



A bidirectionally frozen carbon aerogel reinforced by tetrapod ZnO bridges for high-performance pressure sensing

Wang Yichen¹, Suo Fang², Ben Yihang¹, Guo Rui³, Yao Yongtao^{2,*}, Liu Zhenbo^{1,*}

(1. Key Laboratory of Bio-Based Material Science and Technology of Ministry of Education, Northeast Forestry University, Harbin 150040, China;

2. National Key Laboratory of Science and Technology for Advanced Composites in Special Environments,

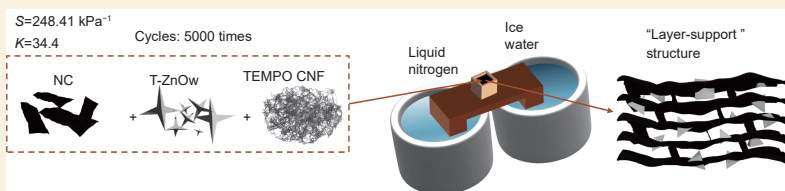
Harbin Institute of Technology, Harbin 150080, China;

3. State Key Laboratory of Space Powersources, Shanghai Institute of Space Power-sources, Shanghai 200245, China)

Abstract: The development of flexible pressure sensors that simultaneously achieve high sensitivity, mechanical strength, and long-term stability remains challenging, particularly for biomass-derived carbon aerogels that are intrinsically brittle and prone to structural collapse.

We have used bidirectional freezing to reorganize randomly distributed cellulose nanofibers, pre-synthesized nitrogen-doped carbon nanosheets, and tetrapod-shaped ZnO whiskers (T-ZnOWs) into a mechanically stable load-bearing network of parallel layers. T-ZnOWs were incorporated as rigid interlayer pillars bridging adjacent carbon lamellae, forming a mechanically stable “layer-support” structure that enables efficient and directional stress transfer while suppressing interlayer slippage and structural instability, thereby promoting cooperative deformation of the lamellar units. The nitrogen-doped carbon nanosheets introduce defect-rich conductive paths that increase the piezoresistive response, while the T-ZnOWs function as both rigid interlayer pillars and piezoelectric activation units. Because of the modulus mismatch between the supports and carbon layers, any applied stress is preferentially concentrated at the layer/support interfaces, generating localized high-stress regions. Consequently, small mechanical stimuli induce pronounced electrical resistance changes, resulting in an amplified electrical signal. To improve the device durability, it was infiltrated with polydimethylsiloxane (PDMS) to form a conformal elastic encapsulating layer. The resulting aerogel sensor has a high gauge factor of 34.4, an ultrahigh sensitivity of 248.41 kPa⁻¹ over a broad pressure range (0–19 kPa), fast response (24 ms) and recovery (69 ms) times and stable operation over 5000 loading–unloading cycles. The sensor reliably detects physiological signals and joint motions, demonstrating its potential for wearable and intelligent sensing applications. This work provides a way to improve the mechanical reliability and sensing performance of biomass-derived carbon aerogels.

Key words: Cellulose-derived carbon aerogels; Hierarchical porous structure; Structural engineering; Wearable sensors



1 Introduction

The development of flexible pressure sensors that simultaneously exhibit high sensitivity, mechanical robustness, and long-term durability remain challenging, particularly for biomass-derived carbon aerogels that are intrinsically brittle and prone to structural collapse under cyclic loading^[1–2]. There is an increasing demand for sensors that combine high sensitivity, broad frequency response and environmental robustness^[3–5]. However, conventional sensor materials are derived from mineral resources, which incur high processing costs and are not biodegradable, potentially leading to environmental pollution upon dispos-

al^[6]. Cellulose, the most abundant natural biomass polymer, and its derivative cellulose nanofibers (CNFs) are commonly used to prepare sensor aerogels, enhancing their surface area, surface roughness, and mechanical strength^[7]. Cellulose-based aerogels possess a unique three-dimensional porous structure and abundant surface functional groups, which endows them with a variety of functional properties, making

Received: March 09, 2026

Revised: May 06, 2026

Accepted: May 07, 2026



them ideal materials for constructing high-performance sensors^[8]. As a sustainable alternative to synthetic polymers, cellulose offers advantages in biodegradability and tunable porosity^[9]. Furthermore, CNFs can easily be composited with conductive materials, such as carbon black, graphene, carbon nanotubes (CNTs), MXenes and liquid metals^[10–12], to form various types of sensors, including piezoresistive^[13], piezoelectric^[14], triboelectric^[15] and capacitive^[16] sensors. Among them, cellulose-derived ultralight and compressible carbon aerogels are particularly attractive due to their potential multifunctionality and stability^[13–17]. The conductive network and the porous structure provide a large specific surface area and great deformation capacity^[18]. To date, researchers have developed various types of carbon aerogels through methods such as nanomaterial doping, ice templating and emulsion-assisted assembly^[19–21]. Reported sensors based on nanocellulose aerogels generally suffer from low sensitivity and limited detection range^[22]. Meanwhile, their insufficient mechanical performance often leads to structural fragility and a narrow response bandwidth. In addition, the high fabrication cost^[23] and hygroscopicity^[15] further restrict their broad implementation and practical applications^[24]. Most reported carbon aerogel sensors suffer from a trade-off between sensitivity and detection range, while their fragile lamellar frameworks lead to rapid mechanical degradation under repeated deformation^[25–26].

Structural engineering by bidirectional freezing provides a scalable route to tailor anisotropic stress-transfer pathways in porous aerogels by guiding ice-crystal growth along multiple temperature gradients. The conventional ice-templating method typically employs unidirectional freezing to generate vertically aligned ice crystals. In contrast, bidirectional freezing enables the creation of more intricate hierarchical architectures. By introducing an additional temperature gradient on the basis of unidirectional freezing, ice crystals are guided to grow along 2 directions, forming parallel layered structures^[27–28]. This process can enhance the material properties in specific directions,

thereby endowing it with higher sensitivity, improved compressive performance, and longer service life as compared with unidirectional freezing. Therefore, it is particularly suitable for fabricating cellulose-based carbon aerogels with complex anisotropic structures^[29].

A novel preparation strategy for compressible carbon aerogels involves assembling carbon nanostructural building blocks (such as CNTs, graphene, graphene oxide (GO), carbon nanofibers and MXenes) into three-dimensional (3D) self-supporting macroscopic structures^[30–32]. However, the high cost of these materials has hindered the further practical applications of these technologies. Currently, a low-cost synthesis route based on the pyrolysis of a sugar and dicyandiamide mixture has been proven to be effective for producing two-dimensional (2D) carbon materials, ranging from self-supporting monolayers to few-layer structures, offering potential for large-scale production^[33–35]. Moreover, nitrogen doping introduces a high density of defect sites, which are essential for the formation of defect-rich conductive pathways. Defects in carbon nanomaterials, such as Stone–Wales defects, single vacancies and heteroatom substitutions, are well known to influence electronic transport properties and electrical conductivity significantly^[36–37]. When nitrogen atoms are incorporated into the carbon lattice as heteroatom dopants, the mismatch in atomic radius and the nitrogen electronegativity relative to carbon inevitably induces lattice distortion and structural defects^[38]. These defects act as active charge-transport centers, facilitating electron tunnelling pathways and leading to enhanced macroscopic conductivity^[39]. More importantly, defect-rich regions increase the sensitivity of charge transport to deformed lattice, enabling pronounced resistance variations under applied strain and thereby enhancing the piezoresistive response^[40–41].

T-ZnOw, a doped tetrapod-shaped ZnO whisker, is a semiconducting piezoelectric material that is the only whisker material with a regular 3D spatial structure to date^[42–44]. Due to its unique morphology, its piezoelectric effect is more pronounced compared to

ordinary ZnO^[45]. T-ZnOw is uniquely suited as 3D load-bearing unit due to the rigid tetrahedral geometry, which serves as piezoelectric activation centers under compressive stress. This property enhances the mechanical, thermal and dimensional stability^[46–49]. T-ZnOw can withstand temperatures as high as 1720 °C, with structural stability maintained below 1000 °C at atmospheric pressure. This characteristic makes it particularly suitable for use as a reinforcing filler in composite materials at high temperatures. Such a multifunctional role enables their integration as structural and functional nodes within engineered porous architectures. However, as an inorganic filler, T-ZnOw faces the challenge of bonding with the organic phase of composites. During the compositing process, it tends to agglomerate and deposit, resulting in interfacial debonding or agglomeration. To address these issues, a silane coupling agent (KH570) was employed to modify T-ZnOw to improve its interfacial interactions^[50].

Herein, we report a structure-engineered cellulose-derived carbon aerogel featuring a bidirectional freezing-induced “layer-support” architecture reinforced by T-ZnOw. This engineered framework enables efficient stress transfer across parallel carbon lamellae and promotes synergistic piezoresistive–piezoelectric coupling. Furthermore, polydimethylsiloxane (PDMS) impregnation is employed as an elastic constraint layer to enhance mechanical robustness, hydrophobicity and long-term durability, resulting in a flexible sensor with high sensitivity, broad pressure sensing range and excellent cycling stability.

