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2019

Pan, S., Liu, Z., Wang, M., Jiang, Y., Luo, Y., Wan, C., . . . Chen, X. (2019).
Mechanocombinatorially screening sensitivity of stretchable strain sensors. *Advanced Materials*, 31(35), 1903130-. doi:10.1002/adma.201903130

<https://hdl.handle.net/10356/137878>

<https://doi.org/10.1002/adma.201903130>

This is the peer reviewed version of the following article: Pan, S., Liu, Z., Wang, M., Jiang, Y., Luo, Y., Wan, C., . . . Chen, X. (2019). Mechanocombinatorially screening sensitivity of stretchable strain sensors. *Advanced Materials*, 31(35), 1903130-. doi:10.1002/adma.201903130, which has been published in final form at <https://doi.org/10.1002/adma.201903130>. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.

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Mechanocombinatorially Screening Sensitivity of Stretchable Strain Sensors

*Shaowu Pan, Zhiyuan Liu, Ming Wang, Ying Jiang, Yifei Luo, Changjin Wan, Dianpeng Qi, Changxian Wang, Xiang Ge, and Xiaodong Chen**

Dr. S. Pan, Dr. Z. Liu, Dr. M. Wang, Y. Jiang, Y. Luo, Dr. C. Wan, Dr. D. Qi, Dr. C. Wang, Dr. X. Ge, Prof. X. Chen,
Innovative Center for Flexible Devices (iFLEX), School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
E-mail: chenxd@ntu.edu.sg

Keywords: mechanocombinatorics, sensitivity screening, stretchable strain sensors, heterogeneous substrates, strain redistribution

Abstract

Stretchable strain sensors have aroused great interest for their application in human activity recognition, health monitoring and soft robotics. For various scenarios involving the application of different strain ranges, specific sensitivities need to be developed, due to a trade-off between sensor sensitivity and stretchability. Traditional stretchable strain sensors are developed based on conductive sensing materials, and still lack the function of customizable sensitivity. Herein, a novel strategy of mechanocombinatorics is proposed to screen the sensor sensitivity based on mechanically heterogeneous substrates. Strain redistribution over substrates is optimized by mechanics and structure parameters, which gives rise to customizable sensitivity. As a proof of concept, a local illumination method is used to fabricate heterogeneous substrates with customizable mechanics and structure parameters. A library of mechanocombinatorial strain sensors is created for extracting the specific sensitivity. Thus, this work not only demonstrates an effective strategy for screening of sensor sensitivity, but also contributes to the mechanocombinatorial strategy for personalized stretchable electronics.

Stretchable strain sensors, which transduce mechanical deformation into easily readable electrical signal, find wide application in human activity recognition, health monitoring and

soft robotics.^[1-15] Minute skin deformations induced by breathing, pulsing, and speaking are recorded for health assessment.^[16-20] Large deformations like bending/straightening of body joints are monitored for analysis of motion patterns.^[21-24] Among various application scenarios of different strain ranges, the requirement of sensitivity is different. For instance, high-sensitivity (gauge factor ≥ 20) is a prerequisite for extracting the detailed medical information in radial pulse detection.^[25,26] By contrast, low-sensitivity (gauge factor ≈ 1) is usually sufficient for the detection of large-scale strain in a majority of joint movements.^[1,27] Furthermore, there is a trade-off between the sensor sensitivity and stretchability. In other words, highly sensitive strain sensors are often realized at the expense of stretchability, and vice versa. Hence, developing strain sensors with customizable sensitivity could be vital for reliable sensing. The sensitivity of resistive-type strain sensors is defined by gauge factor, $GF = (\Delta R / R_0) / \varepsilon$, where ΔR is the resistance change with strain, R_0 is the resistance before strain, and ε is the applied strain.^[28] Currently, a large number of stretchable strain sensors are developed based on conductive materials, such as carbon nanotubes, graphene, metal networks, and liquid metal.^[1,2,26,29-34] The sensitivity is highly scattered and independent due to different sensing materials and diverse fabrication methods (Table S1, Supporting Information). Thus, it still remains a challenge to screen out the specific sensitivity from these traditional strain sensors.

