Proceedings of the 12th IEEE International
Conference on Nano/Micro Engineered and Molecular Systems
April 9-12, 2017, Los Angeles, USA

A Novel Multi-functional Self-powered Pressure Sensor With Hierarchical Wrinkle Structure

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***Abstract*—This paper reports a novel multi-functional self-powered pressure sensor with hierarchical wrinkle structure which is able to detect pressure as well as harvest the mechanical energy. Due to the utilization of hierarchical wrinkle structure, the device shows high sensitivity of 2.0 kPa-1 with the excellent response performance of 0.15 ms (rise-time) and 0.7 ms (release-time), respectively. In addition, the high-density surface charges on the fluoride PDMS wrinkle structure deriving from the contact of PDMS layer and ITO layer enable the device to act as an energy harvester. This self-powered pressure sensor can figure out different stimuli (bending & pressure), the device generates 300V and 3μA under bending while generating 75V and 17μA under pressure. Therefore, the device can be utilized to identify differentiate mechanical stimuli without external batteries.**

Keywords—multi-function; hierarchical wrinkle structure; highly-sensitive; mechanical stimuli differentiation

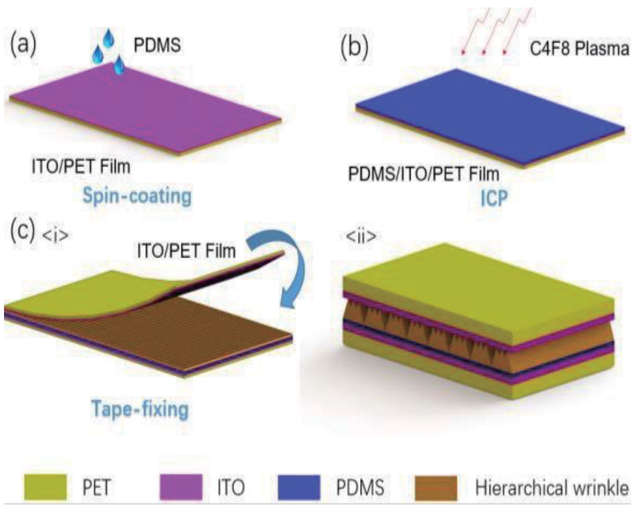
I. INTRODUCTION

With the development of wearable devices[1], kinds of sensors with high sensitivity have drawn more attention. Especially, pressure sensors[2] have gained great interest due to their wide application fields such as wearable healthcare monitors[3], electronic skins[4,5], and robotic skins[6]. However, batteries are becoming one of the crucial problems in the development of the wearable devices because of their limited energy storage, bucky size and lack of flexibility. Therefore, mechanical energy harvested from human motion is considered as one of most sustainable and accessible energy source around the human body[7,8]. Triboelectric nanogenerator (TENG)[9,10] as a potential solution for harvesting mechanical energy, has been studied for powering electronic devices.

To date, most of the pressure sensors and generators are designed independently[11,12]. Meanwhile some multi-functional devices are complicatedly designed, requiring multi-step fabrication[13]. Besides, the microstructure on the surface of the device such as pyramids or nanofibers which is employed with photolithographic technique or CVD, also increases the difficulty, complexity and cost in the fabrication.

Wrinkle structures formed on polymer such as polydimethylsiloxane (PDMS) attract people's attention for their unique advantages such as simple fabrication process, flexibility, stretchability, and the adaptation for large area pattern[14]. Meanwhile, wrinkle structures on PDMS have a variety of scientific and technological applications that range from stretchable electronics, tunable adhesion and wettability to tissue engineering, microfluidics and lab on chip devices[15-18]. Many researches have indicated that comprising a stiff layer on an elastic polymer substrate can result in wrinkle structure on the multilayered film. Recently, the excellent property of wrinkle structure have drawn much attentions in TENG due to its enlarged surface areas, which contribute to dramatic high output voltage and current [19].

In this work, we utilize hierarchical PDMS wrinkle structure to the design and fabricate of the pressure sensor, which not only simplifies the fabrication of the device but also enabling a capacitive pressure sensor with high performance. The hierarchical wrinkle structure can even differentiate mechanical stimuli (bending & pressure) without extra batteries.



II. EXPERIMENTAL PROCEDURES

2.1 Fabrication process

Figure 1: Schematic of the fabrication process of the sensor with the hierarchical wrinkle structure.

