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A Novel Capacitive-Based Flexible Pressure Sensor Based on Stretchable Composite Electrodes and a Dielectric Elastomer With Microstructures

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ABSTRACT This paper presents a novel capacitive-based flexible pressure sensor that achieves a relatively high sensitivity with an outstanding linearity over a large measurement range, as well as low-pressure detection capacity. The proposed sensor mainly consists of two flexible conductive composite electrodes and one micro-structured elastomer with both pillars and cavities. The highly stretchable modal fabrics and carbon nanotubes conductive paste have been proposed for mixture to generate flexible capacitor electrode plates, and provide improved attributes in terms of excellent flexibility, conductivity, and air permeability. The micro-structured elastomers have been proposed and fabricated via demolding the silicone poured into the high-precision patterns that are produced by the 3D printing techniques. The exerted compression on assembled sensor prototype can induce decreased distance between electrode plates and increased dielectric constant due to the air deflation, leading to enhanced sensor sensitivity. By comparing three types of microstructures for the elastomers, it is found that the cubic-structure type can achieve a high sensitivity ($232*10^{-4}$ kPa^{-1}) with an excellent linearity of 99.4% in the measurement range of [0 kPa, 100 kPa]. The proposed flexible sensor has been prototyped, and several experiments have been performed for quantitative investigation and assessment. The grasp-and-release operations of a water-filled paper cup have been performed using a wearable glove embedded with two sensor prototypes, proving the effectiveness and feasibility of the proposed sensor design.

INDEX TERMS Capacitive sensors, flexible sensors, wearable sensors, pressure sensors.

I. INTRODUCTION

Flexible pressure sensors have received constant attention due to their merits in terms of high compliance, large deformability and great potentials in convenient integration with various objects [1]–[3]. These advantages support their extensive and promising applications in soft robotics [4]–[6], electronic skins [7], [8] and wearable devices [9]–[11]. The pressure values that are produced by interactions between human and the designed flexible sensor devices in these applications, are typically distributed and classified in low-pressure range (<10 kPa) and medium pressure range (10-100 kPa) [3]. In order to have sufficient sensory coverage of pressure measurement range for various applications, it is necessary to maintain a high sensitivity in a large measurement range and meanwhile detect delicate pressure changes.

Several emerging technologies such as, piezoresistive sensors [12], [13], capacitive sensors [14]–[16], optical sensors [17], [18], and magnetic sensors [19], have been attempted and implemented to fulfill this aim. Piezoresistive sensors are mainly produced based on elastomeric composite materials and can be manufactured by simple procedures. However, they commonly suffer from issues regarding large nonlinearity and slow response. Optical sensors typically involve detecting the applied force-induced light variations of intensity, frequency or phase. However, they undergo either

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expensive implementation or complicated manufacturing process. The magnetic ones commonly consist of a magnetic source, a magnetic field sensing element, and an elastomer. Although this method is simple and provides compact designs, it is easily interfered by the environmental magnetic field and ferromagnetic objects, limiting its potential applications. In contrast, capacitive sensors depend on generating strain or shrinkage under external stimuli to cause changes in capacitance value. These sensors provide advantages in terms of low power consumption, relative simplicity, convenient integration and signal repeatability [2], [20], facilitating their developments and wide introduction into soft robotics and wearable devices.

The typical capacitive flexible pressure sensors are mainly composed of two stretchable electrode plates on both sides and one elastomer as the intermediate dielectric layer [21], as illustrated in Fig.1. However, in most studies, after the sensor is subjected to external pressure, the thickness change of the dielectric elastomer is relatively small, making it difficult to balance the trade-off between high sensitivity and large response range. Many of them involve applying complex MEMS fabrication procedures to produce sensor prototypes [7]. In this context, to improve the performances of flexible sensors, it is important to fabricate the flexible electrodes with excellent characteristics of both elasticity and conductivity, as well as implementation of simplified and convenient fabrication procedures for sensor prototype. The efforts to increase sensitivity can be mainly grouped into the following two categories. Flexible materials with conductive properties (silver textiles, ITOs) demonstrate great advantages in conductivity and mechanical strechability [2], [22], but suffer from low sensitivity and limited working range. Conductive composites such as, silicone-based composites which are made by the mixture of the silicone and conductive materials (carbon-based materials, nanowires) [23], [24], typically possess excellent stability, but commonly experience a significant reduction in sensitivity [16]. In the choice of elastomer materials and structures, existing research has attempted various methods to target largely deformable elastomers. A dielectric elastomer layer fabricated with micropores, surface modification and mold forming can achieve larger capacitance change at an identical pressure level. The microporous structure is typically produced by using the solid particle (salt, sugar) leaching method, which is able to generate a strong deformability and a large change in dielectric constant [25]. However, the consistency of sensor production cannot be guaranteed, owing to the random distribution of sugar/salt inside silicone. The surface-modified elastomer structure method and the mold forming method typically produce multiscale-structured elastomer layers [7], [14]. These methods can achieve high sensitivity but have limitations in measurement range.

