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IMPROVED FLEXIBLE MICROWIRE ARRAY ELECTRODE FOR INTRACORTICAL SIGNALS RECORDING

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ABSTRACT

Implanted electrodes are the first piece of hardware in an intracortical signals recording pathway. This work presents an improved flexible microwire array electrode for intracortical recordings. Only ready-made materials and general mechanical tools are used to fabricate a microelectrode. The proposed procedure is relatively simple, even for a novice worker to implement in-house. Many key steps in producing a good microwire array electrode are facilitated. These main steps include selecting materials, preparing for fabrication, and assembling the electrode. The assembly of the microwire array electrode includes connecting and positioning PCB pattern, arraying and fixing microwires, and soldering and packaging the electrode. A practiced researcher can assemble the microelectrode in about 2 h and implant it in approximately three. The mass of this assembled microelectrode is 1.96 g. The cost of the materials in the entire array is less than US$1.5, and the array is suitable for implantation in the cortex of rats for invasive studies. In this study, electrochemical impedance spectroscopy is also applied to measure the impedance and the phase between the electrode and the electrolyte, and then to obtain an equivalent circuit. The improved microwire array electrode is adopted to record the intracortical signal of cerebrum. The microwire array electrode can be fabricated and used for multi-site, multiple single-unit recording experiments. Several experimental results are presented, along with applications that demonstrate the feasibility and advantages of the proposed approach.

Keywords: Microwire array electrode; Printed circuit board; Intracortical; Electrochemical impedance spectroscopy; Artificial cerebral spinal fluid.

INTRODUCTION

Many metal microelectrodes have been used to record and stimulate neural tissue activity for more than 40 years. Numerous neural probes have been developed, including bundles of microwires,[1–3] microwires embedded in neurotrophic assemblies,[4] polymer substrate probes, and several silicon-substrate probes. Various microwire array electrodes have been utilized in multi-site, multiple single-unit recording experiments.[5,6] For example, Chapin *et al.*,[7] constructed 24 microwires to use in rats and Wessberg *et al.*,[8] designed 96 microwires to apply in monkeys, which can be feasibly used to record neural signal in conscious animals. Many multi-electrode arrays can be bought from commercial vendors to suit various experimental designs. They involve various cost, time,

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materials, tools, and technique of microelectrode manufacture, offering flexibility of the experimental design. Developing in-house fabrication methods remains very worthwhile especially for those research teams that are limited by funds.

This work describes an improved flexible microwire array electrode for intracortical recording. The main steps of the method comprise selecting materials, preparing for fabrication, and assembling the electrode. The assembly of the microwire array electrode includes connecting and positioning the printed circuit board (PCB), arraying and fixing microwires, and soldering and packaging the electrode. A six-channel microwire array electrode for multi-site and another 16-channel microwire array electrode for multiple single-units are described to elucidate the fabrication procedure. Electrochemical impedance spectroscopy (EIS) is used to measure the impedance and the phase between the electrode and the electrolyte, and then to obtain an equivalent circuit. Finally, the proposed microelectrode is applied successfully to record intracortical signals at the right S1HL of the primary somatosensory cortex (SI) upon mechanical stimulation using a brush.

MATERIALS AND METHODS

In the presented approach, the microwire array electrode is composed of teflon-insulated tungsten microwires, a PCB pattern, a flexible flat cable (FFC) and connector and viscose of epoxy A+B that is proposed herein. Fabricating a microelectrode requires under US$1.5 in materials. The assembly of the microwire array electrode includes connecting and positioning PCB pattern, arraying and fixing microwires, and soldering and packaging the electrode. Implementing a microelectrode requires about 2 h. A six-channel microwire array electrode for a multi-site and another 16-channel microwire array electrode for multiple single-units are described to illustrate the fabrication procedure.

Materials

Microwire

General microwires are bundles of 8–32 wires (25–50 μm diameter), normally of stainless steel, tungsten, or platinum, and insulated with Teflon, polyimide, or S-isonels.[2] In this study, the microwire array electrode consists of 50 μm-diam teflon-insulated tungsten wires (A-M Systems, Carlsberg, WA, #795500). Tungsten wire offers the highest strength and stiffness of all A-M system wires. Teflon-insulated tungsten wires are typically 25 feet (7.5 m) long per spool. They are cut every 20 mm into microwire probes. Every spool costs $60. Therefore, the average cost of each section is $0.157. This material is chosen because it is cheap, hard and, above all, easily processed by an individual.

Printed circuit board

The PCB is double-sided, 1ounce of copper and FR-4 epoxy glass with a thickness 0.064″. The market cost of an area of 100 cm^2 of glass-epoxy double-sided photoresist board. Therefore, a PCB with an area of around 1 cm^2 costs under US$0.012. Such a PCB after design and sculpturing is regarded as the base of the microelectrode and is called the PCB pattern. The PCB is used because it is light and thin, universal, inexpensive and easy to obtain. In particular, the PCB pattern has a flat surface and a convenient workbench can be used to fabricate the microwire array electrode. The user can conveniently and rapidly revise it to various experiments.

Flexible flat cable

In this work, the FFC is B-type (with conductor exposed on one side), with a 1.0 mm pitch, a total length of 100 mm, and conductor pins. A connector, mounted to one or both ends of the FFC, is generally employed with a set of electrical receptacles or sockets that are designed to receive terminal posts or contact pads on the PCB. The FFC connector has a 1.0 mm pitch and 10 conductor pins. The price of one set is US$ 0.358; each set includes both FFC and connector. The advantages of selecting this FFC and connector include precision, recyclability, flexibility and various styles, among others. In particular, plugging in and pulling out can be repeated easily. These advantages reduce injury to the rat during the experiment.

Preparations

Before an electrode fabrication can work, the circuit layout and the sculpturing of the PCB must be completed, and the microwires straightened. The procedures of preparation and techniques of operation are introduced separately below.

