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Tuning the sensing range and sensitivity of three axes tactile sensors using the polymer composite membrane

Chih-Chieh Wen [a], Weileun Fang [a,b,*]

[a] *Power Mechanical Engineering Department, National Tsing Hua University, Hsinchu, Taiwan*
[b] *MEMS Institute, National Tsing Hua University, Hsinchu, Taiwan*

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Abstract

This study has successfully demonstrated a novel three axes polymer tactile sensor with built-in piezoresistive sensors. The sensor consists of polymer membrane and four sensing cantilevers with piezoresistors on both top and side walls to measure the in-plane and out-of-plane loads. By adding the nano-particles into the polymer, the stiffness of the membrane can be easily tuned. Thus, the sensing range and sensitivity of the present tactile sensor can also be tuned after the change of polymer membrane stiffness. The fabrication process allows the changing of polymer membrane material easily. The experiments show that the stiffness of the PDMS membrane increases from 1.32 to 479.25 MPa after adding Co particles of PDMS/Co = 10/1. Meanwhile, the sensitivity of tactile sensor is significantly decreased. However, the maximum tolerable load of tactile sensor is increased.

Keywords: Tactile sensor; Side-wall doping; Polymer; Piezoresistor

1. Introduction

The MEMS technology has already found various applications in the area of microsensors, for instance, the inertia sensor, the pressure sensor, the chemical sensor, etc. The MEMS sensors have many commercialized products in the areas of automobile and consumer electronics. Presently, the tactile sensor is regarded as one of the most promising MEMS sensors. According to the characteristics higher sensitivity, small size, and easy integration with other sensors, the silicon-based MEMS tactile sensor finds extensive applications in robots' fingers sensing, human body weight measurement, etc. There are various fabrication processes have been exploited to implement the tactile sensors. For instance, the silicon-based process [1–6], such as the CMOS and bulk micromachining processes, and the non-silicon-based process [7–12], such as the polymer process. As a result, the variety as well as the performance of the tactile sensor has been significantly improved by the fabrication processes.

The piezoresistive sensing and capacitive sensing have been frequently employed for silicon-based MEMS tactile sensors [13,14]. In general, various issues give limitations in the design and implementation of MEMS tactile sensors. For instance, the performances of the tactile sensor can be tuned by the mechanical properties of micromachined structures, such as membrane and beam. However, it is difficult to vary the sensing range and sensitivity of the tactile sensor for a particular mask design [15]. Moreover, it is not straightforward to determine the shear force using the conventional piezoresistive sensor. The existing approach for shear force determination [16] is to measure the resistance variations of two opposite piezoresistors after applying load. As a result, it is difficult to improve the sensitivity of this approach.

This study reports a novel three axes MEMS tactile sensor with the capability of tunable sensing range. The present sensor consists of silicon-based piezoresistive sensing beams covered by polymer membrane. In addition to the well-known out-of-plane piezoresistive sensor (i.e. piezoresistor which embedded into the substrate surface with a normal vector in the out-of-plane direction), the in-plane piezoresistive sensors are also realized by

* Corresponding author at: Power Mechanical Engineering Department, National Tsing Hua University, Hsinchu, Taiwan. Tel.: +886 3 574 2923; fax: +886 3 573 9372.
E-mail address: fang@pme.nthu.edu.tw (W. Fang).

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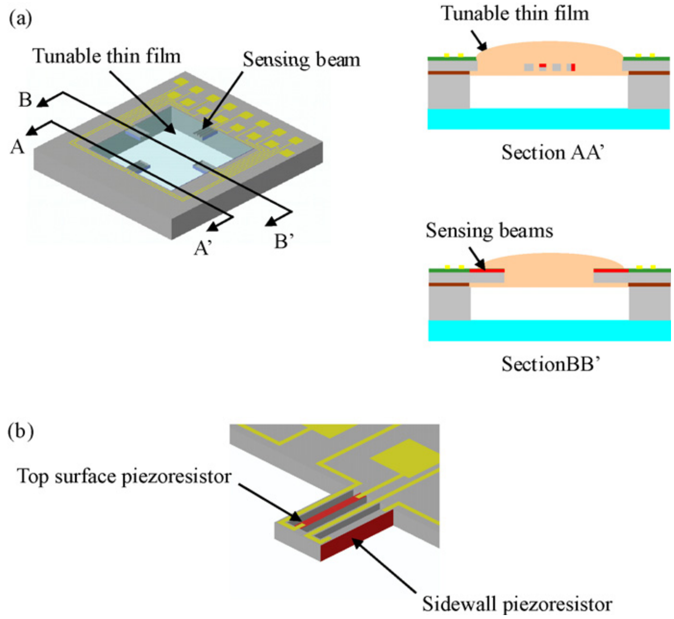

Fig. 1. The schematic illustrations of three axes and thin-film-tunable tactile sensor: (a) the sensor consists of four piezoresistive sensing beams covered with polymer membrane, and the cross-section views of the sensor and (b) zoom in of the sensing beam to show the top and side-wall doping piezoresistors.

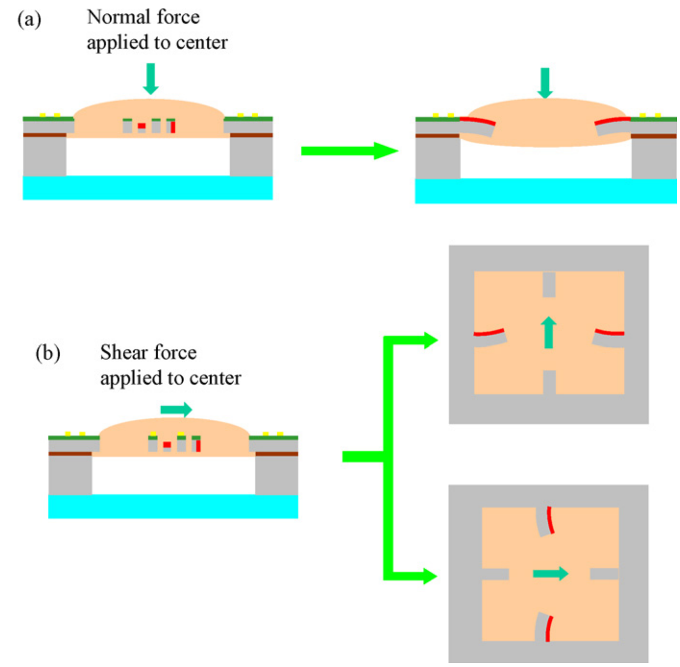

Fig. 2. The schematic illustrations to show the deformation of the polymer membrane and sensing beams resulted from (a) normal load and (b) shear load.

