

A universal and facile design strategy for ultrasensitive strain sensors with a 3.365 $\mu\epsilon$ detection limit

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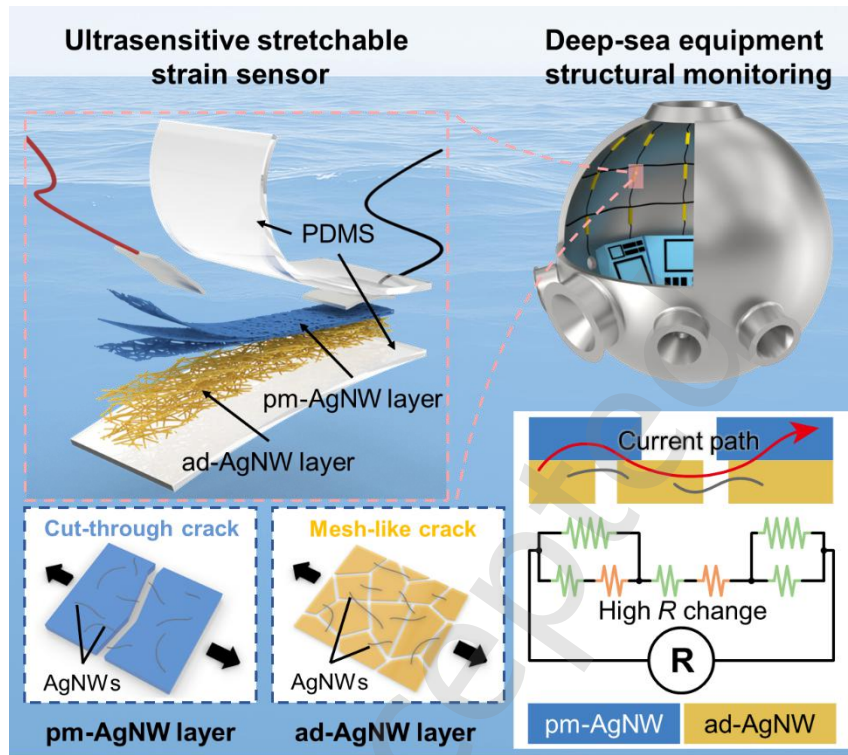
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This work presents an ultrasensitive dual-crack-modulated strain sensor for precise, stable small-strain detection, thus achieving conformal, high-SNR measurements of the compressive strain in deep-sea equipment.

Research Article

A universal and facile design strategy for ultrasensitive strain sensors with a 3.365 $\mu\epsilon$ detection limit

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ABSTRACT

Precise small-strain detection is critical for various applications, yet most existing technologies lack conformability, environmental robustness, high performance, and fabrication simplicity. Here, we introduce a material-independent design strategy to prepare ultrasensitive stretchable sensors that leverage two cracking mechanisms: cut-through cracks abruptly rupture dominant conductive pathways, while mesh-like cracks drive the progressive degradation of auxiliary conductive pathways, collectively leading to a rapid and stable resistance increase under small strains. The resulting sensor possesses an ultrahigh gauge factor (~ 430), an ultralow detection limit (0.0003365% strain), and high durability ($> 5,000$ tensile cycles). Through conformal, *in situ*, and real-time structural monitoring with a high signal-to-noise ratio (> 50 dB), the sensor reliably captured a small compressive strain signal for deep-sea equipment under extreme hydrostatic pressure (50 MPa). Our design offers a general, scalable route for ultrasensitive sensing in aerospace, ocean engineering, and precision manufacturing.

KEYWORDS: ultrasensitive stretchable strain sensor, ultralow detection limit, crack-modulated bilayer structure, conformal structural health monitoring, deep-sea equipment

1 Introduction

High-fidelity monitoring of small strains (e.g., $< 1\%$) is crucial in aerospace [1, 2], ocean engineering [3-5], precision manufacturing [6, 7], and biomedical applications [8-10] because these signals often mark the onset of early-stage damage, subtle dysfunctional evolution, or subsurface anomalies in materials and structures [11, 12]. Such strain signatures can be extremely weak; for example, the strain variation of deep-sea equipment during submergence can be as low as 0.000625% per 10 m [13], and even in the Mariana Trench (the deepest ocean trench), the maximum strain of deep-sea equipment can remain below 1%. These ultrasensitive deformations are

therefore readily buried by noise [14, 15], demanding sensors that deliver both high sensitivity to amplify weak strain signals and an ultralow detection limit to identify minimal effective signals. Moreover, many monitoring objects, such as aero-engine blades, deep-sea equipment shells, and biological tissues, feature complex curvatures, imposing requirements for highly conformal adhesion and accurate strain transfer [16, 17].

A range of high-sensitivity approaches has been explored for small-strain sensing, yet significant bottlenecks still exist under complex surface deployment and environmental interference. For instance, fiber grating sensors can reach detection limits lower than 0.001% strain [18, 19], but the brittleness of optical fibers hinders conformal attachment to complex curved surfaces, leading to signal distortion. Sensors based on guided ultrasonic waves enable large-area detection of internal microcracks, but mode overlap and multipath propagation limit feature repeatability and reduce robustness [20, 21]. Magnetic-field-based strategies offer several advantages, such as non-contact measurement and fast response, but they are vulnerable to external electromagnetic interference that can introduce false signals and drift [22, 23]. To overcome these constraints, a high-performance small-strain monitoring technology is highly desirable, featuring conformal deployability, robust and repeatable signal readout, and high electromagnetic interference resistance.

Resistive strain sensors have emerged as promising candidates for small-strain sensing owing to their electromagnetic interference immunity, compact size, and capability for *in situ* and real-time measurement [24, 25]. Advances in stretchable materials—including polydimethylsiloxane (PDMS) [26-29], silicone [30, 31], hydrogels [32-35], and other elastomers [36-41]—have been developed to unlock desirable sensor capabilities on complex surfaces. Ren et al. [33] reported a hydrogel-based strain sensor to monitor the underwater movements of animals, with a limited sensitivity of 0.362. Wang et al. [40] fabricated a stretchable strain sensor based on thermoplastic polyurethane, demonstrating a gauge factor (GF) of ~ 5 at 10% strain during human motion monitoring. Strategies involving bio-mimetic architectures [42-44], composite materials [45-48], and molecular-level modulation

[49, 50] have further enhanced sensitivity. Yu et al. [44] proposed a high-sensitivity strain sensor based on fern-leaf-inspired hierarchical structures, reaching a GF of ~ 270 within the 0%–22% strain range. Li et al. [49] presented a stretchable strain sensor with a GF of ~ 500 at 0.05% strain, in which the strong thiol–silver coordination bonds improve the performance of the sensor. However, achieving an ultralow detection limit ($< 0.001\%$ strain), which is essential for distinguishing early-stage damage indicators from background interference, remains challenging. Another obstacle is that existing strategies rely on complex materials [43, 50–53] or advanced fabrication techniques [16, 45, 54, 55], thus presenting barriers to reproducibility, scalable manufacturing, and widespread application.

Herein, we introduce a universal structural design concept for ultrasensitive strain sensors. This material-independent approach employs a one-step pressurization process to reconfigure metallic nanowires (e.g., silver nanowires, AgNWs) network with dual-cracking mechanisms, thereby enabling the formation of conductive bilayers with distinct sensing behaviors, all encapsulated within an elastomeric matrix. Notably, cut-through cracks can abruptly rupture the dominant conductive pathways under small tensile strains, whereas mesh-like cracks drive the progressive degradation of auxiliary conductive pathways. Together, the resulting dual-crack-modulated strain (DCMS) sensor exhibits ultrahigh sensitivity (GF ≈ 300 at 1% strain and 430 at 3% strain), an ultralow detection limit ($3.365\ \mu\epsilon$, equal to 0.0003365% strain), and high durability ($> 5,000$ tensile cycles). By integrating with a custom, modular data acquisition system, we demonstrate real-time, *in situ*, and high signal-to-noise-ratio (SNR; > 50 dB) structural health monitoring in deep-sea equipment under hydrostatic pressures of 50 MPa. This work establishes a scalable strategy for advancing the sensitivity, detection limits, and robustness of stretchable strain sensors, with broad implications for aerospace, precision instrumentation, and biomedical engineering.

2 Methods

2.1 Materials

The ethylene glycol (EG), ethanol, polyvinylpyrrolidone (PVP), silver nitrate (AgNO_3), and ferric chloride (FeCl_3 , 600 $\mu\text{mol/L}$) used in this work were all purchased from Aladdin Biochemical Technology Co., Ltd. (Shanghai, China). The polyimide (PI) film with a thickness of 125 μm was purchased from Chenxiang Co., Ltd. (Shenzhen, China). The PI tape (with thicknesses of 40 μm and 80 μm) was purchased from Yongnai Co. (Shenzhen, China). The PDMS prepolymer and the cross-linking agent (Sylgard 184) were purchased from Dow Corning (Midland, MI, USA). The Loctite 406 instant adhesive, Loctite 770 primer, and Loctite 496 cyanoacrylate adhesive used for sensor bonding were all purchased from Henkel AG & Co. KGaA (Düsseldorf, Germany).

2.2 Preparation of AgNWs

AgNWs were synthesized according to the protocol reported by Wang et al. [56] Firstly, 25g of EG was added into a 100 ml beaker and stirred using a magnetic stirrer. Then, 0.2g of PVP was added to the beaker, and the solution was heated to 110°C under continuous stirring. After complete dissolution of PVP, 0.25g of AgNO_3 powder was slowly added into the solution and stirred for 5 min. Subsequently, 3.4g of FeCl_3 solution was added into the reaction mixture. After 45 s, the beaker was transferred to a constant-temperature heating oven preheated to 110°C for 12-hour reaction. After the reaction is completed, the solution was cooled to room temperature (25°C), and the products were collected by centrifugation after washing with acetone. The precipitates were further purified by ethanol washing to remove residual acetone. Finally, a 3 wt.% AgNW solution was obtained for subsequent experimental procedures.

