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Fabrication of a Silicon-Based Microprobe for Neural Interface Applications*

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Abstract: A two-dimensional (2D) multi-channel silicon-based microelectrode array is developed for recording neural signals. Three photolithographic masks are utilized in the fabrication process. SEM images show that the microprobe is 1.2mm long, 100μm wide, and 30μm thick, with recording sites spaced 200μm apart for good signal isolation. For the individual recording sites, the characteristics of impedance versus frequency are shown by in vitro testing. The impedance declines from 14MΩ to 1.9kΩ as the frequency changes from 0 to 10MHz. A compatible PCB (print circuit board) aids in the less troublesome implantation and stabilization of the microprobe.

Key words: microelectrode array; neural interface; MEMS
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1 Introduction

There is increasing interest in the use of microelectrodes to record extracellular biopotentials generated electrochemically within individual neurons, which is crucial to the study of the central nervous system at the neuronal level[1~3]. One kind of traditional microelectrode prevalent in the early stages of system neuroscience is a small-diameter insulated microwire[4] made of stainless steel, tungsten, or platinum. To accomplish the functional operation of a neural network, a microelectrode array with tens of uniform electrodes must be adopted. However, due to the difficulty of achieving so many uniform microwires and the feasibility of MEMS (micro-electromechanical system) technology, silicon-based microelectrodes are increasingly popular with neuroscientists. One of the desired features of this technology is that it offers the potential of integrating signal processing circuitry on the microelectrode to enhance the signal integrity and SNR (signal-to-noise ratio). Another important advantage is its high yield, volume production, and batch fabrication process with reliable interconnects. Furthermore, silicon dioxide and silicon nitride are biocompatible with biological tissue. Hence the silicon-based microelectrode array offers several advantages over microwires due to the availability of sophisticated processing techniques and biocompatibility.

Scientific researchers from the Brown University[5], the University of Michigan[6], the University of Utah[7], and other research groups have achieved 2D and 3D silicon-based microprobes with a few to one hundred channels, some of which were hybrid-integrated with active devices such as low-noise preamplifiers, multiplexers, and A/D converters.

To realize acute or short-term cortical recordings, we present a 2D micromachined silicon microprobe. Double-layer metal Ti/Au (titanium/gold) was used as interconnect wires. ICP (inductively-coupled plasma) technology defined the probe shape, and the 30μm thick probe was obtained by EPW (ethylenediamine pyrocatechol water), which does not attack silicon dioxide or the metals used.

2 Manufacturing technology

A sketch of a single probe shank is shown in

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Fig.1 with the dimensions marked.

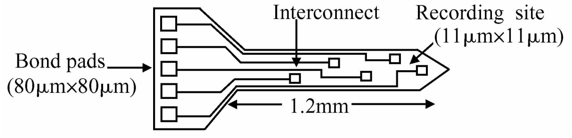

Fig.1 Illustration of a single probe shank (not to scale)

The fabrication process of the micromachined probe is as follows. (1) A 20μm lower layer of SiO_2 is deposited on the (100) silicon wafer by CVD (chemical vapor deposition). (2) 100nm/400nm of Ti/Au is sputtered on the lower silicon dioxide and patterned as conductor traces by diluted BOE (buffered oxide etchant) and gold corrosive. (3) A 300nm upper layer of SiO_2 is deposited by PECVD (plasma-enhanced chemical vapor deposition) to insulate the metal layer from the tissue solution. (4) The upper silicon-dioxide is etched by BOE to open contact holes (recording sites) near the tip and bond pads at the rear. (5) With the probe shank protected by photoresist, ICP is used to etch the upper SiO_2 layer to the lower SiO_2-silicon interface, and the lateral dimension of the probe is determined. (6) The bulk silicon is thinned to 125μm by physical methods. (7) The probe is released by EPW, taking one and a half hours at a constant temperature of 80℃.

SEM pictures after the ICP process are shown in Fig.2. It is clear that this probe is composed of a 20μm upper silicon dioxide and the recording sites are completely exposed.

