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Giant Tunneling Piezoresistance of Composite Elastomers with Interlocked Microdome Arrays for Ultrasensitive and Multimodal Electronic Skins

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Introduction

- Human skin possesses a high degree of flexibility and stretchability and can sense pressure, shear, strain, temperature, humidity, fluid flow, and pain.

- As such, it is an ideal system to model multifunctional and flexible electronic skins, which are used in wearable electronics, prosthetic limbs, robotic skins, and remote surgery, as well as in a wide range of other electronic and biomedical applications.

- Piezoresistive composite elastomers hold substantial promise for the realization of electronic skins, owing to their inherent flexibility, stretchability, and chemical stability and simple, scalable, and low-cost fabrication processes.

- Traditionally, conductive fillers such as carbon blacks, graphites, metal particles, and carbon nanotubes (CNTs) are incorporated into elastomers to generate piezoresistive behavior.

- The piezoresistivities are primarily attributed to the variation in tunneling resistance when the interfiller distance changes under external stress.

In this paper…

- To maximize the piezoresistive effects, the concentration of conductive fillers is kept near the percolation threshold; under external stress, the resistance then changes sharply. However, sensors that are based on composite elastomers suffer from poor sensitivities and are not suitable for detection in low-pressure regimes (<~10 kPa).

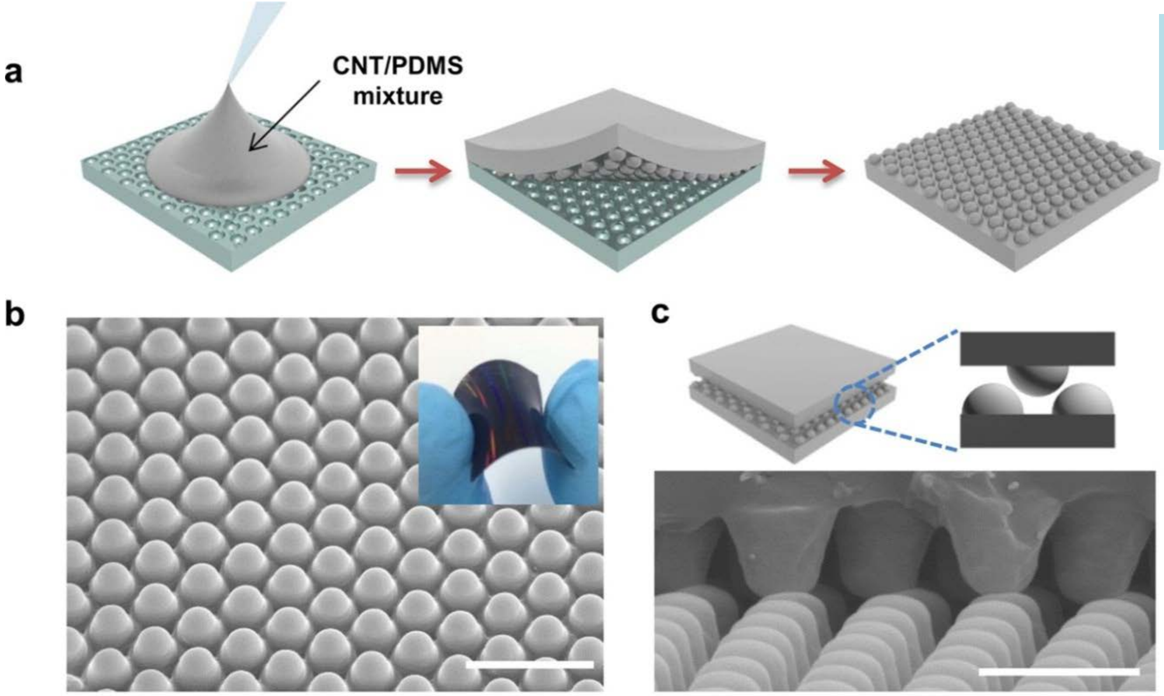
- Moreover, they exhibit negative effects under temperature variation, due to polymer swelling and changes in interfiller distances.

- Finally, the intrinsic viscoelastic properties of composite elastomers result in significant hysteresis and slow response/ relaxation times, which present a significant challenge for their applications in high-performance electronic skins.

- In this study, a novel design for conventional piezoresistive composite films is demonstrated that overcomes many of the shortcomings listed above.

