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A novel implantable multichannel silicon-based microelectrode*

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Silicon-based microelectrodes have been confirmed to be helpful in neural prostheses. The fabricated 7-channel silicon-based microelectrode was feasible to be implanted into the brain cortex. The manufacturing process by micro-electromechanical system (MEMS) technology was detailed with four photolithographic masks. The microscopic photographs and SEM images indicated that the probe shank was 3 mm long, 100 μm wide and 20 μm thick with the recording sites spaced 120 μm apart for good signal isolation. To facilitate the insertion and minimize the trauma, the microelectrode is narrowed down gradually near the tip with the tip taper angle of 6 degrees. Curve of the single recording site impedance versus frequency was shown by test in vitro and the impedance declined from 150.5 kΩ to 6.0 kΩ with frequency changing from 10 k to 10 MHz.

Keywords: MEMS, extracellular recording, microelectrode
PACC: 7360F, 6480G

1. Introduction

Neural prostheses[1,2] are popular with many scholars from biomedical fields. Passive microelectrode arrays have already been chronically or acutely implanted into animal brains such as rats and macaque monkeys to realize function electrical stimulation (FES)[3,4] and the recording of neural signals. Owing to the absence of on-chip active components such as preamplifiers and A/D converters, the recorded neural signals by the passive microelectrode arrays must be transmitted through wires to the back-end signal processing modules mounted on printed circuit board (PCB). This will increase volume and weight of the whole system. In view of the rigid requirements of small volume and light weight of the implanted devices for FES or neural recordings, active microelectrode arrays with on-chip integrated signal processing circuit structures are preferred, which is based on the accomplishment of silicon-based microelectrode. Although the Utah[5] and Michigan[6] silicon-based microelectrodes have been used in some circumstances, the fabrication cost is increased due to the relatively complex semiconductor manufacturing process. As far as most acute cortical recordings are concerned, a novel implantable multichannel silicon-based microelectrode was described by simpler surface micromachining technology.

The 5-channel microelectrode arrays were fabricated in our former work.[7] As these microprobes were not long enough with a limited number of channels, the novel implantable 7-channel silicon-based microelectrodes were achieved with the length of 3 mm and the recording sites located in the centre of probe shank. Thereby, the novel silicon-based microelectrode can be implanted into the brain cortex. The fabrication details by micro-electromechanical system (MEMS)[8] technology and impedance characteristics tested in vitro were presented herein.

2. Fabrication methodology

In comparison with the manufacturing process in our former work, one additional photolithographic mask is used to fill the circular recording sites with titanium/gold metal so as to closely contact the neurons and enhance the signal-to-noise ratio (SNR). The particular fabrication process flow of the novel silicon-

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based microelectrode is explained as follows. a) Lower silicon dioxide (SiO_2) of 20 μm is deposited on the (100) silicon substrate by chemical vapour deposition. b) Lower titanium/gold (Ti/Au) of 1000 Å/3000 Å is sputtered on the lower silicon dioxide successively and patterned as conductor traces by diluted buffered oxide etching (BOE) and gold corrosive, respectively. Then the probe is annealed at 380 °C for 40 min. c) Upper 3000 Å SiO_2 is deposited by plasma enhanced chemical vapour deposition[9] to insulate the metal layer from the tissue solution. d) The upper SiO_2 layer is etched by BOE to open Φ6 μm contact holes near the tip and bond pads at the rear. e) Upper Ti/Au of 1000 Å/3000 Å is sputtered and patterned with those over the contact holes and bond pads remained and then the Φ10 μm recording sites are formed. f) With the probe shank protected by thick photoresist, inductively-coupled plasma (ICP) dry etching process is used to etch the upper SiO_2 layer until the lower SiO_2–silicon interface, and the lateral dimension of the probe is determined simultaneously. g) The bulk silicon is thinned to about 200 μm by mechanical methods. h) The probe is released by 25% tetra methyl ammonium hydroxide (TMAH) anisotropic solution without attacking silicon dioxide or gold,[10] and this process step takes about three hours at constant temperature of 80 °C. After this process, the microelectrode with about 20 μm-thick probe shank can be obtained with thin film of rough silicon below the SiO_2.

