

Flexible Wearable MXene – Based Printed Temperature Sensor for Multifunctional Applications

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Summary:

1. Fully printed flexible wearable temperature sensor was realized on polyimide (PI) substrate using dimethyl sulfoxide (DMSO)-enhanced $\text{Ti}_3\text{C}_2\text{T}_x$ MXene ink through a customized, scalable 3D-printing approach.
2. The sensor demonstrated reliable 20–60 °C sensing, with pronounced negative temperature coefficient (NTC), a temperature coefficient of resistance (TCR) of $-0.84\%/^{\circ}\text{C}$, and high linearity (Coefficient of Determination (R^2) = 0.98).
3. It maintained stable response and recovery with negligible drift over 90 days, demonstrating excellent long-term reliability.

Keywords: Flexible sensor; Temperature; Enhanced MXene; Wearable electronics; Multifunctional

Background, Motivation, and Objective

Flexible wearable sensors are conformable, non-invasive platforms for real-time monitoring in healthcare, environmental systems, human-machine interfaces, and soft robotics [1,2]. Among the physical variables they measure, temperature is particularly important because it reflects both physiological state and local thermal conditions, enabling on-body diagnostics and thermal mapping [1,2]. Despite progress, flexible temperature sensors face trade-offs among sensitivity, mechanical compliance, signal stability under deformation, and scalable manufacturing [2,4,6]. At the material level, polymer systems require molecular engineering to combine softness with strong thermal response [3], inorganic or metal-oxide thin films suffer from poor toughness and limited deformation tolerance [4], and carbon-based conductive networks often need explicit strain–temperature decoupling to avoid cross-signal interference [5]. In parallel, fabrication depends on tight control of ink formulation, printing precision, conformal deposition, and device integration, complicating reproducible, low-cost, and scalable production [6]. Here, we report a fully printed temperature sensor on a flexible substrate using a customized process, enabling high-performance sensing for multifunctional applications under bending-prone conditions.

Experimental Details

The sensing material consisted of DMSO-enhanced $\text{Ti}_3\text{C}_2\text{T}_x$ MXene ink, prepared by repeatedly exchanging the aqueous solvent with DMSO, followed by filtration and drying to obtain a DMSO-rich MXene mud (Fig. 1a). MXene formation was verified by SEM and XRD: SEM (Fig. 1b) showed stacked, accordion-like flakes with clear interlayer galleries, indicating effective etching and delami-

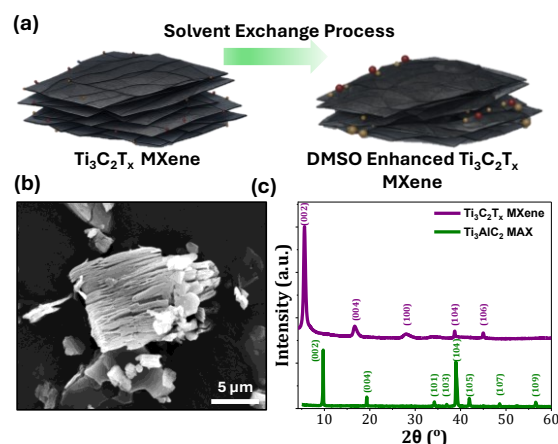


Fig. 1. (a) Solvent-exchange process for MXene ink preparation, (b) SEM image showing accordion-like layered morphology, and (c) XRD patterns confirming conversion of Ti_3AlC_2 MAX to $\text{Ti}_3\text{C}_2\text{T}_x$ MXene with enlarged interlayer spacing.

nation, while XRD (Fig. 1c) confirmed conversion of Ti_3AlC_2 MAX to $\text{Ti}_3\text{C}_2\text{T}_x$ MXene through the shift of the (002) peak from 9.5° to $\sim 6.8^\circ$ and suppression of MAX-phase reflections, evidencing increased interlayer spacing and layered MXene formation. The dried MXene was redispersed in DMSO to produce a homogeneous 45 mg mL^{-1} ink, with its conductivity–viscosity relationship shown in Fig. 2a. Temperature sensor was fabricated on $150 \text{ }\mu\text{m}$ -thick PI substrate, which was cleaned with isopropyl alcohol (IPA) and UV-treated for 120 s to enhance adhesion. The ink was printed through a $230 \text{ }\mu\text{m}$ disposable nozzle on a Voltera V-One printer using a custom alignment and material-swap method (Fig. 2b). After systematic optimization of feed rate, flow rate, trim length, baking temperature, and baking time, the device was cured at 45°C for 6 h. The fabricated sensor (Fig. 2c) was electrically characterized in a closed thermal chamber using a Keithley 2450 source meter at 1 V bias and 100