PCB design and sculpturing

In the experiment, a two-sided PCB is used. The PCB for each microelectrode is 11.0 mm long, 9.0 mm wide, and approximately 1.6 mm thick. A specially designed PCB is developed to bond the microwire array to

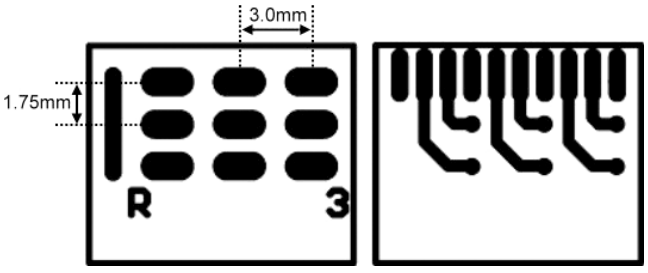

Fig. 1 Top and bottom layers of PCB with completed layout. Left-hand picture displays the top layer that forms the front of PCB pattern. The right-hand picture presents the bottom layer, which constitutes the back of the PCB pattern.

the electrode. The PCB after finishing the procedure of design and sculpture becomes PCB pattern. The front of the PCB pattern contains nine elliptical pieces of copper, which have an area of $2.2 \times 1.2\,\text{mm}^2$ and one rectangular piece of copper, which has an area of $0.7 \times 4.7\,\text{mm}^2$. The vertical separation between the ellipses is 1.75 mm and the horizontal separation is 3.0 mm, as displayed in the picture on the left in Fig. 1. The tops of the individual microwires are cleaned and soldered onto an elliptic piece of copper. The back of the PCB pattern contains 10 finger connectors, which match correspond to a high-density 10-pin single row FFC connector matrix, presented in the right-hand image in Fig. 1, for use in chronic experiments. The inter-finger connector separation is 1.0 mm for a total width of about 9.0 mm. The routing connections are from the penetrating pads to the finger connectors. The PCB can be made by a board manufacturer or by the experimenter, and its dimensions depend on the practical experiment. After the circuit layout has been completed, the PCB pattern is sculptured, as presented in Fig. 2. The PCB pattern provides a flat surface to supply as the fabrication plate, facilitating the fabrication of the microwire array electrode, especially while arranging microwires into a desirable configuration and soldering microwires to the corresponding copper. In order to increase the precision and convenience while arranging the spacing of the electrode tips and separation of the inter-electrode, the microwire slots can be processed on the under blank of PCB pattern by PCB sculpture machine, laser cutting machine, or board manufacturer.

Straightening the microwires

Microwires cut from the spool are curved using nickel-plated steel wire scissors ($5\frac{1}{2}$ inches); thus, they are unsuited to the fabricating electrode arrays. The curved microwires are straightened by a pair of nickel-plated hemostats ($5\frac{1}{2}$ inches, Kelly hemostat, straight). Spooled microwires were cut into 10 cm segments. A hemostat is clipped to each end of the curved microwires; the upper end is fixed while the lower end is gently allowed to spin until the microwires are straightened. The straightened microwires are cut into 2.0 cm segments, and around 2 mm of insulation is removed from one end by briefly holding it over a small flame.

Fabrication of Electrodes

The PCB pattern of eight-channel microelectrodes is used to implement the fabricative process. A six-channel microwire array electrode is fabricated to cooperate with the bio-signal capture and recording system

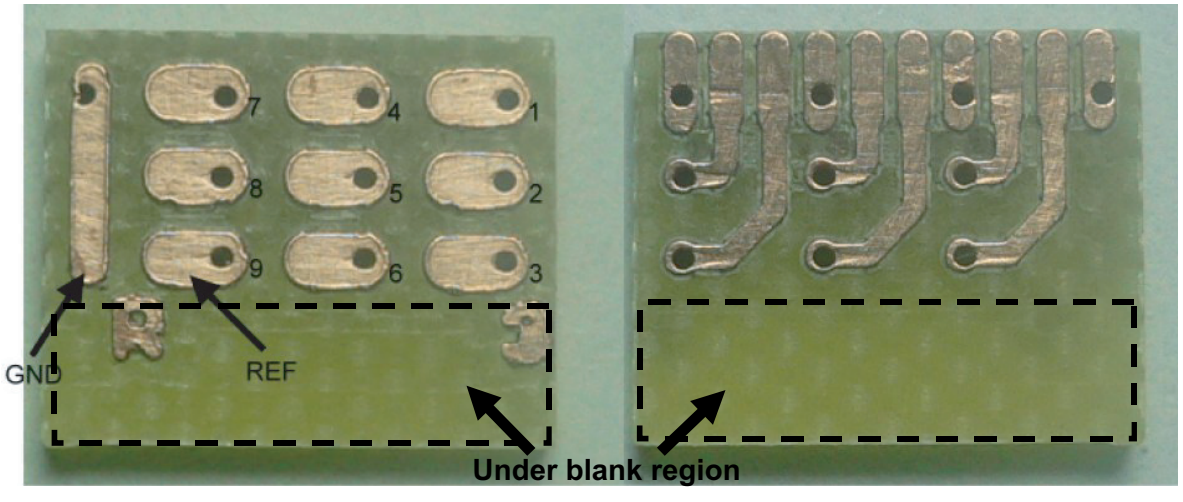

Fig. 2 PCB pattern of eight-channel microelectrodes. The serial numbers of nine elliptical pieces of copper run from the top-right to the bottom-left. The left-hand image is the front of the PCB pattern. The right-hand image is the back of the PCB pattern.

