Ultrasensitive mechanical crack–based sensor inspired by the spider sensory system

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Recently developed flexible mechanosensors based on inorganic silicon1–3, organic semiconductors4–6, carbon nanotubes7, graphene platelets8, pressure-sensitive rubber9 and self-powered devices10,11 are highly sensitive and can be applied to human skin. However, the development of a multifunctional sensor satisfying the requirements of ultra-high mechanosensitivity, flexibility and durability remains a challenge. In nature, spiders sense extremely small variations in mechanical stress using crack-shaped slit organs near their leg joints12. Here we demonstrate that sensors based on nanoscale crack junctions and inspired by the geometry of a spider’s slit organ can attain ultrahigh sensitivity and serve multiple purposes. The sensors are sensitive to strain (with a gauge factor of over 2,000 in the 0–2 per cent strain range) and vibration (with the ability to detect amplitudes of approximately 10 nanometres). The device is reversible, reproducible, durable and mechanically flexible, and can thus be easily mounted on human skin as an electronic multipixel array. The ultrahigh mechanosensitivity is attributed to the disconnection–reconnection process undergone by the zip-like nanoscale crack junctions under strain or vibration. The proposed theoretical model is consistent with experimental data that we report here. We also demonstrate that sensors based on nanoscale crack junctions are applicable to highly selective speech pattern recognition and the detection of physiological signals. The nanoscale crack junction–based sensory system could be useful in diverse applications requiring ultra-high displacement sensitivity.

Spiders have crack-shaped slit organs to detect vibrations in their surroundings12. The slit geometry enables ultrasensitive displacement detection by allowing for mechanical compliance, which results in the deformation of the slit in response to small external force variations12,13. Inspired by this ability, we designed a multifunctional sensor based on nanoscale crack junctions (a ‘nanoscale crack sensor’) and demonstrated its ultrahigh sensitivity to physiological signals (for example speech patterns and heart rates) and external forces (for example pressure, strain and vibration). The analogy between our nanoscale crack sensor and the spider slit organ is partial because the signal transduction through a spider’s neurons and the electrical conduction through our sensor are different. The similarity lies in the slit geometry, which is known to be the key to slit organ ultrasensitivity1,2.

An illustration of the spider’s slit organ is presented in Fig. 1. The spider has strain detectors located near the leg joint between the metatarsus and tarsus bones12. The detectors are composed of a viscoelastic pad, with the slit organ consisting of approximately parallel sensory lyriforms embedded in the mechanically stiff exoskeleton (Fig. 1b). The slits are directly connected to the nervous system to collect external vibrations. In this work, we mimicked the geometry of the slit organ to design sensors by depositing a stiff, 20 nm-thick platinum (Pt) layer on top of a viscoelastic polymer, polyurethane acrylate11 (PUA) (details in ‘Experimental section’ in Supplementary Information). Analogous to the crack-shaped slit organ, we generated controlled cracks in the Pt film across which electrical conductance can be measured. The Pt film on PUA was mechanically bent by applying various radii of curvature (1, 2 and 3 mm), and the cracks were formed in a controlled manner in terms of crack density and direction. Studies of controlled crack formation using notches and confined surface stress have been reported15–17, although cracks were typically considered as a defect to be avoided. As shown in Supplementary Fig. 1, the crack spacing (or density) can be controlled by bending the sample with different radii of curvature. The sensor performance is affected by the crack density. The cracked Pt on PUA shown in Fig. 1d has lateral dimensions of 5 mm × 10 mm on 10 μm-thick PUA. Figure 1e illustrates that cracks are formed in the transverse direction to the extension force applied with a bending curvature radius of 1 mm. Supplementary Fig. 2 shows that the cracks penetrate the Pt film and extend into the PUA substrate with a total crack depth of approximately 40–50 nm (ref. 19). The crack gap increases with strain, as shown in Supplementary Fig. 2 and Fig. 1f. Even at 0% strain, a small gap (~5 nm) exists between matching crack edges, indicating that not all of these edges are in contact with each other. A simplified sketch of our nanoscale crack sensor is shown in Fig. 1c. Figure 1g illustrates the widening of the 50 nm-deep crack gap by stretching using finite-element method simulations.