The resistive-type stretchable strain sensors are typically composed of conductive films and polymer substrates.^[28,35,36] The mechanism involves the transfer of strain from the substrate to the conductive film during stretching, which induces cracks and thus increases electrical resistance; when the strain is released, the resistance returns to its initial value.^[6] Hence, the strain distribution of polymer substrates largely determines the resistance-strain behavior of the conductive film, thereby determining sensitivity. According to mechanics of materials, strain is uniformly distributed over a mechanically homogeneous film (Figure S1, Supporting Information). In contrast, taking a simplest mechanically heterogeneous film for

example, strain is redistributed over the film, and local strain is determined by two factors, mechanics and structure parameters (Figure S2, Supporting Information). Therefore, for the resistive-type stretchable strain sensors, the sensitivity could be screened via strain distribution of substrates. Based on finite element modeling (FEM), strain is indeed redistributed on mechanically heterogeneous substrates, which are composed of low and high modulus regions (**Figures 1a** and **b**). Numerous gradient structures can be precisely obtained by changing the parameter of substrates. By combining both mechanics and structure parameters of the substrates, a strategy we termed mechanocombinatorics, strain redistribution could be systematically studied. The strain enhancement is well customized by mechanically combined parameters, modulus ratio and pitch, which can be directly extracted from the strain enhancement library (Figure 1c).

Thus, we sought to screen sensitivity of stretchable strain sensors by the new strategy of mechanocombinatorics based on mechanically heterogeneous substrates. To demonstrate this concept, we first proposed a local illumination method to fabricate mechanically heterogeneous substrates composed of low and high modulus regions. The mechanical property of substrates can be exactly customized by the illumination time and mask design. Strain is redistributed over the mechanically heterogeneous substrates, thus leading to local strain enhancement in low modulus regions. This local strain enhancement enables longer microcracks in the gold films, resulting in larger electrical resistance of films. By the combination of mechanical parameters, the strain enhancement is fully tunable, and the sensitivity of strain sensors could be screened by mechanocombinatorics. In addition, the introduction of chemical bonds between conductive layers and elastomer substrates significantly enhances the adhesion strength, which is 10.3 times of the conventional metal as adhesive layer. Our proposed mechanocombinatorics not only provides an effective approach for screening of the sensitivity of strain sensors, but also is helpful in materials design and electronics technology towards personalized stretchable devices.

Fabrication of mechanically heterogeneous substrates is the key step to screen the sensitivity of stretchable strain sensors based on the above discussion. Polydimethylsiloxane (PDMS) is the most widely used substrate for flexible and stretchable electronics due to its excellent elasticity, biocompatibility and stability. In the typical thermal curing process, PDMS prepolymer are crosslinked to form Si-CH₂-CH₂-Si junction via reaction between vinyl group and silicon hydride group. The modulus of PDMS can be regulated by the mass ratio of base monomer to curing agent,^[37,38] which is not suitable to making a single piece of PDMS film with domains of different modulus. Till now, the main strategy to realize different mechanical domains in a single film is embedding rigid materials, e.g., polyimide, polyethylene terephthalate and photoresist, into the elastomers.^[39-42] However, the photolithography fabrication process is complicated, and the interface between different materials is hard to control in the current method. Furthermore, the mechanical property of these composite films is hard to regulate. Hence, it is infeasible to realize heterogeneous films with tunable mechanical properties. Herein, we proposed a local illumination method to fabricate mechanically heterogeneous films. Benzophenone, a kind of photoinitiator, was added into the PDMS prepolymer. Benzophenone reacts with the silicon hydride group under UV illumination.^[43,44] Hence, the crosslinking degree of PDMS would be tuned by UV illumination time of the prepolymer composite. A typical fabrication process of the mechanically heterogeneous substrate-based strain sensor is summarized in **Figure 2a**. Firstly, gold was thermally evaporated onto the poly(methyl methacrylate)/silicon (PMMA/Si) substrate. The gold film was soaked in thiol ethanol solution before spin-coating of benzophenone-PDMS prepolymer composites. Secondly, the prepolymer composites were locally illuminated under a photomask, and then the treated composites were thermally cured. Finally, the Au/PDMS film was released by dissolving the PMMA sacrificial layer. By changing the design of photomasks, heterogeneous films with different patterns can be fabricated following the same procedure. Unless specifically stated, heterogeneous films with