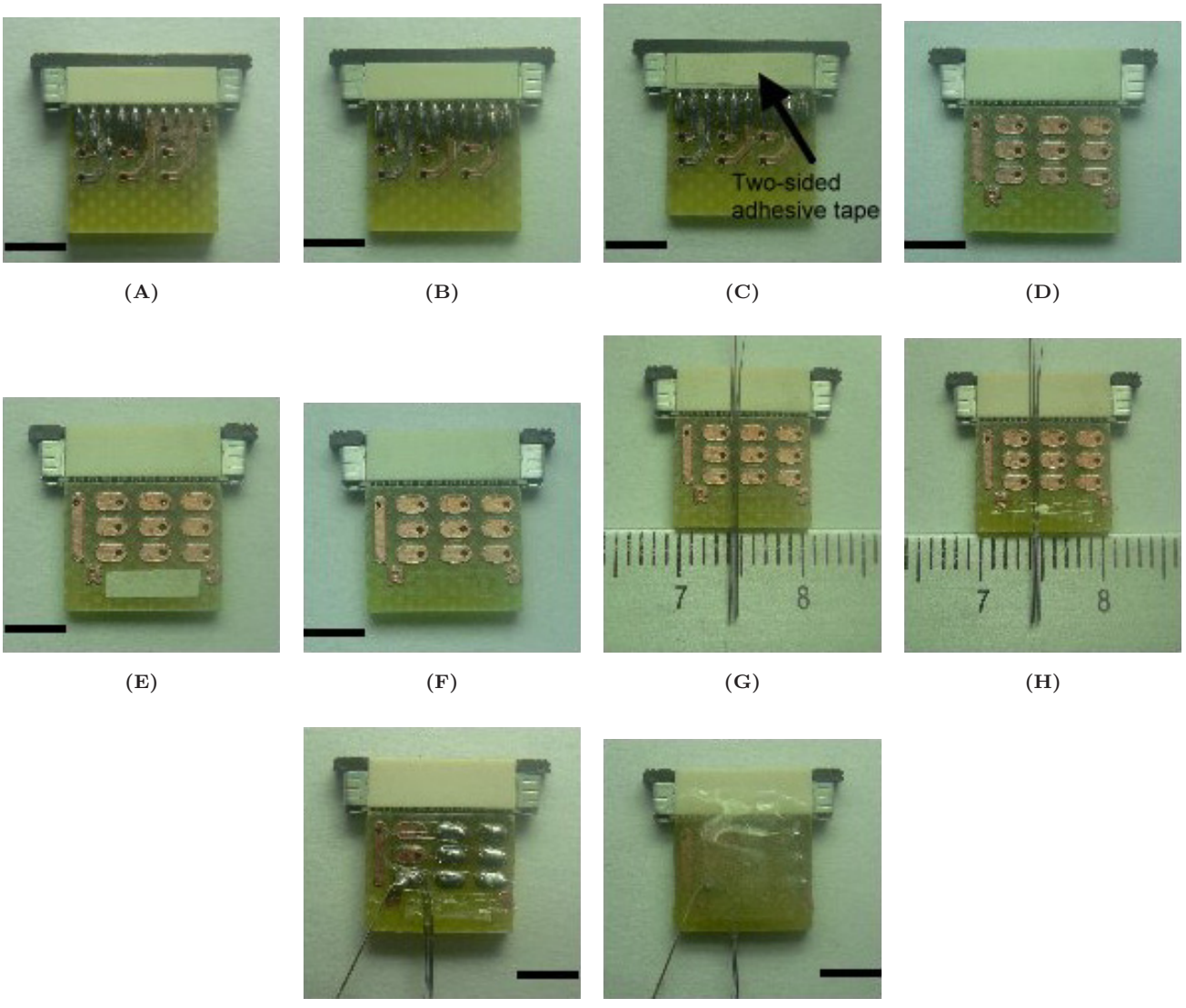

Fig. 3 Fabrication of six-channel microwire array electrode for multi-site recording. Calibration bars of **(A–F)**, **(I)**, and **(J)**: 5 mm.

and is applied to measure the cortical signal. The microelectrode fabrication steps include connecting the FFC connector, positioning the PCB, arraying, fixing, and soldering the microwires, and packaging the microelectrode. Figures 3(A)–3(J) show the procedures. The fabrication steps are described below.

Connecting and positioning

The first operation is the linking of the FFC connector to the PCB pattern. A soldering iron is used to weld each pin of the connector to a pin on the bottom layer of the PCB, as shown in Figs. 3(A)–3(B). Then, the two-sided adhesive tape is cut into lengths of 5 mm and widths of 2 mm. The tape is stuck on the back of the connector, which has already been welded onto the PCB. The two-sided adhesive tape is used to fix the PCB to the work bench, as shown in Figs. 3(C)–3(D). After it has been positioned, the PCB is not moved during the subsequent steps. This entire process takes approximately 10 min.

Arraying and fixing

The two-sided adhesive tape is again cut to lengths of 3 mm and widths of 1 mm. It is stuck onto the layer below the top layer of the PCB pattern: this blank space has no copper, as shown in Figs. 3(E)–3(F). The tape is then used to fasten lightly the microwires to the PCB pattern. Six cut microwires are placed on the adhesive tape sequentially. A dissection microscope is applied to help adjust the relative positions of the

two tips. As shown in Fig. 3(G), the microwires have been arrayed on PCB. When all of the microwires are properly positioned, a small drop of epoxy glue is spread on a site close to the bottom edge of the PCB pattern to secure them. Figure 3(H) depicts the situation after these microwires have been fixed on PCB. Microwire arraying takes about 10 min, but fixing the microwires solidly takes 30 min.

Soldering and packaging

After all of the microwires have been fixed reliably, the microwires are soldered to the elliptical pieces of copper. When the epoxy glue has solidified, the longer ends of the microwires are ordered connected to the corresponding pieces of copper. About 2 mm of insulation is removed from one end of each of the straightened microwires by briefly holding it in a small flame. A soldering iron is used to weld each microwire to the corresponding copper. The statement associated with Fig. 2 regarding the serial numbers of elliptical pieces of copper on the PCB pattern also applies here. Consider the six-channel microelectrode as an example: the first six copper dots on the top layer of the PCB pattern are used soldered to the six microwires. A stainless-steel wire is soldered to the ninth copper dot, as shown in Fig. 3(I). This wire is the reference end of the signal capture circuit. The tenth copper dot of the PCB top layer is connected to the ground end of the signal capture circuit and the body of the animal. The seventh dot on the PCB top layer can be used to measure the EMG signal, and the eighth dot can be used to measure the ambient environmental signal. When all microwires and other signal wires have been successfully soldered to the top layer of the PCB pattern, the surface of the PCB pattern is packaged using epoxy, as shown as Fig. 3(J). The soldering of the microwires probably takes half an hour, and another half an hour is required for the packaging of the microelectrode to solidify.