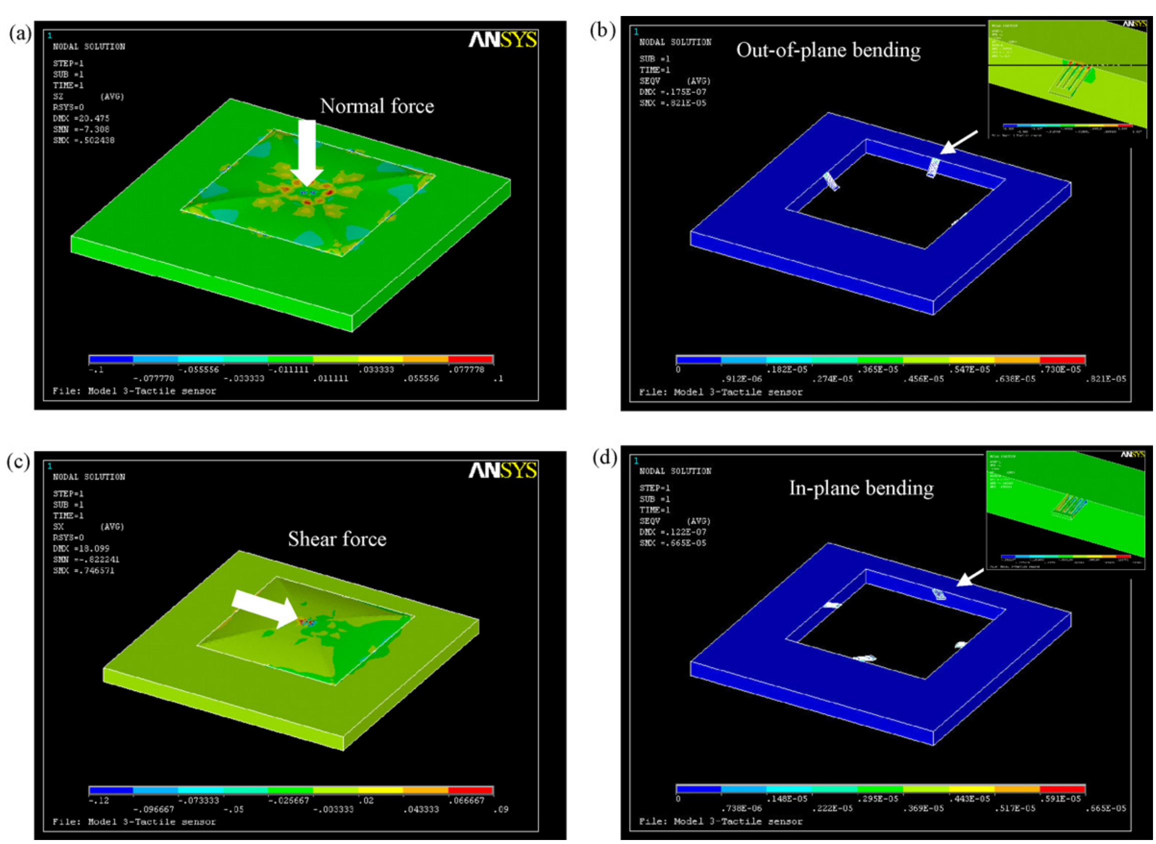

Fig. 3. Typical finite element simulation results to show the stress distribution on membrane and sensing beam after applying (a) normal load and (b) shear load on the present sensor.

employing the side-wall doping method [17,18]. In general, the out-of-plane piezoresistors is mainly used to sense the normal forces applied to sensor. Meanwhile, the in-plane piezoresistors is exploited to detect the shear forces applied to sensor. Since each sensing beam consists of in-plane and out-of-plane piezoresistors, it can measure both normal and shear forces. In addition, by varying the material properties of polymer membrane, it is easy to tune the sensing range of the tactile sensor without changing the design of MEMS structures and photo masks.

2. Design and analysis

Fig. 1 schematically illustrates the design concept of the present 3D tactile sensor. As shown in Fig. 1a, the sensor consists of four single-crystal-silicon sensing beams covered by polymer membrane with tactile-bump. The sensing beam has boron-doped piezoresistors on top surface and side walls, as shown in Fig. 1b. The load applying on the tactile-bump will lead to the deformation of the sensing beams. As shown in Fig. 2a, the normal load will lead to out-of-plane bending of all sensing beams. Thus, the piezoresistors on top surface are used to measure the normal load on sensor. On the other hand, the shear force will lead to in-plane bending of sensing beams, as illustrated in Fig. 2b. Hence the shear load on sensor is measured by the piezoresistors on side walls. It is easy to change the stiffness of polymer material by adding nano-particles during the fabrication process. Thus, the sensing range of the present tactile sensor can be easily tuned by varying the material properties of polymer membrane.

