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Ultrasensitive self-powered pressure sensing system

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ABSTRACT

Portable and flexible pressure sensors with highly sensitive and small size have great potential applications in areas such as wearable electronics, environmental monitoring, and medical equipment. Here, we demonstrate an integrated self-powered pressure sensing system made of a passive resistive pressure sensor and a triboelectric nanogenerator. Based on wrinkled and flexible polydimethylsiloxane films, the whole device is of sandwich structure with ultrahigh sensitivity to pressure (204.4 kPa^{-1}), which is more than one order of magnitude higher than all previously reported flexible pressure sensors. And our system exhibits a very low detection limit, rapid response time, and long-term stability. In addition, we built a self-powered, portable visualization system for semi-quantitative analysis of pressure, which can directly convert a pressure information to visual display.

1. Introduction

Highly sensitive, cost-effective, flexible and portable pressure sensors hold an essential position in the development of artificial sensing system. So far, pressure sensors have been reported based on various detection mechanisms, such as resistive [1–9], capacitive [10–12], piezoelectric [13–15], optical [16,17], and triboelectric [18,19]. Among these, resistive pressure sensor (resis-sensor) is used more frequently due to its significant advantages of high sensitivity and rapid response. And it has an excellent performance in monitoring continuous pressure. A common drawback of this type of sensors is that a power source is required for their operation. Most recently, the triboelectric nanogenerator (TENG) [20] has been invented as a promising energy harvesting technology and used for self-powered pressure sensing [18,19]. Even more enticing, TENG operates as a sensor using the electric signal generated by itself without applying an external power source, named as active sensor [21]. This kind of active pressure sensor is very sensitive to the pulse pressure. Moreover, it can be easily assembled into a sensor array for self-powered positioning and imaging [19,22–25], although its sensitivity needs to be further improved. With the development of microelectronics and nanotechnology, the power consumption of the resistive pressure sensors gradually reduce, which is beneficial to be powered by energy-harvesting devices [8], such as TENG. Therefore, it might be a feasible way to overcome the shortcomings of these two kinds of pressure sensors through integrating the resis-sensor and TENG into a single device.

In recent years, owing to its simplicity, cost-effectiveness, flexibility, stretchability, and the ability to be patterned in large areas, surface wrinkling on polydimethylsiloxane (PDMS) has received special attention as a key technology for various future applications, such as optical switching devices [26,27], tunable diffraction gratings [28–30], tunable microfluidics [31,32], microcontact printing masters [33,34], and flexible electronic devices [35,36]. Additionally, it has been proven that the

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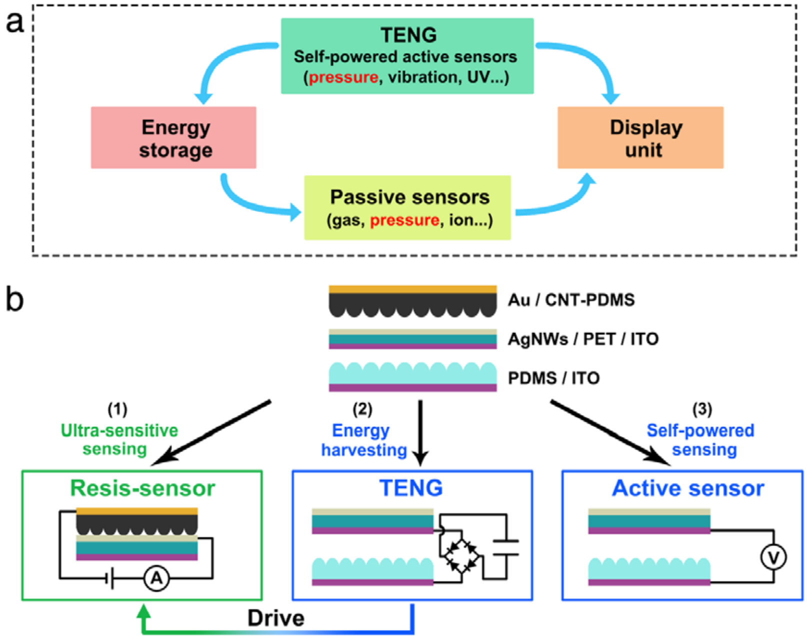

Fig. 1. Schematic diagram of the integrated self-powered sensing system. (a) The integrated self-powered sensing system composed of four parts: TENG, energy storage unit, sensors and display unit. (b) A typical case of self-powered pressure sensing system through the combination of TENG and passive resistive pressure sensor together.

microstructured PDMS can apparently improve the performance of TENGs and flexible pressure sensors [7,10,12,18]. Despite the superior properties of the wrinkled PDMS, to date, it has not yet been used in designing TENGs and flexible pressure sensors.

Here, based on the wrinkled and flexible structure, we devised an ultrasensitive self-powered pressure sensing system, by innovatively integrated the resis-sensor and TENG into a signal device. The wrinkled PDMS employed in the present work effectively improves the electrical output performance of the TENG and the sensitivity of pressure sensors. The whole sensing system exhibits excellent performances of ultra-high sensitivity, very low detection limit, rapid response time, and long-term stability. Combining a display unit, we further built a portable visualization pressure sensing system, which is able to convert the pressure information to visual display directly. We anticipate that this self-powered sensing system could be expanded to other types of self-powered sensors, such as gas sensor, ion sensor, biosensor, and multifunctional sensing might be realized. This work greatly promotes the development of self-powered system, and lays a solid foundation for establishing the future self-powered sensing network.

2. Result and discussion

Concept of the self-powered sensing system. The concept of our integrated self-powered sensing system is illustrated in Fig. 1(a). Firstly, the TENG can be used as self-powered active sensors. In the same time, it harvests different kinds of energy from the environment and stores it in the energy storage unit. Then the collected energy is used to drive the other passive sensor. These two kinds of sensors can work simultaneously and complementarily. The magnitude of detection parameters will be revealed in the display unit. Fig. 1(b) shows a typical example of our self-powered sensing system through the combination of active triboelectric pressure sensor and passive resistive pressure sensor together. The basic working principle of this system is composed of three modes: (1) the upper part is the ultra-sensitive resis-sensor with low operating voltage, which is suitable for continuous monitoring of pressures. But it can work only under the drive of a power source. (2) The lower part is a high-performance TENG for harvesting the environmental energy, and this generating power can be used to drive the resis-sensor. (3) The TENG can be used as a self-powered active pressure sensor, which is suitable to detect the pulsing pressure. Note that the AgNWs and ITO electrodes in the middle layer are connected with each other, constructing an integrated electrode, and these two parts share the middle electrode together, which effectively improves the operating facility of the device. With such a sandwich structure, the device can choose to work in proper mode, depending on different requirement.

Fabrication and characterization of the device. Fig. 2(a) illustrates the fabrication process of the ultra-sensitive self-powered pressure sensing system. The wrinkled carbon nanotube-polydimethylsiloxane (CNT-PDMS) and PDMS were fabricated by mechanical stretching the CNT-PDMS and PDMS films, followed by ultraviolet-ozone (UVO) exposure and strain release. Fig. 2(b) and (c) are SEM images (top, and side view, respectively) showing the detailed microstructure of the wrinkled PDMS film constructed with plenty of parallel wrinkles. The wrinkle wavelength is ~30 μm, and the wrinkle amplitude is ~10 μm. The optical microscope image shows the surface topography of the wrinkled PDMS with large area (Fig. S1), indicating that the surface wrinkles are very uniform,