The electrical conductance of a metal strip with a straight transverse cut experiences a sudden jump from a finite value when the edges of the cut are in contact, to zero when they disconnect. For cracks in the Pt film, the high strain sensitivity originates from the rare yet large gap–bridging steps on opposite edges of a zigzag crack. Large variations in resistance are obtained with high repeatability for a cracked sample with a bending curvature radius of 1 mm when the sensor is loaded to produce up to 2% strain and unloaded back to 0% strain at a sweeping speed of 1 mm min−1 (Fig. 2a). Figure 2b shows such cyclic variations in resistance for different peak strains, in sharp contrast to the case with a nearly flat bare Pt film with no cracks (yellow curve). The current–voltage (I–V) curves for the crack sample and the bare film without cracks are presented in Supplementary Fig. 3 for various strains. The same cyclic measurements performed at a slower sweeping speed of 0.1 mm min−1 in Fig. 2c illustrate that the loading and unloading are nearly reversible. When compared with the case with no crack (Fig. 2c, inset), the crack sample exhibits a 450-fold-higher resistance variation (AR) at 0.5% strain. We obtained reproducible results from thirty different samples (Supplementary Fig. 4). The durability was confirmed by performing 5,000 cyclic strain tests (Supplementary Fig. 5). As noted earlier, controlled crack formation using different bending curvature radii resulted in different crack spacings (Supplementary Fig. 1), which affected the sensor performance in a controllable manner (Supplementary Fig. 6). The gauge factor determined from the definition18 (AR/R0) exceeds 2,000 at strains of 0–2% (Supplementary Fig. 7). The strain-dependent gauge factors determined by measuring the derivative of R/R0 in Fig. 2c were compared with those obtained from the approach to sensor construction based on graphene platelets19 (Supplementary Fig. 8).

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To demonstrate the device’s scalability and ability to detect mechanical vibrations and pressure, we used a sensing network of 64 pixels (8 × 8 pixel array) with dimensions of 5 cm × 5 cm (Fig. 2d; details in ‘Experimental section’ in Supplementary Information and Supplementary Figs 9 and 10). The flexible format of a multipixel array (Fig. 2g) enables the simultaneous measurement of two different stimuli, pressure and vibration, using a simple analyser scheme (Fig. 2h). The results for static pressure applied using a piece of PDMS piece (5 Pa; Fig. 2e) and dynamic pressure simulating a flapping ladybird (5 Pa of pressure and a vibration of frequency 200 Hz and amplitude 14 μm; Supplementary Fig. 11) are shown in Fig. 2k and Fig. 2l, respectively. A piece of PDMS was placed on the blue-boxed region in Fig. 2d and a piezoelectric vibrator was placed on the red-boxed region in Fig. 2d as a vibration source simulating a ladybird’s flapping. The distributions of applied pressure from both stimuli can be detected at both locations (Fig. 2i). However, the vibration signal is selectively detected only at the spot where the vibration input is applied (Fig. 2j).

Figure 1 | Schematic illustrations and images of an ultra-mechanosensitive nanoscale crack junction-based sensor inspired by the spider sensory system. a. The spider has highly sensitive organs located on its leg joints (black arrows) for the detection of external forces and vibrations. Inset, enlarged images of the sensory slit organs in the vicinity of the leg joint between the metatarsus and the tarsus. b. The slits are connected to the nervous system to monitor vibrations. The slits are in the highly stiff exoskeleton (surface) and a viscoelastic pad (below the exoskeleton). c. Illustration of the crack-based sensor and its measurement scheme. Grey, platinum layer; beige, viscoelastic polymer layer. d. Left, image of the spider-inspired sensor with a cracked, 20 nm-thick Pt layer formed by bending with a 1 mm radius of curvature. The sensor has lateral dimensions of 5 mm × 10 mm on 10 μm-thick PUA.