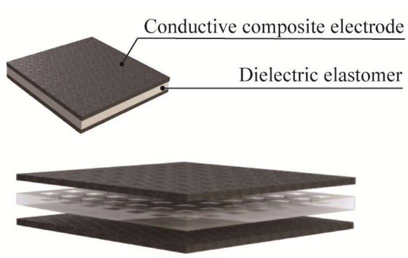

FIGURE 1. Schematic diagram of the composition of the pressure sensor.

To address the above-mentioned issues, this work proposed and demonstrated a relatively simple, fast, mass-production and low-cost fabrication method to produce a flexible capacitive pressure sensor that is composed of conductive composite electrodes and a dielectric elastomer layer with microstructures. The highly stretchable and flexible electrodes have been proposed and fabricated based on the combination of high-elastic modal fabrics and carbon-based materials. Therefore, the fabricated electrodes inherit their advantages in terms of great mechanical stretchability and excellent electrical conductivity. The flexible dielectric elastomers with micro-structured pillars and cavities have been proposed and made. The 3D printing technique has been applied to fabricate high-precision rigid molds with different microstructures. Silicone is followed to pour into these molds, and the high-precision geometric micro-structured elastomers can be produced after drying and demolding. The flexible capacitive sensor prototype can be formed by sandwiching two electrodes and one elastomer. The stretchable electrodes and elastomers support the realization of a relatively large working range with excellent resilience. When subjected to pressure loading and unloading, the air deflation and inflation are generated through the cavities inside the elastomer, resulting in enhanced dielectric constant and capacitance change. This working principle contributes to high sensitivity and the ability to detect ultra-low pressure. The proposed sensor prototypes with three different micro-structured elastomers have been analyzed and compared. In the meantime, the factors that influence the sensor's performances have been investigated. Furthermore, the wearable glove embedded with two sensor prototypes have been applied to perform grasp-and-release operations of a water-filled paper cup to prove its effectiveness.

II. MATERIALS AND METHODS

A. PREPARATION OF THE CONDUCTIVE COMPOSITE ELECTRODES

This design proposed to combine highly stretchable modal fabrics and multi-walled carbon nanotubes (MWCNTs) conductive paste to produce electrode plates with improved conductivity and resilience. The commercially available modal fabrics possess excellent elastic performances, but cannot be directly utilized as capacitor electrode plates, owing to the lack of conductive property. The CNT-based conductive paste provides excellent conductivity, however, the brittle property in a solidified state and the lack of ductility makes it difficult for this paste to be directly applied to produce the electrode plate. The CNTs conductive paste's adhesivity