Fabrication

Conductive composite elastomers with interlocked microdome arrays

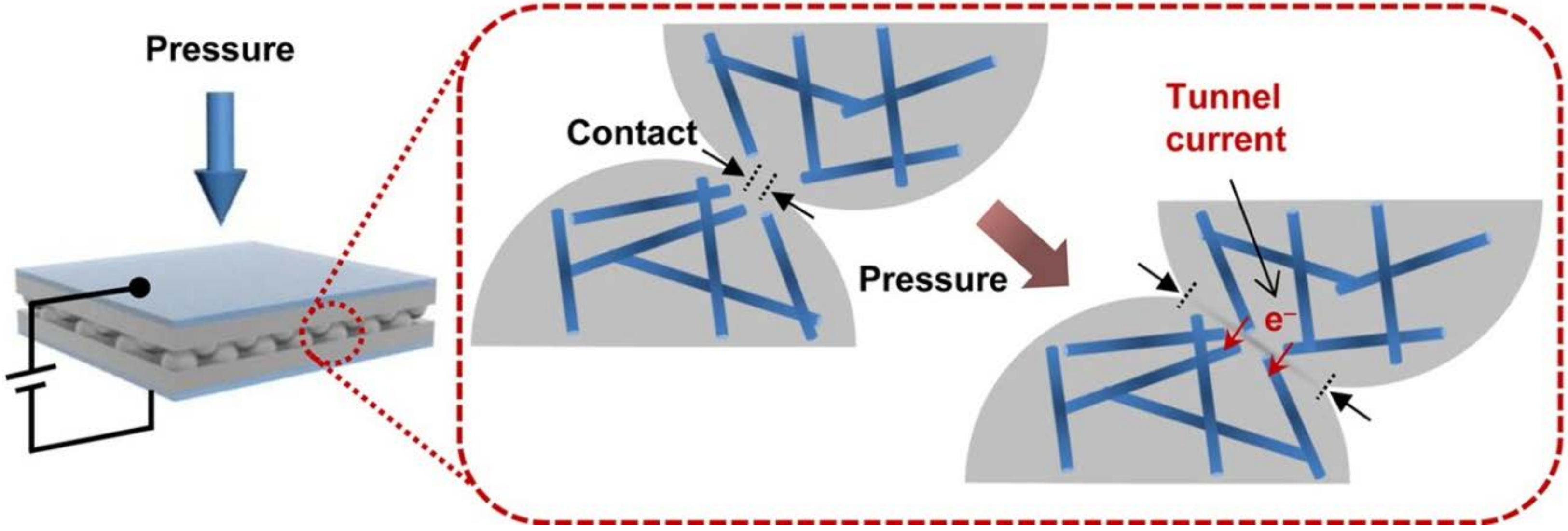


- ❑ Films were fabricated by micromolding a liquid mixture composed of CNTs, polydimethylsiloxane (PDMS) prepolymer, and a curing agent with a microhole-patterned silicon mold.

- ❖ The micromolding process produces a flexible composite film with regular microdome arrays, characterized by a height of ~3 μm, a diameter of ~4 μm, and a pitch of 6 μm.

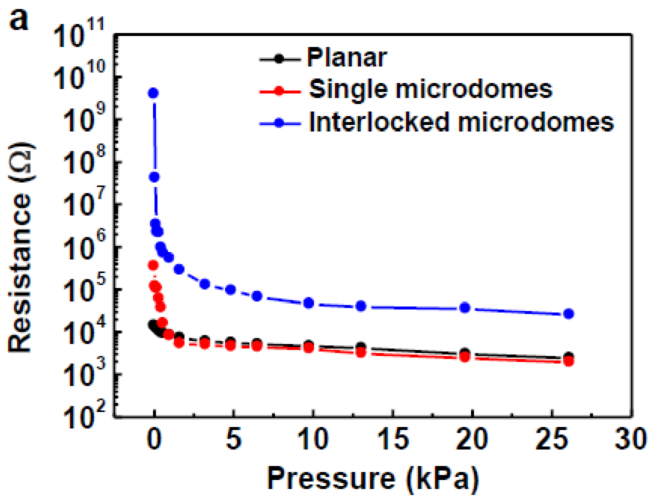
- ❖ For the fabrication of electronic skins, two composite films with microdome arrays are combined with the patterned sides facing each other. This construction produces an interlocked geometry of microdome arrays.

