ZHEJIANG UNIVERSITY

High performance flexible piezoresistive sensor with graft-copolymerized composites

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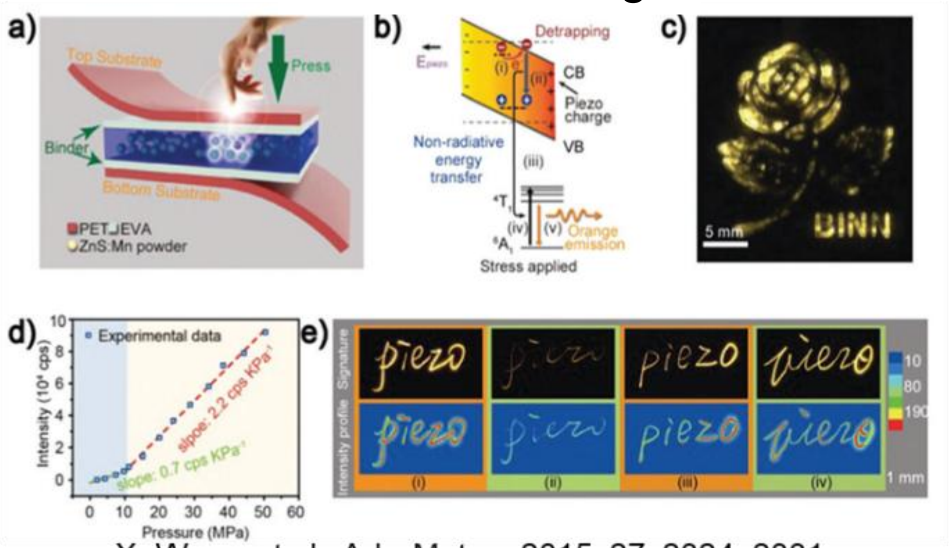
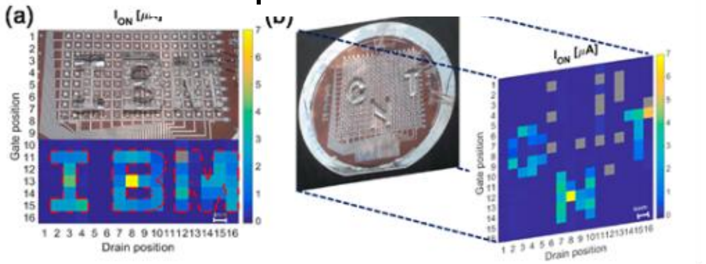
Example from Research group –flexible pressure sensor

Pressure tracing



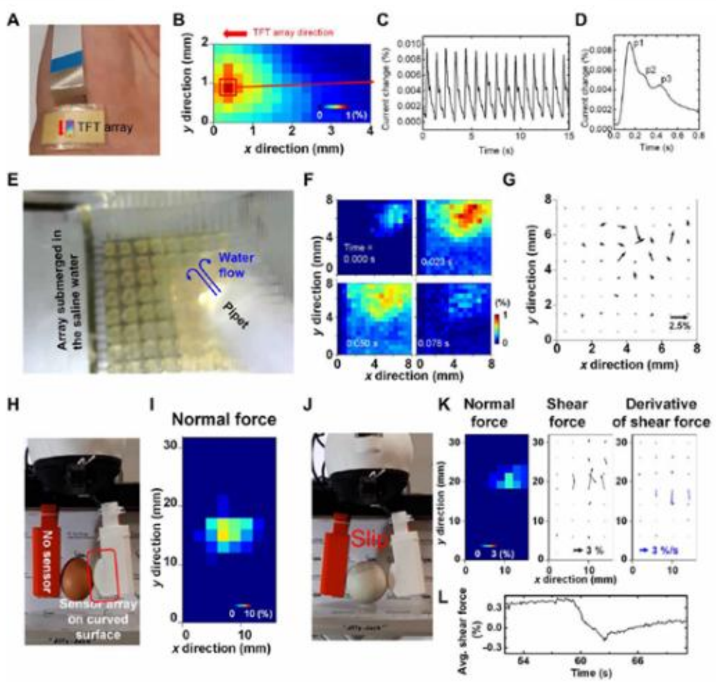
X. Wang, et al., Adv. Mater., 2015, 27, 2324–2331.

Shape detection



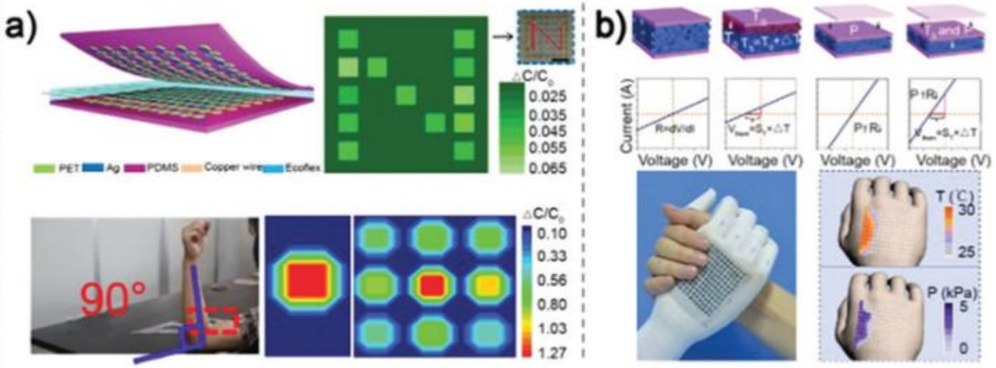
Nela, L., et al. (2018). Nano letters 18(3): 2054-2059.

Mechanical arm



Oh, H., et al., Sci. Adv., 2020, 6(46): eabd7795.

E-skin



F. Zhang, et al., Nat. Commun., 2015, 6, 8356.

Avatar

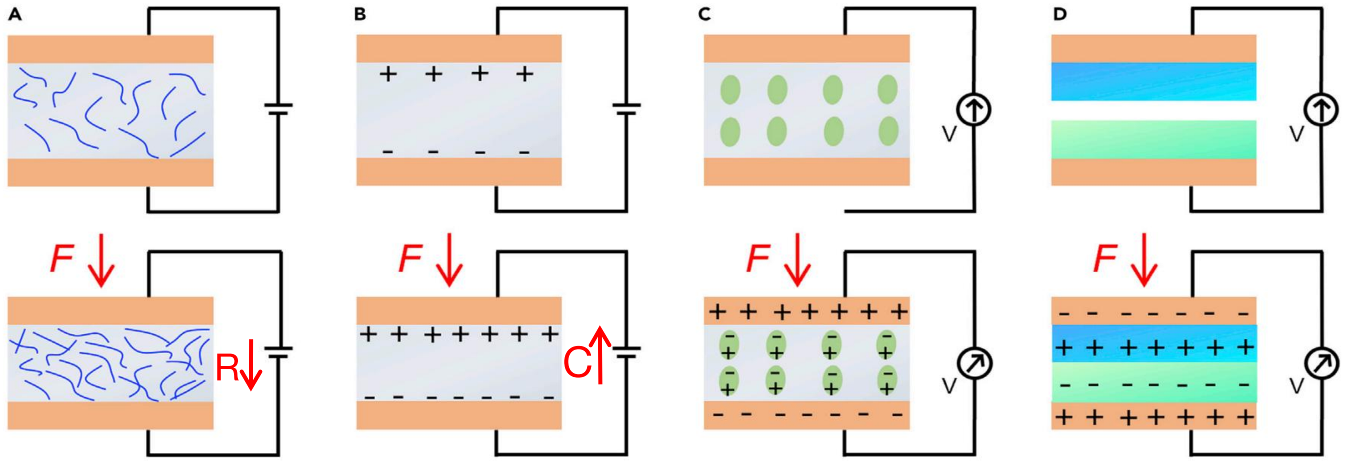
Virtual reality(VR)

Augmented Reality(AR)

Meta

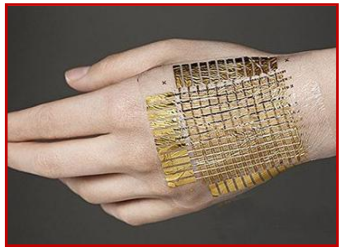
The pressure sensing mechanism and application

Pressure sensing mechanism:



piezoresistive capacitive piezoelectric triboelectric

E-skin



Medical

Intelligent limb

Traditional piezoresistive sensor

Flexible and thin film piezoresistive sensor

Piezoresistive advantages:

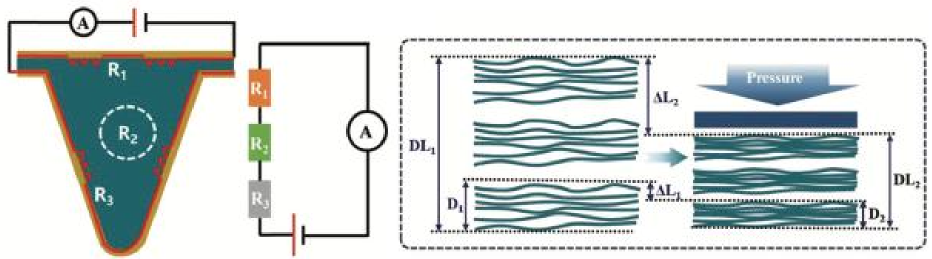
- **High sensitivity (Medical & Health)**
- **Low power dissipation**
- **High resolution**
- **... ...**

Curved surface or narrow space (such as inside eye), special shape materials and devices are required!

Sensors & Actuators: A. Physical 344 (2022) 113770

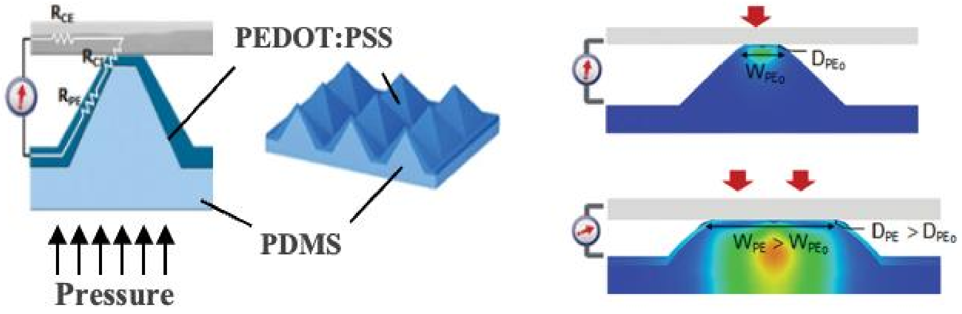
Three most widely reported piezoresistive materials

(a)



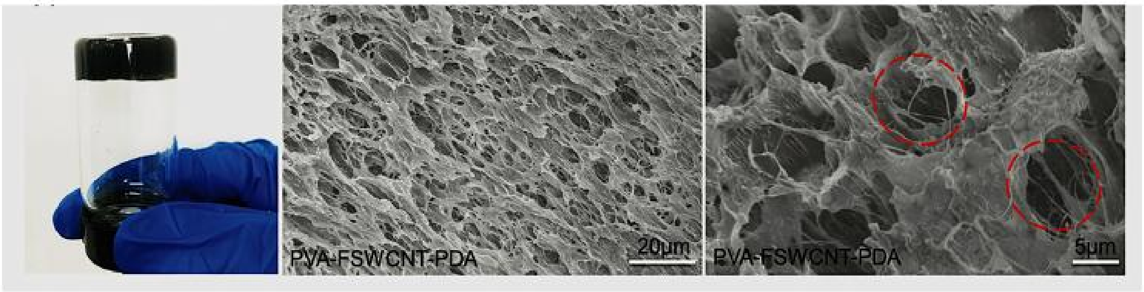
2D, sensitive, narrow sensitive regime

(b)