The finite element model has been established to analyze the performances of the sensor. In this study, the PDMS (Dow Corning SYLGARD 184) was used as the polymer material, and the

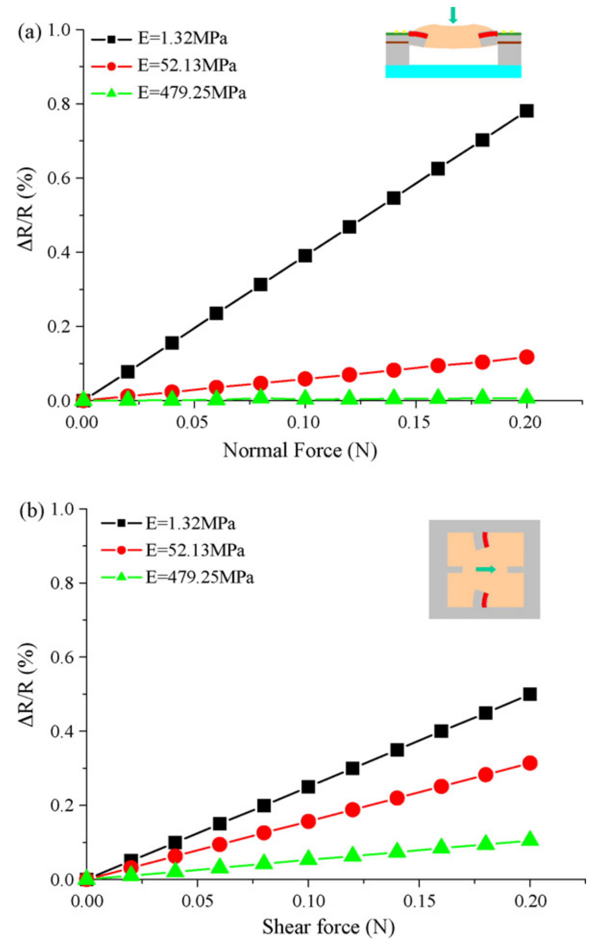

Fig. 4. Typical predicted resistance changes for membranes of different stiffness due to (a) normal load and (b) shear load.

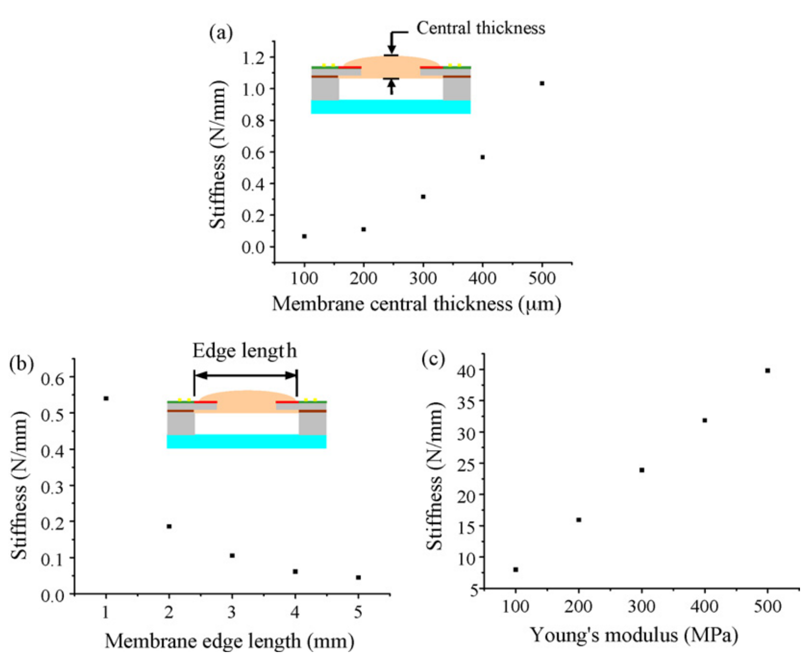

Fig. 5. Typical finite element simulation results to show the variation of membrane stiffness with (a) the central thickness, (b) the edge length, and (c) the Young's modulus of membrane.

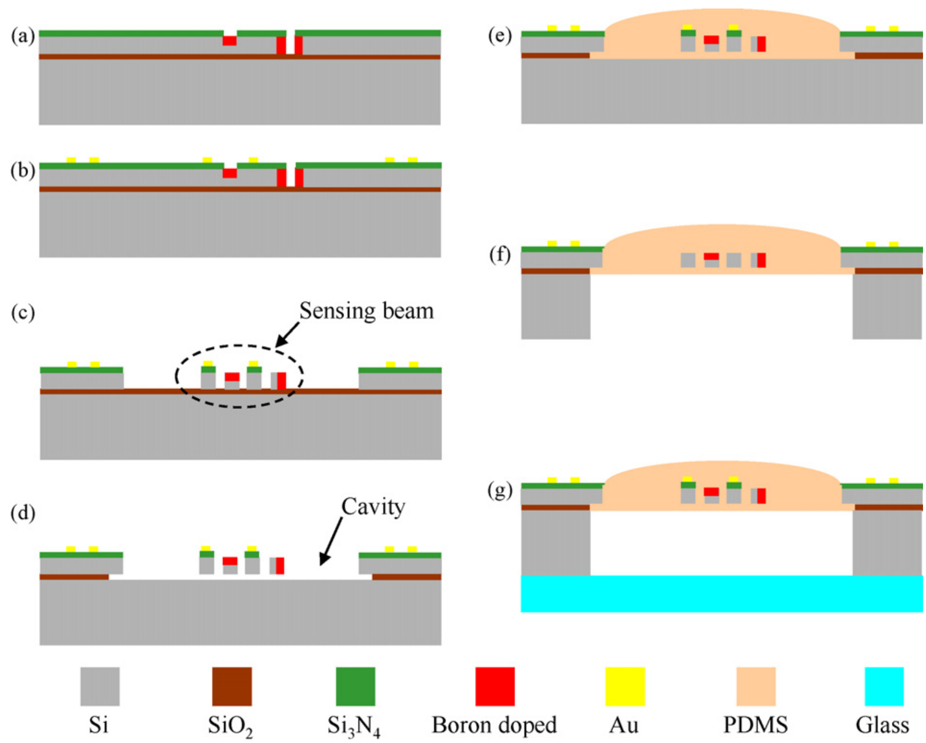

Fig. 6. Fabrication process steps.

elastic modulus of polymer membrane was modulated by mixing with Co nano-particles. The polymer membranes of three different PDMS/Co ratios were investigated. The measured elastic moduli of PDMS/Co films were 1.32 MPa (no Co), 52.13 MPa (PDMS/Co = 20/1) and 479.25 MPa (PDMS/Co = 10/1), respectively. The sensing beam material in this model was single crystal silicon with a Young's modulus of $E = 169$ GPa. These material properties were used in the FEM analysis (ANSYS). As shown in Fig. 2, the normal and shear forces were applied at the center of membrane to stimulate out-of-plane and in-plane loads, respectively. The stress distribution of the deformed sensing beam was predicted by the FEM analysis. After that, the variation of the resistance due to the stress was determined [19].