2.3 Fabrication of DCMS Sensor

A PI film, cleaned with ethanol, served as the substrate and was uniformly fixed in place with 40 μm -thick PI tape. The AgNW solution was drop-cast onto the PI film and dried in an oven (60°C, 2 min) to form one AgNW layer, with this process repeated multiple times until the desired number of pressurized layers was achieved. Another PI film was then laminated as a spacer layer on top of the AgNW layers. The

structure was subsequently calendared using a roller press to compress the AgNW layers, with a pressure of 700 psi and a velocity of 100 mm/s. After the pressing treatment, AgNW solution was continuously drop-cast onto the pressurized layer and oven-dried (60°C, 2 min) through multiple cycles to form non-pressurized layers. Next, the substrate PI film was thermally annealed at 210°C for 90 min to enhance interlayer adhesion and improve the conductivity of the AgNW network [57]. After cooling, a patterned PI tape (with a thickness of 80 μm) was covered on the top of AgNW network. Then poured the 0.4 mm layer of the liquid PDMS onto the polyimide tape to form the first protective layer. After cured the PDMS at 60°C for 120 min, the PDMS is peeled off and flipped over, and the exposed AgNW network in the patterned tape will be carried away with PDMS. This process induces bending and stretching of the AgNW network, leading to the formation of cracks. The electrical connection between the fabricated sensors and external circuits was established using silver paste to bond the sensor terminals to copper wires (treated with 90°C, 60 min). Finally, another layer of liquid PDMS with a thickness about 0.5 mm was casted onto the sample to seal the AgNW layer inside the sensor, and cured at 60°C for 120 min. Finally, the sensor was cut into 40 mm $\times$ 10 mm for subsequent testing.

2.4 Sensor Characterization

The crack morphology images were taken by the optical microscopes (BX53M, Olympus Corp., Japan). The SEM images were taken by CrossBeam 350 (Carl Zeiss AG, Germany). The AFM images were taken by the Vista One (Molecular Vista Inc., USA) with a scanning area of 10 μm $\times$ 10 μm , a scanning speed of 0.25 lines/sec and the scanning mode is sideband mode with set point = 75%. The universal testing machine (EZ-LX, Shimadzu Corp., Japan) was used to test the strain-sensing characteristics of DCMS sensor, then uniform strain/release cycles were applied to the samples while the changes of resistance were measured by a digital multimeter (34461A, Keysight Technologies, USA) with 4-wire mode. The tensile test specimen size is 40 mm $\times$ 10 mm $\times$ 1 mm and tensile speed is 5 mm min⁻¹. The electrochemical impedance spectrum of the DCMS sensor was measured using a E4980A precision LCR Meter from Keysight Technologies.

The gauge factor (GF) of the sensor was calculated by the following formula (Eq. (1)):

$$GF = \frac{\left(\frac{R - R_0}{R_0} \right)}{\varepsilon} \quad (1)$$

where R was the dynamic resistance value under different strains, R_0 was the initial resistance before sensor deformation, and ε was the strain.

2.5 Deep-sea Hydrostatic Pressure Test

The DCMS sensor was bonded to the titanium alloy surface using Loctite 406 instant adhesive in conjunction with Loctite 770 primer. The data acquisition system comprises multiple functional modules: a multi-channel analog-to-digital converter (ADC), a STM32 development board, a serial communication interface, a TF card read–write module, and a constant current source. The entire system was powered via a USB connection to an external power bank. During the external simulated seawater pressure loading, the titanium alloy capsule underwent inward compression deformation, which induced corresponding resistance variations in the attached sensors. A constant current of 49.6 mA was supplied to the sensors by the current source module, while the resulting voltage signals were acquired via the multi-channel ADC. The analog data are then converted into digital format and stored locally on a TF card for post-experimental analysis on a computer. For comparative purposes, a commercial strain gauge (RunesKee, 350-3EB full-bridge strain gauge) was mounted next to the DCMS sensor using Loctite 496 cyanoacrylate adhesive. The signal from the strain gauge was conditioned and acquired through its matched full-bridge transmitter module. A high-precision temperature–depth sensor (RBR*duet*³ T.D, RBR Ltd., Ottawa, Canada) was used to record the pressure and temperature changes inside the deep-sea hydrostatic pressure test equipment.

3 Results and Discussion

3.1 Structure and principle of the ultrasensitive DCMS sensor

To enable the detection of small strains—such as those induced in deep-sea equipment during submersion—we developed a stretchable DCMS sensor with ultrahigh

sensitivity and an ultralow detection limit. The DCMS sensor features a multilayered elastomer–nanowire–elastomer (i.e., PDMS–AgNW–PDMS) architecture (**Figure 1a**), designed for conformal integration onto complex curvatures. The internal conductive layers comprise two configurations of AgNW networks (**Figure S1**): pressure-modulated AgNW (pm-AgNW) layers and as-deposited AgNW (ad-AgNW) layers; the synergy between these networks enables higher performance by simultaneously extending the strain sensing range and the sensitivity. The stretchable PDMS matrix serves as the encapsulation layer, effectively shielding the internal AgNW networks from environmental interference while providing electrical insulation. This structural framework is highly versatile because the choice of stretchable elastomer and metallic nanowires can be extended to other materials, such as Ecoflex and copper nanowires, depending on the application requirements.

The two types of conductive layers exhibit distinct microstructures owing to their different preparation treatments, laying the foundation for divergent crack propagation mechanisms, which are closely associated with the key advantages of the sensor. The pm-AgNW layers have a compact, lamellar, and pressurized structure (**Figure 1b**; **Figure S2a-b**), where the pressurization process forms robust cold-welded configurations at the AgNW nanojunctions, resulting in a markedly low initial resistance and establishing a high-performance primary conduction pathway [58]. Upon application of tensile strain, inherent microdefects and structural inhomogeneities introduced during fabrication act as stress concentration sites [59, 60]. Cracks preferentially propagate along paths of least resistance—typically through regions with lower AgNW density—and extend perpendicular to the strain direction [61], forming large cut-through cracks. In contrast, the ad-AgNW layers retain a loosely packed, porous hierarchical architecture (**Figure 1c**; **Figure S2c-d**), contributing supplementary conductivity as an auxiliary pathway. The weak inter-nanowire connections, primarily governed by van der Waals forces and mechanical entanglement [62], support a relatively uniform stress distribution across the network. This leads to the formation of numerous mesh-like cracks under tensile strain, creating isolated conductive islands. A subsequent thermal sintering treatment

at 210°C further reduces the contact resistance between adjacent AgNWs and promotes the integration of both morphological variants into a unified conductive layer [57].

The differing crack morphologies between these two conductive layers result in distinct resistance responses under tensile strain, and their synergistic effect endows the sensor with superior sensing performance. The pm-AgNW layers exhibit a rapid increase in resistance upon strain-induced crack propagation, as the formation of cut-through cracks disrupts the primary conductive pathway (**Figure 1d(i)**). Conversely, the ad-AgNW layers exhibit a gradual resistance change during stretching, as some AgNWs maintain electrical connectivity by bridging adjacent conductive islands (**Figure 1d(ii)**). Notably, these islands can also span the larger cut-through cracks within the pm-AgNW layers, forming auxiliary conduction routes that prevent complete electrical failure (**Figure 1d(iii)**). Sensors dominated by cut-through cracks show a sharp resistance increase but a limited sensing range, whereas those comprising mainly mesh-like cracks offer a wider strain range but lower sensitivity (**Figure 1e**). By integrating both crack morphologies, the DCMS sensor achieves a rapid and stable resistance response under applied strain, exhibiting ultrahigh sensitivity within a small strain range.

Owing to the soft and stretchable PDMS encapsulation, the sensor exhibits beneficial mechanical characteristics, allowing it to be twisted, bent, and conformally attached to complex surfaces with small curvatures (**Figure 1f**). The DCMS sensor significantly surpasses existing resistive stretchable strain sensors in terms of their sensitivity and detection limits (**Figure 1g; Table S1**), establishing a foundation for next-generation small-strain sensing in diverse applications and complex environments.