2-2 composite, sensitive, Young’s modulus mismatch

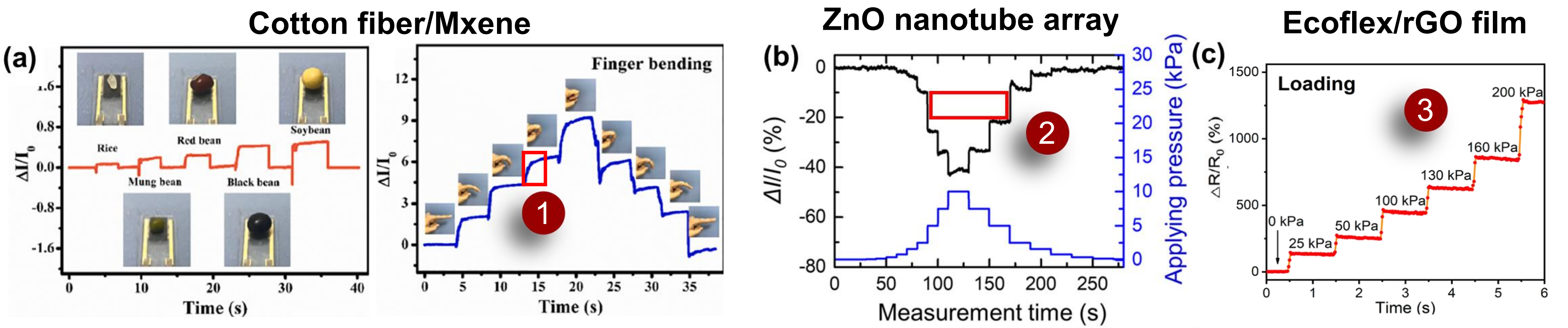
(c)



(0,1,2)-3 composite, sensitive regime and reliability

Easy to deform fastly, easy to achieve high sensitivity

The problems of widely reported pressure sensor



Chem. Eng. J., 2021. 420, 127720

NPG Asia Materials, 2021. 13(1), 57

ACS Nano, 2020. 14(8), 10104

1 Slow stabilization	slow	(1) The relaxation is obvious, hard to get stabilized
2 Poor repeatability	drift and hysteresis	(2) Creep or even plastic deformation
3 Poor stability	delamination	(3) Young's modulus mismatch
4 Low sensitivity	insensitive	(4) Trade off between sensitivity and stability

Relaxation time

Relaxation: Relaxation time： the speed of relaxation process

One equilibrium state

At certain temperature

By molecular movement

Another equilibrium state

small molecules are transient processes

take $10^{-8} \sim 10^{-10}$ s

polymer

Longer time

Motion units are of different size

Entropy and Friction between molecular

Relaxation time: minutes, days or even years

Prolong the relaxation time

Whether the process can be regarded as a relaxation process depends on observation time

1) Relaxation time τ << observation time —— transient processes;

2) Relaxation time $\tau \approx$ observation time —— relaxation processes ;

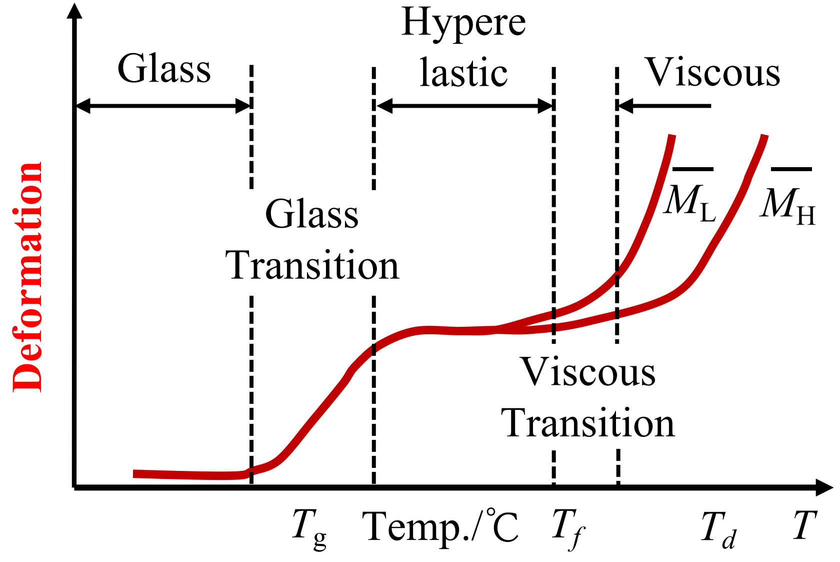
3) Relaxation time τ >> observation time —— relaxation is hard to occur;

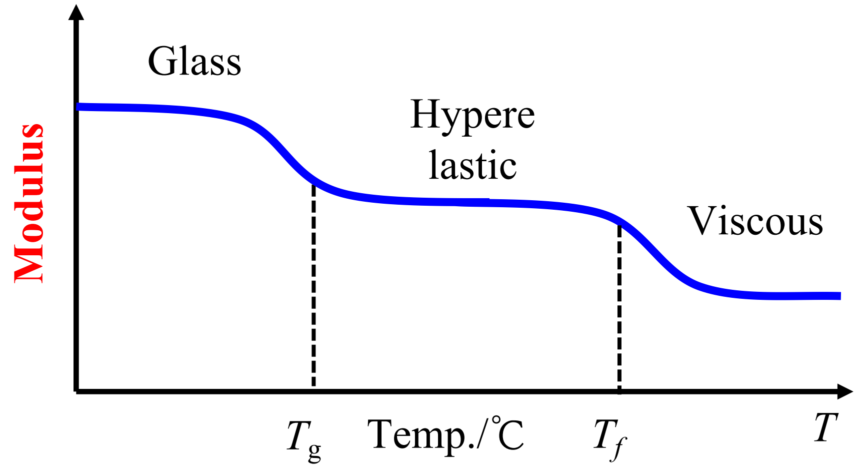
How to avoid relaxation of segments:

1) energy (determined by temperature)

2) space; (free volume)

Methods: Principles of relaxation and creep





Working temperature < Tg

Glass Transition (Tg)

- **Segment movement**

  Deformation increases

Viscous Transition (Tf)

- **Chain movement begins**
- **Flow**

Conditions of movement

- Energy (Temperature)
- Space (Free volume)

Iso-free-volume

Glass state

Chain movement resistance

Glass transition temp. (Tg)

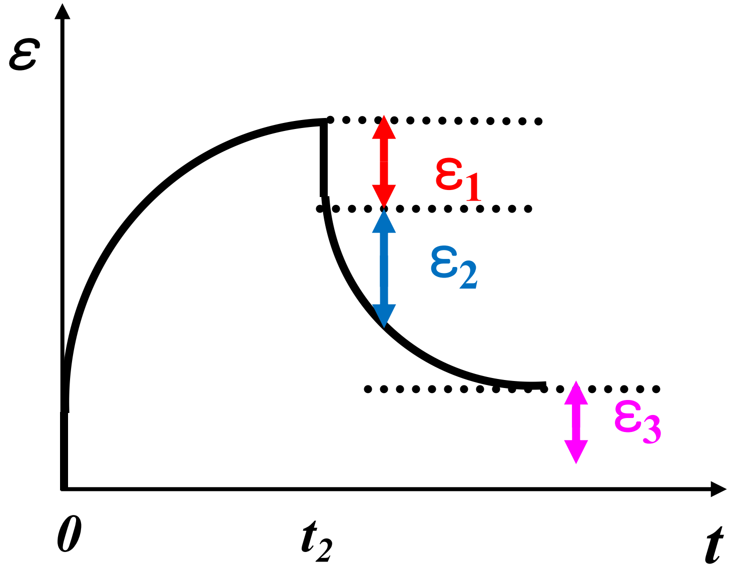
**The polymer with higher Tg, higher modulus,
longer relaxation time and higher stability could be achieved.**

But, lower sensitivity and plastic deformation

How to enhance sensitivity on the basis of stability???

Typical creep curve

When compressed, three kinds of deformation might occur simultaneously:



- Elastic ε_1: rebound immediately;
- Viscoelastic ε_2: entropy derived,
- Plastic ε_3: permanent and irreversible

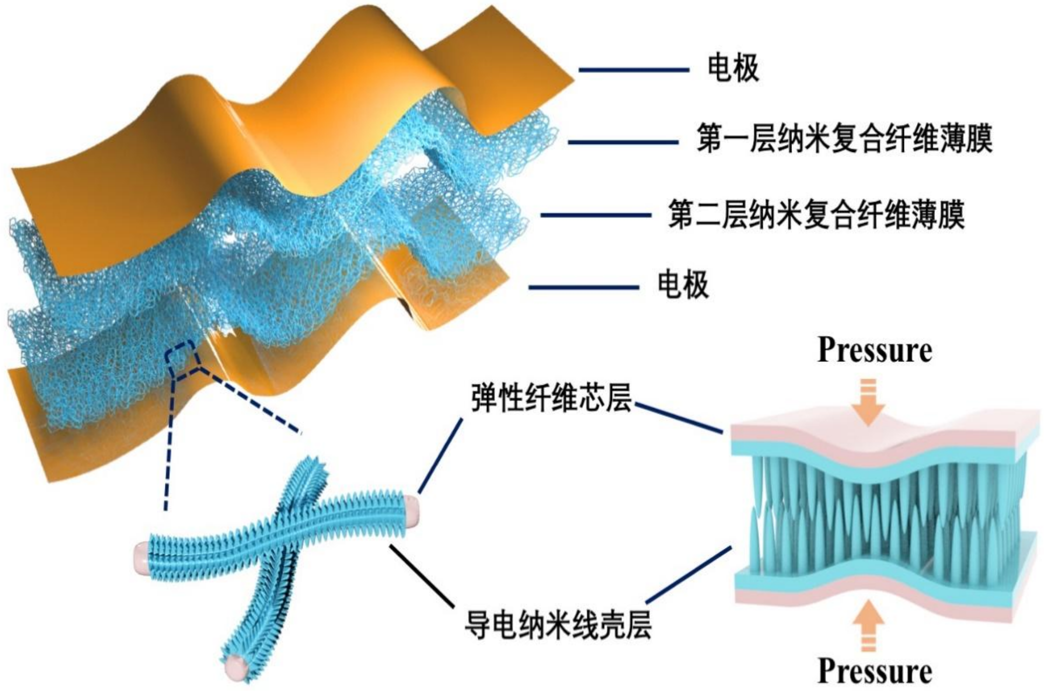
The total deformation:

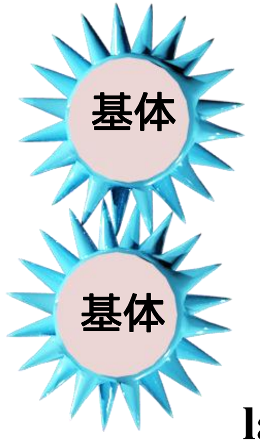
$$\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = \sigma_0\left[\frac{1}{E_1} + \frac{1}{E_2}(1 - e^{-t/\tau}) + \frac{t}{\eta_3}\right]$$

Design a piezoresistive composite with high Young's modulus, without ε_3 or even ε_2,

Fast response, high stability, how about high sensitivity?