2 Experimental

2.1 Materials

D-anhydrous glucose (99.5%) and dicyandiamide (99%) were obtained from Aladdin Reagents (Shanghai, China). Nanocellulose (2% by mass) produced by the 2,2,6,6-Tetramethylpiperidine-1-oxyl free radical (TEMPO) oxidation method was sourced from Jinhao New Materials Co., Ltd. (Zhejiang, China). T-ZnOw (99%) was obtained from Jikon New Materials Co., Ltd. (Hangzhou, China). PDMS and its

curing agent were sourced from Dow Corning Corporation (Midland, MI, USA), Sylgard™ 184 silicone elastomer and its silane coupling agent (KH570) was supplied by Kangjin New Materials Co., Ltd. (Nanjing, China). Other reagents, including ethanol, acetic acid and ethyl acetate, were obtained from Fuyu Fine Chemical Co., Ltd. (Tianjin, China). All chemical reagents were of analytical grade and used without further purification.

2.2 Preparation of the nitrogen-doped carbon nanosheets (NCs)

After glucose and dicyandiamide in a 1 : 20 mass ratio were mixed and ground until homogeneous, the mixture was pressed flat in a quartz boat. The sample was then heated under a nitrogen atmosphere at a rate of 3 °C/min from 30 to 900 °C, and held at 900 °C for 2 h to obtain NCs (Fig. 1b).

2.3 Preparation of the modified T-ZnOw

Firstly, to improve the dispersion of T-ZnOw, its surface was modified using KH570. T-ZnOw (5 g) was placed in anhydrous ethanol and sonicated for 30 min to remove surface impurities. It was then dried in a vacuum oven for 2 h. The hydrolyzed KH570 solution was slowly added dropwise into the T-ZnOw dispersion, with the KH570 dosage controlled at 2% relative to the mass of T-ZnOw, followed by stirring at 70 °C for 3 h. After the reaction, the mixture was washed and vacuum filtered. The filtered cake was dried in a vacuum oven at 80 °C until constant weight, and then ground to obtain the modified T-ZnOw powder.

2.4 Preparation of the aerogel

NC (75 mg) was finely ground using a mortar and pestle, and then mixed with an equal weight of the modified T-ZnOw and dispersed into a 1% TEMPO(2,2,6,6-Tetramethylpiperidine-1-oxyl) CNF solution (20 g). The mixture was sonicated for 1 h after stirring for 3 h. The suspension was then poured into a square mold made of Polytetrafluoroethylene (PTFE) with a brass bottom (mold dimensions: length 24 mm, width 24 mm, height 20 mm), and subjected to bidirectional freezing on a copper bridge connected to liquid nitrogen (−196 °C) and ice water (0 °C). The sample was freeze-dried for 48 h to obtain aerogel I ,

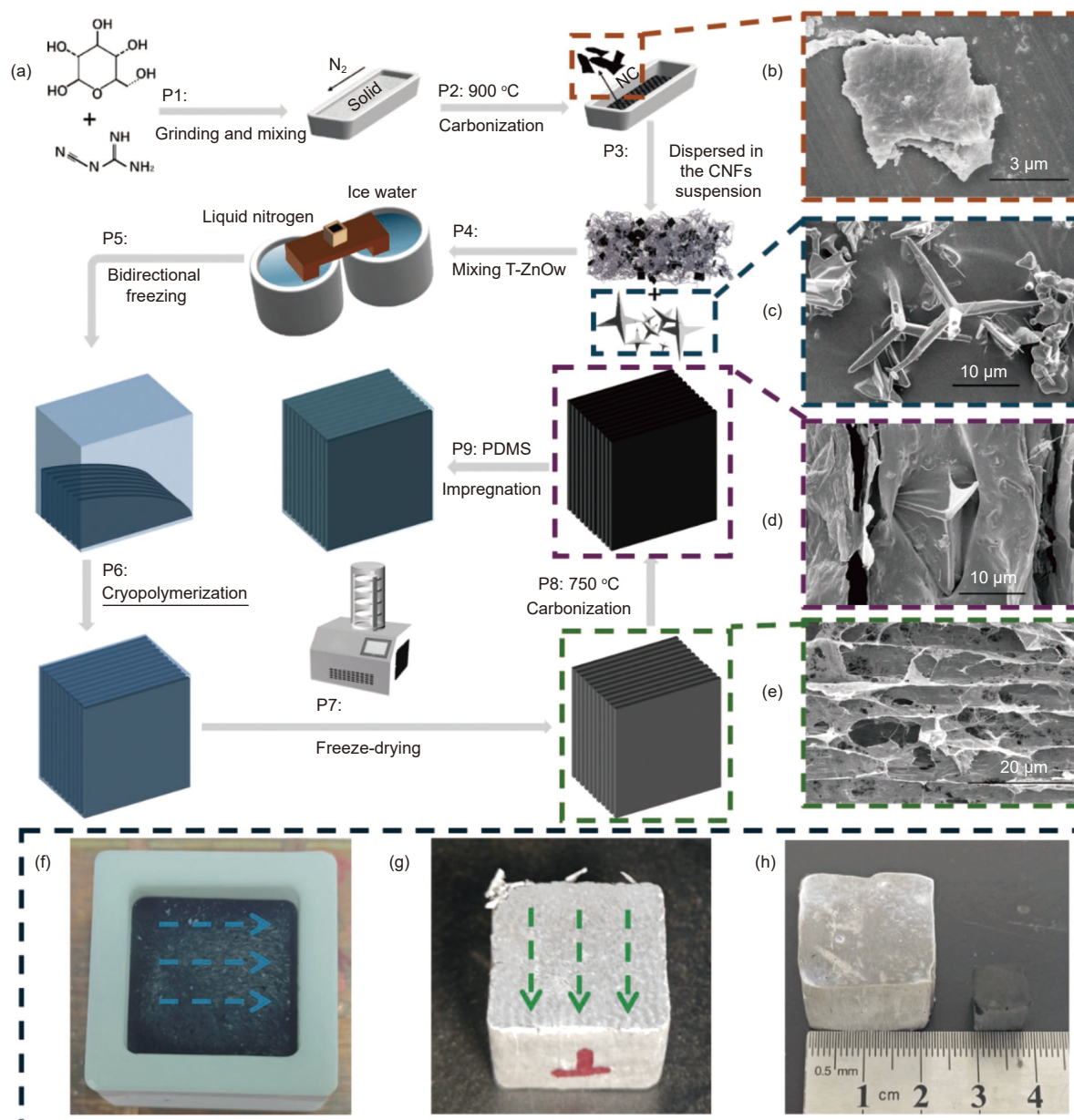


Fig. 1 (a) Material preparation process. SEM images of (b) NC, (c) T-ZnOw, (d) calcined T-NTAC and (e) uncalcined T-NTAU. (f) Ice crystal structure after bidirectional freezing. (g) Parallel-aligned pore channels in the aerogel after freeze-drying. (h) Size comparison before and after calcination

named T-ZnOw modified nitrogen-doped carbon nanosheets/TEMPO-oxidized nanocellulose aerogel (Uncalcined) (T-NTAU).

Then, the T-NTAU was pyrolyzed in a tube furnace under a nitrogen atmosphere. The temperature was increased at a rate of 3 °C/min from 30 to 750 °C, and maintained at 750 °C for 2 h to prepare aerogel II. The resulting aerogel was named T-ZnOw modified N-doped carbon nanosheets/TEMPO-oxidized nanocellulose aerogel (Calcined) (T-NTAC) (Fig. 1a).

For comparison, two aerogels without T-ZnOw were prepared using the same process. The freeze-

dried aerogel was named nitrogen-doped carbon nanosheets/TEMPO-oxidized nanocellulose aerogel (Uncalcined) (NTAU), and the calcined aerogel was named N-doped carbon nanosheets/TEMPO-oxidized nanocellulose aerogel (Calcined) (NTAC).

2.5 Packaging of the aerogel sensor

The PDMS prepolymer with a mass ratio of Sylgard 184 to KH570 of 10 : 1 was mixed with ethyl acetate in a mass ratio of 1 : 3. The T-NTAC aerogel was immersed in the PDMS/ethyl acetate solution, and vacuum-assisted impregnation (−0.08 MPa, 20 min) was applied to promote penetration. The aero-

gels were then pre-cured at 60 °C for 1 h to allow the evaporation of ethyl acetate and cured at 80 °C for 4 h to form an elastic support layer. The encapsulated aerogel was named PDMS-T-NTAC (PT-NTAC).

Conductive silver paste was used to connect copper tape as electrodes at both ends of the aerogels. After attaching the wires, thin polyimide (PI) tape was used to wrap and secure the sensor, resulting in the final sensor.