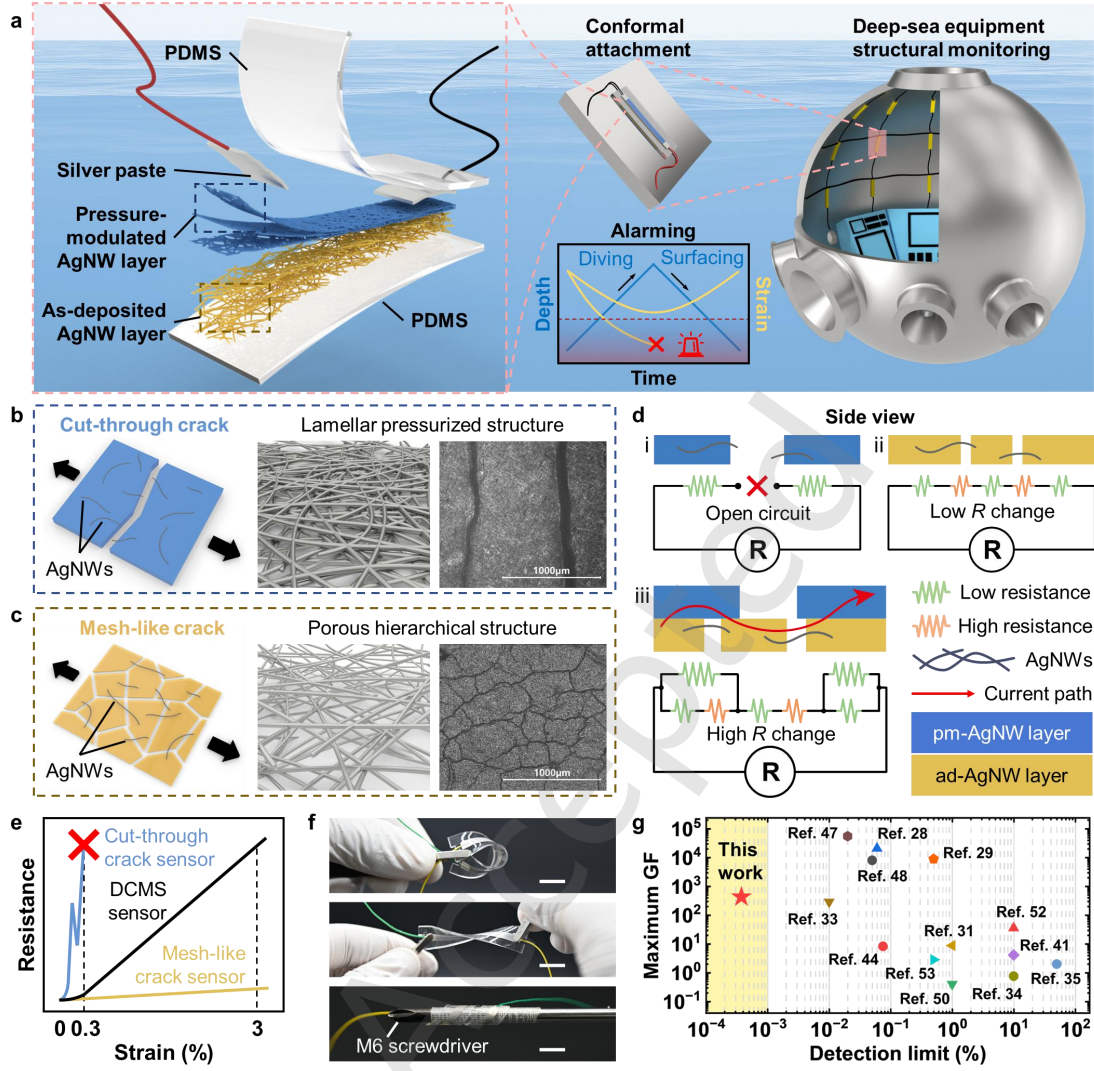


Figure 1 Ultrasensitive stretchable strain sensor based on a scalable, conductive bilayer design. (a) Schematic illustration showing the structure of the DCMS sensor and the integration on the surface of deep-sea equipment. Morphologies and mechanisms of (b) the cut-through crack and (c) mesh-like crack configurations; insets in (b) and (c) show the corresponding optical microscopy images of the two types of cracks. (d) Dual-crack conductive bilayer operating principle. (e) Schematic illustration of the cut-through crack sensor, mesh-like crack sensor, and DCMS sensor. (f) Photos of the DCMS sensors demonstrate their high mechanical compliance during bending, twisting, and conformal adhesion when attached to an M6 screwdriver. Scale bar: 1 cm. (g) Comparison of the DCMS sensor with other resistive stretchable strain sensors [28, 29, 31, 33-35, 40, 41, 44, 47, 48, 52, 53] in terms of detection limit and sensitivity. Abbreviations: AgNW, silver nanowires; ad-AgNW, as-deposited silver

nanowires; pm-AgNW, pressure-modulated silver nanowires; DCMS, dual-crack modulated strain; PDMS, polydimethylsiloxane.

3.2 Fabrication and characterization of the ultrasensitive DCMS sensor

The DCMS sensor was fabricated through a layer-by-layer assembly process, enabling control over the deposition of the AgNW network (**Figure 2a**, details in **Experimental Section**). Briefly, the facile process begins by applying pressure to a portion of the deposited AgNW network (pm-AgNW), followed by drop-casting another AgNW solution on top and drying it *in situ* to form a non-pressurized network (ad-AgNW). This one-step pressurization process requires no customized equipment or complex modification, allowing it to be directly applied to other conductive nanowire/elastomer systems. Furthermore, full encapsulation with a stretchable PDMS substrate was employed to ensure mechanical integrity and protect the sensitive components from degradation, thereby enhancing the sensor's durability under operational stresses.

The obtained DCMS sensor features a well-defined layered structure, as shown in the cross-sectional scanning electron microscopy (SEM) image (**Figure 2b**). The pm-AgNW networks demonstrate enhanced interlayer compactness, leading to a higher density of nanowire junctions and significantly improving the overall electrical conductivity. The intimate contact formed between the ad-AgNW and pm-AgNW layers during casting effectively prevents interlayer delamination. Energy-dispersive X-ray spectroscopy (EDS) analysis further confirmed that both pm-AgNW and ad-AgNW layers are fully embedded within the stretchable PDMS substrate, forming an integrated structure that significantly enhances sensor stability. The corresponding full EDS spectrum is consistent with the expected chemical composition of the material (**Figure S3**).

To investigate the effect of applied pressure on morphology, the surface topographies of pressurized and non-pressurized bilayer AgNW networks were characterized by atomic force microscopy (AFM; **Figure 2c**) and SEM (**Figure S4**), and the measured root mean square roughness values of AgNW layers are provided

(**Figure 2d**). The surface roughness of the AgNW layers significantly decreased after pressing, from 337.9 to 76.1 nm. Under identical testing conditions, we evaluated the stress evolution during stretching for sensors comprising pure PDMS, PDMS with pm-AgNWs, and PDMS with ad-AgNWs (**Figs. S5 and S6**). Tensile stress–strain curves derived from these measurements were used to determine key mechanical properties, including Young’s modulus, tensile strength, elongation at break, and toughness (see **Table S2**). The results indicate that the incorporation of AgNWs into PDMS reduces the fracture strain but significantly enhances the tensile strength, Young’s modulus, and toughness. Furthermore, sensors fabricated with only pm-AgNW layers exhibit an increased tensile strength and Young’s modulus compared with those of their non-pressurized counterparts, contributing to their ultra-high sensitivity.

To maximize the sensitivity, sensing range, and output stability of the DCMS sensor, two critical parameters—the layer ratio of pm-AgNW and ad-AgNW (X:Y) and the curing agent-to-base ratio of the PDMS substrate (A:B)—were optimized (**Figure 2e**). Because the pm-AgNW and ad-AgNW layers exhibit distinct electrical responses under tensile strain, adjusting their relative proportion within the conductive network directly governs the overall sensing performance. A series of sensors with varying conductive layer ratios was fabricated and subjected to a consistent small-strain cycle (0%–3%) with the tensile strain rate maintained at 1%/min. The sensitivity increased with the proportion of pm-AgNW layers (**Figure 2f**). Specifically, the sensor with a 9:3 layer ratio exhibited an average GF of ~430 within the 0–3% strain range (**Figure S7**), representing an improvement of approximately 1,400% compared with the maximum GF of 30 for the 0:12 sensor, which contained no pressurized layers. In contrast, sensors containing only pm-AgNW conductive layers (X:Y = 12:0) fractured at approximately 0.288% strain (**Figure S8**).

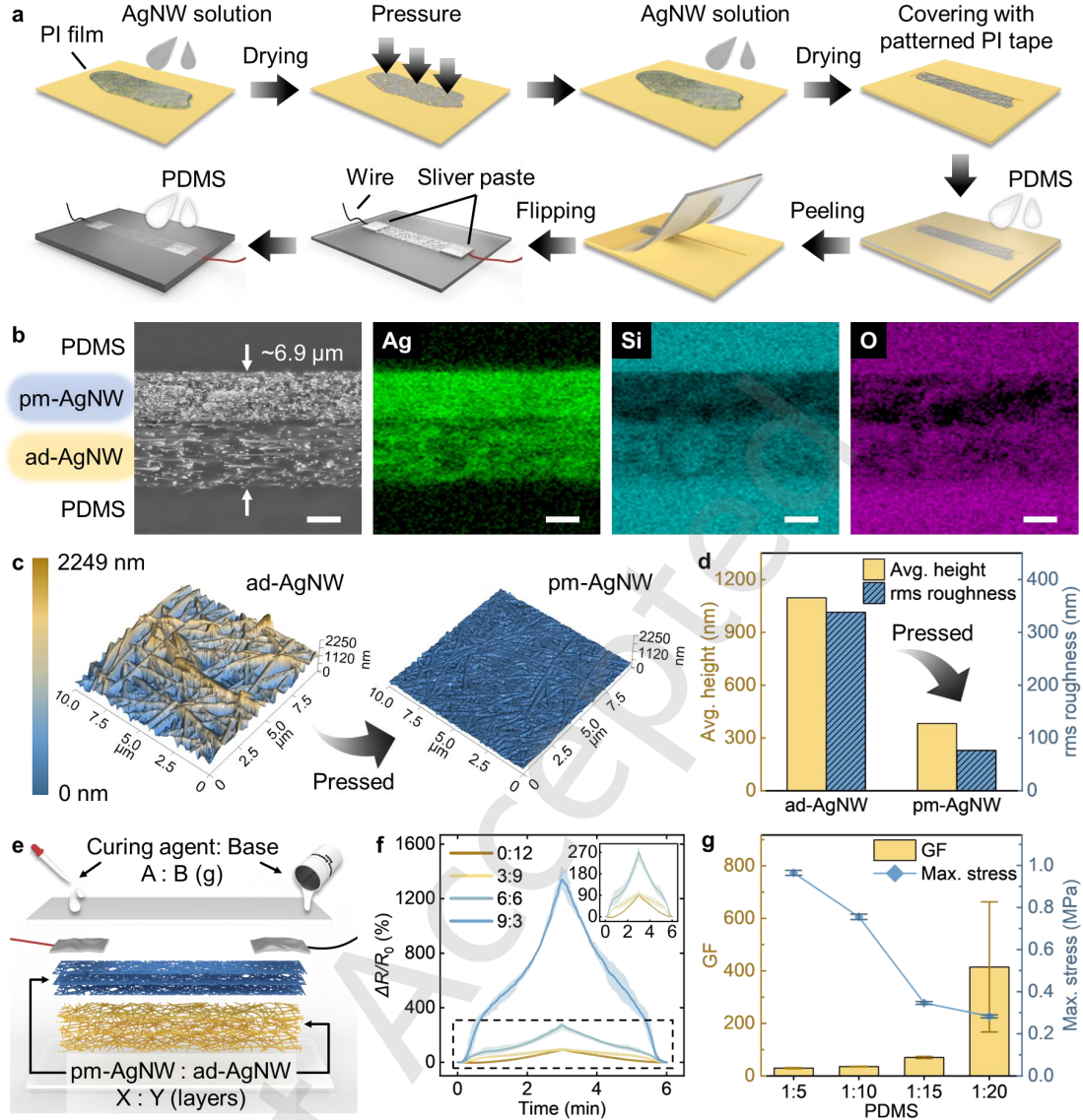


Figure 2 Fabrication, morphology characterization, and parameter optimization of the ultrasensitive DCMS sensor. (a) Fabrication process of the DCMS sensor. (b) Cross-sectional SEM image and EDS element maps of Ag, O, and Si in the DCMS sensor. Scale bar: 2 μm . (c) AFM images of the as-deposited and pressurized AgNW networks. (d) Comparison of average height and roughness of AgNW networks before and after pressurization. (e) Two critical parameters affecting sensor performance: the ratio of PDMS base and curing agent, and the ratio of the two AgNW layers. (f) 3% tensile-release tests of the DCMS sensor at a speed of 1%/min, according to the different X:Y ratios. (g) The sensitivity and maximum stress of the DCMS sensor at 3% strain, for different A:B ratios. Abbreviations: EDS, energy-dispersive X-ray spectroscopy; GF, gauge factor; PI, polyimide; SEM, scanning electron microscopy.

