Microelectronic Engineering 87 (2010) 1400–1403

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Flexible and tactile sensor based on a photosensitive polymer

Ji-Chang Lee, Dong-Weon Lee *

MEMS & Nanotechnology Laboratory, School of Mechanical Systems Engineering, Chonnam National University, Gwangju, Republic of Korea

ARTICLE INFO

Article history:
Received 14 September 2009
Received in revised form 25 November 2009
Accepted 27 November 2009
Available online 3 December 2009

Keywords:
Piezoresistive
Tactile sensor
Biocompatible
Flexible
SU-8

ABSTRACT

This paper presents a novel design of tactile sensing arrays with integrated strain gauges for the measurement of contact force. Surface stress or strain changes on the sensor area due to applied force are measured by the encapsulated Au gauges. The fabricated tactile sensors are highly flexible and durable so that they can conform to more complex surfaces without damaging the skin structure and the metal interconnects on the sensing array. The experimental results show the output characteristics are linear with contact force from 0 to 700 gf and a sensitivity of 3%/100 gf within the full scale range of 700 gf. The effect of electrode structure and position on the enhancement of sensitivity are also numerically simulated by a finite element method and verified experimentally. The measured tactile sensors are robust enough for direct contact with human and contaminants without undue care.

1. Introduction

Recently, the research on humanoid robots has progressed rapidly around the world. In order for ensuring effective and safe interactions between robots and humans, many sensing capabilities, such as tactile, temperature, vision and auditory senses, are indispensable. Flexible artificial skins with tactile array sensing capability are essential for robots to detect physical contact with humans/environment. Various approaches of realizing tactile sensing arrays have been proposed by many groups based on micromaching. MEMS tactile sensors are typically used for robotic end effectors to sense a contact force or pressure when touching objects. Other potential applications of this sensor include the sensing of organic tissue on a small scale at the end of a catheter or on the fingers of an endoscopic-surgery tele-manipulator. MEMS tactile sensors offer several advantages over conventional sensors, including miniaturization, high sensitivity, and multi-dimensional functionality. A wide variety of MEMS tactile sensors that are mostly based on silicon micromachining have been demonstrated. The MEMS tactile sensors are generally classified based on sensing mechanisms. These include piezoresistive [1–3], capacitive [4], piezoelectric [5], and optical tactile sensors. Among them, the piezoresistive method is widely used because it provides easy fabrication and a low-cost. Due to the difficulty of further applications of the tactile sensor with a stiff body, recent reports have been focused on polymer-based MEMS tactile sensors [6]. Also, other studies have combined some of the strengths of Si with polymer-based devices, e.g., by embedding Si elements in polymer skins or covering Si-based devices in a protective polymer layer [7]. In finger-mounted tactile sensors that meet the requirements for typical applications [8], many types of sensor have been developed that they offer some degree of tactile sensing; however, a true flexible tactile sensor has not been used commercially. In particular, many silicon force-sensors have been reported, but they are not useful as finger-mounted tactile sensors because they are packaged in a bulky and hard thermoplastic case, measure pressure not force, and lack overload protection.

In this paper, we present a novel approach to realize a highly-twistable and reliable artificial skin. The advantages of this approach include increased robustness because of the polymer substrate material, decreased fabrication cost and complexity, low temperature process by the use of SU-8 and improved strain transfer from membrane to strain gauges. Mechanical issues such as deflection and stress distributions are investigated using a finite element method. The proposed tactile sensors are successfully fabricated and evaluated. This is our first step towards developing a flexible smart skin that can provide information in various forms regarding contact with external objects.

2. Design and fabrication of tactile sensor

Fig. 1a and b show a schematic diagram of a designed tactile sensor with four strain gauges (S_1–S_4). The size of the tactile sensor is about 30 mm × 30 mm and the thickness of a membrane is 200 μm. Under a given amount of membrane displacement at the center, the stress and strain experienced at the surface are proportional to the thickness of the membrane. From these statements, it

* Corresponding author. Tel./fax: +82 062 530 1684.
E-mail address: mems@jnu.ac.kr (D.-W. Lee).