Illustration of working principle

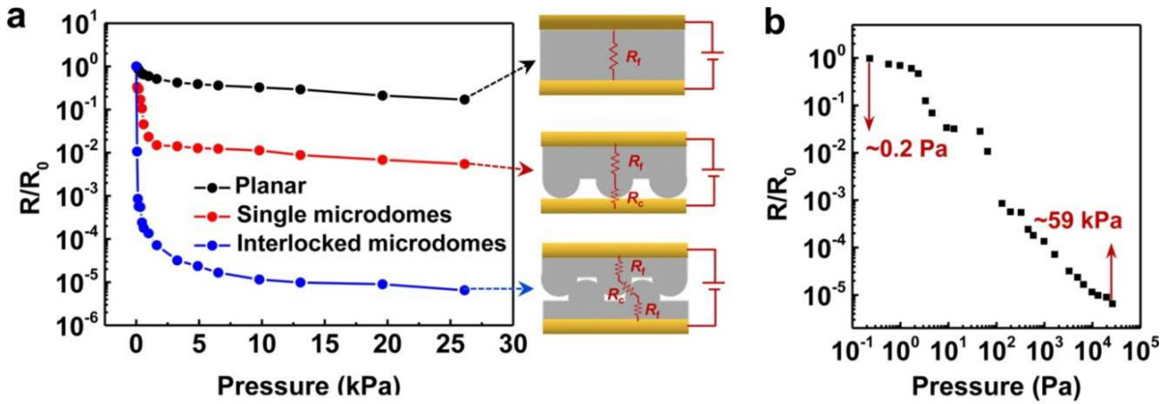


- The external pressure induces stress concentrations at the small contact spots and local deformations in the microdomes.
- Contact area between the interlocked microdome arrays increases significantly and affects the tunneling resistance at the contact spots.
- This results in a giant tunneling piezoresistance in the flexible films.

Performance of the pressure sensor



- Initial resistances (R_0) are $1.4*10^4$, $3.5*10^5$, and $3.9*10^9$ Ω for planar, single microdome, and interlocked microdomes, respectively.
- R_{OFF}/R_{ON} ratios exhibited by these three systems are 2, 100 and 10000 when pressure is increased from 0 to 10 kPa.
- This ratio in low pressure region (10 kPa) is comparable with piezoresistive composites (~10^6 at ~1 MPa).

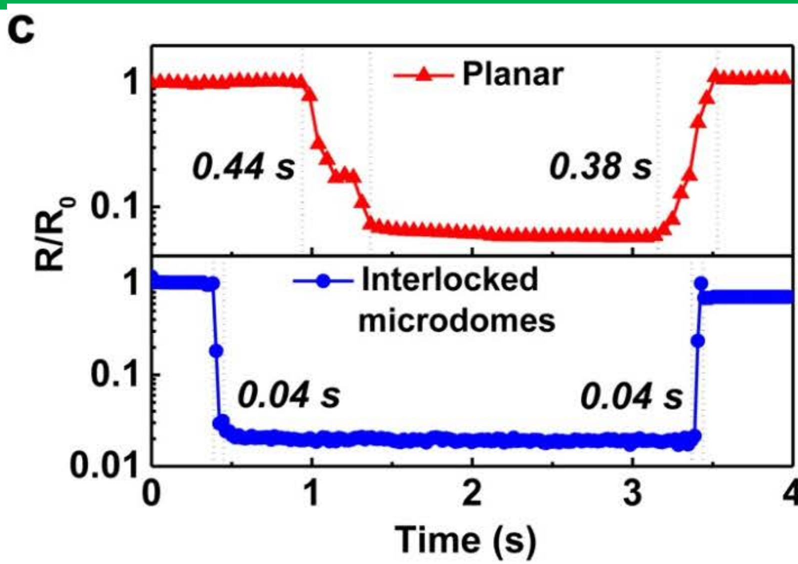


Piezoresistive pressure sensitivity

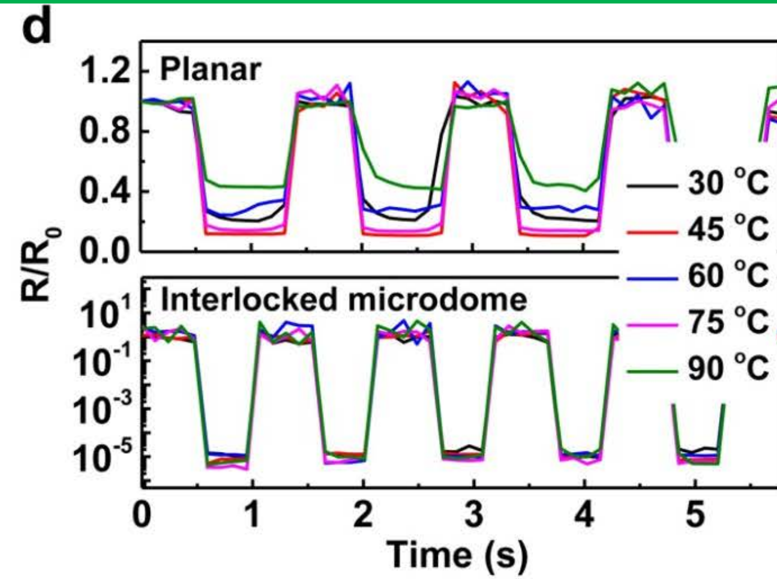
$$S = (\Delta R/R_0)/(\Delta P)$$

- In the low-pressure range (<0.5 kPa) of the linear regime, the sensitivities of interlocked microdome films are ~3 and ~24 times higher than the sensitivities of single microdome films and planar films, respectively.
- The sensors can detect a minimum applied pressure of ~0.2 Pa, which is below the gentle touch (~1 kPa) of human fingertips and the minimum detection limits (>~1 kPa) of traditional piezoresistive composites.
- This is also comparable with values recently reported for resistive (5 Pa), capacitive (3 Pa), piezoelectric (0.1 Pa), and triboelectric (0.4 Pa) sensors.