Fig. 3 shows the typical FEM simulation results to predict the resistance variations of three PDMS/Co films under different normal and shear forces. Fig. 3a and b shows the stress distribution on membrane and sensing beam after applying normal load on the present sensor. Moreover, the stress distribution on membrane and sensing beam due to shear load are also available in Fig. 3c and d. The out-of-plane and in-plane bending of the sensing beams resulted respectively from the normal and shear forces can be observed. In this study, the in-plane dimension of membrane was 3 mm × 3 mm, and the membrane thickness

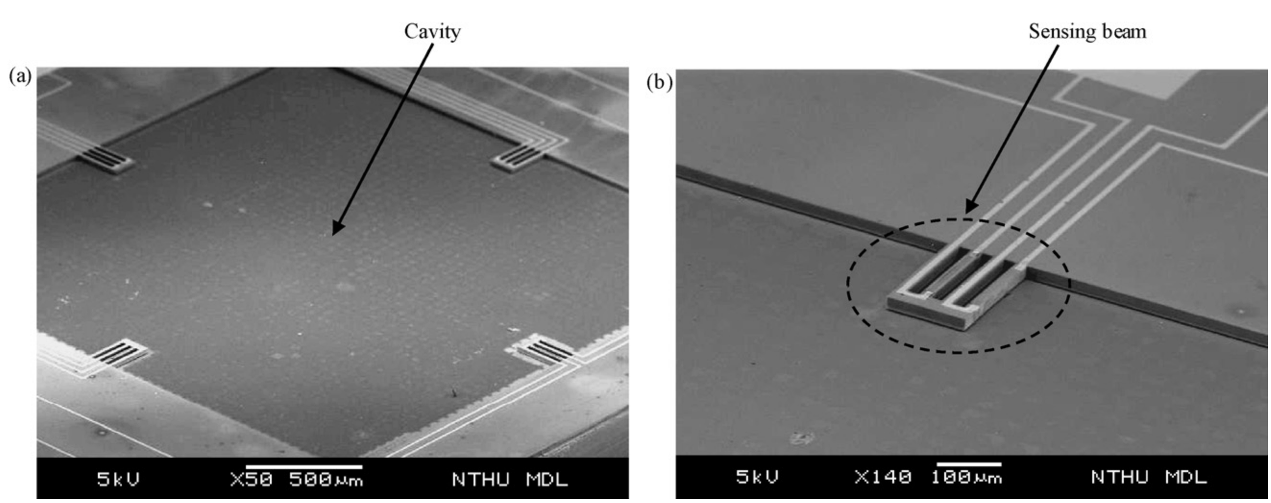

Fig. 7. The SEM photos of typical fabrication results before dispensing of polymer: (a) the sensing unit consists of four sensing beams and (b) zoom-in of a sensing beam.

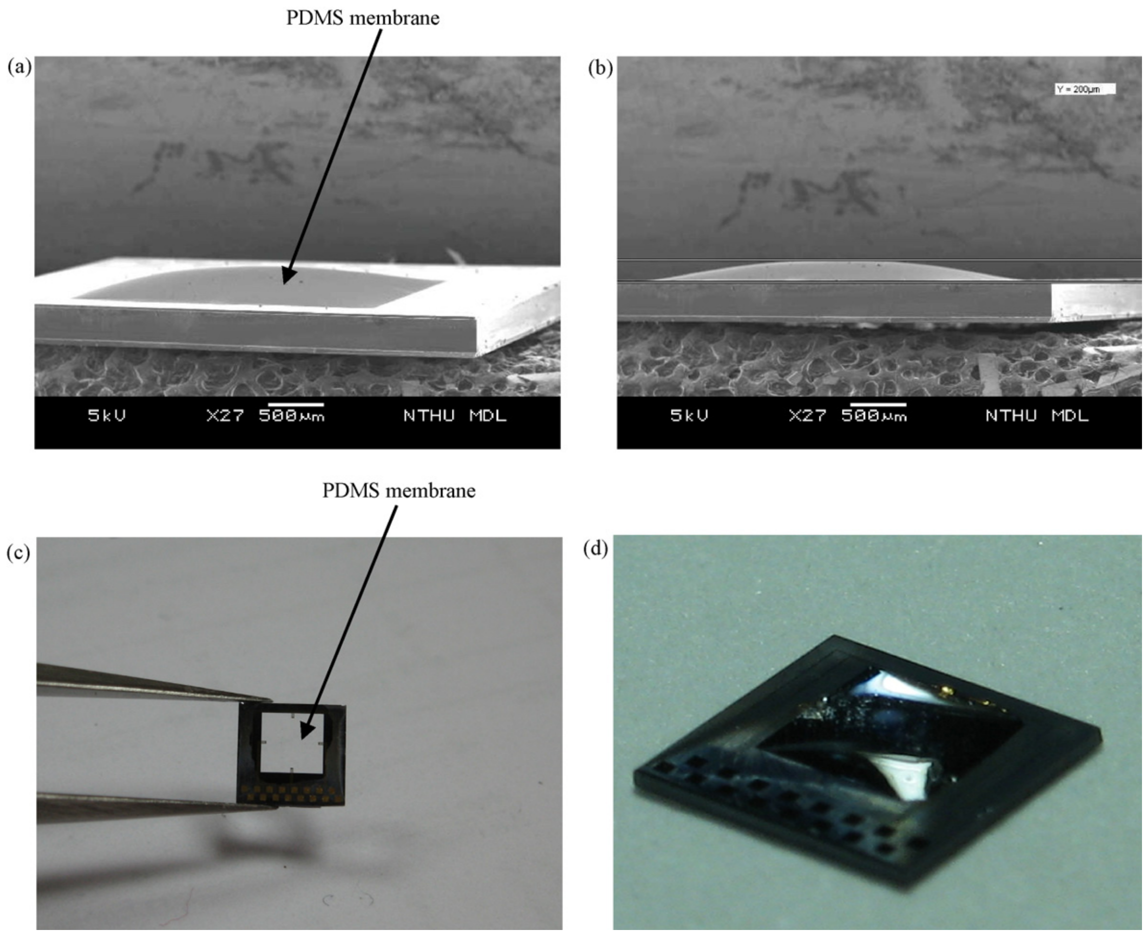

Fig. 8. The photos of typical fabrication results after polymer dispensed: (a) the tactile sensor, (b) the side view photo to show the polymer tactile-bump, (c) the photo to show the transparent polymer membrane, and (d) the completed sensor chip.

