears completely, while the (002) and (004) peaks are preserved and shifted, confirming successful delamination [37]. Upon alkalization, the (002) peak shifts markedly from 8.9° to 5.8° (Fig. S6 in the ESM). A rough estimate using Bragg's law translates this shift to an increase in the interlayer distance from  $\sim 1.0$  to  $\sim 1.5$  nm, as driven by  $\text{Na}^+$  intercalation [25, 38]. This widened gallery spacing is likely beneficial to humidity sensing, as it facilitates water molecule diffusion and accelerates adsorption/desorption kinetics [25, 39]. X-ray photoelectron spectroscopy (XPS) characterizes the compositional changes accompanying PDA polymerization (see Fig. 1(c) and Fig. S7 in the ESM). While the alkaline-treated MXene shows no distinct features in the N 1s region (Fig. 1(c) and Fig. S7 in the ESM), the subsequent polymerization step introduces prominent peaks at 401.3 and 399.4 eV, corresponding to C–N and –NH<sub>2</sub> bonds, respectively [35]. This confirms the successful deposition of amine-rich PDA onto the MXene surface—a finding further corroborated by energy-dispersive X-ray spectroscopy (EDS) elemental mapping (Fig. S8 in the ESM). TEM is employed to visualize the morphological features. As shown in Fig. 1(d), the alkalized MXene exhibits a clean nanosheet architecture, indicating negligible damage during the treatment process. After polymerization, rich nanoparticles are anchored onto the MXene surfaces, confirming the self-assembly of PDA into fine aggregates. Furthermore, the elemental maps in Fig. 1(e) reveal a highly



**Figure 1** Structure and characterization of the PDA-modified alkalized MXene. (a) Schematic illustration of the chemical preparation process: pristine  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene is first alkalinized, followed by surface modification via dopamine self-polymerization. (b) XRD patterns of pristine, alkalized MXene and MAX phase. (c) High-resolution XPS core-level spectra (N 1s region) of alkalized and PDA-coated MXene. (d) TEM images of alkalized and PDA-coated MXene. (e) EDS elemental maps for Ti, C, O, and N of the PDA-coated MXene. (f) Zeta potential data showing the surface charge evolution during chemical modification. (g) Relative absorbance retention (at 550 nm) of pristine and PDA-coated MXene dispersions as a function of storage time. (h) Optical images of PDA-coated MXene dispersions at the initial state and after 7 days of storage.

homogeneous distributions of the four elements (Ti, C, O, and N) without detectable segregation. Overall, these results confirm that the PDA is uniformly deposited onto the alkalized MXene nanosheets. In Fig. 1(f), zeta potential measurements trace the evolution of surface charge. Pristine MXene displays a negative zeta potential of  $-39.7$  mV, originating from its abundant negative surface charges [22, 25]. After alkalization, the zeta potential becomes slightly less negative ( $-35.5$  mV), likely because intercalated  $\text{Na}^+$  ions partially screen the surface charges. Following PDA polymerization, the potential rises further to  $-30.5$  mV, as the positively charged amine groups lead to partial charge neutralization [40]. All samples retain large absolute zeta potential

values, indicating sufficient electrostatic repulsion to maintain colloidal stability. Although the strong surface charges help stabilize the dispersions, MXene is known to gradually oxidize in aqueous media, deteriorating its electrical properties. Accordingly, all inks are stored at a low temperature of  $4^\circ\text{C}$  to slow oxidation [41].

The long-term colloidal dispersion stability is evaluated by sedimentation tests (Fig. 1(g)). All dispersions are prepared at an identical initial concentration of  $1.0$  mg/mL. The relative absorbance retention is calculated by normalizing the optical absorbance at each time point to the initial value on Day 0. The pristine MXene dispersion shows negligible sedimentation after several days of standing, with its absorbance retention decreasing

