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Polyimide-based multi-channel arrayed electrode for measuring EEG signal on the skull of mouse

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and Sang-Hoon Lee

***Abstract*— in this paper, we have developed 40 channel multiple electrodes mounted on the surface of mouse's skull using polyimide substrate and tested its performance by measuring EEG signals. The recording site of the electrode was electroplated by Pt to enhance both contact impedance and adhesive strength by applying proper current, cleaning surface and removing H_2 gas bubbles. For in vivo test, the electrode was placed on the skull of F1 mouse and EEG signals were measured. We observed the suitability of electrode for measuring EEG signals from multiple areas on the skull. The spectrum of EEG signal to change was observed by urethane administration.**

I. Introduction

Neural prostheses and therapies based on nerve stimulation and recording require multiple microelectrodes which can be chronically interfaced to the central and peripheral nervous systems [1]. This multiple microelectrode connects neurons to the outside equipments and an ideal electrode requires low impedance. Despite great progress in technology, direct measurement of intracortical signals is still challengeable, because of the high risky brain surgery, biocompatibility of electrode, and difficulty in stable and long term recording of signals. Moreover measurement of EEG signals on the skin of head provides weak signals including several errors such that it is difficult to obtain accurate signals [2]-[3].

To address these problems, recording of neural signals on the skull surface is desirable and attracts attentions to the safety and stability. In this case, the cortical signals are transmitted through the CSF (CerebroSpinal Fluid) and bone, and the reduction of high error rate and improvement of signal-to-noise ratio is most important factors. If the signals are measured accurately, this method has lots of advantages over intracortical or EEG-based methods. For the stable measurement of signal, the development of electrode array with low contact impedance is one of key requirements. In this paper, we have developed 40 channel multiple electrodes mounted on the surface of mouse's skull using polyimide substrate and tested its performance by measuring EEG signals.

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II. Materials and Methods

A. Fabrication of polyimide based electrode

As a substrate material, we used polyimide (Durimide7510TM, Fuji-film) which has excellent physical and electrical properties (Table II) [4]. We designed 40 channels arrayed electrode to cover mouse's whole brain. The fabrication process is illustrated in Fig. 1. The detail procedures are as followed: a polyimide thin layer (thickness: 15 μm) was spin-coated on the Al layer with the speed of 3000 rpm and baked 3 min at 95°C on the hotplate for soft baking. And 1st polyimide layer was exposed to UV radiation (150 mJ/cm^2). The UV exposed polyimide layer was post-baked 3 min at 95°C and chemical develop-process was performed by dipping in the develop-solution for 5 min. The metal deposition and patterning for interconnects lines, interconnection pad and recording site were carried out afterward. Titanium (500Å thickness) and Gold (2500Å thickness) were sequentially deposited by using e-beam evaporator. On the deposited metal layer, AZ1512 (Positive tone PR, AZ electronic materials) was spin-coated and patterned by UV radiation and developing process. The gold and Ti etchant (HCl: HNO_3=3:1 for gold layer, H_2O: HF: HNO_3 = 50:1:1 for Ti layer) were sequentially applied for the metal patterning. And then the AZ1512 used for mask of metal pattern was removed by the chemical stripping process (by dipping in Acetone for 3 min). On the metal patterned layer, the 2nd polyimide layer was fabricated for the passivation of metal line and exposure of contacting area to skull. Similar to 1st layer fabrication process, the polyimide was spin-coated and soft-baked. We connected a 40 pin SMT type connector on the interconnection pad of polyimide based electrode after peel-off the polyimide based electrode on the Si-wafer.

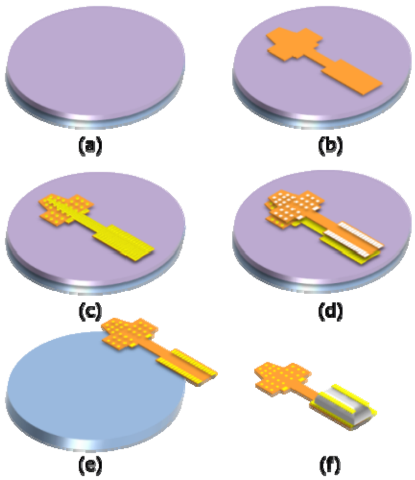


Fig. 1. A schematic overview of polyimide based electrode process. (a) Sacrificial layer (Al). (b) Polyimide for 1st layer spin-coating and patterning. (c) Metallization (Ti/Au). (d) Polyimide for 2nd layer spin-coating and patterning. (e) peel-off the polyimide base electrode. (f) Connector connection.