The design of high Tg graft-copolymerized composite





1. Stability: extend relaxation time

   1). matrix： high Tg_1

   2). semiconductor: high Tg_2

2. Sensitivity: increase the active site

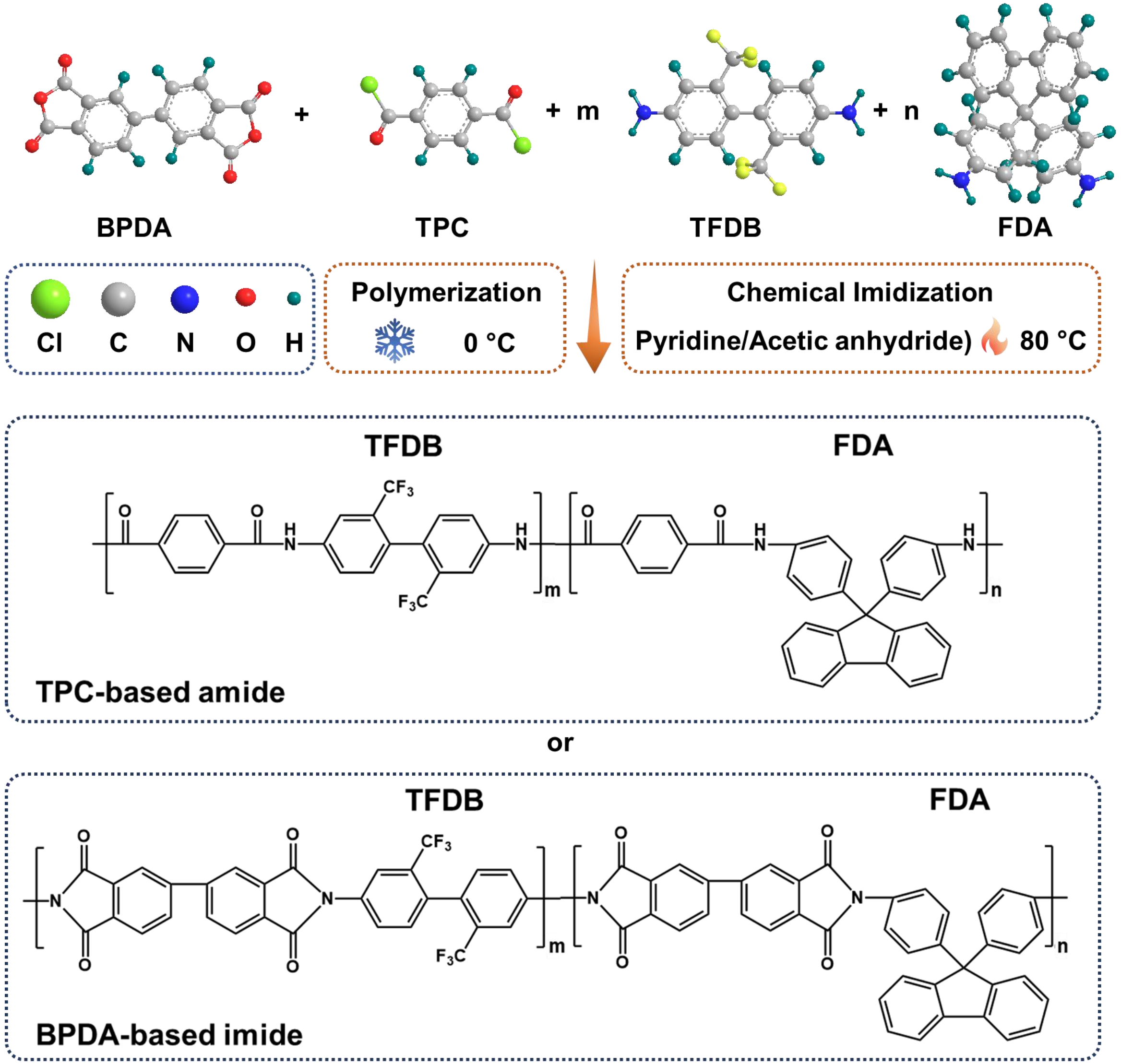
large specific surface area matrix+ grating nanostructure

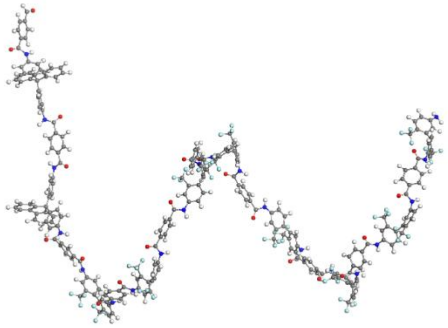
The key： strong interfacial bonding, thermodynamic compatibility and form high Tg composite

$$\frac{1}{T_g}=\frac{1}{\omega_1+B\omega_2}\left[\frac{\omega_1}{\boxed{T_{g1}}}+\frac{B\omega_2}{\boxed{T_{g2}}}\right]$$

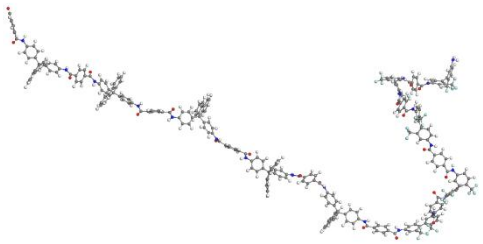
The thermodynamic compatibility of the copolymer, one Tg.

The design of high Tg matrix

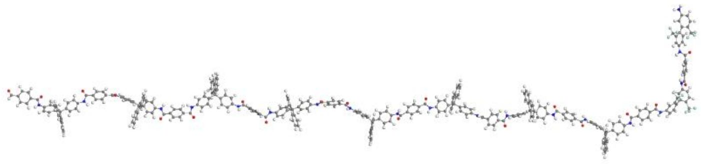




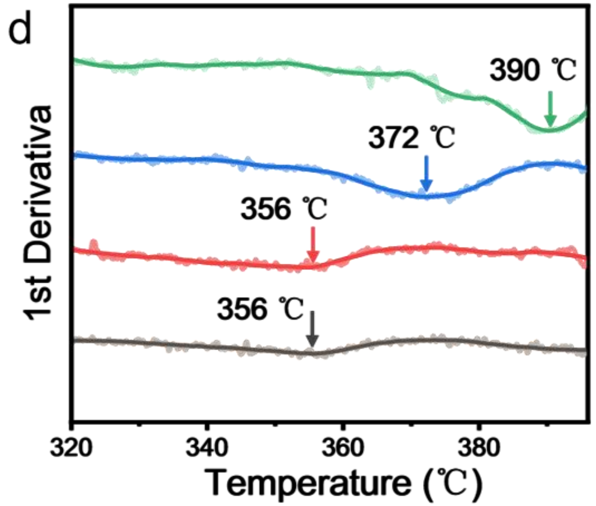
TFDB:FDA=8:2
radius of gyration: 23.15 Å



