© ISA, 1990 - Paper #90-026
0067-8856/90/161-165/$0 + .50pp

A 100 ELECTRODE INTRACORTICAL ARRAY: STRUCTURAL VARIABILITY

Patrick K. Campbell, Kelly E. Jones, and Richard A. Normann

Department of Bioengineering
University of Utah
Salt Lake City, UT 84112

ABSTRACT

A technique has been developed for fabricating three dimensional "hair brush" electrode arrays from monocrystalline silicon blocks. Arrays consist of a square pattern of 100 penetrating electrodes, with 400μm interelectrode spacing. Each electrode is 1.5mm in length and tapers from about 100μm at its base to a sharp point at the tip. The tips of each electrode are coated with platinum and the entire structure, with the exception of the tips, is insulated with polyimide. Electrical connection to selected electrodes is made by wire bonding polyimide insulated 25μm diameter gold lead wires to bonding pads on the rear surface of the array.

As the geometrical characteristics of the electrodes in such an array will influence their electrical properties (such as impedance, capacitance, spreading resistance in an electrolyte, etc.) it is desirable that such an array have minimal variability in geometry from electrode to electrode. A study was performed to determine the geometrical variability resulting from our micromachining techniques. Measurements of the diameter of each of the 100 electrodes were made at various planes above the silicon substrate of the array. For the array that was measured, the standard deviation of the diameters was approximately 9% of the mean diameter near the tip, 8% near the middle, and 6% near the base. We describe fabrication techniques which should further reduce these variabilities.

Key words: Microelectrode arrays, Stimulation, Micromachining

INTRODUCTION

The use of silicon as a substrate for microelectrode arrays has recently attracted considerable interest. The material can be easily micromachined using a variety of mechanical and chemical techniques. Structures can be built with dimensions on the order of the cells that make up the central nervous system. Examples of electrode arrays which have been based upon silicon micromachining technologies are "dagger" (1) and "comb" structures (4, 5).

Our goal is to develop an electrode array which can stimulate a laminar population of neurons at a given depth beneath the surface of the cortex. We have used a new set of silicon micromachining technologies to produce electrode arrays with a unique geometry. The shape, which we refer to as a "hair brush" geometry, consists of 100 penetrating silicon needles positioned in a 10 x 10 array. The needles emerge from a 200μm thick, 4.2mm x 4.2mm continuous substrate of silicon. The needles in the array are 1.5mm long and are on 400μm centers. The needles, made of a highly doped/low resistance silicon, are electrically isolated from each other due to a high impedance pathway (a pair of apposed pn junctions). To facilitate charge transfer to the cortical tissue, each penetrating needle is coated with platinum at the sharpened distal end.

The back of the silicon substrate contains 100 bonding pads, each of which is electrically connected to a penetrating electrode that emerges from the opposite side of the substrate. Gold percutaneous lead wires are ultrasonically bonded to selected pads on the back of the substrate, allowing current passage through the corresponding electrodes. The electrode array (with the exception of the platinum coated needle tips) and connecting lead wires are insulated with polyimide.

The intracortical electrode array is designed to be implanted subdurally into the crown of a single gyrus. The substrate of the array floats on the cortical surface. The leads of the array pass up through the dura and through a burr hole drilled in the animals skull. The lead wires then course to a percutaneous connector mounted on the skull.

To use these electrodes for intracortical stimulation or recording, uniformity and predictability of electrode impedance, capacitance, and spacing are of great importance. This uniformity is dependent on the geometrical uniformity and dimensional accuracy of the array, which are dependent upon the micromachining processes employed.

While many of the fabrication processes used in standard integrated circuit production are highly reproducible, those processes developed in our laboratory for the array fabrication are much less so. This paper contains a brief description of the micromachining process currently employed to produce these microsystems, as well as an analysis of electrode dimensional uniformity over a single electrode array.

METHODS AND MATERIALS

The hair brush electrode array described in this paper will be used clinically as a neural interface, either for use in restoring a lost sensory modality (sight, hearing, touch) via electrical stimulation, or for the recording of neural signals to control an external prosthesis. The electrode arrays described herein have been designed to be implanted into the feline visual cortex. Thus, the array dimensions as well as the electrode numbers are constrained by those cortical structural characteristics.

Manufacturing Processes

The arrays are manufactured from a three inch diameter, 1.7 mm thick, 6 to 20 ohm-cm, n type, <100> orientation silicon wafer. A process known as thermomigration is employed to create 100 trails of p+ type silicon leading from one side of the silicon wafer to the other (2). This is a high temperature process which involves applying a thermal gradient to the silicon wafer, causing aluminum pads (photolithographically deposited on the rear surface of the wafer) to migrate through the wafer as an Al-Si eutectic droplet. As the eutectic droplets pass through the wafer, trails of recrystallized silicon remain which are highly doped with aluminum. The wafer is allowed to cool, and the surfaces of the wafer are polished. Since aluminum is a p type dopant, the remaining trails are highly conductive p^+ silicon. Since the wafer started as n type silicon, each p^+ trail forms a pn diode with the surrounding n type substrate. This results in back-to-back diodes between each pair of p^+ trails. The impedance between each electrode pair is on the order of 20 to 30 Mohms.