The nanoscale crack sensor is able to monitor minute vibrations caused by sound waves. To demonstrate its performance as a sound monitor, the sensor was attached to the surface of a violin (Fig. 3a). The sensor measures the strings’ vibrations on the right side of the instrument above the f-hole, which allows the resonating air inside the violin to emerge. The measured G-, D-, A- and E-string sounds reveal peak signals at different frequencies that correspond to the known frequencies (Fig. 3b). Time-dependent resistance variations were also measured while Elgar’s ‘Salut d’Amour’ was played, and they were converted into digital signals (Supplementary Video 1). From those signals, the real-time peak spectrogram was retrieved (Fig. 3c). The harmonic frequency of each note is recorded correctly.

A flexible sensor attached to a human neck can be used as a speech pattern recognition system. A microphone-based system cannot filter unnecessary information in a noisy environment, in contrast to the human auditory system (known as the ‘cocktail party phenomenon’). We asked ten human speakers to repeat four simple words (‘go’, ‘jump’, ‘shoo’ and ‘stop’) more than ten times with the crack sensor attached to their necks (Fig. 3f) and in front of a standing microphone (Supplementary Fig. 14). The acoustic waveforms and auditory spectrograms of the human speakers were analysed by real-time fast Fourier transform. In silence, the acoustic waveforms (Fig. 3d, top) and their respective spectrograms (Fig. 3d, bottom) from both tools, the nanoscale crack sensor (blue) and the standing microphone (red), are stable. However, in a noisy environment of approximately 92 dB (measured using a Bruel & Kjaer Type 2250 sound level meter), the spectrogram from the nanoscale crack sensor (Fig. 3e, green) remains stable, whereas that from the standing microphone (Fig. 3e, black) becomes noisy. We also tested the commercially available CMP-756 electret condenser microphone (CUI Inc.) while it was attached to a speaker’s neck to compare the accuracy of word recognition (Supplementary Fig. 14). The accuracy of simple word recognition for our nanoscale crack sensor was approximately
To investigate the sensor mechanism, we studied the normalized conductance, \( S = R_0/R \), as a function of strain (Supplementary Fig. 18). This revealed an intriguing fluctuating behaviour, particularly at lower strains (Supplementary Fig. 18, inset). The derivative \(-dS/d\epsilon\) displays large fluctuations with negative and positive values, particularly at strains of less than 1% (Fig. 4a). These fluctuations are well beyond the noise level observed for the bare film without cracks (Fig. 4a, inset). We attribute these intriguing fluctuations to the disconnection–reconnection events of the crack edges. A positive \(-dS/d\epsilon\) value represents a disconnection event whereas a negative \(-dS/d\epsilon\) value represents a reconnection. A cracked film over an elastic substrate with a positive Poisson’s ratio could be compressed in the transverse direction while being extended in the axial direction. This indicates that the axial extension could disconnect the crack edges and that the lateral compression could reconnect them. In Fig. 4a, there are two distinct strain regions with the larger strain region being characterized by only positive fluctuations. This confirms that the larger steps in the crack edges preferentially disconnect under loading. At lower strains, the fluctuations are both positive and negative, indicating disconnections and reconnections for numerous small steps in the crack edges. Averaging the positive and negative steps \((\langle -dS/d\epsilon\rangle)\) (Fig. 4b, red and grey curves) yields a positive value in all areas, indicating that the net effect of disconnection–reconnection is to reduce conductance as the extension proceeds. A further detailed description of the disconnection–reconnection process is provided in Supplementary Fig. 19. This overall behaviour of \(-dS/d\epsilon\) is related to the crack asperity size distribution because the disconnection–reconnection events should depend on the crack asperity size distribution. Dynamic sweeping motion results in sweeping rate-dependent resistance variations, although the curves are nearly reversible (Supplementary Fig. 20). The sweeping rate-dependent resistance variation is attributed to the rate-dependent nature of the crack disconnection–reconnection process (Supplementary Fig. 20).

