

Matrix-Addressed Flexible Capacitive Pressure Sensor With Suppressed Crosstalk for Artificial Electronic Skin

Sujie Chen^{ID}, Ming Li, Yukun Huang^{ID}, Haipeng Xu, Guoying Gu^{ID}, and Xiaojun Guo^{ID}, *Member, IEEE*

Abstract—Matrix-addressed flexible pressure sensors, being able to accurately measure both local contact force and spatial distribution, are pursued for many electronic skin applications. One key issue to be addressed is that the local force being applied onto the target areas may be passed to the neighboring pixels through deformation of the touched top electrode layer. It causes significant signal crosstalk and also loss of measurement accuracy. A new top electrode layer structure is proposed with the development of processes for matrix-addressed pressure sensor systems. It is composed of a patterned layer of high Young's modulus and a low-modulus encapsulation layer. The former is able to sustain a relatively high processing temperature for forming reliable and high-density electrical connections. The latter is to protect the patterned layer while having low Young's modulus to minimize the spreading of local deformation at the pressed pixel to the surrounding ones. A 10×10 matrix-addressed flexible capacitive pressure sensor system is constructed to verify this design, showing effective suppression of the pixel-to-pixel signal crosstalk and improvement of measurement accuracy. The flexible pressure sensor system is integrated onto a prosthetic hand, showing capabilities of differentiating details of massage balls.

Index Terms—Crosstalk, electronic skin (E-skin), laser patterning, pressure sensor array.

I. INTRODUCTION

ELECTRONIC skin (E-skin) sensor systems, being able to accurately measure both local contact force and spatial distribution, are pursued for a wide range of promising applications in personal healthcare [1]–[4], intelligent robots [5], [6], medical surgery [7], [8], and biomimetic prosthetics [9], [10]. In the past, intensive studies have been carried out on materials and processing techniques for developing flexible pressure sensors based on various transduction mechanisms, including

capacitive [11], resistive [12], piezoelectric [13], and triboelectric [14] transducers, to construct such E-skin systems. Although these sensors show capabilities of measuring weak pressure signals, most of them are individual devices or in arrays of very low resolution and are not applicable for measuring spatial pressure distribution details. To develop matrix-addressed pressure sensors of relatively high resolution, vertical structures with the active layer being sandwiched between the bottom and the top electrode layers are commonly adopted [15], [16]. One key issue to be addressed is that the local force being applied onto the target areas may be passed to the neighboring pixels through deformation of the touched top electrode layer. It causes significant signal crosstalk and also loss of measurement accuracy [17]–[19]. To reduce the crosstalk and improve measurement accuracy, a possible approach is through using low Young's modulus top electrode layers [20]–[23]. However, such low Young's modulus layers are prone to distortion under higher temperatures during the processes, especially when bonding external wire connections, and are thus difficult for forming reliable electrical connections for matrix-addressed sensor systems [24]–[26]. Structure design using a rigid spacer with reduced pixel electrode area was shown to be able to significantly reduce the crosstalk, but the sensitivity was deteriorated [27].

In this article, a new top electrode layer structure is proposed with the development of processes for matrix-addressed pressure sensor systems. It is composed of a patterned layer of high Young's modulus and a low-modulus encapsulation layer. The former is able to sustain a relatively high processing temperature for forming reliable and high-density electrical connections. The latter is to protect the patterned layer while having low Young's modulus to minimize the spreading of local mechanical deformation at the pressed pixel to the surrounding ones. A 10×10 matrix-addressed flexible capacitive pressure sensor system is constructed to verify this design, showing effective suppression of the pixel-to-pixel signal crosstalk and improvement of measurement accuracy. The flexible pressure sensor system is integrated onto a prosthetic hand, showing capabilities of differentiating details of the massage balls.

II. METHOD

A. Structure Design

As shown in Fig. 1(a), in a conventional sandwich structure pressure sensor design, a top electrode layer of high Young's

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Sujie Chen, Ming Li, Yukun Huang, and Xiaojun Guo are with the Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: x.guo@sjtu.edu.cn).

