Polymer/Metal Based Flexible MEMS Biosensors for Nerve Signal Monitoring and Sensitive Skin

Yong-Ho Kim, Eun-Soo Hwang, and Yong-Jun Kim

Abstract—**This paper presents fabrication process and experimental results of two different types of flexible MEMS biosensors based on polymer/metal multilayer processing techniques. One type of a biosensor is a microelectrode array (MEA) for nerve signal monitoring through implanting the MEA into a living body, and another is a tactile sensor capable of being mounted on an arbitrary-shaped surface. The microelectrode array was fabricated and its electrical characteristics have been examined through in vivo and in vitro experiment. For sensitive skin, flexible tactile sensor array was fabricated and its sensitivity has been analyzed. Mechanical flexibility of these biosensors has been achieved by using a polymer, and it is verified by implanting a MEA to an animal and mounting the tactile sensor on an arbitrary-shaped surface.**

Index Terms—**Polymer, Flexible, Biosensor, Microelectrode array, Tactile Sensor**

I. Introduction

Conventional microelectronics is based on silicon processing. Silicon is a kind of a ceramic which is highly brittle. But for bio/medical application of a micro sensor, properties of the micro sensor have to be similar to those of a living body. Otherwise, it can be delaminated from a surface when it is mounted on a human skin or harm adjacent organs when it is implanted into a human body. Silicon is difficult to meet the requirement due to its brittleness even though it can be flexible to some extent when its thickness becomes below 100 μm. A polymer is a promising candidate to realize a fully flexible sensor since it shows highly flexibility even when its thickness is over hundreds of micro meters.

In this study, two different kinds of a flexible biosensor were realized using polymer/metal multilayer processing techniques [1], and their characterization was carried out.

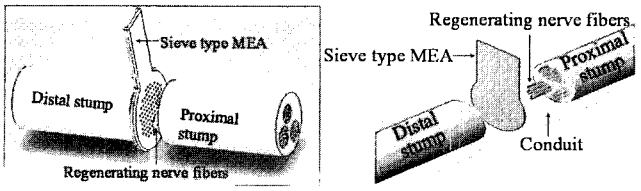
Manuscript received January 15, 2005; revised March 15, 2005
School of Mechanical Engineering, Yonsei University, Republic of Korea
E-mail : yonghokim@yonsei.ac.kr

II. Flexible Biosensors

1. Microelectrode Array (MEA)

Nerve injuries have frequently occurred due to trauma and surgical removal of a tumor. A neuron is one of the most differentiated cells and is not capable of mitosis. But for the peripheral nerve system, a neuron can regenerate axons when a portion of an axon is injured. By inserting a MEA between a proximal and a distal nerve stump, the regenerating state of the nerve can be monitored (Figure 1).

Many researches related to a microelectrode array, based on the nerve regeneration phenomenon, had been carried out to recover a function of an injured peripheral nerve. They can be classified into two types according to a substrate material. One method is using silicon as a substrate [2] and the other is using polymer substrate [3]. For cased using a silicon substrate, it is difficult to satisfy a physical compatibility that means no side effects, such as scratch to adjacent organs due to a brittle characteristic of silicon. For cases using a polymer substrate, the method potentially contains possibility to change and/or destroy an



