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Development of a versatile capacitive tactile sensor based on transparent flexible materials integrating an excellent sensitivity and a high resolution

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A versatile capacitive tactile sensor based on transparent flexible materials is developed in a simple and low-cost fabrication process. The sensor shows an excellent sensitivity ($S=2.05 \, \text{N}^{-1}$), and is highly sensitive to the load as low as about 3 mN. Moreover, it exhibits a prominent resolution. The excellent device performance is attributed to the creative design of polydimethylsiloxane (PDMS) polymer layer, used as the structural material of the sensor, in which each sensing section acting as a sensor unit is a concave square with hemispheric micro-structured PDMS arrays. Meanwhile, other sections without any PDMS arrays serving as perfect natural wall-barriers can make each sensor unit separated effectively.

In recent years, there have been considerable researches on developing assistant robots and artificial biomedical skin, since J. Sullivan demonstrated the first brain-controlled robotic arm. Human beings can dexterously handle a variety of tasks with their hands depending on a sophisticated tactile sensor system in human skin. Therefore, in order to emulate real tactile sensing properties of natural human and behave as humans do, tactile sensors are indispensable for both robots and artificial skin to detect tactile information effectively. Definitely, the tactile sensor units are required with the high sensitivity for this aim. The early pilot researches were still focusing on the silicon-based material, while tactile sensors were fabricated mainly using some conventional microelectromechanical systems (MEMS) process, and these tactile sensors actually have achieved the impressive sensitivity. However, apart from the high sensitivity, it is also imperative to possess the properties of superior biocompatibility, and good flexibility. In this context many flexible tactile sensors employing different flexible polymer materials such as polymer foam, fabric, polyimide, PDMS, have been developed to solve the bottlenecks that early tactile sensors have suffered. In our work, PDMS polymer is used as the structural material of the tactile sensors owing to its excellent well-matched properties such as good biomedical compatibility with human tissue, much better flexibility than other polymer, chemical stability, and transparency.

In addition to the structural material, sensing mechanism is also of great importance for the implementation of high-performance tactile sensors. Only a few types of tactile sensors based on flexible materials have been reported. Hussain et al. proposed a resistive sensor using conductive rubber thin film as the structural material, but exhibiting poor sensitivity in low pressure regime. Compared with resistive ones, capacitive tactile sensors are viewed as a preferable type for higher sensitivity and better immunity to temperature. Bao et al. have demonstrated flexible capacitive pressure sensors based on PDMS polymer, and showed excellent sensitivity, short response times, but...
low spatial resolution. Lee et al. have reported a 3-D capacitive force sensor with high sensitivity and superior spatial resolution, but high complexity of fabrication process.

In this work, we report on the development of a versatile capacitive tactile sensor, which is combining an excellent sensitivity with a good resolution, based on fully transparent flexible materials in a simple and low-cost fabrication process. The sensor is composed of bottom indium tin oxide (ITO)-PET electrode layer, structured-PDMS layer, insulation PDMS layer and top ITO-PET electrode layer. It is noteworthy that each layer presented in our device is processed separately, and laminated in sequence. All layers are sealed up with PDMS, and can be bonded together well after the hot treatment at 90 °C for about 30 minutes. The prototype sensor consists of a 3×3 arrays of sensor units and each sensor unit is 6×6 mm². The schematic structure of tactile sensor is shown in Fig. 1(a). The fabrication processes for the bottom and the top electrode layers are described below. ITO-PET film with the ITO thin-film thickness of ~120 nm is commercially available, and the sheet resistance value of ITO film is 45 Ω/□. ITO electrode patterns on PET are created by UV lithographic process with spin-coating SPR6112B photoresist. The spin speed and time are 2000 rpm and 60 s, respectively. Subsequently, the photoresist is baked on a hot plate at 95 °C for 10 minutes. After that, the ITO-PET electrode layer is treated under UV exposure for 4 s, developed with the MIF developer of AZ300 for 45s, and rinsed in DI water in order. Then the ITO film is etched by using diluted concentrated hydrochloric acid (10 % HCl) at room temperature for about 35 s. Finally, the photoresist is stripped off with the acetone for 10 s. The ITO electrode patterns on PET with good transparency are illustrated in Fig. 1(b).
As the key component of sensor, PDMS layer has a decisive effect on the device performance. The obtainment of high-performance sensor is ascribed to the novel design of PDMS layer, in which micro-structured PDMS surface is exploited by moulding surface topology into the PDMS film. In our work, a cheap and simple mold containing reverse micro-structuring arrays from the feature of our presented PDMS layer was utilized, which can be designed and obtained by wet-etching copper plate or stainless steel plate, and is commercially available. Also, the mold can be easily fabricated in the lab. Fig. 1(c) shows the micro-structured PDMS layer, in which sensing sections are concave squares with hemispheric micro-structured PDMS arrays of feature size 200 $\mu$m and pitch 200 $\mu$m, which are well separated by other sections without any micro-structured PDMS array. The procedures of fabrication are given as follows. First, the PDMS mixture of base and cross-linker (Sylgard 184 A:B = 10:1 in weight) is vacuum-degassed, and poured onto our designed mould. Then the PDMS is cured at a temperature of 90 °C for 60 minutes. After curing, the PDMS film with micro-structured arrays is peeled off the mould. Fig. 2 shows scanning electron microscope (SEM) images of PDMS film with hemispheric arrays. Micro-structured arrays owning a mass of voids provide the microstructure surface with enough room to deform elastically in great degree on application of external pressure. Thereby, it is effortless for tactile sensor to store and release the energy reversibly. Furthermore, due to an obvious difference of dielectric constant between voids ($\varepsilon_{\text{air}} \sim 1.0$) and PDMS ($\varepsilon_{\text{PDMS}} \sim 3.0$), capacitive tactile sensor can take full advantage of this property to obtain a high sensing sensitivity. We will give further explanations in the subsequent section.

