A silicon-based flexible tactile sensor for ubiquitous robot companion applications

Kunnyun Kim\(^2\), Kang Ryeol Lee\(^1,2\), Dae Sung Lee\(^2\), Nam-Kyu Cho\(^2\), Won Hyo Kim\(^2\), Kwang-Bum Park\(^2\), Hyo-Derk Park\(^2\), Yong Kook Kim\(^3\), Yon-Kyu Park\(^4\) and Jong-Ho Kim\(^4\)

\(^2\) Nano Mechatronics Research Center, Korea Electronics Technology Institute, #68 Yatap-dong, Bundang-gu, Seongnam-si, Gyeonggi-do 463-816, Korea
\(^3\) Department of Electronics and Computer Engineering, Korea University, Korea
\(^4\) Mass and Force Group, Korea Research Institute of Standards and Science, Korea

E-mail: lkr@mju.ac.kr

Abstract. We present the fabrication process and characteristics of a 3-axes flexible tactile sensor available for normal and shear mode fabricated using Si micromachining and packaging technologies. The fabrication processes for the 3 axes flexible tactile sensor were classified in the fabrication of sensor chips and their packaging on the flexible PCB. The variation rate of resistance was about 2.1\%/N and 0.5\%/N in applying normal and shear force, respectively. Because this tactile sensor can measure the variations of resistance of the semiconductor strain gauge for normal and shear force, it can be used to sense touch, pressure, hardness, and slip.

1. Introduction

Tactile sensors are an area of MEMS technology for applications to robotics in medicine and industrial automation [1–2]. They have been of much interest for use in the fingertips or hands of humanoid robots. Recently, reported work has focused on Si-based sensors using piezoresistance or capacitance for sensing and polymer-based approaches using metal strain gauge deposited on the polymer film [2–5]. Also, other works have combined some of the strengths of Si with polymer-based devices, such as embedding Si elements in polymer skins [6], or covering Si-based devices in a protective polymer layer [3–4]. In the finger-mounted tactile sensors that meet the requirements for typical applications, many types of available sensors have been developed that give some degree of tactile sensing, but a true tactile sensor has not been used commercially [6].

In particular, many silicon force sensors have been reported recently, and silicon pressure sensors are widely commercialized, but they are not useful as finger-mounted tactile sensors because they are packaged in a bulky and hard thermoplastic case, they measure pressure not force, and they lack overload protection. However, in this work, to solve the above problems of silicon sensors, they were...
individually packaged on the flexible PCB after fabricated with diced sensor chips (chip size: 1.5mm×1.5mm).

Thus a 3-axes flexible tactile sensor available for normal and shear mode was fabricated using silicon micromachining and packaging technology. The fabrication processes for the flexible tactile sensor were classified in the fabrication of sensor chips and their packaging on the flexible PCB.

2. Design

The dimension of the tactile sensor is shown in Fig. 1. In conventional micromachining of bulk sensors, the diaphragm is etched from the backside with the KOH wet etching process. Diaphragm size is 1.2mm×1.2mm and strain gauges are placed at the diaphragm edge to achieve high force sensitivity. When a force is applied, the diaphragm will be deformed, and the stress induced in the strain gauges will lead to resistance changes. To achieve maximum sensitivity, the strain gauges should be placed at the points of maximum stress.

A commercially available simulation tool (ANSYS) was used to show the distribution of tensile and compressive stress in the diaphragm under a normal load along the $z$ axis. When the normal force is applied on the loading block, the sensor diaphragm is bent as shown in Fig. 2, and the maximum stress is at the edge of the diaphragm where piezoresistors are embedded.

The magnitude of surface stresses is found to be greatest near the edges of the diaphragm for both square and circular diaphragms. Under a given displacement of the diaphragm by the deflection at the center, the stress and thus strain experienced at the surface are proportional to the thickness of the diaphragm. From these statements, it is clear that the strain sensing elements in a tactile sensor must be placed at the surface and periphery of the membrane. Also, for slip detection by shear load along the $x$ or $y$-axis, 4 piezoresistors are placed as sensing elements on each edge of the square diaphragm.
3. Fabrication

The fabrication process of the proposed tactile sensor array is shown in Figure 3. The starting substrate is a bare p-type Si wafer \( t=500\mu m \), double side polished and \( \rho=1–10\Omega\cdot cm \) with a \( 0.2\mu m \) of silicon nitride. Silicon nitride thin film as a passivation layer was patterned for ion implantation and the KOH wet etching process (Fig. 3a). The strain gauges were formed using high-impedance piezoresistors obtained by phosphorus ion implantation. Piezoresistors were implanted using phosphorus doses of \( 1.5\times10^{14} \) atoms/cm\(^2\) and then annealed at \( 1100^\circ C \) for 50min in a nitrogen atmosphere (Fig. 3b). The Cr(300Å)/Au(3000Å) metal layer was then deposited by evaporation for the electrode and pad on the front side of silicon wafer and etched by wet etching (Fig. 3c). To apply normal or shear force, the loading block was formed by patterning the SU-8 photoresist and diaphragm by wet etching in 26 wt% KOH solution at \( 80^\circ C \) (Fig. 3d). The wafer level sensor array is diced into individual chips for attachment on the flexible PCB. Epoxy adhesive (3M, DP-420) is coated on the flexible PCB by the screen printing method for bonding with a chip level sensor array (Fig. 3e). Sensor chips are mounted onto the flexible PCB, which is cured at \( 110^\circ C \) by ramping (Fig. 3f). It is important that the bond not crack over time or suffer from creep. Then wire bonds were used to provide interconnects of the tactile sensor array to the flexible PCB (Fig. 3g). Finally, we covered the sensor chip array surface with two-component silicone rubber as a protective layer (Fig. 3h). Two-component silicone rubber exhibits good stability with regard to most chemicals, including weak acids and polar solvents. The 3-axes flexible tactile sensor is successfully completed by removal of the jig after curing at room temperature for 24hrs (Fig. 3i).