(a) Assembly implantation (b) Interfascicular suture

Fig. 1. Schematic of two implantation methods

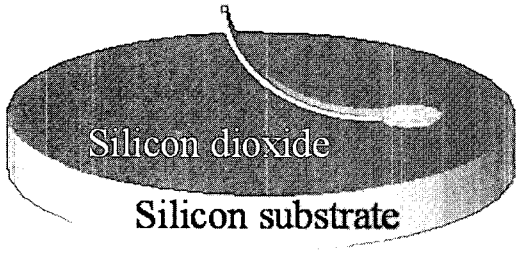


Fig. 2. Schematic of the 'etch-release' scheme

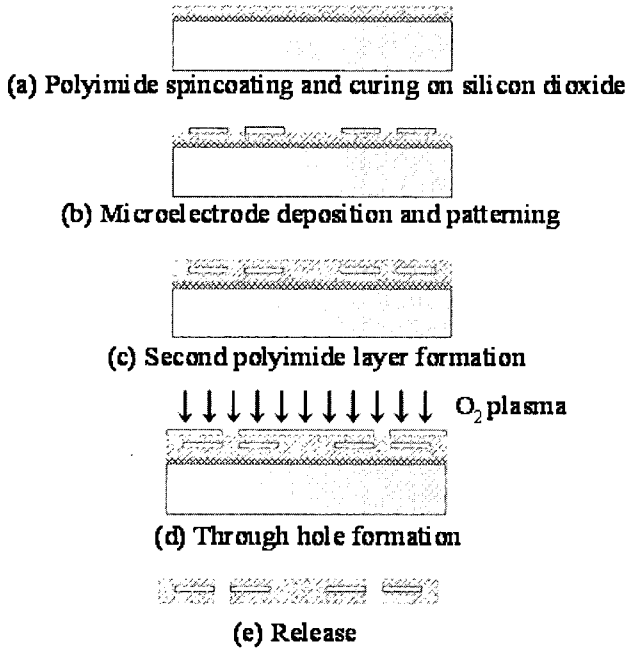
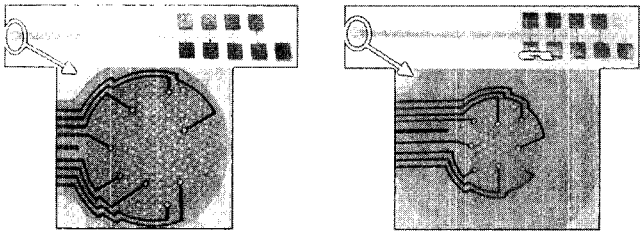


Fig. 3. Simplified fabrication process of the MEA



(a) Assembly implantation (b) Interfascicular suture

Fig. 4. Optical photographs of the fabricated MEAs for two different implantations

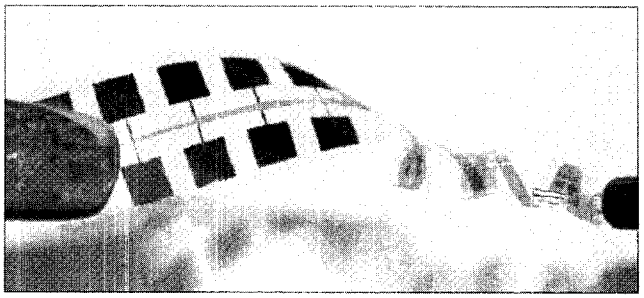


Fig. 5. Flexible characteristic of the fabricated MEA

(a) Direct implantation (b) Assembly implantation

Fig. 6. Implanted MEA with two different methods

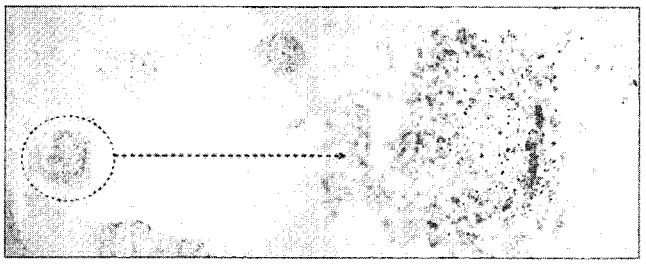


Fig. 7. Optical photographs of regenerated nerve fibers of a rat through the implanted MEAs

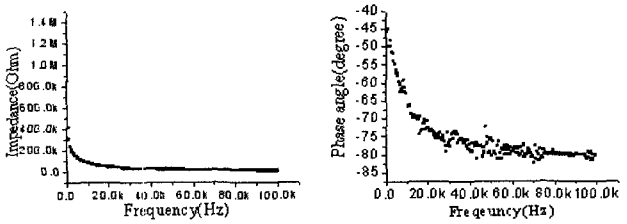
original shape of a sieve part including through holes. The problem is originated from mechanical 'peeling-off' step.