increased from 20 μm at its edge to 200 μm at its center. In addition, each sensing unit contained four sensing beams, as illustrated in Fig. 1a. The dimensions of sensing beam were 200 μm in length, 20 μm in width, and 20 μm in thickness. The loads applied in the FEM model ranged form 0 to 0.2 N. Fig. 4a and b shows typical FEM simulation results. As indicated in Fig. 4a and b, the sensitivities for normal force and shear force decrease 99.12% and 78.96%, respectively, when the stiffness of membrane increases from 1.32 to 479.25 MPa. According to the analysis, the sensing beams covered by the stiffer membrane will experience a smaller deflection under the same applied load. As a result, the polymer membrane with larger stiffness has lower sensitivity yet larger measurable load range. In conclusion, the sensitivity and sensing range of the tactile sensor are easily tuned using the present approach. Moreover, the membrane stiffness as well as the sensitivity and sensing range of the tactile sensor

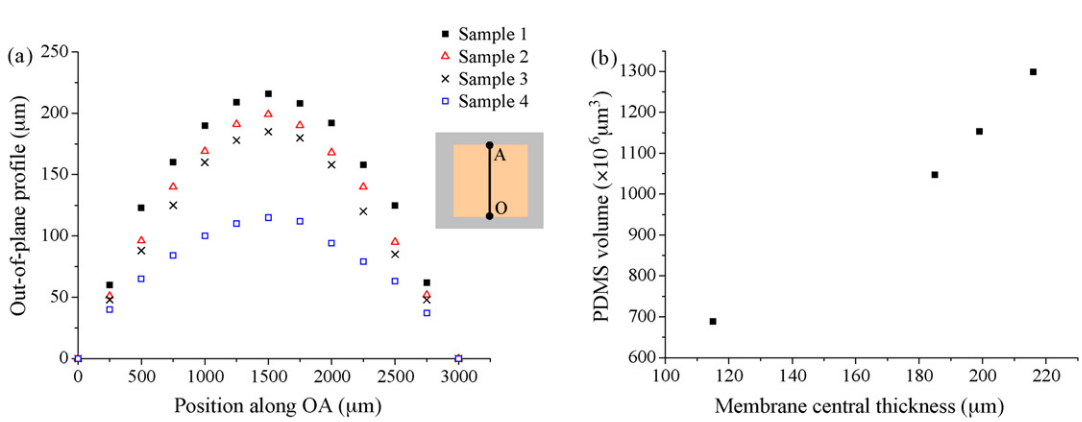

Fig. 9. (a) The typical measured surface profiles of membrane for different volume of the dripped PDMS and (b) variation of the membrane central thickness with the volume of PDMS.

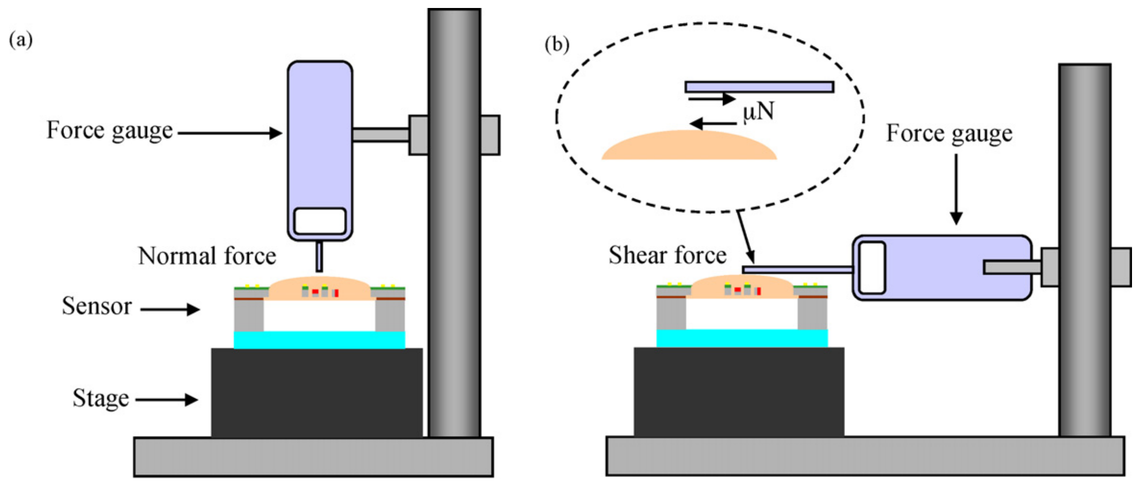

Fig. 10. The experimental setups to measure (a) normal force and (b) shear forces.

can also be tuned by varying the dimensions and Young's modulus of membrane, as the typical results predicted by the FEM in Fig. 5.

3. Experiment and results

To demonstrate the present concept, a five masks fabrication process has been established to implement the tactile sensor in Fig. 1. The key processes in this study are the fabrication of side-wall piezoresistors and the flexible membrane. The boron diffusion [17] but not ion implantation [18] has been employed to realize the process. In addition, the molding process was exploited to integrate polymer membrane and silicon piezoresistive sensor.