Haipeng Xu and Guoying Gu are with the Robotics Institute, Shanghai Jiao Tong University, Shanghai 200240, China.

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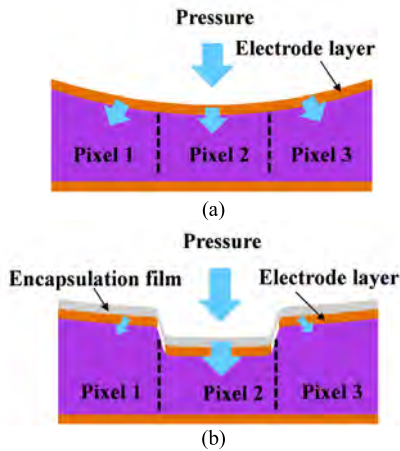


Fig. 1. Schematic illustration of cross-sectional view of deformation of (a) conventional and (b) designed sensor arrays under pressure.

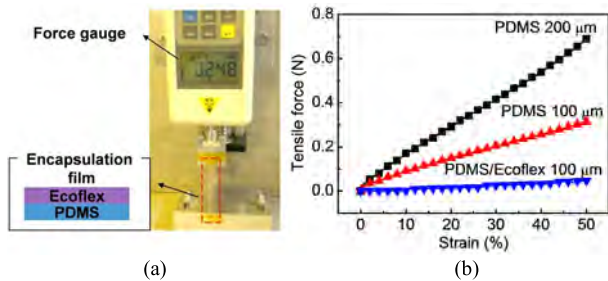


Fig. 2. (a) Experimental setup for measuring the real-time tensile force. (b) Measured tensile force as a function of the strain for the stretchable encapsulation film of PDMS and PDMS/Ecoflex with different thicknesses.

modulus is needed to form reliable electrical connections, but pressure-induced mechanical deformation will cause signal crosstalk to the neighboring pixels. This article proposes a new structure design for the top electrode layer, as illustrated in Fig. 1(b), which is composed of a patterned high Young's modulus layer and a low Young's modulus encapsulation film on the top. The former is able to sustain a high processing temperature for making fine-resolution electrodes and reliable electrical connections. The latter is only for the protection of the patterned layer, and thus low Young's modulus material can be used to minimize the spreading of local mechanical deformation at the pressed pixel to the surrounding ones.

As shown in Fig. 2(a), such an encapsulation film is obtained by stacking two low Young's modulus elastomer layers of polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning) and Ecoflex silicone elastomer (0030, Smooth-on) with a bar coating process [28]. The PDMS layer is used to be easily delaminated from the polyvinyl pyrrolidone- (PVP, k90, Sigma Aldrich) coated glass substrate. The film thickness was controlled by varying the layer number of PI tapes, which were put on both sides of a glass substrate as the spacer during the processes. The mixed solution of PDMS prepolymer and its curing agent with a proportion of 10:1 was coated on a PVP-coated glass substrate with the bar moving speed of 2 mm/s, followed by annealing at 100 °C for 30 min. Ecoflex silicone elastomer was then coated on the PDMS layer and

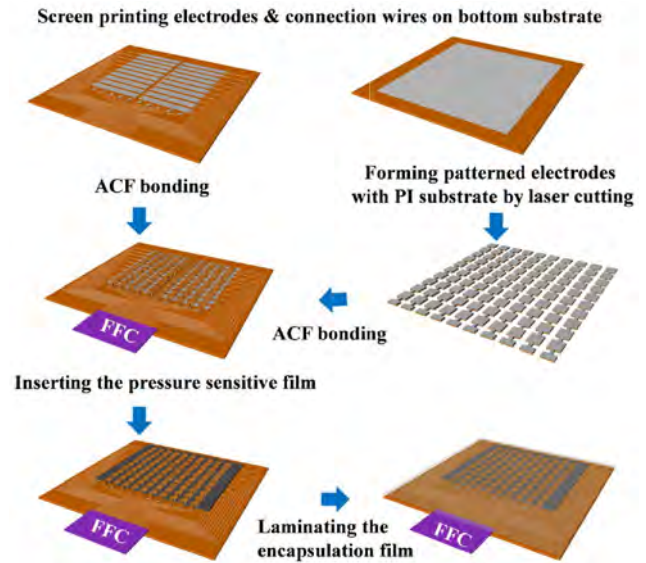


Fig. 3. Schematic illustration of the fabrication process of the pressure sensor arrays with patterned top electrode layer and stretchable encapsulation film.

annealed at 100 °C for 10 min. Finally, the encapsulation film was peeled off from the PVP surface directly.