If an eight-channel microelectrode is to be fabricated, then the microwires are welded to the dots of the PCB pattern from the first to the eighth. The reference end of the neural signal capture circuit is connected to the ninth dots of the PCB pattern. The body of the animal is connected to the tenth dots of the PCB pattern. If a microwire array electrode is required for use in a multiple single-unit recording experiment, then given a slight modification of the PCB layout, the procedures are similar to those associated with the multi-site microelectrode. In Fig. 4, the 16-channel electrode is a sample that is finished for use in a multiple

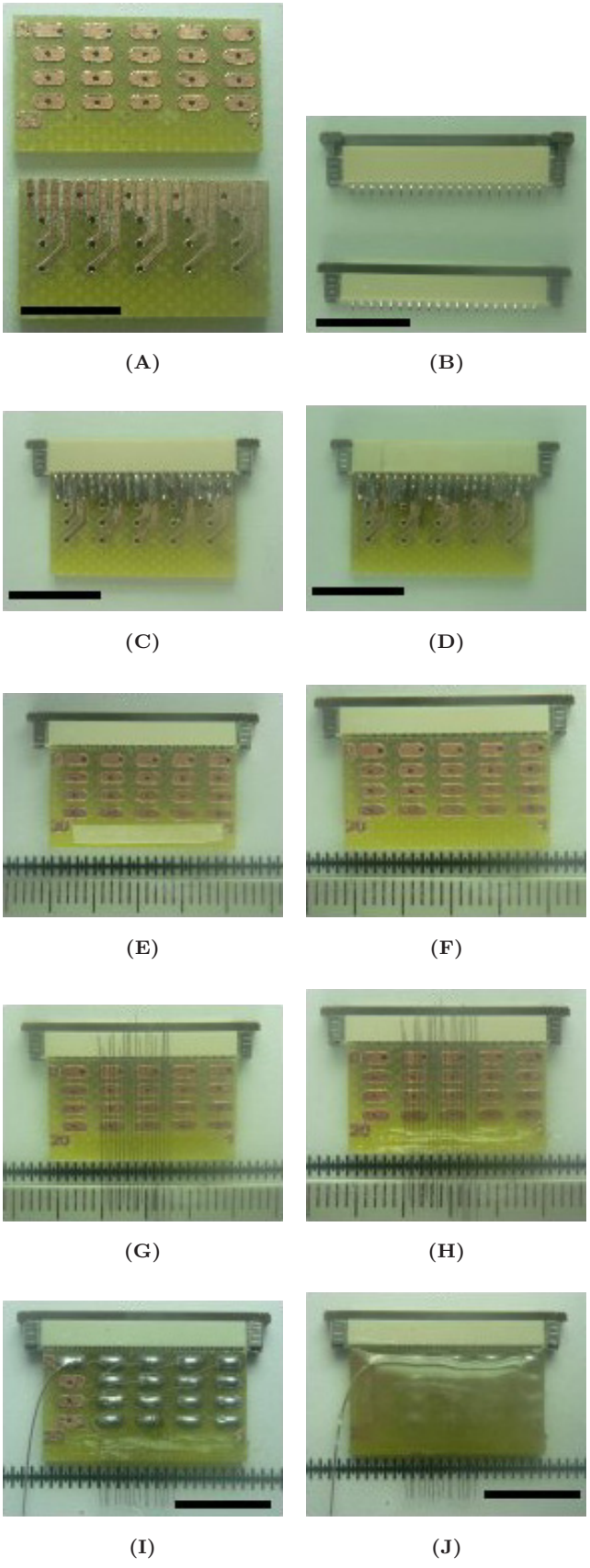

Fig. 4 Assembly of 16-channel microwire array electrode for multiple single-unit recording. Calibration bars of **(A–F)**, **(I)**, and **(J)**: 10 mm.

single-unit recording experiment. The microwire array microelectrode comprises 16 teflon-insulated tungsten wires (A-M Systems, Carlsberg, WA, #795500) that are aligned in series file, with an inter-electrode separation of 0.45–0.55 mm for a total horizontal span of 7.5–8.0 mm. The microelectrode in this style is suited to single-unit recording from a large brain region, such as the primary somatosensory cortex, the primary motor cortex, and the occipital cortex in the rat.

RESULTS

The nature of signals available is again different when electrodes are placed into the cortex; it is at this level that electrodes can record either field potentials or spiking. Low-pass filtering of intracortical activity yields a local field potential (LFP) signal.[9] The LFP signal represents the summed synaptic activity occurring near the tip of the electrode. It is a combined measure of local processing and synaptic inputs from other brain regions regardless of whether or not spikes are generated.[10–12] In contrast, spiking activity represents the results of local neural processing and is the output signal from the neurons near the tip of the electrode.[11,12] The intracortical recording from the cell aggregates of the SI is performed with a six-channel data acquisition system, where the sampling frequency of each channel is set to 30 kHz and the data sampling of the input band of spikes within 3 kHz including a high pass 300 Hz filter is executed in a way that is similar to other studies.[13,14]

Microelectrode Testing

EIS is performed on a microwire probe array in an artificial cerebral spinal fluid (ACSF) at room temperature. The composition of the ACSF is NaCl 6603 mg/L, KCl 223 mg/L, NaH_2PO_4 165.5 mg/L, $CaCl_2$ 220.5 mg/L, $MgCl_2$ 203.3 mg/L, $NaHCO_3$ 2520 mg/L and Dextrose 5405 mg/L.[15] An impedance spectrum analyzer IM6ex (IM6ex, ZAHNER-elektrik GmbH & Co. KG) is used. Thales software automatically supports all options and processes. A silver/silver chloride reference electrode and platinum counter electrode are utilized, as presented in Fig. 5.

