

Fully Printed MWCNT/PEDOT: PSS/Ecoflex Tactile–Thermal Sensor with Dual-Mode Piezoresistive and Thermoresistive Transduction

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Summary:

1. Fully printed, flexible tactile–thermal sensor using a single MWCNT/PEDOT: PSS/Ecoflex (MPE) active film on printed two-terminal, interdigitated electrodes (IDEs) for scalable e-skin integration.
2. Pressure sensing up to ~ 95 kPa with two linear regimes: ~ 0.0035 kPa⁻¹ (0–20 kPa) and ~ 0.0085 kPa⁻¹ (20–95 kPa).
3. Temperature sensing over ~ 20 – 80 °C with near-linear NTC behavior (~ 0.0045 °C⁻¹).
4. Fast pressure dynamics (reported ~ 0.4 s response/recovery) and distinct thermal kinetics (~ 2.5 s response, ~ 18 s recovery) support robust multimodal tactile sensing.

Keywords: Printed e-skin; multimodal sensor; Ecoflex composite; MWCNT/PEDOT:PSS; tactile–thermal sensing

Background, Motivation, and Objective

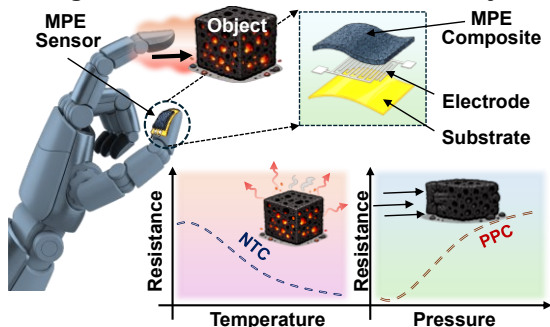


Fig. 1 Printed MPE tactile–thermal sensor concept and principle: NTC response to temperature and PPC response to pressure on a robotic fingertip.

Soft robotic grippers and wearable e-skins increasingly require co-located pressure and temperature perception to safely interpret contact state, object thermal condition, and interaction dynamics. Recent progress in flexible pressure/tactile sensors has been accelerated through micro-structured elastomers and conductive networks that provide large piezoresistive signals with simple readout [1]. However, when pressure and temperature must be sensed from the same contact region, conventional resistive composites face a fundamental limitation: the resistance is simultaneously modulated by mechanically driven junction/tunneling changes and by temperature-dependent carrier transport/percolation, producing coupled outputs that are difficult to interpret under real touch events [2]. Prior multimodal solutions often pursue device-level separation by integrating dedicated pixels/functional units (e.g., active-matrix multimodal arrays), hybrid optoelectronic/structured fibers, or ionic/impedance-derived multimodal receptors. While powerful, these

strategies typically require multilayer stacks, specialized readout electronics, or complex integration workflows that limit rapid manufacturing and scaling [3,4].

Here, the objective is to demonstrate a new route to multimodal tactile–thermal sensing that preserves fabrication simplicity: a fully printed, two-terminal sensor in which a single composite film provides both pressure and temperature responses.

Experimental Details

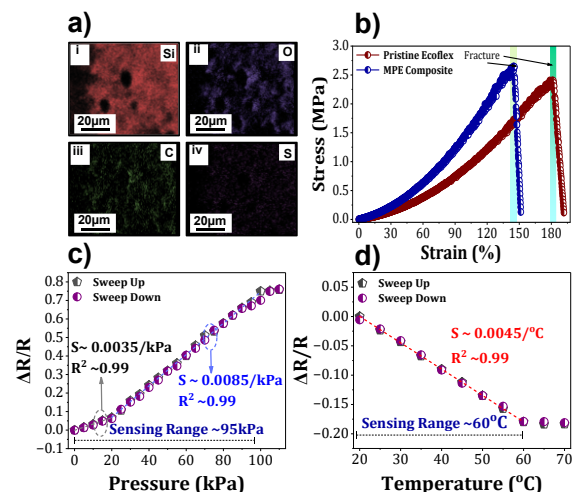


Fig. 2. (a) EDS maps (Si, O, C, S) of the MPE composite. (b) Tensile stress–strain of pristine Ecoflex vs MPE composite. (c) Pressure calibration (0–95 kPa; two linear regimes). (d) Temperature calibration (~ 60 °C range; NTC response).

