Flexible Capacitive Pressure Sensors and Approaches to Enhance Sensitivity

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Abstract. Many research groups have become interested in the flexible capacitive pressure sensor in recent years. It has many applications, such as electronic skin and fingerprint collection devices. One of the challenges is optimizing the sensor's design, which can be achieved by improving its sensitivity. The flexible capacitive pressure sensor outperforms other pressure sensors in terms of efficiency, response time, and cost. In the future, more applications will use the flexible capacitive pressure sensor as the component. Thus, improving its sensitivity becomes significant. The topic of this review is to briefly introduce the flexible capacitive pressure sensor's mechanism, how to achieve high sensitivity and any potential applications that already exist in the market. It will also go over some experiments to improve the sensor's sensitivity and their benefits. In the end, the future expectations of the capacitive pressure sensor will also be discussed. The topic of this review will be significant to the development of electronic devices.

Keywords: Flexible, Capacitive Pressure Sensor, Sensitivity Enhancement.

1. Introduction

A sensor can sense something and then convert it into electric signals. It is always used to send messages to other electronic devices. It can appear everywhere, for instance, in restaurants or at home. The standard to evaluate a sensor is to check its sensitivity. The enhancement of the sensitivity of sensors is always a great topic to explore. This introduction will introduce the flexible sensor and pressure sensor.

The flexible sensor is bendable and stretchable and thus is used to measure the amount of bending or deflection. The sensor's resistance is linearly related to the amount of bend of the object. It has many applications, such as electronic skins, wearable healthcare monitors [1], robotic skins, etc. This is because such technologies require the sensor to be highly sensitive, mechanically flexible, or stretchable. Thus, a flexible sensor becomes a good choice to make things possible.

A pressure sensor can convert external pressure into electric signals. It is commonly used in pressure detection and monitoring [1]. There are many pressure sensors, including capacitive, piezoresistive, optical, and piezoelectric pressure sensors.

The piezoresistive pressure sensor is the earliest pressure with excellent durability and low cost. It has simple readout circuits and can carry out the high-resolution measurement [1]. This sensor exhibits linearity as the output increases when pressure increases. A power source needs to be connected to the sensor. Moreover, the sensor's output depends on the temperature, which is a disadvantage in cases where temperature changes a lot.

The optical pressure sensor detects changes in light to determine pressure differences. As the pressure increases, it will block the light progressively [1]. As electromagnetic interference will not influence the optical pressure sensor, it is commonly used in harsh environments. It has many advantages, such as small size, flexibility, and non-toxic materials. These make the sensor suitable for medical use. However, it requires more power compared with other pressure sensors.

The piezoelectric pressure sensor is made of rigid materials and consists of a silicon diaphragm, which detects the strain caused by external pressure. It can generate an output under small deformation [1]. The sensor is robust and can tolerate high temperatures (up to 1000ºC). The above advantages allow the piezoelectric pressure sensor to be applied to the jet engines' pressure measurement. Its characteristic of a self-powered system makes it neither sensitive to electromagnetic

interference. As this type of sensor is powerful, it also has the most complicated internal structure, making it hard to fabricate.

The flexible capacitive pressure sensor has many functions described above and has the best cost performance, which exhibits the necessary tasks at a low cost. It has the simplest structure and can detect variations in the electrical capacitance of the device to test the external pressure. Three parameters must be considered when testing its performance: the components, structure, and sensitivity [2]. The sensor has good stability and a simple structure, but there is a limitation. Due to the dielectric layer's limited elasticity [2], it is difficult to improve sensitivity.

The advancement of capacitive pressure sensors is critical to the development of many electronic devices. As the demand for pressure sensor accuracy grows, many studies have been performed to improve the sensor's sensitivity. After reading this review, readers will know more about this sensor and some methods to improve its sensitivity. It will also introduce two such experiments that research groups completed.