The detail fabrication process of the multi-functional pressure sensor with hierarchical wrinkle structure is shown in Figure 1. Firstly, the base solution and curing agent of commercial PDMS (Sylgard 184, Dow Corning Corporation) are mixed with a quantity ratio of 10:1. The vacuum degassed mixture of PDMS base and cross-linker is spin coated on the indium tin oxide (ITO) coated polyethylene terephthalate (PET) film. Secondly, the thin PDMS/ITO/PET film is heated at 100 ℃ for 45 seconds to make a half-cured PDMS. Next a C_4F_8 plasma treatment is implemented on the PDMS/ITO/PET film's half-cured PDMS surface for 1000 seconds, after which the PDMS/ITO/PET film is heated again till the curing of the thin PDMS layer. Finally, cover the wrinkle-structured film with another ITO/PET film. Figure 1c<ii> shows the schematic of the device with 5 layers which are PET, ITO, wrinkle PDMS structure, ITO and PET, respectively.

The photograph of the device is shown in Figure 2. Since it is fabricated with micromachine technology, the sensor can be made as thin as 260μm with great flexibility as shown in Figure 2a<ii> and Figure 2a<iii>. The area of the whole device is about 6.25 cm^2.

The multi-functional pressure sensor works as both a capacitive effect sensor and triboelectric nanogenerator. As a capacitive effect sensor, the two ITO layers work as two electrodes and the PDMS hierarchical wrinkle structure, the thin PDMS layer and the air between the wrinkle gap work together as a dielectric layer together. When the pressure applied on the top of device, the dielectric layer is compressed and thus the capacitance of the device is changed. As mentioned above, the PDMS/ITO/PET film with hierarchical wrinkle structure is assembled with another ITO/PET film to form an TENG. Considering the feature of energy harvesting, the PDMS with hierarchical wrinkle structure and the ITO layer work together as two charges generation surface and the air among the wrinkle gap enables the PDMS layer and the ITO layer to contact and separate. Both of their working mechanisms are illustrated in Figure 2b and c.

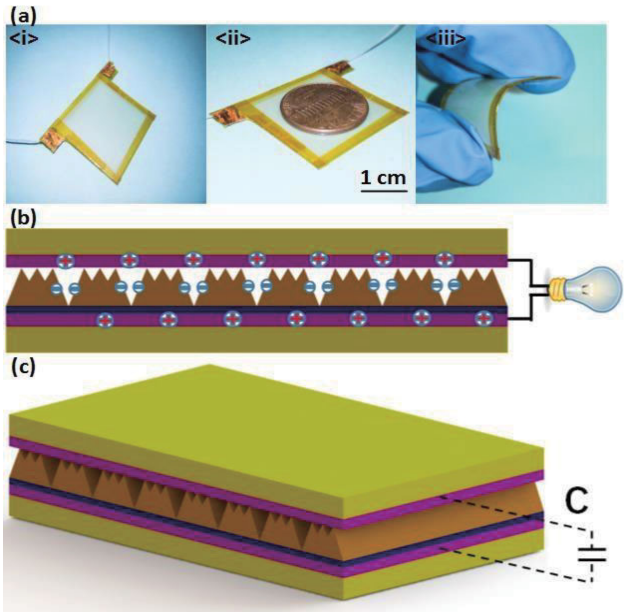


Figure 2: (a) Photographs of the multi-functional pressure sensor. (b) Schematic of the workings mechanism as a generator. (c) Schematic of the workings mechanism as a pressure sensor.

2.2 Measurement and Analysis

The 3D hierarchical wrinkle structure of the multi-functional pressure sensor was analyzed using a LSM. The output voltage was measured via a digital oscilloscope (Agilent DSO-X 2014A) using a 100 MΩ probe (HP9258), and the current was amplified by a SR570 low noise current amplifier from Stanford Research systems.

III. Results and Discussions

3.1 confocal microscopy image analysis

Figure 3 shows the confocal microscopy image of the hierarchical wrinkle structure. It is very clear the surface of the big wrinkle is not smooth as the other reported monolayer wrinkle. As mentioned before, the hierarchical wrinkle is thin and the amplitude is about 10 μm. The wavelength of the big wrinkle is about 40 μm, while the wavelength of the small wrinkle existing on the surface of the big wrinkle is about 5 μm.

