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# Development of a conformable electronic skin based on silver nanowires and PDMS

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**Abstract.** This paper presented the designed and tested a flexible and stretchable pressure sensor array that could be used to cover 3D surface to measure contact pressure. The sensor array is laminated into a thin film with 1 mm in thickness and can easily be stretched without losing its functionality. The fabricated sensor array contained 8×8 sensing elements, each could measure the pressure up to 180 kPa. An improved sandwich structure is used to build the sensor array. The upper and lower layers were PDMS thin films embedded with conductor strips formed by PDMS-based silver nanowires (AgNWs) networks covered with nano-scale thin metal film. The middle layer was formed a porous PDMS film inserted with circular conductive rubber. The sensor array could detect the contact pressure within 30% stretching rate. In this paper, the performance of the pressure sensor array was systematically studied. With the corresponding scanning power-supply circuit and data acquisition system, it is demonstrated that the system can successfully capture the tactile images induced by objects of different shapes. Such sensor system could be applied on complex surfaces in robots or medical devices for contact pressure detection and feedback.

## 1. Introduction

E-skin for contact pressure measurement is a key component for next generation humanoid robots and medical devices [1-3]. It is formed through the embedment an array of pressure sensors in a flexible, stretchable, or foldable substrate. Nowadays, the skin-like tactile sensor has been widely applied to the robotics and medical devices [4, 5]. Smart e-skin which acquires pressure information can be used to cover the surfaces of robotics and medical devices to sense the physical contact with human/environment [6, 7]. Flexibility and stretch ability are two of the most important factors for the application of such sensor array to the humanoid robots and medical devices. The flexibility of the senor array is desired to make the sensor conform to the shape of its applied device. The stretch ability of the sensor has advantages that the sensor is nonbreakable and that the sensor can be easily mounted on complex surfaces or deformable parts such as the joints of a device [8, 9].

Several research studies on flexible or stretchable pressure sensor array have been reported, which resulted in various skin-like pressure sensor arrays. Most of these sensor arrays are based on capacitive or piezoresistive force sensing principles. Reference [10] presents a stretchable and multifunctional capacitive sensor. This sensor was made through the embedment of gold-trace stripes into silicone rubber thin films. Although the mechanical compliance of the gold-trace stripes and silicone membranes

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allows the device to bend, fold, and stretch, the low conductivity of the gold thin films and its poor adhesion with the substrate impede the integration of the sensor array. Bao et al. [11] developed a skin-like pressure and strain sensor array based on transparent elastic films of carbon nanotubes with PDMS as the substrates. The applied pressure was measured through the change of the capacitance among the grid of capacitors formed by the perpendicular strips of nanotubes. Their device can detect pressures above 50kPa. Someya et al. [12] demonstrated an application that used organic field-effect transistors (FETs) with pressure-sensitive rubber to realize a stretchable pressure sensor matrix. The sensor's stretch ability was achieved through its fishnet style. Although the device can detect pressure up to 10kPa, its stretch ability may lose when the working condition requires the device to stick to the host surface. Pan et al. [13] proposed an ultra-sensitive resistive pressure sensor based on hollow-sphere microstructure induced elasticity in conducting polymer. The pressure sensor based on the elastic microstructured thin film enables the detection of pressures of less than 1 Pa and exhibits a short response time, good reproducibility, excellent cycling stability and temperature-stable sensing. However, the low conformability limit its application. Yang et al. [14] designed a highly twistable tactile sensor array. Extendable spiral electrodes were employed as elastic interconnects of sensor array. The tactile sensing elements were formed by dispensing conductive polymer on the spiral electrodes. The fabricated sensor array can be twisted up to 70º without any damage in the structure or functionality. However, the sensor array fabrication method may deteriorate the non-uniformity of the sensing elements which is one of the drawbacks that the sensor arrays usually suffer from. In this paper, we present a novel design of a flexible and stretchable pressure sensor array based on piezoresistive principle for e-skin application. The AgNWs/PDMS based conductors instead of metals are served as interconnects and electrodes for the sensor arrays to improve its flexibility and stretch ability. The sandwiched sensing layer consisting of the porous PDMS film and circular conductive rubber enables the sensor array to be highly flexible and stretchable. The characteristic and performance of the sensor array have been measured and discussed.

