FLEXIBLE TACTILE SENSOR ARRAY UTILIZING MICROSTRUCTURED PDMS BUMPS WITH PEDOT:PSS CONDUCTIVE POLYMER

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ABSTRACT

This work presents a novel flexible tactile sensor array fabricated with PEDOT:PSS conductive polymer modified micro-structured polydimethylsiloxane (PDMS) bumps. PDMS bump arrays with micro-structures are coated with PEDOT:PSS conductive polymer for resistive tactile sensing. The micro-structures on PDMS bumps are produced by replicating the formed thermal bubble cavities during laser ablation of polymethyl methacrylate (PMMA) substrate. The micro-structures on the PDMS bumps greatly enhance the small force response such that the developed sensor exhibits a good response for detecting forces ranging from 0.2~0.7 N. Results also indicate that the developed PDMS-based tactile sensor has good elastic property with the spring constant of 8.3 N/mm with excellent reproducibility. The developed method provides a simple yet high performance way to produce flexible tactile sensor for electronic skin applications.

INTRODUCTION

There are a number of receptor cells for tactile sensing on human skin. For example, the meissner corpuscle, pacinian corpuscle and ruffini ending in skin are to sense normal force, shear stress and the traction force of different sizes, respectively [1]. In this regard, humans can identify the shape and appearance of object through physical contact. Although a mechanical scale can detect light weight, it is not able to perceive the multiple contact pressures of light objects. Tactile sensors are potentially to be used in precision machining processes and automation systems for handling soft objects [2]. Precisely monitoring the forces during work can effectively prevent damaging or dropping the soft objects in an automation system. Therefore, there are real demands for developing tactile sensors with the capability of detecting small force distribution. Typical force sensors utilize piezoelectric materials to measure the physical response of the object and convert it into electronic signals. However, conventional piezoelectric sensors are bulky and expensive, which is not suitable for building an array sensor.

"Electronic skin" has become a popular research topic in the recent years due to the rapid development of human-like robots [3]. A variety of haptic devices have been developed and applied to the daily workplace. For example, smart robots integrated with flexible force sensors into the robot arm to precisely control the grapping strength on the object using a force feedback system [4]. Similar concept has also been adopted on clinical surgical tools to assist the surgical operation [5]. Recent high performance tactile sensors aim to increase the sensing area, sensor flexibility, spatial resolution and force sensitivity [6].

In general, the detecting mechanism of tactile sensors can be divided into categories including piezoresistive, piezo-electric, capacitive and optical detection scheme. The piezoresistive detection scheme measures the resistance change of the material due to stress caused deformation [7]. This approach is one of the most common scheme used in tactile sensing. Alternatively, piezoelectric detection uses piezoelectric material as the sensing layer and measures the signals generated by piezoelectric effect [7]. Piezoelectric detection exhibits high sensitivity for force sensing but it is not suitable for detecting steady-state loadings. Alternatively, capacitance detection measures the gap distance or the overlapping area of parallel electrode plates [7]. Nevertheless, the capacitance change is small which is easy to be influenced by surrounding interferences. The optical detection scheme usually uses embedded optical fibers or optical waveguides for transducing the optical signal changes induced by the material deformation [7]. Although the optical detection provides high sensing accuracy, this scheme relies on using expensive and bulky optical components for acquiring the optical signals. One another issue is that optical detection may be problematic while detecting flexing surfaces. Therefore, resistive-type tactile sensor is the most common scheme due to its simple structure design and easy integration with electronic circuits.