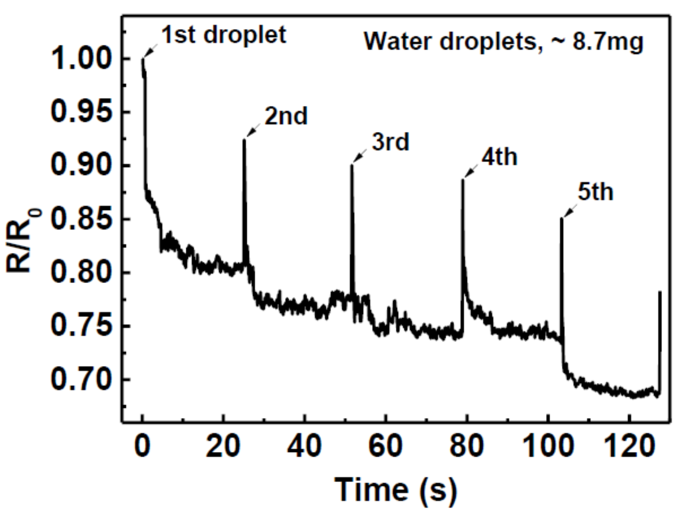
Performance of the pressure sensor



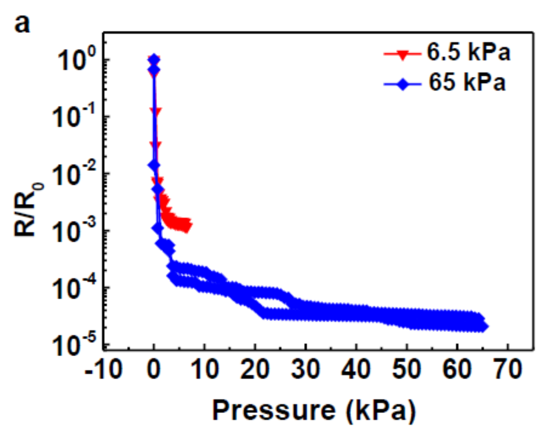
Low response/ relaxation time



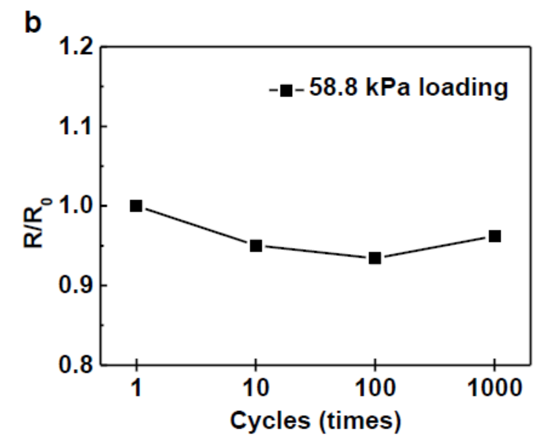
Reduced temperature dependence



Detection of water droplets