## 2. Structure Design

The schematic diagram of the proposed pressure sensor array is shown in Fig. 1(a). In the sensor array, the AgNWs/PDMS conductor strips are used as stretchable interconnects and sensing electrode. The soft metal layer adhered on the conductors and conductive rubber can improve the contact quality between the electrodes and piezoresistive material. The porous PDMS thin film holds the circular piezoresistive elements together and improves the stretch ability of the middle layer. In addition, its isolation among piezoresistive elements eliminates the crosstalk problem [14, 15]. The middle sensing layer is sandwiched between the two electrode layers, each of which brings rows of parallel AgNWs/PDMS based conductive strips in contact with the circular piezoresistive elements. The conductive strips in the top and bottom layers are placed orthogonal to each other. Together with the sensing elements in the middle layer, a array of sensing elements is built up. Fig. 1(b) describes the sensing principle of the pressure sensor array. When a pressure is applied on the sensor, the resistance between conductive strips and piezoresistive film varies, which allows the measurement of the pressure based on the resistance change.

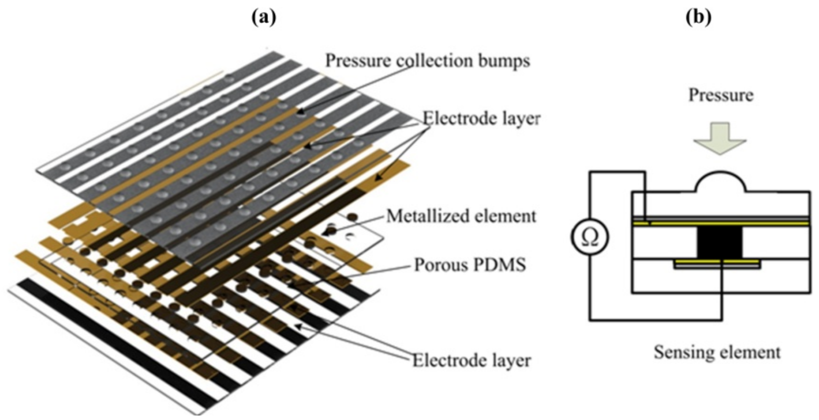


**Figure 1.** (a) The schematic of the proposed pressure sensor array. (b) The sensing element under pressure.

## 3. Fabrication Procedure

The pressure sensor array prototype fabricated is shown in Figure 2. The manufacturing cost of each force sensor array is around \$25. The cost will be decreased further if more sensor array are fabricated.