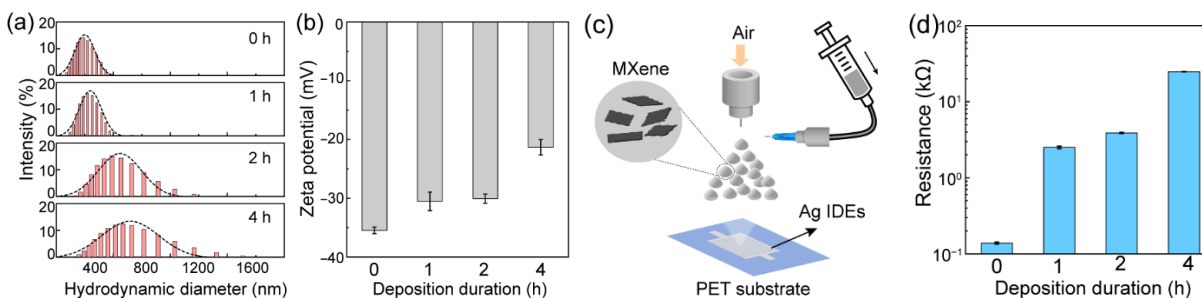
only slightly to 96.6% by Day 7. After PDA polymerization, the decline in absorbance retention becomes somewhat more pronounced, yet the value remains above 90% on Day 7, indicating favorable colloidal stability. The distinctive Tyndall effect further provides direct visual evidence of the excellent colloidal state of both the pristine and PDA-coated MXene aqueous dispersions (Fig. S10 in the ESM). **Figure 1(h)** presents optical images of a representative dispersion of the PDA-modified MXene, taken immediately after vigorous shaking and after 7 days of static storage. The absence of obvious layering or changes further confirms excellent dispersion stability—a prerequisite for solution-based processing such as spray coating. Notably, alkalization is critical for achieving uniform PDA immobilization on  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene to form a high-quality dispersion. This treatment expands the interlayer galleries and increases the hydroxyl groups on the MXene surfaces, thereby facilitating PDA deposition. As a control experiment, direct PDA coating on pristine MXene without alkalization generates an unstable dispersion that tends to precipitate and phase-separate within one day of storage (see Fig. S9 in the ESM), highlighting the importance of the alkalization treatment.

The oxidative self-polymerization of dopamine offers a convenient way to control the amount of deposited PDA simply by varying the reaction time. DLS analysis (**Fig. 2(a)**) reveals a progressive increase in the hydrodynamic diameter of the PDA-modified nanosheets with deposition time. The hydrodynamic diameter assumes an effective sphere model diffusing through the aqueous solution, which grows from  $\sim 263 \pm 4.33$  to  $\sim 494 \pm 6.52$  nm as the reaction is extended from 1 to 4 h. The trend essentially reflects the continuous deposition of PDA onto the MXene sheets. Consistent with DLS measurements, complementary XPS results (Fig. S11 in the ESM) reveal a continuous increase of N in MXene with deposition time, directly confirming tunable PDA loading. Specifically, high-resolution XPS analysis reveals that the surface nitrogen atomic percentage increases monotonically from  $\sim 1.6\%$  to  $8.9\%$  as the polymerization duration extends from 1 to 8 h. This increase suggests the controllable loading of PDA nanoparticles, aligning with the hydrodynamic diameter evolution observed in the solution phase. Concurrently, zeta potential measurements in **Fig. 2(b)** reveal  $-30.5$ ,  $-30.0$ , and  $-21.3$  mV for 1, 2, and 4 h deposition duration, suggesting continuous decrease in the surface charge. This reduction in electrostatic stability is associated with progressive charge neutralization by the deposited PDA. To evaluate electrical properties, MXene nanosheets were spray-deposited onto interdigitated electrodes on a flexible PET substrate to form nanocomposite films (see **Fig. 2(c)**). The film prepared from