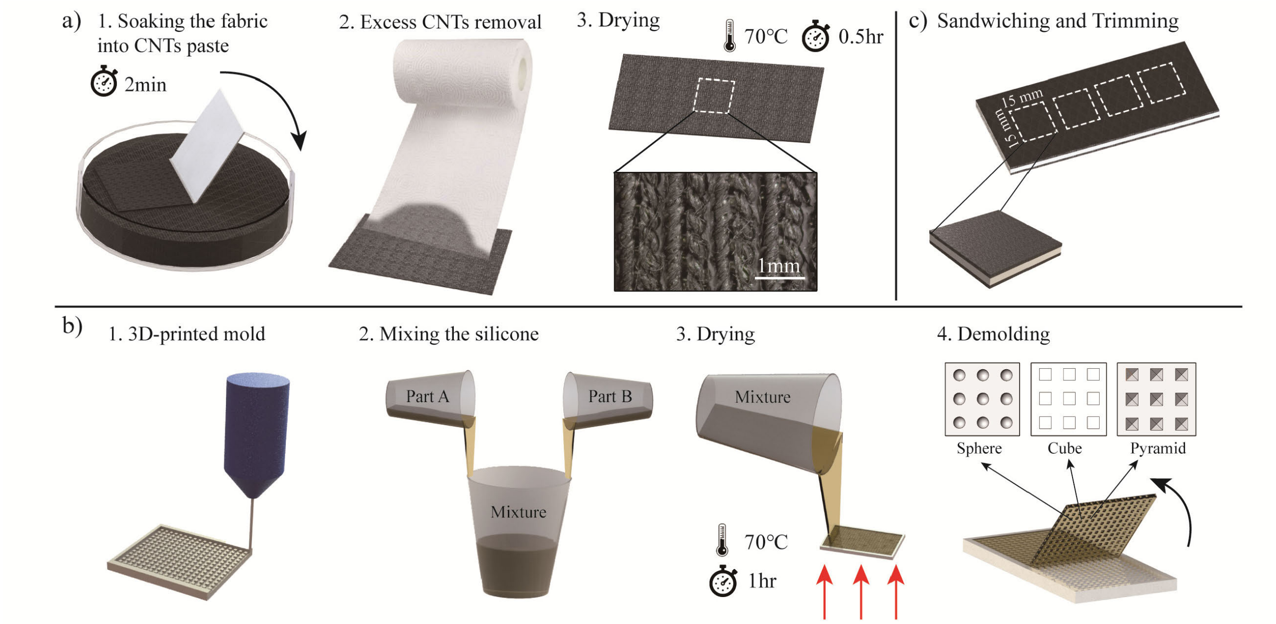

FIGURE 2. The manufacturing process of the flexible capacitive pressure sensor. a) Schematic diagram of manufacturing flexible conductive composite electrodes using CNTs paste and modal fabrics b) Schematic diagram of fabricating the silicone elastomer with three microstructures in the rigid resin mold made by 3D printing technology c) Schematic layout of sensor assembly.

supports its mixture with flexible fabrics, and this mixture procedure has been proposed and introduced to enable the CNTs to be evenly embedded and distributed into fabric fiber networks. This combination offers robust percolated structures and enables to provide improved attributes in terms of excellent flexibility, conductivity and air permeability. The manufacturing process of the electrode plates mainly consists of the following three steps, as illustrated in Fig.2 a). The first step involved soaking the fabric (Modal fabric, Jimengse, CN) into the CNTs conductive paste (Turing Evolution Technology, CN). The fabrics were cut into a rectangle shape with a size of 30 mm*60 mm in advance. Then, the fabric piece was completely immersed in the uniform CNTs paste for 2 minutes, as shown in Fig.2 a1). This immersion supported the CNTs to be fully mixed onto the surface of the fabric fibers. After immersion, an absorbent paper was utilized to absorb and remove the excess liquid paste on the fabric surface. This measure avoided the remaining carbon nanotubes from blocking the tiny pores on the fiber surface, as indicated in Fig.2 a2). Excess CNTs paste can hamper taking-in and release of the air through the conductive plate, reducing elasticity of the modal fabrics and resulting in a lower measurement range. Thereafter, the composite electrode plate was cured in a drying oven (DHG-9035A, BluePard, CN) for 0.5 hours at 70 °C. The detailed texture of the conductive composites had been imaged under an optical microscopy, as illustrated in Fig.2 a3). It can be found that the CNTs are evenly adhered and distributed on the surface of the fabric fibers, while retaining the high elasticity of the fabric itself. Through the above-presented procedure, electrode plates with excellent conductivity and flexibility can be produced.

B. DESIGN AND FABRICATION OF THE SOFT DIELECTRIC ELASTOMER WITH MICROSTRUCTURES

The dielectric elastomer part employs the 3D printing technology (Lite 600HD, UnionTech, CN) to produce an internal microstructure pattern that consists of pillars and air-filled cavities. When the elastomer is subjected to pressure, these air cavities can discharge its internal air, increasing the dielectric constant and capacitance values. The detailed fabrication procedure to produce the soft dielectric elastomer has been illustrated in Fig.2 b). The rigid resin molds (DSM IMAGE8000, WeNext Technology, Shenzhen, CN) with three different microstructures of cubes, spheres, and quadrangular pyramids have been produced with high-precision fabrication and complex morphology based on the utilization of the 3D printing technology, as shown in Fig.2 b1). The silicone material demonstrated excellent flexibility after solidification, therefore, it is selected as the main constituent material to produce different flexible dielectric elastomers. The molding material was formed by mixing and stirring components of silicone part A and part B (PS6600, Yipin, CN) with a ratio of 9:1 by weight. This ratio was chosen to balance the trade-off between the sensor sensitivity and structural durability. Subsequently, the mixed liquid silicone was uniformly and slowly poured into the 3D printed resin mold that was sprayed with Ease Release 200 spray (Mann Release Technologies, USA), as indicated in Fig.2 b2)-b3). Next, the mold filled with silicone was placed into a drying oven at 70°C for more than 1 hour to solidify. After its solidification, the cured silicone rubber was removed from the mold, and the protruding edges was trimmed. By repeating such procedures, the dielectric elastomer with three geometric micro-structured patterns have been completed with high

TABLE 1. Performance characterization of the pressure sensors with three types of microstructure-based elastomers.