2.6 Characterization

The microstructure of the aerogels was observed using a field emission scanning electron microscope (FE-SEM, Thermoscientific Apreo S). X-ray diffraction (XRD) patterns were obtained using a polycrystalline diffractometer (Rigaku Smartlab) with Cu $K\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) at a scan rate of $10^\circ/\text{min}$. Raman spectroscopy was performed using an inVia-Rex Raman spectrometer, with a 532 nm laser as the light source. Fourier transform infrared (FTIR) spectra were measured using a micro-imaging infrared spectrometer (Thermo Fisher Nicolet IS50). The material composition was characterized by X-ray photoelectron spectroscopy (XPS, Thermo Scientific K-Alpha), using a monochromated Al $K\alpha$ source as the X-ray source. Mechanical properties were tested using a universal testing machine (Senstest UTM2103). Resistance changes were measured using a digital source meter (Keithley 2450), while cyclic life testing was conducted with a linear motor (Beijing Naneng Technology R-LP3) and an electrometer (Keithley 6514). Thermogravimetric analysis (TGA) was performed using a HITACHI STA200.

3 Results and discussion

3.1 Characterization of composite aerogels

The core performance of carbon aerogel sensors are high sensitivity and operational stability^[51]. To develop a lightweight, durable, and highly responsive elastic aerogel sensor with integrated piezoelectric functionality, tailored material compositions and structures were designed. The detailed preparation process is shown in Fig. 1a. Graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) generated through the thermal polymeriza-

tion of dicyandiamide was used as a 2D template to guide the formation of aromatic carbon intermediates during the carbonization of glucose. These intermediates underwent 2D growth and graphitization between the layers of $g\text{-C}_3\text{N}_4$. Finally, the $g\text{-C}_3\text{N}_4$ template completely decomposed and volatilized at high temperature, leaving independent, N-doped graphene sheets. The resulting carbon nanosheet structure is shown in Fig. 1b. During the bidirectional freezing process, the water in the solution forms ice crystals that grow in 2D. The blue dashed arrows in Fig. 1f indicate the direction of the parallel ice crystals along the temperature gradient. The parallel ice crystals (x-axis, direction of the arrows) and the ice crystals growing upward from the brass bottom of the mold (z-axis, outward from Fig. 1f) jointly compress CNF, NC and T-ZnOw, forming a basic parallel layered framework. After freeze-drying, the ice crystals sublimate, leaving behind a nearly parallel porous structure (Fig. 1g). The alignment direction of the pores is indicated by green dashed arrows in the figure, ultimately leading to the formation of the aerogel. SEM image reveals a highly ordered, parallel microscopic architecture (Fig. 1c), and this structure is also preserved after calcination (Supporting Information, Fig. S1, S2). Fig. 1e shows the SEM image of T-NTAC, clearly demonstrating the supporting role of the tetrapod structure on the carbon parallel layers. The dimensions of the NTAU material are approximately $22 \text{ mm} \times 22 \text{ mm} \times 20 \text{ mm}$, and after calcination, the size is reduced to around $9 \text{ mm} \times 10 \text{ mm} \times 11 \text{ mm}$ (Fig. 1h), the volume reduction rate is approximately 89.77%. The densities before and after calcination are similar, around 0.036 g/cm^3 .

Raman spectroscopy was employed to analyze the graphitic quality and composition of NTAC and T-NTAC aerogels. Fig. 2a shows that both NTAC and T-NTAC aerogels exhibit 2 peaks at approximately 1347 and 1596 cm^{-1} , corresponding to the D band (disorder-induced vibration of sp^2 carbon) and the G band (E_{2g} mode of graphitic sp^2 carbon), respectively, indicating that both aerogels contain some graphitic structures^[52]. Meanwhile, a characteristic peak ob-

served at 500–550 cm^{-1} in the T-NTAC aerogel indicates the successful incorporation of T-ZnOw.

The XRD patterns are shown in Fig. 2b. For both NTAC and T-NTAC samples, diffraction peaks are observed at approximately 22.58° and 45.31° , corresponding to the typical (002) and (100) crystallographic planes of graphitic carbon, respectively^[53]. This indicates that the 2 materials share similar structural characteristics. Fig. S3 presents a comparison of the XRD patterns of pure T-ZnOw and T-NTAU, where the peak positions are fully consistent. Notably, T-NTAC also exhibits characteristic peaks of T-ZnOw in 30° – 40° range, whereas no such peaks are observed for NTAU, thereby confirming the successful incorporation of T-ZnOw^[54].

TG analysis indicates that NTAU and T-NTAU begin to undergo carbonization at around 200 $^\circ\text{C}$ (Fig. 2c). Due to the presence of T-ZnOw, T-NTAU retains more solid residue after calcination, with a mass loss of 51.38%, which is lower than the mass loss of 58.25% observed for NTAU.

XPS analysis was performed on NTAC and T-NTAC aerogels. The survey spectra (Fig. 2d) show that both aerogels have similar main compositions. The high-resolution N 1s spectra reveal two deconvoluted peaks around ~ 398.4 and ~ 400.3 eV for both aerogels, which are associated with pyridinic N and pyrrolic N^[55]. This result indicates that both aerogels are N-doped due to the introduction of dicyandiamide. The high-resolution Zn 2p spectra clearly show the presence of Zn in the T-ZnOw component, which is consistent with the results obtained from Raman spectroscopy and XRD (Fig. 2e).

FTIR spectroscopy (Fig. 2f) comparison shows that PT-NTAC exhibits a typical ZnO lattice vibration peak around 794 cm^{-1} due to the incorporation of KH570-modified tetrapod Zn oxide (T-ZnOw), indicating the successful integration of T-ZnOw^[56]. After hydrolysis, the silane coupling agent KH570 forms Si–O–Si or Si–O–Zn bonds, with a stretching vibration peak of Si–O–C/Si–O–Zn appearing around 1077 cm^{-1} ^[57]. Both materials show a peak

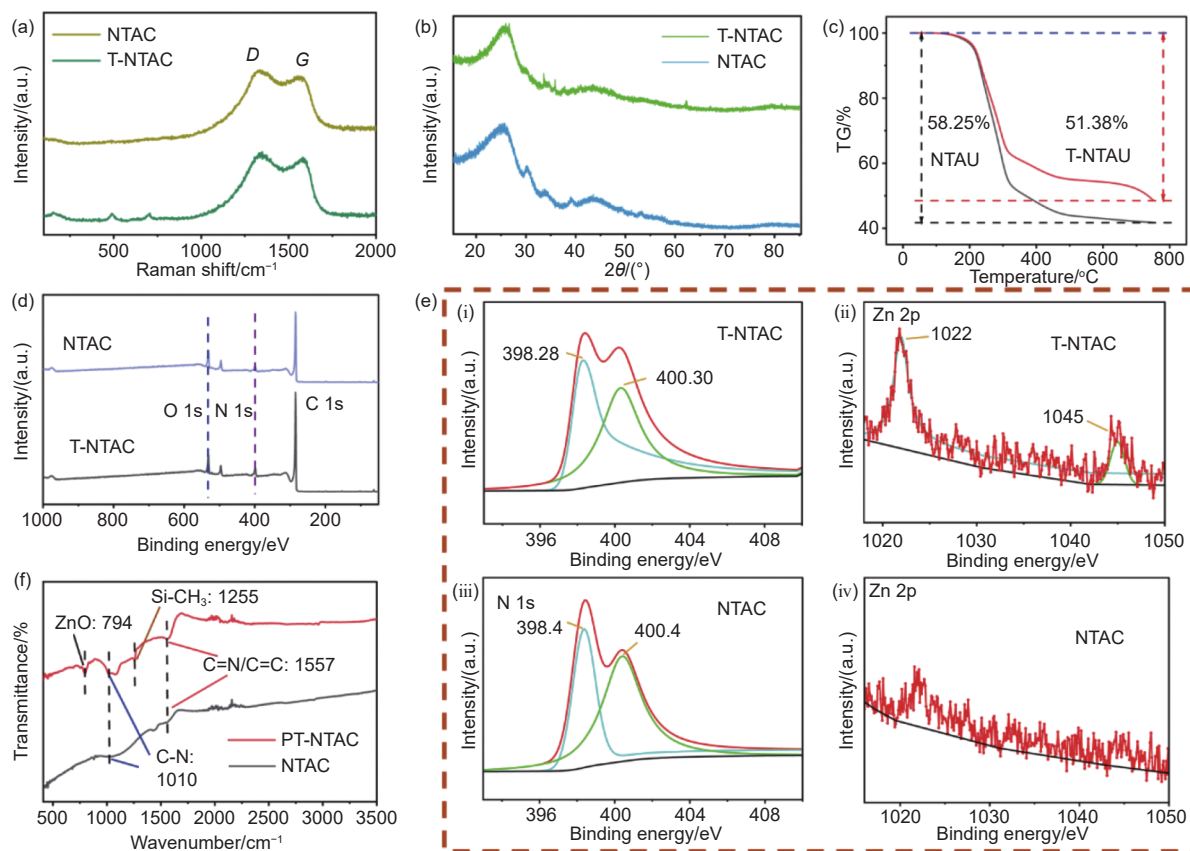


Fig. 2 (a) Raman spectra. (b) XRD patterns. (c) Thermogravimetric curves and (d) XPS survey spectra of T-NTAC and NTAC. (e) Comparison of N 1s and Zn 2p peaks. (f) FTIR spectra of PT-NTAC and NTAC

around 1557 cm^{-1} , attributed to the C=N stretching vibration (pyridine-type nitrogen) or the C=C aromatic ring skeletal vibration^[58], originating from the pyrolysis products of dicyandiamide. This confirms the successful modification of T-ZnOw.