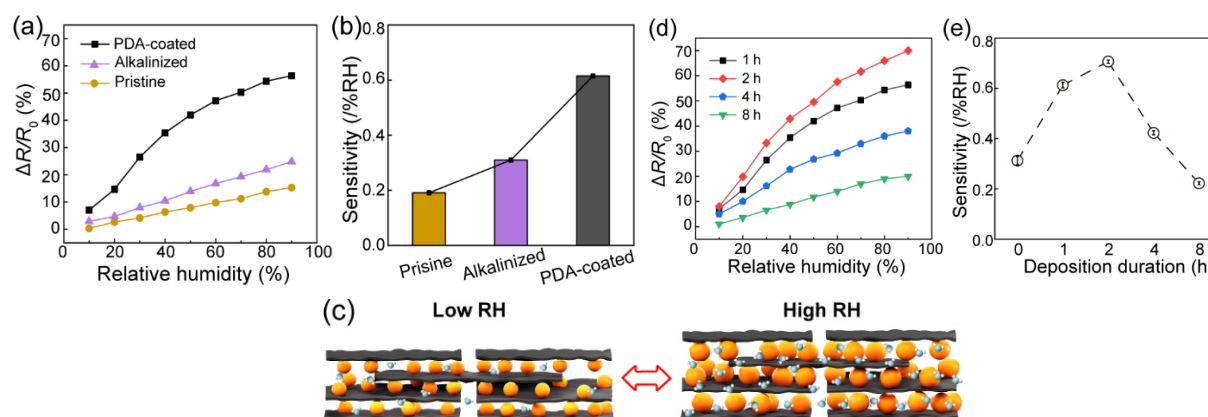
pristine MXene nanosheets exhibit a resistance of only  $3.9 \Omega$  (**Fig. 2(d)**). Alkalization substantially increases the resistance of the nanocomposite film to  $138.8 \Omega$ , which can be attributed to partial oxidation and interlayer expansion [25, 42]. Furthermore, the resistance increases monotonically with PDA deposition time:  $2.5 \text{ k}\Omega$  at 1 h,  $3.9 \text{ k}\Omega$  at 2 h,  $24.9 \text{ k}\Omega$  at 4 h, and  $33.2 \text{ k}\Omega$  at 8 h, respectively. This trend reflects the widening gaps between adjacent MXene nanosheets, which drastically suppresses electron tunneling across adjacent MXene sheets [42]. It is interesting to note that the PDA polymerization can modulate the film resistance over one order of magnitude by simply enlarging interlayer galleries.

**Figure 3(a)** presents the response curves of different MXene films. All films exhibit a positive humidity response, with resistance increasing monotonically with relative humidity. Both the pristine and alkalized MXene exhibit quasi-linear responses. The slightly improved performance of the alkalized MXene is likely associated with its expanded interlayer distance to facilitate water diffusion [25]. The PDA-modified MXene film shows significantly enhanced, non-linear responses. **Figure 3(b)** presents the extracted relative sensitivity, defined as  $(\Delta R/R_0)/\Delta \text{RH}$ . The markedly improved sensitivity enables them to better capture weak humidity fluctuations. The potential humidity sensing mechanism of PDA-modified MXene is proposed, as shown in **Fig. 3(c)**. Water adsorption induces the swelling of PDA nanoparticles and hence the expansion of the gaps between MXene nanosheets [43, 44], thereby substantially increasing the tunneling resistance [39]. Desorption reverses this process, restoring the conductive pathways. The deposited PDA plays an essential role in modulating the humidity response. In **Fig. 3(d)**, the response of the PDA-modified MXene shows a complex correlation to the duration of MXene deposition. The extracted sensitivity is shown in **Fig. 3(e)**. The initial deposition up to 2 h leads to significantly enhanced sensitivity, by decorating more PDA nanoparticles to modulate the response. The added PDA nanoparticles simply alter the tunneling between MXene to a highly sensitive state to the gap spacing. Subsequently, the additional deposition up to 8 h leads to substantially reduced responses likely due to the excessively widened spacing between MXene sheets. As the sensor performance relies on the continuous conductive network formed by MXene nanosheets, an overly thick PDA layer disrupts the electron transport pathways, ultimately leading to high resistance and electrical failure. The 2 h deposition delivers the optimal performance, exhibiting a high relative sensitivity of  $0.707/\% \text{RH}$  within  $10\% \sim 90\% \text{ RH}$  (**Fig. 3(e)**). As a result, such a composite film is adopted for the following experiment unless specified otherwise.

The MXene nanocomposite film is systematically investigated for humidity sensing. **Figure 4(a)** presents the resistance variations



**Figure 2** Influence of dopamine deposition on MXene. (a) Dynamic light scattering size distribution histograms of MXene dispersions at different deposition durations. (b) Corresponding zeta potential values. (c) Schematic illustration of the fabrication of a flexible MXene humidity sensor via spray deposition. (d) Measured resistance of MXene sensors prepared with different dopamine polymerization durations.