The tensile force of the fabricated different encapsulation films under stretching was measured as shown in Fig. 2(b). The films were cut into the same size of 1 cm × 5 cm and stretched by a tensile testing stage, with the tensile force being measured by a force gauge (HP-20, Handpi). It can be seen that thinner PDMS films have smaller tensile forces. Combining the lower Young's modulus Ecoflex, the 100-μm-thick PDMS/Ecoflex bilayer structure film presents the smallest tensile force and is thus chosen for fabricating the sensor array.

B. Construction of Sensor Array System

Based on the above design, a matrix-addressed capacitive pressure sensor system was constructed as illustrated in Fig. 3. The bottom electrodes and the connecting wires on a 50-μm-thick PI substrate were formed through screen printing silver paste (HS-200MS-2F, Kunshan Hisense Electronics Company) followed by an annealing process at 140 °C for 20 min. The patterned top PI strips with square-shaped pixel electrodes and narrow connecting lines were obtained through laser cutting (VLS3.50, Universal Laser System Company). The square shape of the electrode was chosen for ease of processing with an area to obtain large enough capacitance values being detectable via the readout circuit. For processing needs, the pixel electrodes on the same row were physically connected, which was different from the ideal structure as shown in Fig. 1(b). It would cause certain spreading of local mechanic deformation along the row direction. To minimize that, the interpixel connection lines should be minimized. In this article, the width of the connection lines was 1 mm, which was limited by the laser patterning process. The top electrodes were bonded to the wires on the bottom PI substrate with an anisotropic conductive film (ACF, AC-7813KM-25, Hitachi). These wires were then connected to a flat flexible

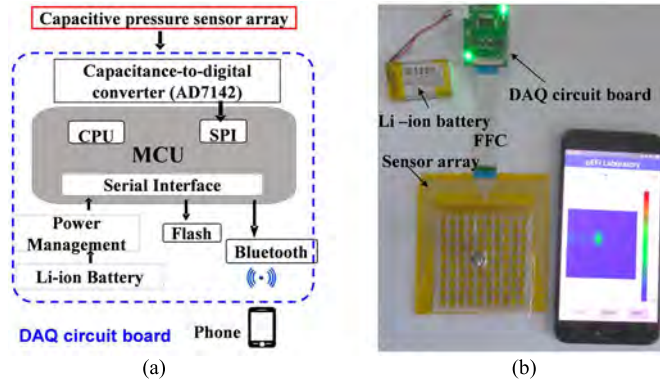


Fig. 4. (a) Schematic illustration of the designed DAQ system. (b) Measurement setup for characterization of the sensor array.

cable (FFC) also through ACF bonding. The temperature, pressure, and press time of the ACF bonding process were set to be 220 °C, 1 MPa, and 40 s, respectively, to achieve reliable connections. Therefore, the PI film of high Young's modulus is required. A 2-mm-thick porous PDMS film with a high density of air void microfeatures was inserted between the bottom and the top electrodes as the pressure-sensitive layer. The film was fabricated by adding a foaming agent into the PDMS prepolymer mixture as described in [29]. Finally, the prefabricated PDMS/Ecoflex encapsulation film of low Young's modulus material was laminated on the top to complete the fabrication of a 10 × 10 pressure sensor array. The pixel area is 6 mm × 6 mm with the sensing electrode area of 4 mm × 4 mm. A sensor array of the same resolution was fabricated based on the conventional structure using a continuous PI top electrode layer for comparison. It has the same dimensions of the pixel and the pixel electrode with those of the sensor array based on the proposed structure.