The microscopic photograph of the top view and SEM images of the microelectrode probe after ICP process technology are shown in Fig.1 and Fig.2 respectively. Seven bond pads corresponding to seven different recording sites are clearly shown in Fig.1 with the lateral dimensions marked. The probe shank is 3 mm long and 100 μm wide, and the seven recording sites are located in the centre of the shank within the range of 1 mm far from the tip. Since the shank is narrowed down like a sharp-edged sword near the tip, it is qualified to penetrate into the brain cortex with the tip angle of 6 degrees.

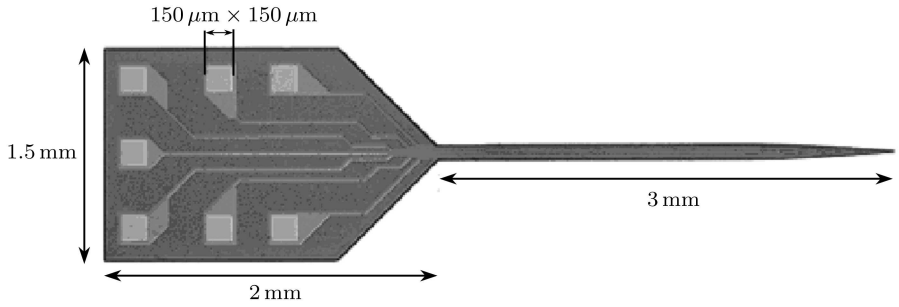


Fig.1. Microscopic photograph of the microelectrode top view.

The SEM images clarify the profiles of the tip and recording sites of the microelectrode probe. Figure 2(a) shows the 5 μm-wide connection traces and circular recording sites of Φ10 μm. In this novel microelectrode, the recording sites are 4 μm larger than the contact holes in diameter, which ensures the close contact between recording sites and outside neurons. Consequently, the SNR can be intensified greatly. Figure 2(b) shows the cross-section of the microelectrode tip composed of 20 μm lower silicon dioxide.

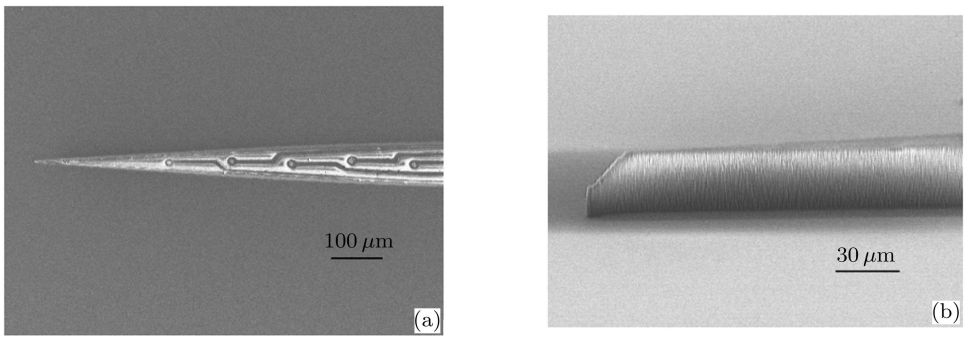


Fig.2. SEM images of the microelectrode probe following the ICP dry etching: (a) top view of the probe tip with recording sites, (b) cross-sectional illustration of the tip.

After the TMAH anisotropic etching, the ultimate microelectrode probes were obtained with the thickness of about 20 μm, which implies that thin-film rough silicon is added to configure the probe with the 20 μm silicon dioxide.

In order to realize the insertion into brain cortex, the microelectrode must be strong and flexible. Although the silicon dioxide primarily forms the probe microstructure, the addition of silicon can effectively strengthen the microprobe flexibility, the probes are strong and flexible enough to acutely record brain neural signals due to the opening up of skull and dura before insertion. From the viewpoint of biocompatibility, the implanted probe must have stable chemical and physical properties in the surroundings of biological tissues, and at the same time, the neuronal activities can not be restricted owing to the microprobes. Silicon, silicon dioxide and silicon nitride have favourable biocompatibility[11] and the golden recording sites have sufficient chemical and physical stability, as a result, the microprobes are biocompatible with brain tissues. In addition, the microprobes have narrow and thin shanks with sharp tips, so the implanted devices are volume-free and do almost no mechanical trauma to brain cortex. Then the developed microelectrode probes are suitable for brain neural signal recordings.

