Sensitivity Improvements of Flexible Capacitive Pressure Sensors

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Abstract. In recent years, wearable electronic devices have developed rapidly and flexible sensors have been increasingly used in medical, aerospace, automotive, industrial and commercial applications. Flexible pressure sensors are critical in human-robot interaction, physiological signal monitoring and robotic haptics. Among them, capacitive type flexible pressure sensors are widely used due to their unsophisticated structure, good stability, small temperature deviation and environmentally friendly. Currently, most of capacitive sensors adopt the design with an electrical membrane inserted between two electrodes. This paper presents a comprehensive review of the development of flexible capacitive pressure sensor from the perspective of technological and engineering developments. This paper firstly introduces the capacitive pressure sensor by using the working mechanism as an entry point. Secondly, this paper discusses three general methods to increase the sensitivity of pressure sensing, including changing the dielectric microstructure, the dielectric constant, and different dielectric materials. Finally, the advantages and disadvantages of three methods for sensitivity improvement were discussed.

Keywords: Capacitive pressure sensors, Sensitivity variations, Dielectric constant.

1. Introduction

With the emergence of the internet of things (IoT) and wearable electronic devices in recent years, people's lifestyles have changed dramatically. Recently, the range of everyday use of pressure sensors in medical, aerospace, automotive, industrial and commercial applications has increased dramatically [1]. Soft pressure sensors are used in electronic skin, human interface, and physiological signal control as basic tools [2]. Compared to conventional electronic elements, which are based on cream, soft-skinned electronic elements are very well adapted to different surfaces and materials [3]. Due to its special performance, extensive studies have been carried out on related electronic devices, which has led to the development of areas such as LEDs, batteries, antennas and sensors [4].

Flexible pressure sensors are now widely used in people's daily life. Three types are generally produced by the working principle of the sensors, which roughly include piezoresistive, capacitive and piezoelectric pressure sensors [5]. In particular, the sensor has the advantages of simple structure, great fixity, low-temperature excursion, and being environmentally friendly. These advantages make the flexible capacitive sensor very worthy to be investigated. Most capacitive pressure sensors are constructed on the model of a parallel flat capacitor consisting of an intermediate electrical layer between two electrodes. According to Equation (1) shown, the distance between two electrodes is generally represented by d, the effective distance between two electrodes by A, and the dielectric constant of the dielectric layer by ε. These factors make it possible to determine the change of a capacitance value. Thanks to the excellent overall performance, capacitive sensors have proven great potential for detecting human data signals and communicating with humans with computers, which is critical for the application of wearable smart electronics [6]. Under external pressure, d or ε changes, which leads to a change in capacitance. Usually, the sensor thickness is only a few tens to a few hundred microns to facilitate applying pressure components, e.g., to fit the human skin.

Based on the development of science, technology and engineering in this field, this paper reviews elastic pressure-sensitive components. The paper starts with the working mechanism of the capacitor and explains its working principle. Then, common approaches to sensitivity improvement were introduced. The first aspect addresses the study of the dielectric layer microstructure and finds that different structures can lead to different sensitivities; the second aspect is that the dielectric constant can be changed, and it is hoped that the sensitivity can be changed by increasing this value; the last aspect is explored for the choice of materials selection. For example, microfabricated sensors worked with elastic foam dielectric films and stretchable metal electrodes show faster response times to detect general force in the range of 1 kPa to 100 kPa range. Finally, the importance of sensitivity improvement in capacitive pressure sensors was concluded and different approaches for improving general applications, including healthcare, human-machine interface and other functions, are presented.

2. Sensitivity improvements of sensors

2.1. Sensing mechanism

Capacitor pressure sensors can detect static loads. General purpose capacitive pressure sensors have a number of advantages, including less energy required, less signal drift, and timely results. The dielectric layer is the main design target for capacitive pressure sensors to improve sensitivity and pressure response range. Because flexible materials are incompressible, their sensitivity is poor without special construction. Therefore, some special sensor structures are created. Thus, the sensitivity of capacitors can be greatly improved by forming specific microstructures such as spheres, columns and cones, which can also be described as microstructures, by using highly elastic materials, introducing air gaps and making the insulator a porous foam [7].