Measurements are made over a frequency range of 100–50 kHz at open circuit potential with a sinusoidal perturbation voltage of 20 mV. The impedance-spectroscopic measurements characterize the electrochemical properties of the electrode and ensure that the electrical integrity of the signal path is maintained after packaging and implantation in the brain. Figure 6 plots

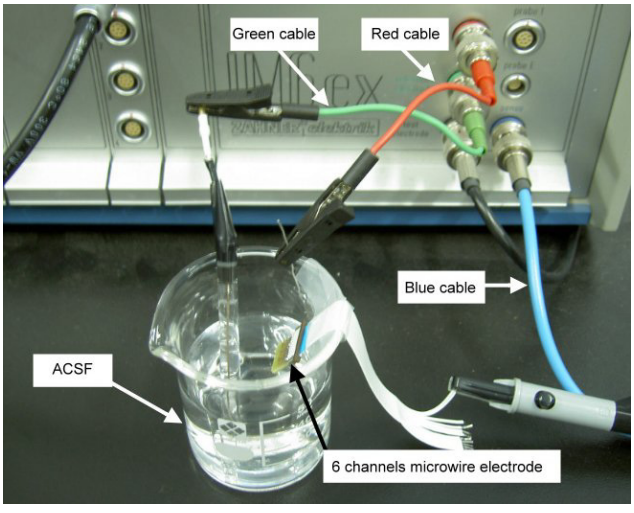

Fig. 5 EIS using the IM6ex instrument is performed on a six-channel microwires electrode. The red cable connects to the silver/silver chloride reference electrode, the green cable connects to the platinum counter electrode, and the blue cable connects to the microelectrode.

results for a six-channel microelectrode measured from the EIS. The impedance values of the channels associated with our proposed design, from EIS graph, are 200, 220, 225, 225, 190, and 215 kΩ, respectively. A mean impedance of 212.5 kΩ, standard deviation of 13.15 kΩ, and coefficient of variation of 6.18% are obtained for six-channel microwires electrode at 1 kHz. The phases of the channels are 50°, 55°, 47°, 40°, 57°, and 52°, respectively. The average phase is 50.17°; standard deviation is 5.58°, and coefficient of variation is 11.12%. Observe the coefficient of variation of impedance and phase that the presented microwire array electrode is suitable for recording electro-physiological activity.

Regression of the impedance data is performed to obtain an equivalent circuit describing the physical nature of the electrode/electrolyte interface. Its impedance modeled by "Randles"' equivalent circuit represents the most appropriate circuit of microwire electrode. Taking channel 4 as an example, its equivalent circuit is shown in Fig. 7. Parameters of the circuit reflect a liquid volume resistance Rs and an electrode–liquid interface represented by a double layer capacitance C connected in parallel with a charge transfer resistance Rw and a mass transfer impedance W.[16,17] Parameters of each channel equivalent circuit are presented in Table 1.

Electrodes such as those discussed in Moxon *et al.*[18] and Nordhausen *et al.*[19] have impedances from 80 kΩ to 4 MΩ, typically measured at 1 kHz in saline solution. Two main factors affect electrode impedance. These are (1) the small cross-sectional area of the electrode

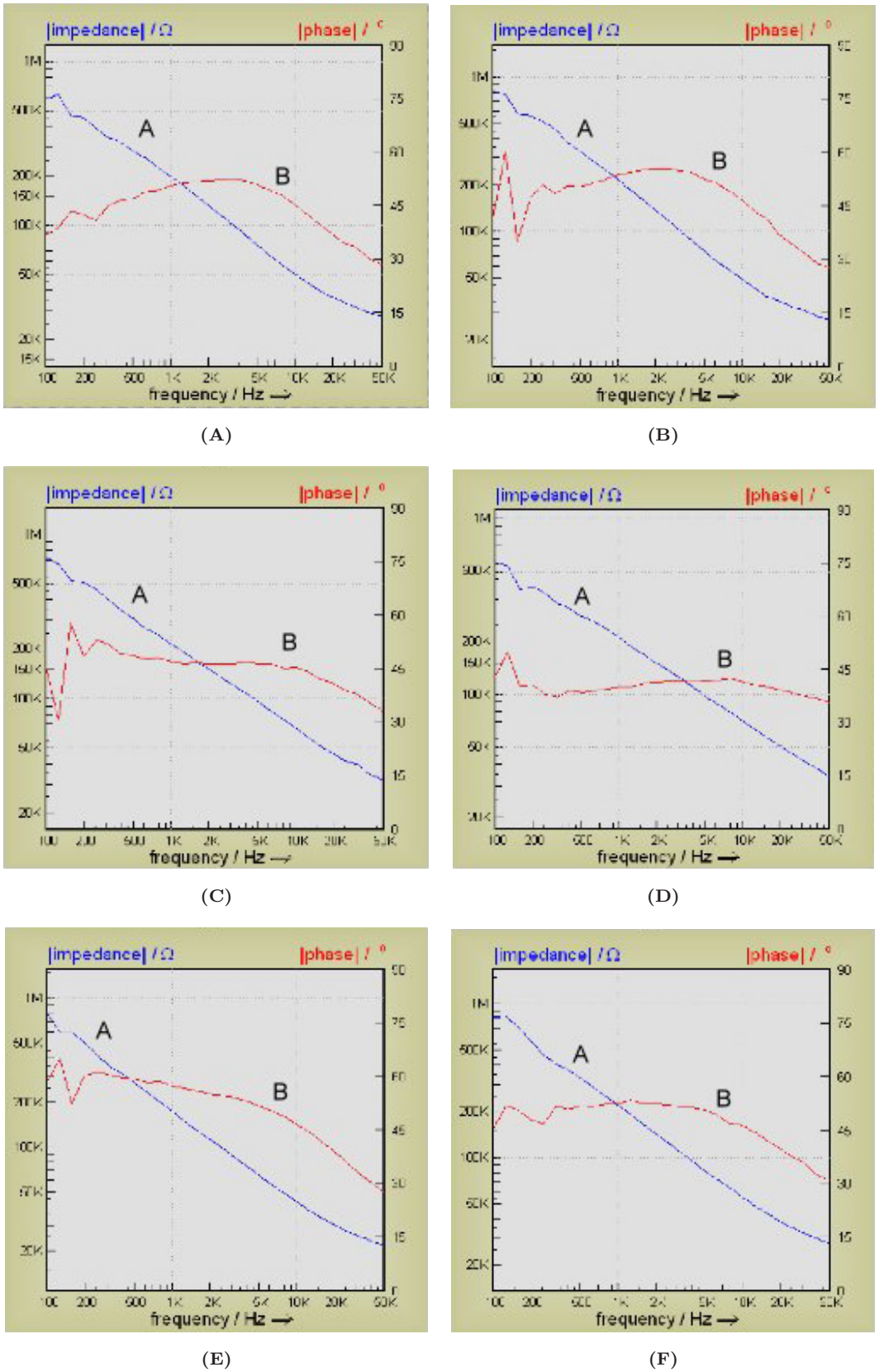

Fig. 6 Relationships between impedance and frequency (mark A) and between phase and frequency (mark B) for a six-channel microelectrode, measured using EIS. The horizontal axis represents frequency; the left-hand vertical axis represents impedance, and the right-hand vertical axis represents phase.