0167-9317/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.mee.2009.11.161

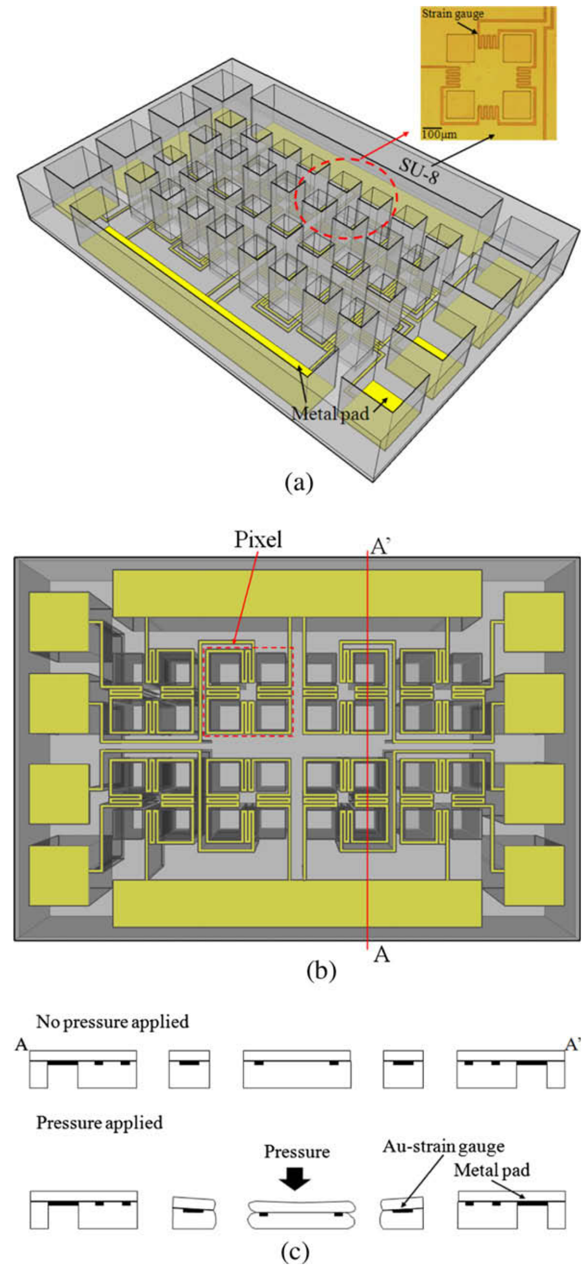

Fig. 1. Schematic views of a SU-8 tactile sensor with integrated strain gauges and operation principle.

is clear that the strain sensing elements in a tactile sensor must be placed at the surface and periphery of the membrane. In addition, the thickness of the membrane for maximum sensitivity must be as large as possible within the elastic limits of the membrane and sensing material. Typical silicon-based membrane sensors use film less than 5 μm in thickness; however, when working with polymers, film thickness can range from 0.1 μm to thousands of μm. Most of micromachined tactile sensors use doped silicon as the strain gage material. However, doped silicon is not readily compatible with polymer substrates and requires a high temperature during fabrication. Thus a thin-film metal is used as the strain sensing element as shown in Fig. 1c. The fabricated tactile sensor is made from a photoresist SU-8 with negative-tone. The SU-8 is an epoxy-based photoresist that is cross-linked, when exposed to UV light. After cross-linkage, SU-8 becomes thermally and chemically stable, making it an excellent material for permanent applications. Lower Young's modulus together with its microfabrication ability makes the SU-8 an attractive material for the tactile applications. It could be produce the tactile sensor with much lower spring constant at the reasonable sensor thickness, which is suitable for flexible systems.

The process-flow for the fabrication of tactile sensors is illustrated in Fig. 2. P-type Si wafer (1 0 0) was used as a substrate. In order to release the finished devices, a sacrificial layer of Al with a thickness of 100 nm is first evaporated on the substrate. Microfabrication processes of the SU-8 were performed in a very similar manner as described elsewhere. The SU-8 2002 was deposited at 3000 rpm for 50 s resulting in a 1.5–2 μm thick SU-8 layer onto the substrate with the Al coating. The SU-8 layer was soft baked at 90 °C and was then exposed to UV light. The SU-8 was post-exposure baked for several minutes and developed in a commercial developer. The resistors and wires in the sensor were defined by a lift-off process using AZ5214E negative photoresist. A 20/80 nm thick Au/Cr bilayer was evaporated on the patterned photoresist and the resistors and wires were released by removing the photoresist in acetone. Due to the rater low adhesion between metal and SU-8 layer ultrasonic should be very careful. A second layer of SU-8 2050 layer was deposited at 1000 rpm for 30 s resulting in a 100 μm thick SU-8 layer onto the metal layer. Two step contact hotplate process was employed for best result of SU-8 structures. After the exposure process the SU-8 was developed to form the sensor body. The fabricated tactile sensor was hard-baked at 120 °C for 15 min to complete the cross-linkage of SU-8. Finished sensors were released by etching the Al layer in buffered HF solu-

