

# An Ultrasensitive, Durable and Stretchable Strain Sensor with Crack-wrinkle Structure for Human Motion Monitoring

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## Electronic Supplementary Information

**Abstract** Flexible strain sensor has promising features in successful application of health monitoring, electronic skins and smart robotics, etc. Here, we report an ultrasensitive strain sensor with a novel crack-wrinkle structure (CWS) based on graphite nanoplates (GNPs)/thermoplastic urethane (TPU)/polydimethylsiloxane (PDMS) nanocomposite. The CWS is constructed by pressing and dragging GNP layer on TPU substrate, followed by encapsulating with PDMS as a protective layer. On the basis of the area statistics, the ratio of the crack and wrinkle structures accounts for 31.8% and 9.5%, respectively. When the sensor is stretched, the cracks fracture, the wrinkles could reduce the unrecoverable destruction of cracks, resulting in an excellent recoverability and stability. Based on introduction of the designed CWS in the sensor, the hysteresis effect is limited effectively. The CWS sensor possesses a satisfactory sensitivity ( $GF=750$  under 24% strain), an ultralow detectable limit (strain=0.1%) and a short respond time of 90 ms. For the sensing service behaviors, the CWS sensor exhibits an ultrahigh durability (high stability  $>2 \times 10^4$  stretching-releasing cycles). The excellent practicality of CWS sensor is demonstrated through various human motion tests, including vigorous exercises of various joint bending, and subtle motions of phonation, facial movements and wrist pulse. The present CWS sensor shows great developing potential in the field of cost-effective, portable and high-performance electronic skins.

**Keywords** Polymer nanocomposites; Microstructure; Flexible strain sensor; Human motion monitoring

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## INTRODUCTION

In recent years, flexible strain sensing devices have been increasingly investigated to develop fitness instruction tools, electronic skin-based sensors, and human motion detectors, etc.<sup>[1–7]</sup> For the successful application of flexible strain sensors in wearable devices, health monitors, and electronic skins, the dynamic range and sensitivities of strain measurement devices should be improved, in particular, the gauge factor (GF), which is an important indicator for flexible strain sensor. For health monitors, strains of about ca. 20% should be measurable to detect large deformations, such as the hands or joints motions, while ca. 0.5% to 2% strains should also be detectable when monitoring tiny deformations, for example, the pulse and neck phonatory vibrations.<sup>[3]</sup> Conventional strain sensing devices based on rigid materials such as semiconductor or ceramics typically display high sensitivity, fast response, and high durability.<sup>[8–11]</sup> However, they are severely limited by their

brittleness with a stretchability lower than 5% strain.<sup>[12]</sup> Recent advances have shown conductive nanocomposites with flexible polymer as matrix are highly stretchable.<sup>[13–19]</sup> Zhu *et al.* demonstrated a flexible sensor based on carbon nanotubes (CNTs)/thermoplastic urethane (TPU) composite.<sup>[13]</sup> Despite the ultrahigh stretchability (up to 400%), this composite material exhibited a relatively low GF and a hysteresis effect, limiting its applicability for monitoring subtle movements to some extent. Fu *et al.* fabricated a strain sensing device using CVD-grown graphene on transparent flexible polydimethylsiloxane (PDMS) substrate, achieving a high GF up to 151 but a low strain range (about 5%).<sup>[20]</sup> A new type of sensor combining both a high sensitivity and good stretchability is meaningful. Typically, stretchable and flexible high-strain sensors have been created using ZnO nanowires (NWs) on a flexible polystyrene nanofiber (PSNF) membrane.<sup>[21]</sup> The sensor displays suitable strain ranges (from 0% to 50%) and high sensitivities ( $GF > 100$ ) for the detection of human movements. However, the complicated fabrication process and poor electrical properties limit their large-scale production. Therefore, developing a flexible sensor with ultrahigh mechanosensitivity, low cost, high durability, and simple processing remains highly challenging.<sup>[11,22–38]</sup> To create

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a highly sensitive structure, researchers have asked nature for inspiration. For example, spiders can respond quickly to small vibrations in their webs. The sensory receptor is a crack-based system embedded in their exoskeleton.<sup>[25]</sup> Spiders sense forces via the deformation of cracks in these sensory organs, even when the vibrations are subtle. Inspired by the spider's crack-based sensory system, researchers have developed strain sensors by creating a cracked structure in nanomaterials. When devices are stretched (compressed), the cracks become larger (smaller), leading to an increase (a decrease) in the electro-mechanical responses. However, typical strain sensors based on cracks with ultra-high sensitivity always cannot accommodate for large stretching. For example, Kim *et al.* reported a mechanical crack-based sensor on the basis of polyurethane acrylate and platinum (PUA/Pt) showing a GF up to 2000 but with a limited strain range of only 2%, which held down its implementation for human motion detections.<sup>[34,35]</sup> Furthermore, artificial wrinkles with orientated structure offer fascinating stability for strain sensor. Such wrinkle structures are capable of enduring a large deformation.<sup>[28,29]</sup> Zhu *et al.* fabricated wavy ribbons of CNTs/PDMS stretchable conductors by a pre-stretching method that exhibited a high stretchability (about 100%) and a good stability.<sup>[38]</sup> Roda *et al.* reported a strain sensor by using wrinkled gold films, which presented a high linearity over a maximum applied strain of 140%.<sup>[31]</sup> Sun *et al.* produced a stretchable yarn strain sensor with a wrinkle-assisted crack structure, achieving excellent sensing performances and good stability towards varying deformations.<sup>[32]</sup>

In this work, a flexible strain sensor with a crack-wrinkle structure (CWS) and high sensitivity is fabricated based on graphite nanoplatelets (GNP)/TPU/PDMS. This new CWS was created by subjecting the material to a sequential tension and pressure. Wrinkles, composed of GNPs, were uniformly distributed on the TPU layer, and the cracks were developed with the same orientation of the wrinkles. The strain sensing performance of the sensor was investigated under tension, bending, and compression. The sensor exhibited a high GF (~ 750). A rapid response, a good stretchability, a low-cost together with a good stability were achieved synchronously. The sensing mechanism based on the microstructure change of the cracks and wrinkles was discussed in detail. The sensing device based on our CWS sensor was assembled to detect both the large and subtle human motions.

## EXPERIMENTAL

### Materials

TPU was purchased from Elastollan with a model of 1185A and density of 1.12 g/cm<sup>3</sup>. GNP conductive ink was supplied by Nanjing XFNANO Materials Tech. Co., Ltd. The PDMS was bought with two-part liquid component kits, *i.e.*, base polymer (Kit A) and curing agent (Kit B) from Sylgard 184 Silicone Elastomer, Dow Corning Corp., USA.