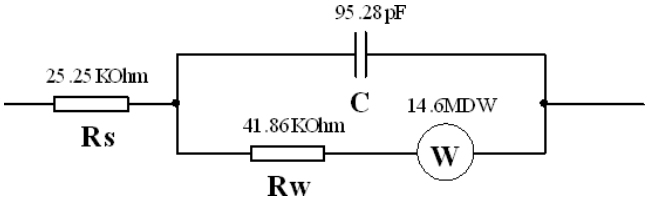

Fig. 7 Taking channel 4 as an example, its Randles' equivalent circuits showing the solution resistance Rs, double layer capacitance C, charge transfer resistance Rw, and mass transfer impedance W.

Table 1. Parameters of Each Channel Equivalent Circuit are Summarized.

	Element Value				Mod. Impedance error/%		Phase Angle Error/Deg	
	W	***Rw***	***C***	***Rs***	**Mean**	**Maximum**	**Mean**	**Maximum**
Ch1	17.01 M	4.13 K	201.4 pF	19.58 K	0.8 %	10.3%	0.7	9.9
Ch2	21.48 M	2.47 K	247.4 pF	21.37 K	0.9 %	9.7%	0.7	14.5
Ch3	18.45 M	2.73 K	112.3 pF	19.18 K	0.6 %	8.6%	0.8	15.1
Ch4	14.60 M	41.86 K	95.28 pF	25.25 K	0.5 %	5.9%	0.5	12.5
Ch5	21.17 M	1.35 K	265.5 pF	19.43 K	0.9 %	9.5%	0.9	13.9
Ch6	21.27 M	3.86 K	204.2 pF	20.92 K	0.9 %	16.3%	0.3	4.4

(recall the resistance rule that $R = \alpha \cdot L/A$) and (2) the impedance of the electrode–electrolyte interface.[20] EIS was adopted to measure the impedance and phase between the electrode and the electrolyte, and then to obtain an equivalent circuit. The cortical signal recording circuit has further applications. To prevent the loading effect, a suitable matching resistance is used to reduce the noise of the operation amplifier and decide the cut-off frequency of the high-pass filter that yields the original neural signals, which is determined. EIS testing indicates that this improved microwire array electrode is suitable for recording the intracortical signal.

In Vivo Recording

Electrode implantation

Adult male Wistar rats (400–500 g) from the National Defense Medical Center Laboratory Animal Center were maintained in a colony room. They were housed, six per cage, in a room in a controlled environment with a normal 12 h dark–light cycle (light phase 6:00 am–6:00 pm) for at least one week before surgery was performed. The animals had free access to water and food and ambient temperature was maintained at $24 \pm 1\,^{\circ}C$. All experiments were performed following the guidelines of the Institute of the National Defense Medical Center. All efforts were made to minimize animal suffering and the number of animals used.

For electrode implantation, the rats were anesthetized using chloral hydrate (1 mg/100 g) and fixed in the stereotaxic apparatus. The animals were administered general anesthesia by intra-peritoneal injection with an initial dosage of 1 ml regular anesthesia supplements at 20% of the initial dosage of anaesthetic per 100 g body mass throughout the surgical procedure. The observation site was located in the right-hind-leg region of the cortex. One small craniotomy was made to implant the microelectrode array. The coordinates of the craniotomy were, based on the atlas of Paxinos and Watson,[21] as follows for the primary somatosensory cortex (SI): 1.5 mm posterior to the bregma, 3.0 mm lateral to the midline, and 2.0 mm ventral to the skull surface. Arrays of teflon-insulated tungsten microwires (50 μm diameter) were slowly lowered into the target areas. The microelectrode arrays were secured onto the cranium using dental cement and skull screws as anchors. Animals were administered penicillin before surgery to prevent infection and housed individually after surgery. All of the experiments were performed following the guidelines of the "Animal Experiments Committee of the National Defense Medical Center."

Neuron recording

The proposed microelectrode was used to observe the neural signal from the primary somatosensory cortex (SI) that was evoked by mechanical stimulation of a brush. A six-channel electrode was used to record intracortical evoked potentials in the right S1HL and a reference electrode was placed in the cerebellum region. To record the neuron-evoked potential, a brain signal