TFDB:FDA=5:5
radius of gyration: 31.83 Å

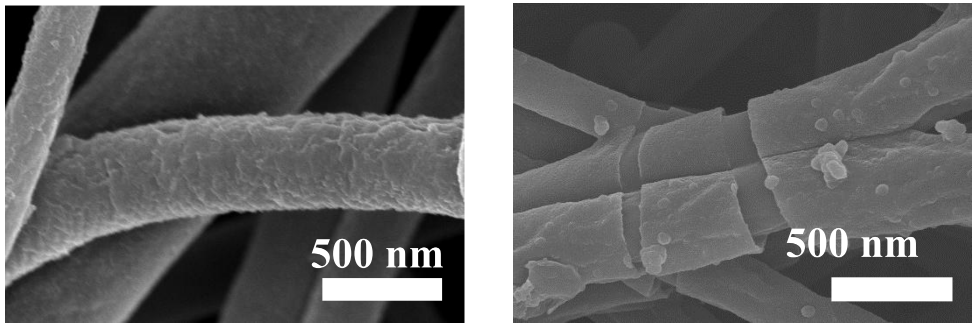


TFDB:FDA=2:8
radius of gyration: 46.8 Å

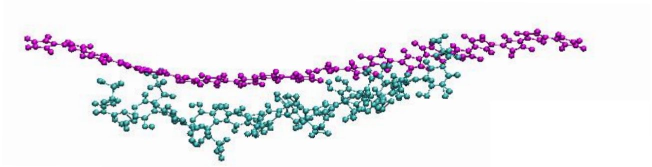


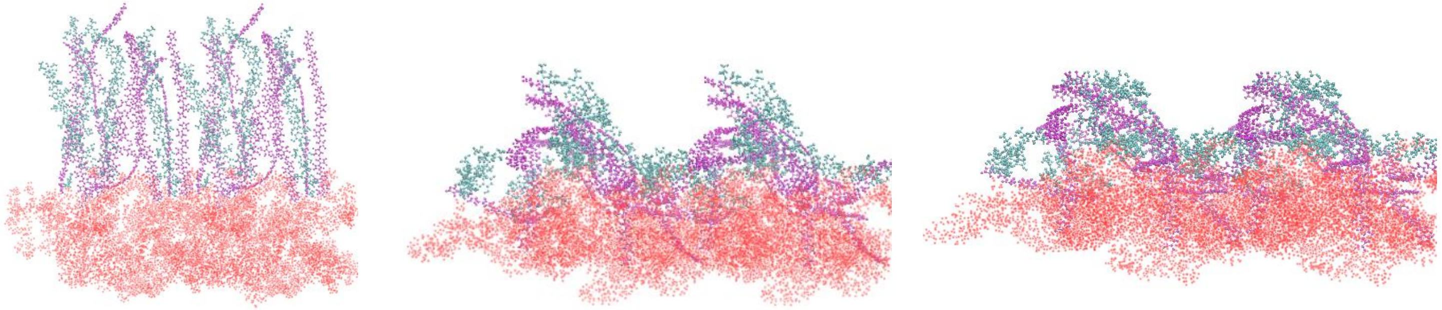
Strong interface bonding

Weak interface bonding，shear fracture

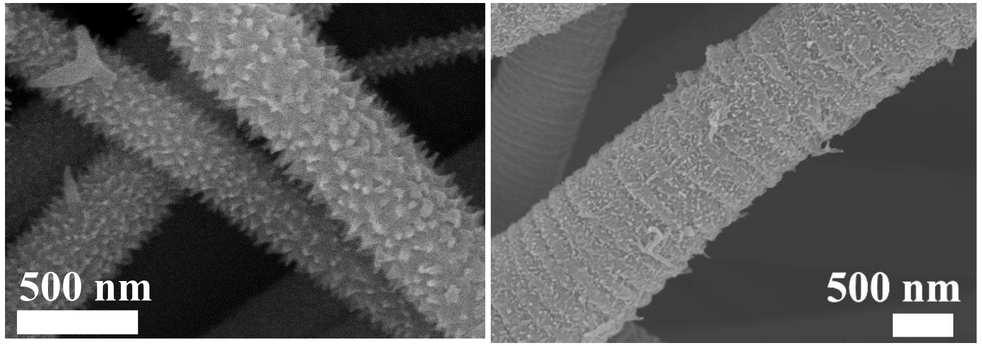


W/O HCl

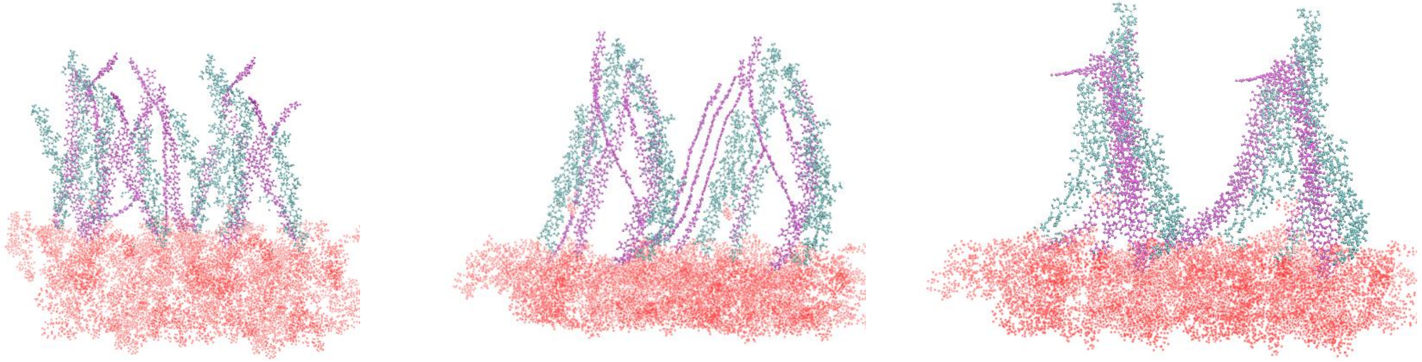




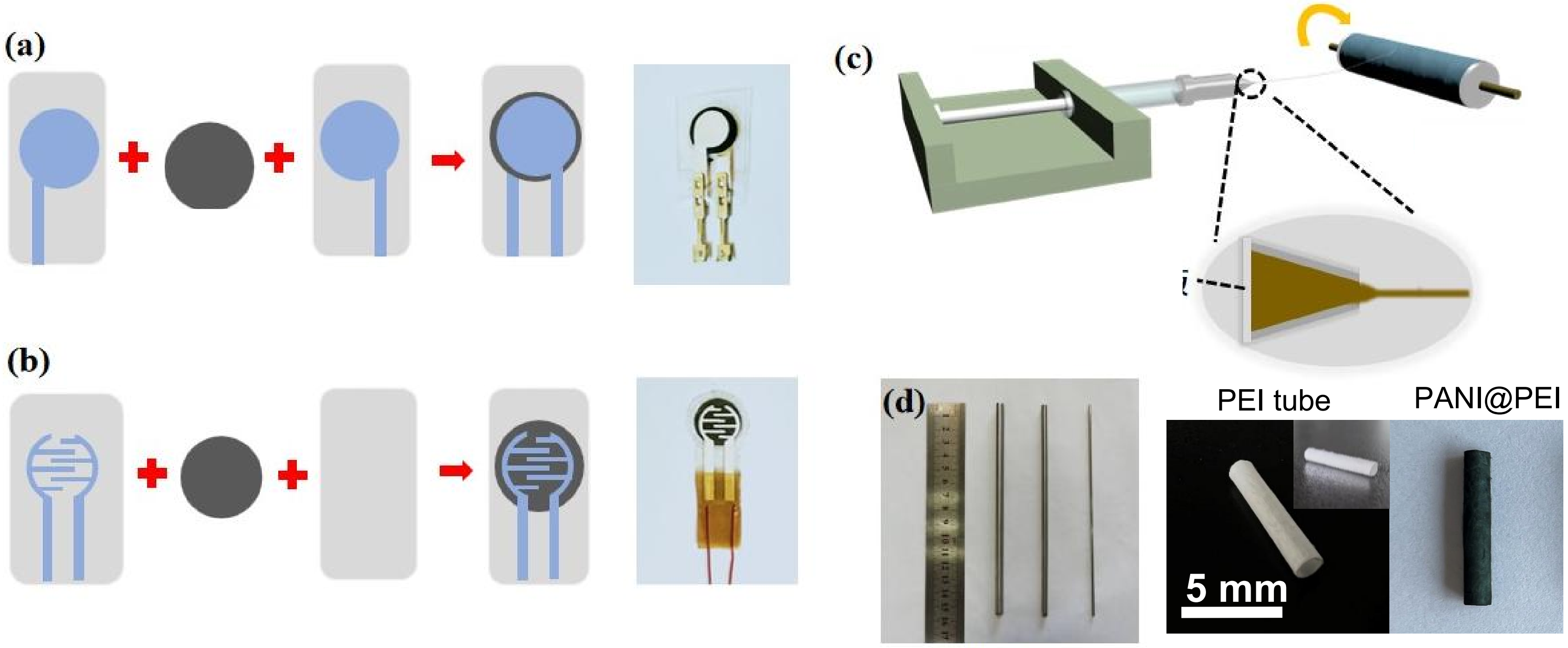
Strong interface bonding，high stress transfer efficiency



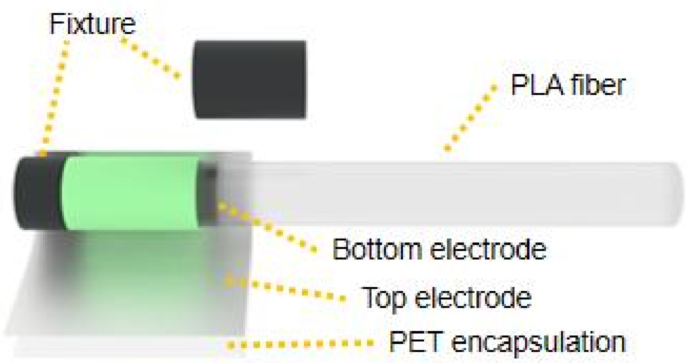
W HCl

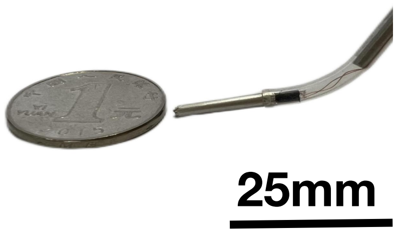


The design and construction of the pressure sensor



Planar device construction





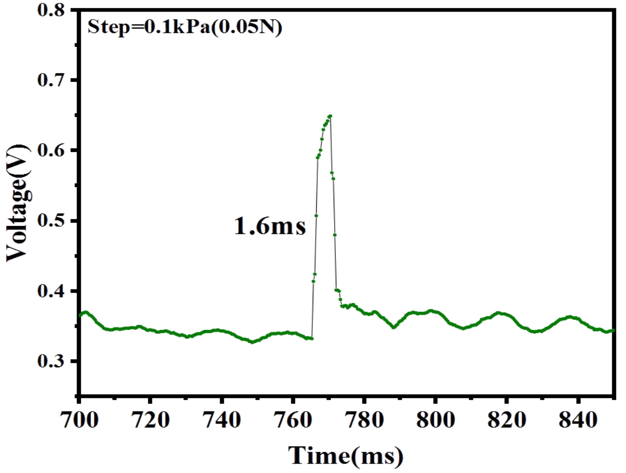
Tubular device construction
(With shape memory effect)

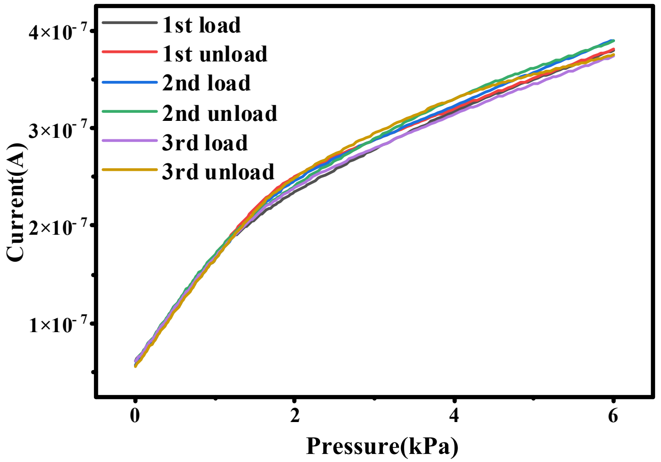
The key parameters of the pressure sensor