For uniaxial strain, the elastic strip becomes compressed transversally, and small edge steps remain in contact until the strain completely disconnects them. This process occurs when the gap distance overcomes the crack asperity height (in the simplified diagram in Fig. 4c, \(d\), the height of two blue grains is defined as the crack asperity height, with each grain representing a small step). Scanning electron microscope (SEM) images illustrate that the gap distance is proportional to the strain: \(d = k_0\epsilon\), where \(k_0 \approx 70 \text{ nm}\) and \(\epsilon\) is in per cent (Supplementary Fig. 21). A central component of the mechanism of conduction across a crack is a simplified expression for \(S\) that accounts for the sudden termination of a contact when the gap \(k_0\epsilon\) exceeds \(h_i = k_0h\), the height of the crack’s ith asperity.

97.5% even with noise. Another test was done to confirm that our sensor could successfully pick up complicated voice patterns from a song by attaching our sensor to the diaphragm of a loudspeaker while the song was played in a noisy environment.

Figure 3g, h presents another example in which we measured heart rates under two different conditions, normal and after running. The signals were successfully monitored in situ and provide crucial heart physiology information, such as the diastolic and systolic movements of the heart (Supplementary Fig. 15). To demonstrate another application, the nanoscale crack sensor was integrated into a microfluidic system to measure the input flow rate by showing the linear variation of resistance change with flow rate (Fig. 3i and Supplementary Fig. 16). The results of sensing information, such as the diastolic and systolic movements of the heart (Supplementary Fig. 18, inset). The derivative \(-dS/d\epsilon\) reveals an intriguing fluctuating behaviour, particularly at lower strains.

The normalized resistance measured at a strain sweep rate of 2 mm min\(^{-1}\). b, Reversible loading–unloading behaviour for various final strains. c, Resistance at the slowest loading–unloading rate, of 0.1 mm min\(^{-1}\), compared with the theoretical fit. Inset, results for no cracks. d, The 8 × 8 array of the crack sensor. Pressure was applied with a piece of polydimethylsiloxane (PDMS; red), and vibration and pressure were applied using a flapping ladybird (blue). The overall dimensions of the device are 5 cm × 5 cm, and each pixel is 2 mm × 2 mm. e, Region where pressure was applied using PDMS. f, Region where pressure and 0.2 kHz vibration were applied using a flapping ladybird. g, Representative image of the nanoscale crack sensor’s flexibility. h, Simple circuit scheme of the array in d for multiplexing. i, Pressure distribution with a piece of PDMS and a non-flapping ladybird. j, Vibration distribution with a piece of PDMS and a flapping ladybird. k, Dynamic pressure change in the red box in d. Inset, no vibration measured in the green shaded region. l, Dynamic pressure change with 0.2 kHz vibrations. Inset, frequency of 0.2 kHz measured in the green shaded region.
Figure 3 | Nanoscale crack junction-based sensor applications for sound and speech pattern recognition, human physiology monitoring and flow rate indicators. a, Image of a nanoscale crack sensor attached to a violin for sound wave recognition. The device is placed on the right string above the f-hole of the violin using commercial tape. b, E (yellow), A (green), D (blue) and G (red) strings played open (that is, with no finger stopping) produce different waveforms, which we collected using the nanoscale crack sensor. The E, A, D and G strings have fundamental frequencies of 659, 440, 294 and 196 Hz, respectively, as measured by the sensor. c, The measured sound waves of music playing (Salut d’Amour; excerpt shown at top). d, e, Comparisons of the acoustic waveform and auditory spectrogram changes measured by electrical resistance using the nanoscale crack sensor (left-hand images) and a standing microphone (right-hand images) in quiet (d) and noisy (e; ~92 dB) environments. All of the signals are measurements of a person saying ‘go’, ‘jump’, ‘shoot’ and ‘stop’. The signals from both the nanoscale crack sensor and the microphone are recorded clearly without noise (d). The signal from the standing microphone is not clear with ~92 dB of noise (right-hand image in e), whereas our crack sensor maintains its high level of accuracy under the same noise level (left-hand image in e). f, Image of the nanoscale crack sensor attached to a person’s neck for human speech recording. g, Image of the nanoscale crack sensor attached to a person's wrist for pulse measurement. h, Measured characteristics of the resistance difference for the nanoscale crack sensor attached to a person’s wrist. The detailed variations of the pulses for the reference (no load; black), normal heart rate (load of ~100 Pa; blue) and heart rate after running (300–400 Pa; red) are clearly observed. i, Resistance change at various flow rates as a function of time, measured using the nanoscale crack sensor encapsulated by a PDMS spacer in a microchannel. Inset, image of the nanoscale crack sensor attached to a microfluidic channel for liquid flow rate measurement.