The sensing composite uses Ecoflex 00-30 loaded with 5 wt% (multi-walled carbon nanotubes) MWCNTs and 3 wt% (Dimethyl sulfoxide) DMSO-activated PEDOT: PSS nanoparticles. MWCNTs are first dispersed in IPA by bath ultra-sonication for 30 minutes, followed by the

addition and further sonication of dried PEDOT: PSS powder. The suspension is then mixed into Ecoflex prepolymer (A: B = 1:1), degassed, and the solvent is allowed to evaporate to produce a homogeneous composite precursor. IDTs are printed on polyimide (Kapton) using a Voltera V-One printer (finger width approximately 200 μm , gap approximately 500 μm , 12 fingers), then cured and lightly surface conditioned for adhesion. The composite is pattern-coated over the IDEs to form a continuous film about 1 mm thick and cured at 60 $^{\circ}\text{C}$ for 8 hours. Electrical measurements are conducted in a two-terminal setup using a Keithley 2450 (3 V bias, 100 ms sampling). Pressure is applied with an instrumented PTI-03 setup, while temperature is controlled via a heater stage managed by a W1209 controller and powered by a GW Instek GP8-4303 DC supply.

Description of the New Method

We present a fully printed, single-film tactile–thermal sensor where one composite layer simultaneously provides (i) a positive pressure coefficient (PPC) of resistance response, which is governed by reversible junction/tunneling modulation within a MWCNT/PEDOT: PSS percolation network, and (ii) a negative temperature coefficient (NTC) of resistance response, dominated by temperature-dependent transport in the same network; all using a minimal, two-terminal resistive architecture (see Fig. 1).

Results

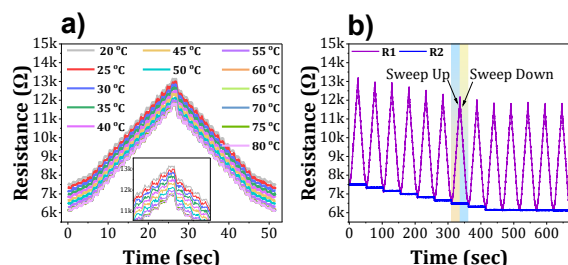


Fig. 3. Mixed pressure–temperature response: (a) pressure sweeps at different temperatures; (b) real-time pressure cycling during a temperature changes.

The MPE composite was thoroughly analyzed to verify its composition and multifunctional performance (Fig. 2). EDS maps reveal strong Si/O signals from the Ecoflex matrix and a spatially distributed S signal from PEDOT: PSS, indicating a well-dispersed conductive phase (Fig. 2a). The composite (160% strain at 2.6MPa) shows enhanced elastomeric mechanics compared to pristine Ecoflex (180% strain at 2.25MPa), supporting repeatable deformation during sensing. Pressure calibration covers a wide range up to approximately 95 kPa with two linear regimes ($S \approx 0.0035 \text{ kPa}^{-1}$ for 0–20 kPa; $S \approx 0.0085 \text{ kPa}^{-1}$ for 20–95 kPa), consistent with progressive

densification under load. Temperature calibration displays a near-linear NTC response ($\sim 0.0045 \text{ }^{\circ}\text{C}^{-1}$) over about 60 $^{\circ}\text{C}$, confirming effective thermoresistive behavior. Collectively, these results confirm the material's structure and baseline pressure/temperature sensing capabilities needed for printed tactile–thermal skins.

Fig. 3 demonstrates the sensor's intrinsic thermo-mechanical coupling under conditions where pressure and temperature co-vary. For identical pressure sweeps at different temperatures (Fig. 3a), the pressure-induced modulation is preserved while the baseline shifts with temperature, confirming mixed sensitivity in the composite resistance. In real-time cycling (Fig. 3b), pressure pulses remain clearly resolved despite baseline drift during a temperature transition (highlighted), showing the device can capture dynamic tactile events under changing thermal conditions—critical for robotic tactile skins handling objects at different temperatures.

Conclusion

We demonstrated a fully printed Ecoflex–MWCNT–PEDOT: PSS tactile–thermal sensor with a simple two-terminal resistive readout. The device senses pressure up to $\sim 95 \text{ kPa}$ with two linear regimes and shows a near-linear NTC temperature response over $\sim 60 \text{ }^{\circ}\text{C}$, supported by EDS and mechanical characterization. Mixed tests confirm pressure signals remain resolvable under temperature changes, highlighting suitability for robotic skin integration and scalable printed fabrication.

Acknowledgment

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