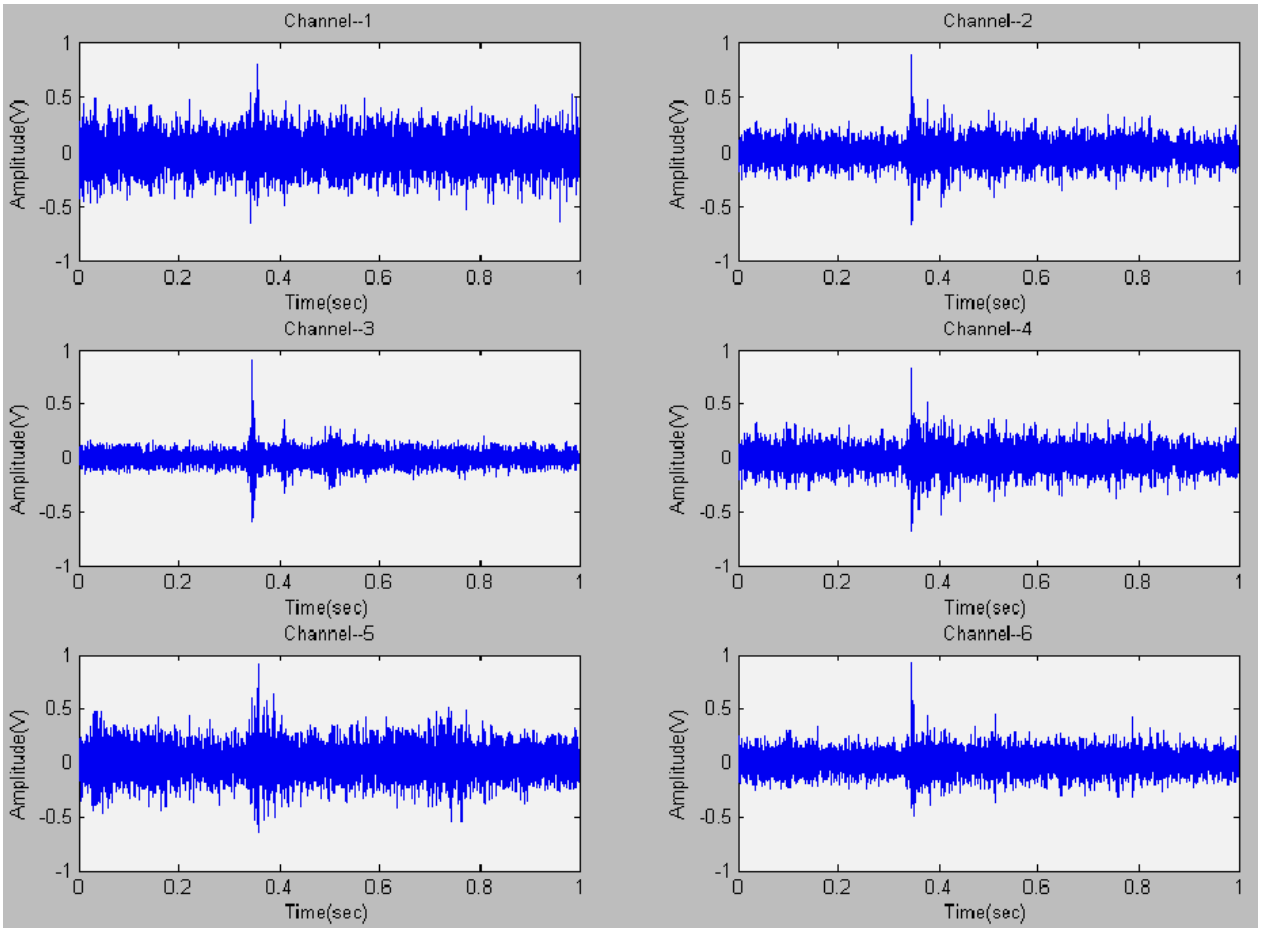

Fig. 8 Section of continuously recorded waveform of an anesthetized rat when a brush was used to stimulate the claw of its left hind leg.

capture and recording system was used. The recording system comprised a preamplifier, a filter with a band-pass of 300–3000 Hz, and a postamplifier. The total gain of each channel was adjusted to 10,000. The sampling rate of recording was 30 kHz; the data acquisition system was based on a PC. In the experiment, only the evoked potentials under external stimulus were observed. Figure 8 presents a section of continuously recorded waveform from an anesthetized rat when a brush was used to stimulate the claw of the left hind leg.

The responses of an anesthetized rat to stimulation by scratching using a brush are obtained. In Fig. 9, the top window plot, Fig. 9(A), shows the period of 1 s; the middle window, Fig. 9(B), covers the period from 0.58 to 0.76 s. The bottom window, Fig. 9(C), plots one section of the raw recording from 0.645 to 0.685 s. This section presents the potential evoked when the left back sole of the rat is stimulated. The improved microwire array electrode can be feasibly used to record the neural signal *in vivo*. Figure 10 presents the conscious rat in which the microelectrode has been successfully implanted.

DISCUSSION

A headstage or preamplifier must frequently be inserted and extracted from an overhead socket of a rat during experiments. This process can easily injure the animal and affect the quality of implanted microelectrode. Besides, no matter wire or wireless that most current neuronal recording systems use wires to transmit the signal from the microelectrodes to the headstage, analog front end or transfer. For these systems, the animal must be tethered, which restricts the subject's movements. The wires must be harnessed in a fashion to avoid entangling. Because of the weight of the headstage and drag and rock of the transmission wires, it is apt to cause slacking or dropping of the microelectrode. In this study, a lithe FFC and a precise connector are used. It can be easily repeatedly plugged in and pulled out. In addition to FFC and connector, the PCB