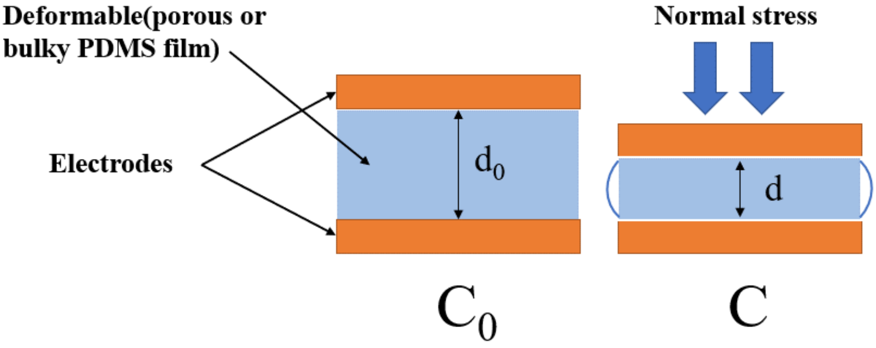

Figure 1. Schematic illustrations of sensing mechanisms of Capacitance pressure sensors.

Capacitive pressure sensors measure the pressure based on the change in capacitance due to the movement of the film (Fig. 1). When the sensing film between the two capacitor electrodes is deformed due to the difference in air pressure, its capacitance imbalance with the two electrodes occurs. The capacitance bridge line detects this imbalance and converts it into a 4-20 mA output. In this case, the movement of the flexible diaphragm against the stationary plate can be measured based on the change in capacitance. The second spacer acts as a guard against the sensing film. The capacitance is two conductive sheets connected in parallel with a gap in the middle. Capacitance is defined as:

$$C= \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{1}$$

From the above equation, it is clear that the capacity of capacitive pressure sensors is related to the size of the sheet and pitch. The capacity of capacitive pressure sensors also varies depending on the dielectric coefficient of the media they use [7]. Thus, capacity of capacitive pressure sensors depends on several factors. These factors all include the dielectric material, the area of the plates and the spacing between the plates. Depending on the components, there are three different capacitors: the microstructure, dielectric constant and the material. A change in these variables will cause a corresponding change in the capacitor. The easiest to grasp is the spacing. This can be done with one or two thin sheets to make a flexible film due to pressure changes. Generally, one of these is a film that responds to pressure, and the other is stationary. An easy way to determine the change in capacitance is to use it as a component, which generally includes an inductor and an inductance. This may affect the frequency of an oscillator or the alternation of a resonant circuit.

Capacitive flexible pressure sensors have received more attention based on new pressure-sensitive elements. From the point of view of circuitry, capacitors and resistive types of sensors have a lot in common. For example, a micro Polydimethylsilicon (PDMS) film can be used as a capacitor or as a capacitor or as a dielectric layer. There are naturally some differences in the production process of the two sensors. The method has a fast response time and low power consumption compared to other methods of operation.

2.2. Microstructure of dielectric layer

Among them, according to the equation, there is a strong correlation between microstructure and sensitivity. Fabricating a novel microstructure in the dielectric layer can be of great help to improve the sensitivity. Because changing the structural layer between the two electrodes and making a new microstructure can make the gap between the electrodes larger, making it easier to change the shape of the dielectric layer. When using pressurization, the air gap can be reduced. As a result, the sensors with micro dielectrics and electrodes at the same voltage and with the same dielectric layer and dielectric have a higher sensitivity due to their large initial capacitance values and capacitor capacity.

In this paper, somebody reports an ultrasensitive capacitive pressure-sensitive element based on a porous conical dielectric (Fig.2). Compared with a conventional conical insulating layer, its sensitivity rapidly increases to 44.5 kPa^{-1} at less than 100 Pa, which is unprecedented. The increase in sensitivity at a given pressure is mainly due to a large change in its effective dielectric coefficient at a given pressure. Changing the structure is very effective; where this experiment places the sensor on a special elastomer structure, the sensor is insensitive to stress changes. These pressure-sensitive elements also do not respond to temperature. In addition, chemical grafting with conductive polymers has been performed, and a contact resistive pressure-sensitive element with high sensitivity has been introduced [8].