### Roller Coating of the GNP Ink on TPU Film

The TPU film was hot pressed at 200 °C with a pressure of 2 MPa. GNP conductive ink (3 mL) was dropped on the surface of a TPU film, dispersed by a roller coating (rolling 10 times in a single direction), and cured at 70 °C for 1 h to evaporate the water.

### Formation of CWS on the GNP Layer and Packing with PDMS Protective Layer

Cracks and wrinkles were formed on the GNP layer by pressing and dragging the sample using a homemade device (Fig. S1 in the electronic supplementary information, ESI). The GNP/TPU films were folded before it was fixed and pressed to the upper film at 2 kPa and 2 Pa. The underlying film was then dragged at a uniform speed (0.1 m/min) until the folded region reached a fixed position on the upper film. The film was then dragged in the opposite direction under the same conditions. This process was repeated for three times. A control sample without the treatment was also prepared for comparison. PDMS (3 mL) was then spin-coated on the GNP layer at 1000 r/min for 3 min. The weight ratio of PDMS base to curing agent was 10:1. The samples were finally cured at 70 °C for 3 h.

### Characterization

The morphology of CWS sensors was imaged using field emission scanning electron microscopy (FE-SEM, 7500F JEOL), field emission transmission electron microscopy (FE-TEM, JEM-1200EX, 120 kV) and white-light interferometry (BRUKER, Contour GT-K). Raman spectra were recorded by a Raman spectrometer (HORIBA, Labram HR800 Evo) with a 50-mV laser excitation at a wavelength of 532 nm. The strain induced deformation of cracks was observed with a Microtest (Linkam, TST350) and an optical microscope (Olympus, BX61). Current-voltage (*I*-*V*) measurements were acquired with an electrochemical workstation (Suzhou Risetest Electronic Co., Ltd., RST 5200F, China). An electronic universal testing machine (Shenzhen SUNS, UTM2203, China) was used for applying and releasing strain. Resistance was calculated using Ohm's law ( $R = U/I$  at a constant voltage of 3 V).

## RESULTS AND DISCUSSION

The fabrication process of the GNPs/TPU/PDMS CWS sensor is illustrated in Fig. 1. TPU film is prepared by hot pressing and cut into rectangular shape (Fig. 1a); then GNPs conductive ink is coated on the TPU film to form a uniform GNPs layer on surface of the TPU membrane (Fig. 1b). The GNPs/TPU film was folded at one side of the sample; the tension was conducted to the bottom of the film, while the pressure was applied on the film simultaneously (Fig. 1c). As a result, microstructures were formed on the folded position synchronously (Fig. 1d). Fig. S1 (in ESI) shows the homemade equipment used for the fabrication of the crack-wrinkle structure. In order to ensure a good contact, copper tapes were connected with the film as electrodes by coating silver paste on each end of the strain sensor (Fig. 1e). Finally, we deposited a layer of PDMS on surface of the GNP by spin-coating as a protective film (Fig. 1f). Our CWS sensor can sustain obvious stretching, twisting and bending, as shown in Figs. 1(g)–1(j), showing an excellent flexibility. Fig. 1(k) shows the scanning electron microscopy (SEM) image of fractured surface of the CWS sensor with a layer-by-layer structure; it is observed that the GNPs layer shows a good adhesion with TPU and PDMS. Furthermore, GNPs are coated regularly on the TPU layer (Fig. 1l). SEM images of the CWS surface are shown in Figs. 1(m) and 1(n) in detail; a plenty of cracks and wrinkles with the same orientation structures are distributed on the surface of GNP layer. Some cracks are generated with the appearance of

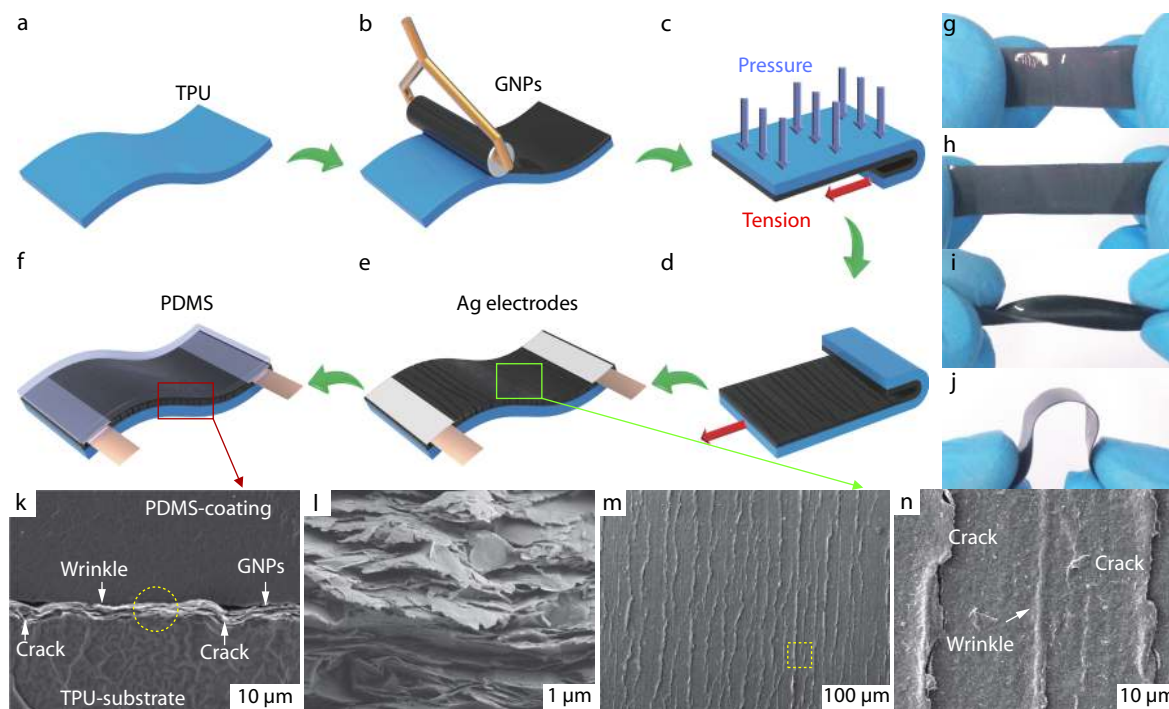


**Fig. 1** (a–f) Schematic illustration of the preparation of CWS sensor. Photographs of the CWS sensor (g) at the initial state and during (h) stretching, (i) twisting and (j) bending. Typical SEM images of the CWS sensor: (k) cross-sectional view of the CWS sensor; (l) magnified view of the structure of GNP layer marked by the yellow circle in (k). (m) SEM image of the surface of GNP layer, (n) the magnified view marked by the yellow box in (m).

the wrinkle structure; overlapping structure is also observed, showing multifarious microstructures (Fig. S2 in ESI).