The fabrication process steps of the present tactile sensor are shown in Fig. 6. The process began with a n-type SOI substrate of 20 μm thick device layer (ρ, ∼10 Ω-cm). The silicon nitride film was deposited and patterned to act as the diffusion mask for the following boron doping process. First, the silicon nitride film was deposited and patterned to define the location of top layer piezoresistors. After that, the photolithography and DRIE were used to define the location of side-wall piezoresistors. As illustrated in Fig. 6a, a boron-doped process was employed after removing the photoresist, and the top surface

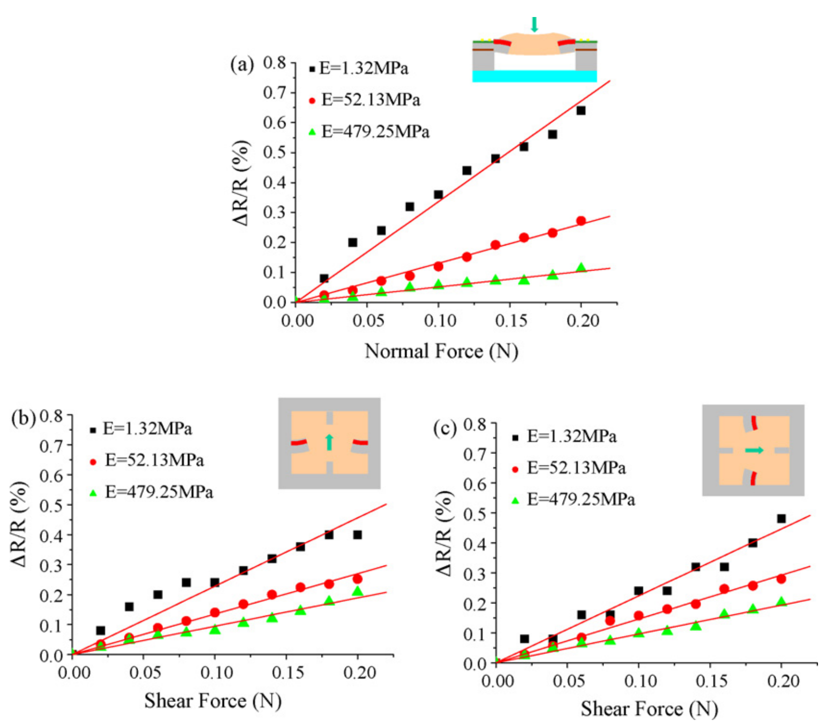

Fig. 11. The measurement results to show the variation of resistance change with (a) normal load and (b and c) shear loads in different directions, and at three different membrane stiffness.

and side-wall piezoresistors were realized. As shown in Fig. 6b, the conducting wires were deposited and patterned using lift-off process. The silicon device layer was then patterned to form sensing beams inside a cavity using DRIE, as shown in Fig. 6c. The top and side-wall piezoresistors were placed on the sensing beams. As illustrated in Fig. 6d, the sensing beams were fully suspended after removing silicon oxide layer with HF. In the present case, the sensing beams had a 2 μm gap with the handling silicon substrate underneath. The polymer was then dripped into the cavity defined in Fig. 6c using a pneumatically controlled micropipette. As shown in Fig. 6e, the cavity acted as a mold to define the planar shape of the polymer membrane, and the sensing beams with piezoresistors were fully covered by this polymer membrane. After patterned with photoresist, the handling silicon layer was then backside etched by DRIE to fully release the polymer membrane from substrate, as shown in Fig. 6f. Finally, the tactile sensor was mounted to pyrex 7740 glass holder, to protect the sensor from broken, as depicted in Fig. 5g.

Fig. 7a shows the SEM photos of a typical sensing unit after the process of Fig. 6d. The four sensing beams in this unit have been fully suspended. Fig. 7b shows the zoom in photo of a sensing beam. Fig. 8a and b shows the SEM photos of a sensing unit covered by the PDMS membrane after the process of Fig. 6e. In this case, the edge of square membrane is 3 mm in length, and the sensing beam is 200 μm in length. Because of surface tension, the PDMS thin film was molded in the square cavity defined on silicon device layer. The PDMS automatically formed a 200 μm-high tactile-bump, and the membrane thickness increased from 20 μm at its edge to 200 μm at its center, as in Fig. 8b. In addition, the process in Fig. 6e was performed at room temperature to reduce the residual stress of PDMS membrane. Thus, the influence of the PDMS residual stress on the sensing performance was ignored. Finally, Fig. 8c and d shows the photos of sensor chip after the process. The four sensing beams can be clearly observed in the photo of Fig. 8c since the PDMS membrane is transparent. Fig. 9a shows four typical measured membrane profiles for different volume of the dripped PDMS. The relationship between the volume of the dripped PDMS and membrane profile is depicted in Fig. 9b. In short, the in-plane dimensions (length and width) of the sensing beam and membrane can be easily tuned using the photolithography. The thickness of the sensing beam and membrane can be changed by varying the device layer thickness of SOI wafer. Moreover, the height and shape of tactile-bump are tuned by the volume of polymer.

The test setup in Fig. 10 was established to characterize the present tactile sensor. A Wheatstone bridge and amplifier circuit was used to measure the resistance change during test. The resistance change versus applied force was characterized by a micro-force gauge with a resolution of 0.001 N. The tactile sensors with membranes of different PDMS/Co ratio were tested; and the measured Young's modului were 1.32, 52.13, and 479.25 MPa, respectively. The Young's modulus of PDMS film was determined using the resonant frequency of test cantilevers [20]. Fig. 11a shows the variation of resistance change ($\Delta R/R$) after applying a normal force of 0.2 N in Fig. 10a. In this test, the $\Delta R/R$ was the average resistance change from the top surface piezoresistors of four out-of-lane bending beams. The sensitivities of the tactile sensors with different membrane stiffness are 3.36%/N, 1.31%/N, and 0.52%/N, respectively; and the linearity are approximately $R^2 = 0.99$. Fig. 11b and c shows the variation of $\Delta R/R$ after applying shear forces of 0.2 N in x-axis and y-axis (in Fig. 10b), respectively. For the measurement of each axis, the $\Delta R/R$ was the average resistance change from the sidewall piezoresistors of two in-lane bending beams. The results in Fig. 11b indicate the sensitivities of these three sensors are 2.28%/N, 1.35%/N, and 0.95%/N with a linearity of $R^2 = 0.977$, 0.996, and 0.986, respectively. In addition, the results in Fig. 11c indicate the sensitivities of these three sensors are 2.23%/N, 1.46%/N, and 0.96%/N with a linearity of $R^2 = 0.986$, 0.994, and 0.992, respectively. In summary, the tactile sensor with a stiffer polymer membrane has a smaller sensitivity. It is also expected form the linear relation of measurement results that the stiffer polymer membrane has a larger sensing range of the applied load. The trend in Fig. 11 agrees qualitatively with the results predicted in Fig. 4.