circle patterns were used for analysis. An optical image of the as-prepared conductive stretchable film is shown in Figure 2b. The exposed domains show lower modulus compared to the non-exposed domains. This was the result of fewer silicon hydride groups available for thermal curing in exposed domains, where some of silicon hydride groups reacted with benzophenone under UV illumination. The reaction degree in exposed domain can be controlled by the illumination time. A gradual step-down modulus of PDMS was realized by increasing illumination time (Figure 2c). The modulus of exposed PDMS could be expressed as follows.

$$E_e = 2.28 - 0.096t \quad (1)$$

where E_e is the modulus of exposed PDMS, and t is the exposure time. In this way, the mechanical property of heterogeneous films could be easily and accurately customized by exposure time. The value of modulus ratio (exposed domains to non-exposed domains), representing mechanical property of the heterogeneous film, can be calculated as follows.

$$\alpha_E = 1 - 0.042t \quad (2)$$

where α_E is modulus ratio, and t is the exposure time. In addition, the illuminated PDMS films maintained good stretchability (Figure S3, Supporting Information), which is crucial for stretchable electrodes.

Adhesion strength between conductive sensing materials and polymer substrates is crucial for stable performance and real application of stretchable electrodes. High adhesion strength can avoid unstable performance that arises from scraping during wearable electronics application. Till now, a few methods have been reported for improving adhesion strength. For instance, chromium was frequently introduced as the adhesive layer for enhancing adhesion strength between gold and elastomer substrates.^[45] An interlocking structure between gold and PDMS film was developed by using the anodic aluminum oxide membrane as the template.^[33] However, these physical adhesion enhancement methods either are poorly

effective or require complicated fabrication process. In our approach, we used (3-mercaptopropyl)trimethoxysilane (MPTS) as a “bridge molecule” to bond gold with PDMS. It is well known that the thiol molecule forms monolayers on the gold film by formation of covalent bond between gold and sulfhydryl.^[46-48] The MPTS-treated gold film became more hydrophilic after chemical modification, as shown by the reduction of contact angle from 84.5 ° to 65.1 ° after chemical modification (Figure S4, Supporting Information), indicating the presence of methoxy groups on the gold surface (Figure S5, Supporting Information). Following the MPTS treatment, PDMS prepolymer was crosslinked on top of the gold film, and the Au/PDMS laminate was easily released from the Si support by dissolving the PMMA sacrificial layer.

We firstly qualitatively evaluated the adhesion strength between gold and PDMS film. Adhesive polyimide tapes were used in an attempt to peel off gold film from PDMS. In MPTS-treated samples, the gold film could not be peeled off from PDMS substrates (Figures S6a and S6b; Video S1, Supporting Information). In the control experiment, samples were prepared by the commonly used adhesion strength enhancement method, chromium as adhesion layer. On the contrary, the gold film in control samples was totally removed by the tape, exposing the underlying PDMS (Figures S6c and S6d; Video S2, Supporting Information). The high adhesion between gold and PDMS film in our sample is due to the introduction of MPTS “bridge molecule”. As discussed before, the gold film reacted with sulfhydryl functional groups to form thiolate-gold bonds. Meanwhile, the other end Si-OCH₃ functional groups reacted with the PDMS prepolymer to form the Si-O-Si bond (Figure S7, Supporting Information). Hence, a high adhesion between gold and PDMS films could be achieved through introduction of chemical bonding. In order to verify the above explanation, we used the dodecanethiol as a control “bridge molecule”, and the gold film cannot adhere to PDMS film because of its lack of functional groups to form Si-O-Si bond with PDMS prepolymer (Video S3, Supporting Information). The adhesion strength was further

quantitatively measured via the standard tensile testing,^[49,50] which was carried out using a rigid rod and epoxy resin as glue (Figure S8a, Supporting Information). The typical sample for testing the adhesion strength is shown in Figure S8b. The value of adhesion strength is the peeling stress divided by the peeling area. The adhesion strength in MPTS-modified samples is 2.87 MPa, whereas the adhesion strength is only 0.19 MPa for samples without metallic adhesion layer. Even for the Cr-modified sample, the adhesion strength is only 0.28 MPa. The adhesion strength based on our method is 10.3 times of Cr-modified method (Figure 2d). Undoubtedly, our strategy utilizing the chemical bonding is very effective for improving of adhesion strength between conductive materials and elastomers in stretchable devices.