B. Platinum (Pt) electro-plating

After fabrication process of polyimide electrode, we carried out Pt electro-plating for improving contact- impedance between skull and electrode. Because the surface areas were increased by the porous structure, the Pt electroplating (generally called Pt black) has been broadly used to enhance the contact property with tissue. However, there are critical problems to be addressed and often encountered problems are as follows: (1) Control the thickness is difficult and (2) the adhesive strength to the substrate is weak. So we developed a method to improve adhesive strength of Pt layer and optimized the electroplating condition as follows: (1) by changing the current density (3 currents: 0.4 mA/cm^2, 2.0 mA/cm^2, 5.9 mA/cm^2), (2) by cleaning gold surface with chemical-treatment (H_2SO_4 for 20sec) and (3) by applying ultrasonic wave for removing gas bubbles generated during electroplating process. Electro-plating solution contains H_2PtCl_2 5g (Chloroplatinic acid, Sigma-Aldrich), Pb $(NO_3)_2$ 71.4mg (lead acetate, Sigma-Aldrich) in DI-water 357mL.

TABLE I
ELECTROPLATING CONDITIONS

Method #01	Method #02	Method #03
chemical-treatment	chemical-treatment	ultra-sonic
	ultra-sonic	

The constant current was supplied during 2 minutes at room temperature using Keithley 2400 (Keithley instruments Inc.) [5]-[6]. We observed the electroplated surface using FE-SEM (S-4700, Hitachi High Technologies Co., and Tokyo, Japan).

C. Electrical & Mechanical characterization

The electrodes was electrochemically characterized by impedance spectroscopy. The impedance of polyimide electrodes was measured in Phosphate Buffered Saline (1X PBS) at room temperature using a potentiostat (EIS-300, Garmy) over low frequency range (from 1Hz to 1000Hz). The impedance spectrum were measured with three electrodes (platinum electrode-counter electrode (CE), Ag/AgCl-reference electrode (RE), polyimide based electrode- working electrode (WE)) and the CE was used to supply a sinusoidal ac voltage of 30mV$_{p\text{-}p}$. The relative adhesive strength of platinum layer was tested by the peel-off test using adhesive tape.

D. In-vivo test

F1 mouse were generated by mating heterozygotes from C57BL/6J and 129S4/SvJae. Animal care and handling followed institutional guidelines (the Korea Institute of Science and Technology). We implanted a polyimide multi-channel electrode on the surface of the skull in mice. Ketamine/Xylazine was used to induce anesthesia (120 mg/kg and 6 mg/kg, respectively). The surgery process was as follows: (1) middle scalp was incised about 2 cm from between eyes down to neck muscle, and the periosteum using cotton tips was removed without damaging boundary tissues, (2) a few numbers of 0.6 mm holes are made with dental drill at the coordinates of choice when it is necessary for extra electrodes or chronic fixation of polyimide electrode on the skull as in Fig. 2.

Fig. 2. Placement of polyimide based electrode on the exposed skull of a mouse before measurement EEG signal.

III. RESULT AND DISCUSSION

A. Fabrication of polyimide based electrode

In Fig.3, Polyimide based electrode was successfully fabricated and the fabricated polyimide electrode was connected to 40 pin wire connector. The shape of electrodes was designed to cover whole skull for measuring the mice EEG signal. Also, the thin polyimide substrate was flexible enough to enable the close contact between electrode and skull surface for low contact impedance. The size of interconnection pad was small (width and length: 400 μm and 1000 μm), and it was needed skill and time to connect pad with small wire connector. To address this problem, ACF film was used for electrical connection between interconnection pad and SMT type connector and a house made device which can supply heat and pressure simultaneously was fabricated for the easy and stable connection. The connection process was very simple and total connection time was less than 2 minutes. The size of recording area on electrode was 250 μm×250 μm).