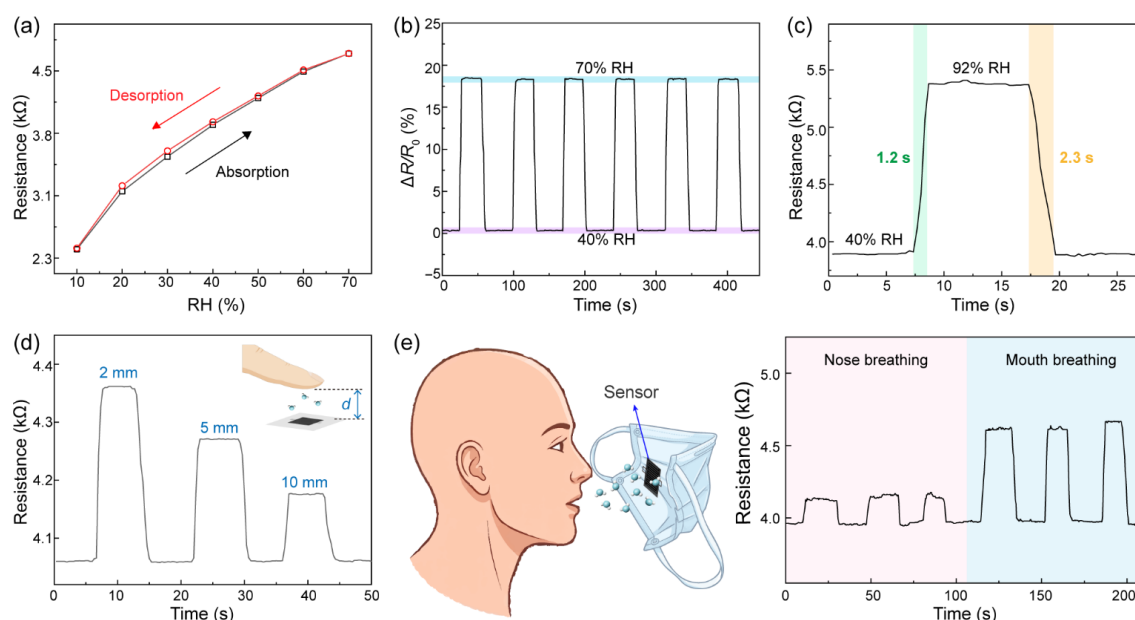


**Figure 3** Humidity-sensing characteristics and underlying response mechanism. (a) Relative resistance change ( $\Delta R/R_0$ ) of pristine, alkalized, and PDA-coated MXene (with 1 h deposition) sensors across 10%–90% RH. (b) Corresponding relative sensitivity. (c) Schematic of the humidity response mechanism, showing that water molecules interact with the PDA-modified MXene films to reversibly modulate the gaps between MXene nanosheets. (d) Relative resistance change ( $\Delta R/R_0$ ) for PDA-coated MXene films with varying deposition durations across 10%–90% RH. (e) Corresponding relative sensitivity.

associated with water adsorption and desorption processes. The adsorption and desorption response curves nearly overlap, confirming excellent reversibility with negligible hysteresis [45]. This is likely because the alkalization intercalation, together with the spacer effect of PDA nanoparticles, creates rich diffusion channels that minimize the diffusion resistance of water molecules. The sensor is further subjected to stepwise humidity switching between 40% and 70% RH (Fig. 4(b)). The device maintains a highly stable baseline at low humidity. It responds rapidly to increasing humidity and displays a flat resistance, followed by full recovery to the original baseline upon humidity decrease. The consistent response amplitude across multiple cycles underscores the excellent cyclic stability of the device. According to the  $T_{90}$  standard [46], the response and recovery times are determined to be 1.2 and 2.3 s, respectively (Fig. 4(c)). Such rapid response dynamics are critical for capturing environmental changes in real time. Capitalizing on

this high sensitivity and rapid response, the sensor can detect humidity variations induced by the proximity of a body part. Figure 4(d) shows the resistance response to a hovering fingertip placed at varying distances. The clear, distance-dependent signals highlight its potential for touchless human-machine interfaces with an operational range exceeding 10 mm. The device is also integrated into a face mask to monitor exhaled humidity (Fig. 4(e)). Thanks to its rapid response, the device generates a distinct resistance variation with each breathing event. Despite minor fluctuations, oral breathing consistently elicited a substantially larger response amplitude than nasal breathing, attributable to the larger tidal volume and moisture flux [39, 47].