Understanding surface morphology of conductive sensing materials is essential for study of the electrical resistance change of stretchable strain sensors. From foregoing analysis, strain is redistributed in the mechanically heterogeneous substrate-based strain sensors (**Figure 3a**). In order to quantify local strain, we selected a small unit of the mechanically heterogeneous substrate to study in detail. Viewed from its corresponding 3D map of strain distribution, local strain in low modulus part was obviously larger than that in high modulus part. Moreover, local strain in low modulus part was larger than the applied strain; in other words, local strain is enhanced at these regions (Figure 3a). The local strain could affect the surface morphology of conductive materials as aforementioned. Therefore, gold surface morphology of the heterogeneous substrate-based strain sensor was observed. Figure 3b shows the SEM image of the gold film on modulus transition region, from high modulus domain (Part I) to low modulus domain (Part II) at 50% strain. Cracks perpendicular to the stretching direction were formed in the gold film, which is the result of release of strain energy for intrinsic unstretchable materials.^[51-53] Meanwhile, different crack morphologies were found in these two different modulus parts from enlarged views (Figures 3c and 3d), longer cracks appeared in low modulus parts. We further obtained statistic analysis result, which verified that the length of cracks in low modulus part was longer than those from the

high modulus part (Figure 3e). This phenomenon stems from strain redistribution. Local strain in low modulus part was greatly enhanced compared to that in high modulus part (Figure S9, Supporting Information), which induces larger strain in gold film, leading to longer and wider cracks. On the contrary, uniformly distributed cracks appeared in the gold film on mechanically homogeneous film under the same applied strain (Figure S10, Supporting Information), due to its homogeneous local strain distribution. Longer cracks normally result in increased electrical resistance.^[54] We further simulated the voltage distribution of SEM images to show their electrical conductivity using previous reported method.^[55] SEM images were turned binary from grayscale, and the voltage distribution was simulated by applying a voltage drop on both the left and right sides (Figures 3f and 3g). It clearly showed that voltage distribution of conductive film on low modulus parts drops much faster than that of high modulus parts, indicating larger electrical resistance in low modulus parts.

The strain distribution of substrates affects the resistance-strain property of strain sensors, and this is the reason for screening of sensitivity using mechanically heterogeneous substrates. We firstly studied the resistance-strain property of heterogeneous substrates-based strain sensors under uniaxial tensile strain of 50%. The value of resistance ratio (R/R_0) increased with increasing strain, and went back to original resistance after the release of strain (**Figure 4a**). The R_0 and R refer to the electrical resistance at unstretched and stretched state, respectively. Then, a series of strain sensors with different pitches were fabricated by tuning the photomask parameter. We recorded the resistance change of heterogeneous substrates-based strain sensors with different pitches under applied strain. The resistance ratio reaches the maximal value at a pitch of 1.06 mm (Figure 4b). For comprehensive understanding of the resistance ratio change, we built the contour maps of the value of resistance ratio versus applied strain and pitch (Figure 4c). The value of resistance ratio increased as the applied strain increased. The highest value was close to 38, which appeared at a pitch of 1.06 mm and

50% strain.