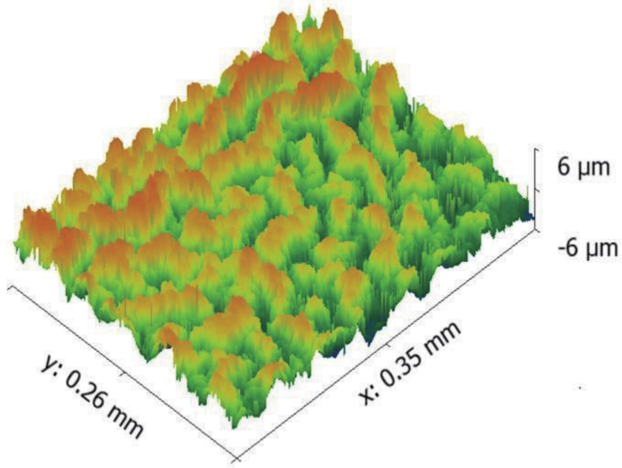


Figure 3: Confocal microscopy image of the hierarchical wrinkle structure of the multi-functional pressure sensor.

The hierarchical wrinkle is the result of the long C_4F_8 treating time. The formation process can be explained as follows. At first, the accelerated fluorocarbon polymer deposits directly on the surface of uncured PDMS, which forms a stiff layer and causes the big deformation of the PDMS. As C_4F_8 plasma continues to deposit on the stiff layer, the plasma also make the stiff layer deform with smaller structure. When the PDMS recovers to its undeformed state, the hierarchical wrinkle structure occurs.

3.2 Electrical characterization and analysis

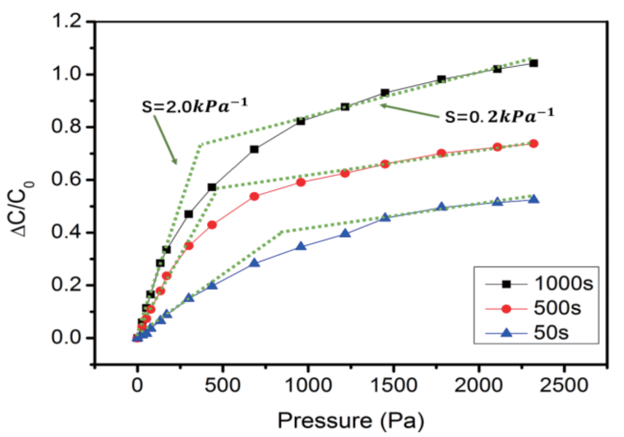


Figure 4: Characterization of the capacitive pressure sensitivity of the sensor with the dual-scale wrinkle structure (1000s C4F8 plasma-treating) and single-scale wrinkle structure (500s&50s C4F8 plasma-treating).

Figure 4 shows the sensitivity of 3 capacitive pressure sensors fabricated using different parameter combinations (monolayer wrinkle structure: 50s, 500s; hierarchical wrinkle structure: 1000s) of C_4F_8 treatment. Since extending C_4F_8 plasma treating time to 1000s can produce hierarchical wrinkle structure rather than monolayer wrinkle structure on the PDMS surface, the sensitivity in the relatively low pressure regime (0-500 Pa) can get an obvious promotion from 0.5 kPa^{-1} (50s plasma treating), 1.0 kPa^{-1} (500s plasma treating) to 2.0 kPa^{-1} (1000s plasma treating). Moreover, in the relatively high pressure regime (more than 1500 Pa), the sensitivity of the sensor gets a slight promotion from 0.1 kPa^{-1} (50s & 500s plasma treating) to 0.2 kPa^{-1} (1000s plasma treating).

When the C_4F_8 plasma treating time is reduced from 1000 seconds to 500 seconds, the hierarchical wrinkle structure can not occur and the PDMS surface form only monolayer wrinkle structure. Also continually reducing the plasma treating time shows the same phenomenon.

As shown in Figure 5, the response performance is excellent with the release-time is 0.7 ms and the rise-time is even only 0.15 ms. That means the mechanical pressure can rapidly deform the wrinkle structure and change the capacitance of the device.

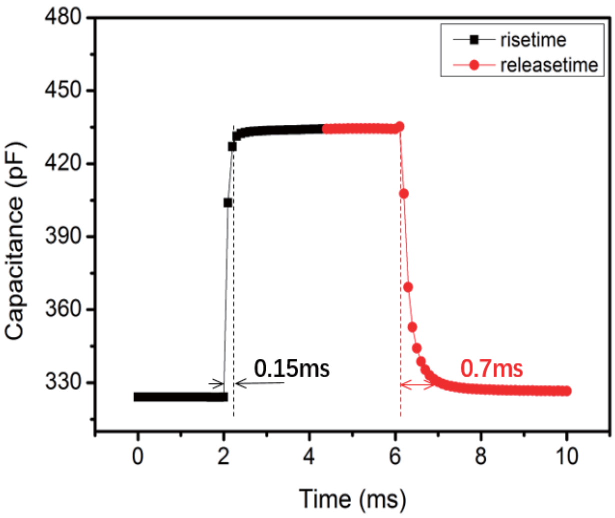


Figure 5: Characterization of the response time of the capacitive pressure sensor with the hierarchical wrinkle structure.