In addition to humidity-sensing capability, practical on-skin wearable applications demand mechanical stretchability to accommodate body motion. Despite excellent bendability, MXene films tend to crack under minute tensile strains, leading to

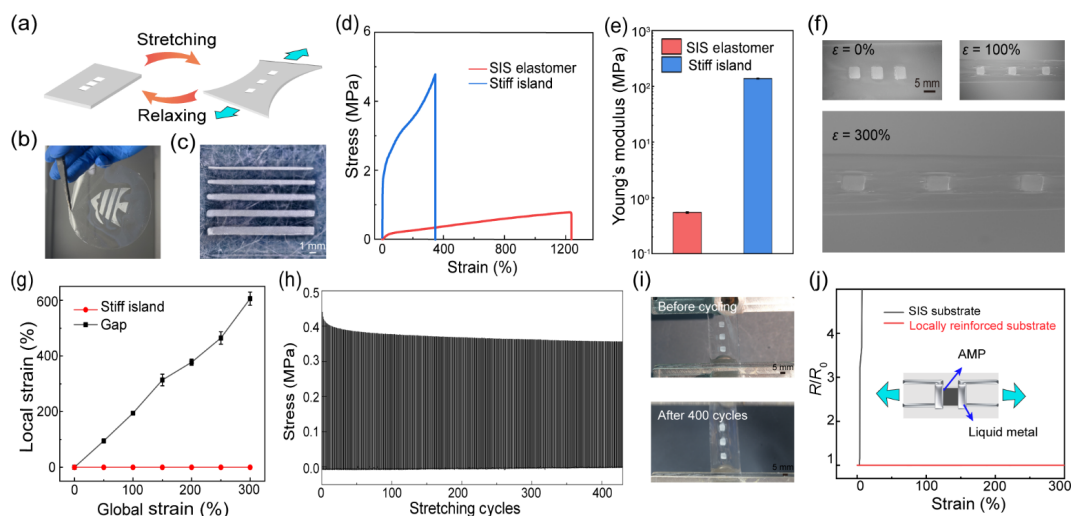


**Figure 4** Characterization of humidity-sensing characteristics of PDA-coated MXene sensors. (a) Resistance evolution during humidity increase/decrease over 10%–70% RH. (b) Cycling stability under repeated switching between 40% and 70% RH. (c) Transient response and recovery curves during dynamic switching between 40% and 92% RH, highlighting a fast response time of 1.2 s and a recovery time of 2.3 s. (d) Non-contact proximity detection showing the real-time resistance response to an approaching human fingertip at fixed distances of 2, 5, and 10 mm. (e) Schematic layout of the flexible humidity sensor integrated into a disposable face mask for non-invasive respiratory monitoring, along with the corresponding resistance response signal profiles for nasal and oral breathing modes.

pronounced resistance variations—a characteristic appealing for strain sensing [31–33]. While this sensitivity is advantageous for strain sensors, it poses a critical challenge for stretchable humidity sensors, where the active film must exhibit minimal strain-induced resistance change to avoid signal cross-talk. To address this, we adopt a strain engineering strategy by embedding stiff islands into a soft elastomer substrate [8, 48, 49]. Figure 5(a) schematically illustrates the tensile deformation of such a heterogeneous two-phase substrate. The gray region represents the SIS elastomer matrix, and the embedded white squares correspond to the glass microfiber-reinforced SEBS stiff islands. Upon uniaxial stretching, the low-modulus elastomer matrix deforms uniformly and accommodates the majority of the applied strain. In contrast, high-modulus stiff islands undergo negligible tensile deformation due to the pronounced modulus mismatch. This strain redistribution effectively isolates mechanical deformation from the stiff islands [49], creating nearly strain-free zones to host delicate sensing materials. For fabrication, these stiff islands are printed onto a low-adhesion wafer. The soft elastomer solution is then drop-cast around them to form a composite substrate. For more details, please refer to the Experimental Section and Fig. S3 in the ESM. The printing process allows convenient definition of the stiff phase in arbitrary designs, as exemplified by a tropical fish pattern (Fig. 5(b)). The minimum feature size, determined by printing a series of striped features, is approximately 300  $\mu\text{m}$  (Fig. 5(c)). Figure 5(d) presents the tensile stress–strain curves of the two material components. The soft elastomer matrix exhibits a low modulus of 0.55 MPa and a fracture strain above 1200%. In comparison, the stiff phase possesses a Young's modulus of 137.4 MPa, roughly 250 times higher than the soft matrix. This large modulus contrast is beneficial for effective strain isolation. Under uniaxial tensile stretching, the composite maintained its structural integrity without delamination or fracture of the stiff islands up to 300% strain, indicating robust interfacial adhesion (Fig. 5(f)). Figure 5(g) provides quantitative analysis of the local strain in the composite substrate under tensile loading. Figure 5(g) provides quantitative analysis of the local strain in the