Component	Cube	Sphere	Pyramid
Sensitivity	$232*10^{-4}$ kPa^{-1}	$105*10^{-4}$ kPa^{-1}	$52*10^{-4}$ kPa^{-1}
Measuring Range	0-100 kPa	0-100 kPa	0-100 kPa
Fitting Curve	Y = 0.02326*X + 0.1479	Y = 0.01058*X + 0.1801	Y = 0.005215*X + 0.09542
R-square (R^2)	0.9947	0.9645	0.9682
Standard Error of Estimate (Sy.x)	0.05598	0.07079	0.03076

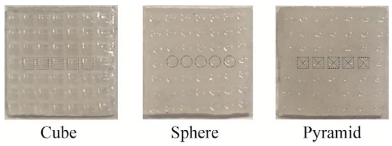

FIGURE 3. The dielectric elastomers with three micro-structured types of cubic, spherical and pyramid forms.

compliance and precision, as illustrated in Fig.3. Their performances have been experimentally investigated and compared in the following section.

C. PERFORMANCE COMPARISON FOR CAPACITIVE SENSORS WITH THREE MICRO-STRUCTURED ELASTOMERS

To further investigate the performances of three types of micro-structured sensors, the thin silicone layer was utilized and configured at both sides of the elastomer as the adhesion layer. The proposed flexible conductive composite electrodes were adhered to each surface by applying pressure via self-made roller to form the sandwich sensor structure. These procedures guaranteed the strong bonding between the electrodes and the elastomer. Then, each of them was trimmed into 15 mm*15 mm, as illustrated in Fig.2 c). This method guaranteed the batch manufacturing rate and ensured the consistency of the basic performance. The microstructures led to generating air-filled chambers inside. The performance characterizations of the flexible pressure sensors have been performed, as illustrated in Fig.4. When the pressure ranges 0-100 kPa, the pressure sensitivity for the sensor embedded with a cubic-shaped microstructure elastomer achieves the highest value of $232*10^{-4}$ kPa^{-1}, while the other two with sphere and quadrangular pyramid structures reach the lower values of $105*10^{-4}$ kPa^{-1} and $52*10^{-4}$ kPa^{-1} respectively, as illustrated in Table 1. From the theoretical perspective, the working principle of the capacitance-based pressure sensor mainly depends on the distance change between the two electrode plates and the dielectric constant variation. The formulas to determine the sensor capacitance have been described below:

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

$$GF = \frac{\Delta C}{C_0 P} \tag{2}$$

$$\Delta C = C_1 - C_0 = \frac{\varepsilon_0 k_1 A}{d_1} - \frac{\varepsilon_0 k_0 A}{d_0} \tag{3}$$

where, C represents the capacitance value, and ε_0 denotes the dielectric constant under vacuum. k represents the ratio of the dielectric constant of the dielectric elastomer medium to the vacuum, that is, the relative dielectric constant. A expresses the opposite area, and d is the distance between the two plates, as illustrated in Fig.5. According to Equation (1), the change in capacitance is proportional to the relative dielectric constant k and inversely proportional to the capacitor plate distance d. The pressure sensitivity can be derived as Equation (2), and the amount of capacitance change ΔC, is proportional to the sensitivity value, as determined in Equation (3). Thus, given that the initial capacitance C_0 is a constant, the larger C_1 value can induce a larger value of ΔC. The proposed elastomer is composed of two materials that include air and silicone. Therefore, k_0 in Equation (3) is mainly composed of the air dielectric constant value ($\varepsilon_{air} = 1$) and silicone dielectric constant value ($\varepsilon_{silicone} = 3$) by volume ratio. It can be defined as $k_0 = V_{air}\%^*\varepsilon_{air} + V_{silicone}\%^*\varepsilon_{silicone}$. $V_{air}\%$ and $V_{silicone}\%$ represent the proportion of air and silicone with respect to the dielectric layer respectively. When the sensor is subjected to compression, the elastomer with microstructures will evacuate the air inside the micro-structured cavities. This leads to an increasement in the silicone volume ratio, which causes the proportion of the dielectric constant after compression greater than that of the uncompressed dielectric constant($k_1 > k_0$). Meanwhile, the compliance of flexible electrode and elastomer can contribute to the decreased d under compression.

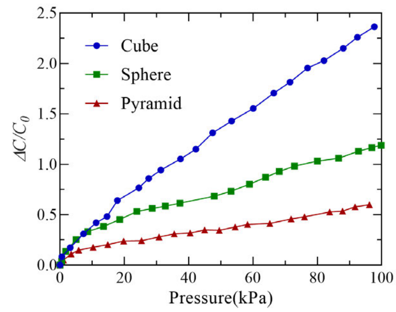

FIGURE 4. The relationship between the applied pressure and capacitance value change for the dielectric elastomers with three different micro-structured types.