2. Working principle of the flexible capacitive pressure sensor

The most common type of flexible capacitive pressure sensor is made of parallel capacitors. Each capacitor contains a dielectric layer as well as two flexible electrodes. It can use equation (1) to find the approximate capacitance of such a sensor:

$$C = \frac{\varepsilon A}{d}, \tag{1}$$

The parameters are the dielectric constant of the middle layer Ɛ, the intersecting region between the two flexible electrodes A, and their separation, d. The above equation shows that the intersecting region and the separation are variable [3]. Because the overlapping region is usually tiny, the dielectric constant and the separation gap are the main factors influencing capacitance [3].

To test a flexible capacitive pressure sensor, its stability, speed of response, and sensitivity are three critical parameters that need to be considered. The stability is good when the two measured capacitances are as close as possible. The system's response time will reflect how fast the sensor responds to an externally applied force.

The electrodes are essential to the structure of such sensors. There are some requirements for the material of the electrode: high conductivity, good stability, and good mechanical properties. The most common type of electrode is a metal electrode which is commonly made of gold, copper, or silver [3]. Because of their high environmental stability and mechanical properties, metal electrodes are commonly used in the construction of integrated circuits. Conductive polymer films and carbon-based materials have proven to be effective in the fabrication of electrodes for this sensor in recent years. In hospitals, sensor arrays have been applied in bed sensors to detect the position of elders [3]. They are used due to their ability to detect pressure distribution, making it possible to monitor human breathing and artery pulse.

The dielectric layer is outside of the two flexible electrodes. The materials used to build the dielectric layer always have a large dielectric constant [4]. The dielectric layers people are manufacturing today always consist of different dielectric materials such as graphene and metal oxides [4]. Other materials, such as artificial cilia array and ionic hydrogels, can also be applied in the dielectric layer [5]. Some elastomeric dielectric materials are also used to construct the dielectric layer because the layer deforms when it is influenced by an external force, changing the capacitance of the device.

3. Sensitivity improvement

Improving the sensitivity is a necessary process. The most common way to accomplish that is micro-structuring the dielectric layers and electrodes so that only little external stress is applied to the

electrodes to deform them [6]. However, it is hard to complete the microstructure. Thus, developing a low-cost and high-sensitive pressure sensor requires a facile technique.

Much work has been done to realize the enhancement of sensitivity. Shuai et al. reported a comparatively more straightforward technique to manufacture such a sensor with high sensitivity [7]. In their design, they used the polyvinylidene fluoride (PVDF) film and polydimethylsiloxane (PDMS) substrate coated with silver nanowires (AgNWs) as the dielectric layer and the electrodes [7]. According to their report, the surface of the PDMS films will become curved spontaneously when treated under dry low-pressure air plasma. Their experiment is illustrated by the figure below:

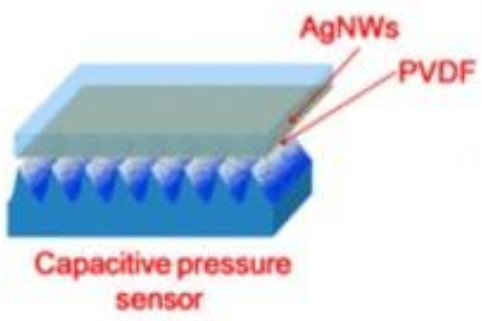


Figure 1. Schematic of Shuai's investigation [7].

When applying a force to the electrode's surface, the distance between the electrodes and the effective permittivity changes a lot. This demonstrates the sensor's high-pressure-sensitivity.

Their design shows larger deformation when influenced by the same pressure compared with the traditional pressure sensor, which is illustrated in Figure 2 and 3.