Similarly, varying the PDMS encapsulation formulation A:B significantly influenced sensor performance, which is attributed to changes in the crosslinking density and mechanical modulus of the elastomer [63]. For sensors of the same thickness, a decrease in the curing agent content led to increased sensitivity and reduced mechanical stress (**Figure 2g**). However, sensors with a PDMS ratio of 1:20 exhibited unstable response behavior during stretching and releasing cycles (**Figure S9 and S10**). Unless otherwise specified, all subsequent sensors were fabricated using a PDMS curing agent-to-base ratio (A:B) of 1:15 and a pm-AgNW to ad-AgNW layer ratio (X:Y) of 9:3.

3.3 Performance analysis of the ultrasensitive DCMS sensor

To evaluate the high-gain sensing performance of the DCMS sensor within the 1% small-strain range, the sensor was mounted on a universal testing machine and subjected to various strain inputs (**Figure 3a**). Under a frequency of 0.5 Hz and corresponding cyclic strains ranging from 0.1% to 1%, the DCMS sensor exhibited repeatable and stable relative resistance variations (**Figure 3b**), reaching a sensitivity (GF) of approximately 300 at 1% strain. The response speed is a critical factor determining the sensor's performance under external forces. Frequency-dependent performance was investigated at 0.5% strain across frequencies of 0.1, 0.3, 0.5, 0.8, and 1 Hz (**Figure 3c**). The sensor demonstrated consistently rapid response signals with high reproducibility, confirming its high efficiency in adapting to dynamic strains across a broad frequency range. Under different microstrains, the cyclic variations in the relative resistance of the DCMS sensor were characterized (**Figure 3d**). The sensor exhibits an ultralow strain detection limit of 0.0003365% (3.365 $\mu\epsilon$), outperforming most reported stretchable strain sensors in the literature (**Figure 1g**). This level of high precision in detecting ultrasensitive strain changes highlights the potential of the DCMS sensor in a wide range of highly sensitive applications. Cyclic tensile tests were conducted across a strain range of 0%–0.5% (**Figure 3e**), demonstrating the durability over 5,000 stretch–release cycles. Long-term testing revealed high stability in both the peak and baseline resistance, indicating the

mechanical robustness and electrical reliability. Moreover, the stretch–release curves exhibit minimal hysteresis throughout all stages of cyclic testing (**Figure 3f**). To quantify the electrical hysteresis, the degree of hysteresis (DH) is defined as (**Eq. (2)**) [64]:

$$DH = \frac{|A_S - A_R|}{A_S} \times 100\% \quad (2)$$

where A_S and A_R are the areas under the loading and unloading curves, respectively. The DCMS sensor shows a low hysteresis value of less than 4.9% during stretch–release cycles, thus supporting durable and reliable dynamic operations.

The detailed strain response of the sensor, showing the variation in impedance Z with measurement frequency under pre-strains of 0%, 0.2%, and 0.5%, is illustrated in **Figure 3g**. At measurement frequencies below $\sim 10^5$ Hz, the impedance remains relatively constant and independent of frequency, which is primarily attributed to the ohmic resistance of the conductive network. Beyond this threshold, a marked increase in impedance is observed for all pre-strain levels, owing to the growing contribution of capacitive reactance. Notably, applying the pre-strain resulted in an upward shift of the entire impedance curve. This indicates that stretching disrupted portions of the conductive network, increasing the overall electrical resistance; nevertheless, the fundamental transition from a resistive to a capacitive-dominated response remained unaffected. The dynamic impedance response of the sensor to a 0.5% cyclic strain was investigated at three distinct measurement frequencies: 100 Hz, 10 kHz, and 1 MHz (**Figure 3h**). Despite the baseline resistance drift at 1 MHz, the cyclic response remains stable at all three frequencies, verifying the reliable and frequency-insensitive dynamic sensing capability of the DCMS sensor under small-strain conditions. Collectively, these results demonstrate that the DCMS sensor features ultrahigh sensitivity, an ultralow detection limit, low hysteresis, frequency insensitivity, and long-term durability, highlighting its strong potential for practical high-precision small-strain monitoring.

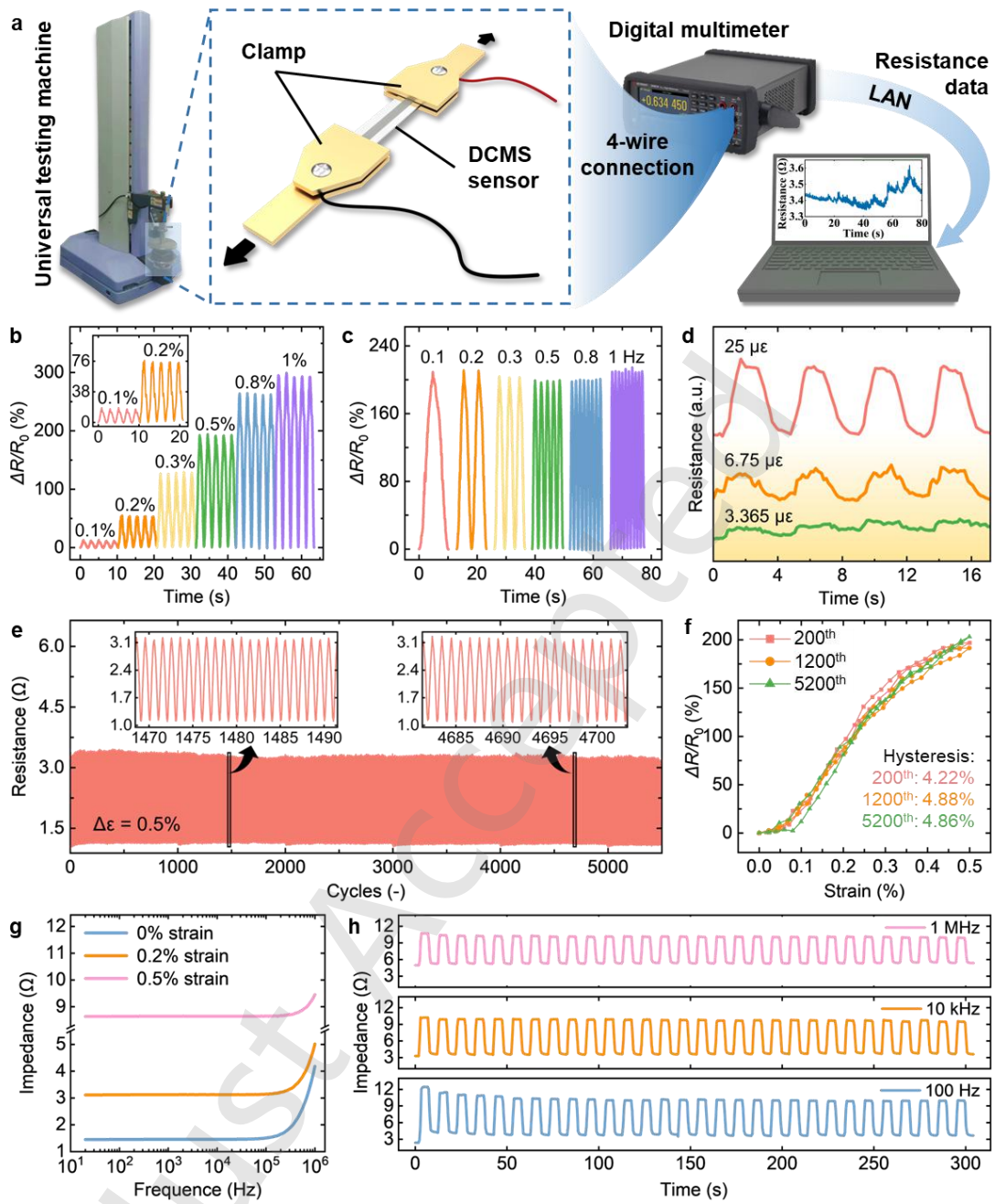


Figure 3 Strain-sensing performance of the ultrasensitive DCMS sensor. (a) Schematic illustration of the DCMS sensor being stretched during measurements. (b) Relative resistance changes during multiple cyclic tensile tests under different strains. (c) Relative resistance changes during 0.5% tensile strain tests under different frequencies. (d) Relative resistance changes with ultralow strain applied and released on the sensor. (e) Long-term durability of the DCMS sensor tested with 0.5% strain. Almost identical responses are well maintained for over 5,000 cycles. (f) The curves of the DCMS sensor at the 200th, 1,200th, and 5,200th cycles. (g) Electrochemical

impedance spectroscopy of the DCMS sensor under various static strain levels (0%, 0.2%, and 0.5%). (h) Time-dependent impedance response of the sensor under cyclic stretching at a constant strain amplitude of 0.5%, measured at different frequencies. Abbreviation: LAN, local area network.

3.4 Underwater application of the DCMS sensor

Leveraging complete PDMS encapsulation, water penetration into the conductive layer is effectively suppressed, thereby preventing unstable signal outputs. This design imbues the DCMS sensor with high water resistance, enabling reliable small-strain monitoring in deep-sea equipment and underwater infrastructure. The sensor was affixed to an acrylic plate and immersed in water for continuous resistance monitoring (**Figure 4a**). Even after 800 h, the sensor exhibited no significant performance degradation (**Figure 4b**). The underwater sensing performance was further validated through underwater bending tests (**Figure 4c**). A titanium alloy plate with the attached sensor was submerged and subjected to multiple forward and reverse bending cycles. Throughout the testing period, the DCMS sensor accurately tracked the applied strain over numerous cycles in both directions (i.e., multiple cycles of tension-relaxation and compression-relaxation), confirming its robustness under simultaneous mechanical deformation and environmental exposure to water (**Figure 4d**).

A submerged disturbance monitoring test was performed to further validate the ultrahigh sensitivity of the DCMS sensor to underwater small-strain signals. The sensor was mounted on a cantilever beam using double-sided adhesive tape. Then, the beam was vertically fixed at the bottom of a water tank, with one end clamped and the other (free end) remaining above the water surface, while the sensor was fully submerged (**Figure 4e**). Individual water droplets (~25 mg each) were released from a height (H) of 15 cm, and the sensor's response to disturbances was tested by varying the lateral distance ($D = 5, 10, \text{ and } 20 \text{ cm}$) that the droplet was released from the beam. The waves generated upon droplet impact induced displacement of the cantilever beam, leading to a sharp increase in the sensor's resistance, and the magnitude of the

resistance change increased as the droplet-release distance (D) decreased (**Figure 4f**). Furthermore, the impact produced an upward recoiling jet [65], whose breakup and subsequent fallback of secondary droplets onto the water surface excited a second wave (**Figure S11** and **Movie S1**). This secondary wave was distinctly recorded as a subsequent resistance peak in the sensor signal (**Figure 4g**). Analysis of the temporal response revealed an interval of approximately 0.9 s between the two peaks corresponding to the primary and secondary waves.