In general, flexible polymer substrates have been widely used in the development of tactile sensors. Thomas et al. reported a flexible tactile sensor with a large area of 100 × 100 mm^2 [8]. Conducting adhesive printed with screen printing technology was used to pattern the resistive sensing array. Forces from different directions were successfully detected using the sensing array. Alternatively, Cheng et al. reported a resistive tactile sensor with great flexibility. Mixed conductive composites composed of carbon black, copper powder, silver powder and PDMS elastomer was printed on a spiral structure by ink-jet printing. The produced force sensor was capable of twisting up to 70^o without damage [9]. However, the tactile sensor was fabricated by doping conductive polymer for resistive measurement which was low sensitive to small force conditions [6]. Therefore, some researchers used microstructured sensing layer combined with conductive polymer to enhance the sensitivity in the small force conditions. Choong et al. reported the use of micro-pyramid PDMS structures replicated from a delicate silicon mold produced with wet etching process. The sharp pyramid tips were easy to deform such way that the small force sensitivity was enhanced. Successful detection of pressured region of 10- kPa with a sensitivity of 4.88 μA/ kPa was demonstrated [10]. Nevertheless, the fabrication process for producing the conductive pyramidal array was delicate and time consuming. In this regard, developing a flexible tactile sensor produced with a simple fabrication process and exhibiting good sensing performance is essential. This work presents a simple yet effective method to produce tactile sensor array for small force detection. Micro-structured PDMS bumps are produced by replicating the cavities produced by the laser ablation of PMMA substrate. The formed micro-structured PDMS bumps are coated with PEDOT:PSS conductive polymer for high-performance resistive tactile sensing.

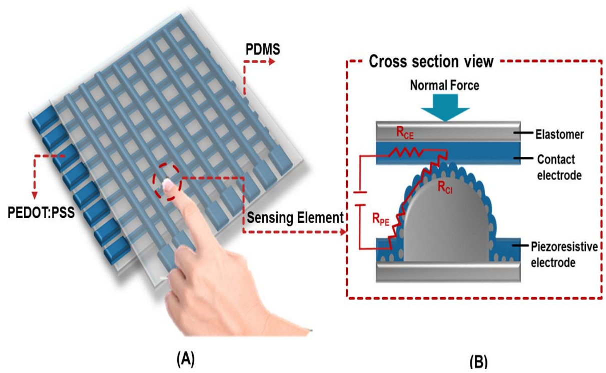

Figure 1: (A) Schematic showing the proposed tactile sensor array. (B) Working principle of tactile sensor composed with microstructure PDMS bump.

DEVICE DESIGN

Fig. 1(A) shows the schematic and the cross section view of the developed tactile sensor array. The device consists of two parallel PDMS films coated with patterned conductive arrays for resistive measurement. The cured PDMS elastomer has good mechanical properties but low Young's modulus, which is good for producing flexible tactile sensors. In order to enhance the conductivity response of the produced tactile sensor, PEDOT:PSS conductive polymer was coated on the substrate surface following a laser ablation to pattern the conductive sensor array and the contact electrodes. With this approach, the sensing electrode array and contact electrodes could be simultaneously produced. Conventional metal electrodes produced with delicate lithography process could be excluded for fabricating the tactile sensor. The magnitude and the distribution of the applied force could be investigated by measuring the contact resistance of the corresponding sensing elements. Fig. 1(B) shows the structure details for the cross section of the developed tactile sensor. This work used micro-structured PDMS bumps to enhance the small force sensitivity. The micro structures on the PDMS bump are easy to deform in such way that the small force sensitivity can be greatly enhanced. The PEDOT:PSS thin film was deposited on the micro-structured PDMS bumps and was used as the lower piezoresistive electrode while the upper electrode was a planar PDMS coated with conductive polymer. The contact area of the coated conductive polymer between the two electrodes increased rapidly with the elastic deformation of the microstructure, resulting in a change of resistance.

Figure 2 presents the concept for producing the PDMS bumps with micro-structures. PMMA substrate was firstly machined to form the master mold for producing the PDMS bumps. Concave groove could easily be produced on PMMA substrate due to the Gaussian distributed energy of laser beam. Alternatively, the energetic CO_2 laser ablation simultaneously decomposed the PMMA polymer into species of small molecular weights and escaped from the machined surface due to thermal vaporization (Fig. 2A). The laser process generated a great numbers of thermal bubbles on the ablated groove surface due to thermal decomposition (Fig. 2B and 2C). The PDMS bumps with micro structures for high performance tactile sensing could be easily produced by replicating the laser ablated grooves.