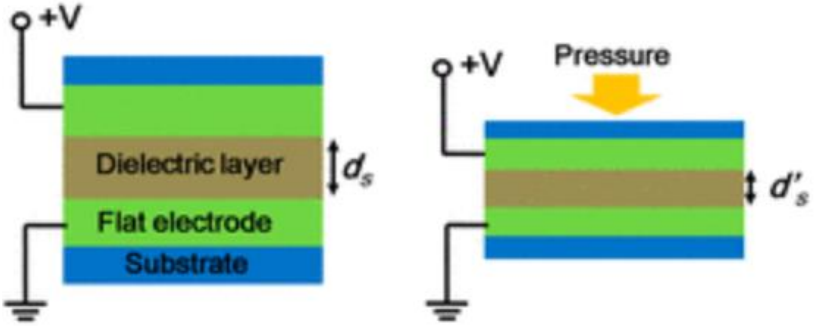


Figure 2. Deformation of pressure sensor based on flat electrode under same pressure [7].

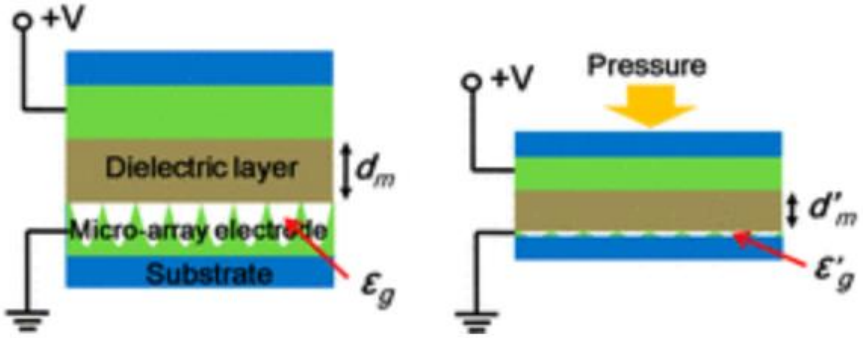


Figure 3. Deformation of pressure sensor with microarray electrode under same pressure [7].

During the experiment, they found that the dielectric layer greatly influenced the pressure sensor's performance. After many trials, they made the thickness to be 3.5 μm for the dielectric layer so that it has the response range of 6700 Pa which is the best [7]. This type of sensor has many advantages, including a sensitivity of 2.94 kPa^{-1}, a detection limit that is smaller than 3 Pa, a response time smaller than 50 ms, and excellent stability [7]. The sensor's high position sensitivity allows it to accurately detect the intensity and allocation of the pressure. It can be applied to devices like wearable healthcare monitors.

Unlike Shuai's group, Li et al. developed another method to achieve sensitivity enhancement. Their approach is to use the microstructures of plants as a soft mold to build the patterned electrode [8]. At first, they thought of using mimosa leaves to make touch-sensitive pressure sensors. However, that took a lot of work to achieve because of the narrow detection range. They successfully used the lotus leaf to create micropatterned substrate to fabricate the flexible capacitive tactile sensor.

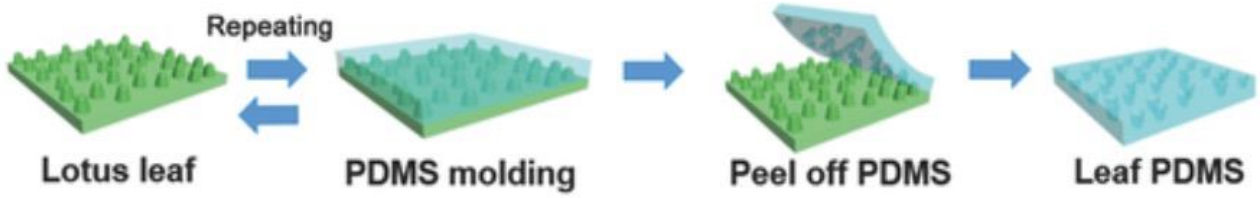


Figure 4. Process of making leaf PDMS [8].