C. Characterization

The sensing performance of the individual sensor devices based on the porous PDMS dielectric layer was characterized in the previous work [29] and also showed good environmental stabilities [30]. In this article, to read out the capacitance changes in the sensor array upon applied pressure, a data acquisition (DAQ) circuit board was designed as depicted in Fig. 4. The circuit board consists of two high-resolution capacitance-to-digital converters (CDCs) (AD7142, analog devices), a microcontroller (MCU) (STM32F0, ST micro-electronics), and a Bluetooth module (BC-04-B, Cambridge Silicon Radio). The CDC acquires the capacitance values from the connected sensor array and converts them into digital voltage signals. The MCU receives the data from the CDC through a serial peripheral interface (SPI) and transmits the processed data to the smartphone via the Bluetooth module. The whole DAQ system is powered by a 3.3-V Li-ion battery. A program developed in Android was run in the smartphone to display the test results in real time.

III. RESULTS AND DISCUSSION

A. Simulation

3-D finite element numerical simulation with COMSOL was performed to compare the sensing performance of a 3 × 3

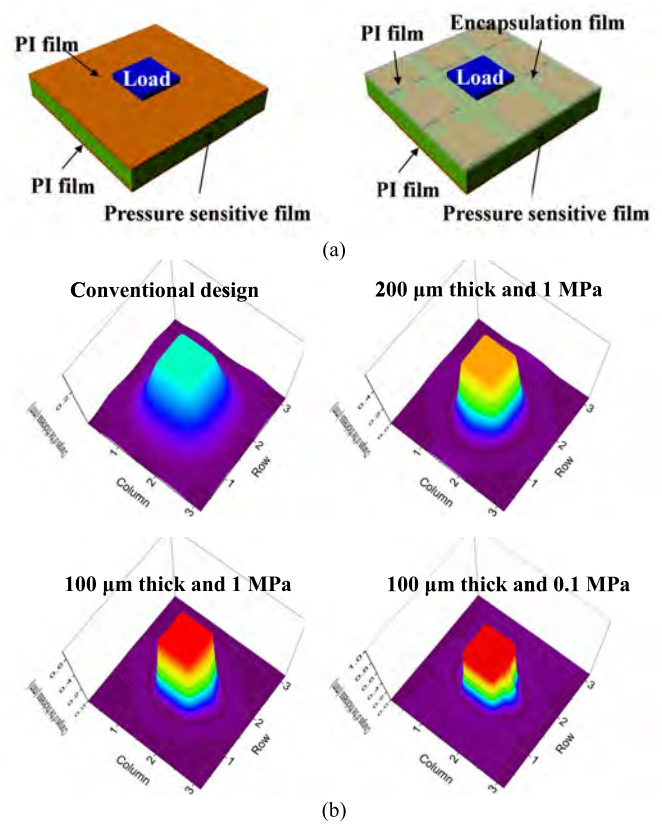


Fig. 5. (a) 3-D simulation molds of the pressure sensor arrays with conventional and designed structure. (b) Simulation results of the thickness changes in the pressure-sensitive film of the sensor array with a conventional structure, designed structure with a 200-μm-thick and 1-MPa Young's modulus encapsulation film, designed structure with a 100-μm-thick and 1-MPa Young's modulus encapsulation film, and designed structure with a 100-μm-thick and 0.1-MPa Young's modulus encapsulation film, respectively.

sensor array upon a 0.1-N load on the central pixel based on the conventional structure and the proposed design, as illustrated in Fig. 5(a). An encapsulation film of different thickness and Young's modulus was used for the latter. The thickness values of each layer and the sizes of the pixel electrodes are the same as the fabricated sensor arrays. The simulations are performed for a qualitative comparison of the performance difference instead of calibration with the measurement data. From the simulation results [Fig. 5(b)], it can be clearly seen that the proposed design exhibits suppressed crosstalk and more accurate measurement of the applied pressure compared with the conventional structure, and its performance can be enhanced with a thinner encapsulation film of lower Young's modulus.