In this research, polyimide was used to meet physical and biocompatibility, and stress-free 'etch-release' scheme [4] was used to get rid of the possible change and/or failure of the through hole configuration. Figure 2 represents the stress-free 'etch-release' scheme in which MEAs are obtained by chemical removing a sacrificial layer, silicon dioxide in this case.

A MEA was fabricated using polymer/metal multilayer processing techniques (Figure 3). Fabrica-tion starts with a sacrificial layer deposition followed by a flexible substrate formation whose thickness was approximately 6 μm. Microelectrodes (Cr/Au) were defined, and then a second polyimide layer was spin-coated and cured to passivate microelectrodes from a harsh environment, a living body in this case. After patterning Al mask, through holes were defined by 100% O_2 reactive ion etching (RIE). The last

step is removing the sacrificial layer to get the final device. This step was performed with 25% diluted HF for 45 minutes. Figure 4 shows a fabricated device for two different implantation methods, and Figure 5 represents flexibility of the fabricated device.

To verify biocompatibility and long-term stability, in vivo experiment was performed. The MEAs was implanted with two different implantation methods. One is



(a) Interfacial impedance (b) Phase angle

Fig. 8. Measured interfacial impedance characteristics

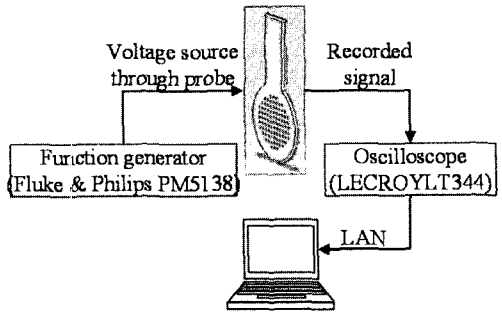


Fig. 9. Measurement flow of the signal transfer characterization

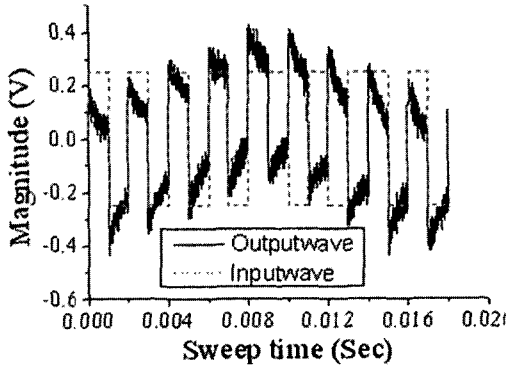


Fig. 10. Measured signal transfer characteristics

using a conduit that guides regenerating nerves and minimizes relative movement of the implanted de-vices. The other is an implantation by a direct interfascicular suture technique. Figure 6 shows the implanted MEAs to a peroneal nerve of a rabbit and a sciatic nerve of a rat. Any side effects, such as neuroma, had not been observed for implantation periods of 4 months, and nerve fibers were successfully regenerated (Figure 7).

For feasibility test of measuring nerve signal through the MEAs, interfacial impedance between micro-electrodes and a body fluid and signal transfer characteristics were measured. The interfacial impedance was measured through impedance analyzer (HP4294A) for a frequency range from 40 Hz to 100 kHz (Figure 8). The impedance at 1 kHz was approximately 420 kΩ, of which value is lower than that of G. T. A. Kovacs et al, 600kΩ [5], and E. Valderrama et al, 500MΩ [6]. Along side with measuring the interfacial impedance, signal transfer characteristics were measured for square waves with different magnitudes at frequency of 500 MHz. Schematic measurement flow is depicted in Figure 9, and the result is shown in Figure 10.

According to these results, it is expected that nerve signal can be measured through microelectrodes due to its low magnitude of impedance and good signal transfer characteristics if proper circuitries such as a filter and an amplifier.