two-phase substrate under tensile loading. The stiff islands essentially experience no deformation, with the local strain remaining below 0.5% for global tensile strain up to 300%. In contrast, the soft elastomer regions experience significantly amplified local strain due to the strain redistribution effect. The two-phase substrate is subjected to 400 cyclic tensile loadings at 100% strain to characterize its structural integrity and fatigue resistance. As illustrated in Fig. 5(h), the peak stress stabilizes over subsequent cycling, suggesting the gradual stabilization of mechanical performance under long-term cyclic deformation. Representative stress–strain hysteresis loops at 50-cycle intervals are shown in Fig. S12 in the ESM. Moreover, optical images of the substrate before and after cycling reveal no cracks (see Fig. 5(i)), interfacial delamination or notable permanent deformation after 400 cycles, directly validating the excellent structural integrity and robust interfacial bonding of the two-phase architecture. To evaluate the impact of this structural design on device stability, PDA-modified MXene was deposited onto both homogeneous elastomer substrates and locally reinforced composite substrates (Fig. 5(j)). The inset shows the design of the device for the four-probe electrical resistance measurement using liquid metal leads. The conductive film on the homogeneous in soft elastomer suffered catastrophic electrical failure at a tensile strain of only 35%, with the resistance rising sharply to an open circuit. In stark contrast, the film on the locally reinforced substrate exhibits excellent resistance stability, with minimal change even under extreme tensile deformation up to 300% strain. This dramatic enhancement in mechanical robustness stems from the stress-isolation effect of the locally reinforced architecture. Crucially, such strain-insensitive electrical behavior ensures that resistance changes during practical use originate predominantly from humidity fluctuations rather than mechanical deformation, eliminating motion artifacts and preserving sensor accuracy.

Encouraged by the above results, we further create a stretchable MXene humidity sensor array as an electronic skin, as schematically illustrated in Fig. 6(a). The device employs PDA-modified MXene films deposited on stiff islands as the sensing layer, which are