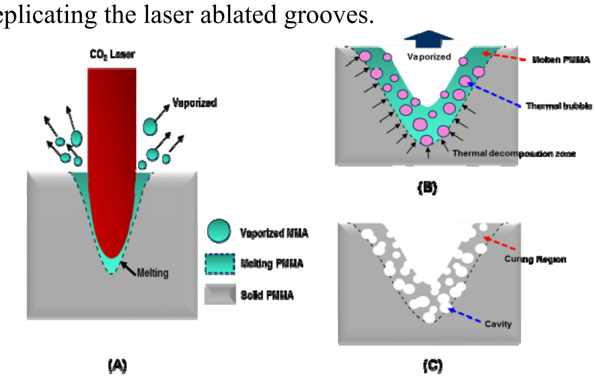

Figure 2: Cavity formation mechanism: (A) PMMA with laser ablation, (B) Thermal bubbles formation due to the decomposition of PMMA and (C) Micro-cavities formed after cooling.

FABRICATION

Figure 3 shows the fabrication of the sensing array. Firstly, master PMMA mold with micro-groove structures was produced on a PMMA substrate using a commercial CO_2 laser processing machine (Venus, GCC Laserpro, Taiwan). Fig. 3A) PDMS elastomer (Sylgard 184, Dow Corning®, USA) prepolymer and the curing agent were mixed with 10:1

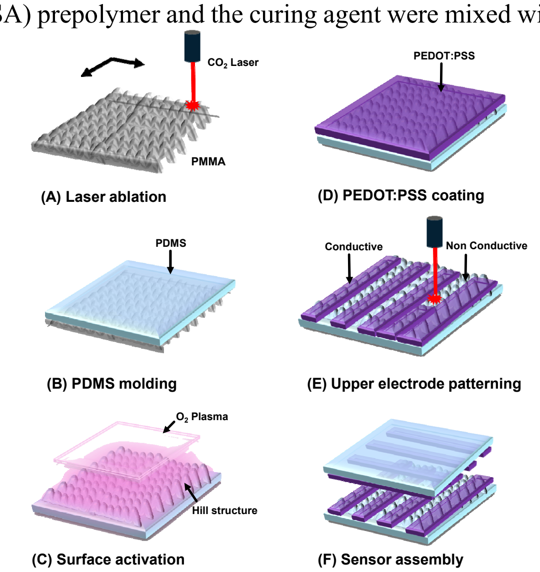

Figure 3: Simplified fabrication process for producing the developed flexible tactile sensor array.

volume ratio and stirred for 10 min. The mixture PDMS elastomer was spin-coated on the PMMA substrate with concave groove and another bare PMMA substrate, respectively. The PDMS elastomer was degassed in a vacuum chamber for fully replicating the micro-cavities in the PMMA groove and was finally cured in an 80°C oven for 1 h (Fig. 3B). The surface of the PDMS was activated with a 100 W oxygen plasma for 5 min to enhance the hydrophilicity (Fig. 3C). PEDOT:PSS solution (FET, Clevios™, Heraeus, Germany) was spin-coated on the surfaces of replicated PDMS substrates and then dried at room temperature to form the conductive film (Fig. 3D). Finally, the conductive PEDOT:PSS layer was again ablated using CO_2 laser to pattern the arrayed sensing electrodes (Fig. 3E). The two upper and lower PDMS substrates were finally aligned and bonded to form the flexible tactile sensor array.

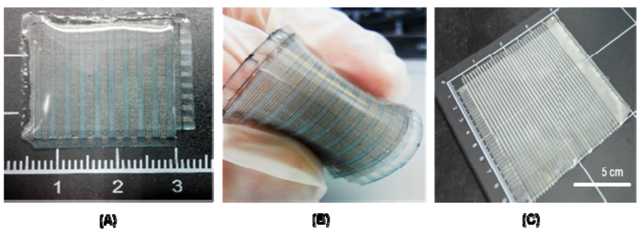

Figure 4: Photo images showing (A) a 30×30 mm² tactile sensor after assembly. (B) Bended sensing array and (C) a large 100×100 mm² sensor array.