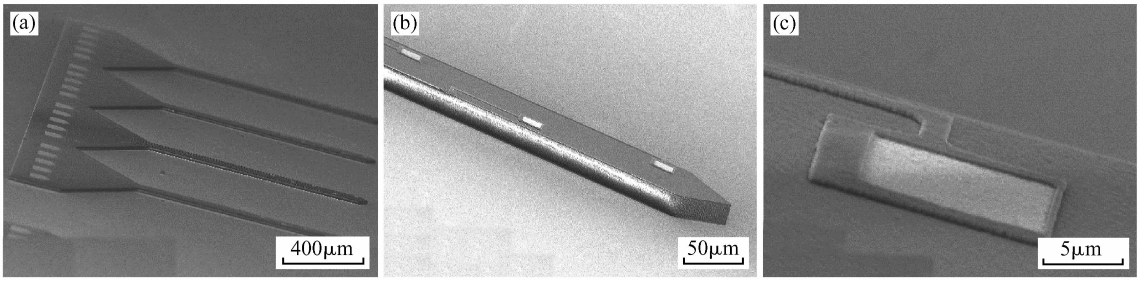

Fig.2 SEM images of the micromachined probe (a) Microelectrode array comprising four probe shanks; (b) A single probe shank; (c) Recording site (contact hole)

The final microelectrode probe after EPW erosion is shown in Fig.3. The sharp probe tip and bond pads are clearly displayed. The probe is composed of 20μm of SiO_2 and 10μm of Si added to enhance the flexibility. Because of the side etching effect, a small part of the silicon below the upper SiO_2 is completely etched near the tip, which does not affect the strength of the probe shank.

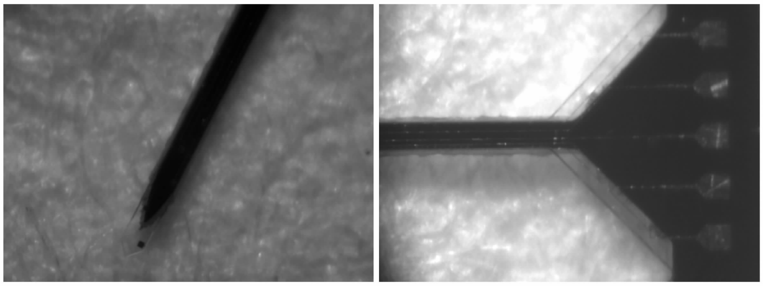

Fig.3 Tip and rear micrographs of the microelectrode probe

To realize the recording of extracellular biopotentials in vivo, the micromachined probe must be thin enough and almost volume-free to be implanted into the brain cortex. Following the procedures discussed above, the probe has a thickness of 30μm and is thin enough to be implanted for neural signal recording.

3 Test results and discussion

After the manufacturing process by MEMS technology, the probe firmly adheres to the PCB (print circuit board) by conductive cream, and 25μm diameter gold 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.

A single excited neuron produces action potentials with constant amplitude and various frequency, and many such neurons embody low-pass characteristics. When the silicon-based probe is implanted into the brain cortex, the exposed recording sites interface with the tissue, and at every recording site of the probe, a metal-electrolyte interface is formed. Figure 4 shows the equivalent circuit of the metal-electrolyte interface[8~10]. Owing to the oxidation-reduction effect between metal and electrolyte, a double-charge layer exists at the metal-electrolyte interface. The signal source V_i denotes the extracellular neural signal with an amplitude of 50～500μV and frequency of 0.1Hz～10kHz. The open-circuit dc potential E represents the polarization voltage at the metal-electrolyte interface. The resistance R_{sp} (spreading resistance in saline) of about 100kΩ models the signal loss due to the distance between the recording sites and the neurons. The capacitance C_e of about 12pF models the capacitance at the interface. The leakage resistance R_e of about 6×10^{12} Ω accounts for the charge carriers realistically crossing the double layer. R_p represents the probe Ti/Au trace resistance of 2～5kΩ.