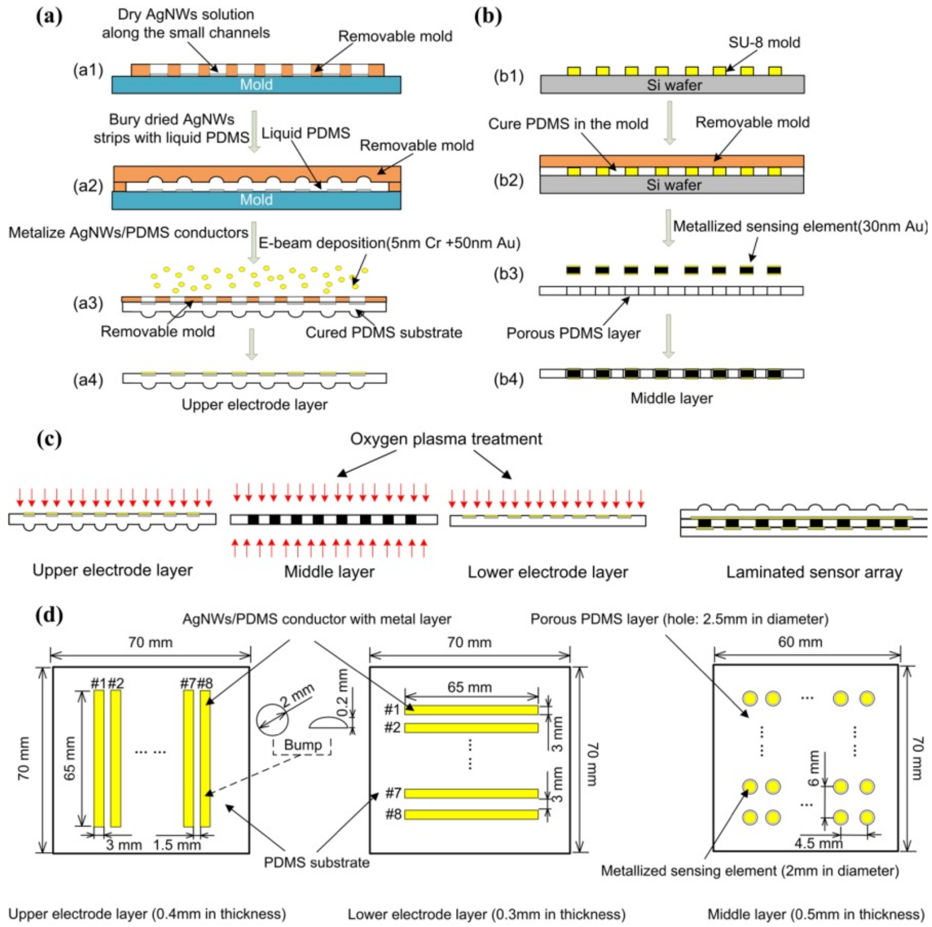


**Figure 2.** (a) Schematic of the fabrication process of electrode layer; (b) Schematic of the fabrication process of middle layer; (c) Lamination of the e-skin with oxygen plasma; (d) The main dimensions of the components for e-skin.

## 4. Measurement Results and Discussion

Following the fabrication and integration of the sensor array, some measurements were carried out toward the characteristics and performance of the sensing element. Fig. 3 shows the schematic of the experimental setup for testing the pressure sensor array. An Epson Scara G3 robot holding a load cell (Phidgets, RB-Phi-113) is used to apply the pressure on one sensing element. A voltage division circuit is designed to measure the resistance of the sensing elements. The output of the sensor cell is labeled as R/R0, where R= R0-R; R0 is the original resistance, ~45 kΩ, between the electrodes, R is the resistance under pressed state with minimum value ~400 Ω. During the measurement, with the increase of the pressure, the resistance change of the sensing element was observed. Correspondingly, the value of the resistance was recorded by a PC. The obtained relationship between the R/R0 and the applied pressure on one sensing element during loading and unloading process is shown in Fig. 4.

The performance such as linearity, hysteresis, sensitivity and pressure resolution ratio of the sensing elements are listed in TABLE I. A commercial soft force sensor Flexiforce sensor, a product of the Tekscan, Inc. is used to compare with the designed sensor. The performances of the Flexiforce sensor were tested. The effective range of the designed pressure sensor array is about 180 kPa. The sensitivity decreases with the increasing load applying on the sensing element. When the load exceeds the effective range the output of the sensor changes very little.