B. Characterization of the Sensor Array

Measurements with the fabricated 10 × 10 pressure sensor array further verify the proposed design. As shown in Fig. 6(a), different counterweights were placed on a 3-D printed acrylonitrile butadiene styrene (ABS) pillar (245 mg) to apply different pressure onto the same region. The measured capacitance changes (ΔC) in the pixel upon the applied pressure for the pressure sensor arrays based on different

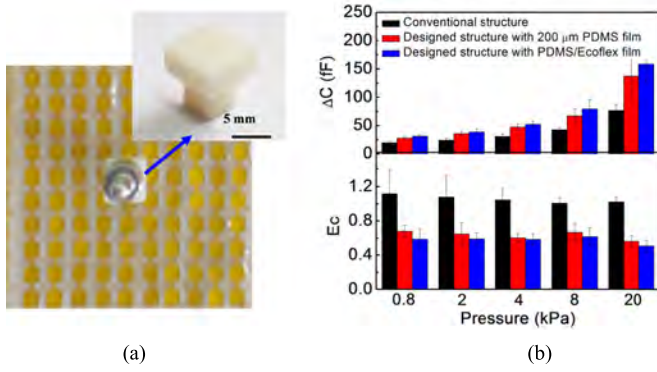


Fig. 6. (a) Measurement setup for loading the pressure on the surface of the sensor array. (b) Measured capacitance changes (ΔC) and the evaluation of the crosstalk (E_c) upon the applied pressure for the pressure sensor arrays with a conventional structure, designed structure with a 200- μ m PDMS encapsulation film and designed structure with a 100- μ m PDMS/Ecoflex encapsulation film.

designs are shown in Fig. 6(b). It can be seen that ΔC upon the applied pressure for the pressure sensor based on the proposed design is significantly enhanced compared with that of the conventional design. As a result, ΔC of the sensor is further increased with PDMS/Ecoflex encapsulation film, which agrees well with the previous simulation results.

A quantitative figure of metric is used for evaluating the crosstalk as described below

$$E_c = \frac{\sigma}{C_{pre}} \times \frac{S_{sur}}{S_{pre}} = \sqrt{\frac{\sum_{i=1}^8 C_{sur}^2}{8C_{pre}^2}} \times \frac{S_{sur}}{S_{pre}}$$

where σ denotes the standard deviation of the capacitance changes in the surrounding pixels, C_{pre} and C_{sur} denote the capacitance change in the pressed pixel and the surrounding pixels, respectively, and S_{pre} and S_{sur} denote the area of the pressed pixel and the surrounding pixels, respectively. The measured E_c values upon different applied pressure for the sensor arrays of different designs are given in Fig. 6(b). Obviously, the proposed design with a thinner and lower Young's modulus encapsulation film presents well-suppressed crosstalk. A four-point pressure test was applied to the pressure sensor arrays using a 3-D printed ABS quadruped structure and placing a 100-g counterweight on the top as shown in Fig. 7. The measured response for both sensor arrays corresponds well to the locations of the four points. The much sharper response of the sensor array based on the proposed design indicates well-suppressed crosstalk. The exhibited larger crosstalk of the proposed structure along the row direction than that along the column direction [Fig. 7(b)] might be caused by the spreading of deformation through the interpixel connection lines.

C. System Demonstration

Finally, to demonstrate its potential for artificial E-skin applications, the pressure sensor array based on the proposed structure was attached to the palm of a prosthetic hand, as shown in Fig. 8(a). Two different massage balls were placed on it for the test. One has a smooth surface and a weight

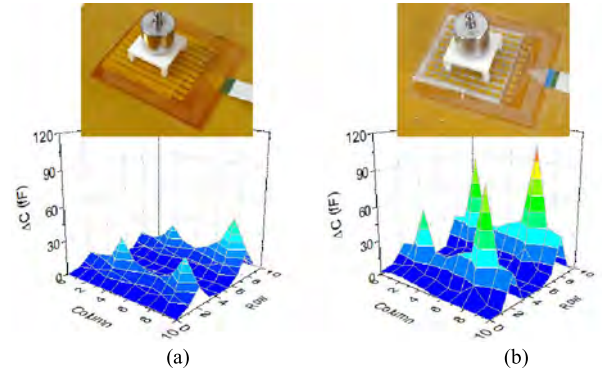


Fig. 7. Measured capacitance changes (ΔC) in the pressure sensor arrays with (a) conventional structure and (b) designed structure with a 100- μ m PDMS/Ecoflex encapsulation film.