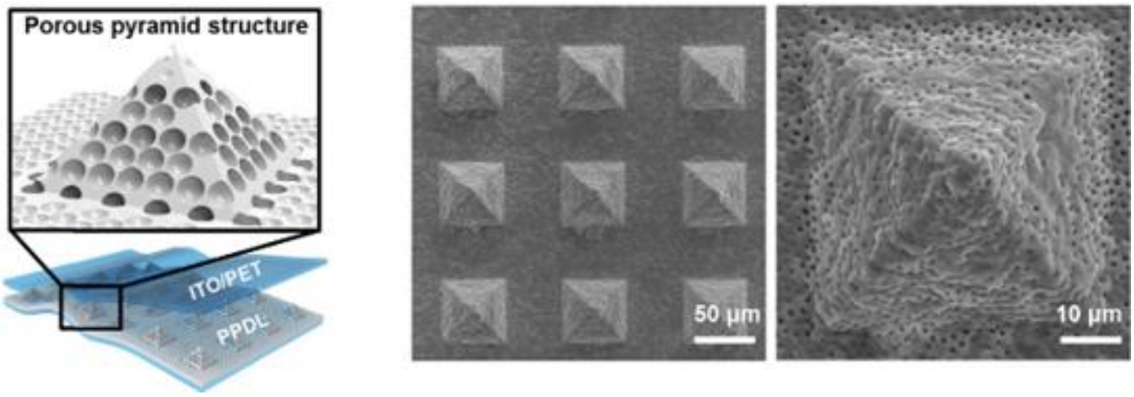

Figure 2. Porous pyramidal media layer microstructure [8].

Elastic sensors are attracting step into people's view because of the sensors' good ability to sense external contacts and pressure (Fig. 3). The one used in this experiment is composed of an elastic capacitive pressure-sensing array, characterized by a high resolution, with values up to 10.3 dpi, consisting of a micro polyvinylidene fluoride (PVDF) membrane and a moving electrode set has been proposed in the press article. The characteristics of this presented sensor also include high sensitivity and linearity, which is most evident when at 20 kPa and has a fast response (<100 ms), good elasticity, and can wrap well around the finger. In addition, the individual pixels change their capacity significantly when subjected to pressure, allowing for the smooth placement of various complex pressure models [9]. It has a huge development space in robotics, touch panel, human-machine interface, real-time pressure measurement, etc.

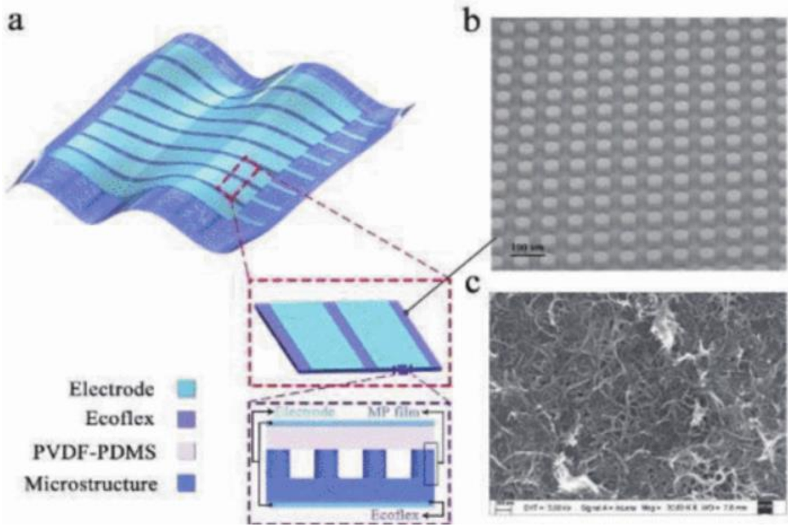

Figure 3. Scanning electron microscopy images of columnar microstructures [9].

Zhongfu He et al. designed a new element that adopts a new structure, which uses a new nylon structure (Figure 4). However, it is still difficult to assemble a capacitor with a simple structure and excellent performance, especially for monitoring fluid flow. In this paper, based on a sandwich form, a movable, low-cost movable capacitor-type pressure transducer is designed, which has many advantages; among them, the features of this element include high response sensitivity, which is accomplished at low voltages of less than 1 kPa. Another feature shows the ultra-low detection limit of 3.3 Pa and excellent stability of the element, and the ability to do all the work that the most basic elements can do. In addition, this sensor has a very fast response time (less than 20 ms) and can detect small pressures generated by liquids as they change the shape of the sensor [10].