TABLE II
PHYSICAL PROPERTIES OF POLYIMIDE (DURIMIDE 7510)

Properties	Durimide	PI2611	SiO_2
Photo sensitivity type	negative	non	
Tensile Strength as break (MPa)	215	300	138
Young's Modulus (GPa)	8	8	68
Dielectric constant	3.5	2.9	3.9
Volume resistivity	$>10^{14}$	$>10^{16}$	10^{16}

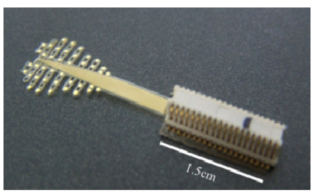
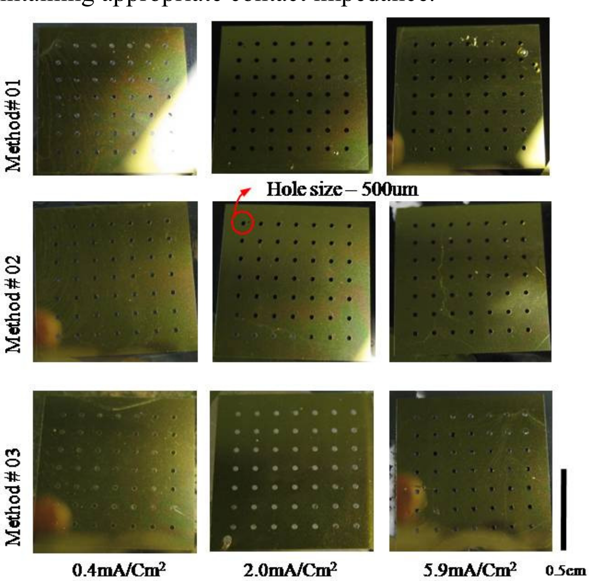


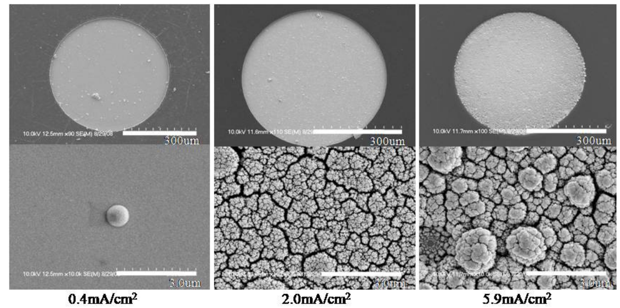
Fig. 3. The multi-channel arrayed polyimide based electrode

B. Platinum (Pt) electro-plating

Platinum is known to improve the stability of reference potentials by decreasing contact impedance. In addition, Pt is comparatively biocompatible material and generally used as a implantable electrode. We found a process to improve adhesive strength of Pt on the seed layer (Au and Ti layer) maintaining appropriate contact impedance.



(a)



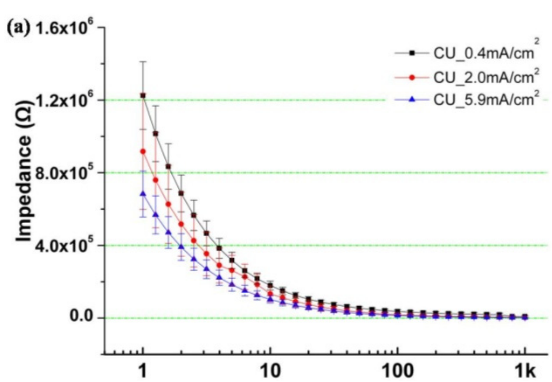
(b)

Fig. 4. (a) electro-plated surface with conditions, respectively. (b) SEM image of method #02 by electro-plating 0.4 mA/cm^2, 2.0 mA/cm^2, 5.9 mA/cm^2.

We employed three electroplating methods with various current densities for optimizing the adhesive strength of the electroplated Pt and the methods are summarized in Table I. 20 sec H_2SO_4 treatment was performed in order to increase the roughness of gold surface area for enhancement of electroplating quality and to serve organic cleaning. On the other hand, ultra-sonic wave process was performed to remove the H_2 gas during the electroplating process [5]. In Fig. 4, the color and structure of electroplated surface were changed to the electroplating conditions (a) and the optical and SEM images after electroplating with three methods under different current densities were shown (b). As the current density increases the impedance decreases, while the adhesive strength was weakened. Among the proposed electroplating conditions, method #02 (H_2SO_4 treatment and ultrasonic application) showed the highest adhesive strength.

C. Electrical & Mechanical characterization

The electrochemical measurements of impedance at the contacting area were carried out, and the result is demonstrated in Fig. 5. Here, we measured the impedance of electrode electroplated with method #02. The impedance of non-electroplated electrode was also measured and compared. It is indicate that electroplated Pt has value 10~70 times lower than bare-gold. As a result, 5.9mA/cm^2 have value the lowest (2 kΩ, at 1 kHz). But 2.0mA/cm^2 has a strong adhesive strength and adequate impedance value for measuring the EEG signal.