This study also demonstrated the integration of the present tactile sensors to form an array type sensing chip. The SEM

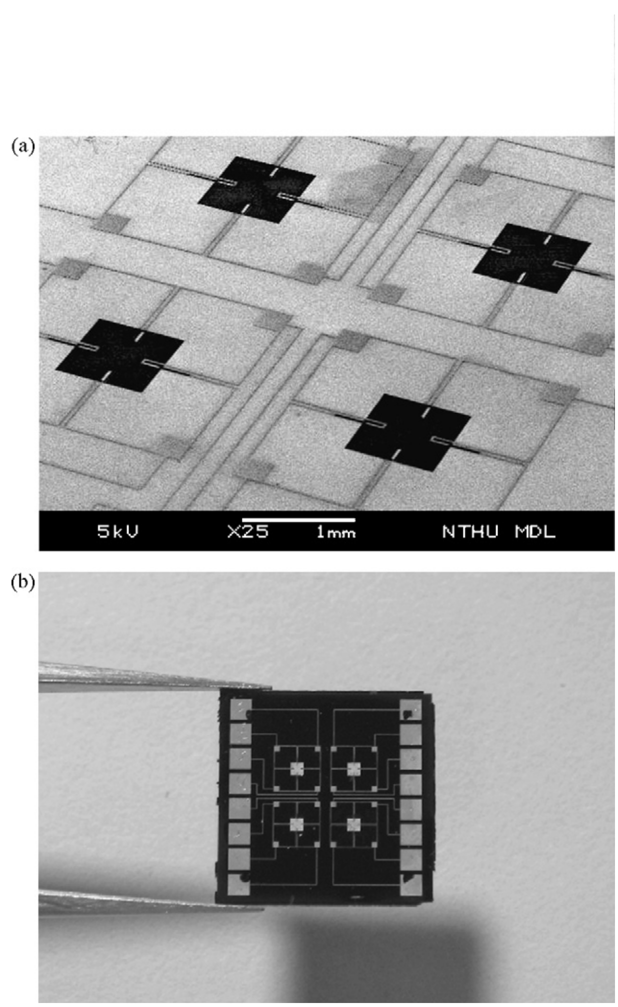

Fig. 12. The SEM photos of a chip with 2 × 2 tactile sensor array: (a) before dispensing of PDMS and (b) after dispensing of PDMS photo.

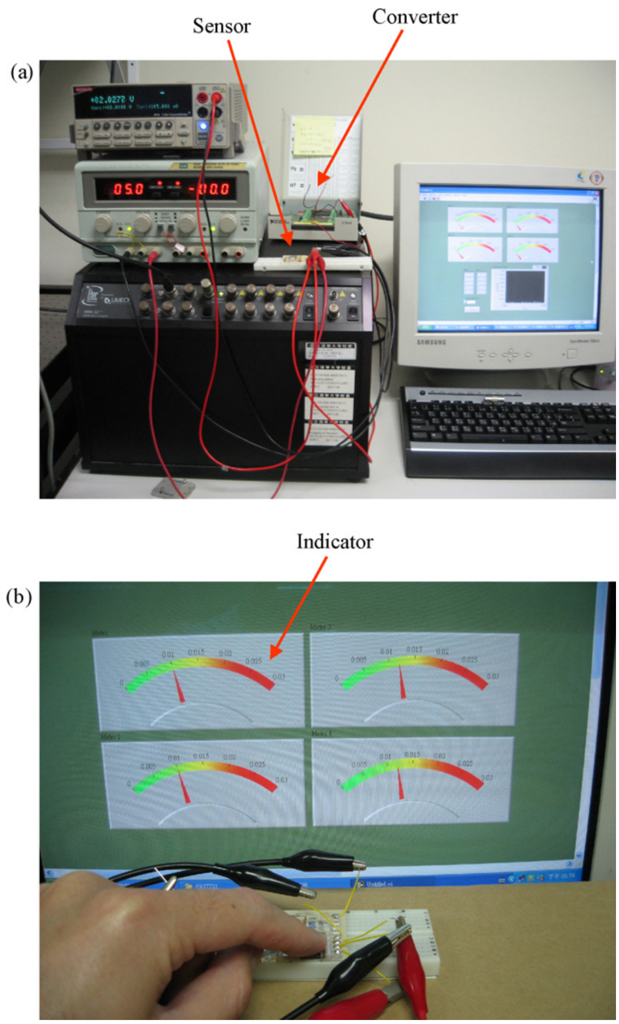

Fig. 13. (a) The test setup to perform the contact test of tactile sensor and (b) the typical measurement result during the test of a 2 × 2 tactile sensor array.

micrographs in Fig. 12a and b show a 2 × 2 sensor array chip before and after dripping with PDMS (PDMS/Co = 10/1). The transparent membranes, the sensing beams and their wire routings, and the bonding pads are clearly observed in Fig. 12b. Fig. 13a further shows the test setup for the sensor array chip. The sensing signal will be input into the computer through the AD/DA converter, and then demonstrated on the computer by means of the Labview software. The four indicators in Fig. 13b show the voltage change of the 2 × 2 sensor array chip due to the normal force introduced by a finger.

4. Discussions and conclusions

This study has successfully demonstrated a novel three axes polymer tactile sensor with built-in piezoresistive sensors. The sensor consists of polymer membrane and four sensing cantilevers with piezoresistors on both top surface and side walls to measure the in-plane and out-of-plane loads. The piezoresistors on both top and side walls were fabricated by boron doping technique. Due to the surface tension of polymer, a tactile-bump is naturally formed on the membrane without any additional process. Moreover, the fabrication process allows the changing of polymer membrane material easily. Thus, the sensing range of the present 3D tactile sensor can be easily tuned by varying the polymer material. In applications, the sensing beams with piezoresistive sensors cover by three different PDMS/Co polymer composites have been implemented and tested. The measurements show that the stiffness of the membrane can be tuned from 1.32 to 479.25 MPa when the ratio of PDMS/Co is 10/1. Meanwhile, the sensitivity of normal force decreases about 82.5%, and that of shear forces decrease about 48–58.33%. However, the maximum tolerable loads of the tactile sensor are increased.