As shown in Figs. 2(a) and 2(b), the height of the wrinkle is about 4  $\mu\text{m}$ , and the cracks spread over the wrinkles evenly. The distance between two adjacent wrinkles is about 5  $\mu\text{m}$ . The depth of crack is about 3  $\mu\text{m}$ . On the basis of the area statistics of the GNP layer, the ratio of the wrinkle and crack structure accounts for 9.5% and 31.8%, respectively (Figs. 2c and 2d and Fig. S3 in ESI). Besides, the features of GNPs are shown in Fig. 3 with atomic force microscopy (AFM) and TEM. In the AFM topography (Fig. 3a), the thickness of GNP is observed to be about 6.25 nm, showing a multi-graphite sheet structure. The TEM image (Fig. 3b) demonstrates the presence of GNP, proving again that the multiple and folded structures exist in GNP. Raman analysis also demonstrates the multilayer microstructure (Fig. S4 in ESI).<sup>[29]</sup> Such structure of GNP is beneficial to the improvement of the response ability to external stimuli owing to the presence of multiple nano-sheets contact points, which is good for the sensing stability. The existence of wrinkles increases the number of dislocation contact points, and the CWS shows stable sensing performance under small deformations.

When the CWS sensor bears the stretching perpendicular to cracks (and wrinkles), the gap in cracks increases and the number of effective conductive pathways decreases. For the wrinkles and other microstructures, the tunneling effect will also be reduced with the increasing strain. The two phenomena result in the increase of the resistance of the sensor. When the sensor is released, the gaps, wrinkles and overlapping structure of the GNPs layers are recovered to their initial

state well on the basis of the excellent flexibility of the TPU and PDMS matrix; the conductive pathways increase gradually, showing a rising resistance. Compared with a traditional crack structure sensor, our CWS sensor possesses a larger tensile test range based on the introduction of the wrinkle structure, which is beneficial to the recoverable destruction of the conductive network in the CWS sensor.

Fig. 4 illustrates the resistive response of the device under strain; a linear response is observed under small strains (Fig. 4e). The sensitivity of the CWS sensor was quantified from the GF:

$$GF = \frac{\Delta R}{R_0 \times \varepsilon} \quad (1)$$

Here,  $\Delta R = R - R_0$ ,  $R$  and  $R_0$  represent the test resistance and the initial resistance of the sample, respectively;  $\varepsilon$  is the strain. The resistance of the CWS sensor increases with the applied strain. The change of the relative resistance ( $\Delta R/R_0$ ) versus the strain shows two stages: during the first stage (strain 0%–20%), the relative electrical resistance increases linearly, and the slope of the curve gives the GF value of 152.9 ( $R^2=0.99856$ ); at the second stage (strain >20%), the relative resistance increases dramatically, and a GF of 750 is achieved due to the fast propagation of cracks and the increasing deformation induced breakage of conductive networks. Finally, the resistance exceeds the maximum measurement range. From optical images (Figs. 4a–4d, Movie S1 in ESI), we can clearly observe the deformation of the cracks when the material is subjected to strain from 0% to 40%. There is an interesting phenomenon in the tensile sensing test. In the original state (Fig. 4a), a small quantity of cracks and wrinkles are uniformly

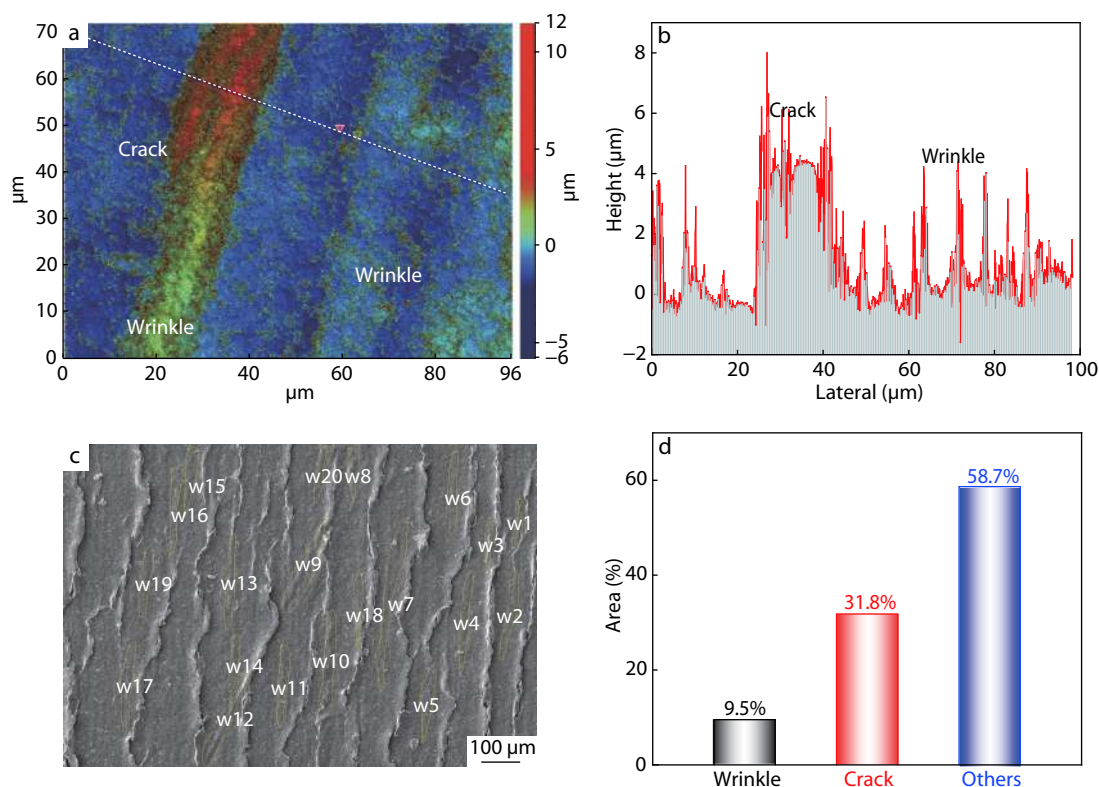


**Fig. 2** (a) Optical microscopy image of the surface of CWS sensor. (b) Height-profile determined along the white dashed line in (a). (c) SEM image of the CWS sensor with the marks of wrinkle area (yellow line). (d) Proportion of microstructure part of crack, wrinkle and others.