3.2 Compressive performance of carbon composite aerogels

Excellent fatigue resistance and elasticity are essential prerequisites for the application of carbon aerogels in piezoresistive sensors. To evaluate their fatigue performance, cyclic compression tests with 30% strain were conducted. The coordinate axes of the compression tests are illustrated in Fig. 3h, where the x -axis corresponds to the parallel-layer direction, the y -axis represents the direction perpendicular to the layers, and the z -axis is orthogonal to the plane defined by x and y .

All three aerogels exhibit crescent-shaped stress-strain curves within the strain range of

5%–30%. The slopes increase with increasing strain. In the low-strain region, the stress curves overlap at different strain ranges, indicating highly reversible elastic deformation (Fig. 3a–c). As shown in Fig. S4, the stress in the y -direction is higher under the same strain, suggesting that the parallel-layer structure formed by bidirectional freezing efficiently transfers stress. We have fitted and determined the compressive moduli of the 3 materials from the initial linear region (0–5% strain) of the stress-strain curves shown in Figs. 3a–c. The results reveal that T-NTAC exhibits the highest compressive modulus (43.559 kPa), followed by NTAC (30.298 kPa), while PT-NTAC shows the lowest compressive modulus of 14.224 kPa. This trend indicates that the incorporation of T-ZnOw effectively reinforces the aerogel framework by providing rigid support, whereas PDMS infiltration introduces a compliant phase that redistributes stress and softens the overall response. Although this re-

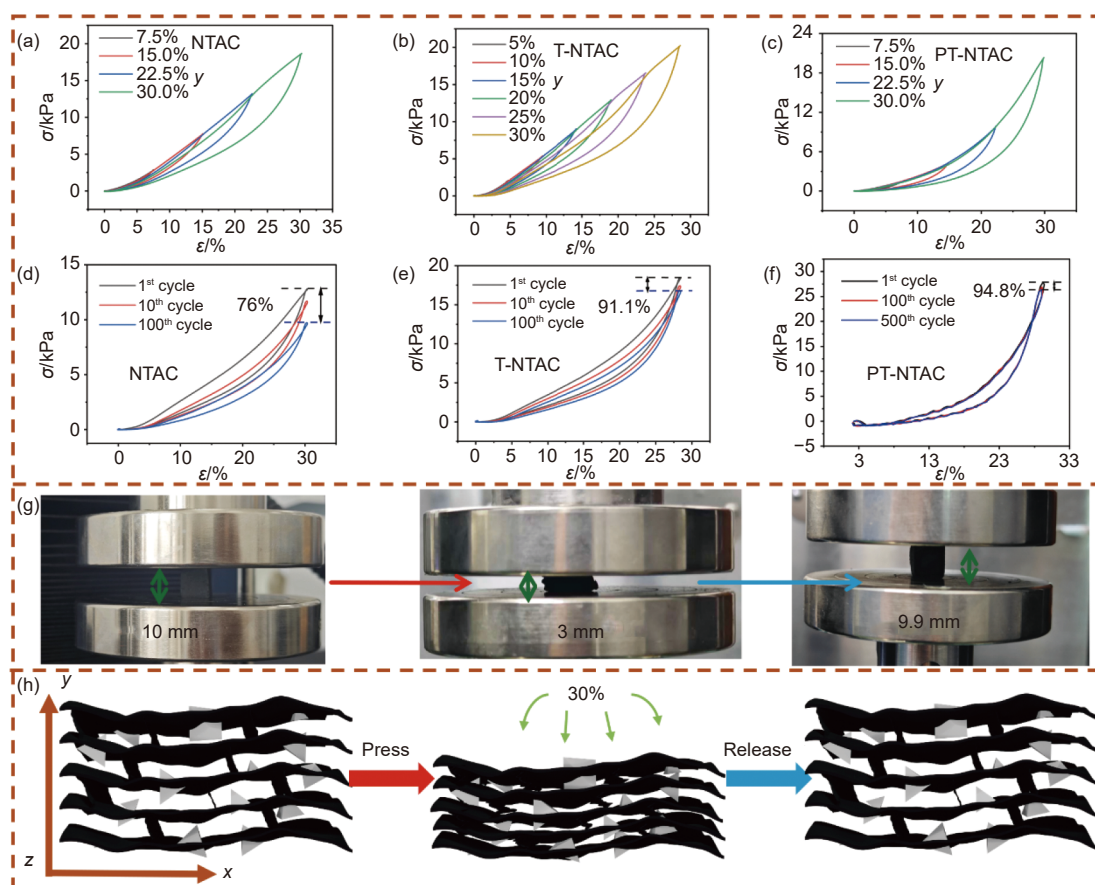


Fig. 3 (a–c) Compressive stress–strain curves of NTAC, T-NTAC, and PT-NTAC at different strain levels. (d–f) Compressive stress–strain curves of NTAC and T-NTAC after 100 compression cycles, and PT-NTAC after 500 cycles. (g) Optical image of PT-NTAC fully recovering after 70% compressive strain. (h) Schematic illustration of the compressive elasticity mechanism of T-NTAC

duces the initial stiffness, it enhances structural recoverability and contributes to a lowered detection limit. The compressive moduli (E) is calculated using the following Eq. (1)

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (1)$$

After 100 compression cycles, T-NTAC maintains excellent fatigue resistance with only 8.9% stress loss (Fig. 3e), significantly lower than NTAC (24%, Fig. 3d). The PT-NTAC exhibits a stress loss of only 5.2% after 500 compression cycles (Fig. 3f), demonstrating that the incorporation of T-NTAC and the PDMS encapsulation significantly improved the mechanical stability. The aerogels also exhibit remarkable compressive elasticity, recovering their original height even after 70% strain (Fig. 3g). Overall, compression tests confirm that T-NTAC possesses high strength, excellent cyclic durability, and a low energy dissipation coefficient.

The excellent elasticity and fatigue resistance of PT-NTAC originate from a synergistic mechanism that transforms potentially catastrophic interlayer sliding into controlled, reversible buckling (Fig. 3h). In conventional carbon aerogels, stress is uniformly distributed across fragile cell walls, leading to rapid crack propagation once local strain exceeds the brittle limit. In sharp contrast, the tetrapod-shaped ZnO whiskers act as distributed rigid “nano-columns” that pierce through multiple carbon lamellae. Upon perpendicular compression, the four needle-like legs of each T-ZnOw first resist relative sliding between adjacent layers, converting shear-dominated deformation into elastic bending of the wavy carbon walls. As strain increases, the legs progressively tilt and generate friction at the carbon–ZnO interface, efficiently dissipating energy through multiple microscale sliding events rather than a single macroscopic fracture. This distributed energy dissipation mechanism dramatically delays damage accumulation, enabling full height recovery even after 70% compressive strain (Fig. 3g) and only 5.2% stress loss after 500 cycles (versus 24% for NTAC). The conformal PDMS shell further constrains lateral expansion of the lamellae, forcing the structure to deform by orderly buckling,

thereby eliminating stress concentrations at the edges that typically initiate cracking in unencapsulated aerogels.

3.3 Performance of T-NTAC-based sensors

The excellent electrical conductivity, superior fatigue resistance, and outstanding compressive performance make T-NTAC an ideal material for pressure sensors. Two piezoresistive sensors were assembled from T-NTAC and PT-NTAC and a series of tests were conducted to evaluate their sensitivity, stability, fatigue resistance and response time. As shown in Fig. 4a, the current-voltage characteristic curve of the PT-NTAC-based sensor under different pressures shows a good linear trend, indicating that the resistance remains stable under a certain pressure. By applying pressure to the aerogel, the brightness of the LED bulb can also be adjusted (Fig. S5). Fig. 4b presents the real-time curve of $\Delta R/R_0$ (where R_0 is the initial resistance and ΔR is the change in resistance under applied strain) at different compressive strains. The sensors exhibit steady and reproducible resistance variations across four applied pressures, indicating excellent signal stability. The response times of the sensor during compression and release are 24 and 69 ms, respectively (Fig. 4c), demonstrating its stability and rapid response capability.

To evaluate the sensitivity of the T-NTAC-based sensor, the sensitivity parameter during the compression process was measured. The sensitivity gauge factor (K) is calculated using the following Eq. (2)^[34]:

$$K = \frac{\Delta R/R_0}{\varepsilon} \quad (2)$$

The response characteristics of the sensor is reflected by the sensitivity (S), which is calculated by the following Eq. (3)^[59].

$$S = \frac{\Delta R/R_0}{\Delta P} \times 100\% \quad (3)$$

where ΔP is the change in the applied pressure. ΔR is the relative change in resistance, R_0 is the sensor initial resistance, and ε is the strain of the material during compression.