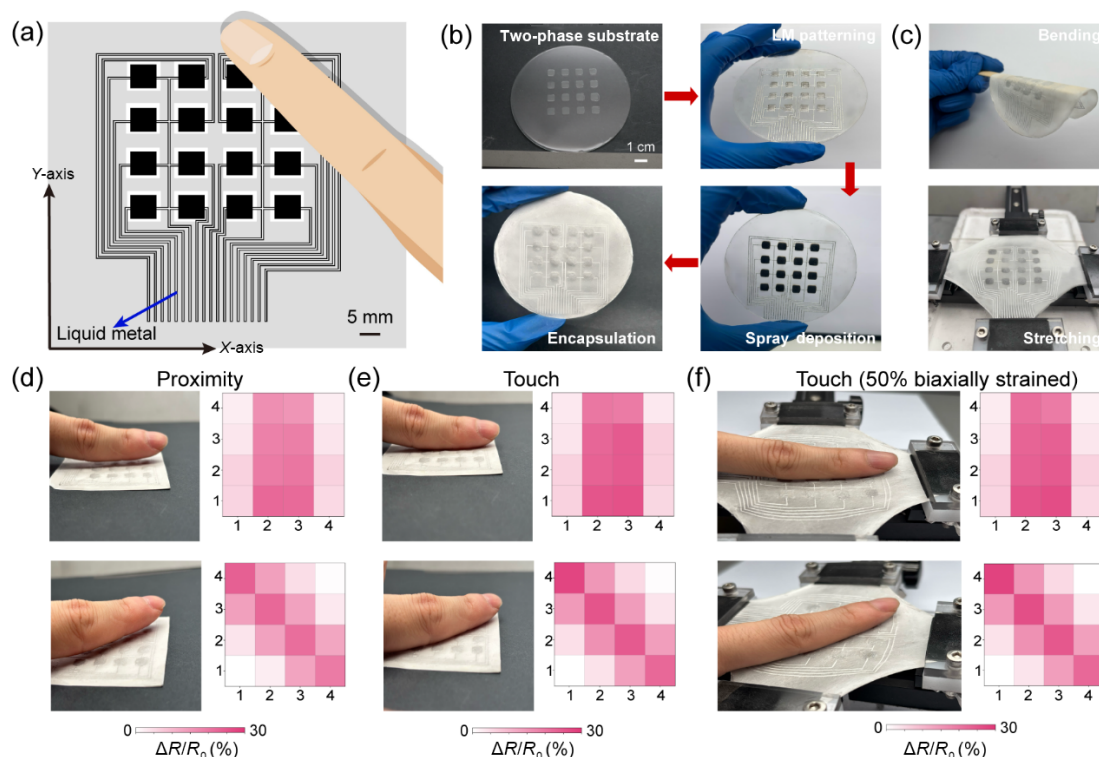
**Figure 5** Strain isolation of the locally reinforced two-phase substrate. (a) Schematic illustration of the two-phase substrate with embedded stiff islands under tensile deformation. (b) Optical image showing a tropical fish-patterned stiff composite. (c) Array of striped patterns demonstrating patterning resolution via stencil printing. (d) Tensile stress–strain curves of the stiff composite and soft elastomer matrix. (e) The corresponding Young's moduli comparison. (f) Optical images capturing the deformation of the locally reinforced two-phase substrate under varying global tensile strains. (g) Local strain within the stiff island and the soft elastomer gap under different global strains. (h) Stress response under 400 stretching cycles. (i) Optical images of the sample before and after the cycling test. (j) Four-probe resistance evolution of the MXene film deposited on the stiff island during tensile deformation with varying global strains.

interconnected by LM conductors. Figure 6(b) illustrates the fabrication process of the sensor array. First, a two-phase composite substrate with  $4 \times 4$  locally reinforced islands is created. The liquid metal is patterned into interdigital electrodes on stiff islands and corresponding electrical interconnects. High-fidelity patterning of the liquid metal adopts a selective wetting strategy [9, 50, 51]. Essentially, a thermally evaporated Cr/Cu film is first patterned as a template. The non-oxidized liquid metal is then selectively coated onto the template, replicating the desired features (see Fig. S13 in the ESM). Next, the PDA-modified MXene is deposited onto the interdigital electrodes through shadow masks. An ultrathin SIS microfiber layer was then produced via electrospinning, acting as a soft and gas-permeable encapsulation. The microfiber encapsulation layer exhibits a highly porous microstructure, ensuring excellent moisture permeability while providing reliable physical protection (see Fig. S14 in the ESM). Figure 6(c) presents the as-prepared sensor array that exhibits compliant mechanical properties to withstand severe bending and stretching. For signal acquisition, the electrical terminals are connected to a data acquisition card via a flexible flat cable. By collecting electrical signals from 16 channels, a spatial humidity distribution is constructed and visualized as a distinct map. As shown in Fig. 6(d), the array successfully resolves non-contact humidity variations induced by finger proximity at a distance of  $\sim 2$  mm. Two representative finger gestures are clearly resolved by the humidity map, namely alignment along the central axis and the diagonal direction. Due to the proximity detection capability, almost all sensing pixels exhibit resistance response. The pixels right underneath the finger exhibit the strongest variations, accompanied