0.6 kPa

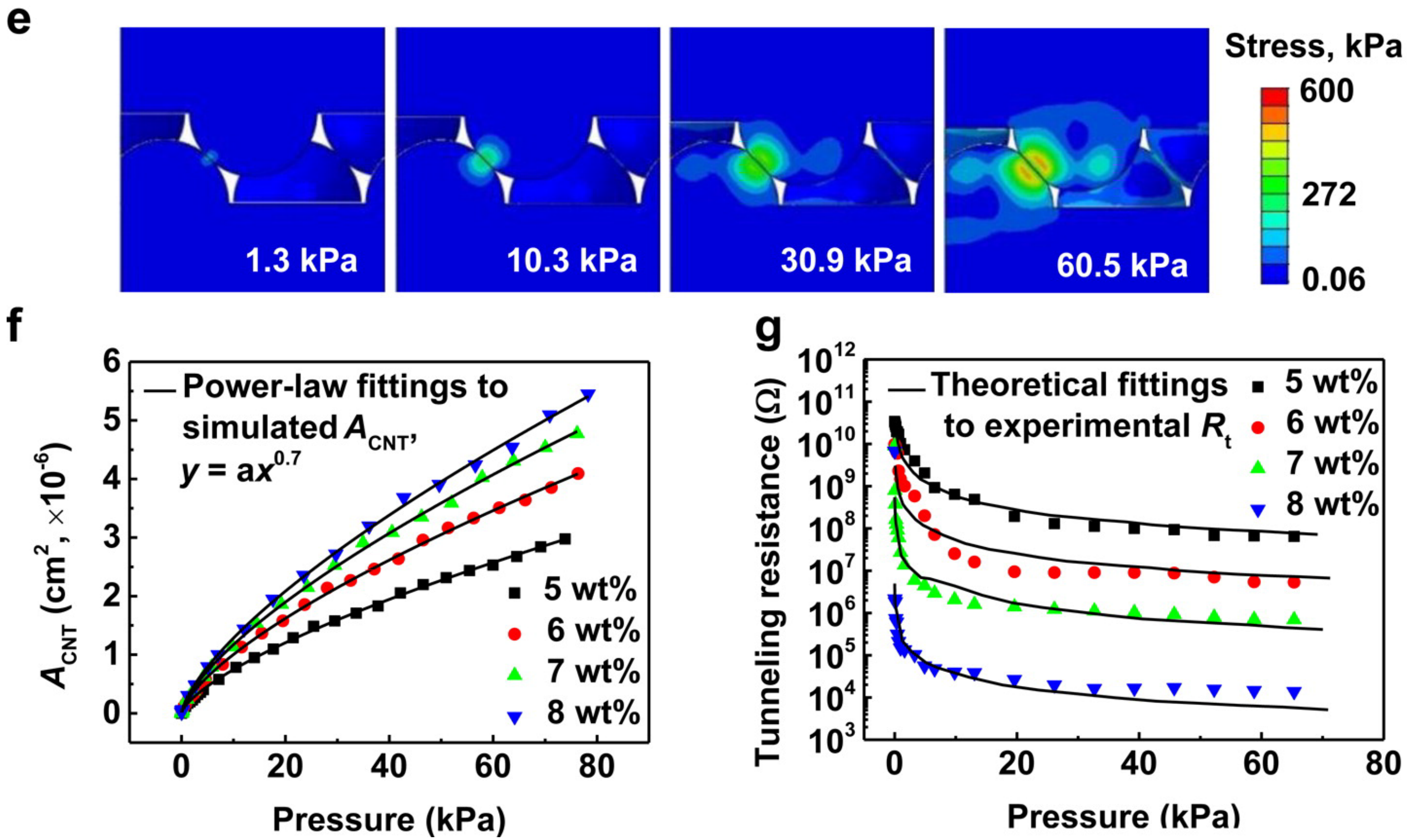


Minimal hysteresis



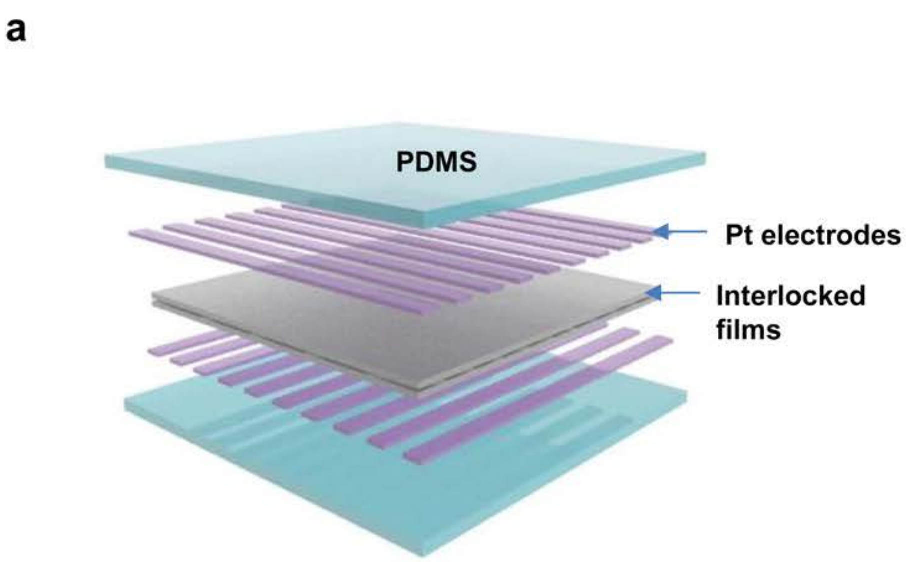
Cyclablity

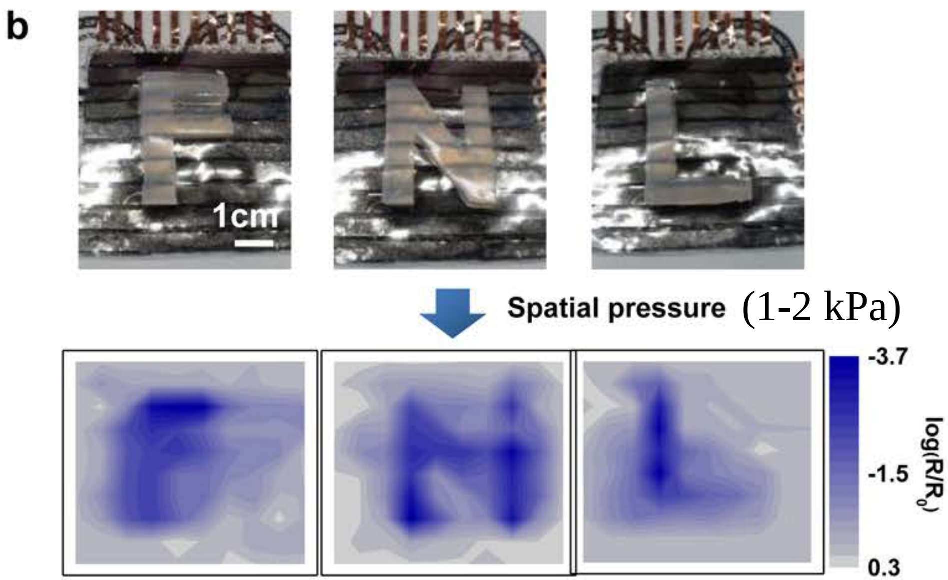
Performance of the pressure sensor-theoretical considerations