peak (Supplementary Fig. 21). The crack surfaces do not all touch the opposite side; judging from the magnified SEM images in Supplementary Fig. 21b, only a small number of contacts exist. However, considering the width (~5 mm) and density (~1,000 cm\(^{-1}\)) of the cracks, many (of order 10\(^5\)) opposing crack surfaces are in contact in each sensor, and these crack surfaces lead to variations in the conductance.

Considering the above process, the simplified form of the normalized conductance can be written as

\[
S = \sum_i N_i \theta(k_i - \epsilon) \sum_i N_i
\]

(1)

where \(\theta(\epsilon - \epsilon)\) is the Heaviside step function and \(N_i\) is the number of crack asperities of height \(k_i\). For a normalized probability distribution function of crack asperity size \(p(\epsilon)\), we rewrite equation (1) as

\[
S = \int_{\epsilon}^{\infty} p(y) dy.
\]

(2)

We argue that the small variations in crack asperity due to grain shifts are distributed in the same manner as the large variations due to grain piling, which yields an equation for \(p(\epsilon)\) as a log-normal distribution function (details in ‘Theory section’ in Supplementary Information; \(\epsilon_0\) and \(\mu\) are fitting parameters):

\[
p(\epsilon) = \exp\left(-\ln(\epsilon/\epsilon_0)^2/\mu^2\right)
\]

(3)

Crack asperity heights have previously been approximated by a log-normal distribution\(^{21}\). Combining equations (3) and (2) yields

\[
S = \frac{1}{2} \left(1 - \text{erf}\left(\frac{\ln(\epsilon/\epsilon_0)}{\mu}\right)\right)
\]

(4)

where erf(\(x\)) is the error function. Equation (4) provides the resistance, \(R = 1/S\), which well fits the experimental data shown in Fig. 2c. The experimental values for –dS/d\(\epsilon\) averaged over different numbers of data points agree well with the theoretical –dS/d\(\epsilon\) obtained from equation (4) (Fig. 4b). The size distribution of the crack asperity heights (\(p(\epsilon)\)) was measured from 50 SEM images and is presented in Fig. 4b for comparison with the log-normal distribution (equation (3)) and the experimental average (–dS/d\(\epsilon\)) because \(p(\epsilon)\) should be equal to –dS/d\(\epsilon\) according to our theoretical model. The crack asperity heights also have a long-tailed skewed distribution that is consistent with equation (3) and (–dS/d\(\epsilon\)) for large strains. The large discrepancy at small strains is attributed to the fact that an initial gap of 5–10 nm exists even at 0% strain (Fig. 1f and Supplementary Fig. 21); thus, the presence of many small crack asperities with magnitudes less than the initial gap does not cause variations in the electrical conductance.
conductance. A different Pt film thickness was also studied to illustrate the hysterisis loops are clearly pronounced for a 100-nm-thick Pt film with cracks (see Supplementary Fig. 22 for an explanation of the hysteresis of thick films). A 20 nm-thick Au film was also studied, and the same bending with a 1 nm curvature radius was performed. Unlike the Pt film, the Au film did not generate similar straight cracks. Both the as-prepared Au film and the bent film exhibited random island-type cracks (Supplementary Fig. 23) and maintained conductivity while the film was stretched22–24 (see Supplementary Table 1 for a comparison of the hysteresis of thick films). A 20 nm-thick Au film was also studied, and with nanoscale, jagged crack edges, similar to those in our Pt film, would be required to provide the demonstrated ultrasensitivity.

Precise engineering of controlled crack formation other than the method of bending that we used here may further improve the performance of our crack-based ultrasensitive mechanosensor.

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Supplementary Information is available in the online version of the paper.