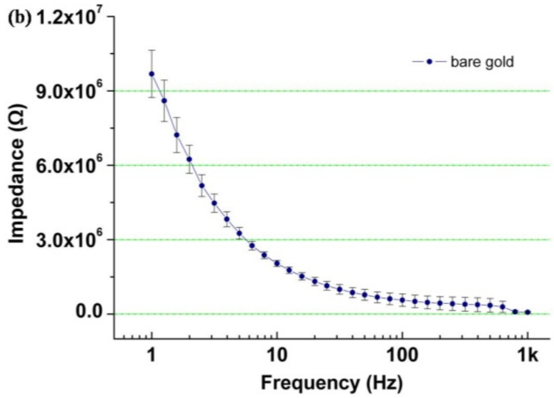


Fig. 5. (a) measured the impedance of electrode electroplated with method #02. (b) measured the impedance of bare gold, non-electroplated on seed layer.

D. *In vivo test*

The EEG signals were filtered at 0.1 to 100Hz and digitized 24 bit resolution continuously at 1 kHz sampling rate. EEG data was analyzed offline. Fig. 6 illustrates the EEG signal measured by the multiple electrodes and signals were successfully measured. And then we check the dosed urethane caused by signal to the generation. After urethane anesthesia, give a stimulus to the tail. After urethane anesthesia the EEG signals was measured and their corresponding spectrums were calculated. By the urethane administration and tail stimulus, the strong peak frequency was appeared at around 5Hz as in Fig. 7. [7]. It is well known that the hippocampal theta rhythm is generated by urethane administration. This result indicates that our film electrode is suitable for the detection of the brain activity, and EEG signals have their own property even though it passes the skull.

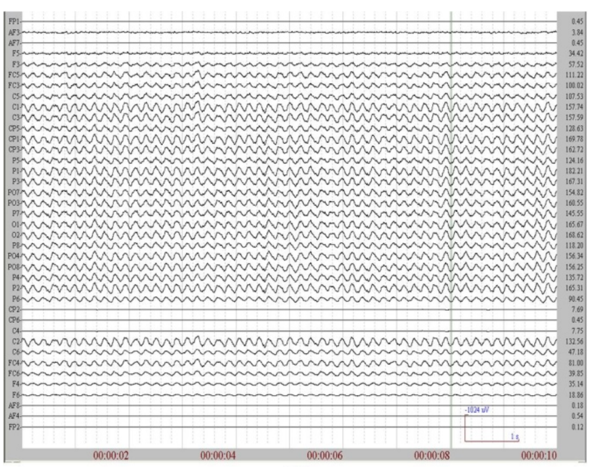


Fig. 6. Base line Electroencephalography (EEG) signals of mouse. 40-channel signals mapped on the mouse's skull was observed.

IV. CONCLUSION

We made Polyimide based electrode (40-channels) mountable on the mouse's skull, which was enough flexible to contact tightly on the skull. By electroplating Pt on the gold surface, the impedance of electrode was enhanced about 70 times. By optimizing the current density, cleaning surface and removing H_2 gas bubbles generated during electroplating, the enhanced performance both impedance and adhesiveness can be achieved. With the in-vivo experiment, we observed suitability of electrode used on the skull and stable EEG signals were measured.

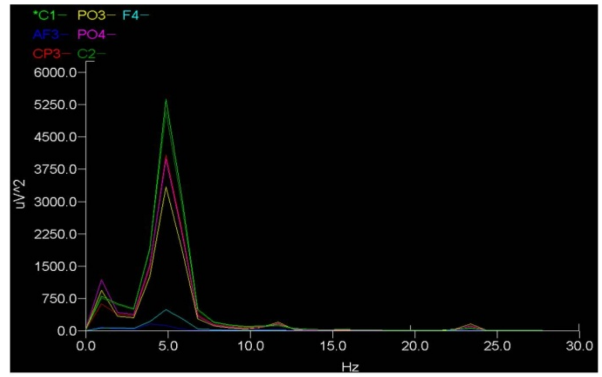


Fig. 7. After the urethane injection, EEG signal changed from around 5Hz by tail stimulus.

APPENDIX

Electroencephalography (EEG), Polyimide, Multi-channel electrode, Pt electro-plating.

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