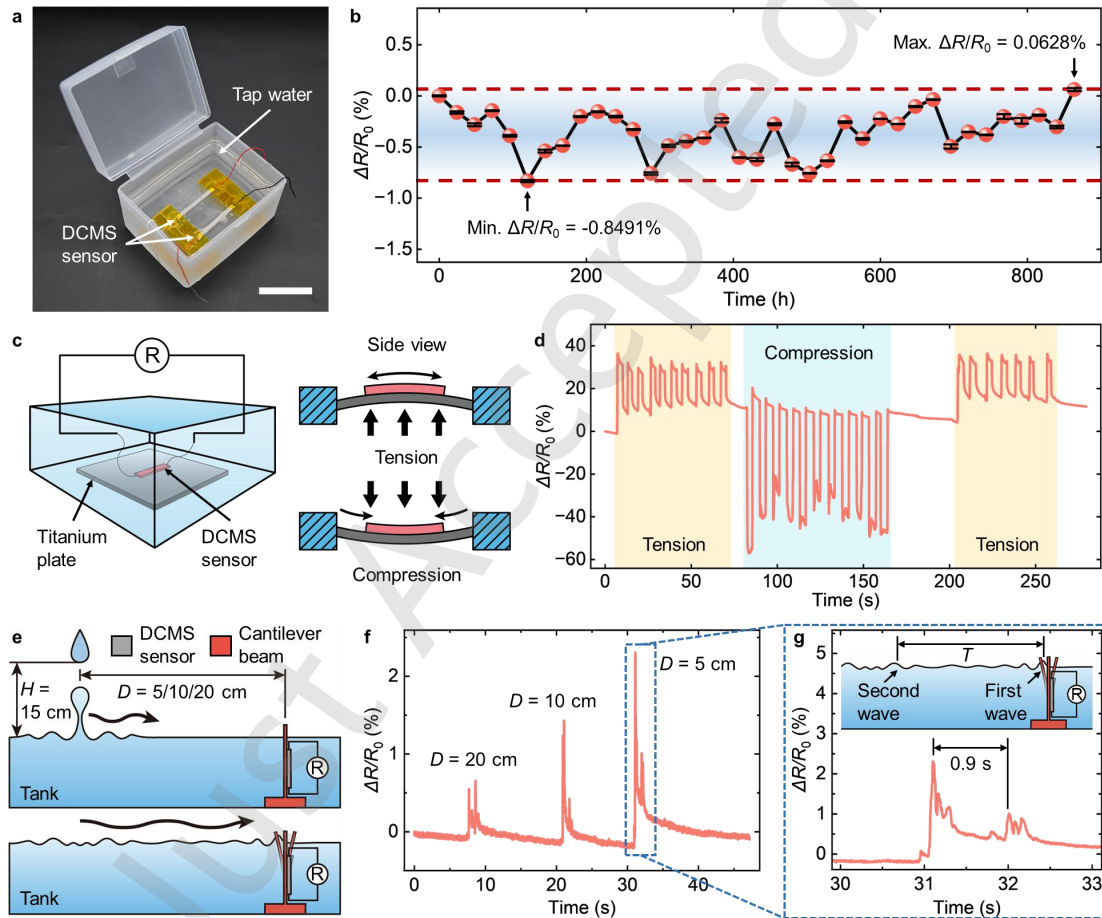


Figure 4 Underwater application of the DCMS sensor. (a) Photograph of the DCMS sensor submerged in water. Scale bar: 4 cm. (b) Variation in relative resistance of the DCMS sensor during 864 h of continuous water immersion. (c) Schematic diagram of the DCMS sensor used for titanium alloy plate deformation detection in water. (d) Sensor performance during underwater bending cycles. (e) Schematic diagram of the DCMS sensor used for single droplet disturbance detection. (f) Sensor response to water droplets impacting the surface at varying distances. (g) Temporal response of

the sensor capturing both primary and secondary waves. Abbreviations: D , the lateral distance between the droplet and the beam; H , the height of the droplet above the water surface.

3.5 Deep-sea equipment strain monitoring system based on the DCMS sensor

Benefiting from ultrahigh sensitivity, an ultralow detection limit, and high durability, we demonstrate the sensor's capability for monitoring small compressive strains during the submergence of deep-sea equipment (**Figure 5a**), which is subjected to hydrostatic pressures up to 110 MPa, resulting in a small strain of $\sim 0.7\%$ [13, 66]. As a proof of concept, the sensor was conformally attached to the interior surface of a cylindrical titanium alloy pressure capsule for *in situ*, real-time monitoring; the capsule was then placed into a hydrostatic pressure chamber for simulated deep-sea testing. An overview of the entire testing system is provided (**Figure 5b(i)**), with a close-up image indicating the deployment of sensors aligned along the circumferential direction of the capsule (**Figure 5b(ii)**). For comparative verification, a commercial strain gauge was installed at the same height near the DCMS sensor.

A data acquisition system featuring a modular architecture is integrated with the titanium alloy capsule to enable real-time signal recording (**Figure 5b(iii)**), with its internal configuration detailed in **Figure 5c**. Simultaneously, an RBR $duet^3$ T.D sensor (rated for 6,000 m depth) was installed inside the test environment to record real-time pressure and temperature variations at a sampling rate of 1 Hz. Structural health monitoring was accomplished by recording the DCMS sensor's resistance variations and correlating them with the pre-calibrated resistance–strain relationship.

To establish a theoretical baseline for comparison with experimental measurements, the deformation of the titanium alloy capsule under hydrostatic pressure was simulated (**Figure 5d**). The uniform pressure applied to the capsule is set at 50 MPa to simulate the hydrostatic pressure at a target depth of approximately 5,000 m. The simulated strain distribution shows that the maximum circumferential strain is located 144 mm from the capsule end-cap, with a value of -0.180% , whereas the axial strain at the same location is only approximately -0.011% (see **Figure S12**),

which is negligible. The sensors were installed at 134 mm from the end-cap, where the simulated circumferential strain is approximately -0.177% .

The titanium alloy capsule was tested with a loading and unloading speed of 2 MPa/min, recorded using the RBR sensor. During pressure loading, the capsule underwent deformation, and the maximum compressive strain measured by the commercial strain gauge was -0.121% (**Figure 5e**), consistent with the theoretical predictions from the finite element simulation. Throughout this process, the DCMS sensor effectively captured the deformation of the capsule wall, and its resistance variation exhibited high temporal synchrony with the signal from the commercial strain gauge. The resistance of the DCMS sensor decreased from an initial value of 1.68 to 1.30 Ω under pressure, remained stable during the holding phase (see the inset in **Figure 5e**), and finally recovered to 1.71 Ω upon unloading.

Additionally, data points collected every 10 MPa during the unloading stage were plotted against the commercial strain gauge readings (**Figure 5f**). The resulting GF was calculated to be 231.68, which is lower than the value obtained under laboratory conditions. This discrepancy arises because the laboratory-measured GF was determined under ideal uniaxial tensile conditions, where the sensor was clamped only at the ends. In practical deployment, however, the sensor is fully bonded to the curved capsule wall using adhesive. Non-uniformity in the adhesive thickness significantly reduces strain transfer efficiency and consequently lowers the sensitivity of the DCMS sensor. Moreover, the noise level and SNR were evaluated during different steady phases of the test (pre-test, pressure-hold, and post-test; **Figure 5g**), calculated by following formulars (**Eq. 3 and 4**):

$$SNR = 20 \log_{10} \left(\frac{\Delta R}{\sigma} \right) \quad (3)$$

$$\sigma = \sqrt{\frac{1}{N-1} \sum (R_i - \mu)^2} \quad (4)$$

where $\Delta R=0.403 \Omega$ was the resistance change induced by the 50 MPa pressure, σ was the standard deviation of the resistance signal in each stage, and μ was the mean resistance in each stage. The post-test phase exhibited the lowest noise floor

(approximately 1.225 mΩ), with a corresponding SNR of 50.44. This low noise floor and high SNR conclusively demonstrate the high durability and robustness of the integrated sensing system, confirming its capability for monitoring small structural deformations in deep-sea equipment.

