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Laser-microengineered flexible electrodes with enhanced sensitivity for wearable pressure sensors

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ABSTRACT

In this study, a laser-microengineered wearable pressure sensor was developed. The sensor offers a sensing range from 0.005 to 50.0 kPa, a sensitivity approximately -0.107 kPa^{-1}, and high durability (>10,000 cycles). The finite element simulation shows that the external forces are amplified and transmitted by the laser-engineered microstructures, contributing to the enhanced sensitivity of the device. The laser-microengineered sensors are promising to be applied in the electronic skin for detecting various external stimuli.

1. Introduction

Wearable pressure sensor is an important sensory cell of electronic skin (E-skin) [1–7], with the indispensable characteristics of flexibility/stretchability for conformably attached to curved surfaces, a large sensing range from a gentle touch to manipulate objects, a high sensitivity to detect mechanical stimuli, and high durability for practical applications [8–17]. Among various devices responding on resistive [18–23], capacitive [24–27], piezoelectric [28–30], and transistor sensing [31–34] modes, the resistive ones are mostly studied, ascribed to the uncomplicated sensing mechanism [7]. However, due to the relatively large modulus viscoelasticity of elastomer substrates used in pressure sensors [35,36], the devices suffer from limited sensing range and low sensitivity [21,22]. To improve the device performance, employment of porous structures [37,38] and integration of microstructures [2,25] are two strategies generally used. The porous structures, including hollow sphere conductive polymer [18], carbon-based sponge [39,40], and carbon aerogels [38], are able to enhance the deformability of the sensors, and thus increase the sensitivities. The integration of microstructures into device is inspired by the intermediate ridges located at the interface of dermal and epidermal layers of human skins. The incorporation of microstructures into device configuration significantly enhances the performance of the wearable pressure sensors [21,25]. Lithography can generate geometry-controllable microstructures on elastomers [2,21]. Nevertheless, it lacks efficiency due to the complicated multi-procedures involved [9]. Duplication of microstructures from natural resources [9,35,41] or sandpapers [42] is cost-effective, but it lacks controllability in the shape and dimensions, and thus the sensitivity of the devices.

Ultra-fast laser microengineering is capable of generating surface structures including peaks, periodic gratings, and ripples for light trapping and hydrophobicity, with advantages of small heat-affected zones, high efficiency, and scalability [43]. This method might provide an alternative solution for generating microstructures on elastomers for wearable pressure sensors. To the best of our knowledge, laser-microengineered sensors have not been investigated so far.

In this work, wearable pressure sensors was developed using laser-microengineered carbon nanotube/polydimethylsiloxane (CNT/PDMS) electrodes. The experiment results showing that: (1) laser-microengineering can effectively modulate the dimensions of the microstructure using different laser power, and thus the sensitivity of the devices. (2) The laser-microengineering can process a PDMS mold with a dimension of 1 × 1 cm^2 within 10 s, demonstrating its high efficiency. The laser-microengineered sensors demonstrate an enhanced sensitivity approximately -0.107 kPa^{-1}, a wide sensing range, response speed around 180 ms, and high durability larger than 10,000 cycles. The laser-microengineered

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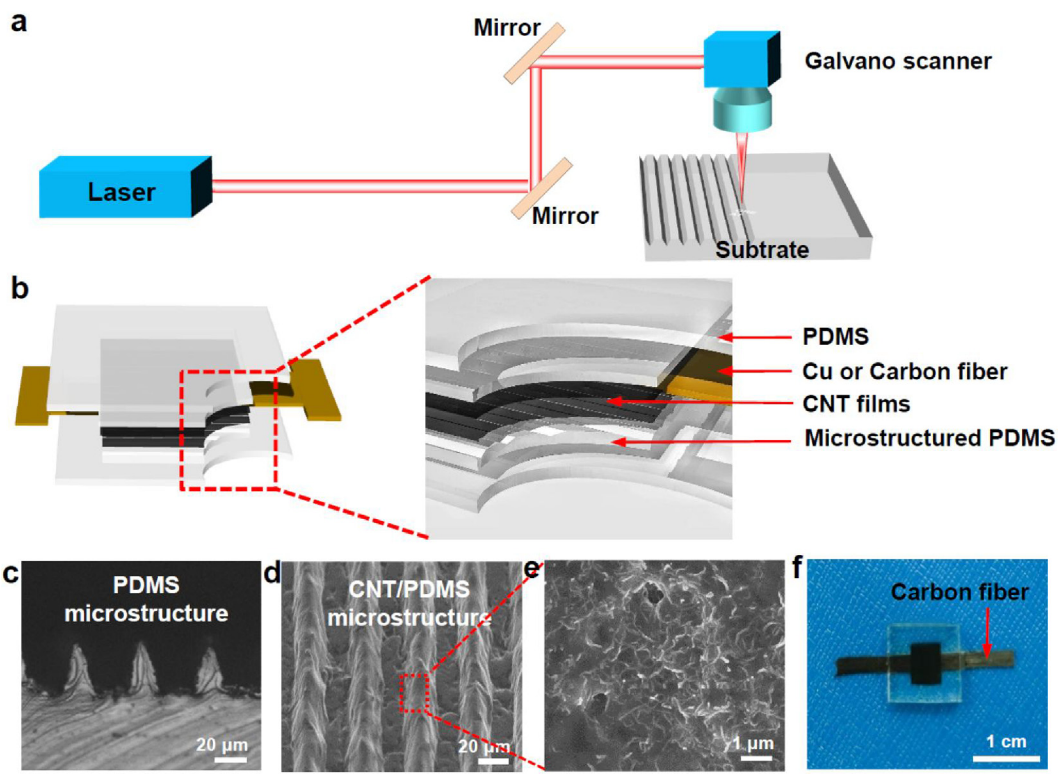