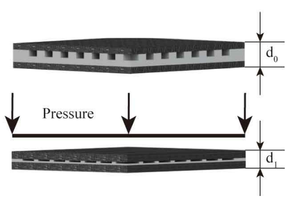

FIGURE 5. Working principle of the capacitive pressure sensor.

Therefore, the combination of increased k and decreased d result in obviously improved sensor sensitivity. According to the capacitor working principle, the change in capacitance value is closely associated with the volume of the air that can be exhausted. The larger volume of the geometric cavity before compression can lead to the higher dielectric constant value after compression. Among these three designs, the volume of a single cavity formed by different microstructures are summarized and compared in Table 2. Under the condition of the same mold size, the microstructures of cubic cavities generate a larger volume, resulting in a higher air ratio for the dielectric constant of the elastomer. It can be found by comparing experimental results with theoretical principles that the variation trend of sensor sensitivity well conforms to the change of cavity volume. In these three geometric configurations, the cubic structure can get more air discharge after compression. Meanwhile, when subject to the applied normal pressure, the cubic structure is more inclined to generate a linear deformation and uniform pressure, inducing a uniform air exhaust volume change. Therefore, the pressure sensitivity and linearity of the cube type is greater than these values of the sphere and pyramid types. The elastomer with a cubic microstructure configuration has been selected to produce the flexible pressure sensor for experiments in the following section.

TABLE 2. Single cavity size and volume of geometric microstructures.

Component	Microstructure dimensions	Cavity Volume
Cube	1 mm*1 mm*0.5 mm	0.5 mm^3
Sphere	D=1 mm	0.26 mm^3
Pyramid	1 mm*1 mm*0.5 mm	0.17 mm^3

III. EXPERIMENTS AND RESULTS

A. EXPERIMENTAL CONFIGURATION FOR PERFORMANCE CHARACTERIZATION OF THE PROPOSED SENSOR

The experimental setup for performance investigation of the proposed sensor has been configured, as illustrated in Fig.6. The weight of the proposed capacitive pressure sensor was about 0.3 g. To facilitate its measurement and reduce interferences from external disturbances, the capacitive pressure sensor was placed between an insulating wooden block and a 3D-printed compression clamp. The insulating tape was employed to fix the connection wires drawn from the two sides to the insulating wooden block. When the sensor prototype was ready, its capacitance change can be measured by an LCR meter (VC4090C, VICTOR, CN) at a frequency of 100 kHz. The standard weights (OIML, Matou, CN) were utilized to analyze the sensing performances of the fabricated sensors. In order to evenly deform the sensor, a square-shaped compression clamp with a size of 15 mm*15 mm has been made. Its weight was around 2.8 g and was placed between the capacitive sensor and standard weights for pressure stimulation.

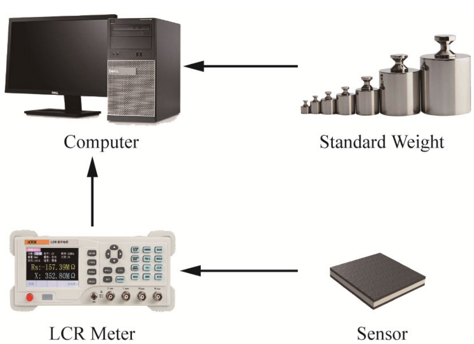

FIGURE 6. Experimental configuration for investigating the performances of the pressure sensor prototype.

B. EXPERIMENTS FOR PERFORMANCE CHARACTERIZATION

To investigate the proposed sensor's performances, the pressure stimulation experiments were applied ranging from 0 kPa to 100 kPa. The relationship between the applied pressure and the capacitance change has been characterized, and the corresponding fitted line and its associated quantitative parameters have been determined based on linear regression analysis, as shown in Fig.7 a). The pressure sensitivity of the capacitive sensor can reach $232*10^{-4}$ kPa^{-1} with a linearity of 99.47%, validating the excellent linear performance and high sensitivity without a significant drop for both low and medium pressure ranges. To investigate the long-term stability and mechanical durability of the proposed sensor, 100 repeated compression and release cycles have been applied ranging from [12.8 g, 1512.8 g] by standard weights (with the compression clamp weight of 2.8 g). That corresponded to the pressure range [0.56 kPa, 67.2 kPa], as shown in Fig.7 b). The capacitance value of the sensor has changed around 5.8% after this loading and unloading process. This occurs because of the small deformation of elastomer induced by multiple compression inputs. Such results validate the excellent performances of the presented pressure sensor in terms of high repeatability and accuracy. In order to study the drift issue under the static loading condition, standard weights have been employed to apply static pressure onto the sensor, and the resulting pressure values of 22.2 kPa, 44.5 kPa and 88.9 kPa were applied to the capacitive pressure sensor with 30 s duration each. The results have been illustrated in Fig.7 c), indicating that this sensor can achieve stable responses under different static pressure inputs. The hysteresis characteristics have also been experimentally explored. Standard weights were employed to apply continuous (40%, 60%, 80%, 100% of the sensor's measurement range) loading and unloading stimulations onto the sensor prototype, as illustrated in Fig.7 d). It can be found that the drift error values are 18.1%, 19.9%, 20.7% and 31.7% for these four loading and unloading cycles respectively. Due to viscoelasticity of the utilized materials, the hysteresis problem becomes increasing, when the sensor experiences higher pressure.