2. Flexible Sensitive Skin

In this part, our objective is the development of an sensitive skin, which is a polymer based flexible pressure sensor array for measuring tractions on the surface of an arbitrary shaped object, especially a robotic body.

Tactile sensing is a form of sensing that can measure given properties of an object through physical contact between the sensor and the object [7]. It is very complex sensing modality and tactile sensor unit (i.e. pressure sensor) must be distributed all around the body. Therefore, to realize sensitive skin needs techniques to make the tactile sensor array flexible and to recognize complicated information through contact. Our strategies are to use polymer substrate for flexibility and to use strain gauge array for tangential load measuring as well as normal load.

When normal load exists on the substrate surface, the substrate will experience stresses for satisfying force equilibrium and these stresses result in deformations of substrate. In rigid silicon cases, thin silicon membranes structures are used to magnify these deformations. In our

study, ductile polymer substrate replaces these thin deformable structures. Figure 11 shows our proposed tactile sensor structure. The strain sensitive material is embedded in polymer substrate with interconnections. When a substrate is subjected to a normal load, the two strain gauges are deformed simultaneously. And when shear load case, one strain gauge experiences tensile stress and the other compressive stress as shown in Figure 12.

The flexible tactile sensor was fabricated using a conventional surface micromachining technique. A 2μm thick phosphorous silica glass (PSG) film is deposited to be used as a sacrificial layer on a silicon wafer. PI2611 (HD microsystems) was coated at 1000 rpm and cured at 350°C.

A 500Å thick Nickel-Chrome film was chosen to be strain gauge material. Ni-Cr film was patterned and coated by a polyimide film with appropriate electroplated interconnections. To realize the desired flexible sensor module, the strain gauge array and polyimide substrate should be separated from the rigid silicon carrier wafer. It can be accomplished by removing the sacrificial layer in HF-based solution. Figure 13 shows the realized flexible tactile sensor. The flexible tactile sensor has simple one layer structure so it shows high flexibility. And the sensor has no fragile structure; excellent overpressure behavior can be attained. These facts make it to be applied to sensitive skin of robots.

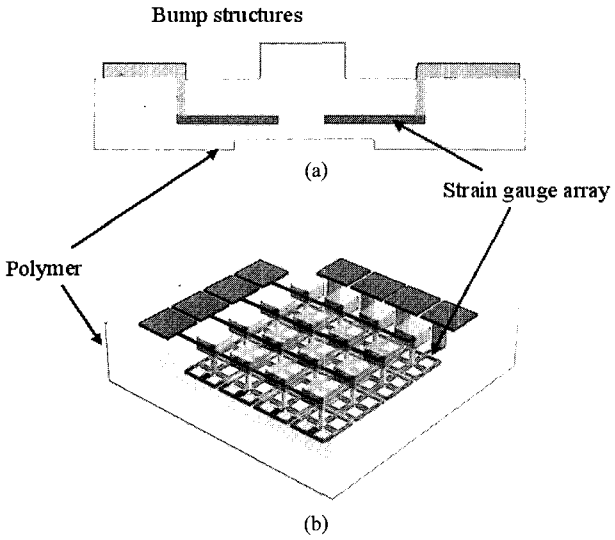


Fig. 11. A side view of proposed flexible sensitive skin structure and schematice. (a) Cross-sectional view, (b) Embedded the strain gauge arrays in polyner substrate

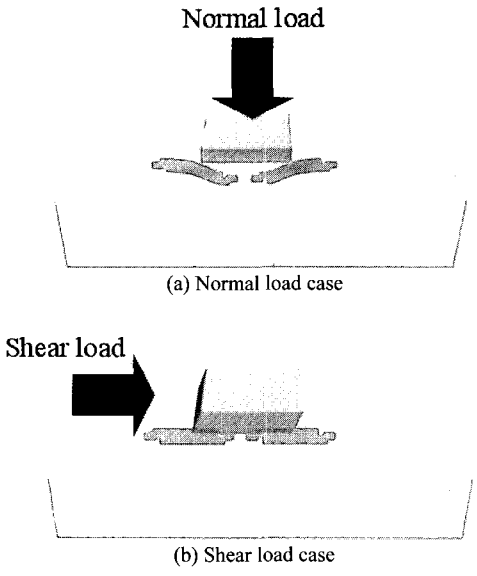


Fig. 12. Sensing mechanism (a) Both gauges are subjected to tensile stress, (b) One gauge is subjected to tensile stress, the other subjected to compressive stress