The sensitivity of this material exhibits a three-stage pattern. At low strain, the sensor sensitivity is highest. It gradually decreases within the strain range

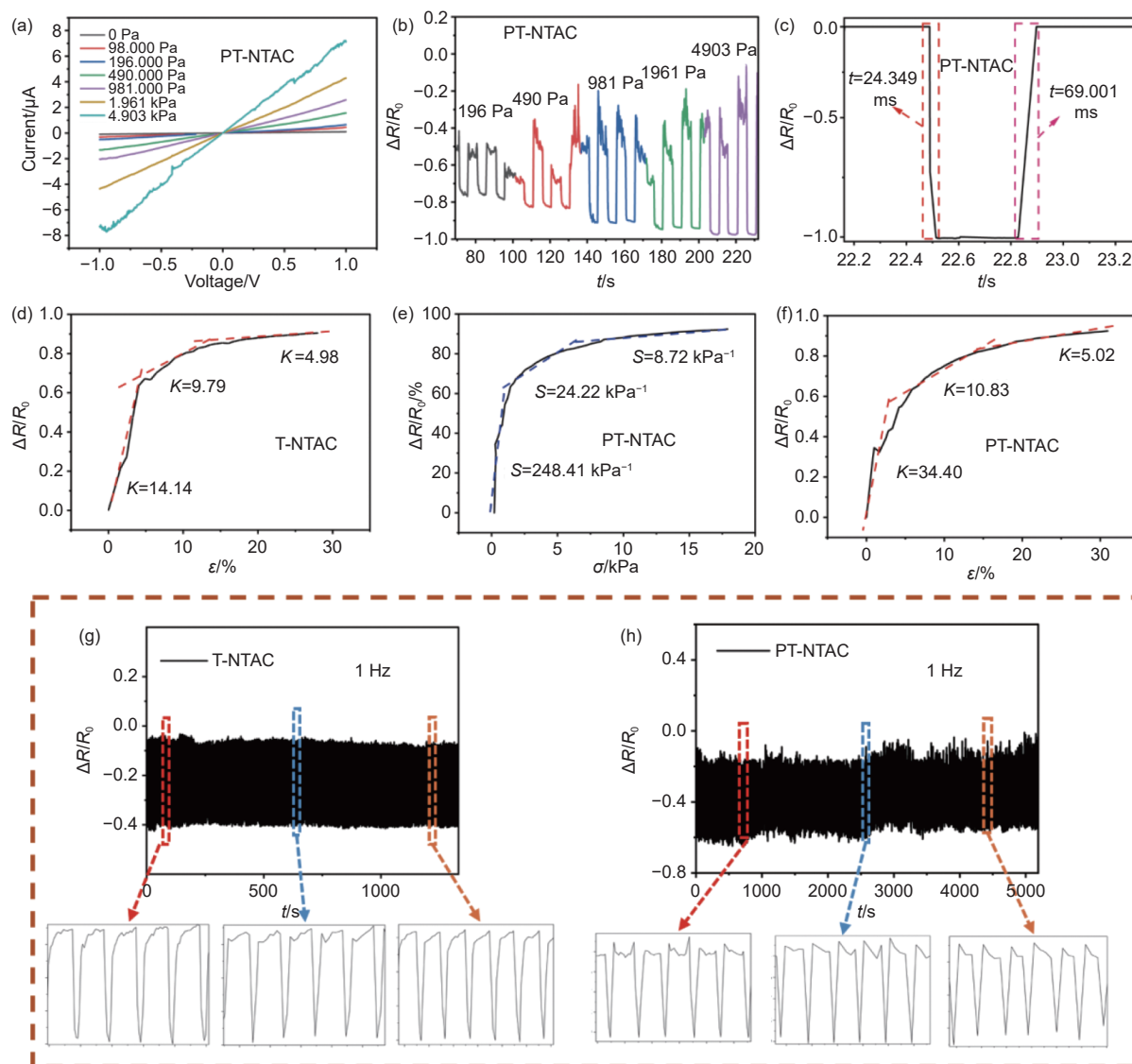


Fig. 4 Piezoresistive performance of PT-NTAC sensor. (a) curves with increasing pressure (0–4903 Pa). (b) Real-time $\Delta R/R_0$ response over 4 loading cycles. (c) Response/recovery times of 24 and 69 ms. (d–f) Three-stage sensitivity and corresponding gauge factors. (g, h) Cycling stability over 5000 (T-NTAC: 1250) cycles at 30% strain

of 5%–15%, and then stabilizes after 15%. PT-NTAC has a higher K of 34.4 than T-NTAC. And the high K and sensitivity arise from a deliberate “contact cascade” mechanism enabled by the “layer-support” geometry. At low strain (<5%), the primary conductive paths are formed by direct contact between the sharp tips of T-ZnOw and opposing carbon layers, producing an exponential increase in contact points and a drastic drop in tunneling distance, explaining the ultrahigh initial GF. In the intermediate regime (5%–15%), further compression induces large-area face-to-face contact between wavy carbon lamellae, supplemented by progressive engagement of the tetra-

pod legs as secondary bridges, yielding a still remarkable but gradual decreasing sensitivity. Beyond 15% strain, most possible contacts are already established, and additional deformation mainly shortens existing pathways with diminishing returns, leading to a stable, lower K . This microstructure-orchestrated three-stage contact evolution delivers exceptional sensitivity across 4 orders of magnitude in pressure (0–19 kPa) (Fig. 4d–f), underpinning the broadband and ultra-sensitive response of the sensor.

In this study, T-ZnOw was utilized as a mechanical scaffold to construct a “layer-support” network, which, in combination with the encapsulated PDMS

shell, endowed the material with excellent fatigue resistance and cycling stability. After encapsulation, the microscopic pore structure of PT-NTAC remained highly aligned and parallel (Fig. S6). Even after 5000 compression–release cycles at 30% strain and 1 Hz, the $\Delta R/R_0$ curve of PT-NTAC maintained a nearly identical profile (Fig. 4h). Meanwhile, T-NTAC exhibited an elastic recovery rate greater than 90% after 1250 cycles under the same strain conditions (30% strain, 1 Hz), with no noticeable performance degradation (Fig. 4g). However, microcracks were easily generated within the aerogel matrix of T-NTAC after prolonged cycling, which adversely affects its mechanical integrity. Repeated tests revealed that when the number of cycles exceeds approximately 1500, the T-NTAC aerogel develops accumulated microcracks that evolve into macroscopic cracks, leading to pronounced structural damage and subsequent mechanical failure. Whereas PT-NTAC exhibits no such damage, demonstrating superior structural durability.

Both the pre- and post-packaged sensor materials can be placed on a dandelion, reflecting their lightweight properties and the low density of the materials discussed earlier (Fig. 5a, d). Additionally, T-NTAC, with its unique advantages, such as a 3D porous network structure, high porosity (as the CT porosity shows in Fig. S7), mechanical stability, and excellent conductivity, is promising for applications in the electrochemical field. After slicing T-NTAC into electrodes, its electrochemical performance was tested using a three-electrode system with a glassy carbon collector in a 1 mol L⁻¹ H₂SO₄ electrolyte^[60]. In the impedance plot (Fig. 5b), the low-frequency region shows a linear slope, while the high-frequency region forms a semicircle. The small semicircle diameter in the electrochemical impedance spectrum indicates the low charge transfer resistance^[61]. The closed curve in the cyclic voltammetry (Fig. 5c) shows that T-NTAC exhibits double-layer capacitance behavior.

While NTAC exhibits an open-circuit voltage of only ~ 0.27 mV, the incorporation of T-ZnOw dramatically elevates the voltage of T-NTAC to ~ 40 mV, achieving a roughly 148-fold enhancement. This

originates from a pronounced local stress concentration effect, which is uniquely amplified by the “layer-support” architecture (Fig. 5e). The tetrapod structure uniquely enables simultaneous load bearing and directional piezoelectric activation. In randomly dispersed ZnO nanoparticle systems, applied stress is diluted across the soft matrix, resulting in minimal piezoelectric polarization. Here, the rigid tetrapod cores are perpendicularly aligned between parallel carbon layers by the bidirectional freezing process, forcing macroscopic compressive stress to be funneled exclusively onto the four needle-like tips. Moreover, the layered geometry ensures that nearly all tetrapods experience consistent uniaxial stress along their polar axis, achieving near-theoretical piezoelectric efficiency and remarkable signal uniformity, a feature unattainable in isotropic composites.

Although the macroscopic “contact cascade” model elucidates the resistance variation derived from geometric deformation, it is insufficient to rationalize the ultrahigh gauge factor and the substantial voltage surge observed. This performance enhancement is intrinsically attributed to the piezotronic modulation effect at the carbon/ZnO heterojunctions. Upon compression, the non-centrosymmetric crystal structure of T-ZnOw induces a piezoelectric polarization field along the crystal axis. As the N-doped carbon nanosheets form a metal-semiconductor interface with the semiconducting ZnO, a Schottky barrier is established. Under applied stress, the local piezo-potential modifies the band structure at the interface, effectively lowering the Schottky barrier height (SBH) and narrowing the depletion region. This electronic modulation facilitates carrier transport by tunneling or thermionic emission across the interface. Consequently, the distinct sensitivity arises from a synergistic coupling where mechanical contact expansion (piezoresistive) and electronic barrier tuning (piezotronic) occur simultaneously, amplifying the current response beyond the limit of pure structural deformation.