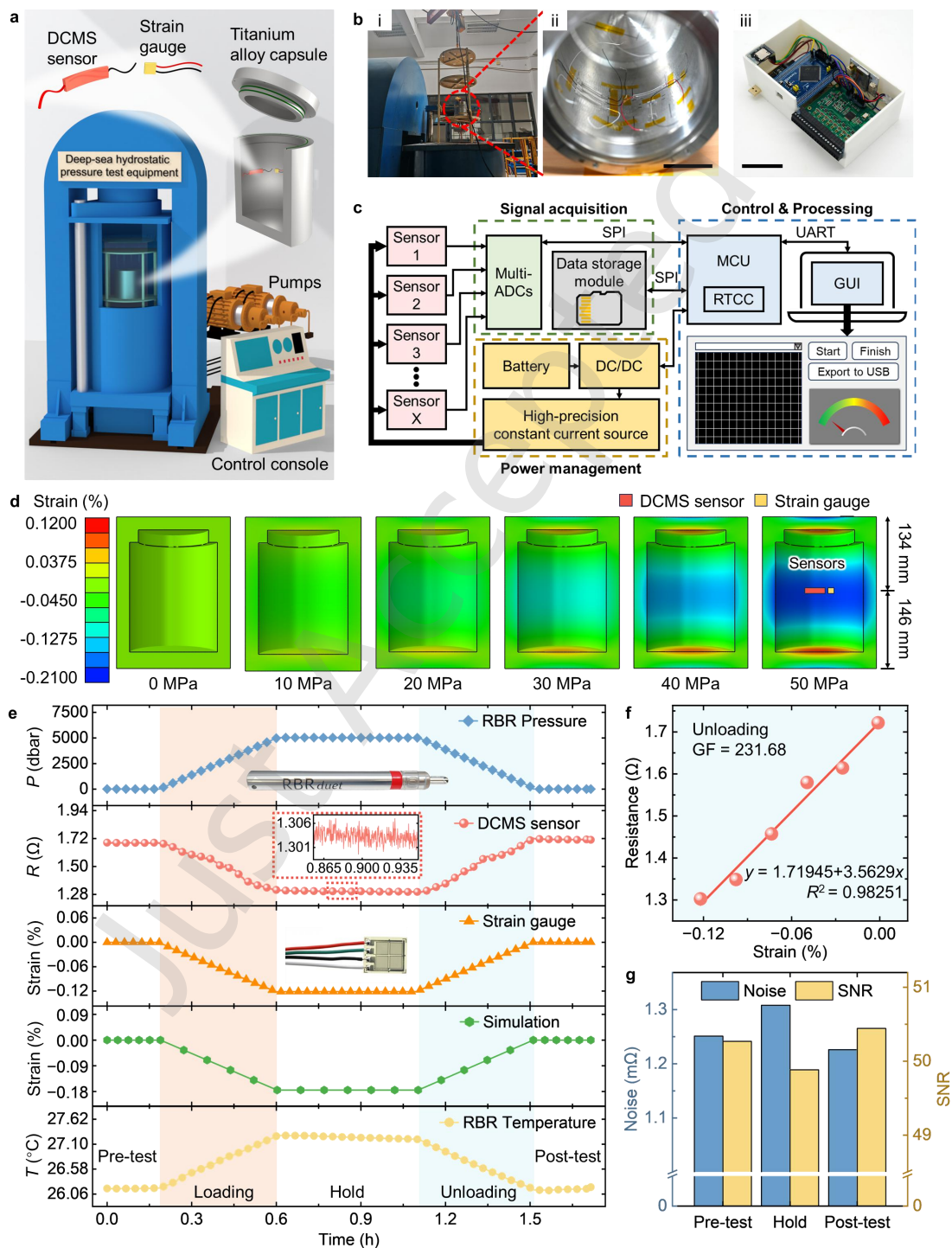


Figure 5 Deep-sea capsule deformation monitoring via a DCMS sensor-based system.

(a) Schematic illustration of a DCMS sensor used for structural health monitoring of

deep-sea equipment. (b) Photographs of (i) the DCMS sensor tested in deep-sea hydrostatic pressure test equipment, (ii) the DCMS sensor attached inside the titanium alloy capsule, and (iii) the data acquisition system. Scale bar: 5 cm. (c) Block diagram of the modular data acquisition system. (d) Simulation results of the titanium alloy capsule under 50 MPa seawater pressure. (e) Recorded data during the test, including hydrostatic pressure, electrical resistance of the DCMS sensor, strain measured by the commercial strain gauge, simulated strain from finite element analysis, and ambient temperature. (f) Sensor output versus the strain measured using a strain gauge at 10 MPa intervals during the unloading stage. (g) Noise and SNR of the system at different stages. Abbreviations: ADC, analog-to-digital converter; GUI, graphical user interface; MCU, microcontroller unit; RBR, RBR^{duet}³ T.D sensor; RTCC, real-time clock and calendar; SNR, signal-to-noise ratio; SPI, serial peripheral interface; UART, universal asynchronous receiver/transmitter.

4 Conclusions

This study describes a universal structural design strategy for the fabrication of resistive DCMS sensors, providing an ultrasensitive and robust strain-sensing platform for small-strain monitoring. Our approach leverages a simple and effective pressurization process to tailor the morphology of deposited AgNW networks, yielding a configuration that is distinct from as-deposited AgNW networks. The compact layer is susceptible to cut-through cracking, which abruptly ruptures dominant conductive pathways and enables high-gain responses, whereas the porous layer forms mesh-like cracks that progressively degrade auxiliary conductive pathways under tensile strain while maintaining robust mechanical stability. This synergistic combination facilitates a rapid and stable increase in electrical resistance under small strains, endowing the DCMS sensor with ultrahigh sensitivity ($GF \approx 430$), an ultralow detection limit ($3.365 \mu\epsilon$), and high durability (capable of withstanding over 5,000 tensile cycles). The outstanding performance of the DCMS sensor arises not from the AgNW/PDMS system alone, but from the performance enhancement enabled by the generalizable dual-crack structure. This design effectively amplifies

the resistance response to small-strain inputs, offering a general strategy to surpass existing performance benchmarks in small-strain sensing.

Building upon the advantageous properties of the DCMS sensor, we demonstrated an integrated sensing system by combining the sensor with a custom, modular data acquisition system, enabling real-time, *in situ*, and high-SNR (> 50 dB) monitoring for deep-sea equipment under extreme hydrostatic pressures (50 MPa). This system provides reliable detection of structural deformations in deep-sea equipment, addressing the challenges of poor conformability to complex geometries, limited sensitivity to small strains, and susceptibility to environmental noise that plague conventional strain monitoring methods. The DCMS-based platform offers a powerful solution for preventing catastrophic failures and extending the service life of critical deep-sea equipment. Furthermore, the proposed dual-crack design principle and facile pressure-tuning strategy can be readily adapted to a wide range of other metal nanowire materials, as their morphologies can also be modulated by pressure. Such ultrasensitive strain sensors are applicable to numerous small-strain sensing fields, including aerospace structures, precision manufacturing, and biomedical engineering, where ultrahigh sensitivity, conformability, and environmental resilience are equally essential.

Electronic Supplementary Material: Supplementary material (AgNW network morphology, SEM images of cut-through and mesh-like cracks, EDS analysis of DCMS sensor, SEM images of ad-AgNW and pm-AgNW networks, tensile stress–strain curves comparison, the sensor before and after tensile test, segmented GF of the resistance-strain curve, tensile-release test results of DCMS sensor with different parameters, photos of droplet disturbance detection test, finite element method simulations) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909123>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

Zhuhan Dai: conceptualization, data curation, formal analysis, investigation, methodology, validation, original draft writing, and manuscript revision. Hai Zhang and Guorui Zhong: methodology. Chenjing Shang, Wanli Li, and Yaxiaer Yalikun: manuscript revision. Yang Yang: conceptualization, funding acquisition, investigation, project administration, resources, supervision, and manuscript revision.

Use of AI statement

None.

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Electronic Supplementary Material

A universal and facile design strategy for ultrasensitive strain sensors with a 3.365 $\mu\epsilon$ detection limit

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This PDF file includes:

Figure S1. AgNW network morphology at the same location under 0% strain, captured from the top view and bottom view, respectively.

Figure S2. SEM images for different crack morphologies under 0% strain.

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Figure S10. The stress experienced by the DCMS sensor during the 3% stretching test process, according to the different A:B ratio: (a) 1:5, (b) 1:10, (c) 1:15, and (d) 1:20.

Figure S11. Photos of DCMS sensor using for single droplet disturbance detection.

Figure S12. Simulation of titanium alloy capsule under 50 MPa hydrostatic pressure.

Table S1. Comparison of the proposed DCMS sensor with various resistive stretchable sensors in the literature.

Table S2. The key mechanical properties of pure PDMS (w/o AgNW), PDMS with pm-AgNWs, and PDMS with ad-AgNWs

Supplementary References

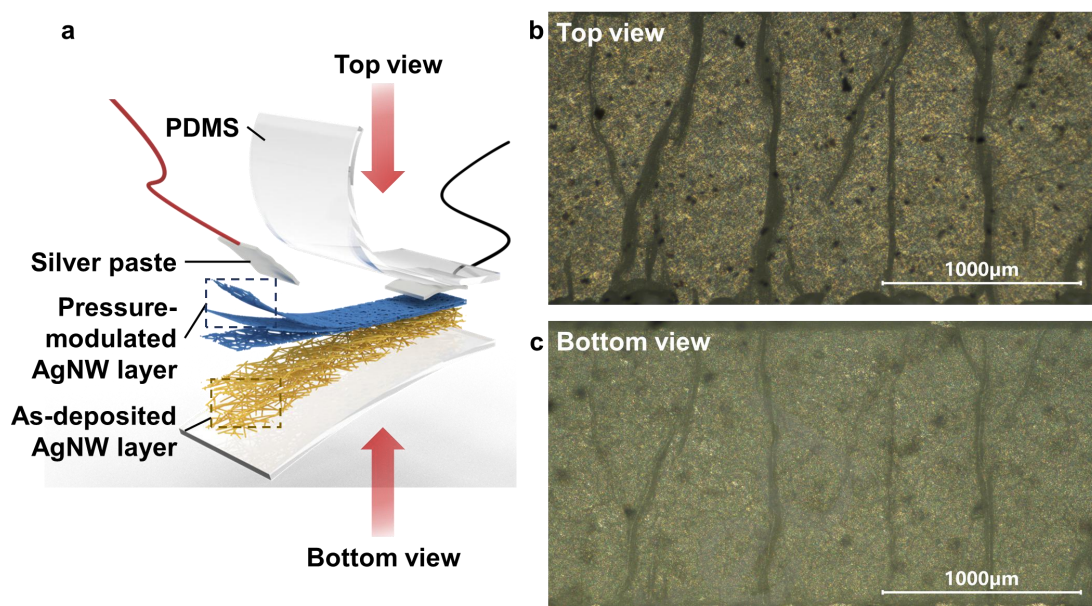


Figure S1. AgNW network morphology at the same location under 0% strain, captured from the top view and bottom view, respectively. (a) Schematic of imaging angles; (b) Top-view image: the pm-AgNW layer is directly facing the camera, showing a flat and reflective surface, where only cut-through cracks are visible; (c) Bottom-view image: both mesh-like cracks and cut-through cracks can be observed simultaneously.

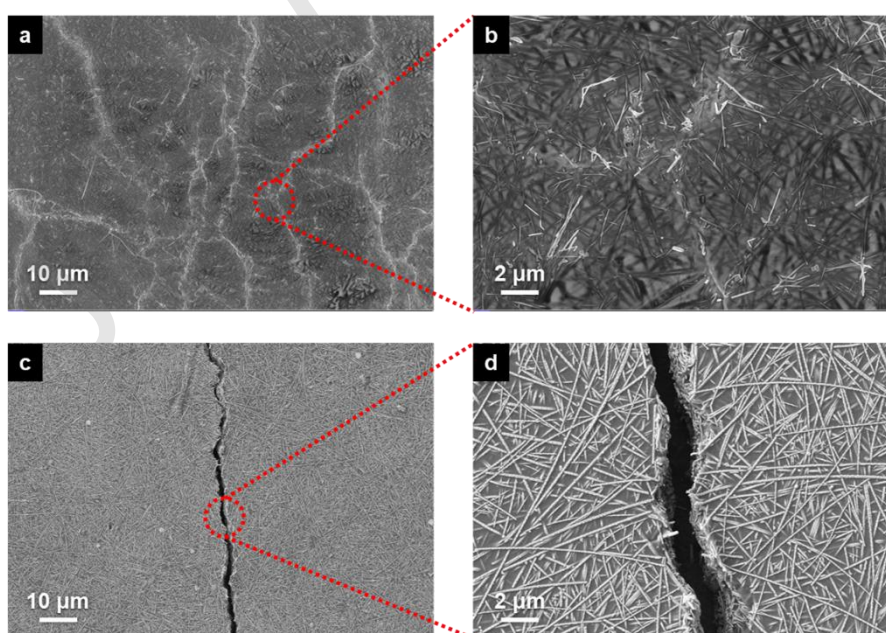


Figure S2. SEM images for different crack morphologies under 0% strain. (a) and (b) show the morphology of mesh-like cracks at magnifications of 1000× and 5000×,

respectively; (c) and (d) show the morphology of cut-through cracks at magnifications of 1000 $\times$ and 5000 $\times$, respectively. Different detectors were used to reveal clear details: (a) and (b) were acquired using the InLens detector, while (c) and (d) were acquired using the SE2 detector.