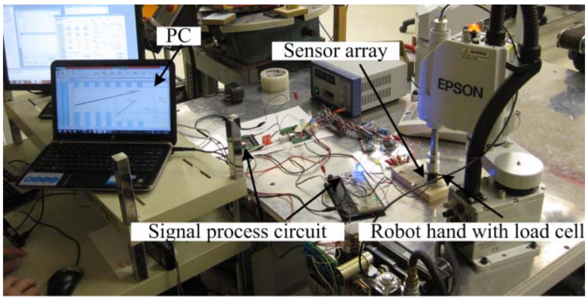


**Figure 3.** Experimental set-up for testing of the sensor array.

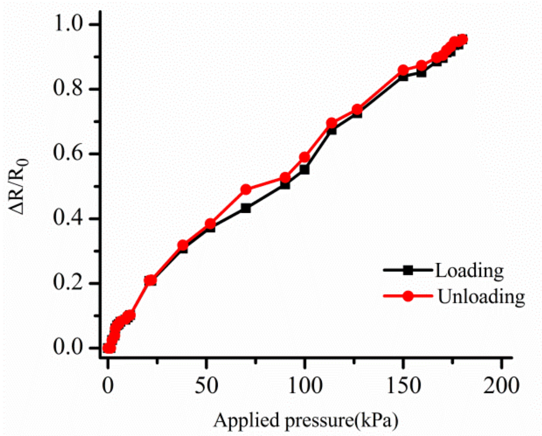


**Figure 4.** Piezoresistance response of the composites with the applied pressure.

**Table 1.** Performance comparison between the tactels of the sensor and flexiforce sensors.

| | Effective measurement range (kPa) | Linearity (%) | Sensitivity (kPa-1) | Pressure resolution (kPa) | Hysteresis (%) |
|---|---|---|---|---|---|
| E-skin | 0-180 | 4.4 | 0.005 | 1-5 | 5.8 |
| Flexiforce sensor | 0-80 | ≤ 10 | 0.009 | > 7 | ≤ 15 |

In order to study the capability of the pressure sensor array to map the pressure distribution, a sensor system based on zero potential method was built. Fig. 5 shows the integrated system which includes our e-skin, a scanning power supply circuitry with the scanning frequency at 300Hz, an 8-channel data acquisition system and a PC. A constant voltage (5V) is applied to the row to be selected as power supply, and all the other rows are set to zero volts. The scanned output-voltages of tactile pressure sensor array are transferred to analog-to-digital converter of a micro programmed control unit (MCU). The PC is used to process the obtained signal and displays the pressure distribution as grey-scale images. Fig.6(a) shows that a PVC tube is pressed on the 8×8 sensor array. The Fig.6(b) shows the pressure distribution produced by the contact shape between the PVC tube and sensor array. Obviously, the shape of the PVC tube is clearly resolved by the sensor array.

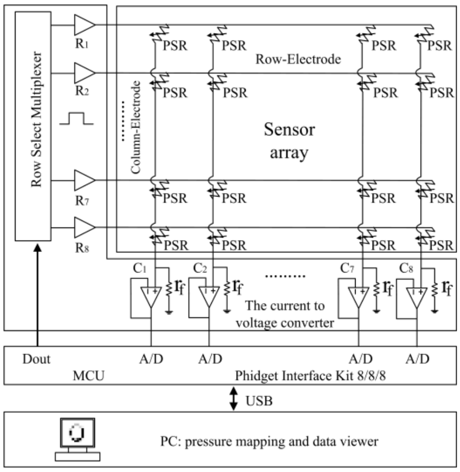


**Figure 5.** Schematic of the tactile sensor array system.

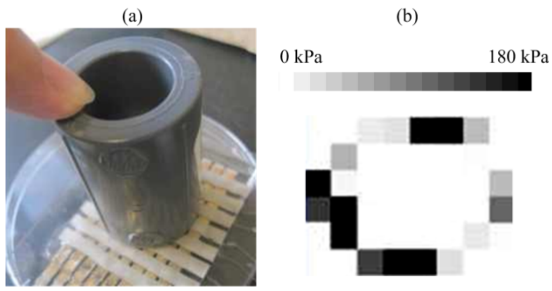


**Figure 6.** Measured pressure distribution using various objects of different shapes.

## 5. Conclusion

The development of a novel type of flexible and stretchable 8×8 pressure sensor array is presented in the paper. The conductive rubber is used as the piezoresistive material for pressure sensing. The AgNWs/PDMS conductors covered with nano-scale thin metal film are employed as stretchable interconnects and sensing electrode. The porous PDMS design can effectively increase the flexibility and stretch ability of the sensor array. The discrete distribution of the sensing elements and designed scanning circuit eliminate the crosstalk among the piezoresistive elements. The static characteristic and the dynamic characteristic are investigated in this paper. The sensor has a low hysteresis and good linearity. The sensor array responds fast and stably enough when a variable pressure is applied on it. The pressure distribution on the contact area induced by placing a PVC tube is successfully detected by the sensor array. The skin-like characteristic of the pressure sensor array makes it well suited for the application on the complex surfaces in robots or medical devices for pressure detection and feedback.

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