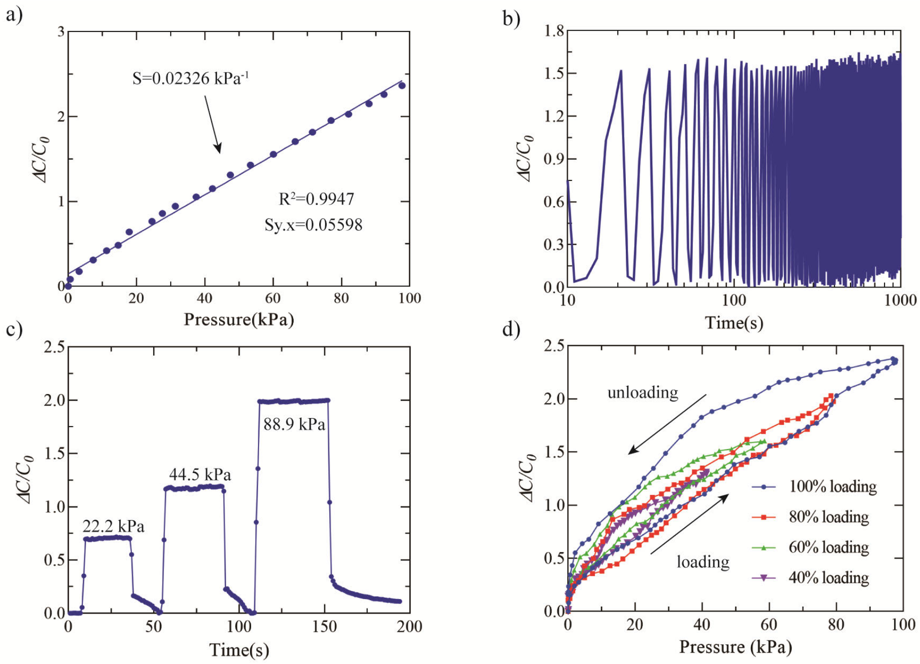

FIGURE 7. (a) Pressure response of capacitive pressure sensor based on cubic microstructures and conductive composite electrode (b) Stability of indication drift of pressure sensor under cyclic test (c) Time-dependent curve of the sensor receiving a fixed pressure in a static state (d) Hysteresis characteristics of the pressure sensor in response to different compression levels.

C. EXPERIMENTS FOR RESISTANCE CAPACITY TO HUMID ENVIRONMENT DISTURBANCES

The sensor's capacity of resisting disturbances in humid environment has been tested by the water drip experiments. A sensor prototype has been placed on a test bench with its two ends connected to the LCR meter through wires. The dropper end was vertically kept 1cm above the sensor surface (also to reduce the impact caused by the free-fall movement of the water drop), and the drip operation was performed every 2 seconds. The capacitance results have been measured, as shown in Fig.8. During the dripping process, the pressure noise fluctuation of the sensor was small. The results indicate that the falling water droplets condensed into a larger water droplet on the surface of the sensor electrode and was not absorbed by the sensor. The weight of one water droplet was around 0.04 g, which equals to the pressure level of 4.96 Pa. Such droplet experiments have validated that this sensor is capable of offering stable response to low pressure inputs.

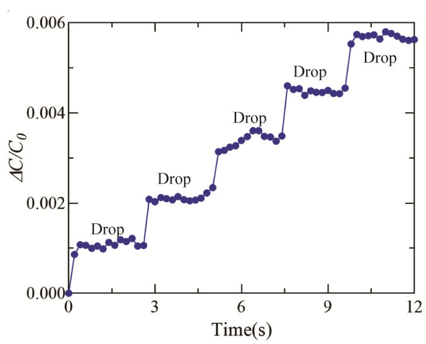

FIGURE 8. The relationship between the droplet and the capacitance value change for the water drip experiments.