The variation in water contact angles before and after encapsulation (Fig. 5f) shows that the left side T-NTAC is highly hygroscopic, with a lowered water

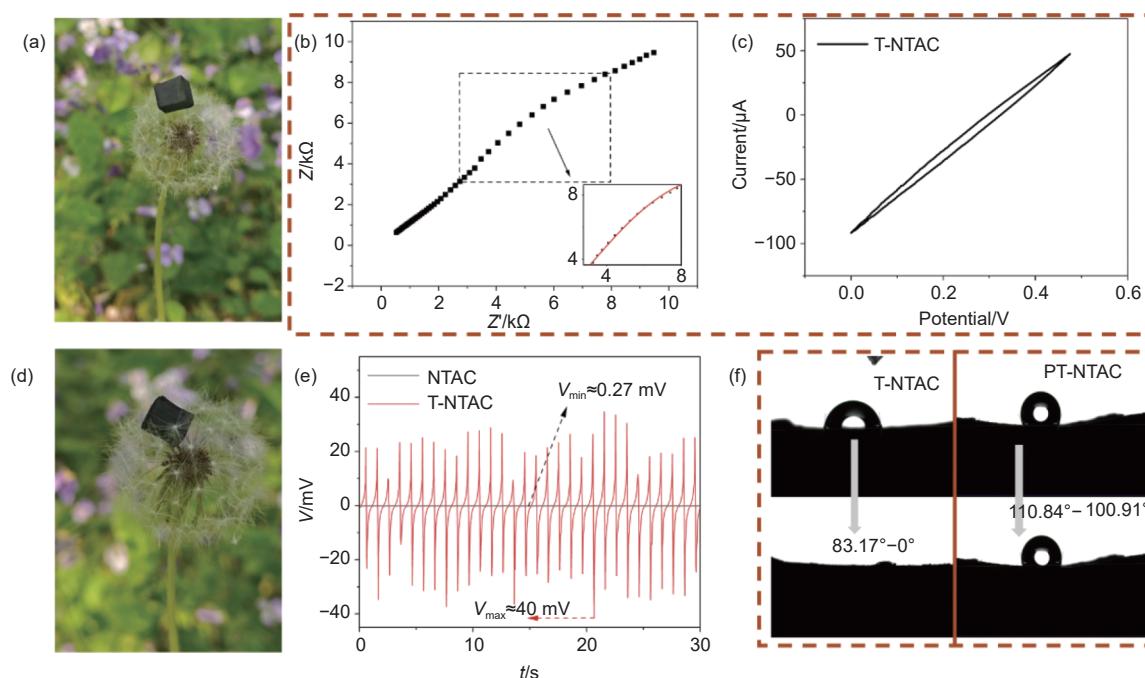


Fig. 5 (a, d) Carbon aerogels before/after packaging placed on a dandelion. (b) Impedance plot and (c) cyclic voltammetry plot of T-NTAC. (e) Voltage signal comparison of NTAC and T-NTAC under 30% strain. (f) Comparison of water contact angles between T-NTAC and PT-NTAC

contact angle. In contrast, the water contact angle of the right side PT-NTAC remains nearly unchanged with a high water contact angle. This demonstrates that PDMS encapsulation effectively improves the hydrophobicity of the sensor, shifting the material surface from hydrophilic to hydrophobic. Overall, the encapsulation enhances the stability of the entire system.

3.4 Applications of the sensor

Owing to its high sensitivity, good mechanical properties, and the ability to detect a wide range of pressures, the T-NTAC sensors hold substantial potential for monitoring human activities. As shown in Fig. 6d, the sensor can accurately and continuously reflect pressure changes.

In strain sensing, the sensor can record bending motions at various body parts, such as swallowing (Fig. 6a), elbow (Fig. 6b), knee (Fig. 6f), and wrist (Fig. 6g) when attached to the corresponding joints or areas. It can also provide stable responses for facial expressions, such as a smile shown in Fig. 6c.

Fig. 6e compares carotid artery signals under resting and exercising conditions, clearly showing differences in pulse intensity. The zoomed-in image (Fig. S8) reveals a clear pulse waveform, including the per-

cussion wave (*P*), tidal wave (*T*), and dicrotic wave (*D*). These three waveforms respectively reflect the rapid ejection capability in early systole, the blood flow during mid-to-late systole, and the elastic recoil following aortic valve closure in early diastole (details in Supporting Information). The intensity and rate of sensor signal variations induced by pulse beats during active periods are significantly greater than those at rest (Fig. 6e). Pulse analysis can help doctors and practitioners diagnose diseases and assess physical health. Sensors can also transmit Morse code signals (Fig. S8).

At the same time, the vibration response of the sensor was tested. It was able to respond to the vibration of a cantilever beam (Fig. 7a) and also to the vibrations of a Bluetooth speaker when music was played (Video 1). After converting the time-domain signal (Fig. 7b) into a frequency-domain signal using Fast Fourier Transform (FFT) (Fig. 7c), clear fifth order resonance peaks were observed. This demonstrates the successful implementation of vibration sensing.

3.5 Comparison of comprehensive performance

As summarized in Table 1, a comprehensive

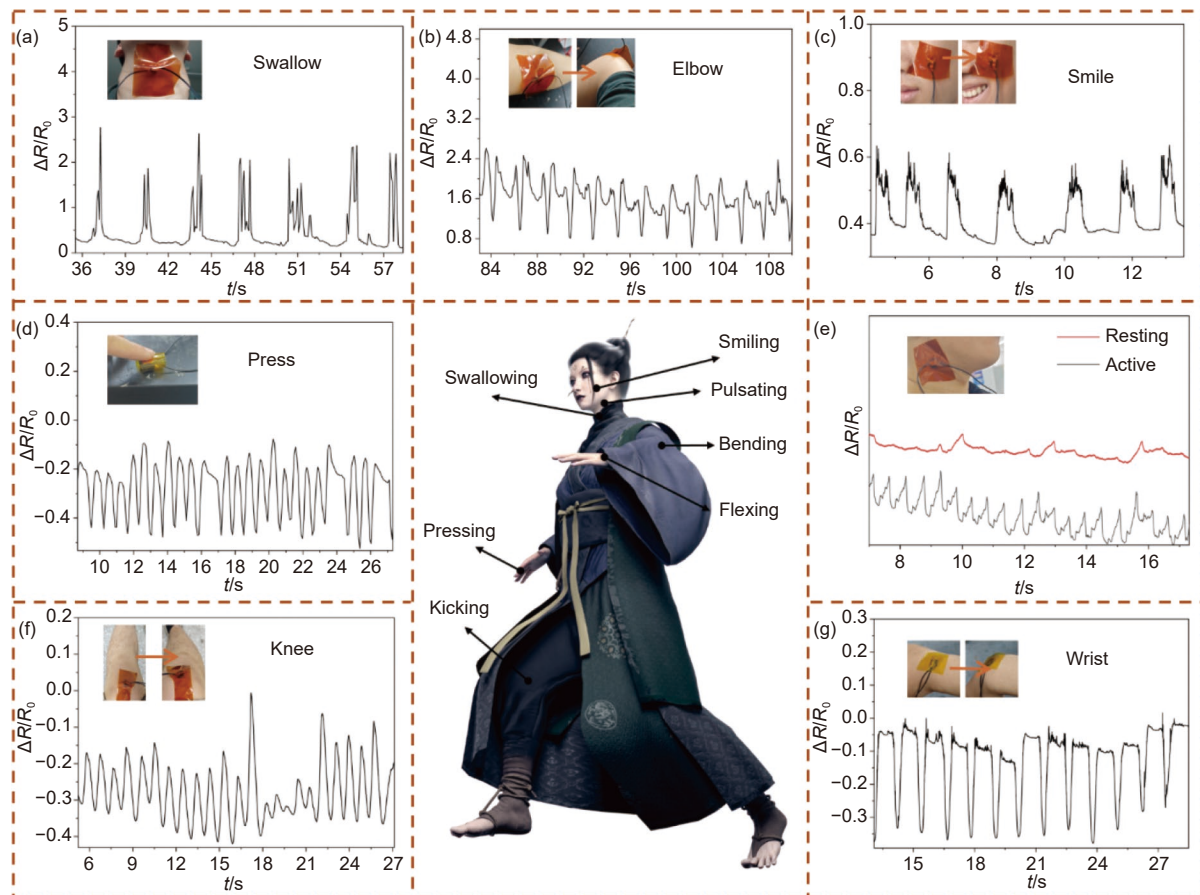


Fig. 6 The resistance change rate of the sensor under the application of force: (a) Monitoring throat movement during swallowing, (b, f, g) monitoring the resistance change during elbow, leg, and wrist joint movements, (c) monitoring facial smile expression and (d) monitoring pressure. (e) Monitoring the carotid artery pulse before and after exercise