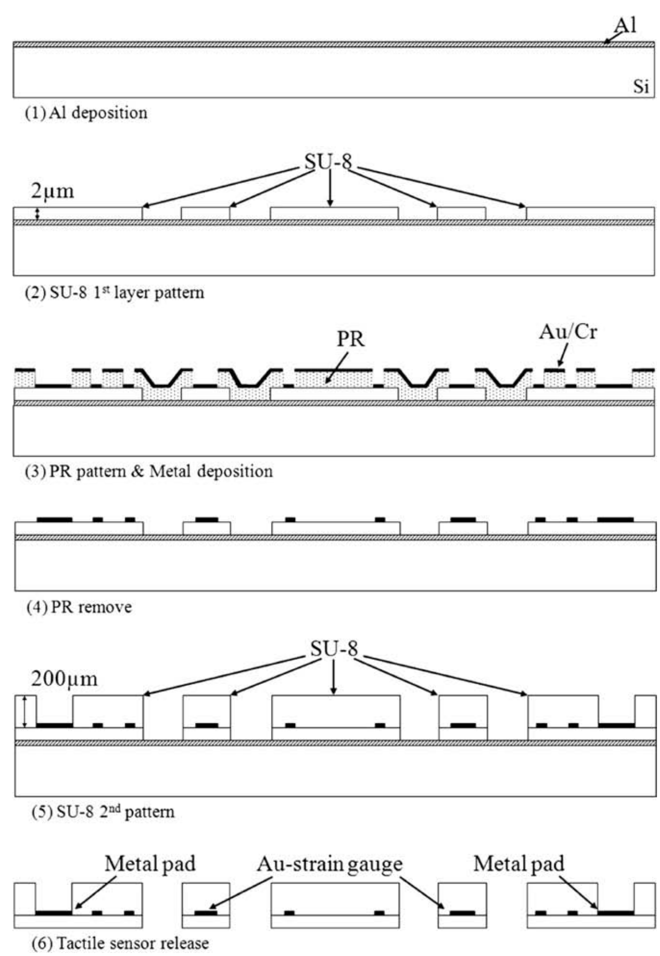

Fig. 2. Process flow of key steps in the fabrication of the tactile sensor.

tion, which has a very fast etching rate of Al. Finally, the fabricated tactile sensor were cleaned and rinsed in various liquids and DI water, respectively. The fabricated flexible tactile sensors separated from the substrate were shown in Fig. 3a.

The size of one sensor pixel is 30×30 mm^2 including interconnecting lines. The fabricated sensor shows good flexibility and transparency as shown in Fig. 3b and c, respectively. Air channels are formed to prevent the squeezed air from affecting the pixel response. These air channels connect all the pixel cavities to the atmosphere and maintain the pressure of each tactile pixel cavity equal to the pressure of the atmosphere.

3. Result and discussion

We set up custom-made equipment for contact force characterization because there is no commercial tool available for the contact force measurement in a small scale. Individual testing of the fabricated tactile sensor was carried out using a precision linearly variable microforce gauge coupled to a manual micromanipulator (*XYZ*-axis) and a motorized microstage (*Z*-axis). The resistance change was measured by using a sourcemeter and Labview system, supplying a constant force to the fabricated tactile sensor. Fig. 4a shows the schematic diagram of the measurement system employed for the tactile sensor experiment. A microforce gauge from AIKOH Engineering Co. has been used with precision *Z*-axis translation stage that has 50 nm resolution. The resistance of the strain gauge is monitored using a six-digit multimeter while a metal micromanipulator tip was used to apply a normal force to the tactile membrane. An individual pixel was loaded and unloaded several times to generate a reasonable data as shown in Fig. 4b. The tactile sensor response versus applied force characterization was not perfect due to limitations of the available force transducer. The relationship between the applied forces and outputs from the tactile sensor is shown in Fig. 5. The results clearly show linear response of the resistance change to the displacement or applied force of an individual pixel. Next, we applied a pulsed force to monitor responsibility and repeatability of the tactile sensor. These characteristics are very important for further application such as extra-vascular blood pressure monitoring. A pulsating pressure variation contained in a blood vessel exerts an outward force that leads to a local displacement of the tissue surface. We also clearly demonstrated feasibility of the application using the fabricated tactile sensors as shown in Fig. 6. The fabricated sensor will become more sensitive as the upper SU-8 layer thickness reduces.