(e) Finite-element calculations that show the deformation and the local stress distribution of interlocked microdome arrays with applied pressure (1.3–60.5 kPa). (f) The electrical contact area (A_{CNT}) as a function of pressure for different CNT wt % (5–8 wt %). A_{CNT} is estimated by considering the CNT areal fraction in the geometrical contact area, which is obtained by using FEM simulation. The solid lines represent power-law fits to A_{CNT} with an exponent of 0.7. (g) Experimental tunneling resistances (dotted plots) of the interlocked microdome arrays for different CNT concentrations (5–8 wt %) fitted to calculated tunneling resistances (solid lines).

Application- Sensing of spatial pressure distribution



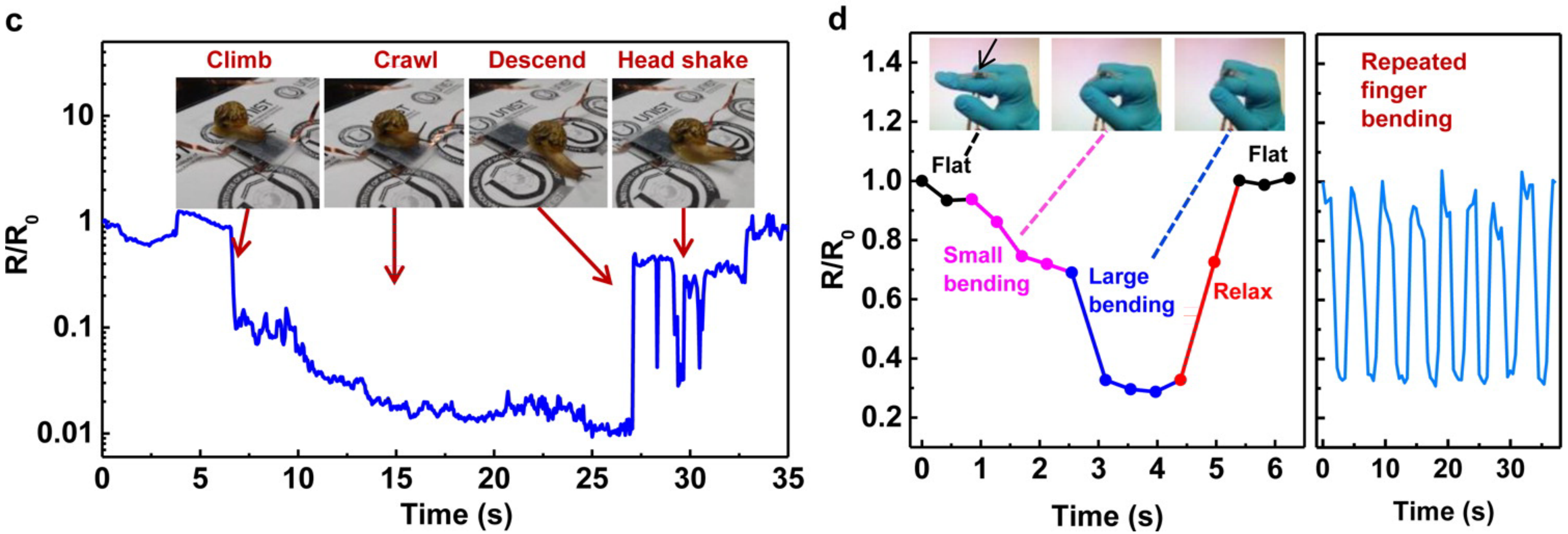


Schematic of the 10 × 10 sensor arrays, which consist of interlocked microdome arrays sandwiched between platinum electrodes and PDMS cover layers

Spatial pressure-mapping capability of the 10 × 10 sensor arrays. The spatial pressure distribution is applied using PDMS weights that are shaped as the letters “F”, “N”, and “L”.