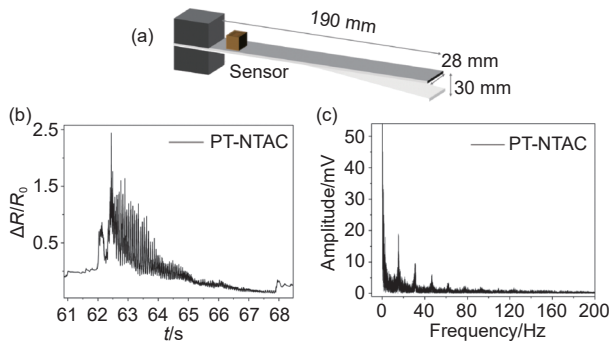


Fig. 7 (a) Schematic diagram of the sensor measuring cantilever beam vibration. (b) PT-NTAC vibration measurement image. (c) Frequency domain chart of PT-NTAC measuring vibration

comparison was conducted between the developed sensor and existing literature regarding strain/stress sensitivity (K , S), cycle life, and response (loading/recovery) times. The results indicate that our work achieves the highest level of sensitivity, presenting a prominent advantage. Furthermore, its cycling stability and response speed are highly competitive with

Table 1 Performance comparison of different sensors

Sensor	Sensitivity: K ; S (kPa^{-1})	Cycling stability (times)	Response/recovery time/ms
CGP-C-1 ^[2]	$S=59.7$	20 000	72/96
MMAT ^[31]	$S=10.51$	1000	220/160
C-NGD ^[34]	$K=9.85$	9000	98/91
MTAS ^[62]	$S=92.22$	6000	11/14
RGO/LDC ^[63]	$S=10$	1000	0.125
MXene/CNF	$S=167.67$	3000	4.71/2.99
Aerogel@PDMS ^[64]			
This research	34.4/248.4	5000	24/69

other state-of-the-art sensors. In summary, by integrating ultrahigh sensitivity, prolonged cycle life and rapid response, the sensor demonstrates exceptional overall performance.

4 Conclusion

A carbon aerogel composite sensor (PT-NTAC) was developed by employing a bidirectional freezing strategy and introducing T-ZnOw, followed by PDMS

encapsulation, which exhibits a unique structure, high sensitivity, and excellent durability. The resulting hierarchical “layer-support” architecture facilitated anisotropic stress distribution through aligned porous channels. The synergistic interactions among the material components enhanced the mechanical robustness of the aerogel while simultaneously imparting piezoelectric functionality. The tetrahedral, needle-like topology of T-ZnOw served as both a mechanical reinforcement phase and a piezoelectric activation unit, leading to an 148-fold increase in output voltage. PDMS encapsulation further improved the material toughness, modulus retention and sensitivity. Consequently, the sensor exhibits a high sensitivity ($K = 34.4$) within a pressure range of 0–19 kPa, with rapid response and recovery times of 24 and 69 ms, respectively.

The PT-NTAC sensor demonstrates excellent multi-scale sensing capabilities, accurately capturing human pulse P–T–D waveforms, joint motions, and facial expressions, as well as detecting vibration spectra of cantilever beams. Moreover, the sustainable fabrication strategy based on biomass-derived cellulose (carbonization ≤ 900 °C) underscores the environmental compatibility of the approach. This work provides a new paradigm for designing high-sensitivity and environmentally robust biomass-derived sensing materials, with promising potential for future applications in flexible electronics and electronic skin through optimization of T-ZnOw dispersion and structural control. Despite these advances, this work still has certain limitations, including the non-uniform dispersion of T-ZnOw, the difficulty in simultaneously achieving high sensitivity and high linearity, and the limited stretchability of the sensor material. In future work, we plan to regulate the size and orientation of T-ZnOw and explore its combination with other functional materials to further improve performance and broaden its applications in flexible electronics and electronic skin.

References

- [1] Li S, Bi Y, Liu J, et al. High-sensitivity piezoresistive biomass-derived carbon aerogel/polydimethylsiloxane composite with extreme temperature adaptability[J]. *Energy & Environmental Materials*, 2026, 9(1): e70079.
- [2] Jiang M, Li B, Zhao Y, et al. Superelastic biomass-based carbon aerogels reinforced by vein-like networks and pillar structures for piezoresistive sensing, high-temperature applications, and supercapacitors[J]. *Advanced Functional Materials*, 2026, 36(1): e13514.
- [3] Sun Y, He W, Jiang C, et al. Wearable biodevices based on two-dimensional materials: From flexible sensors to smart integrated systems[J]. *Nano-Micro Letters*, 2025, 17(1): 109.
- [4] Dalla A, Pelin M, Sosa S, et al. Carbon-based nanomaterials and skin: An overview[J]. *Carbon*, 2022, 196: 683–698.
- [5] Kumar V, Parvin N, Joo W, et al. Great carbon nano materials based composites for electronic skin: Intelligent sensing, and self-powered nano generators[J]. *Nano Energy*, 2025, 137: 110805.
- [6] Alghamdi S, Morgan J, Walsh K, et al. Triboelectric nanogenerator based on cellulose nanocrystals and graphene for energy harvesting from piano playing motion[J]. *Nano Energy*, 2025, 138: 110816.
- [7] Qian C, Li L, Gao M, et al. All-printed 3D hierarchically structured cellulose aerogel based triboelectric nanogenerator for multifunctional sensors[J]. *Nano Energy*, 2019, 63: 103885.
- [8] Xie Q, Zhao J, Wang S, et al. Recent advances in bacterial cellulose-based wearable strain sensors[J]. *European Polymer Journal*, 2025, 236: 114150.
- [9] Liu Y, Wang F, Hu Z, et al. Applications of cellulose-based flexible self-healing sensors for human health monitoring[J]. *Nano Energy*, 2024, 127: 109790.
- [10] Tian L, Gao F, Li Y, et al. High-performance bimodal temperature/pressure tactile sensor based on lamellar CNT/MXene/cellulose nanofibers aerogel with enhanced multifunctionality[J]. *Advanced Functional Materials*, 2024, 35(17): 2418988.
- [11] Li W, Zhu L, Xu Y, et al. Lignocellulose-mediated functionalization of liquid metals toward the frontiers of multifunctional materials[J]. *Advanced Materials*, 2025, 37(12): 2415761.
- [12] Zhang Y, Zhu P, Sun H, et al. Superelastic cellulose sub-micron fibers/carbon black aerogel for highly sensitive pressure sensing[J]. *Small*, 2024, 20(13): 2310038.
- [13] Wang G, Liu X, Song Z, et al. Multifunctional flexible pressure sensor based on a cellulose fiber-derived hierarchical carbon aerogel[J]. *ACS Applied Electronic Materials*, 2023, 5(3): 1581–1591.
- [14] Shen S, Zhang Y, Guo W, et al. Hierarchically piezoelectric aerogels for efficient sound absorption and machine-learning-assisted sensing[J]. *Advanced Functional Materials*, 2024, 34(42): 2406773.