Modulus ratio is another parameter for the sensitivity screening. Local strain in low modulus parts is gradually enhanced when the modulus ratio value is reduced (Figure S11, Supporting Information), which induces larger local strain in the gold film to give a sharper increase of resistance. Strain sensors based on heterogeneous substrates with different modulus ratios were fabricated by different exposure times. The value of resistance ratio was recorded under 50% strain, and the value of resistance ratio gradually increases with increasing modulus ratio at the same pitch, which gives the same variation tendency of gauge factor (Figure 4d). It should be noted that the heterogeneous substrate-based strain sensor has a declining stretchability for the further reduction of modulus ratio. Here, the stretchability means the critical value of the strain sensor from conductive to non-conductive. For instance, the heterogeneous substrate-based strain sensor with a modulus ratio of 0.42 has a stretchability of 40% (Figure S12, Supporting Information). In order to reasonably compare their performances, we did not put them in a single figure. Hence, we give a unified stretchability of 50% for study (Figure 4d). The optimized value of resistance ratio is 38.9 for the heterogeneous substrate-based strain sensor with a pitch of 1.06 mm and modulus ratio of 0.51 under 50% strain, which achieved a gauge factor of 75.8 (Figure 4d). In the control sample of mechanically homogeneous substrate-based strain sensor, it shows a small value of resistance ratio under the same strain (Figure S13, Supporting Information), and has a gauge factor of 3.3. There is a 21.9 fold increase in sensitivity for heterogeneous substrate-based strain sensors.

These results show that pitch and modulus ratio can be used for the screening of gauge factor, ranging from 3.3 to 75.8, in heterogeneous substrates-based strain sensors. In order to systematically understand the mechanocombinatorial strain sensors, the relationship among gauge factor, pitch, and modulus ratio is summarized in the following semiempirical equation (details as shown in Supporting Information).

$$g = g_0 [1 + A(\alpha_E - 1)^3 \exp(-B \frac{(\ln \frac{\sqrt{2}p - 2R}{R})^2}{\frac{\sqrt{2}p - 2R}{R}})] \quad (3)$$

Here, g is the gauge factor of the heterogeneous substrate-based strain sensors; α_E is the modulus ratio; p is the pitch; g_0 is the gauge factor of mechanically homogeneous substrate-based strain sensor, and it is 3.3; R is the radius of circle pattern in high modulus parts, and it is 0.5 mm; A is -172.9; B is 12.33. Based on the Equation 3, the fitting curves of gauge factor based on pitch and modulus ratio can be obtained, which match well with the experimental result (Figure S14, Supporting Information). Furthermore, we created a contour map where the gauge factor could be screened by the combination of pitch and modulus ratio variables (Figure 4e), which could help researchers fully study stretchable strain sensors. Undoubtedly, our mechanocombinatorics strategy not only successfully extracts the optimized sensitivity, but also provides a prototype of customizable sensitivity for strain sensors.

The stability of stretchable strain sensors was studied by repetitive mechanical load and unload test. It retained high performance after 3000 cycles of stretching at 50% strain, which indicate that heterogeneous substrates-based strain sensors have high stability (Figure 4f). The sensitivity of stretchable strain sensor can be further improved by integrating the strain sensor with auxetic mechanical metamaterials (Figure S15, Supporting Information). The incompressible elastomeric substrates are always compressed in transverse direction with expansion in longitudinal direction due to its Poisson's ratio of 0.5, which is detrimental to the sensitivity of strain sensors.^[26] Auxetic mechanical metamaterials was recently proved to be an effective structure to enhance the sensitivity of strain sensor due to its 2D expansion at uniaxial tensile strain.^[26] Here, we used the auxetic metamaterial structure with a Poisson's ratio of 0.25 (Figure S16, Supporting Information). A higher gauge factor of 157 was achieved from this integrated sensor, which was 38.3 times of that of mechanically homogeneous substrate-based strain sensor at the same applied strain (Figure S17, Supporting

Information).

Finally, we demonstrated that our stretchable strain sensors can be used to monitor both large and tiny human motions. Joint movements, which constitute a significant portion of our daily activity, typically involve large deformations. We attached strain sensors onto joints to monitor their motions, and real time signal was transmitted to personal electronic device when strain sensor was integrated with wireless ammeter (Figure S18a, Supporting Information). For example, the resistance signal of a strain sensor attached to the index finger could be read and recorded by an android smartphone (Figure S18b, Supporting Information). The finger bending angle was positively related to the resistance value of strain sensor (Figure S18c, Supporting Information). In addition to sensing large strains from joint movements, heterogeneous substrates-based strain sensors can also detect tiny human motion. We attached stretchable strain sensors onto the throat to detect the swallowing behavior. The repetitive swallowing motion was continuously recorded by the resistance change of strain sensor (Figure S19a, Supporting Information). In comparison, the signal detected by mechanically homogeneous substrate-based strain sensor was almost invisible due to its low sensitivity (Figure S19b, Supporting Information). The signal intensity of heterogeneous substrates-based strain sensors had 25.2 times improvement compared to mechanically homogeneous strain sensors (Figure S19c, Supporting Information). These results indicate that heterogeneous substrates-based strain sensors are capable to satisfy diverse application scenarios, including large joint movements and subtle skin deformations.