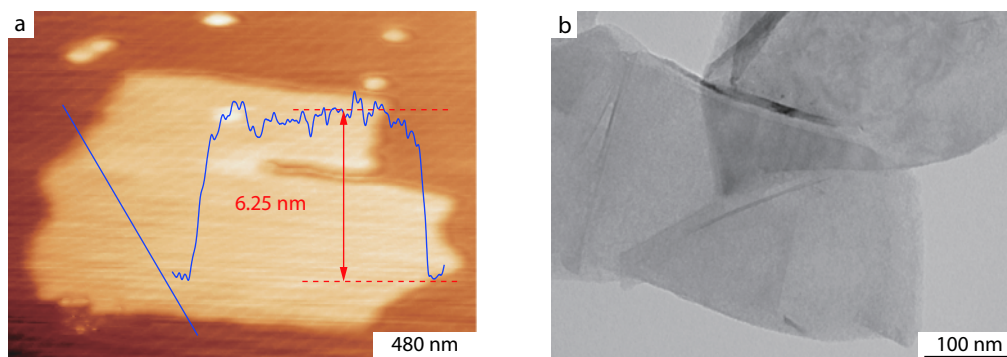


**Fig. 3** (a) AFM results of graphene sheets and profile of blue line. (b) TEM image of graphene sheets.

distributed in the GNP layer, perpendicularly to the stretching direction. When the tensile strain exceeds 10% (Fig. 4b), the gaps between the cracks increase gradually; at the same time, some wrinkles transform into flat state or even cracks under the uniaxial tension. When the strain approaches 20% (Fig. 4c), the deformation increases obviously. Nevertheless, there are lots of wrinkles extended from the edges of the crack; these wrinkles can connect the islands and gaps, ensuring the efficient electronic transport. Electrons can still be transported through adjacent GNP between gaps even at a high tensile strain, leading to a relatively large workable range. And at the last stage (strain=30%, Fig. 4d), the conductive paths are damaged seriously. The deformation of

cracks in the process of stretching and relaxing is shown in the Movie S1 (in ESI). Fig. 4(f) shows the comparison of the GF and maximum sensing range of the strain sensor with those of the counterparts reported in literature, showing a combined advantage of our present CWS sensor among crack based strain sensors.<sup>[30–38]</sup> For the sensing mechanism of CWS, the conductance of above process could be written as:<sup>[34]</sup>

$$S = \frac{1}{2} \left( 1 - \operatorname{erf} \left( \frac{\ln \left( \frac{\varepsilon}{\varepsilon_0} \right)}{\mu} \right) \right) \quad (2)$$

where  $\operatorname{erf}(x)$  is error function,  $\varepsilon$  is the applied strain,  $\varepsilon_0$  and  $\mu$  are fitting parameters.

The electromechanical behavior of the strain sensor was measured in detail at room temperature. The working equip-

ment is shown in Fig. S5 (in ESI). Fig. 5(a) shows current-voltage (*I*-*V*) curves of a typical CWS sensor (with an initial res-

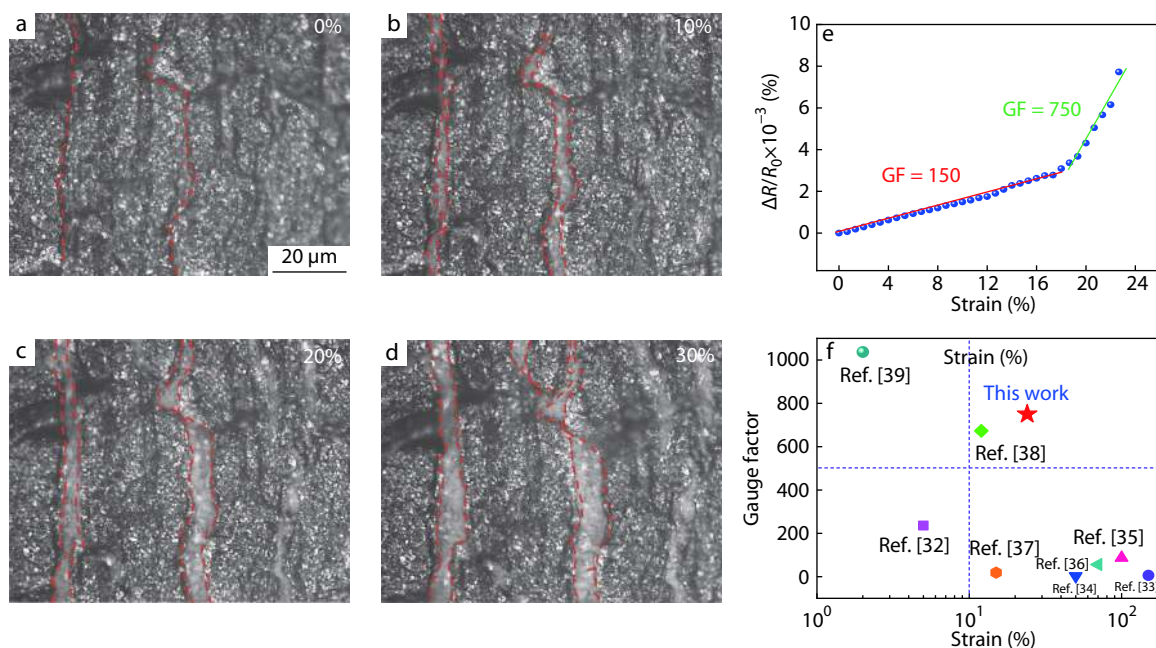


**Fig. 4** Working mechanism of the CWS sensor during the tensile process. Micrograph of the CWS strain sensor: (a) original state, (b) 10% strain, (c) 20% strain, (d) 30% strain. (e) Relative resistance change versus strain for the CWS sensor. (f) The comparison of GF and sensing range between CWS sensor and recent reports of literatures.