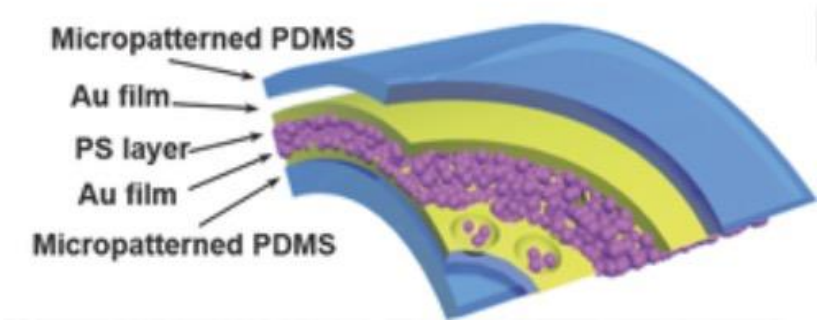


Figure 5. Schematic of Li's sensor [8].

The process of fabricating the micropatterned PDMS film is illustrated in Figure 4, while Figure 5 displays their complete design when the micropatterned PDMS is applied to the tactile sensor. Figure 5 shows that they use parallel capacitors consisting of two micropatterned PDMS films and a PS microsphere. This provides the sensor with good uniformity, and each PS microsphere has a diameter of around 670 nanometers [8].

When the sensor is influenced by pressure from other sources, the small caves in the substrates will be extended, which increases the plate area; the pressure will cause the distance between the electrodes to reduce, and these two factors lead to a significant change in capacitance. This process is explained in Figure 6.

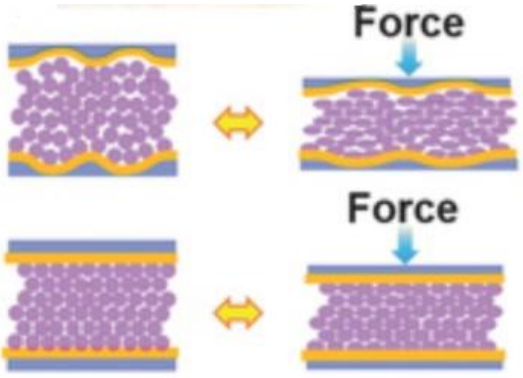


Figure 6. Compare between the deformation of Li's sensor with and without their electrodes [8].

In their design, the new thing is that they control the layer's dynamic change to improve the sensor's sensitivity, which can be achieved by enhancing the area of PDMS on the lotus leaf.

The pressure sensor Li's group developed has uniform surface microstructures and can easily be duplicated. Such sensors respond fast when bent, stretched, or pressed and are very sensitive. Their results indicate that this device can detect and monitor the tension and surface roughness of an object, which is helpful to the development of robotic systems. In addition, it has a sensitivity of 0.815 kPa

-1, a wide response range that varies from 0 to 50 N, and a response time around 38 ms [8]. As a result, it can be used in robotic systems and wearable medical devices.

4. Applications

Electronic devices like smartphones and smartwatches have become necessities in daily life. The manufacturers are exploring possible solutions to enhance the security of devices to protect personal privacy. The technology of biometrics, which can detect the unique characteristics of the human body, makes it possible. More specifically, fingerprint recognition has become the most preferred technique to ensure the security of devices. In this case, flexible capacitive pressure sensors help a lot. Many sensors have been invented to detect the human body's fingerprint.

The thermal-detection-based fingerprint sensor can detect the temperature differences between objects. The integrated sensor is placed in an environment with constant temperature (usually under 33℃) [9]. It captures the surface of the finger. It uses a special material to measure the transfer of heat from the sensor to the fingerprint. The temperature difference between the sensor and the fingerprint will then be used to generate an image of the fingerprint. This sensor has the advantage of high efficiency since the image is usually obtained within 0.1 seconds.

The Optical fingerprint sensor is the earliest fingerprint sensor based on the total reflection of light. In this technique, people must place their fingers on the filming table, usually made of hard plastic. The light emitted from the bottom will radiate to the filming table [9]. The reflected light will be converted into an electrical signal through a charge-coupled device for further processing. The angles of the reflected light will differ because the finger surface is not flat. The device will collect all the information and display the image of the fingerprint. This type of sensor has the advantages of good system ability, long service life, and can collect large-area fingerprints. However, it may not be accurate if some fingerprints are left on the filming table after the collection. It will reduce the quality of images or even cause two fingerprints to overlap.