In summary, the novel strategy of mechaocombinatorics to screen the sensitivity of stretchable strain sensors is proposed. As an example, we fabricated stretchable strain sensors based on mechanically heterogeneous substrates. The local illumination method was used to fabricate heterogeneous substrates with mechanics and structure parameters. We find that mechanically heterogeneous substrates exhibit strain redistribution, which are controlled by the combination of modulus ratio and pitch. A library of stretchable strain sensors based on

numerous mechanically heterogeneous substrates is successfully created for screening of sensitivity. This work is instructive to customize devices via mechanocombinatorial design of substrates, thus opening up a new field of mechanocombinatorics.

Experimental Section

Fabrication of stretchable strain sensors built from heterogeneous substrates. A layer ($\approx 5\ \mu\text{m}$) of poly(methyl methacrylate) (PMMA) was deposited onto the silicon wafer by spin-coating a 7% PMMA chlorobenzene solution, followed by baking at $180\ ^\circ\text{C}$ for 2 min. Then, a thin layer (15 nm) of gold film was thermally evaporated onto the PMMA/Si substrate under an evaporation rate of $0.3\ \text{\AA}\ \text{s}^{-1}$. This gold film was soaked in 25 mM (3-mercaptopropyl)trimethoxysilane ethanol solution for 7 min. After above chemical modification, the gold film was dried under air flow. For preparing UV-tunable PDMS prepolymer mixture, the base monomer and curing agent with a weight ratio of 10:3 was firstly mixed well. Meanwhile, benzophenone photoinitiator was dissolved in xylene solvent with a concentration of 40 wt%. Finally, the benzophenone xylene solution was added into the PDMS prepolymer with a concentration of 6 wt% and then degassed for usage. The photoinitiator-added PDMS prepolymer was spin-coated onto the gold film at 700 rpm for 30 second. Then, the PDMS prepolymer composite was locally illuminated using a photomask. The illuminated PDMS prepolymer was cured in an oven at $80\ ^\circ\text{C}$ for 8 h. The curing sample was soaked in acetone solvent to dissolve PMMA for peeling off the heterogeneous substrate-based strain sensors from the silicon wafer. Numerous strain sensors based on heterogeneous substrates were fabricated by different illumination times and photomask layouts.

Fabrication of Au/PDMS films with and without adhesion layer. For the control sample, a layer of Cr film with a thickness of 10 nm was first thermally evaporated onto PDMS film under an evaporation rate of $0.3\ \text{\AA}\ \text{s}^{-1}$. Then, a layer of gold film with a thickness of 50 nm

was thermally evaporated onto above film at an evaporation rate of $0.3 \text{ \AA s}^{-1}$. In the control sample without Cr adhesion layer, the gold film was directly evaporated onto PDMS films at the same condition.

Supporting information

Supporting information is available from the author.

Acknowledgements

We thank the financial support from the National Research Foundation, Prime Minister's Office, Singapore, under its NRF Investigatorship (NRF2016NRF-NRF1001-21), Singapore Ministry of Education (MOE2014-T2-2-140, MOE2015-T2-2-060), and K. C. Wong Education Foundation.

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Figure 1. Mechanocombinatorially screening sensitivity of stretchable strain sensors based on strain redistribution of mechanically heterogeneous substrates. a) Schematic of mechanically heterogeneous films with different pattern geometries. The gray and black represent low and high modulus material, respectively. Modulus ratio, the ratio of low to high modulus, is used to define the mechanical property. Pitch is the center to center distance between adjacent parts of high modulus. b) Strain distribution of mechanically heterogeneous substrates by finite element modeling analysis. The applied strain is redistributed, and local strain in low modulus part is larger than the applied strain. c) The customizable characteristic of strain enhancement from mechanically heterogeneous substrates by a novel strategy of mechanocombinatorics. The strain enhancement can be controlled by combined variables of modulus ratio and pitch. Local strain of the low modulus part in the structure unit (dotted area) is used for statistic analysis. Strain enhancement is the mean value, which is calculated by dividing local strain increment (local strain minus applied strain) by applied strain.