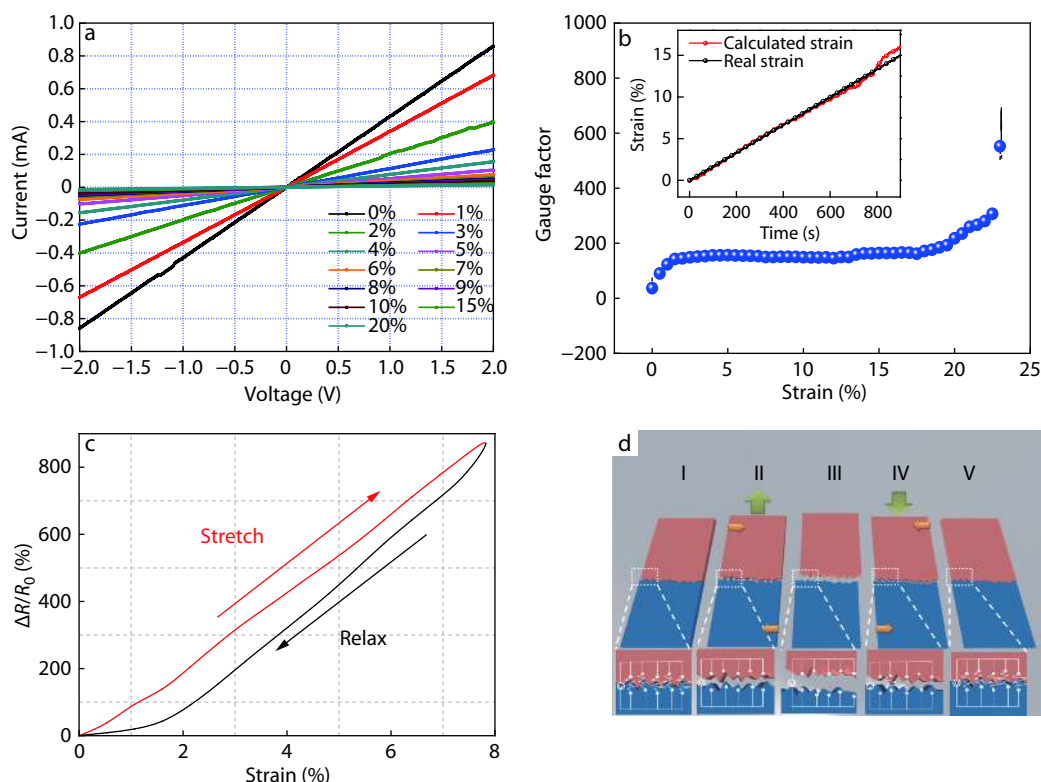


**Fig. 5** Electromechanical behavior of the strain sensor: (a) *I*-*V* characteristics and current changes under various strain; (b) Gauge factor versus strain for the CWS sensor, inset shows the curve of strain versus time: red line—the calculated strain, black line—the test strain; (c) Hysteresis curve for the CWS sensor under 8% strain. (d) Schematic representation of the change in deformation of the crack during stretching and relaxing processes.

istance of  $\sim 2.4$  k $\Omega$ ) under strain from 0% to 20%. The current of the CWS sensor decreases gradually when the applied strain increases, which is ascribed to the change in deformation of cracks under the stretching. The  $I$ - $V$  characteristics show a good linearity. In order to achieve an accurate measurement of a strain sensor, the electrical response should be stable. A constant GF allows to accurately determine the strain sensing performances. The electrical stability of the strain sensor is then tested by studying the GF value as a function of the uniaxial strain (Fig. 5b). From this figure, the GF increases with the strain from 0% to 1% due to the increase of the gap width between cracks based on the tunneling effect.<sup>[39,40]</sup> In the second regime, when the strain approaches between 1% and 17%, the GF value of our CWS is well-sustained ( $GF \approx 150$ ), which is mainly related to the introduction of the wrinkle structures that can maintain the integrity of the conductive network well in this region through the flattening of the wrinkles, and at this state, most of the electrons can still tunnel through the potential barrier. After the

strain increases up to 17%, electrons cannot tunnel through the potential barrier, which makes the GF increase sharply. Inset in Fig. 5(b) illustrates the strain versus time with our sensor; the black line represents the real applied strain and the red line represents the strain calculated by using the value of electrical resistance and the GF (150) through Eq. (3). An excellent agreement is achieved between the real applied strain and the calculated strain. Here, the strain changes ( $\epsilon_c$ ) are calculated by variations in resistance based on the Eq. (2):

$$\epsilon_c = \frac{\Delta R}{R_0 \times GF} \quad (3)$$

Fig. 5(c) illustrates relative resistance of the sensor versus strain in the first stretching-releasing cycle. The relative resistance of the strain sensor could recover to the original state well after the release of the stress, showing weak hysteresis effect. Fig. S6 (in ESI) shows the similar results for strain values of 1%, 2%, 4% and 8%. Hysteresis phenomenon has been frequently reported in strain sensors,<sup>[11,41–44]</sup> while obvious hysteresis is not observed for our CWS strain sensor.<sup>[45]</sup> This