The pressure fingerprint sensor is common in many places. During the collection process, people need to place their fingers on the sensor’s surface and make sure that only the ridges of the finger touch each sensor unit [10]. When external stress is applied, the sensor will generate an electric charge which will be collected by the device to collect fingerprints. It is easy to use the pressure sensor to collect fingerprints and costs less.

The flexible capacitive pressure sensors can also be applied to electronic skins. Like human skins, electronic skins have two crucial functions: pressure sensitivity and mechanical self-healing [10]. It should also be able to sense the external environment no matter how many times it is injured by external damage. The characteristic of continuous self-healing is also helpful to soft robotics. Self-healing electrodes with conductivity greater than 1 S cm−1 and tactile sensors are necessary to achieve that.

Wang et al. reported their experiment of electronic skin, which was made of a supramolecular organic–inorganic composite [11]. Their investigation mainly has two materials: 1.) a supramolecular polymeric hydrogen-bonding network with a glass transition temperature Tg below room temperature and 2.) chemically compatible micro-nickel (μNi) particles with nanoscale surface features [11]. These materials are flexible and can detect flexion forces. In the experiment, they created self-healing piezoresistive sensors by using lower Ni concentrations and particles that were spaced further apart. They successfully used their self-healing materials to construct a tactile sensor, which had the piezoresistive composite inside of the two layers of the conductive composite. At last, they integrated their sensors into a dummy. The figure below shows their achievement and the electrical circuit that is applied to the dummy.

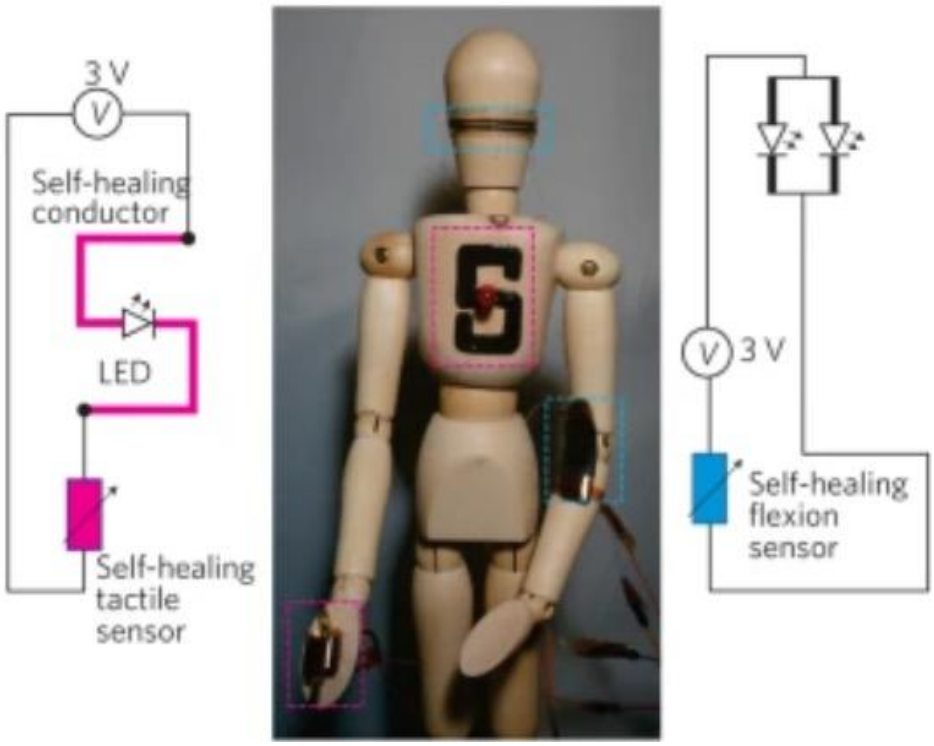


Figure 7. Schematic of Wang's dummy with their sensors integrated inside [11].