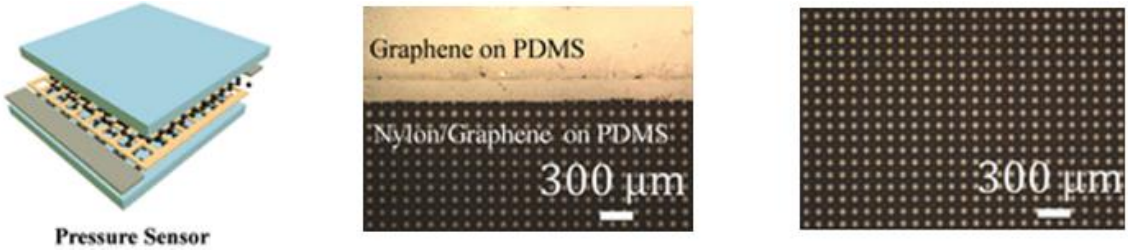

Figure 4. Square hole microstructure using nylon distribution [10].

2.3. Dielectric constant of dielectric layer

A dielectric is a method that can measure electrical energy, which is stored in a substance in an exciting way when an electromagnetic field is present. It is expressed in terms of the ratio of the dielectric coefficient of the medium to the vacuum or dry gas. In fact, the ratio of the capacity of a capacitor with wood as a medium to the capacity of dry air is used to measure this. The water content has a significant effect on the material and there is a powerful interaction with frequency but little interaction with the environment.

The dielectric coefficient is the ratio of the capacity of the measurement medium to the gas capacity and vacuum capacity in the environment under examination. When the dielectric coefficient of the medium increases, the capacitance can store more electrical energy. Thus, the capacitance measurement method can determine the dielectric properties.

The dielectric coefficient is related to different factors such as temperature, humidity and frequency; all these parameters must be kept constant and recorded when the medium is measured. In this capacitive type of sensor, the difference in the dielectric makes the capacitor capacity of the sensor change in different degrees. As the input data changes, the dielectric characteristics of the medium change, thus changing the meter's capacity. This capacitance is corrected by the input and provides a value to be measured. Using this method, the height of the liquid in the hydrogen storage tank was measured and it was found that the hydrogen level on both plates changed, thus changing the dielectric coefficient of the capacitive sensor. This method can be applied to determine the chamber's water and moisture content. As a material with excellent elasticity and high dielectric constant, Graphene oxide (GO) is a new type of wearable electronic product. This paper introduces a new novel capacitor-type pressure-sensitive element using graphene as an electrode to accomplish large-scale area integration using an efficient and low-cost production method and measure the pressure in space (Figure 5). The GO-type sensor presented in this experiment contains some features, the first of which is a high sensitivity that can detect air pressure down to 0.24 Pa. The device responds extremely quickly, detecting the measured value within a range of 100 meters. It has excellent sensor characteristics, flexibility, and robustness, showing its promise for many applications [11].

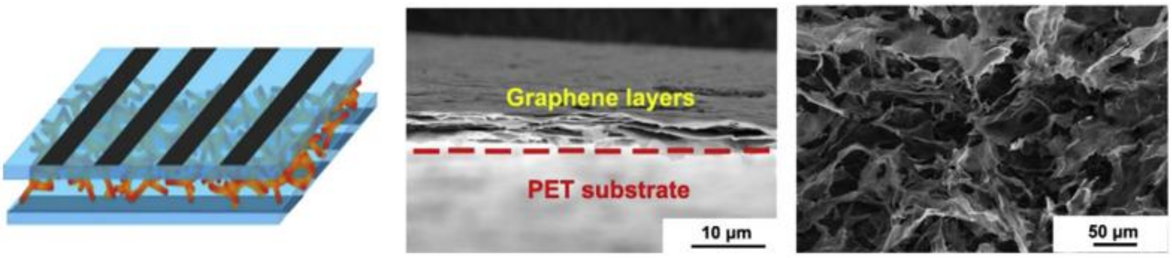

Figure 5. Graphene as an electrode for ultrasensitive capacitive pressure sensor [11].

2.4. Material selection

The films can be made of plastic, glass, silicon, ceramic, etc. and are suitable for various applications. The sensors have a capacity of about 50 to 100 pF in the range of several picofarads. Different sensitivities and different operating pressures can be applied to different materials. To get a large signal, it is necessary to have a sufficiently large sensor, which affects the frequency band in which it operates. However, a small film is more sensitive and responds more quickly. A large, thin film will be very sensitive to noise caused by vibrations (because the same principle is used in making a condenser microphone), especially at lower levels. Thicker films can be applied to pressure transducers to ensure their mechanical properties. Using capacitors with low resistivity, sensing elements that have little effect on ambient temperature can be manufactured. This construction must also have a small delay to ensure accurate and repeatable measurements. Since the film itself is a sensing device, there is no problem in attaching additional parts to the film so that the capacitor operates in a higher environment than any other.