Figure 4A shows the photo image of a 30×30 mm² tactile sensor after assembly. An 8 × 8 tactile sensor array with the crossing resistors of 1.0 mm × 1.0 mm was used for resistance measurement. Note that the size of each sensing element of PDMS bump is 140 μm × 1000 μm and 85 μm in height. (Fig. 4A). Figure 4B presents the picture showing the produced tactile sensor under bending. Since the developed method used molding process and laser ablation to pattern the sensing electrode, the method is capable of fabricating sensors with big size. A flexible tactile sensor array with large detecting area of 100 × 100 mm² was successfully produced (Fig. 4C).

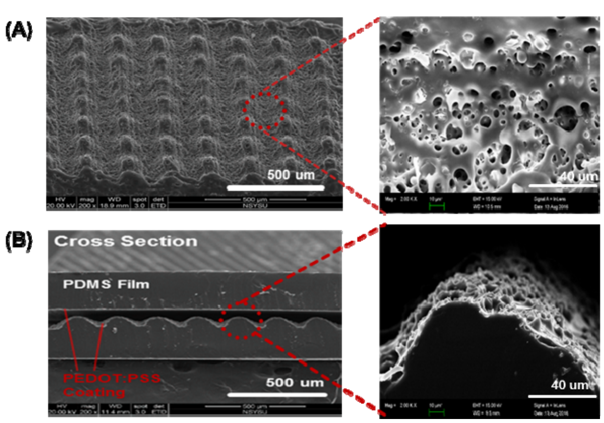

Figure 5: SEM of (A) PMMA substrate and formed micro-cavities after laser ablation. (B) Cross-section view for the sensor with microstructure PDMS bumps.

Figure 5A shows the SEM images for the structural morphology of PMMA surface and the close up view for the formed thermal bubble cavities after laser ablation. It is clear that the micro-cavities were successfully produced with the developed technique. Fig. 5B shows the cross section view of tactile sensing element after assembly and the close up image showing the replicated PDMS microstructures on the PDMS bump. The gap between the PDMS bumps and the upper PDMS film was 50 μm. Results also indicate that the microstructures were well distributed over the bump surface.

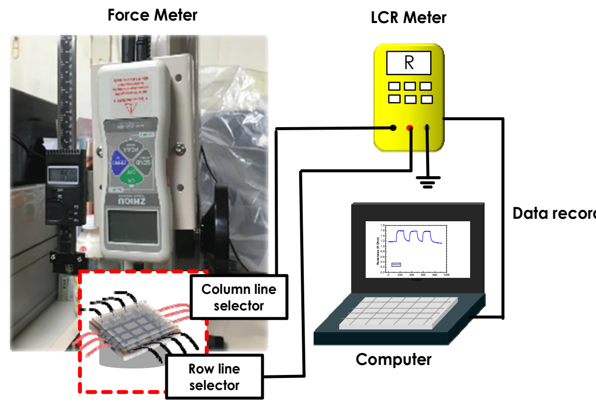

Figure 6: The schematic of the experiment setup for testing the developed PDMS-based tactile sensor array.

MEASUREMENT AND DISCUSSION

Figure 6 shows the experimental setup for testing the produced flexible sensor. Constant normal forces were applied on the sensing elements and the corresponding displacements were recorded using a commercial pressure testing machine (Ds2, Zhiqu, China). The measure resolution for the pressure and the displacement of the gauge were with 1 mN and 10 μm in z-axis direction, respectively. A testing pin with the cross section area of 2.0 x 2.0 mm² was used to apply the normal force on the sensing elements. The resistance change of the sensing element was measured by using a LCR meter (U1732C, Agilent, USA) and recorded with a personal computer.