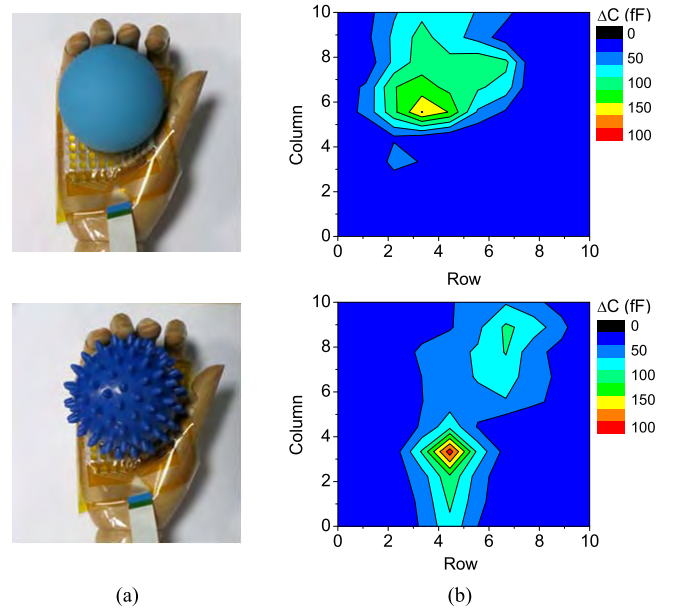


Fig. 8. (a) Photograph of the designed pressure sensor array integrated on the palm of the prosthetic hand with a massage ball with a smooth surface and a massage ball with the thorny surface, respectively. (b) Measured capacitance changes (ΔC) in the designed pressure sensor array with a massage ball with a smooth surface and a massage ball with the thorny surface on the surface, respectively.

of 150 g and the other with a thorny surface has a weight of 75 g. Fig. 8(b) compares the measured pressure distribution through the sensor system with the two balls being put on it, respectively. It can be seen that the measured locations and capacitance changes in the pressure peaks, and pressure distribution contours are quite different. The results prove the capability of such a matrix-addressed pressure sensor system to be integrated as an artificial E-skin for object recognition.

IV. CONCLUSION

In summary, a new top electrode layer structure is developed for matrix-addressed pressure sensor systems, composed of a patterned layer of high Young's modulus and a low-modulus encapsulation layer. The former is able to sustain a relatively high processing temperature for forming reliable and high-density electrical connections. The latter is to protect the patterned layer while having low Young's modulus to minimize the spreading of local deformation at the pressed pixel

to the surrounding ones. Both the simulation and experimental results prove this design to be able to effectively suppress the pixel-to-pixel signal crosstalk and improve measurement accuracy. The fabricated flexible matrix-addressed sensor system is attached to a prosthetic hand, showing capabilities of differentiating details of the massage balls. This article would provide a useful technical route for realizing high-resolution and low-crosstalk artificial E-skin sensor systems in human-machine interaction and prosthetics applications.

The design and processing technologies have the following limitations to be addressed for further work.

- 1) For processing needs, the pixel electrodes on the same row are still physically connected, causing obvious crosstalk along the row directions. To address this problem, the possibility of implementing interpixel connection lines in stretchable shapes (e.g., zigzag) would be considered.
- 2) To down-scale the feature size of the sensor structures and the interconnects for higher resolution sensor arrays, the thickness of the sensitive layer needs to be decreased and the process resolution should be improved.
- 3) The current design is based on qualitative analysis. Development of a mathematic model to quantitatively describe the dependence of the sensing performance and crosstalk on the structure parameters would be able to provide a more straightforward method for the optimal design of the sensor array system.

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