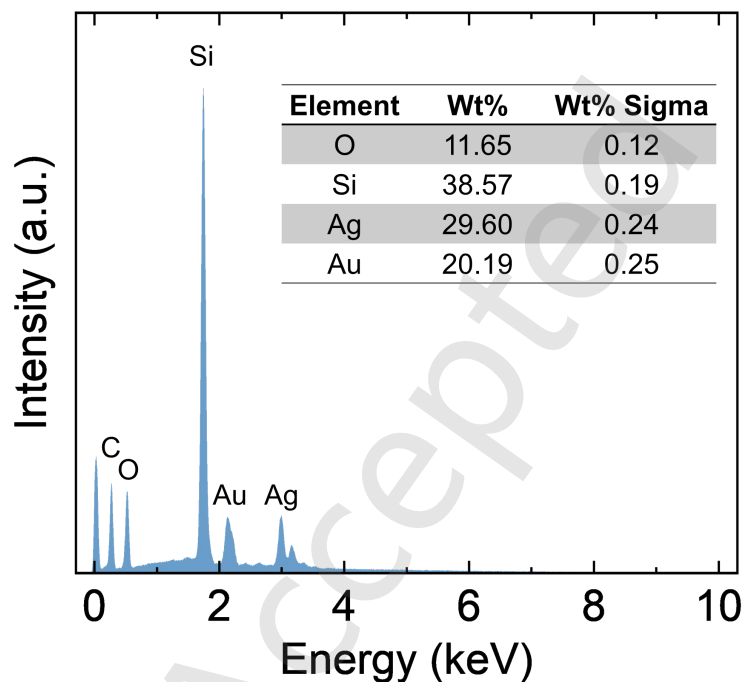


Figure S3 EDS pattern of the cross-section of the DCMS sensor. Abbreviations: EDS, energy-dispersive X-ray spectroscopy; DCMS, dual-crack modulated strain; a.u., arbitrary units.

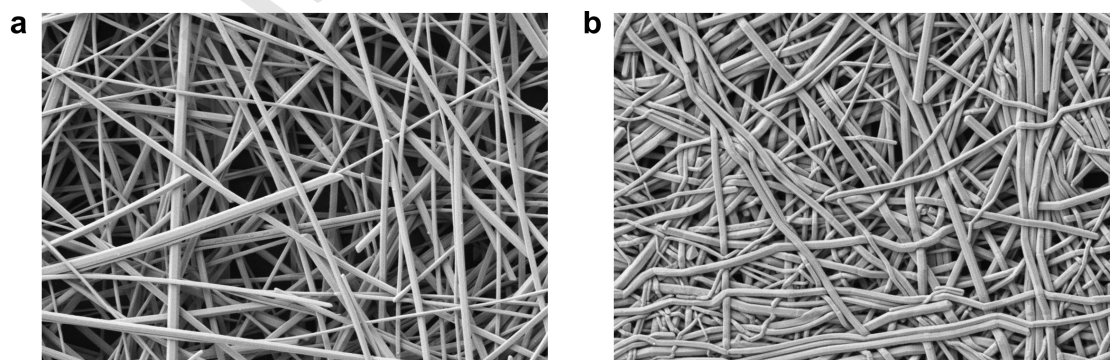


Figure S4 SEM images of the (a) ad-AgNW and (b) pm-AgNW. Abbreviations: pm-AgNW, pressure-modulated silver nanowire; ad-AgNW, as-deposited silver nanowire.

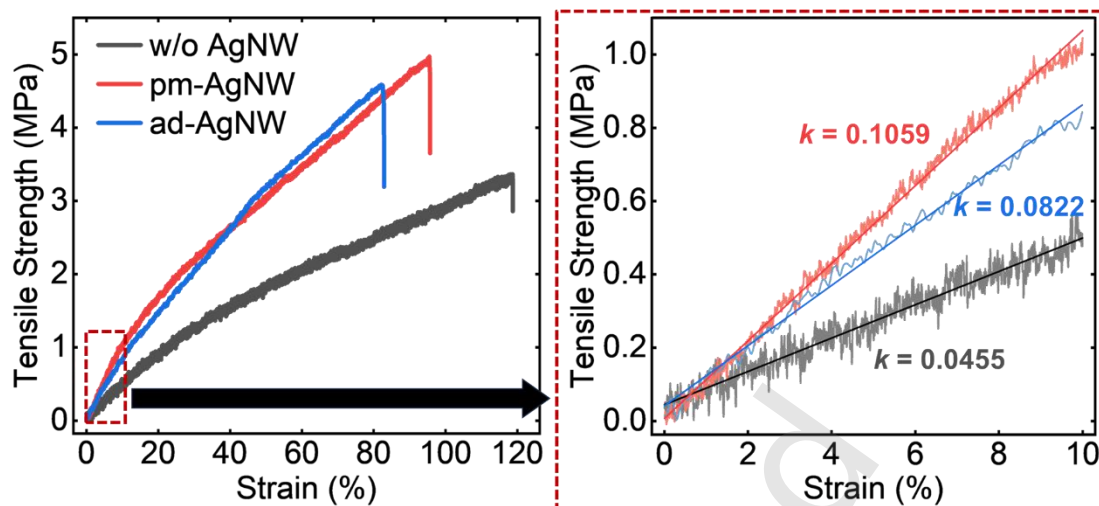


Figure S5 Tensile stress–strain curves of pure PDMS (w/o AgNW), PDMS with pressurized (pm-AgNW) and non-pressurized (ad-AgNW) conductive layers. Abbreviation: PDMS, polydimethylsiloxane.

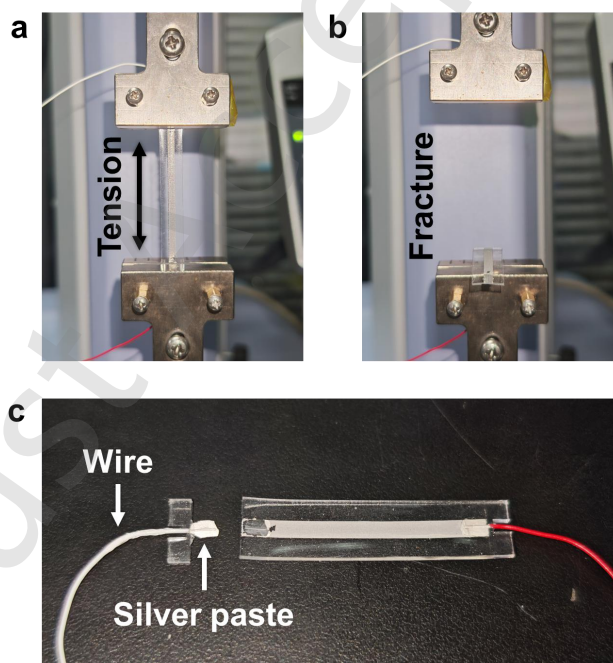


Figure S6 Tensile tests of the DCMS sensor. (a) The sensor during stretching; (b) Fracture of the sensor after reaching its tensile limit; (c) The sensor after fracture. The fracture occurs at the junction between the silver paste and the AgNW network, caused by stress concentration resulting from modulus mismatch.

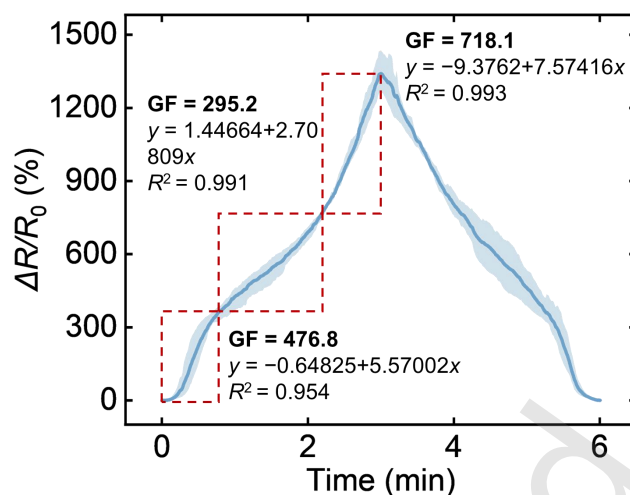


Figure S7 The segmented GF values of the resistance-strain curve for the DCMS sensor with a 9:3 layer ratio. 0–0.696% strain: GF=476.8; 0.696%–2.223% strain: GF=295.2; 2.223%–3% strain: GF=718.1.

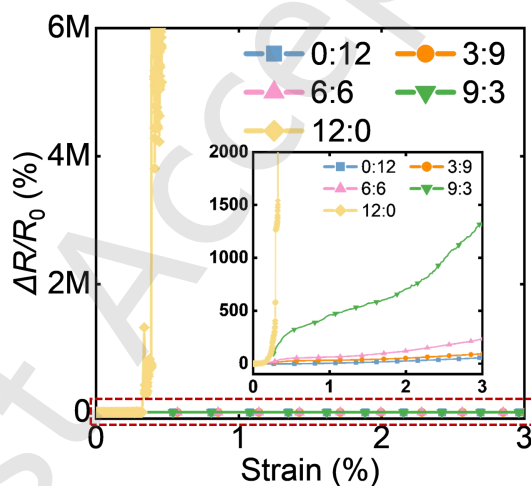


Figure S8 3% tensile-release tests of the DCMS sensor with different pm-AgNW and ad-AgNW (X:Y) ratio. The sensor with only pm-AgNW conductive layers (X:Y=12:0) fractured at approximately 0.288% strain, resulting in a rapid increase in resistance.