The SU-8 based tactile sensor has been developed for industry applications. SU-8 allows for an inexpensive and easy fabrication method so that the sensor can be used as a changeable part of a tactile device. Piezoresistive strain sensors have been integrated in the tactile for detection of surface stress changes due to applied force with the normal direction. The sensitivity of the strain sensors depends on the ratio of the gauge factor K and the Young's modulus E. The gauge factor of Si is about 50 times higher than the gauge factor of Au ($K_{Au} = 2$), but since the Young's modulus of Si is about 40 times higher than for SU-8 (4.5 GPa), resulting sensitivity of the two types of tactile sensors should be approximately same. A big advantage of the proposed tactile sensor in comparing with Si-based tactile sensor was the fabricated tactile sensors were highly flexible and can be deflected more than 180°. The sensitivity of the polymeric tactile sensor can be improved by making by using a piezoresistive material with a much higher gauge factor than Au. One possibility is to use SU-8 mixed with conductive car-

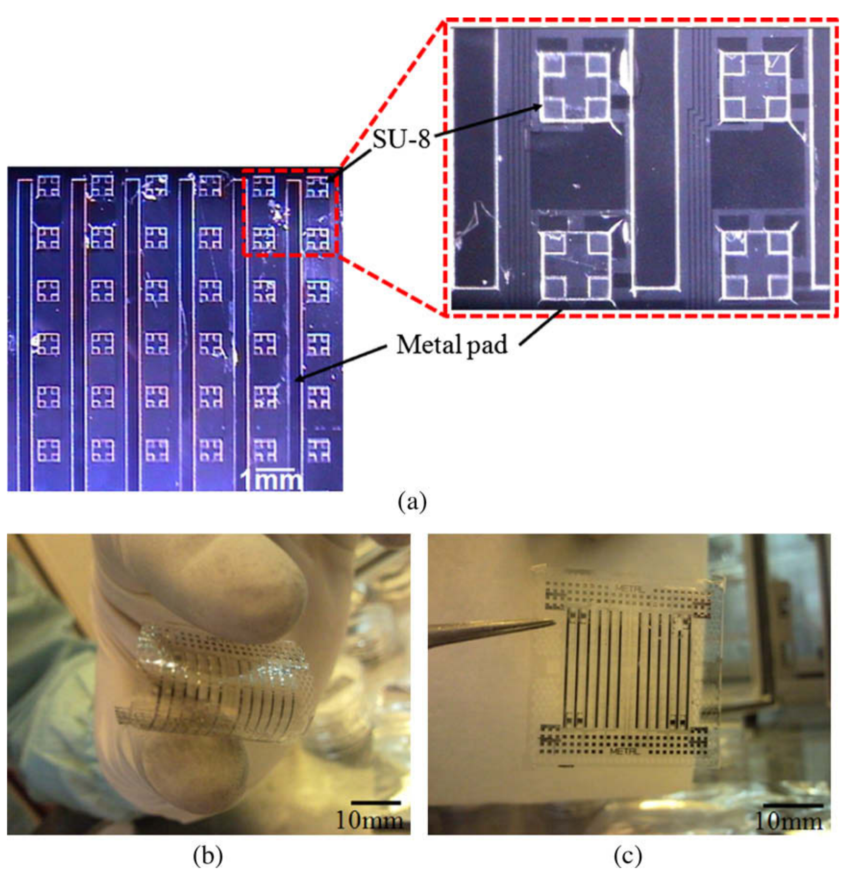

Fig. 3. Optical images of the flexible and transparent tactile sensor with 12×12 pixels. The size of each pixel is 30×30 mm^2.

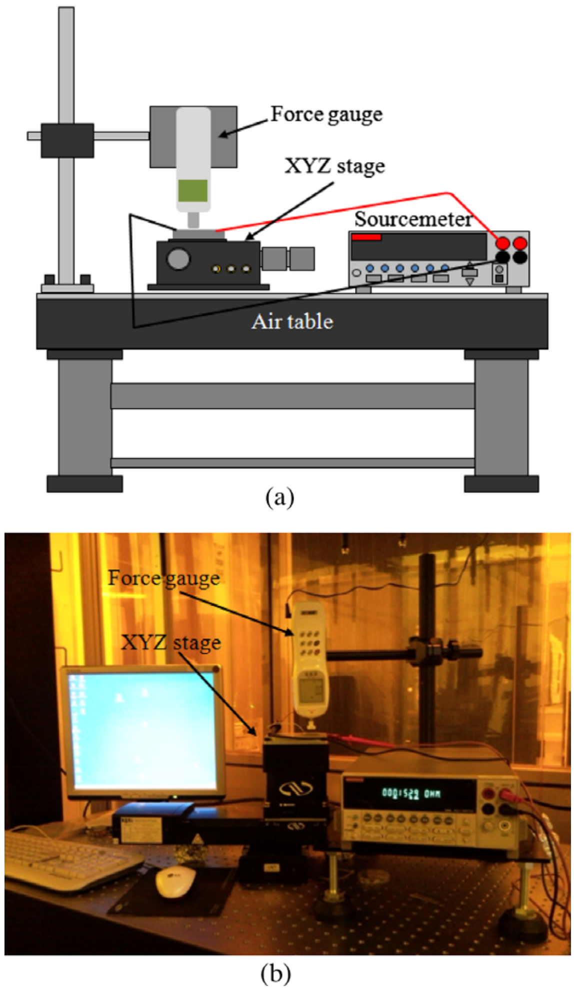

Fig. 4. Measurement setup for characterization of the fabricated tactile sensor.