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References

[1] K. Kim, K.R. Lee, Y.K. Kim, D.S. Lee, N.K. Cho, W.H. Kim, K.B. Park, H.D. Park, Y.K. Park, J.H. Kim, J.J. Pak, 3-Axes flexible tactile sensor fabricated by Si micromachining and packaging technology, in: Proceedings of the MEMS'06, Istanbul, Turkey, January, 2006, pp. 678–681.
[2] Y. Hasegawa, M. Shikida, T. Shimizu, T. Miyaji, H. Sasaki, K. Sato, K. Itoigawa, A micromachined active tactile sensor for hardness detection, Sens. Actuators A 114 (2004) 141–146.
[3] Y. Hasegawa, M. Shikida, H. Sasaki, K. Itoigawa, K. Sato, An active sensor for detecting mechanical characteristics of contacted objects, J. Micromech. Microeng. 16 (2006) 1625–1632.
[4] H. Takao, K. Sawada, M. Ishida, Silicon smart tactile image sensor with pneumatically swollen single diaphragm structure, in: Proceedings of the MEMS'04, Maastricht, The Netherlands, January, 2006, pp. 846–849.
[5] C.T. Ko, J.P. Wu, W.C. Wang, C.H. Huang, S.H. Tseng, Y.L. Chen, M.S.C. Lu, A Highly sensitive CMOS-MEMS capacitive tactile sensor, in: Proceedings of the MEMS'06, Istanbul, Turkey, January, 2006, pp. 642–645.
[6] K. Kim, K.R. Lee, D.S. Lee, N.K. Cho, W.H. Kim, K.B. Park, H.D. Park, Y.K. Kim, Y.K. Park, J.H. Kim, A silicon-based flexible tactile sensor for ubiquitous robot companion applications, J. Phys.: Conf. Ser. 34 (2006) 399–403.
[7] H.K. Lee, S.I. Chang, E. Yoon, A capacitive proximity sensor in dual implementation with tactile imaging capability on a single flexible platform for robot assistant applications, in: Proceedings of the MEMS'06, Istanbul, Turkey, January, 2006, pp. 606–609.
[8] E.S. Hwang, J.H. Seo, Y.J. Kim, A polymer-based flexible tactile sensor for normal and shear load detection, in: Proceedings of the MEMS'06, Istanbul, Turkey, January, 2006, pp. 714–717.
[9] J. Engle, J. Chen, C. Liu, Development of polyimide flexible tactile sensor skin, J. Micromech. Microeng. 13 (2003) 359–366.
[10] N. Sato, K. Machida, H. Morimura, S. Shigematsu, K. Kudou, M. Yano, H. Kyuragi, MEMS fingerprint sensor immune to various finger surface conditions, IEEE Trans. Electron Devices 50 (2003) 1109–1115.
[11] N. Sato, S. Shigematsu, H. Morimura, M. Yano, K. Kudou, T. Kamei, K. Machida, Novel surface structure and its fabrication process for MEMS fingerprint sensor, IEEE Trans. Electron Devices 52 (2005) 1026–1032.
[12] J. Engel, J. Chen, Z. Fan, C. Liu, Polymer micromachined multimodal tactile sensors, Sens. Actuators A 117 (2005) 50–61.

[13] M. Leineweber, G. Pelz, M. Schmidt, H. Kappert, G. Zimmer, New tactile sensor chip with silicon rubber cover, Sens. Actuators A 84 (2000) 236–245.
[14] M. Shikida, T. Shimizu, K. Sato, K. Itoigawa, Active tactile sensor for detecting contact force, Sens. Actuators A 103 (2003) 213–218.
[15] B.J. Kane, G.T.A. Kovacs, A CMOS compatible traction stress element for use in high resolution tactile imaging, in: Proceedings of the Transducers'95, Stockholm, Sweden, June, 1995, pp. 648–651.
[16] M. Sohgawa, Y.M. Huang, K. Yamashita, T. Kanashima, M. Noda, M. Okuyama, H. Noma, Fabrication and characterization of silicon-polymer beam structures for cantilever-type tactile sensors, in: Proceedings of the Transducers'07, Lyon, France, June, 2007, pp. 1461–1464.
[17] B.K. Nguyen, K. Hoshino, K. Matsumoto, I. Shimoyama, Insertion force sensor by sidewall-doping with rapid thermal diffusion, in: Proceedings of the MEMS'06, Istanbul, Turkey, January, 2006, pp. 662–665.
[18] B.W. Chui, T.W. Kenny, H.J. Mamin, B.D. Terris, D. Rugau, Independent detection of vertical and lateral forces with a sidewall-implanted dual-axes piezoresistive cantilever, Appl. Phys. Lett. (1998) 1388–1390.
[19] S.M. Sze, Semiconductor Sensors, Wiley–Interscience Publication, 1994, p. 178.
[20] H.-C. Tsai, W. Fang, Determining the Poisson's ratio of thin film materials using resonant method, Sens. Actuators A (2003) 377–383.

Biographies

Chih-Chieh Wen was born in MiaoLi, Taiwan, in 1976. He received the BS degree in civil engineering from Feng Chia University in 1998 and the MS degree in Institute of Biomedical Engineering form National Taiwan University in 2003. He is working toward the PhD degree at National Tsing Hua University From 2004 to present. His research interests include sensors, polymer-based and bio-MEMS.

Weileun Fang was born in Taipei, Taiwan, in 1962. He received his PhD degree from Carnegie Mellon University in 1995. His doctoral research focused on the determining of the mechanical properties of thin films using micromachined structures. In 1995, he worked as a postdoctoral research at Synchrotron Radiation Research Center, Taiwan. He joined the Power Mechanical Engineering Department at the National Tsing Hua University (Taiwan) in 1996, where he is now a professor as well as a faculty of MEMS Institute. From June to September 1999, he was with Prof. Y.-C. Tai at California Inst. Tech. as a visiting associate. He has established a MEMS testing and characterization lab. His research interests include MEMS with emphasis on microfabrication/packaging technologies, micro optical systems, microactuators, and the characterization of the mechanical properties of thin films.