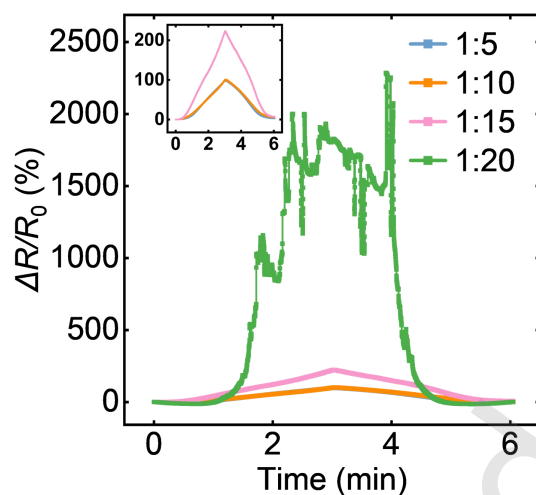


Figure S9 3% tensile-release tests of the DCMS sensor at a speed of 1%/min, according to the different curing agent-to-base ratio (A:B) of the PDMS substrate.

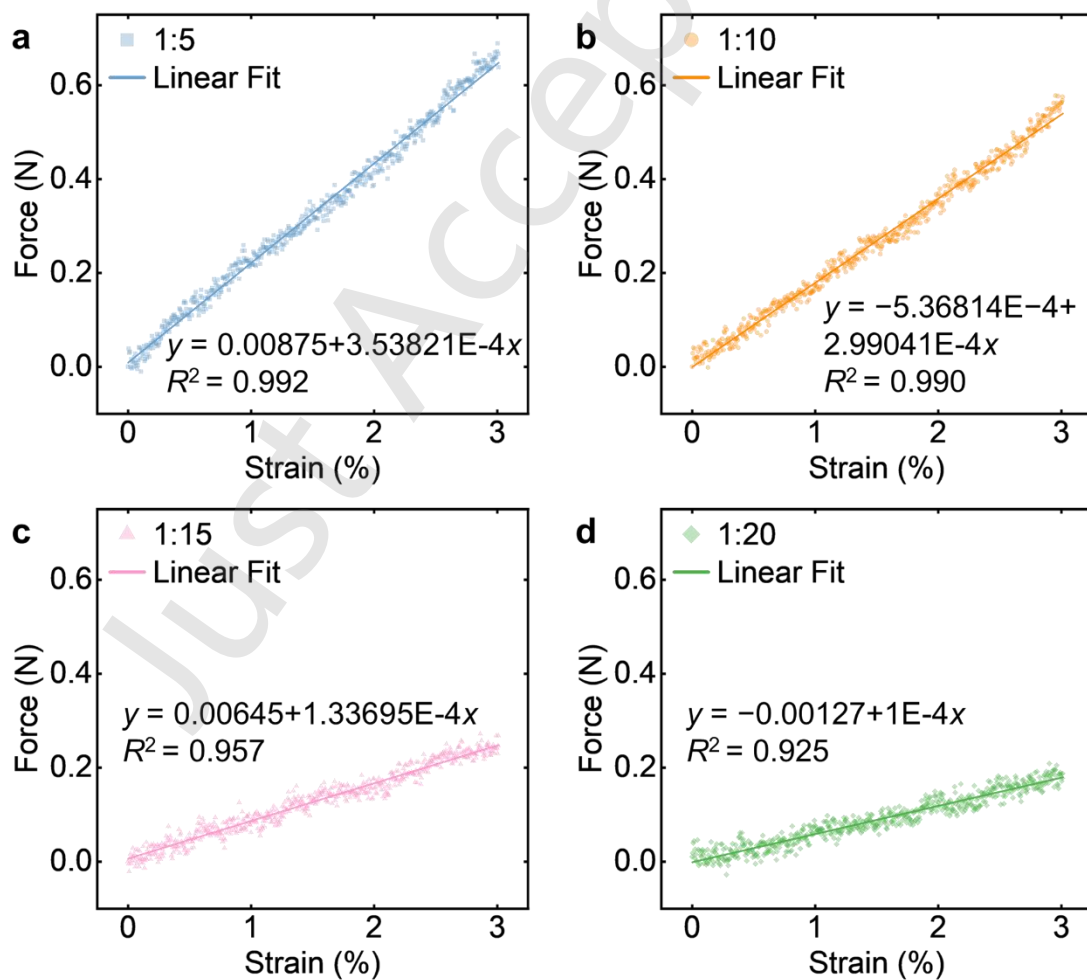


Figure S10 The stress experienced by the DCMS sensor during the 3% stretching test process, according to the different A:B ratio: (a) 1:5, (b) 1:10, (c) 1:15, and (d) 1:20.

As the base content increases, the sensor becomes softer and the variance of the fitting curve gradually increases.

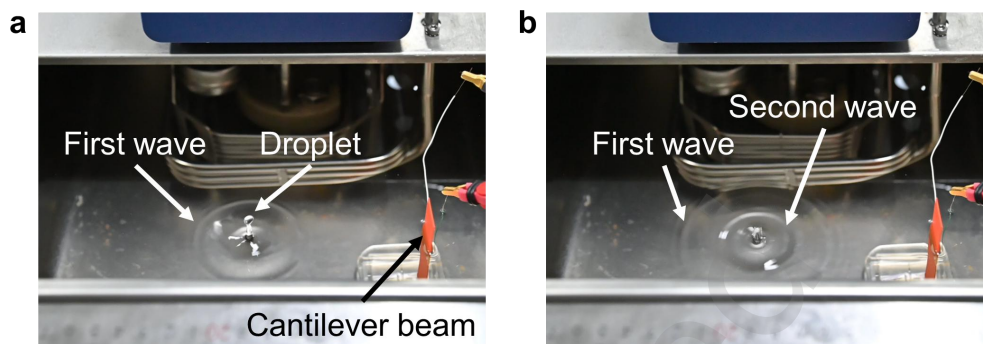


Figure S11 Photos of DCMS sensor using for single droplet disturbance detection. (a) A droplet falls onto the water surface and generates the first wave; (b) As the recoiling jet falls back into the water, a second wave is formed.

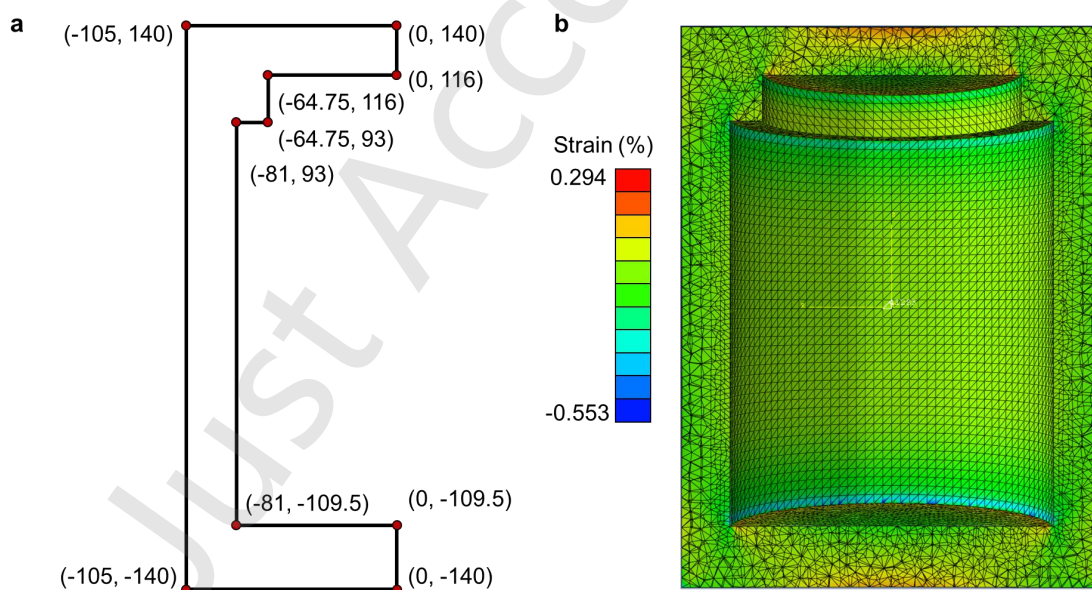


Figure S12 Simulation of titanium alloy capsule under 50 MPa hydrostatic pressure. (a) The cross-sectional dimensions of the titanium alloy capsule used for simulation analysis; (b) The axial strain of titanium alloy capsule under 50 MPa hydrostatic pressure.

Table S1 Comparison of the proposed DCMS sensor with various resistive stretchable sensors in the literature.

Ref.	Material type	Fabrication method	Materials	Max. gauge factor	Detection limit (%)	Strain range (%)
2020[1]	Ceramics	Vacuum filtration	BN	35.7	10	0–160
2021[2]	Polymers	Wet spinning	Polyimide hydrogel fibers	0.76	10	0–100
2021[3]	Hybrid materials	Electrospinning/ ultrasonication	TPU/CB	8962.7	0.5	0-160
2022[4]	Carbons	Friction spinning	CNT	4.13	10	10–160
2022[5]	Gels	Sol-gel method	Iongel	2	50	0–300
2023[6]	Metals	Spin coating	AgNW	290.1	0.01	0-35
2023[7]	Carbons	Micronano fabrication	Carbon	8.81	1	0–200
2024[8]	Hybrid materials	Spraying	Graphene/CNT	8.28	0.075	0–120
2024[9]	Gels	Freeze-thaw	PVA/PSBMA-H ₂ S O ₄	<0.4	1	0-300
2024[10]	Carbons	Dip-coating	CNT	2.84	0.5	0.5–100
2025[11]	Carbons	Scratch coating	CNT	55442	0.02	0–80
2025[12]	Hybrid materials	Dip-coating	Mxene/CNT	8089.7	0.05	0–450

2025[13]	Hybrid materials	Magnetron sputtering	Cr/Ag/Cr	20940	0.06	0-40
This work	Metals	Rolling deformation	AgNW	430	0.000375	0-3

Abbreviations: CNT, carbon nanotubes; PVA, polyvinyl alcohol; PSBMA, poly(sulfobetaine methacrylate); H₂SO₄, sulfuric acid; TPU, thermoplastic polyurethane; CB, carbon black; Mxene, transition metal carbides/nitrides; BN, boron nitride

Table S2 The key mechanical properties of pure PDMS (w/o AgNW), PDMS with pm-AgNWs, and PDMS with ad-AgNWs.

	Tensile strength	Young's modulus (0~10%)	Elongation at break	Toughness
w/o AgNW	3.30	4.55	118.7	2.29
ad-AgNW	4.58	8.22	82.90	2.15
pm-AgNW	4.97	10.59	95.71	2.74

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