Flexible Pressure Sensors Based on Three-dimensional Structure for High Sensitivity

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Abstract

The importance of flexible polymer-based pressure sensors is growing in fields like healthcare monitoring, tactile recognition, gesture recognition, human-machine interface, and robot skin. In particular, health monitoring and tactile devices require high sensor sensitivity. Researchers have worked on sensor material and structure to achieve high sensitivity. A simple and effective method has been to employ three-dimensional pressure sensors. Three-dimensional (3D) structures dramatically increase sensor sensitivity by achieving larger local deformations for the same pressure. In this paper, the performance, manufacturing method, material, and structure of high-sensitivity flexible pressure sensors based on 3D structures, are reviewed.

Keywords: Flexible pressure sensors, Three-dimensional structure, High sensitivity, Healthcare monitoring, Motion recognition, Human-machine interface

1. INTRODUCTION

Flexible pressure sensors are attracting attention in fields like healthcare monitoring, gesture sensors, tactile sensors, human machine interfaces, and robot skins due to unique properties like flexibility, lightness, high sensitivity, and ease of fabrication [1-7]. In daily life too, applications such as pulse monitoring, finger movement, soft touch, and foot pressure measurement require recognition with high sensitivity in the low pressure (0–10 kPa) and medium pressure (10–100 kPa) regions [8]. According to the sensing mechanism, pressure sensors are divided into three types—piezoresistive [9,10], piezocapacitive [11,12], and piezoelectric [13,14]. Recently, ultra-sensitive sensors based on triboelectricity have also been introduced [15-18]. In piezoresistive pressure sensors, a physical stimulus changes the contact area between two electrodes, which changes the resistance, and therefore the current between the two electrodes. Although piezoresistive sensors have disadvantages such as sensitivity to temperature, they are widely used in flexible pressure sensors due to advantages such as relatively easy operation, high sensing sensitivity, simple structure, and fast response. In the piezocapacitive method, the distance between the two electrodes changes according to a physical stimulus and the pressure is measured by recognizing the change in the dielectric constant between the two electrodes. Piezocapacitive pressure sensors have advantages such as ease of fabrication, low hysteresis, and high stability. However, the relative complexity and noise of signal acquisition are disadvantages of piezocapacitive sensors. Piezoelectric pressure sensors work by converting mechanical energy into electrical energy. Since the performance of piezoelectric sensors is dependent on intrinsic material properties rather than the spatial change relative to pressure, this paper focuses on piezoresistive and piezocapacitive pressure sensors, and reviews their progress. To secure high sensitivity in piezoresistive and piezocapacitive pressure sensors, materials and structures that generate a large amount of deformation for the same pressure are essential [19,20]. If a material with a low modulus of elasticity is utilized, a larger deformation can be obtained for the same pressure. There are technologies that use three-dimensional (3D) porous structures to generate a deformation greater than that obtained through material change [21]. In addition, there are key methods for improving sensitivity by maximizing the change in the contact area or distance between electrodes at the same pressure, using 3D protrusion structures. A 3D sensor is a sensor that forms a...
structure having length, breadth and height inside or outside.

In this paper, the ongoing efforts for increasing the sensitivity of pressure sensors, and the progress of various studies on materials, structures, and manufacturing methods, are reviewed. In addition, some high-sensitivity flexible pressure sensor applications are introduced. Finally, the limitations of flexible pressure sensor studies, and their development directions are discussed.

2. FLEXIBLE PRESSURE SENSORS WITH 3D STRUCTURE

Constructing microstructures such as pyramids, domes, and pillars is an effective approach for fabricating flexible pressure sensors with high sensitivity. Microstructures on the surface of a sensor’s active layer reduces elastic resistance owing to the air void in the film, resulting in excellent sensing performance. A flexible pressure sensor based on Polydimethylsiloxane (PDMS) dielectric layers formed into microstructured pyramids is shown in Fig. 1a. The microstructured PDMS dielectric layer was produced by a prefabricated patterned mold using lithography and etching. The microstructured dielectric layer not only improves the sensitivity by over 27 times compared to unstructured PDMS dielectric layers, but also decreases the relaxation time because of reduced viscoelastic property of the PDMS dielectric layer [22].