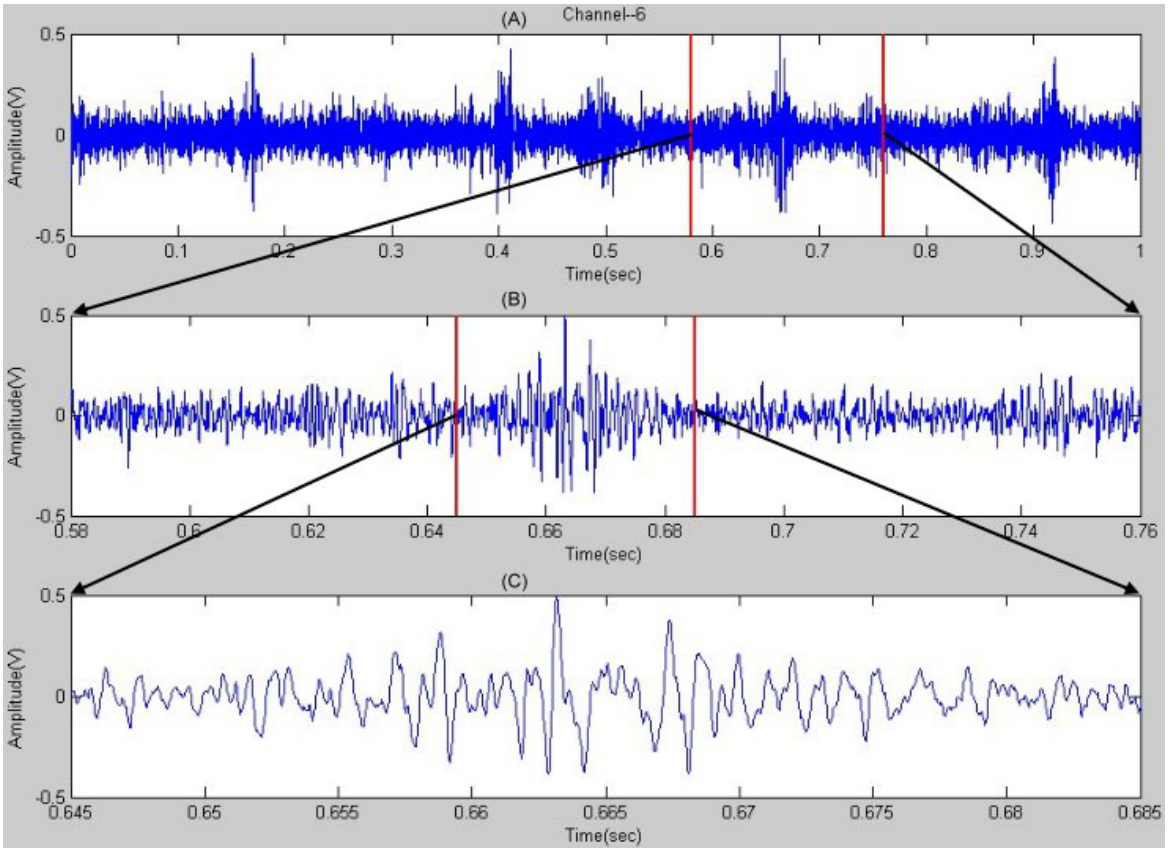

Fig. 9 Evoked potential waveform when left back paw of rat is stimulated.

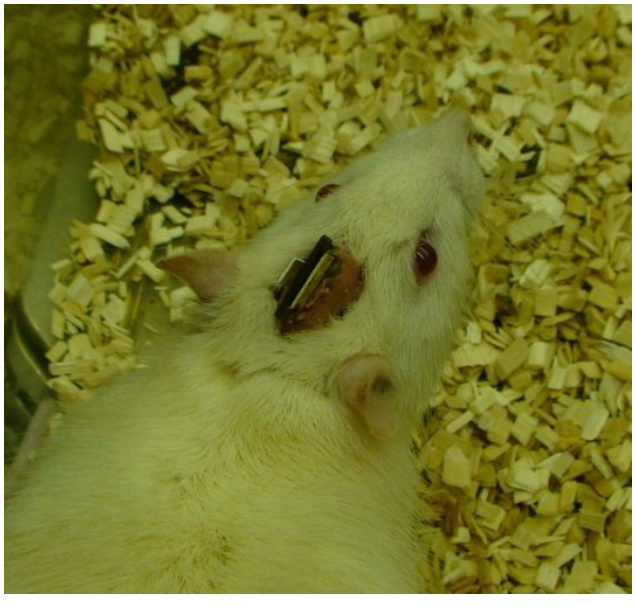

Fig. 10 Conscious rat with successfully implanted microelectrode.

pattern is light and thin too. We choose these materials to reduce the weight of the microelectrode greatly. Then the presented microelectrode uses the FFC to deliver the neural signal from overhead socket to headstage or analog front end. And the headstage or analog front end can be put into a backpack and tied on the body of rat. An improved flexible microwire array electrode can reduce injury to the rat during an experiment to measure the intracortical signal. The variation among the impedances of the channels of the microelectrode is important. Carelessly it can cause additional interference signals and induce the preamplifier go into saturation. Therefore, length, region of insulation, and area of the contact-tip of each microwire must be carefully examined, during the assembly of a microwire array electrode. In this work, EIS is performed on a microwire array electrode in ACSF. The measurements reveal that the microelectrodes are suitable for recording electrophysiological activity. The microelectrode impedance data are regressed to obtain an equivalent circuit of the electrode/electrolyte interface.

The thing about the spacing of the electrode tips have been discussed in many literatures. An array of parallel wire electrodes is constructed by using two springs.[22] A special fabrication jig is built by draping the microwires over fine musical instrument wire.[1] Tsai and Yen[23] described a simple method for constructing a variety of shapes and sizes of fabrication jig by two slim

bamboos onto a piece of paper. The presented method is that the PCB pattern provides an integrative shaping, flexible outline, and flat surface to supply as the fabrication plate, facilitating the fabrication of the microwire array electrode. Especially while arranging microwires into a desirable configuration and soldering microwires to the corresponding copper. The spacing among the electrode tips and the inter-electrode separation can be adjusted under a dissecting microscope: spacing can be reduced and separation set more precisely. The dimensions and shape of this PCB pattern can be elastically adjusted based on the position of the implanting or the range of the recording. A researcher can conveniently design and revise it to meet the demands of differential experiment. For instance, he/she can cut each microwire to a particular length to fit the experiment, and weld it to the under blank region of PCB pattern for research in different layers of the cortex. Microwires can be soldered in bunched to different site of the PCB pattern to conduct experiments at different positions in brain. Various PCB patterns of the proposed microwire array electrode can be overlapped and a 3D electrode constructed for various intentions of research. The microwire array electrode supports flexible selection of the parameters that govern intracortical recordings.

Another advantage of the proposed microwire array electrode includes the universal availability of its material, its cost-effectiveness, the general availability of the tools required to produce it, simplicity, convenience and ease of reproduction. Moreover, using this presented method is conducive to controlling of experiment progress, modifying of different specifications, and collocating with the acquisition circuit. An assembled six-channel microwire array electrode has a mass of only 1.96 g. The material of the entire microelectrode costs less than US$ 1.5. The manufacture of electrode arrays takes approximately 2 h for a practiced researcher. The procedure described herein is relatively simple even for a novice worker to implement in-house. Even so, it requires enough time and repeated exercise in advance to produce the microelectrodes with consistent good quality and easy fabrication.

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