The sensing sensitivity of tactile sensor is tested by connecting the upper and bottom ITO electrodes onto designed printed circuit board (PCB) with silver pastes. The sensing sensitivity of each sensor unit is characterized with LCR meter, which is wire-connected to the PCB, in the change of capacitance ($\Delta C$) as the exerting external loads. Fig. 3(a) shows the pressure responses (at 1 MHz, 1 V) of tactile unit on the variation of loads. The pressure sensitivity $S$ is defined by using the following expression, and is extracted by taking the slope of the curve in Fig. 3(a).

$$S = \frac{\delta (C/C_0)}{\delta F} = \frac{1}{C_0} \delta C/\delta F,$$

where $F$ denotes the applied pressure, $C$ and $C_0$ denote the capacitances with and without applied pressure, respectively. In the test, a small plastic plate of equal size (30 mg) is placed between the sensor surface and load. It offers an evident benefit that makes external pressure uniformly apply to the whole tactile sensor area, and enables all micro-structured arrays in sensing unit to deform elastically. This contributes a good role in the achievement of high-sensitivity tactile sensor. Apart from this, the fabrication of excellent sensitive sensor is preferably attributed to our well-designed micro-structured PMDS film. As above mentioned, there are a large number of voids in structured PDMS arrays, the volume of which will reduce rapidly when the sensor units are pressed. On the contrary, the proportion of PDMS will increase vigorously. Due to a lower dielectric constant of air than PDMS, equivalent dielectric constant increases on application of external pressure, resultantly resulting in the booming increase of capacitance. Moreover, the increase in the capacitance is also attributed to the reduction in the distance between two electrode plates. Competitively, unique hemispheric micro-structured PDMS arrays can deform earlier than other structures such as square and cylindrical structure, when only tiny pressure is exerted on the sensor unit. All these benefits derive to a remarkable sensitivity ($S= 2.05$ N$^{-1}$) of our tactile sensor in the low-pressure regime (< 2 kPa). Our tactile sensor with hemispheric micro-structured PDMS arrays can even repeatedly detect the load as low as about 3 mN, as shown in Fig. 3(b). We can also see from Fig. 3(b) that the response time is obviously transient switching the sensor from on-state to off-state, or vice versa, so it indicates the response speed of our sensor is quite rapid. In addition to that, the sensor showed only a little feeble hysteresis when such a low force was loaded or unloaded. However, there is a reduction in sensitivity ($S= 0.15$ N$^{-1}$) of structured sensor in the higher-pressure regime (> 2 kPa). It is attributed to the hemispheric arrays as well, the elastic resistance of which increases rapidly with the increased loads. This property of sensor is desirable in detect higher pressure and improves the range of detectable pressure, as Bao et al. have reported. Herein, we also have compared the sensitivity of sensor based on micro-structured PDMS film with that using unstructured PDMS film.
FIG. 2. SEM images: (a) Cross-sectional schematic, and (b) Top view of PDMS with hemispheric micro-structured PDMS arrays.

under the load (5 g), taking the maximum of slope of Fig. 3(a). The unstructured sensor is hardly of any response to such a load and shows a significantly low sensitivity, not shown in the figure.

On top of above mentioned advantages, our sensor exhibits a great resolution, as showed in the Fig. 3(c). A, B, C, D and E is corresponding to each sensor unit of Fig. 1(a), respectively. Fig. 3(c) shows the response of test sensor unit C to the application of same load (5 g) on each sensor unit A, B, C, D, and E, separately, where the color of light gray corresponds to the initial capacitance (5.69 pF) of sensor unit C before exerting the external pressure. In our sensor, the capacitance of sensing unit C was only changing from the initial 5.69 pF to 5.77 pF when exerting the external pressure to other sensing units. But, the change in the capacitance of sensing unit C was from the initial 5.69 pF
FIG. 3. (a) Pressure-response characteristics of tactile sensor unit (at 1 MHz and 1V), and the inset depicts the frequency dependence of the complex permittivity of structured PDMS at 1V. (b) Pressure-response curves of tactile sensor under a load as low as 30 mg and after unloading, and (c) The diagram of resolution of tactile sensor based on the response of test sensor unit C to an application of load (5 g) on each sensor unit of A, B, C, D and E, respectively, which is shown in the Fig. 1(a).
to 6.34 pF when applying the same external pressure to sensing unit C itself. So, the capacitance change in magnitude is big enough to discriminate different sensing areas. Although the capacitance change in percentage seemed low that is because of high based-test capacitance including the high circuit capacitance. The good resolution of sensor is also owing to the creative design of structured PDMS layer, in which concave square areas of sensing units with micro-structured PDMS arrays are effectively separated by unstructured PDMS sections, which are acting as the perfect natural wall-barriers.