Their self-healing composite can electrically heal itself within 15s and may increase the skin's functional lifespan [11]. However, one limitation is that the healing efficiency of the material will decrease after the surface is exposed for some time.

5. Discussions

This review introduces the mechanism of the flexible capacitive pressure sensor, some potential approaches to enhance the sensor's sensitivity, and its applications that are popular in the market. In general, such a sensor is constructed of parallel capacitors. Each capacitor has a structure like a sandwich in which the dielectric layer is inside the flexible electrodes. The flexible capacitive pressure sensor has many applications, such as electronic skins and fingerprint sensors. Such sensors have become popular because of their distinct advantages, including easy structure and simple fabrication. In addition, they are slightly influenced by temperature and humidity compared with other sensors and are stable and fast. In recent years, much research has shown that such pressure sensors can be potentially applied in wearable electronic sensing devices. Therefore, it is significant to fabricate more competitive pressure sensors, which can be achieved by improving their sensitivities.

The capacitance of the capacitors depends on three aspects: the dielectric layer's permittivity, the overlapping region, and the separation gap between the two electrodes. A practical approach to achieve sensitivity enhancement is micro-structuring the dielectric layers and electrodes. This review discusses two experiments: one completed by Shuai's group and another by Li's group.

In Shuai's experiment, they designed a flexible sensor with high sensitivity by micro-structuring PDMS electrodes. Their pressure sensor with microarray electrode is observed to be more significantly deformed than the traditional sensor under the same external force. Their design uses electrodes with a microarray structure on its surface, increasing the permittivity and significantly changing the gap between the electrodes when a force is induced. Such characteristic makes it possible to spend low cost on improving sensitivity.

Li et al. took a different perspective when thinking about solutions to improve the sensor's performance. The bionic-inspired fabrication strategy inspired their idea, and they used the microstructure of the lotus leaf as the soft mold to fabricate the electrodes. In their design, they used

two micropatterned PDMS films as electrodes and a PS microsphere as the dielectric layer, ensuring the sensor's excellent uniformity. Like Shuai's team, the capacitance of Li's sensor will also experience a more remarkable change than other sensors when external pressure is applied. Overall, Li et al. proposed a easy solution to manufacture a flexible capacitive tactile sensor, which should be helpful to the development of electronic skins.

There are many applications for such sensors in the market. It is primarily used in electronic skins in robotics. Also, the capacitive pressure sensors are essential to the fingerprint collection process. Similar techniques will likely emerge, and capacitive pressure sensors will be more prevalent in the market. However, the sensor's design should focus on not only the materials but also the cost and efficiency of it. It is also an unavoidable challenge for researchers to integrate their sensors into the circuit to achieve practical application.

6. Conclusions

This review briefly introduces the flexible capacitive pressure sensor and its advantages compared with other sensors. This type of sensor consists of several capacitors, and each capacitor has two electrodes with one dielectric layer inside. It has a small size and simple structure which is easy to fabricate. The enhancement of sensitivity is essential to developing capacitive pressure sensors, which can be achieved by micro-structuring the electrodes or dielectric layer of the sensor.

Moreover, other sensor parameters must be considered, including response time, stability, and cost. The flexible capacitive pressure sensor has many distinct advantages, such as short response time, long-term stability, and low detection limit. In addition, its flexibility makes it applicable to bending and stretching forces as well. Such advantages make the flexible capacitive pressure sensor the most popular sensor that can be applied to electronic skins. In one sentence, the sensor's overall performance is the most important, not only the sensitivity. It is worth researching to develop a more sensitive capacitive pressure sensor.