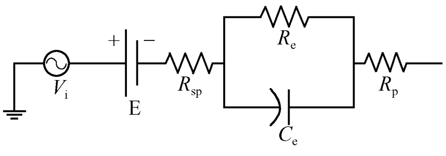

Fig. 4　Equivalent circuit of metal-electrolyte interface

The impedance as a function of frequency of the recording sites was tested. Herein in the experiment in vitro, the PCB is moved to immerse the tip of the probe in the buffered phosphate solution. Through the pins of the PCB, the impedance of any recording site can be determined by a Hewlett Packard 4275A. Figure 5 shows the curve of impedance versus frequency. It is obvious that the recorded neural signal actually passes through a low-pass filter to arrive at the recording site, which is consistent with the theoretical analysis.

The tested probe impedance is determined by all the passive devices in Fig. 4. Owing to the weak neural signals, a preamplifier must be used to amplify these signals. In view of the MOS input structures of popular preamplifiers, the low-frequency input impedance is of the order of GΩ. Therefore, an equivalent impedance of less than a few tens of MΩ can be used for extracellular recordings. In this case, the test results show that the equivalent impedance is less than 14MΩ, so it definitely can be used to record neural signals.

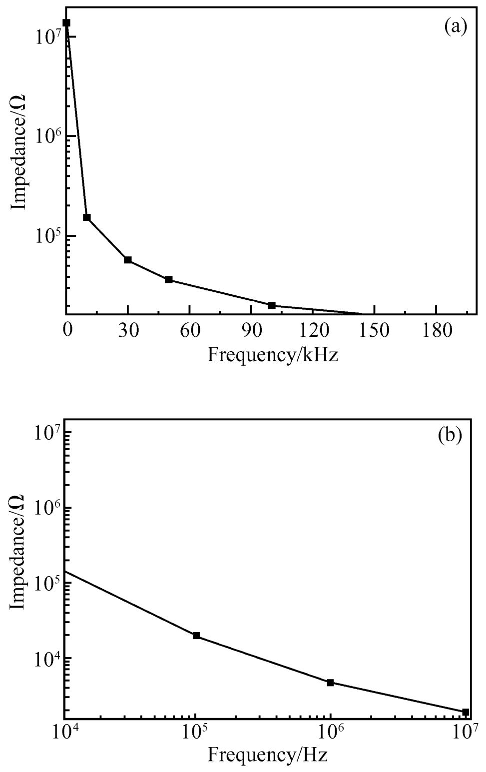

Fig. 5　Plots of impedance versus frequency　(a) Linear frequency characteristic; (b) Logarithmic frequency characteristic

4　Conclusion

At present, the probe is being implanted into a rat cortex, and the test results will be public soon. Some features of this micromachined probe can be improved as follows. The probe shank must be further lengthened to 3mm and thinned to 20μm or so in order to effectively record neural signals in a brain cortex. Despite the 10μm of silicon incorporated, the probe was mainly composed of silicon dioxide; therefore, it was not as strong as a silicon probe when implanted into the brain cortex. Therefore, a different process will be adopted to realize a silicon-dominated probe for implantation.

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适用于神经接口的硅基微电极制作*

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摘要： 采用表面 MEMS 工艺制作了二维多通道的硅基微电极阵列，用于提取脑神经电信号．在整个工艺制作过程中需要三步光刻，制作的硅针长 1.2mm，宽 100μm，厚 30μm，同时各个记录点的间距为 200μm，可以形成良好的信号隔离．对微电极的阻抗特性进行了体外测试，结果表明，随着频率由 0 变为 10MHz，单个记录点阻抗由 14MΩ 下降到 1.9kΩ．将微电极黏附到印刷线路板，通过金丝压焊提取各个通道信号，大大提高了植入的可操作性以及信号提取的可靠性．

关键词： 微电极阵列；神经接口；MEMS 工艺

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