Towards high aspect ratio tungsten Micro Electrode Array for neural recording and stimulation applications

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Abstract

The design and fabrication of high aspect ratio microelectrode array is described. 10 × 10 array of electrically isolated square columns was fabricated using µ-wire Electrical Discharge Machining (EDM) from pure tungsten block. The square columns were machined to be of length 5 mm and width 200 µm with pitch 400 µm. The Utah Electrode Array [1] design was adapted in building this array. The array of square columns was later etched electrochemically to form an array of tapered/needle-shaped electrodes. Epoxy resin, EPOTEK 354, was used to isolate the individual electrodes at the base of the electrodes. Accelerated leakage current across this epoxy in simulated physiological environment was measured to test its long term stability. Variations of this array design can be built using the developed techniques for use of such arrays in intracortical and peripheral nerve recording and stimulating applications.

1. Introduction

Development of neural interfaces to record and stimulate neural signals, to assist neurologically impaired, has been pursued for decades. Of the several techniques currently available for measuring the extracellular potentials of neurons, single-neuron action potential recording and stimulation using microelectrodes gives highest precision and most useful recording data. The most widely accepted and used designs of microelectrodes in this field are those developed at the University of Utah (Utah electrode array, UEA) [1, 2] and University of Michigan (Michigan array) [3, 4].

UEA, in general, is a 10 × 10 array of silicon-based needle-shaped electrodes isolated at the base with dielectric glass. The limitations in conventional technologies used to fabricate these arrays restrict the lengths of the electrodes at 1.5 mm on a base footprint of 16 mm². The recent scientific advances in the fields of neuro prosthetic therapies and the desire to gain scientific insights into the way populations of neurons interact in the complex, distributed systems that generate behavior, forces the need for longer penetrating electrodes. There have been few attempts made in the past to fabricate electrode arrays based on UEA design to reach deeper areas of brain and nerves [5] but none have really shown the high density and long electrode lengths described here.

This paper presents the processes developed for fabricating ultra-high aspect ratio UEA based microelectrode array. Tungsten was selected as the electrode material based on its mechanical, chemical properties and lack of any long term toxicity (tested for 4 months) [6] when implanted inside the body. 99.99 % pure tungsten block (obtained from Goodfellow Inc.) was machined by EDM and later electrochemically etched to form needle-shaped electrode array. USP class VI approved epoxy resin, EPO-TEK 354, was used to electrically isolate the electrodes at the base of the array.

2. Method

The structural fabrication of the microelectrode array basically consists of four steps: (1) machining of crisscross channels of about 500 µm deep and 90 µm wide and pitch 400 µm in the bulk work piece; (2) filling channels with bubble-free epoxy; (3) machining about 5mm long, 200 µm wide square columns such that the columns are isolated by the epoxy channels, (4) electrochemical etching of the columns to form the pointed needles. These steps are shown in Figure 1.

2.1 µ-wire Electrical Discharge Machining

Cutting wire EDM uses the potential difference between the cutting wire and the work piece to generate short electrical discharges in the form of sparks and high temperatures causing the work piece surface to melt locally and there by allows machining it as the movement of wire and work piece are controlled. Zinc coated, CuZn37 wire with tensile strength 900N/mm² (Trade name, cobra cut A) of diameter 150 µm was used to
machine the $10 \times 10$ array of square columns. Parameters described in Table 1 were used during machining.

Table 1: Parameters used for EDM the array

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Finish Machining</th>
<th>Rough Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flushing pressure (bar)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Pulse OFF time (µsec)</td>
<td>12.5</td>
<td>42.5</td>
</tr>
<tr>
<td>Open circuit voltage (volts)</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Pulse ON time (µsec)</td>
<td>52.4</td>
<td>4.5</td>
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<tr>
<td>Wire tension</td>
<td>2 N</td>
<td>2 N</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>1.74 mm/minute</td>
<td>1.74 mm/minute</td>
</tr>
<tr>
<td>Wire speed</td>
<td>90 mm/minute</td>
<td>90 mm/minute</td>
</tr>
</tbody>
</table>