- [15] Kang J, Zhao Q, Mao M, et al. Multi-crosslinked network enables robust cellulose/chitosan composite aerogel for triboelectric sensor with humidity adaptivity[J]. *Chemical Engineering Journal*, 2025, 519: 165385.
- [16] Dong Z, Zhong L, Zhang Y, et al. Construction of multifunctional cellulose nanofibers/reduced graphene oxide carbon aerogels by bidirectional freezing for supercapacitor electrodes and strain sensors[J]. *Diamond and Related Materials*, 2023, 140: 110555.
- [17] Ye W, Meng L, Xi J, et al. Superelastic carbon aerogels with anisotropic and hierarchically-enhanced cellular structure for wearable piezoresistive sensors[J]. *Journal of Colloid and Interface Science*, 2024, 666: 529-539.
- [18] Fu Y, Ye H, Yuan K, et al. Advance and perspective of carbon-based aerogels and their composites[J]. *Chemical Engineering Journal*, 2025, 519: 165304.
- [19] Rathi K, Kim D. Super-compressible and mechanically stable reduced graphene oxide aerogel for wearable functional devices[J]. *Science and Technology of Advanced Materials*, 2023, 24(1): 2214854.
- [20] Baimova A, Shcherbinin A. Strength and deformation behavior of graphene aerogel of different morphologies[J]. *Materials*, 2023, 16(23): 7388.
- [21] Zhang C, Liao D, Wang Y, et al. Pickering emulsion strategy for high compressive carbon aerogel for use as insulation material and dual-mode pressure/magnetic sensor[J]. *Ceramics International*, 2023, 49(5): 8121-8131.
- [22] Cai H, Zheng J, Zhang J, et al. Synergistically reinforced bamboo cellulose-graphene aerogel sensors with highly elasticity and strain sensitivity[J]. *ACS Applied Electronic Materials*, 2025, 7(16): 7755-7765.
- [23] Thomas B, Geng S, Wei J, et al. Ice-templating of lignin and cellulose nanofiber-based carbon aerogels: Implications for energy storage applications[J]. *ACS Applied Nano Materials*, 2022, 5(6): 7954-7966.
- [24] Wei S, Qiu X, An J, et al. Highly sensitive, flexible, green synthesized graphene/biomass aerogels for pressure sensing application[J]. *Composites Science and Technology*, 2021, 207: 108730.
- [25] Wei L, Wu Z, Tang S, et al. Tracheid-inspired nanoarchitected carbon-based aerogels with ultra-compressibility for wearable piezoresistive sensors[J]. *Carbon*, 2023, 203: 386-396.
- [26] Ye W, Meng L, Xi J, et al. Anisotropic carbon aerogels with XYZ three-direction superelasticity for piezoresistive sensing applications[J]. *Chemical Engineering Journal*, 2024, 500: 157290.
- [27] Miao S, Wang Y, Lu M, et al. Freezing-derived functional materials[J]. *Materials Today*, 2024, 74: 235-268.
- [28] Bai Y, Zhang H. Freeze-enabled synthesis of functional materials: Fundamental, progress, and applications[J]. *Progress in Materials Science*, 2026, 155: 101523.
- [29] Li M, Zheng Y, Bai H, et al. Advances in ice-templated graphene aerogels: Fabrication, properties, and applications[J]. *ACS Applied Materials & Interfaces*, 2025, 17(13): 19247-19262.
- [30] Yang M, Wen J, Han J, et al. Superhydrophobic, multifunctional, and mechanically durable carbon aerogel composites for high-performance underwater piezoresistive sensing[J]. *ACS Applied Materials & Interfaces*, 2024, 16(46): 64101-64112.
- [31] Ye Y, Tong X, Zhou J, et al. Spider web-inspired multifunctional aerogel sensor: MWCNT/MXene/TOCNF synergize to achieve high-sensitivity multiple detection of humidity, pressure, and photothermal stimuli[J]. *Chemical Engineering Journal*, 2025, 523: 168325.
- [32] Ding M, Li S, Guo L, et al. Metal ion-induced assembly of MXene aerogels via biomimetic microtextures for electromagnetic interference shielding, capacitive deionization, and microsupercapacitors[J]. *Advanced Energy Mater*, 2021, 11(35): 2101494.
- [33] Li X, Kurasch S, Kaiser U, et al. Synthesis of monolayer-patched graphene from glucose[J]. *Angewandte Chemie International Edition*, 2012, 51(38): 9689-9692.
- [34] Long S, Feng Y, He F, et al. Biomass-derived, multifunctional and wave-layered carbon aerogels toward wearable pressure sensors, supercapacitors and triboelectric nanogenerators[J]. *Nano Energy*, 2021, 85: 105973.
- [35] Yu H, Shang L, Bian T, et al. Nitrogen-doped porous carbon nanosheets templated from g-C₃N₄ as metal-free electrocatalysts for efficient oxygen reduction reaction[J]. *Advanced Materials*, 2016, 28(25): 5080-5086.
- [36] Dong S, Li Y, Zhang M, et al. Controllable engineering of intrinsic defects on carbon nanosheets enables fast and stable potassium storage performance[J]. *Carbon*, 2023, 204: 507-515.
- [37] Lyu W, Zhu T, Wang Y, et al. Tailored defects for metal-free nitrogen-doped carbons toward efficient oxygen reduction reaction using tripolycyanamide-based microporous polymer as precursor[J]. *Electrochimica Acta*, 2022, 433: 141205.
- [38] Ji P, Chen J, Li M, et al. Effect of nitrogen doping on the structure and electrochemical properties of vertical graphene sheets prepared by HWP-CVD[J]. *Vacuum*, 2023, 207: 111624.
- [39] Cheng Z, Yin K, Xu X, et al. Insights into the efficient water treatment over N-doped carbon nanosheets with layered minerals as template: The role of interfacial electron tunneling and transfer[J]. *Journal of Hazardous Materials*, 2024, 469: 133924.
- [40] Mikhalchan A, Labordet V, Zarzoso M, et al. The effects of CNT type, alignment and dopants on piezoresistance in CNT fibres[J]. *Carbon*, 2025, 232: 119810.
- [41] Chen A, Wang C, Abu A, et al. MXene@nitrogen-doped carbon films for supercapacitor and piezoresistive sensing applications[J]. *Composites Part A: Applied Science and Manufacturing*, 2022, 163: 107174.

- [42] Zhou Z, Peng W, Ke S, et al. Tetrapod-shaped ZnO whisker and its composites[J]. *Journal of Materials Processing Technology*, 1999, 89-90: 415-418.
- [43] Mishra K, Adelung R. ZnO tetrapod materials for functional applications[J]. *Materials Today*, 2018, 21(6): 631-651.
- [44] Yang X, Wang S, Huang Z, et al. Surface treated ZnO whisker optimizing the comprehensive performance of the self-adaptive dielectrics[J]. *Composites Science and Technology*, 2023, 233: 109918.
- [45] Zhang Z, Zhao X, Zhang Q, et al. Fully sprayed MXene-based high-performance flexible piezoresistive sensor for image recognition[J]. *Nano Materials Science*, 2024, 6(1): 77-85.
- [46] Nie S Q, Zhang X L, Luo J, et al. Synergistic effect of boron nitride and tetrapod-shaped zinc oxide whisker hybrid fillers on filler networks in thermal conductive HDPE composites[J]. *Polymer Composites*, 2017, 38(9): 1902-1909.
- [47] Yuan F, Zhang H, Li X, et al. Synergistic effect of boron nitride flakes and tetrapod-shaped ZnO whiskers on the thermal conductivity of electrically insulating phenol formaldehyde composites[J]. *Composites Part A: Applied Science and Manufacturing*, 2013, 53: 137-144.
- [48] Guo W, Zhao F, Wang Y, et al. Characterization of the mechanical behaviors and bioactivity of tetrapod ZnO whiskers reinforced bioactive glass/gelatin composite scaffolds[J]. *Journal of the Mechanical Behavior of Biomedical Materials*, 2017, 68: 8-15.
- [49] Jiang Y, Sun R, Zhang H, et al. Graphene-coated ZnO tetrapod whiskers for thermally and electrically conductive epoxy composites[J]. *Composites Part A: Applied Science and Manufacturing*, 2017, 94: 104-112.
- [50] Kim D, Jang M, Seo J, et al. UV-cured poly(urethane acrylate) composite films containing surface-modified tetrapod ZnO whiskers[J]. *Composites Science and Technology*, 2013, 75: 84-92.
- [51] Yang M, Peng K, Li Z, et al. Recent progress in flexible materials for wearable devices for body function and athletic performance monitoring[J]. *Chemical Engineering Journal*, 2025, 505: 159659.
- [52] Janes A, Kurig H, Lust E. Characterisation of activated nanoporous carbon for supercapacitor electrode materials[J]. *Carbon*, 2007, 45(6): 1226-1233.
- [53] Lipomi D J, Vosgueritchian M, Tee B C K, et al. Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes[J]. *Nature Nanotechnology*, 2011, 6(12): 788-792.
- [54] Wang K, Ma J, Zhang C, et al. Self-powered high-sensitivity piezoelectric sensors for end-fixtured force sensing in surgical robots based on T-ZnO[J]. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2024, 697: 134424.
- [55] Feng Y, Long S, Yan G, et al. Manganese catalyzed transfer hydrogenation of biomass-derived aldehydes: Insights to the catalytic performance and mechanism[J]. *Journal of Catalysis*, 2020, 389: 157-165.
- [56] Zhu H, Wang B, Liu D, et al. Preparation of superhydrophobic polyurethane sponge with photodegradation function and study on its oil-water separation performance[J]. *Materials Today Communications*, 2024, 41: 110831.
- [57] Duan Y, FU Y, Shi Y, et al. T-ZnOw/FCIPs with vertical-orientated structure achieving temperature-stable broadband microwave absorption[J]. *Applied Surface Science*, 2023, 613: 155988.
- [58] Ma X, Kong Z, Gao Y, et al. Anisotropic free-standing aerogels based on graphene/silk for pressure sensing and efficient adsorption[J]. *ACS Applied Materials & Interfaces*, 2023, 15(25): 30630-30642.
- [59] Tan Z, Hu Q, Yang B, et al. Superelastic and highly sensitive biomass-derived piezoresistive aerogels for deep-learning-assisted sensing[J]. *Advanced Functional Materials*, 2025: e11831.
- [60] Wang Q, Yuan W, Zhang Y, et al. Tailoring the structural design of covalent organic frameworks for enhanced photocatalytic carbon dioxide reduction: A review[J]. *Renewable and Sustainable Energy Reviews*, 2025, 217: 115754.
- [61] Zhu G, Wang H, Xu H, et al. Enhanced capacitive deionization by nitrogen-doped porous carbon nanofiber aerogel derived from bacterial-cellulose[J]. *Journal of Electroanalytical Chemistry*, 2018, 822: 81-88.
- [62] Zhao H, Zhang Y, Han L, et al. Intelligent recognition using ultralight multifunctional nano-layered carbon aerogel sensors with human-like tactile perception[J]. *Nano-Micro Letters*, 2024, 11: 16.
- [63] Zeng Z, Wu N, Yang W, et al. Sustainable-macromolecule-assisted preparation of cross-linked, ultralight, flexible graphene aerogel sensors toward low-frequency strain/pressure to high-frequency vibration sensing[J]. *Small*, 2022, 18: 2202047.
- [64] Wang A, Gao Z, Wu S, et al. Superelastic and ultra-soft MXene/CNF aerogel@PDMS-based dual-modal pressure sensor for complex stimuli monitoring[J]. *Advanced Science*, 2025, 12: 2502797.