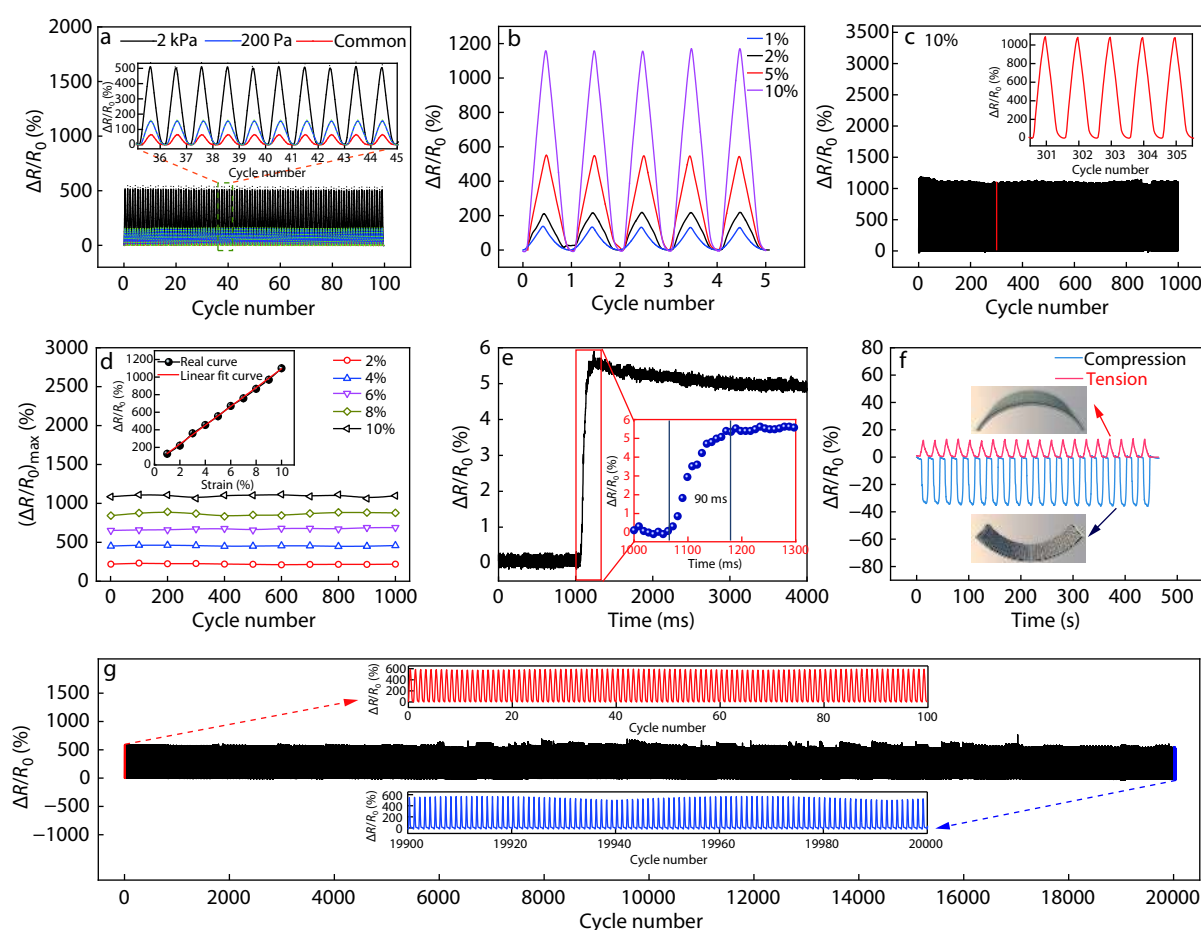


**Fig. 6** (a) Relative resistance variation towards 5% strain values of different sensors (black: fabricated under pressure of 2 kPa, blue: fabricated under pressure of 200 Pa, red: common sample without cracks) test over 100 cycles. Strain sensing performance of CWS sensor: relative change in resistance under repeated stretching-releasing cycles; (b) 1%, 2%, 5%, and 10% strain in 5 cycles and (c) 10% strain in 1000 cycles. (d) Relative resistance change at the maximum response peak versus cycle number for 2% (red), 4% (blue), 6% (pink), 8% (olive) and 10% (black) strain in 1000 cycles. (e) Relative resistance change of the CWS sensor subjected to a quasi-transient step strain of 0.1%. (f) Relative change in resistance of the CWS sensor under tensile (red) and compressive (blue) bending cycles. (g) Durability of the CWS sensor revealed by the relative change in resistance under repeated stretching-releasing tests at 5% strain for 20000 cycles, the insets show the first 100 cycles in red and last 100 cycles in blue.

phenomenon was attributed to the interesting microstructure of our CWS of the sensor. Fig. 5(d) shows the deformation of cracks during a stretching-releasing process. At the stage I, the sensor was stretched under a low strain: the gap between cracks increases and the crack edges are subjected to only axial force. With the increase of the strain (stages II and III), the sensor is compressed transversally and the crack edges start sliding transversally. At the release stages IV and V, because of the viscoelasticity of polymer substrate, crack edges could not return to the original position in transversal direction; crack edges contacted with each other ahead of time.<sup>[34]</sup> This novel phenomenon is beneficial to improving the response time caused by hysteresis effect.

In practical applications, a remarkable durability and high response speed are both required for widening the applicability and reducing the cost/use ratio of a strain sensor. In order to study the durability and the response speed of the CWS sensor, our CWS sensor was repeatedly stretched and released by a universal test machine at a frequency of 0.66 Hz. The performance is compared with CWS sensors fabricated without cracks, prepared at a pressure of 200 Pa and 2 kPa, respectively. The CWS sensor fabricated under 2 kPa shows the highest sensitivity (Fig. 6a); therefore, we selected

samples fabricated at this pressure in the following measurements. The change of relative resistance versus time is collected in Figs. 6(b) and 6(c). Remarkably, Fig. 4(b) shows the cyclic resistance variations towards different strains, showing an excellent sensing discernibility. Within 1000 cycles (Fig. 6c), the relative resistance reached almost the same value in each cycle and fully recovered to the original state under the applied strain of 10%, indicating that our CWS sensor has a high reproducibility and good durability. Inset in Fig. 6(c) represents random episodes extracted from the curve. Results of the sensing performances under other low strains of 1%–9% are collected in Fig. 7, all showing excellent sensing stability.

Fig. 6(d) shows the relative change in resistance at the maximum peak as a function of the cycle number, under different strains (2%, 4%, 6%, 8% and 10%); the relative resistance can return to the original value well after 1000 cycles. The CWS sensor demonstrates the same remarkable durability under other strains (Fig. S7 in ESI). This indicates that our strain sensor displays a remarkable stability and reproducibility in the sensing range. Furthermore, a highly linear relationship is achieved between the relative resistance change and the strain (see the inset) as testified by the optimum linear fit ( $R^2=0.999$ ) characterized by a slope of 117. To further investig-