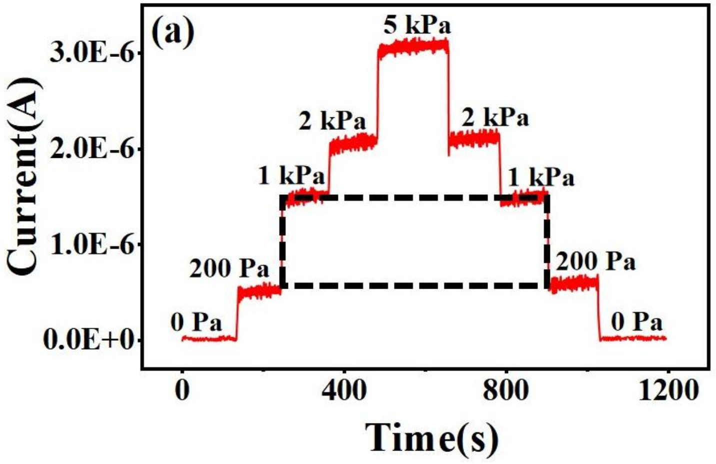
Fast response time < 1.6ms

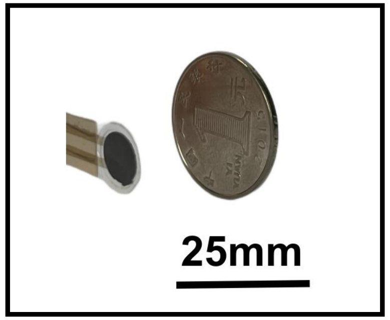
Stable low drift （<5% in 30 days）

sensitive <100Pa



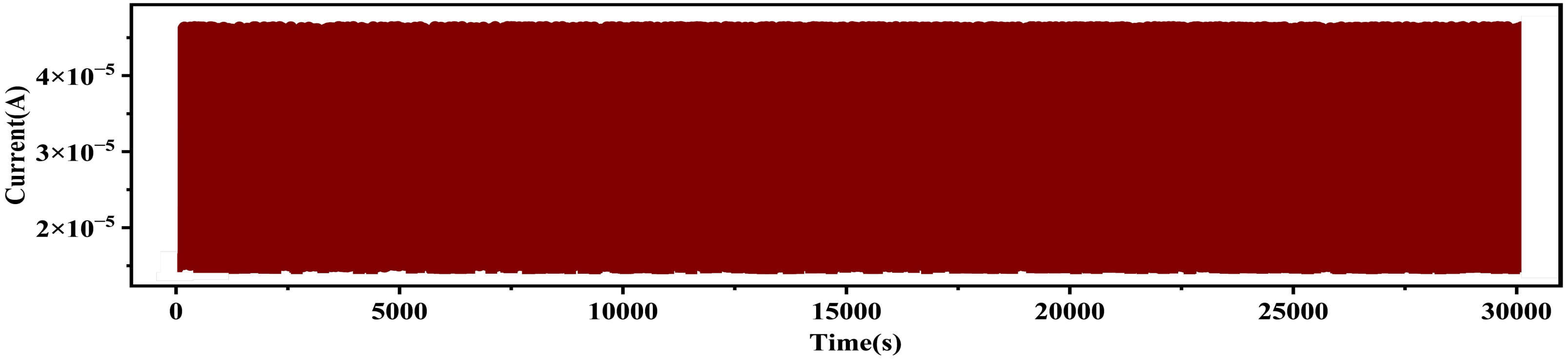




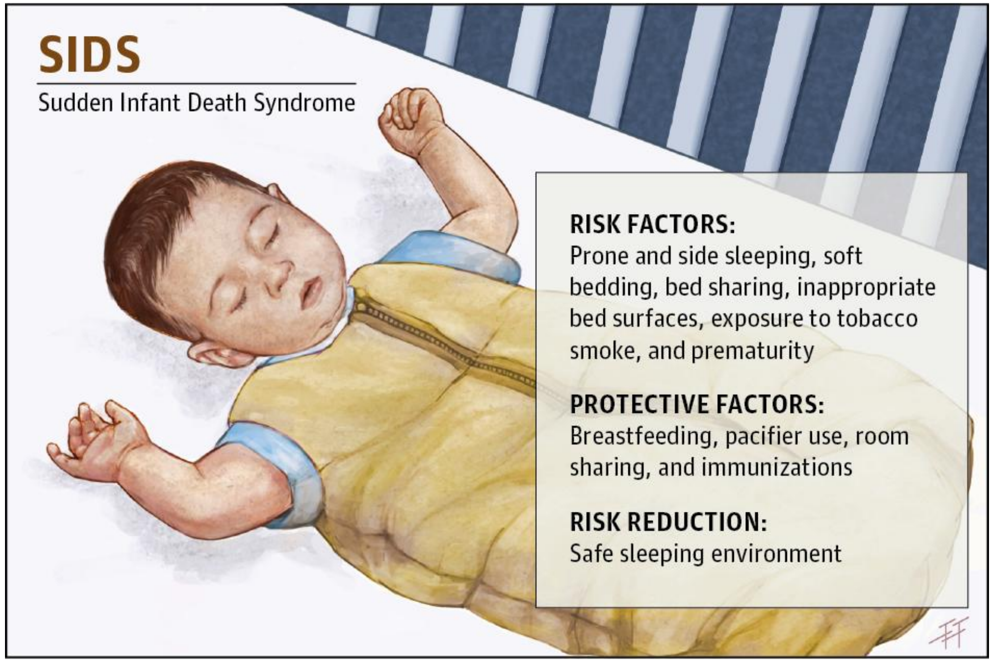


High dynamic stability:

The decay <2% after 40000 cycles



Sudden infant death syndrome



JAMA Pediatr. 2017;171(2):204.

I. Occur during sleep – sleep apnea

II. No clear criterion for the confirmation of possible victims

III. No effective interventions while asleep

Apnea monitor

medlineplus.gov

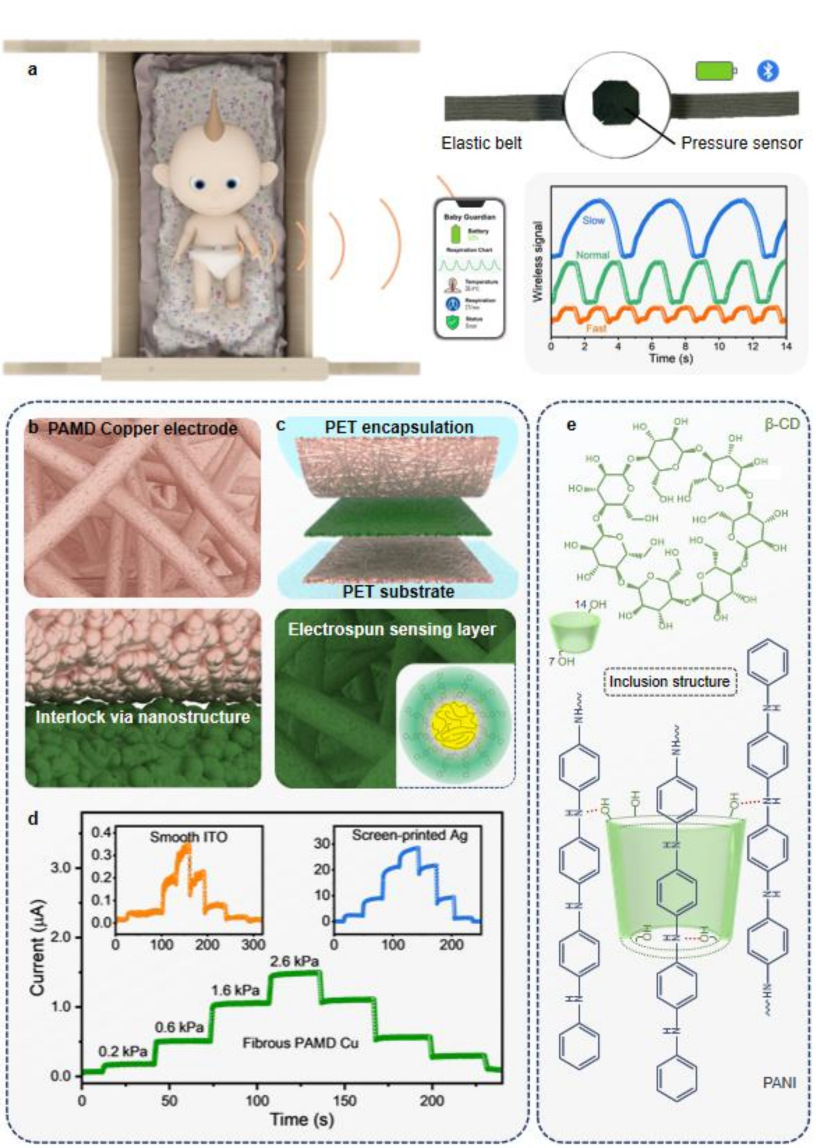
- Newborns
- Especially premie

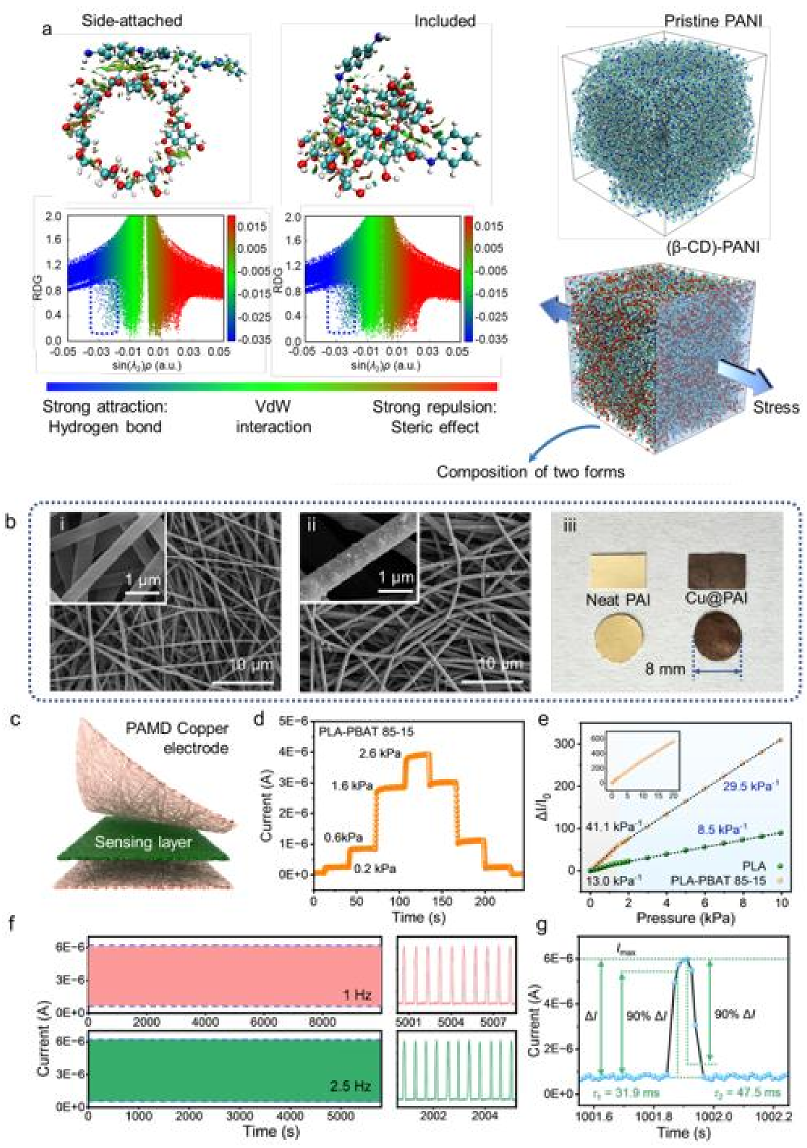
- **Wired**
- **Expensive for home care**