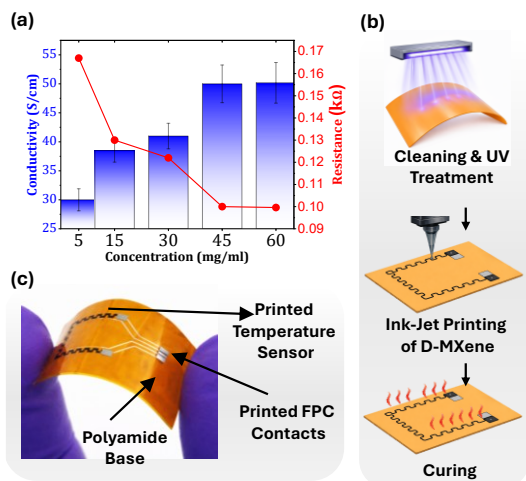


Fig. 2. (a) Conductivity and viscosity relation of the MXene ink, (b) Schematic illustration of the printing process used in sensor fabrication (c) Photograph of the final printed temperature sensor with FPC.

ms sampling interval, while chamber temperature was regulated by a heater with a REX-C100 controller and K-type thermocouple feedback. Silver-based flexible printed circuits (FPCs) were also fabricated to support future IoT integration.

Description of the New Method

We report a fully printed strategy for the fabrication of flexible wearable temperature sensors based on DMSO-enhanced $\text{Ti}_3\text{C}_2\text{T}_x$ MXene ink. The sensing material shows pronounced NTC and a TCR value. Combined optimization of ink formulation, material characterization, and printing parameters enabled the realization of sensors on flexible substrates with high sensitivity, and excellent repeatability.

Results

The temperature-sensing performance of the device was systematically evaluated by increasing the chamber temperature stepwise and recording the stabilized resistance at each setpoint. The resistance decreased continuously with increasing temperature, confirming NTC behavior over the 20–60 °C range (Fig. 3a). The corresponding resistance–temperature relationship (Fig. 3b) exhibited an approximately linear trend, with an R^2 value of 0.98 and a TCR of $-0.84\%/^{\circ}\text{C}$. This behavior is attributed to thermally activated carrier tunneling across interflake barriers, which becomes more favorable at elevated temperatures and thereby reduces junction resistance. The transient response (Fig. 3c) was evaluated by heating the sensor to 40 °C and allowing it to return to ambient conditions, yielding a response time of ~ 278 s and a recovery time of ~ 242 s. Long-term repeatability was assessed at 30-day intervals over 90 days, and the results in Fig. 3d show only marginal variation in the response curves and corresponding linear fits, with sensitivity changing by less than 1% after 90 days, confirming reliable long-term operation.

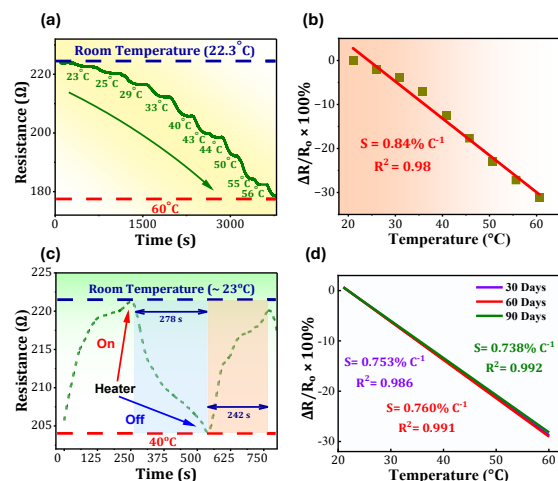


Fig. 3. (a) Stepwise resistance response of the printed flexible temperature sensor (b) Temperature response of the sensor relationship showing sensitivity and linearity (c) Response-recovery dynamics during heating and cooling (d) Long-term repeatability analysis of the sensor.

Conclusion

This work presents a fully printed flexible wearable temperature sensor based on DMSO-enhanced $\text{Ti}_3\text{C}_2\text{T}_x$ MXene ink on PI substrate. The device showed reliable NTC behavior over 20–60 °C, with near-linear response ($R^2 = 0.98$), a TCR of $-0.84\%/^{\circ}\text{C}$, stable response–recovery performance, and less than 1% sensitivity variation after 90 days. The method provides a scalable route to wearable temperature sensors for diverse monitoring applications.

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