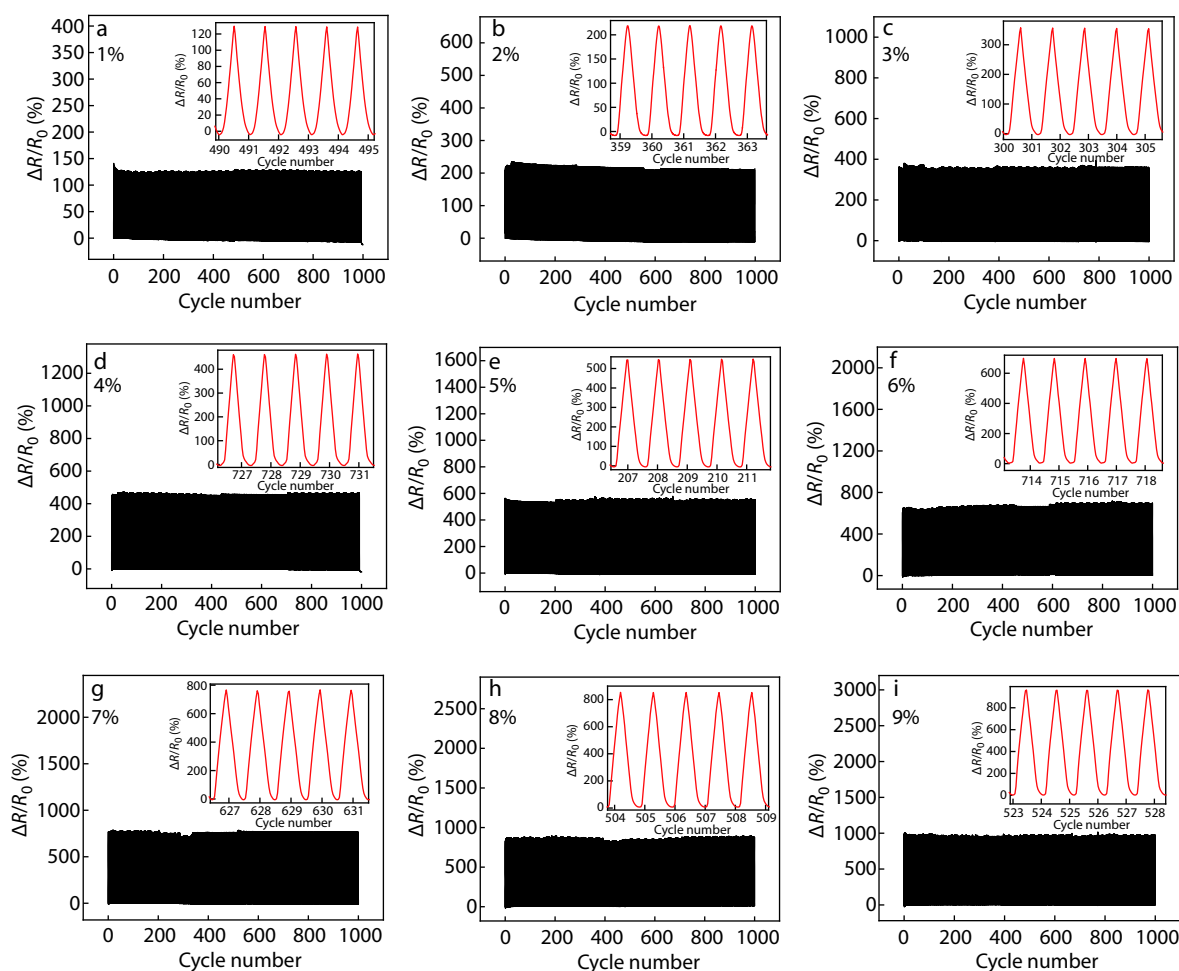


**Fig. 7** Relative change in resistance under 1%–9% strain in 1000 stretching-releasing cycles: (a) 1%, (b) 2%, (c) 3%, (d) 4%, (e) 5%, (f) 6%, (g) 7%, (h) 8%, (i) 9%. The insets show the randomly selected 5 cycles during the 1000 cycles.

ate the long-term durability of our CWS sensor, we conduct an endurance test over  $2 \times 10^4$  stretching-releasing cycles at a strain of 5% and a frequency of 0.66 Hz. As shown in Fig. 6(g), the maximum response signal is almost not changed after  $2 \times 10^4$  cycles. Fig. S8 (in ESI) shows a last 100 stretching-releasing cycles of the durability test, also revealing an excellent sensing stability.

In Fig. 6(e), the strain sensor demonstrates a short response time around 90 ms under stretching condition (the strain was 0.1%, stretching speed of testing machine was 500 mm/min and the sample length was 50 mm). Compared to the response time reported in recent studies,<sup>[26,45–49]</sup> our CWS sensor shows a fast stimulus-response, which is good for detection in real time as wearable electronics. Notably, Fig. 6(e)

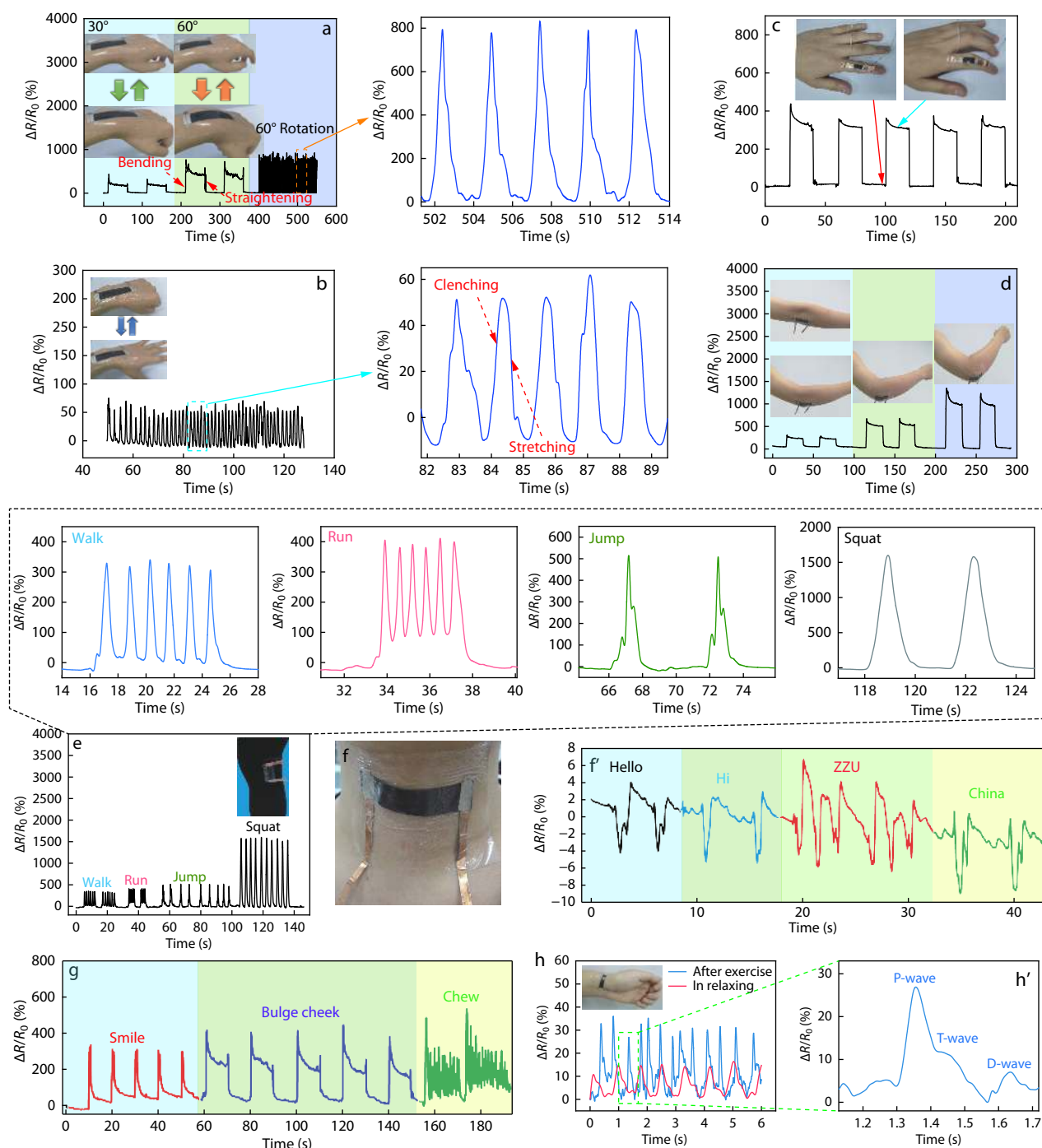


**Fig. 8** Relative resistance change of the CWS sensor in detecting various human motions: (a) wrist bending, (b) palm clenching and stretching, (c) finger bending and (d) elbow bending. (e) Different movements of leg of a volunteer: walking (blue), running (red), jumping (green) and squatting (gray). (f) Phonation of "Hello, Hi, ZZU, China". (g) Facial movements: smiling, bulging cheek and chewing (eating a grape). (h) Pulse: in relaxing (red), after exercise (blue).

also shows that our device can sense strain down to 0.1%, indicating an ultralow detection limit. The electromechanical performance of the CWS sensor under bending is also evaluated. The relative resistance variations with the chord length are shown in Fig. S9 (in ESI). By bending the outer surface (Fig. S9a in ESI), cracks are subjected to tensile stress, which makes the relative resistance increase with the decrease of the chord length ( $\Delta R/R_0$  is 12%). By bending the inner surface (Fig. S9b in ESI), cracks are subjected to compressive stress, and the relative resistance decreases with the reduction of the chord length ( $\Delta R/R_0$  is -35%). As shown in Fig. 6(f), for both bending directions, the CWS sensor demonstrates good mechanical sensitivity and excellent repeatability, indicating our CWS sensor is also suitable for bending sensing measurements.