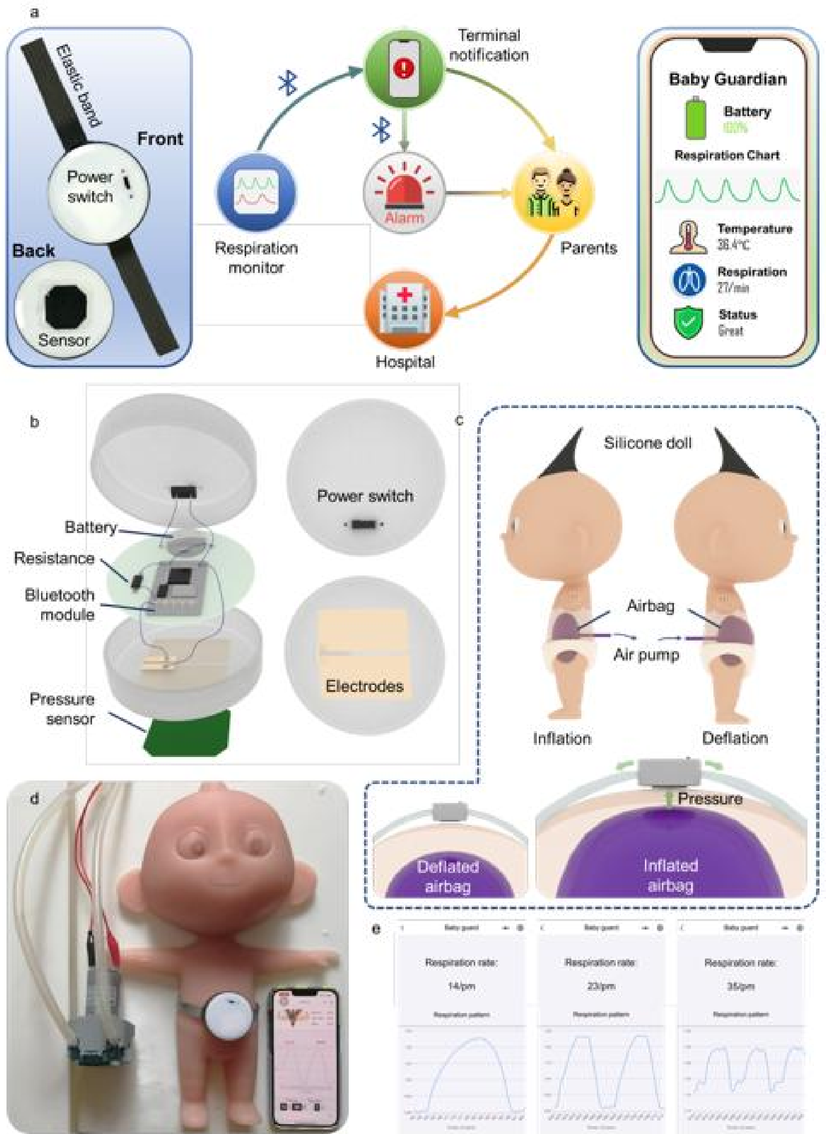
Wearable devices suitable for infants

- ❑ Respiration monitoring
- ❑ Instant notification

Flexible pressure sensor based on PLA-PANI

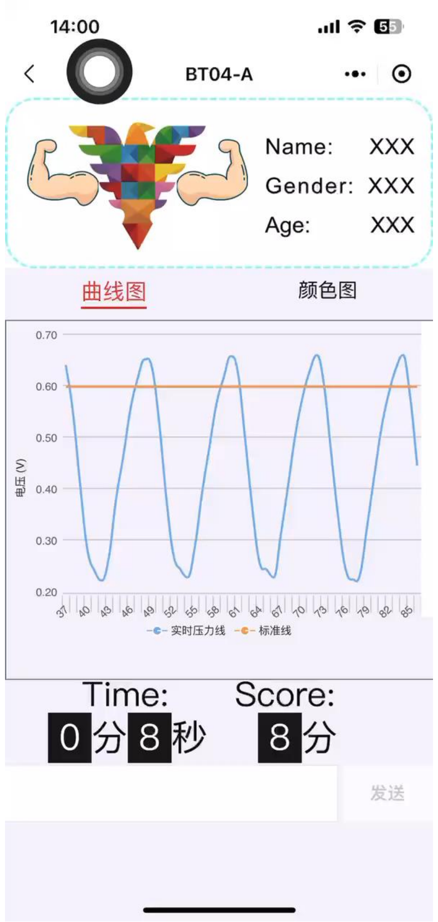


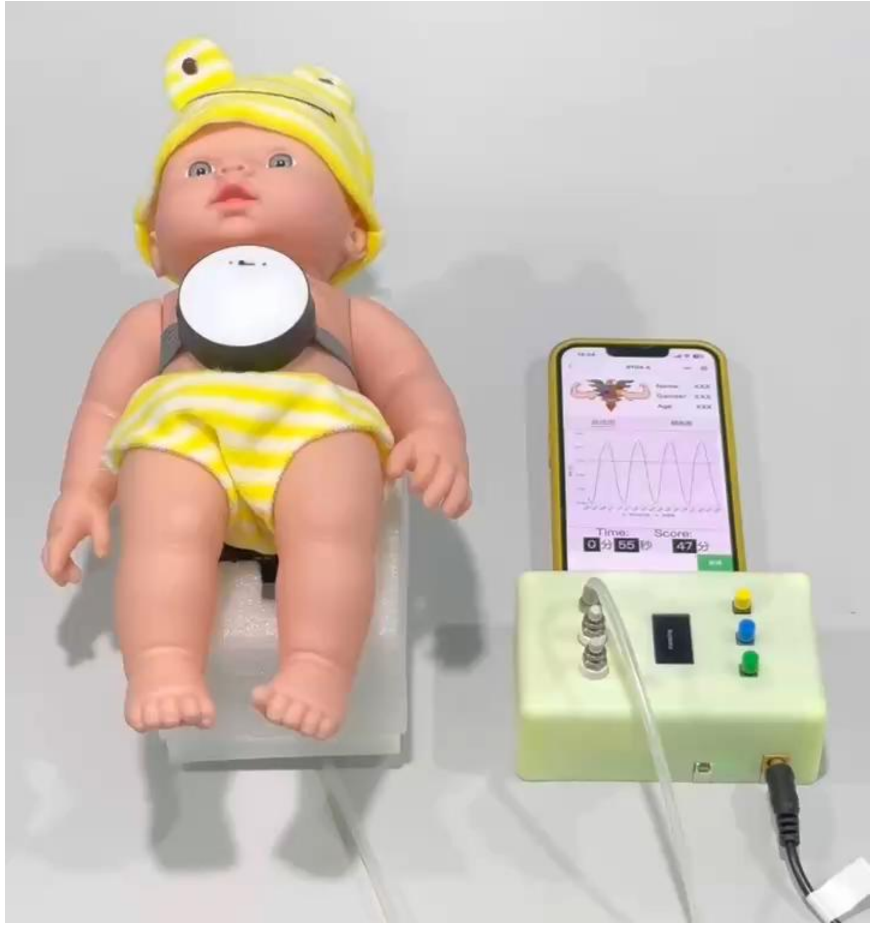




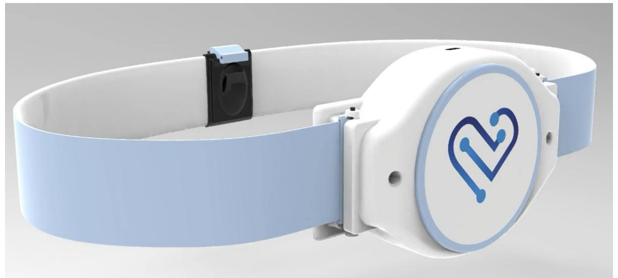
To be submitted

Flexible pressure sensor based on PLA-PANI

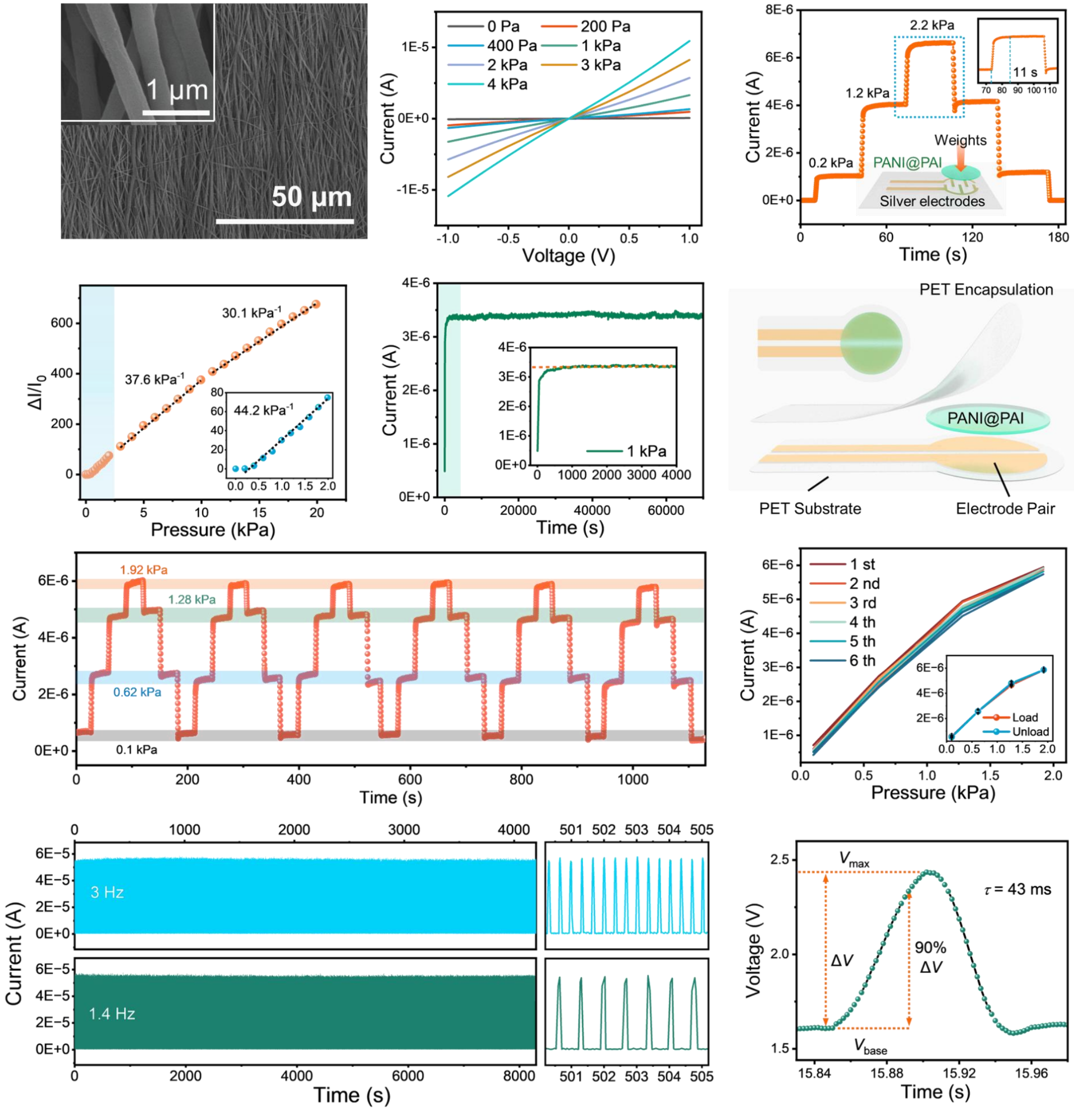


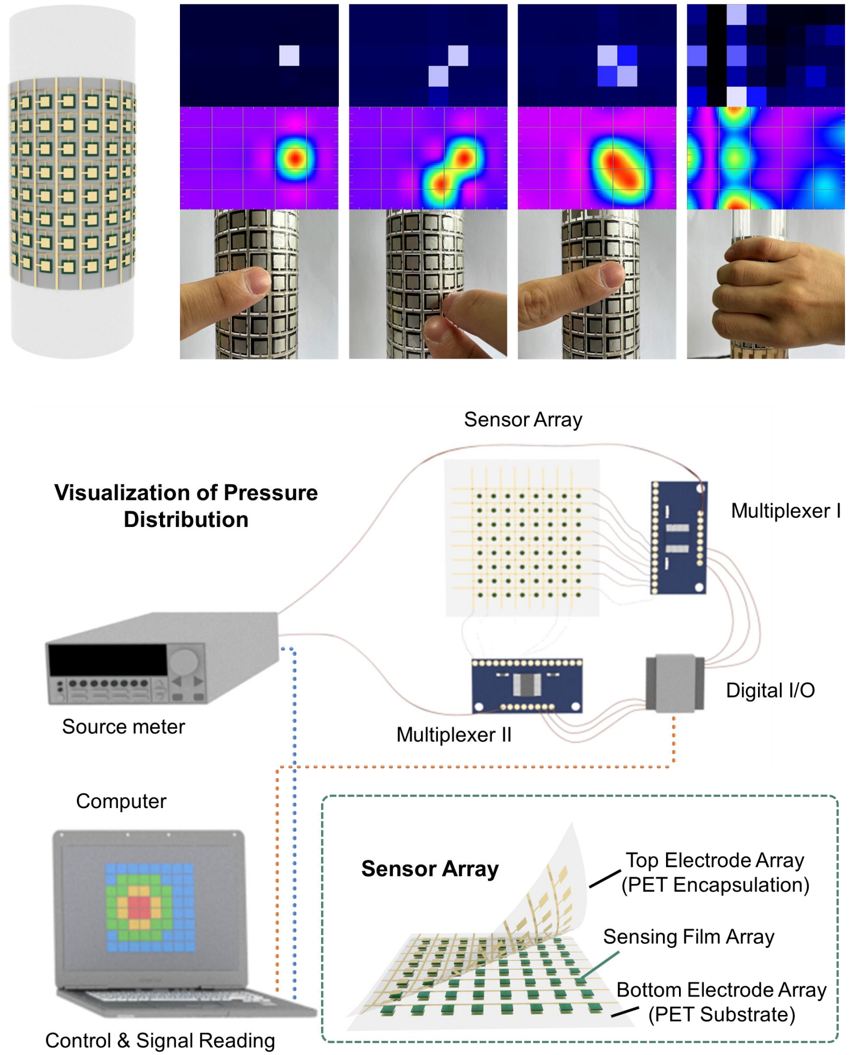


Flexible pressure sensor based on PLA-PANI



Flexible pressure sensor array based on PAI-PANI





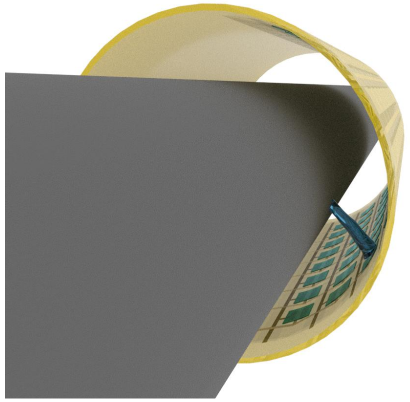