Besides, we research the frequency dependence of the complex permittivity of structured PDMS, which is given in the power-law relationship of equation (2). The frequency dependence is also an important characterization for any electronic device. The structured PDMS shows strong low-frequency dispersion (LFD) behavior, as displayed in the inset to Fig. 3(a).

\[ \varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) \]
\[ = A(i\omega)^{n-1}, \quad (2) \]

(where \(\varepsilon'\) and \(\varepsilon''\) denote the real part, and imaginary part of dielectric permittivity, respectively. A is a constant, and the exponent \((n-1)\) for LFD normally lies between \(-0.7\) and \(-1.0\).) According to the equation (2), the complex dielectric decreases with the increase in frequency, and this is corresponded with our results in the low frequency regime (< 1 MHz). Although the value of complex dielectric in our test is much higher than the real value as it is calculated using the total test capacitance including the high circuit capacitance. Low-frequency dispersion (LFD) behavior that the sensor was exhibiting indicates there will be a decay in device performance when the sensor is used in the low frequency range.

In summary, we present the fabrication of a transparent flexible capacitive sensor using micro-structured PDMS polymer as structural material, and report the LFD behavior of PDMS. The sensor exhibits an excellent performance with a superior sensitivity of 2.05 N\(^{-1}\) and a high resolution. The competitive sensitivity, good resolution, low-cost, together with simple fabrication process of the sensor, based on transparent flexible materials, make it really promising not only in transparent flexible displays as electronic touch interfaces, but also in robots and prosthetic devices of human as electronic skin owing to superior biomedical compatibility of PDMS.

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1. Honda Motor Co., Ltd., Honda Unveils All-new ASIMO with Significant Advancements, November 8, 2011, see http://world.honda.com/ASIMO/.
2. M. S. Kim, I. Kim, S. S. Park, and J. H. Oh, Realization of Stretch-legged Walking of the Humanoid Robot, 8th IEEE-RAS International Conference on Humanoid Robots, Daejeon, Korea, December 1 ~ 3, (2008).
3. H. K. Lee, S. I. Chang, and E. Yoon, ASME/IEEE J. Microelectromech. 15, 1681 (2006).
4. H. K. Lee, S. I. Chang, and E. Yoon, J. IEEE Sensors. 9, 1748 (2009).
5. Ric.org, Introducing Jesse Sullivan, the World’s First “Bionic Man”, http://www.ric.org/research/accomplishments/Bionic.aspx.
6. D. J. Beebe, A. S. Hsieh, D. D. Denton, and R. G. Radwin, Sens. Actuators A, Phys. 50, 55 (1995).
7. M. Leineweber, G. Pelz, M. Schmidt, H. Kappert, and G. Zimmer, Sens. Actuators A, Phys. 84, 236 (2000).
8. C. Metzger, E. Fleisch, J. Meyer, M. Dansachmüller, I. Graz, M. Kaltenbrunner, C. Keppler, and S. Bauer, Appl. Phys. Lett. 92, 013506 (2008).
9. M. Sergio, N. Manaesri, M. Nicolini, D. Gennaretti, M. Tartagni, and R. Guerrieri, Sens. Lett. 2, 153 (2004).
10. J. Engel, J. Chen, and C. Liu, J. Micromech. Microeng. 13, 359 (2003).
11. S. C. B. Mannsfeld, B. C. K. Tee, R. M. Stoltenberg, C. V. H. H. Chen, S. Barman, B. V. O. Muir, A. N. Sokolov, C. Reese, and Z. Bao, Nat. Mater. 9, 859 (2010).
12. P. Peng, R. Rajamani, and A. G. Erdman, J. Micromech. Microeng. 18, 1226 (2009).
13. H. K. Lee, S. I. Chang, and E. Yoon, J. Micromech. Microeng. 21, 035010 (2011).
14. Y. Chan, Y. Mi, D. Trau, P. Huang, and E. Chen, Polymer. 47, 5124 (2006).
15. M. C. Belanger, Y. Marois, and J. Biomed, Mater. Res. 58, 467 (2001).
16. C. Liu, Foundations of MEMS. Upper Saddle River, (Pearson Educ., NJ, 2006).
17. M. Hussain, Y. H. Choa, and K. Niihara, J. Mater. Sci. Lett. 20, 525 (2001).
18. H. K. Lee, J. Chung, S. I. Chang, and E. Yoon, J. Micromech. Microeng. 17, 934 (2008).
19. A. Seal, S. Das, R. Mazumder, and A. Sen, J. Phys. D: Appl. Phys. 40, 7560 (2007).