Many study groups have done experiments to achieve it, but there is still no perfect solution as each experiment has its own weakness. Shuai et al. used the electrodes with a surface of microarray structure to enhance sensitivity, but the process is complicated and hard to complete. Many details need to be considered, which means it is easy to make mistakes during the process. This situation is the same for Li's experiment, where low cost and simple structure are achieved in their design, but the experiment itself is hard to complete. Therefore, further research needs to be done to improve the sensor’s overall performance.

In conclusion, flexible capacitive pressure sensors have contributed a lot to electronic devices and robotics. It also plays an essential role in medical wearable monitors. In the future, researchers should priorly consider the balance between the cost and the sensor's sensitivity. When the technical problem is solved, the technicists will then think of a proper approach to practically integrate it into real-life applications. There is no doubt that better-performance capacitive pressure sensors will be invented. More sensing properties can be developed so that the capacitive pressure sensor will have broad applications.

References

[1] RUTH S R A, BEKER L, TRAN H, et al. Rational Design of Capacitive Pressure Sensors Based on Pyramidal Microstructures for Specialized Monitoring of Biosignals[J/OL]. Advanced Functional Materials, 2020, 30(29): 1903100. https://doi.org/10.1002/adfm.201903100.

[2] SHI Y, LÜ X, ZHAO J, et al. Flexible Capacitive Pressure Sensor Based on Microstructured Composite Dielectric Layer for Broad Linear Range Pressure Sensing Applications[J/OL]. Micromachines, 2022, 13(2): 223. https://doi.org/10.3390/mi13020223.

[3] WANG H, LI Z, LIU Z, et al. Flexible capacitive pressure sensors for wearable electronics[J/OL]. Journal of Materials Chemistry C, 2022, 10(5): 1594-1605. https://doi.org/10.1039/D1TC05304C.

[4] LI R, ZHOU Q, BI Y, et al. Research progress of flexible capacitive pressure sensor for sensitivity enhancement approaches [J/OL]. Sensors and Actuators A: Physical, 2021, 321: 112425. https://doi.org/10.1016/j.sna.2020.112425.

[5] MA Z, ZHANG Y, ZHANG K, et al. Recent progress in flexible capacitive sensors: Structures and properties [J/OL]. Nano Materials Science, 2022: S2589965121000805. https://doi.org/10.1016/j.nanoms.2021.11.002.

[6] LUO Z, CHEN J, ZHU Z, et al. High-Resolution and High-Sensitivity Flexible Capacitive Pressure Sensors Enhanced by a Transferable Electrode Array and a Micropillar–PVDF Film [J/OL]. ACS Applied Materials & Interfaces, 2021, 13(6): 7635-7649. https://doi.org/10.1021/acsami.0c23042.

[7] SHUAI X, ZHU P, ZENG W, et al. Highly Sensitive Flexible Pressure Sensor Based on Silver Nanowires-Embedded Polydimethylsiloxane Electrode with Microarray Structure [J/OL]. ACS Applied Materials & Interfaces, 2017, 9(31): 26314-26324. https://doi.org/10.1021/acsami.7b05753.

[8] LI T, LUO H, QIN L, et al. Flexible Capacitive Tactile Sensor Based on Micropatterned Dielectric Layer [J/OL]. Small, 2016, 12(36): 5042-5048. https://doi.org/10.1002/smll.201600760.

[9] TANG K, LIU A, WANG W, et al. A Novel Fingerprint Sensing Technology Based on Electrostatic Imaging [J/OL]. Sensors, 2018, 18(9): 3050. https://doi.org/10.3390/s18093050.

[10] AN B W, HEO S, JI S, et al. Transparent and flexible fingerprint sensor array with multiplexed detection of tactile pressure and skin temperature [J/OL]. Nature Communications, 2018, 9(1): 2458. https://doi.org/10.1038/s41467-018-04906-1.

[11] TEE B C K, WANG C, ALLEN R, et al. An electrically and mechanically self-healing composite with pressure- and flexion-sensitive properties for electronic skin applications [J/OL]. Nature Nanotechnology, 2012, 7(12): 825-832. https://doi.org/10.1038/nnano.2012.192.