8 x 8 array：

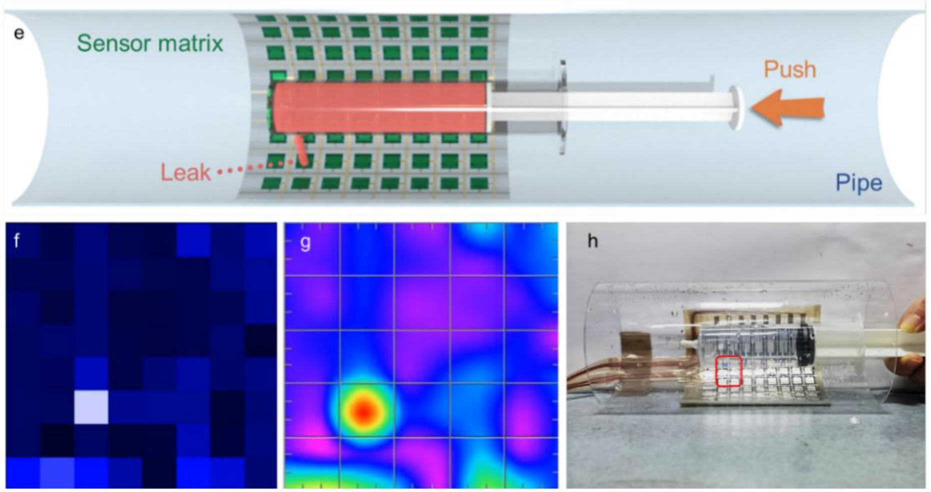
- **2 fps**
- **Detection limit < 100 Pa**

In preparation

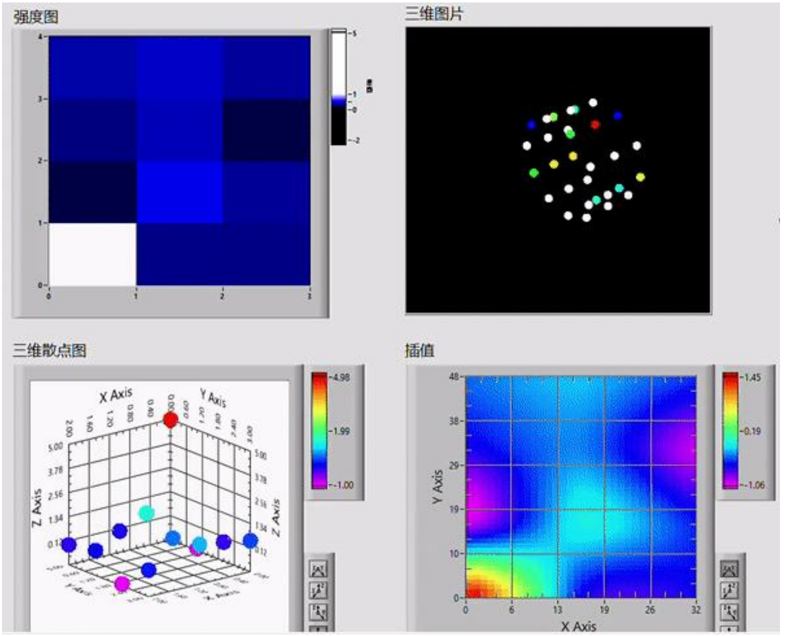
Flexible pressure sensor array

Inside of the tube

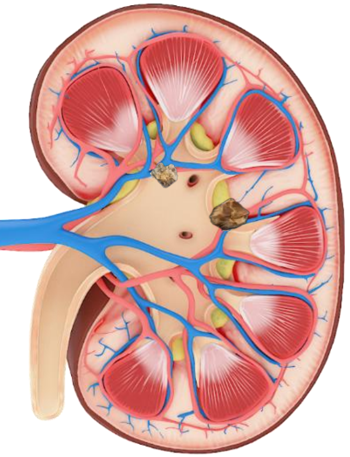




Realtime display of Pressure data

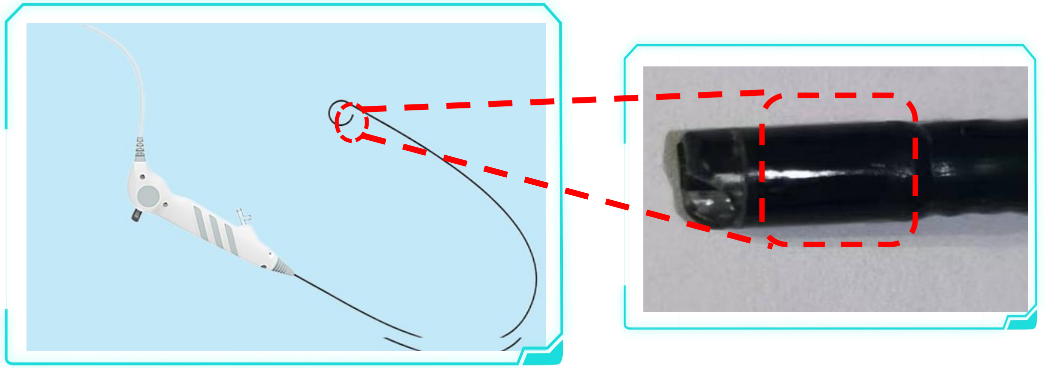


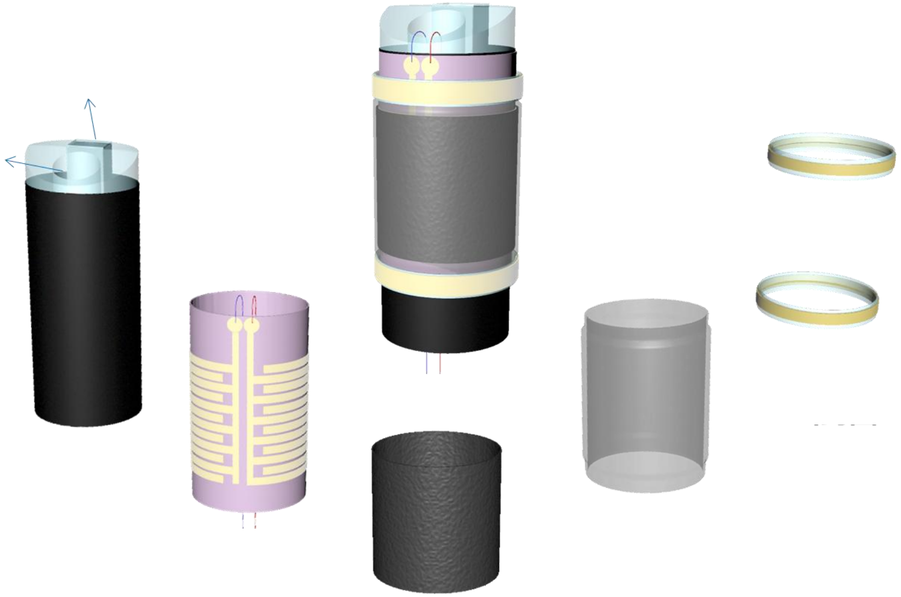
Water pressure detecting application

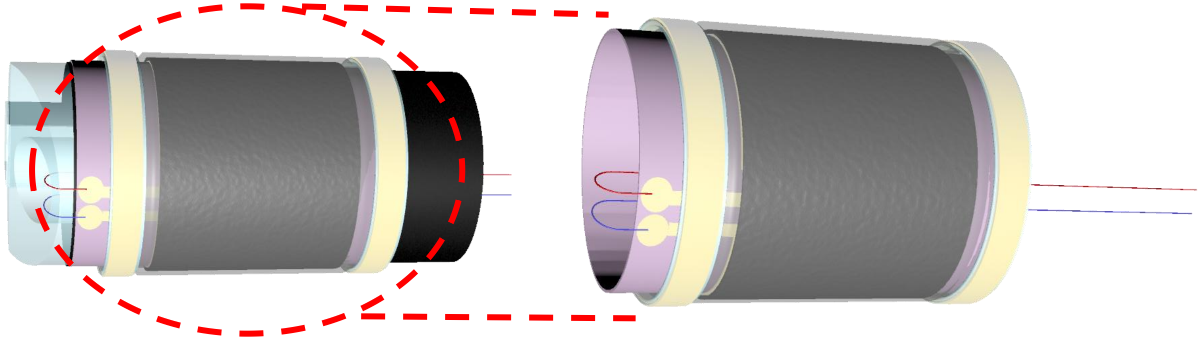


- Water should be poured into kidney
- High pressure will cause damage
- The pressure cannot be detectable in-situ