2.2 Leakage current across the epoxy resin

One of the requirements for the long stability of the microelectrode array after implantation is the electrical stability of the epoxy used as the dielectric material between the electrodes. Accelerated leakage current across the resin was tested in 0.9% NaCl solution on 10 samples to estimate its electrical stability. One of the two electrodes attached to a custom designed test-vial-cap and made of gold was completely coated with 1mm thick EPO-TEK 354 epoxy resin and cured for 2 hrs at 80ºC in 50mTorr vacuum (active for first 90 minutes). All the surfaces of the testing vial were treated with oxygen plasma for 45 seconds just before applying the epoxy, to improve the adhesion of the epoxy to these surfaces. After the epoxy was completely cured, the electrodes were subjected to an electrical stress of 5V in 37 ºC controlled environment without the NaCl solution for the first 3 days and later, the test vials were filled with 0.9% NaCl solution. The initial days of testing without the solution is to make sure that there are no short circuits and find the baseline current. The leakage current was measured every 10 minutes since the start of the experiment in an automatic setup. Figure 2 describes the test setup.

Fig. 2: Custom designed testing vial and the schematic of the leakage current measurement setup.

2.3 Electrochemical etching

The square electrode columns in an array formed after EDM process need to be shaped into tapered needles in the following processes. We have chosen electrochemical etching process and attempted initially to etch single tungsten columns. In order to obtain the desired shape of the electrodes, they are retracted slowly during the process from the etching solution with an automated setup. 2 molar KNO$_3$ solution is used as the etching electrolyte. Platinum coated beaker served as a cathode while the columns to be etched were the anodes. The anodes were mechanically fixed to a vertical actuator and retracted from the etching solution based on the measured current which corresponds to the surface area of the anode. Several combinations of voltage (ranging 5 to 20 V) and frequency (DC to 80 Hz) were tested to optimize the electrochemical etching process in series of experiments and the resulting surfaces and shapes of the electrodes were analyzed. The electrolyte was agitated using a sonicator probe to enhance the diffusion of the ions and allow faster etching [7].

3 Results and Discussion

EDM process was used to realize 5 mm long, 200 µm, 400µm pitch $10 \times 10$ tungsten electrode array shown in Figure 3. We have observed that EDM leaves a recast layer on the surface of the machined part, Figure 4. This recast layer has a rms roughness about few microns depending on the discharge parameters used during machining. The recast layer was removed to reveal a fine surface finish using the optimized electrochemical parameters: 16 V, 20 Hz, 5 minutes under other conditions described in Section 2.3.

During the leakage current experiments, samples with measured current above $10^{-6}$ A are considered failed. Measured leakage current across the epoxy resin is shown in Figure 5. Very low currents around $10^{-14}$ A are indicated during the first 3 days indicate that there are no short circuits, the jump in current to around $10^{-10}$ A when the NaCl solution was added indicates ion displacement.

Fig. 3: High aspect ratio and high density tungsten electrode array formed using EDM.
The measured current on several samples remained stable until the 12th day of the experiment at which time they failed with a jump in current to about $10^{-4}$ A. Although the device would be finally encapsulated with Parylene C except on the sensing/stimulating tips, this failure of epoxy resin after about 10 days of constant low currents in accelerated environment suggests a definite failure mode in the functionality of the device during a long term application/usage. Visual inspection of the failed samples revealed no apparent defects in the samples.

Fig. 4: Base of an electrode showing the rough surface after EDM and the epoxy isolation between electrodes in the array (left), improved surface finish after first electrochemical etching step (right).

Fig. 5: Leakage current across the Epo-tek 354 epoxy resin measured during an accelerated aging test.

Fig. 6: Electrochemically shaped 6 mm cylindrical needle (left) and array of needles (right).

Electrochemical etching was done on single cylindrical electrode and also on an array of electrodes as presented in Figure 6. The influence of voltage, frequency and time on etching was evaluated. We observe that frequency plays a role on the final shape of the electrodes. Higher frequency (max. applied 80 Hz) gives rise to conical shapes and higher currents while lower frequency (~5-40 Hz) retains the original shape of the electrode while reducing the cross-section during etching. Higher voltages lead to convex shapes due to limited ion diffusion.

4 Conclusions

A process to build new high aspect ratio microelectrode array has been developed. The EDM process enables machining electrodes from bulk tungsten and epoxy resin was used to isolate electrodes at the base. Thin, needle-shaped and smooth tungsten microelectrodes were realized with optimized electrochemical etching process. This process enables building sharp tips. The Leakage current tests on the epoxy resin reveal possibility of water uptake and ion transfer limiting the use of this array for acute applications.

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6 References