Fig. 1. (a) A schematic showing the laser microengineering of PDMS. (b) A schematic exhibiting the configuration of the pressure sensor. (c) An optical image of a laser-microengineered PDMS. (d,e) SEM images showing a laser-microengineered electrode. (f) A photograph of a laser-microengineered device.

sensors are used for external stimuli detection, showing promising applications in the E-skins.

2. Results and discussions

Fig. 1a is the schematic exhibiting the laser microengineering procedure of PDMS mold. The depth and the width of the grooves (Fig. 1c and S1) formed on the PDMS molds increase with the increased laser power (Table S1), indicating the geometry controllability of the laser microengineering. A PDMS mold with a dimension of 1×1 cm^2 can be processed within 10 s, demonstrating the efficiency of the method. After the duplication process, PDMS with microstructures (Figure S2) was used for the device fabrication. Fig. 1b shows the structure of the device, configured with a flat CNT/PDMS top electrode and a laser-microengineered CNT/PDMS bottom electrode. The detailed preparation procedures (Figure S3) are described in Supplementary Material. Fig. 1d and e shows the SEM images of the laser-microengineered electrode used for the device construction (Fig. 1f).

The electromechnical behaviors of the laser-microengineered devices were systematically studied. Fig. 2a–c shows the SEM images of the laser-microengineered electrodes prepared using different laser powers. As the laser power increases, the aspect ratio of the microstructrues increases (Table S1). Fig. 2d shows the curves of the relative resistance change ($\Delta R/R_o$) of the devices at applied loadings. The $\Delta R/R_o$ decreases with the increased applied pressures

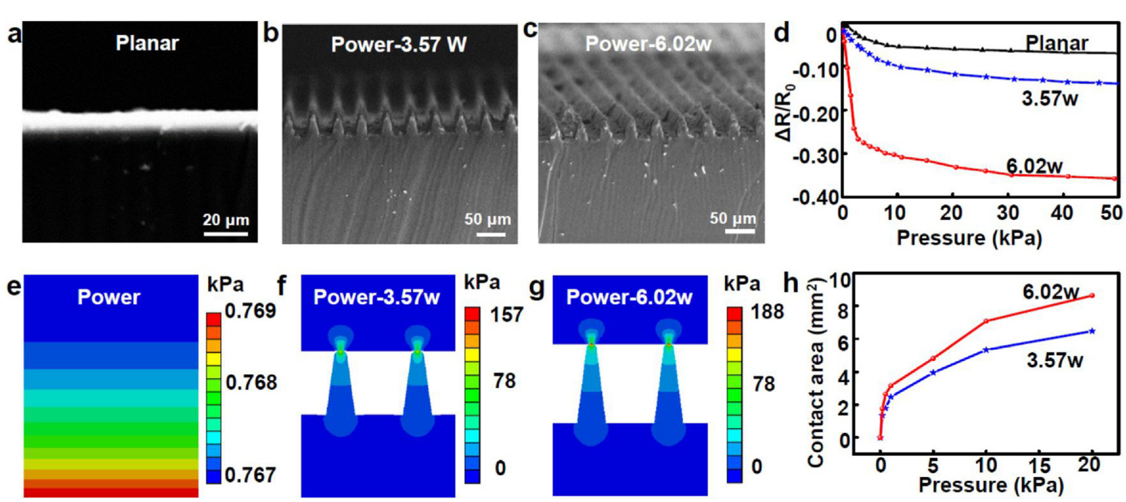

Fig. 2. (a–c) SEM images of laser-microengineered electrodes prepared at 0, 3.57, and 6.02 W. (d) Relative resistance change of the devices at different pressures. (e–g) The local stress distribution of the devices obtained by FEM. (h) Contact area changes in the laser-microengineered sensors.