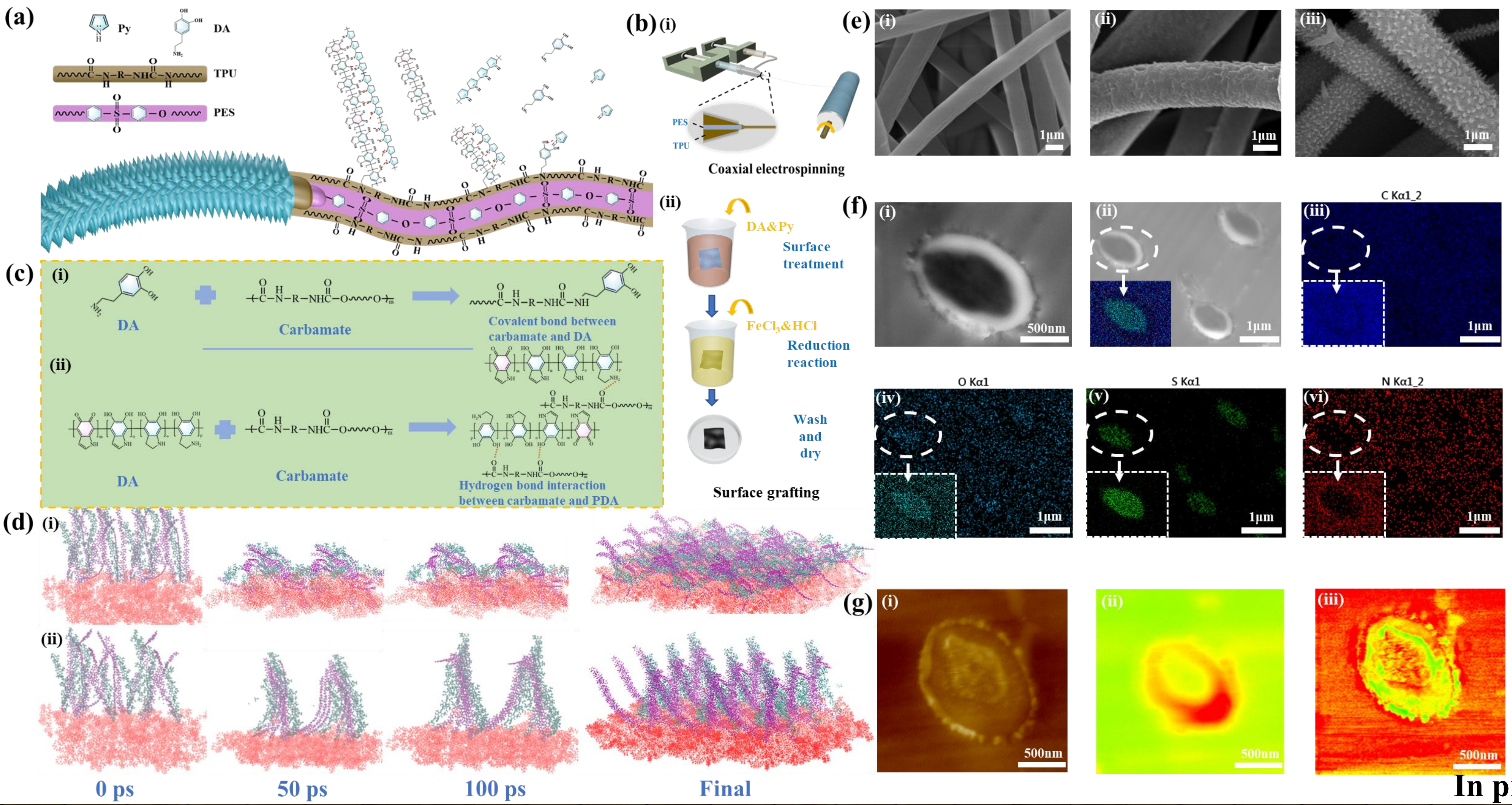
Soft ureteroscope to measure water pressure





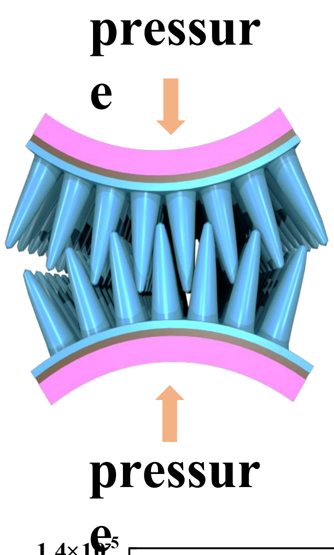


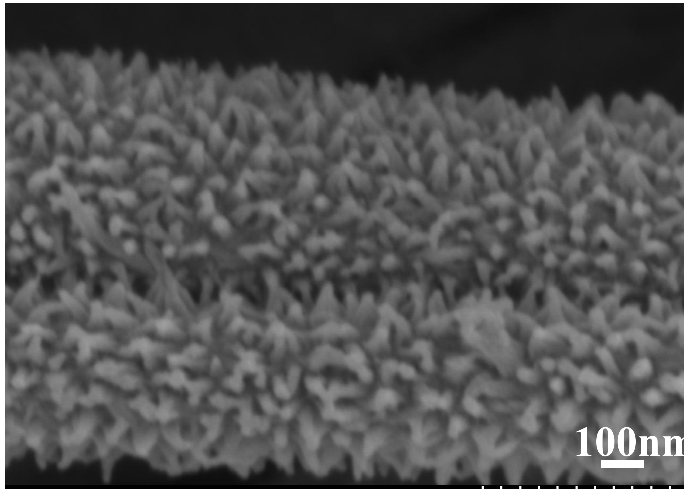
Flexible pressure sensor based on PES/TPU-PPy

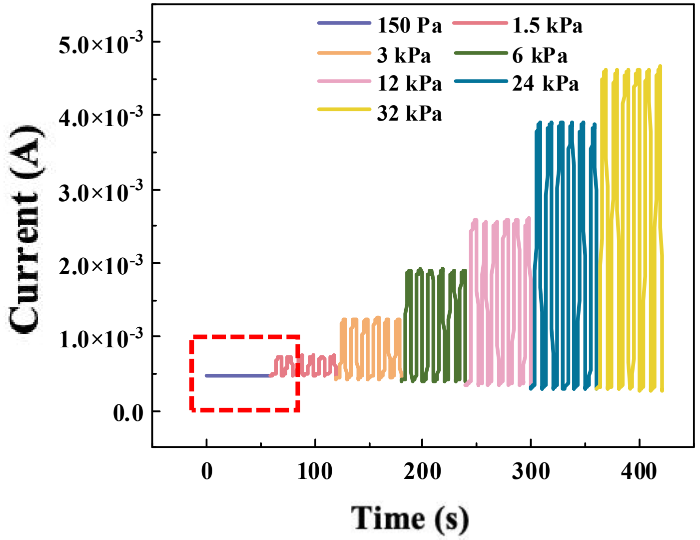


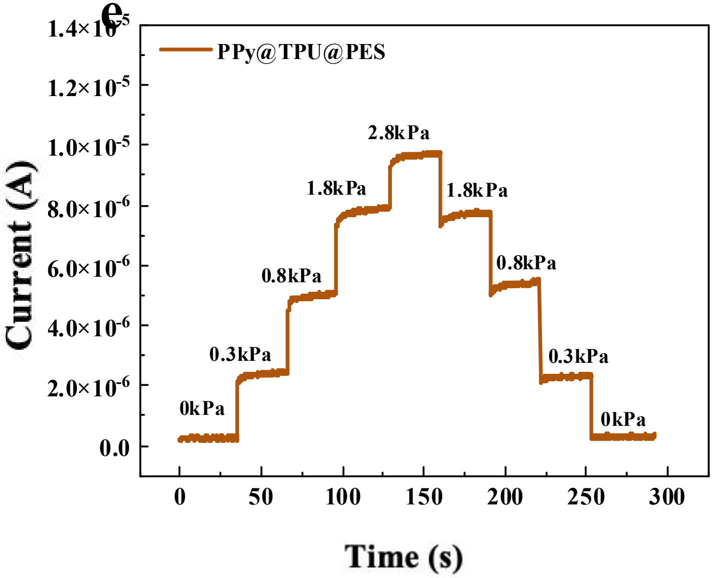
In preparation

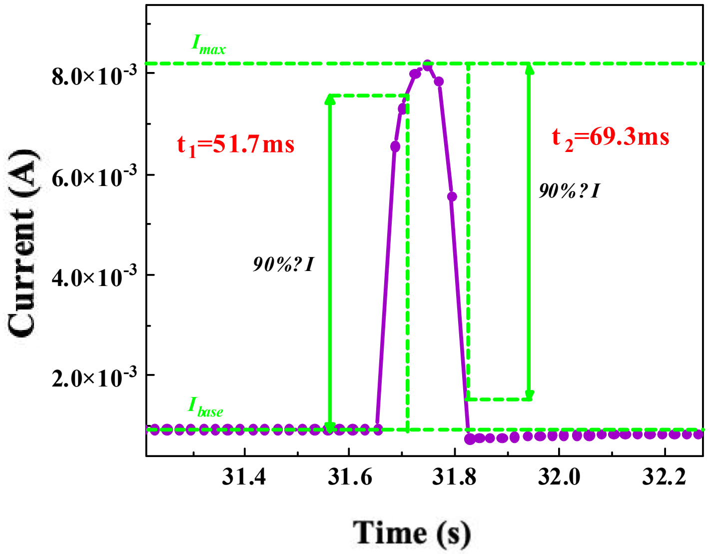
Flexible pressure sensor based on PES/TPU-PPy

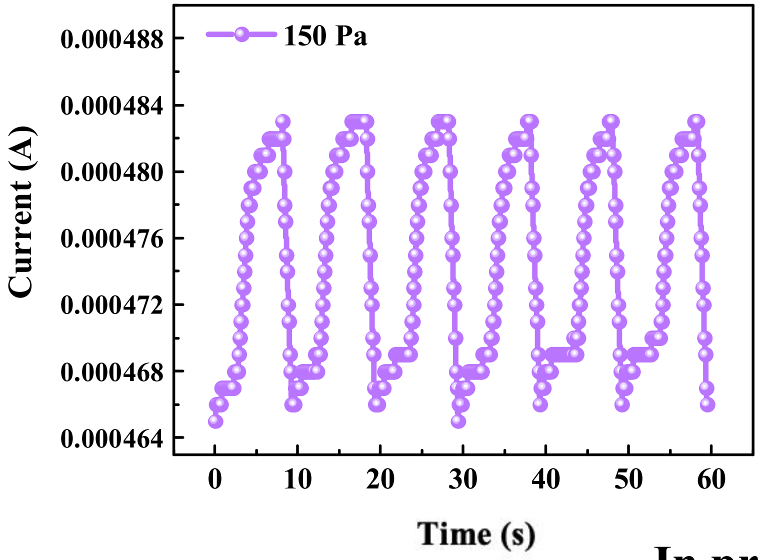












In preparation

Summary

- Decreased **signal drift and hysteresis with high Tg matrix**
- Improved the **stability using strong interfacial bonding** (MD simulation and experiments)
- Prohibited the movement of fibers via **nanostructure interlocking** enabled by PAMD nanostructured electrodes
- Developed a **wireless respiration monitoring system**

Acknowledgement

XMECH 浙江大学交叉力学中心
CENTER FOR X-MECHANICS
ZHEJIANG UNIVERSITY

NSFC

Thanks for listening!