![Fabrication process of the proposed tactile sensor array.](image-url)
4. Results

Figure 4 a) shows a fabricated wafer level tactile sensor array. Individual tactile sensor chips are fabricated through the dicing process as shown Fig. 4b). The unit sensor chip contained four piezoresistors and the loading block. The unit sensor chip size is 1.5mm×1.5mm. The flexible tactile sensor array is mounted on the flexible PCB as shown in Fig. 5. The resulting device is a 7.7mm×7.7mm chip containing a 4×4 tactile sensor. Then, sensor array chips are diced into individual unit cells to achieve the flexibility of sensor chips. Wire bonding was done between pads on sensor chips and the flexible PCB. Then the 3-axes flexible tactile sensor was successfully accomplished by coating and curing two-component silicone rubber based on polydimethylsiloxane similar to human skin.

![Fig. 4. Images of a) fabricated wafer-level tactile sensor and b) diced tactile sensor chips.](image)

Also, characteristics of fabricated sensors were measured using a tactile sensor evaluation test system and signal control system. The experimental apparatus consists of a loading structure, data acquisition, and data analysis. The tip of the tool is positioned at the center of the top surface of the loading block. The sensor is attached to a horizontal loading stage that can be tilted. Then normal and shear forces are applied to the loading block of the diaphragm. Each of the four resistors is connected into a signal control system.

![Fig. 5. Images of flexible tactile sensor array mounted and wired on the flexible PCB.](image)

Figure 6 shows the variations of resistance with applied normal and shear forces in the range of 0 ~ 2N. Both the normal and the shear of an applied force can be calculated from the resistance changes induced by the stress. As shown in Fig. 6, the variation rate of resistance is about 2.1%/N and 0.5%/N in applying normal and shear force, respectively. The experimental results demonstrate that the sensor
is shear sensitive and is capable of measuring both the normal and shear components of an applied load force. Referring to Fig. 6, by comparing the sensor’s outputs at normal loading and shear loading, we can see that the sensitivity at normal applied force is noticeably larger than the sensitivity at shear force.

Fig. 6. Plot of read-out resistance with applied normal and shear force to the range of 0 ~ 2N.

5. Conclusions

The 3-axes flexible tactile sensor available for normal and shear mode was fabricated using silicon micromachining and packaging technology. The fabrication processes for flexible tactile sensors were classified in the fabrication of sensor chips and their packaging on the flexible PCB.

The variations of resistance with the range of 0 ~ 2N was about 2.1%/N and 0.5%/N in applying normal and shear force, respectively. Though not expressed in the paper, it was found using a tactile sensor test system that the breakdown force of the diaphragm was about 3N. The flexibility of the fabricated 3-axes flexible tactile sensor was good enough to place on the fingertip. Therefore, it is thought that this sensor can be not only applied to flat surfaces in industrial robots, but also to finger or arm-like curved surfaces in humanoid robots.

Acknowledgments

This research was supported by the Intelligent Robot Sensor Project (first year) sponsored by the Ministry of Information and Communication under the contract project code A1100-0400-0058.

References

[1] M. H. Lee, and H. R. Nicholls, Tactile sensing for mechatronics - a state of the art survey, Mechatronics 9 (1999) 1–31, doi:10.1016/S0957-4158(98)00045-2.
[2] M. E. H. Eltaib, and J. R. Hewit, Tactile Tactile sensing technology for minimal access surgery - a review, Mechatronics 13 (2003) 1163–1177, doi:10.1016/S0957-4158(03)00048-5.
[3] B. L. Gray and R. S. Fearing, A surface micromachined microtactile sensor array, in P. IEEE Int. Conf. Rob. Auto. (Minneapolis, 1996), pp.1–6.
[4] B. J. Kane, M. R. Cutkosky and G. T. A. Kovacs, A traction stress sensor array for use in high-resolution robotic tactile imaging, J. Microelectromech. Syst. 9 (2000) 425-434.
[5] M. Leineweber, G. Pelz, M. Schmidt, H. Kappert and G. Zimmer, New tactile sensor chip with silicone rubber cover, Sens. Actuat. A 84 (2000) 236-245, doi:10.1016/S0924-4247(00)00310-1.
[6] J. Engel, J. Chen, Z. Fan and C. Liu, Polymer micromachined multimodal tactile sensors, Sens. Actuat. A 117 (2005) 50-61, doi:10.1016/j.sna.2004.05.037.