The hierarchical wrinkle structure plays an important role to explain the high sensitivity of the pressure sensor. When pressure is applied, the small wrinkle firstly works and then sense the pressure quickly and sensitively by forming deformation, thus the sensitivity of the pressure sensor in the relatively low pressure regime can be highly enhanced and the response time is extremely short. When the pressure is applied extremely high, the big wrinkle begins to work and shows a sensitivity of 0.2kPa^{-1} once bigger than that of a PDMS plat.

Figure 6 shows the feature of mechanical stimuli differentiation of the sensor as a generator. The device with hierarchical wrinkle structure shows a high output voltage when received a bending force. It can be clearly seen that the output voltage and output current are obviously different under two mechanical stimuli (bending&pressure). The output voltage of the sensor under bending stimuli is about 300 V, while that of the sensor under pressure stimuli is only about 75 V. The output current of the former is about 3μA, while the latter is about 17μA. The wave pattern under pressure stimuli is sharper than that under bending stimuli.

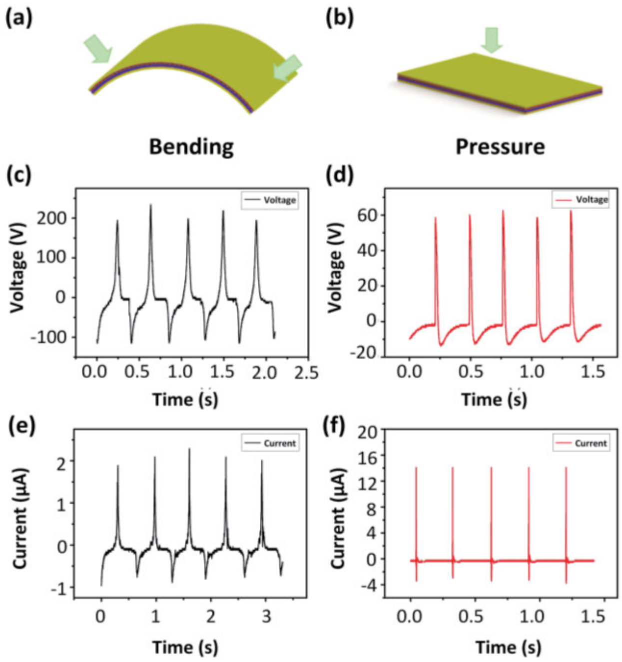


Figure 6: Energy harvesting from different mechanical stimuli. (a, c, e) the output voltage & current when applied bending. (b, d, f) the output voltage & current when applied pressure.

The reason for the feature of mechanical stimuli differentiation of the device can be attributed to the hierarchical wrinkle structure. The two forces can make hierarchical wrinkles contact with the PET/ITO with different deformation which leads to different contact area thus results in output voltage and current. When applied pressure, the small wrinkle firstly gets a perpendicular force and then forms deformation but the gap between the big wrinkle does not contact enough, so causing relatively small contact area. However, when applied bending force, the hierarchical wrinkle structure gets not only a radial pressure at every point of the wrinkle but also a global deformation, which makes the gap between the big wrinkle structure can contact with ITO layer enough. Meanwhile, the increased contact area causes the bigger resistance and leads to the lower output current.

IV. Conclusions

In summary, we fabricated a novel multi-functional pressure sensor with hierarchical wrinkle structure. Hierarchical wrinkle structure is firstly fabricated by one C_4F_8 plasma step, which simplifies the design and fabrication of the electronic device integrating multiple functions and explained the reason for hierarchical wrinkle structure at 1000 seconds C_4F_8 plasma The multi-functional pressure sensor is able to detect pressure as well as harvest the mechanical energy. As a capacitive effect pressure sensor, the device shows a very high sensitivity of 2.0 kPa^{-1} and the excellent response performance of 0.15 ms (rise-time) and 0.7 ms (release-time), respectively. In addition, the surface charges deriving from the contact of PDMS layer and ITO layer on the fluoride PDMS wrinkle structure enable the device to act as a generator with high output voltage of about 300V (Bending), 75V (Pressure) and output current of about 3μA (Bending), 17μA(Pressure). We also explained how hierarchical wrinkle structure differentiate mechanical stimuli (bending & pressure) without external batteries.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (Grant No. 61674004 and 91323304), National Key Research and Development Program of China (2016YFA0202701), and the Beijing Science & Technology Project (Grant No. D151100003315003) and the Beijing Natural Science Foundation of China (Grant No. 4141002).

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