by gradual decay for more distant pixels. Figure 6(e) presents the humidity map when the finger makes actual contact with the sensor. The spatial distribution of the map visually resembles the case for finger in the proximity, despite the actual amplitude obviously increasing. Beyond sensing under mechanically relaxed conditions, we systematically characterize the sensing performance of the e-skin array under biaxial tensile strains applied along the  $x$ - and  $y$ -axes. Four strain combinations were tested, as summarized in Fig. S15 in the ESM. The results confirm stable sensing performance under stretching thanks to the locally reinforced architecture of the two-phase substrate. Figure 6(f) shows the humidity response of the sensor array under a biaxial tensile strain of 50%. The device produces a high-fidelity humidity map to resolve the finger's presence and orientation. Notably, when the entire  $4 \times 4$  integrated array is subjected to a simultaneous 50% biaxial strain ( $\epsilon_x = 50\%$ ,  $\epsilon_y = 50\%$ ), the effective structural areal expansion of the device reaches  $\sim 250\%$ . Considering that the maximum skin strain experienced across various body parts—even at the joints—typically remains below 50% along a single axis, this large areal deformation capability comfortably exceeds the deformation requirements of most wearable electronic skin applications. Collectively, the results demonstrate the suitability of MXene-based humidity sensor arrays as a proximity-sensing e-skin.

## 4 Conclusions

In summary, we have successfully developed a stretchable, highly sensitive, and rapid-response MXene-based humidity sensor array capable of strain-isolated proximity sensing for electronic skin



**Figure 6** Stretchable MXene humidity sensor array serving as an interactive e-skin. (a) Schematic diagram of the integrated  $4 \times 4$  sensor array, showing active MXene sensing films positioned on stiff islands interconnected by liquid metal conductors. (b) Sequential optical images illustrating the fabrication flow: substrate preparation, printing of liquid metal conductors, spray coating of active MXene sensing films, and electrospinning of microfiber textile encapsulation. (c) Images demonstrating the mechanical deformability of the assembled sensor array under bending and biaxially stretching conditions. (d) Spatial humidity map of the e-skin when a finger is in proximity at a vertical distance of  $\sim 2$  mm. (e) Spatial humidity map under finger touch. (f) Spatial humidity map generated by a 50% biaxially stretched e-skin under finger touch.

applications. By implementing a two-step chemical modification involving alkaline intercalation and the *in situ* self-polymerization of PDA nanoparticles, we effectively overcome the chronic restacking issues plaguing pristine 2D  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene films. The expanded interlayer gallery spacing combined with the hygroscopic swelling of the anchored PDA nanoparticles yields an exceptional relative sensitivity of 0.707% RH and rapid response/recovery dynamics (1.2 s/2.3 s).

To decouple humidity transduction from severe mechanical strain interference, the active composite film was integrated onto a structurally engineered heterogeneous substrate. Featuring glass-microfiber-reinforced stiff islands embedded within a highly compliant SIS elastomer matrix, this architecture successfully confines tensile strain to the soft matrix. Consequently, the active sensing elements experience minimal local deformation (0.5%), shielding the device from strain-induced resistance crosstalk up to a 300% global tensile strain. Leveraging this robust electromechanical isolation alongside high-conductivity liquid metal interconnects and a gas-permeable electrospun encapsulation, the fabricated  $4 \times 4$  sensor array demonstrates reliable, high-fidelity spatial moisture mapping and touchless gesture recognition under both relaxed and 50% biaxially strained states. This work provides a robust and scalable strategy for developing high-performance, motion-artifact-free interactive electronic skins, holding immense potential for advanced robotics, non-contact human-machine interfaces, and personalized healthcare.

**Electronic Supplementary Material:** Supplementary material (schematic of the humidity sensing test system, SEM image of multilayer  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene, XRD patterns of MAX, pristine and alkalized MXene, XPS survey spectra of alkalized and PDA-coated MXene, additional EDS elemental maps of the electrospun microfiber layer, fabrication process of the two-phase substrate, detailed parameters of the interdigitated electrodes, optical images illustrating the selective wetting technique) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909125>.

## 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 interests in this work.

## Author contribution statement

Z. J. S.: Conceptualization, investigation, data curation, formal analysis, visualization, validation, writing manuscript. H. X.: Investigation, data curation. J. S. H.: Investigation, methodology. M. Q. Z.: Investigation. J. Q. S.: Investigation. D. S. K.: Conceptualization, project administration, supervision, funding

acquisition, writing manuscript. All the authors have approved the final manuscript.

## Use of AI statement

None.

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