Figure 2. Schematic of fabrication process and related principle of stretchable strain sensors built from mechanically heterogeneous substrates. a) Schematic of fabrication process of stretchable strain sensors based on mechanically heterogeneous substrates: (I) A layer of gold film was deposited onto PMMA/Si substrate by thermal evaporation method. (II) Au/PMMA/Si was soaking in thiol ethanol solution and then a layer of UV-sensitive PDMS prepolymer was spin-coated on the thiol-treated gold film. (III) PDMS prepolymer was selectively exposed to UV light by a photomask. (IV) UV-treated PDMS prepolymer was cured by heating. (V) A thin and conductive film based on the heterogeneous substrate was obtained by dissolving PMMA. b) The optical image (left) and schematic (right) of the heterogeneous substrate-based strain sensor. c) The influence of UV exposure time on Young's modulus of PDMS films. The red line is the fitting curve, and Adj. R^2 is 0.98. d) A comparison of adhesion strength in thiol-modified electrodes, control electrodes without metallic adhesion layer, and conventional Cr-modified control electrodes.

Figure 3. Strain distribution and surface morphology of stretchable strain sensors built from mechanically heterogeneous substrates. a) Strain redistribution of strain sensors based on mechanically heterogeneous substrates under applied strain. The schematic diagram of a stretchable strain sensor based on mechanically heterogeneous substrate (top). The overall strain distribution in a mechanically heterogeneous substrate (left). The detail strain distribution character in dotted box of left figure (middle). The mean value of local strain in the high and low modulus parts in the middle figure (right). b) The SEM image of surface conductive materials (the gold nanofilm) on modulus transition parts in a mechanically heterogeneous substrate-based strain sensor (pitch: 1.06 mm; diameter: 1.0 mm) under applied strain of 50%, parts I and II denote the high and low modulus parts, respectively. c, d) Enlarged SEM images of parts I and II, respectively. e) Statistic analysis of crack length for parts I and II. f, g) Voltage distribution simulation based on SEM images of Figures 3c and d, respectively. Figure 3g, corresponding to the voltage distribution of Figure 3d, shows fast voltage drop and thus indicates a large electrical resistance.

Figure 4. Screening sensitivity of stretchable strain sensors built from mechanically heterogeneous substrates by using a strategy of mechanocombinatorics. a) Resistance ratio of stretchable strain sensors under uniaxial tensile strain. b) Resistance ratio is tuned by pitch under 50% applied strain for strain sensors with modulus ratio of 0.51. c) The contour mapping of resistance ratio as a function of strain degree (horizontal axis) and pitch (vertical axis) for the strain sensors; strain sensors based on heterogeneous substrates have same modulus ratio of 0.51. d) Screening the sensitivity of strain sensors by combination of pitch and modulus ratio variables. e) The contour map of sensitivity based on modulus ratio and pitch obtained by Equation 3. f) Cycling durable testing of strain sensors under continuous stretching.

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A novel strategy of mechanocombinatorics is developed to screen the sensitivity of stretchable strain sensors. Mechanically heterogeneous substrates, defined as substrates comprising low and high modulus regions, are incorporated into strain sensors. Strain distributions over substrates are controlled by combined parameters of mechanics and structure. A library of strain sensors based on heterogeneous substrates is created for screening of sensitivity.

Mechanocombinatorics, sensitivity screening, stretchable strain sensors, heterogeneous substrates, strain redistribution

*Shaowu Pan, Zhiyuan Liu, Ming Wang, Ying Jiang, Yifei Luo, Changjin Wan, Dianpeng Qi, Changxian Wang, Xiang Ge, and Xiaodong Chen**

Mechanocombinatorially Screening Sensitivity of Stretchable Strain Sensors

ToC figure