The excellent flexibility, high sensitivity and ultra-low detection limit of our CWS sensors endow a high potential of our sensor with the application ability for human-machine interaction or wearable devices. In order to characterize the capability of the sensor for detecting large and subtle human motions, the CWS sensor is mounted on human body to acquire different electronic signals. Figs. 8(a)–8(e) show the ability of the CWS sensor to detect large movements, such as the bending of a human joint. As shown in Fig. 8(a), the CWS sensor is attached onto the joint of a wrist to detect real-time motions of the finger bending and releasing. The wrist bent to different angles (about 30° and 60°, and held for 20 s) and then released (for another 20 s). Our sensor could respond well towards the bending of the finger with a good sensitivity ( $\Delta R/R_0$  is ~200% and ~600% when bending angle was 30° and 60°, respectively). The strain sensor could also detect movements, such as the clenching and stretching of the palm (Fig. 8b). Highly reproducible electrical signals are obtained for finger bending (Fig. 8c) and elbow motions (Fig. 8d).

In addition, our CWS strain sensor could be fixed on knee joints to detect and discriminate different leg movements (Fig. 8e), such as the walking and running; obviously, the peak shape towards running is steeper than that for walking. For the jumping, three peaks appear in the electric response, corresponding to the take-off preparation, the jumping up and the falling to the ground. The peak value formed by squatting is clearly distinguished from other motions. Figs. 8(f) and 8(g) show that our CWS sensor mounted on the throat can detect tiny vibration occurring during a speech: different

words such as “Hello”, “Hi”, “ZZU” and “China” could be distinguished precisely. The words “Hello” and “China” have two distinguishable syllables, respectively, so the waveform of two sharp peak is demonstrated in this figure. The word “Hi” shows one huge peak, and a weak shoulder peak can also be found in the waveform for the “i” syllable has a shifted sound. When the word “ZZU” is read, the waveform shows three huge peaks and the third peak has a distinguishable shoulder peak because of the shifted sound of “U” syllable. Besides, a remarkable repeatability is demonstrated in twice speech of every word. This confirms the excellent sensitivity and quick response ability in our CWS sensor.

Furthermore, we installed the CWS sensor onto the cheek to monitor tiny changes of facial expression and muscle movements, such as smile, cheek bulging and chewing (eating a grape, in Fig. 8g). Moreover, the CWS sensor could detect pulse beating. In Figs. 8(h) and 8(h'), the CWS sensor is installed on the wrist. Resistance changes could really reflect the health condition before and after exercise, namely, the pulse frequency in relaxed conditions is calculated to be 68 beats/min and after exercise, it changes to 128 beats/min. It is also found the pulse amplitude was larger than that in relaxation state. We can also observe a single pulse peak in the relaxation condition, and three distinct features of the pulse waveform are distinguished for percussion waves (P-wave), tidal waves (T-wave) and diastolic waves (D-wave).<sup>[17]</sup> To sum up, the CWS sensor reveals high sensitivity, excellent reproducibility, remarkable durability, allowing for an extremely wide range of applications, including various human movements.

Fig. S10 (in ESI) shows the leg bending-extending response by using our sensor; the patellar reflex of the volunteer could also be detected as show in Figs. 9(a) and 9(b). When the knee suffers a knock, the first positive peak is formed due to the vibration of the shank; the shank stretches with the patellar reflex, leading to a negative peak; finally, the shank returns to its original state, which gives rise to the second positive peak. Owing to the ultralow detection limit of the CWS sensor, subtle motions such as pulses, facial and throat movements or other tiny-muscles movements could also be detected accurately. In addition, the CWS sensor also shows a good pressure sensing ability. As show in Fig. 9(c), we press the device gently with the index finger, the relative resistance decreases in real time due to the lowering of the gap width between cracks induced by the squeezing action.

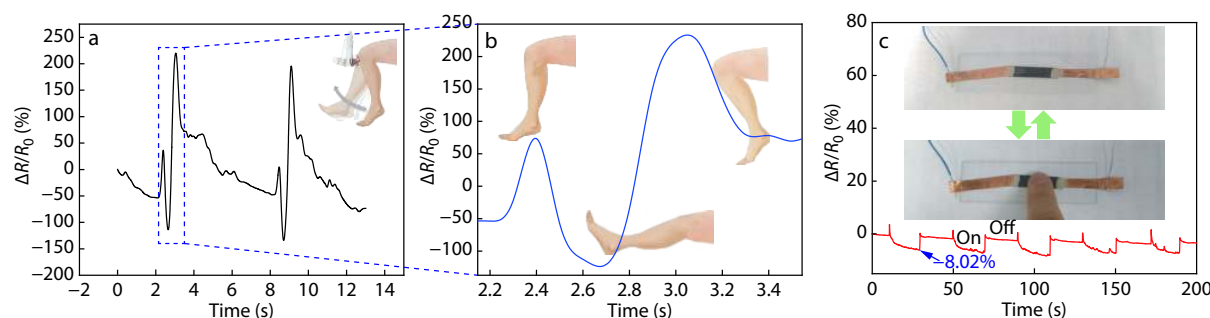


**Fig. 9** Detection of the leg motions by the CWS sensor: (a) patellar reflex and (b) a magnified view of the curve in (a). (c) Finger press on the device and relative change in resistance of the sensor.

## CONCLUSIONS

In summary, a stretchable and flexible strain sensor based on a crack-wrinkle structure is fabricated through a simple process. The strain sensor shows an extremely stable response with high sensitivity ( $GF=750$  at the strain of 24%). Our CWS sensor could detect quite tiny strain variations ( $<0.1\%$  strain) with a fast response ( $<90$  ms), showing an ultra-low detection limit and a short sensing time. The strain sensor demonstrates an excellent long-term durability ( $>2 \times 10^4$  stretching-releasing cycles). No obvious hysteresis effect is observed for our CWS strain sensor. Excellent performance that relies on the unique sensor structure is investigated by microscopy and successfully verified by the sensing performances. The CWS sensor could detect a large set of human movements including vigorous exercises and subtle motions in real-time. In comparison to recently proposed strain sensors, our device combines simple processing, superior sensitivity and durability, and ultralow detection limit, which is in possession of wide prospect in precision measurements, human-machine interaction, electronic skins and human motion monitoring.

## Electronic Supplementary Information

Electronic supplementary information (ESI) is available free of charge in the online version of this article at <https://doi.org/10.1007/s10118-021-2500-8>.

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