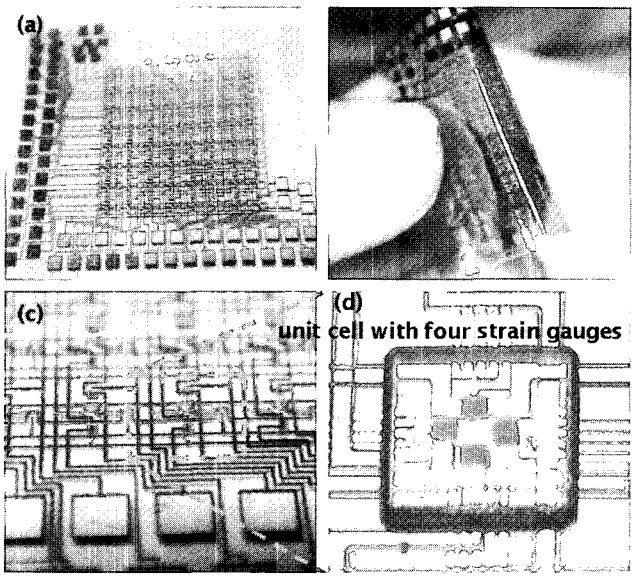


Fig. 13. (a) Photographs of 8×8 flexible tactile sensor array, (b) Flexibility test, (c) and (d) One unit cell composed of four strain gauges

The experimental setup consists of load cell, load cell indicator, amplifier and oscilloscopes. The applied load is measured at load cell indicator. The sensor output signal is measured by oscilloscope through Wheatstone bridge and amplifier. To find the unit cell characteristics, we perform normal load and shear load test. To apply pure shear load we attached scotch tape at the sensor bump and pulled it to horizontal direction with load cell. The results are shown in Figure 14. The normal load deformed the polymer

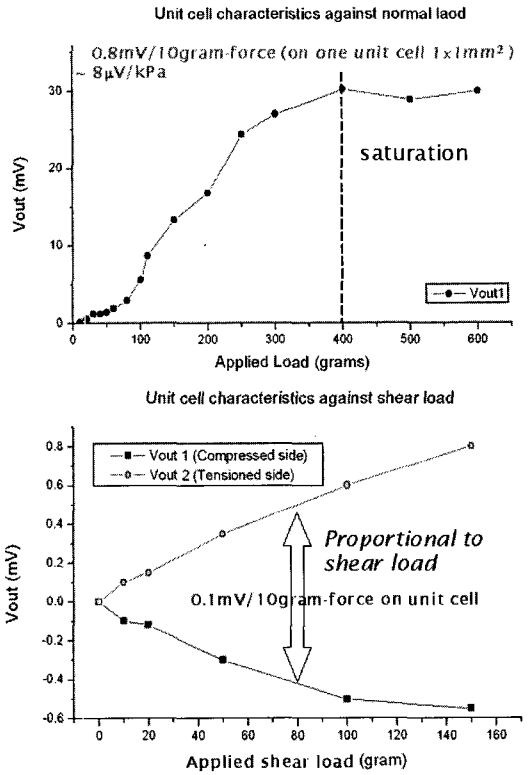


Fig. 14. Unit cell characteristics against normal and shear load

substrate and strain gauges which resulted in increase of strain gauge resistance. In pure shear load case, one strain gauge's resistance increased and the other decreased. The shear load signal was small compared to normal load signal. These results show that the proposed tactile sensor can measure both normal load and shear load by super position principle. Therefore, we can get more detail information through contact.