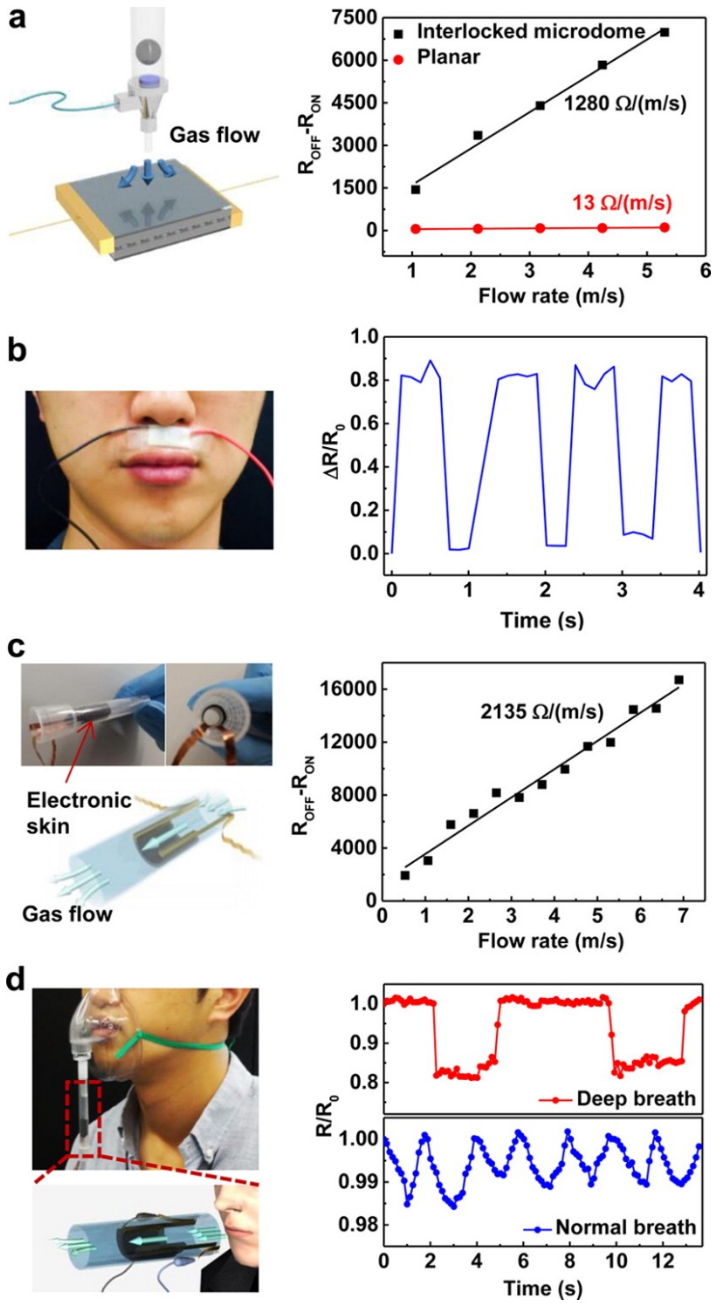
Application- Real-time monitoring of tactile signals

Detection of dynamic variation in pressure



(c) Real-time monitoring of the change in resistance for snail movements (climb, crawl, descend, and head shake) on the surface of the electronic skins. (d) Change in resistance for different bending degrees of a finger (left) and repetitive bending cycles (right).