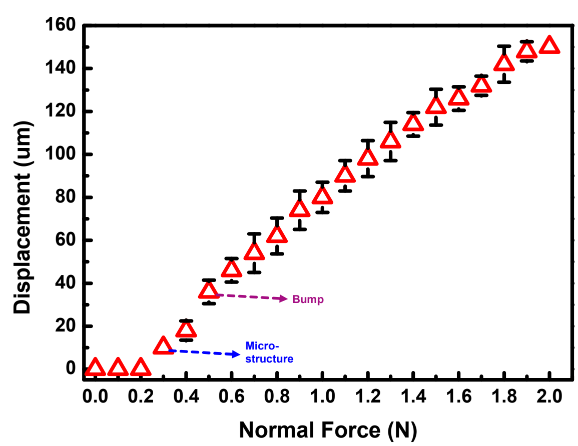

Figure 7: Measured material property for the produced PDMS-based tactile sensor.

Figure 7 shows the measured relationship between the applied normal forces and the corresponding displacement for the produced PDMS-based tactile sensor. The sensing chip is placed on a designed test holder with a rigid and flat bottom support. Normal forces ranging 0 to 2 N were applied on the sensing element using the pressure testing machine. The vertical displacement of the sensing film was recorded using the Vernier caliper mounted on the load cell. Results show that the developed tactile sensor exhibited a good linear response within the force range of 0.2 ~ 2.0 N range. The calculated spring constant of the tactile sensor was 8.3 N/mm. Nevertheless, there was not significant response with applied force smaller than 0.2 N. This small applied force was for eliminating the gap between the upper and lower substrates. Once the upper and lower substrates were in contact, this sensor showed sensitive response to small force.

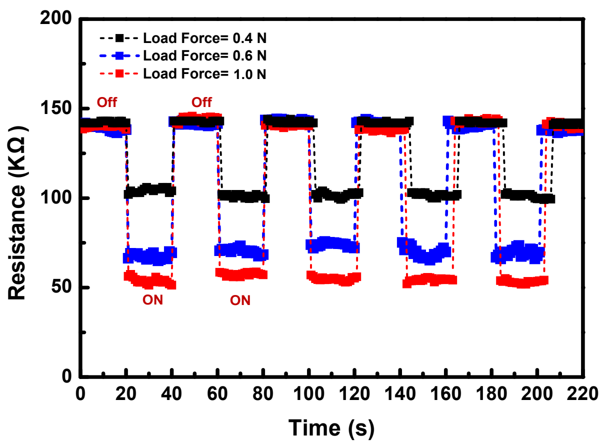

Figure 8: Cyclic loading tests for the developed force sensor array at various applied forces.

In general, the adhesion between the conductive material and the PDMS substrate plays an important role on the repeatability of a tactile sensor. The crack or delamination of the conducting layer could happen after a repeating test. Figure 8 presents the measured results for cyclic loading tests of the sensor under different applied force of 0.4, 0.6 and 1.0 N. Five loading cycles were applied on the same sensing element. Results show that the developed tactile sensors exhibited rapid and good reproducibility for measuring different applied forces. Moreover, no hysteresis phenomenon was observed for the developed sensor since the off value for each test was identical. The cyclic loading test confirmed that the developed PDMS-based tactile sensor is potentially for long-term use.

CONCLUSION

This work has developed a novel method for producing flexible and high performance tactile sensor for small force detection. The conductive polymer PEDOT:PSS combined with the micro-structured PDMS bumps was used for resistive tactile sensing. The microstructures on the PDMS bump greatly enhanced the response of the sensor under small force application. Instead of using conventional MEMS process to produce the sensor, only laser direct ablation and PDMS casting processes were used in such way that the sensing area of the flexible tatile sensor could be simply extented with the method reported in this study. Experimental results also indicated that the developed PDMS-based tactile sensor exhibited linear response at small forces ranging from 0.2 ~2.0 N. Moreover, the flexible sensor also showed good reproducibility and rapid response in cyclic loading tests. The method developed in the present study provided a simple yet high performance way to fabricate flexible tactile sensing arrays. The developed sensor array has also shown its potential to be used as an electronic skin in the future automation systems.

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