D. EXPERIMENTS FOR BENDING RESPONSE INVESTIGATION OF THE PROPOSED SENSOR

In order to investigate the bending responses of the proposed sensor, several semi-cylindrical shaped modules with radius ranging from 12 mm to 40 mm have been fabricated. The prototyped sensor has been placed on curved surfaces of these 3D-printed modules, and measurements have been performed on each module for six times, as shown in Fig.9 a). The response curve between the capacitance variation and bending curvature has been characterized in green, as illustrated in Fig.9 b). Compared with the pressure-caused capacitance variation in blue in Fig.9 b), the curvature change-induced capacitance variation is sufficiently small. Therefore, the proposed pressure sensor is insensitive to bending, supporting its decoupled measurement for bending and compression.

E. PERFORMANCE CHARACTERIZATION OF THE PROPOSED SENSOR APPLIED ON WEARABLE DEVICES

To demonstrate the potential applications in wearable sensing, two sensor prototypes were fabricated and mounted onto the fingertips of the thumb and index finger for testing experiments, as illustrated in Fig.10 a). The grasp-and-release experiments have been designed and implemented. In order to detect the contact force of human hands on objects under different gravity values, one paper cup was filled with

TABLE 3. Performance comparison with other existing capacitive-based pressure sensors.

Groups	Sensitivity (kPa^{-1})	Range (kPa)	Key materials	Method
O. Atalay et.al [25]	0.0121 0.0025	0-100 100-1000	Conductive fabric	Capacitance
J. Yoon et.al [28]	0.0512 0.0109	0-10 10-100	ITO	Capacitance
S. Mannsfeld et.al [7]	0.55 0.15	0-2 2-7	ITO	Capacitance
Yang X et.al [26]	0.09 0.02	0-1 1-6	CNT-PVDF	Capacitance
Pignanelli J et.al [27]	0.1851 0.0373	0-3 3-6	PDMS Microstructures	Capacitance
Luo Y et.al [29]	0.42 0.03	0-2 2-14	Au-PET Tilted Micropillar	Capacitance
X. Wang et.al [11]	1.8 0.79	0-0.3 0.3-1.2	SWNTs	Resistance
Tian H et.al [13]	0.96 0.005	0-50 50-113	Graphene	Resistance
This paper	0.0232	0-100	Carbon nanotube	Capacitance

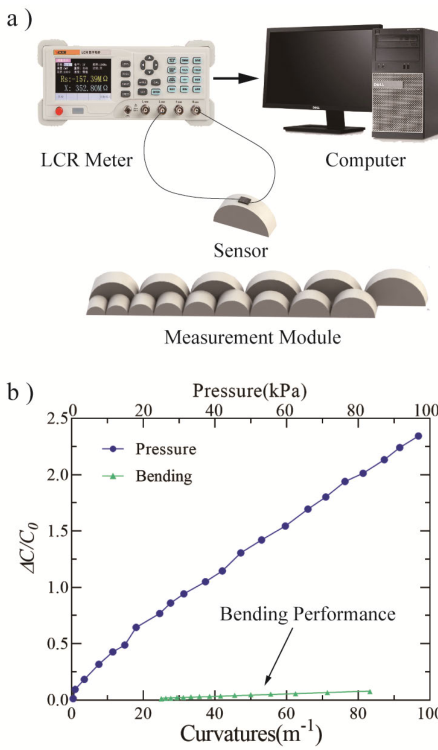

FIGURE 9. **(a) Measurement setup for the bending experiment b) Measured capacitance change under different measurement module compared with pressure performance.**

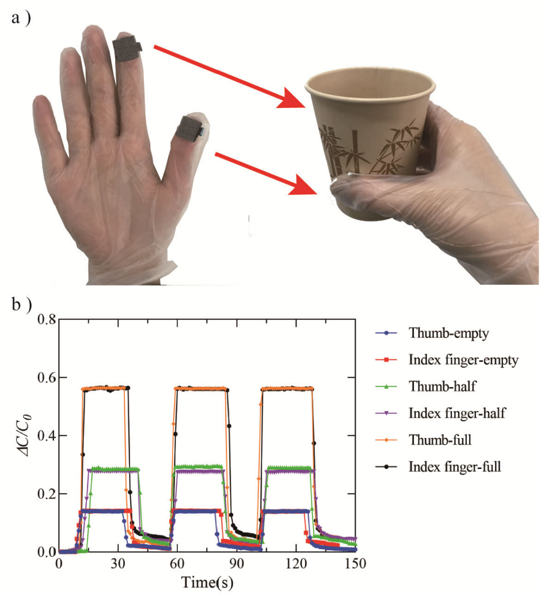

FIGURE 10. **(a) Schematic diagram of sensor placement and cup grasping method b) Place the sensor at the end of the thumb and index finger of the glove to detect the three states of the paper cup.**

different levels of water in sequence to form three different weights of 4.5 g, 90 g and 180 g respectively. The water-filled cup has been repeatedly grasped and released for three times, with each grabbing duration for 20 seconds. The measurement results have been illustrated in Fig.10 b).