Application- Human health monitoring

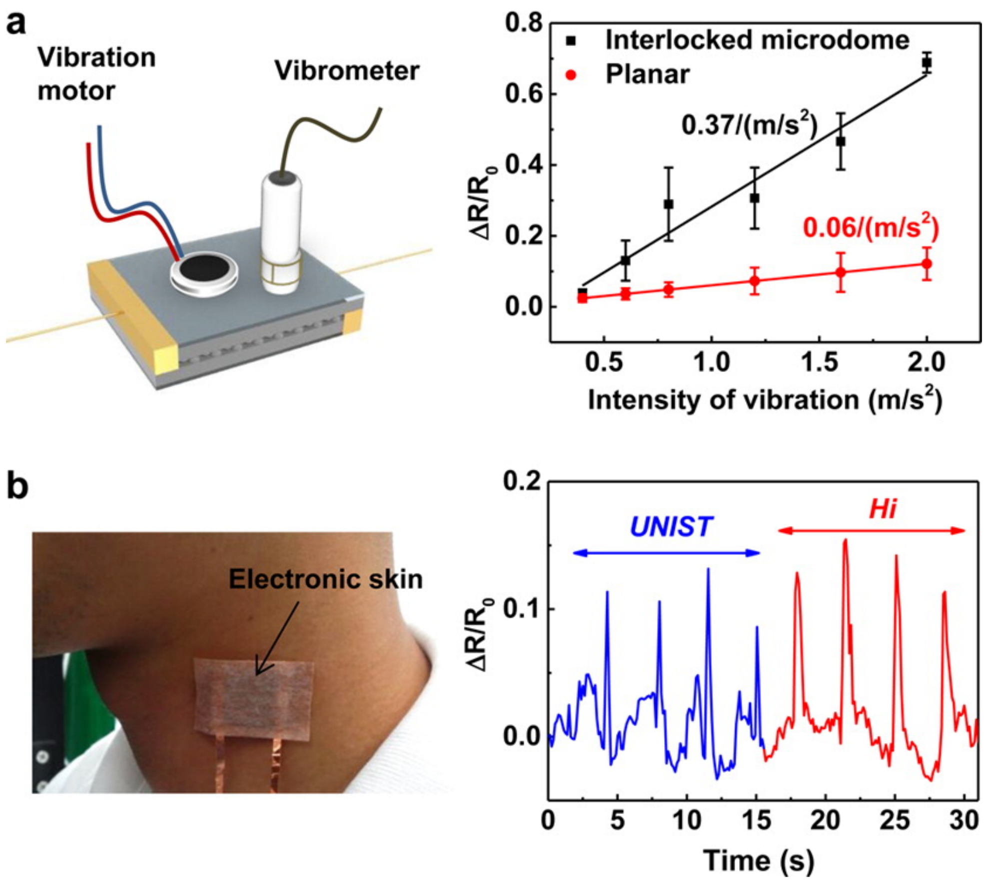


The analysis of human breathing patterns provides a noninvasive and repeatable monitoring technology that can be used in a variety of healthcare applications like screening for cardiovascular diseases or to monitor sleep apnea-hyponea syndrome

Gas flow on the electronic skin's surface can impart normal pressures that deform the interlocked microdome arrays and cause a decrease in resistance.

The higher sensitivity of tubular electronic skin compared to the planar one can be attributed to the difference in effective pressure applied on each sensor. For the tubular sensor, the gas flow is confined and guided by the tubular path,which results in higher effective pressure than that for the planar sensor.

Application- Vibration detection for wearable voice-monitoring systems



(a) Left: schematic of the vibration measurement. A coin-type vibration motor is used to generate vibration signals, and a vibrometer is used to measure the vibration intensity. Right: relative changes in resistance (Δ*R*/*R*0) as a function of vibration intensity. (b) Photograph of the electronic skin attached to a human neck for voice monitoring (right). Relative changes in resistance in response to different voices saying “UNIST” (blue) and “hi” (red).

Summary and conclusions

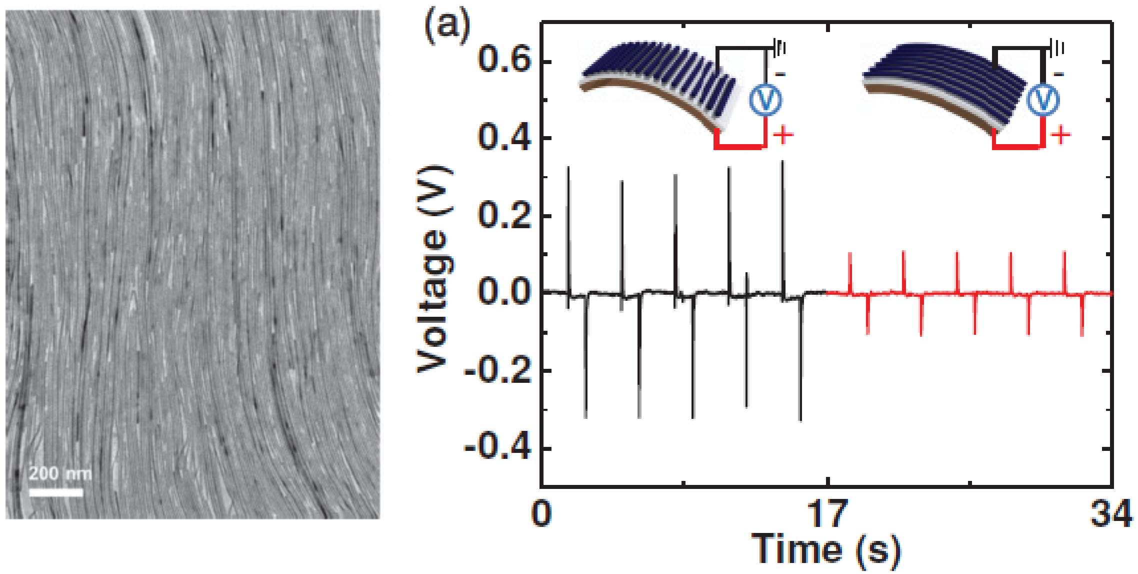
- They have developed an electronic skin that consists of a CNT-composite-based elastomer film featuring interlocked microdome arrays, which lead to the giant tunneling piezoresistance and thus the high pressure sensitivity.

- The materials design and operational principles introduced here present a robust technology platform to further advance the sensitivity and response time of conventional composite elastomers for various sensor applications.

- In addition, when integrated with other types of sensors and active electronic devices, the current platformcould be a key component for the development of multifunctional electronic skin for applications in medical diagnostic tools and wearable human-health monitoring systems.

- Finally, the extreme resistance-switching behavior demonstrated here could enable highly efficient piezotronic transistors.

High-Power Density Piezoelectric Energy Harvesting Using Radially Strained Ultrathin Trigonal Tellurium Nanowire Assembly



Thank You