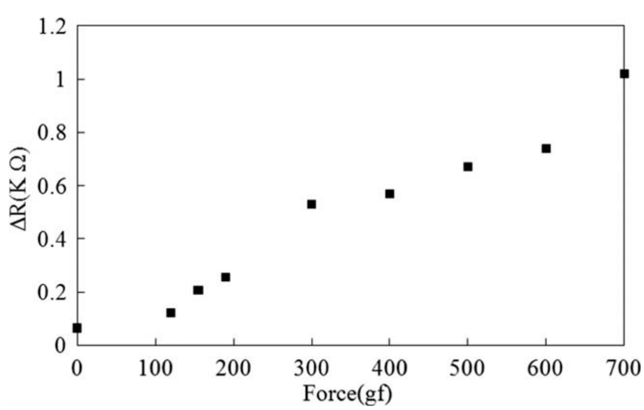

Fig. 5. The change of output resistance, Δ*R*, versus force applied to a pixel of the tactile sensor.

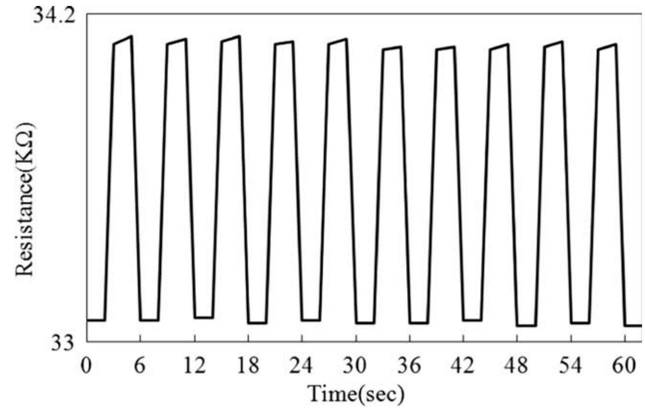

Fig. 6. Repeatability test of the tactile sensor output to pulsed force.

bon particles to improve the sensitivity. We are currently mixing the SU-8 with a highly conducting carbon nanotube(CNT) to find an optimal ration between SU-8 and CNT particles.

4. Conclusions

A novel tactile sensor based on a monolithically integrated sensor chip was presented for all polymer-based MEMS tactile sensors. We successfully fabricated and demonstrated a low-cost tactile sensor array using the presented polymer micromachining techniques and a simple measurement system. The proposed technology enables the development of flexible, robust, multi-modal sensor skins for application to robotics, medicine and industry. Repeatable response to pulsed forces was confirmed using the fabricated tactile sensor. We have also measured the performance of individual pixel as well as the response of an array of pixel.

Acknowledgements

This research was supported by a Grant from the Fundamental R&D Program for Core Technology of Materials and funded by the Ministry of Knowledge Economy and the Korea Science & Engineering Foundation through the NRL Program (Grant R0A-2007-000-10157-0), Republic of Korea.

References

[1] M. Leineweber, G. Pelz, M. Schmidt, H. Kappert, G. Zimmer, Sensors and Actuators A 84 (2000) 236–245.
[2] C.S. Park, J.S. Park, D.W. Lee, Microelectronic Engineering 86 (2009) 1250–1253.
[3] J.H. Kim, J.I. Lee, H.J. Lee, Y.K. Park, M.S. Kim, D.I. Kang, Proceedings of the 2005 IEEE (2005) 2578–2581.
[4] M. Tanaka, Journal of Materials Processing Technology 108 (2001) 253–256.
[5] C.S. Park, B.S. Kang, D.W. Lee, Y.S. Choi, Applied Physics Letter 89 (2006) 223516.
[6] J.J. Carr, Sensors and Circuits, PTR Prentice Hall, Englewood Cliffs, New Jersey, 1993 (US 07632 75).
[7] I. Obieta, F.J. Gracia, Sensor and Actuators A 42 (1994) 685–688.
[8] H.K. Lee, S.I. Chang, E. Yoon, Journal of Microelectromechanical Systems 15 (6) (2006) 1681–1686.