These results indicate that the increase of the detected capacitance values from both fingers well match the weight change of the cup. The experimental results prove that the designed capacitive sensor can be used to detect the pressure level of human fingertips without affecting the normal hand movements. Such design can provide a guideline for the subsequent design of wearable sensing devices or human rehabilitation equipment.

F. DISCUSSION

The performance comparison with the existing flexible pressure sensors have been summarized in Table 3. It is difficult for most capacitive sensors to balance the trade-off between sensitivity and working range. Meanwhile, these implementations commonly experience a significant reduction in sensitivity with the increase of measurement range, resulting in poor linearity or piecewise linearity for both low-pressure and medium pressure ranges. The sensor prototypes in [7], [26], [27] can achieve high sensitivity values, however, the sensing ranges are quite limited in the low-pressure range (less than 10 kPa). The sensor sensitivity in [28] is relatively high in 0-10 kPa, but suffers from a significant drop for the remaining medium pressure range of 10-100 kPa. The resistive sensors typically achieve higher sensitivity values in the low-pressure measurement range and experience the low sensitivity as the pressure increases [11], [13]. For instance, the sensitivity decreases significantly to 5^*10^{-3} kPa^{-1} within the range of [50, 113kPa], much lower than the value of 96^*10^{-2} kPa^{-1} within the range of [0, 50kPa] [13]. Compared with these designs, the proposed method can achieve a high sensitivity of 232^*10^{-4} kPa^{-1} with an excellent linearity of 99.4% in a wider measurement range of 0-100 kPa.

When the proposed sensor prototype is subjected to compression, the electrode distance decreases due to the compliance of flexible electrode and elastomer, and the dielectric constant increases due to the ratio change between the air and the elastomer pillars. Both of them contribute to the improved sensor sensitivity and excellent sensitivity linearity. The proposed simple and repeatable fabrication procedure can guarantee the batch production rate and ensure the closely identical initial capacitance values ($C_0 = 4.059 \pm 0.03$pF) and consistency of the basic performance. It is also worth noting that the proposed pressure sensor is insensitive to bending according to the bending response experiments. The capacitance value change that corresponds to the curvature radius is around two orders of magnitude smaller than the response to pressure input. Therefore, when the proposed sensor is integrated with wearable devices, the bending-induced capacitance change can be ignored, facilitating the data decoupling and interpretation.

However, the sensor indicates a certain deviation between the initial capacitance value and the recovery value at the end of the unloading phase, as shown in Fig.7 c) and Fig.10 b). This occurs because of the nonlinear viscoelastic behaviors of flexible electrodes and elastomer materials, and the relatively slow speed of air inflation. At the end of the unloading phase, the sensor recovery process starts with the recovery from the shrinkage of the conductive electrode material and the resilience of the elastomer. Meanwhile, the air inflation propagates through the fabric gap to pump the cubic cavities and influences the sensor recovery speed. Therefore, future improvements focus on the optimization of the microstructure and electrode gaps to increase the air inflation speed, so as to support fast sensor deformation recovery and suppress drift errors.

IV. CONCLUSION

A flexible capacitive pressure sensor with stretchable conductive composite electrodes and ductile elastomer with cubic-structured pillars and cavities has been proposed and implemented. It achieved a relatively high sensitivity of 232^*10^{-4} kPa^{-1} with an outstanding linearity of 99.4% in the covered measurement range of [0, 100 kPa]. The proposed fabrication approach for electrode and elastomer can induce simultaneously decreased electrode plate distance and increased dielectric constant, leading to a relatively large capacitance change. The simple and repeatable fabrication procedure also supports mass production and aids in achieving the excellent sensitivity linearity. These advantages support overcoming the issues associated with the common flexible capacitive sensor in terms of significant sensitivity reduction and poor linearity or piecewise linearity for the whole working range. The water drip and bending experiments have validated its resistant capacity to environmental disturbances and bending-induced signal decoupling. The wearable glove embedded with the proposed sensors has been utilized to perform grasp-and-release operations with the interaction force information, validating its effectiveness and applicability. Future work involves extending the current work by modifying the arrangement of the electrode plates to form a triaxial pressure sensor, as well as implementing potential applications on human wearable devices. The miniature wireless circuit module can be further developed to transfer and receive the sensing signals for improved portable applications.

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