Fig. 1b. shows an ultra-sensitive sensor using micropillars and nanofibers, and at the same time shows a stretchable sensor with no change in pressure recognition even with a 15 % change in biaxial stress. The sensor’s pressure recognition resolution is 15 Pa and the response time is very short, at 50 ms [23]. In addition, piezoresistive flexible pressure sensors based on microstructures have been suggested. Fig. 1c shows an interlocked microdome array with high-sensitivity achieved due to giant tunneling piezoresistance. The external pressure induces stress concentration at the tips of the microdomes, resulting in large local deformations. They demonstrated high sensitivity as 15.1 kPa$^{-1}$ in the low-pressure range (under 0.5 kPa) and excellent sensing performance such as fast response time, limit of detection, and high reliability [24]. Zhu et al., also suggested piezoresistive flexible pressure sensors based on microstructured graphene arrays to improve sensor sensitivity, as shown in Fig. 1d. They verified that the flexible pressure sensor exhibited a high sensitivity of $-5.53 \text{ kPa}^{-1}$ for a pressure range of 100 Pa, excellent limit of detection capability of 1.5 Pa [25]. Pang et al., proposed randomly distributed microstructures for highly sensitive pressure sensor through the combination of an abrasive paper template and
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reduced graphene oxide, as shown in Fig. 1e. They verified pressure distribution for pressure sensors with different surface geometries using simulation. Polymeric 3D porous structures are typically employed as a dielectric layer in flexible pressure sensor to detect wide pressure ranges. The polymeric porous structures are easily compressed even at small pressures owing to reduced elastic resistance and the anti-barreling phenomenon [26]. Kang et al., suggested bioinspired porous structure for highly sensitive pressure sensor via stacking polystyrene (PS) beads, PDMS coating, and dissolving PS beads as shown in Fig. 2a [27]. The porous structured pressure sensor exhibited a high sensitivity of 0.63 kPa⁻¹, an excellent limit of detection of 2.42 Pa, and stability over 10000 working cycles. Fig. 2b shows a flexible pressure sensor based on the giant piezocapacitive effect of 3D porous dielectric layer. The combination of large deformation and an increased dielectric constant of the 3D porous dielectric layer under applied pressure significantly improve the overall sensor performance. Through this structure, they demonstrated that pressure sensor exhibited high sensitivity of 0.601 kPa⁻¹ in a wide pressure range (0.1 Pa to 130 kPa), which is appropriate for applying to various practical applications [28]. Several studies have been proposed to increase sensing performance, such as sensitivity, linearity, and durability, in conjunction with the development of a 3D porous structure-based pressure sensor. Fig. 2c illustrates the flexible pressure sensor based on a 3D porous composite structure mixed with Ecoflex matrix and carbon nanotubes (CNT), which leads to an improvement in sensor sensitivity due to the synergetic effect of the percolation of CNT fillers [29]. Fig. 2d shows the fabrication of a pressure sensor composed of stacked CNT and PDMS layer. With the addition of CNT in the porous structure, the porous structure is linearly compressed with applied pressure due to the reinforced mechanical properties, thereby resulting in linear sensitivity over a wide pressure range [30]. Finally, Park et al., also suggested shape memory polymer-based pressure sensors with notable durability at a high-pressure range. Shape memory polymers have the capability to return from a deformed state to their original state when induced by applied heat. The fabricated shape memory polymer-based pressure sensor exhibited similar signal values after 100 cycles of applied pressure at 500 kPa and were applied to human motion detection application on a shoe insole [31]. In recent years, flexible pressure sensors based on 3D structure have...
made significant developments and have been applied in various fields. Fig. 3a shows a flexible pressure sensor for monitoring the radial wrist artery in people with different physical conditions. The typical pulse characteristics were collected and segregated into the following categories. The Percussion wave (P-wave), Tidal wave (T-wave), and Diastolic wave (D-wave), which are related to clinical information [32]. A sensor array based on a 3D structure of $6 \times 6$ pixels was developed, as shown in Fig. 3b. The sensor array fully detected and recorded location and pressure information of the objects [33]. Using the bio-inspired micro-hair structure, the research group has developed an ultra-sensitive capacitive sensor that simultaneously increases sensitivity and reduces hysteresis, as shown in Fig. 3c [34]. It was confirmed that this was sufficient for monitoring patients with cardiac abnormalities, and for identifying differences caused by the presence or absence of disease. Finally, a pressure sensor with high sensitivity was applied to a large-area sensor array pad for human-computer interaction, as shown in Fig. 3d [35]. The fabricated sensor array pad was applied to the drawing application, and the gradually increased pressure level was recorded, according to the curved trajectory. The sensor array pad based on a flexible pressure sensor clearly distinguished different patterns caused by different wrist movements and demonstrated the control of the mouse cursor.

3. CONCLUSIONS

Owing to their three-dimensional structure, flexible pressure sensors can sense pressure better than conventional pressure sensors. Currently, they are applied to various fields such as healthcare, gesture recognition, and human-machine interface. To develop a more sensitive and linear sensor, research on various 3D structures is continuously being conducted. In addition, manufacturing methods for 3D structures are being studied. The protruding 3D structure increases the sensitivity of the sensor through local deformation and ensures repeatability through material selection. A 3D porous structure increases sensor sensitivity on account of its low elastic modulus caused by internal pores, which increase the amount of deformation for the same force. Researchers continue to push the boundary on flexible pressure sensors that have high sensitivity, excellent linearity, and good productivity. Efforts are also being made to expand the field of application of the developed flexible pressure sensors.

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