We proposed and demonstrated a new type sensitive skin. The promisings are that the strain gauge embedded sensitive skin has simple one layer structure, and since it has no fragile structure, good overpressure behavior can be attained. Furthermore, since the sensitive skin is mechanically flexible it is easy to make it large array. These facts make it to be applied to sensitive skin of robots.

III. Conclusions

Two different biosensors capable of being mounted on an arbitrary-shaped surface were realized using polymer/metal multilayer processing techniques and their characterization was carried out. Flexibility of the biosensors could be achieved by using a polymer substrate and passivation layer, and it was verified. Due to biocompatibility and flexibility of the polyimide film, the proposed biosensors can be applied to an arbitrary-shaped surface such as inside of living body and skin of human as well as a plane surface. It is expected that the flexible biosensors based on a polymer can exploit new application areas as well as the proposed application.

Acknowledgments

This paper was partially supported by a grant of the Korea Health 21 R&D Project, Ministry of Health & Welfare, Republic of Korea (02-PJ1-PG1-CH07-0001), and partially performed for the Intelligent Robotics Development Program, one of the 21st Century Frontier R&D Programs funded by the Ministry of Commerce, Industry and Energy of Korea.

References

[1] Y.-J. Kim, "Application of polymer/metal multi-layer processing techniques to microelectromechanical systems," *Ph. D. dissertation, Georgia Inst. Tech.*, 1997.

[2] R. M. Bradley et al., "Long-term chronic readings from peripheral sensor fibers using a sieve electrode array," *J. Neuro. Meth.*, Vol. 73, pp. 177-186, 1997.

[3] T. Stieglitz et al., "Flexible polyimide-based neural interfaces," *Proc. NFBIS*, pp. 112-119, 1999.

[4] E. -S. Hwang et al., "Flexible Polysilicon sensor array module using 'etch-release' packaging scheme," *Sen. Act. A*, Vol. 111, pp. 135-141, 2004.

[5] G. T. A. Kovacs et al., "Regeneration microelectrode array for peripheral nerve recording and stimulation," *IEEE Trans. Biomed. Eng.*, Vol. 39, No. 9, pp. 893-902, 1992.

[6] E. Valderrama et al., "Microfabrication and characterization of microelectrode arrays for in vivo nerve signal recording," *Proc. Int. Conf. Trans.* pp. 63-66, 1995.

[7] Mark H. Lee, "Tactile sensing: New Directions, New Chanllenges", *Int. J. Robotics Research*, Vol. 19 No. 7, pp. 636-643, 2000.

Yong-Ho Kim He received the B.S. and M.S. degrees in mechanical engineering from Yonsei University, Seoul, Korea, in 2001 and 2003, respectively. He is currently working toward Ph.D. degree in Microsystems Laboratory, Yonsei University. His research interest includes next generation flexible electronic packaging, flexible sensors for Bio/Medical application and telemetry system.

Eun-Soo Hwang He received his B.S. and M.S. degrees in mechanical engineering from Yonsei University, Seoul, Korea, in 2001 and 2003, respectively. He is a member of the Microsystems Laboratory at department of mechanical engineering, Yonsei University, as a Ph.D. student. His research includes the fabrication and packaging process for flexible substrates and flexible chips, and sensor array modules for sensitive skin.

Yong-Jun Kim He received the Bachelor of Engineering in electrical engineering from Yonsei University, Seoul, Korea, in 1987. He received the Ph.D. degree in electrical engineering from Georgia Institute of Technology in 1997. His thesis work involved the application of polymer/metal multilayers to MEMS. From 1996 to 2000, he was with Samsung Electronics Co. as a senior engineer and project leader working on electronic packaging and various MEMS devices. Since 2000, he joined the faculty of Yonsei University as a Professor in the School of Mechanical Engineering. His current research includes general micromachining, bio and environmental sensors, RF-MEMS, and flexible electronic packaging.