H. Vandeparre et al. reported that micro-capacitor sensors made of flexible foamed insulating films and stretchable metal electrodes exhibit high toughness in the limit case (Fig. 6), containing stretching, tissue folding, and pressure disinfection. When the insulating film is pressurized, its capacity is greatly increased due to the shape of its openings. As the bubble concentration changes, the sensor sensitivity detection environment is set to 1kpa to 100kpa in normal air pressure. Like this type element has the amount of function with the support surface, for example, in artificial skin and wearable robotic arms, such as mattresses, joysticks or prosthetic jacks [12].

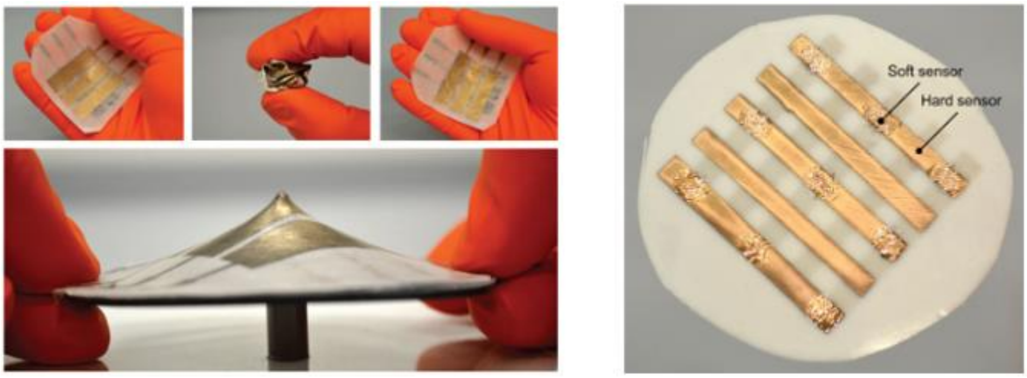

Figure 6. Sensors based on flexible polyurethane foam composition [12].

Yuchao Zhu et al. introduced elastic capacitive pressure-sensitive elements with polyimide as the dielectric, whose performance includes sensitivity, detection limit, and response rate (as shown in the attached Fig. 7). Experimental studies were conducted on polyimide nanofiber films and commercial polyimide films [13]. A sensor using this material can achieve the same results we want, and with remarkable results.

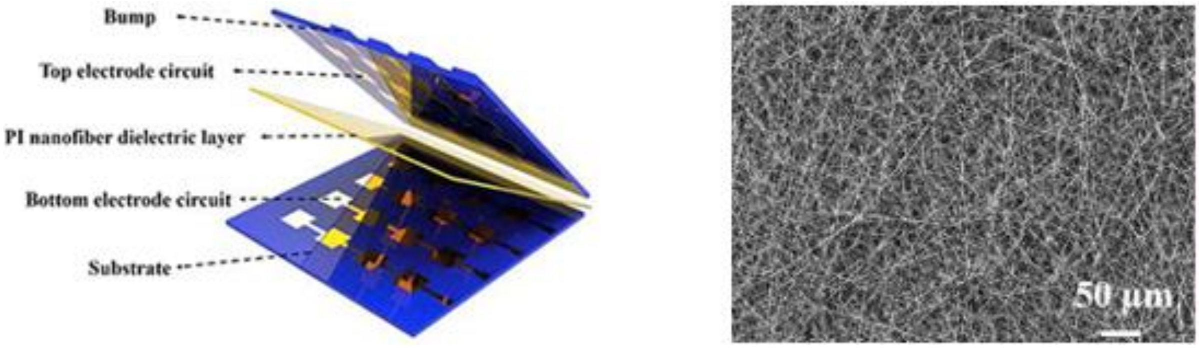

Figure 7. Sensor based on four-needle far-field electrospinning technology [13].