To realize the practicability, the microelectrode probe firmly adheres to PCB by conductive cream, and 25 μm-diameter golden wires connect the bond pads with traces on the PCB. It will be vertically implanted into the brain cortex to record neural signals through the recording sites.

3. Impedance test and discussion

Action potentials produced by excited neurons have constant amplitude with frequency which changes with stimulation strength. With the penetration of the probe shank into the brain cortex, the exposed recording sites interface with the tissue, and metal–electrolyte interfaces form at every recording sites. Figure 3 shows the equivalent circuit of the metal-electrolyte interface.[12,13] The voltage source V_i denotes the extracellular neural signal with the amplitude ranging from tens to hundreds of microvolts and frequency ranging from 0.1 Hz to 10 kHz. The open-circuit DC potential E represents the polarization voltage of hundreds of mV. R_{sp} models the signal loss due to the distance between the recording sites and the neurons. C_e models the capacitance at the double-layer interface. R_e can account for the charge carriers realistically crossing the double layer. R_p represents the probe Ti/Au trace resistance.

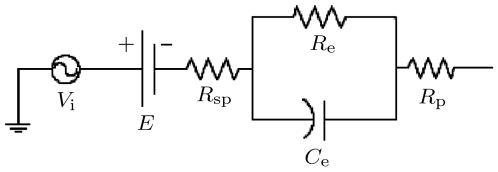


Fig.3. Equivalent circuit of metal–electrolyte interface.

The electrical characteristics and integrity of the microelectrode probes are evaluated by measuring the impedance of each of the seven Ti/Au traces from recording site to connection pad in the phosphate buffered saline (PBS) solution. On one hand, with large recording site area, larger capacitance C_e is obtained which results in lower impedance with reduced thermal noise level and enhanced SNR (sensitivity). On the other hand, the recording site is intended for isolating action potentials of one neuron from some distant ones (selectivity) and spike timing,[14] which needs small site area. Consequently, a tradeoff must be made between selectivity and sensitivity to decide on proper recording site area.

Recording sites are considered as $\Phi 10\,\mu$m which are comparable to the diameter of one neuron. In the experiment in vitro, the PCB mentioned above is moved to immerse the recording sites in PBS solution. Through the pins of PCB, the impedance of any recording site can be determined by Hewlett Packard 4275 A, and Fig.4 plotted the curve of impedance versus frequency.

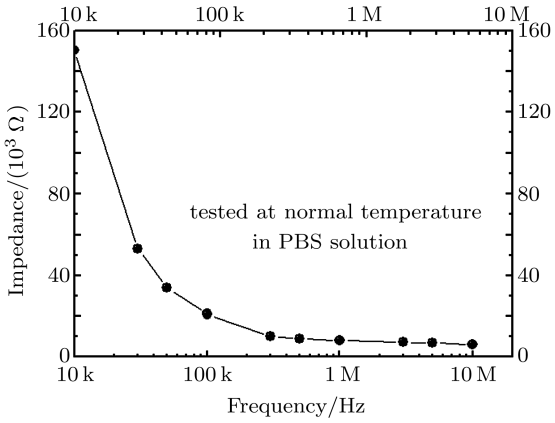


Fig.4. Curve of impedance versus frequency with recording sites of $\Phi 10\mu$m in vitro.

The measured probe impedance is determined by the characteristics of the metal–electrolyte interface. Test results show that the impedance declines from 150.5 kΩ to 6.0 kΩ with frequency changing from 10 kHz to 10 MHz owing to the existence of capacitance C_e in Fig.3. The tested impedance also denotes good electrical characteristics and integrity of the multi-channel microelectrode probes.

In view of the MOS input structures of popular preamplifiers, the low-frequency input impedance is of the order GΩ. Therefore, the microelectrode probe with equivalent impedance of the order kΩ adapts to record extracellular brain neural recordings.

4. Conclusions

Fabrication of the microelectrode probe by the novel methodology simplified the process flow with only four photolithographic masks and increased the uniformity of the seven channels with recording sites centred at the probe shank. In comparison with our former work, the anneal process was adopted to enhance the adhesion of the lower Ti/Au to the lower SiO_2, and contact holes are filled with metal to increase the SNR of the recorded neural signals.

Although the novel microelectrode probe is long and strong enough to penetrate the brain cortex, only acute or short-term recordings can be carried out. There is still much work needed to accomplish the chronic or long-term neural recordings.

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