Kin FongLei et al. reported that a bendable element had been designed for determining the force on the bottom of the foot in bioengineering. PDMS is mainly used to analyze the stiffness of PDMS and cured material in different ratios. The 16:1 ratio of PDMS was chosen because of its excellent properties; the material has the most suitable stress corresponding to the strain curve within the conditions required for the experiment. It is linear over the range. Because this sensor measures the foot, it can measure the maximum air pressure as high as 945 kPa. In addition, using a flexible printed board as the backing for the sensor minimizes the measurement disturbance to the surface while maintaining the overall electronics. Based on this miniature and flexible feature, an integrated sensing system for shoes based on long-range data acquisition can be developed [1].

3. Discussion

The flexible pressure sensor is the key device to realize the external power, and it occupies a pivotal position in many applications such as human wearable and medical monitoring. Currently, the most important aspects are wide linear detection range, fast response time, low latency, and long service life. Applying microstructures to elements is a way to improve their performance. This thesis focuses on microstructure systems such as micromodels, porous, fiber optic networks, and multi-microstructures completed in recent years, with high-performance, elastic pressure-sensitive elements as the main content. The research focuses on using intelligent biosensors based on micro-biotechnology in human and ex vivo and human health monitoring.

This paper improves the sensitivity in three ways. For the microstructure of the dielectric layer, we propose a porous cone-shaped dielectric consisting of a PVDF film, a migratable electrode, and a simple and economical nanofiber mesh material using a microscope as periodically scattered square pores. The sensitivity of this new and efficient capacitive, piezoresistive element can be improved very well. The increased sensitivity of certain constructions in a particular pressure region is mainly due to the reduction of the compaction coefficient. Most constructions allow the pressure sensor to no longer to be affected by more than 60% of the stress, which is more than enough for electronics. Some devices can significantly improve the resolution of sensor arrays to 10.3 dpi with a long lifetime, and their stability and reliability hold great promise in the biomedical field. Some constructions have longer mechanical stability. The sensor's high sensitivity, good stability and good dynamic detection properties make it suitable for wearable instruments and biomedical monitoring.

GO foam is excellent for improving sensitivity when increasing the dielectric coefficient. This material has characteristics of high sensitivity, responsiveness and stability. Our capacitor pressure sensor combines the elasticity produced by this material with the higher dielectric permittivity of GO, and its sensitivity is unprecedented. GO foam manometers have a lot of room for development in many areas due to their high sensitivity, high repeatability, and fast response time, especially in some demanding loads, such as body camera interfaces and robotic technology. For example, such sensors can be integrated into the steering wheel of the vehicle to monitor the state of the driver. When a fatigued driver tends to turn the wheel loose, the sensor will sense a subtle change in air pressure and sound an alarm. The report also predicts that GO foam has great value in flexible devices with controlled structure, high resilience and high dielectric coefficient.

In terms of the material chosen, PDMS, the main material for sensing media, has good dielectric properties and is more flexible. However, PDMS belongs to a class of elastomers with high nonlinearity. A study of PDMS with PDMS was conducted to obtain the polymer's and curing agent's stiffness at different ratios before PDMS. The 16:1 PDMS was chosen because the PDMS has the largest linear-strain relationship between the stress-strain of a straight line in the pressure range. The sensor is capable of detecting air pressures up to 945 kPa and can be used in most underfoot pressure tests. Other substances can utilize soft, flexible foams to design and produce pressure sensors with high adaptability. Their metallic combination with membranes opens new avenues for manufacturing leggy, lightweight and inexpensive tactile skins. A simple production method was eventually developed to make pressure-sensitive elements for capacitors. A high-performance dielectric material was obtained by analyzing the thickness of various dielectrics and PI nanofiber membranes. It was found that the properties of the polyimide-based nanofiber film give a large measurement accuracy.

4. Conclusion

Capacitive flexible pressure sensors play an important role in human-machine interaction and medical monitoring. Wide linear detection range, high responsiveness, low latency and long life are very important. This paper describes three different ways to enhance the sensitivity of the element in detail and analyzes them. It is concluded that their performance can be rapidly improved by using a microstructure design. Then the superiority of dielectric coefficients in enhancing sensitivity is highlighted, as well as the progress of improving the dielectric constant method in pressure sensing. Finally, various materials currently used in tactile sensing arrays are summarized. In the long run, although great progress has been made, most capacitive flexible pressure sensors are still in their infancy, and there is great room for development in multi-function, system, integration, and intelligence. In recent years, many researchers have devoted themselves to obtaining high-precision pressure sensors through nano technologies. Although many researchers have done much research on this, it is rarely used in practice. Therefore, the technology also has a promising future, and more advanced manufacturing technologies must be developed.

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