The silicon wafer is next subjected to a micromachining process which removes all but a thin layer of the n type silicon between the bases of the p+ trails. A Microautomation 1006 dicing saw equipped with a 0.25mm thick diamond embedded metal blade is used to make deep cuts into the silicon wafer, centered between the p^+ trails. This removes all but a thin layer of the remaining n type silicon. Eleven 1.5mm deep cuts are made along one axis, the wafer is rotated 90 degrees, and eleven additional cuts are made. This step creates 100 very high aspect ratio square columns of p^+ silicon, held together at their bases with a thin substrate of n type silicon between the columns.

Next the structure is subjected to a two step wet etching process which removes saw damage produced by the previous step, and shapes the columns into the thin sharp needles required for cortical implantation. Figure 1 is a scanning electron micrograph of this structure after the micromachining process.

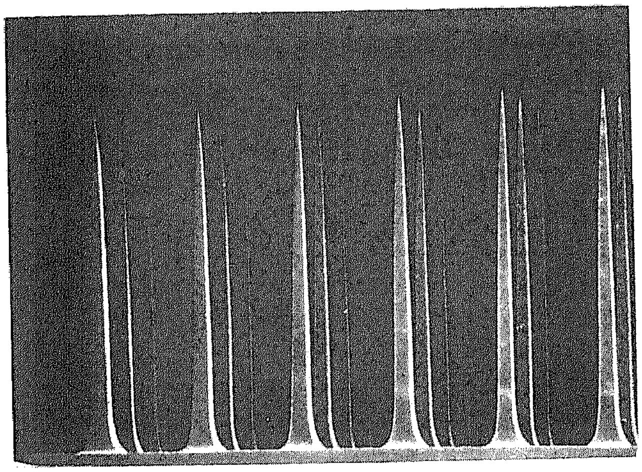

Figure 1: A side view of the electrode array after the micromachining process. Each electrode is 1.5mm tall for scale.

Because these micromachining processes are extremely versatile, electrode geometry can be varied to suit each particular application. Changes in processing can produce a very thin and extremely sharp point with small electrode surface areas or a robust looking "missile" shape with a much larger surface area.

The tips of the needles are next coated with a thin layer of gold, followed by a thin layer of platinum which facilitates ohmic charge transfer from the conductive silicon needle to neural tissue. Insulated gold lead wires are ultrasonically wire bonded to aluminum pads which have been deposited on the back side of the substrate and centered above the silicon needles. The entire structure is then coated in several coatings of DuPont 2550 polyimide, and the polyimide is subsequently etched off of the platinum coated needle tips in an oxygen plasma. The other end of the gold leads are soldered into a percutaneous connector. Figure 2 shows a cross section drawing of a completed array. This entire process is described elsewhere in greater detail (3).

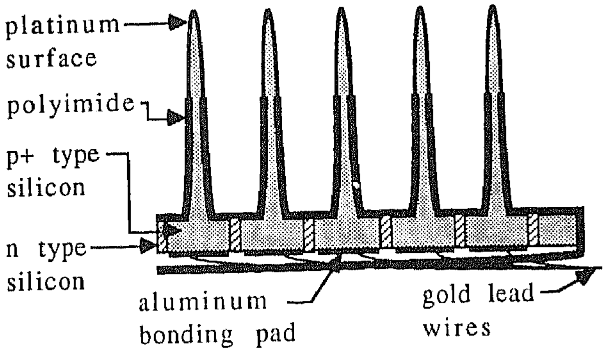

Figure 2: Partial cross section of finished array with 5 platinum coated silicon needles. Gold lead wires bonded to aluminum pads and polyimide insulation are on the back of the substrate.

Measurement of electrode uniformity

Since the electrical properties of the array are dependent upon the dimensional uniformity, we have measured the diameters of each electrode in the array at four different planes above the base of the array. These measurements were made on a single array after it had undergone the micromachining processes described above, but before the lead wire attachment and polyimide coating.

An electrode array was potted in frit glass in an evacuated high temperature oven. The potted array was waxed down to a gauge block, and a diamond embedded grinding wheel was used to remove thin layers of the glass which contained the silicon electrodes. After each layer was ground, the surface was polished and a pattern generator (Research Devices, model 5010) was used in the inspection mode to measure the diameters of all 100 silicon electrodes. A joy-stick was used to position a video image of the polished surface under a set of cross-hairs, while a computer read out the distance traveled by the x-y stage. To evaluate the reproducibility of our measurement technique, we interspersed measurements with repeat measurements of a particular electrode. The standard deviation of 24 repeated measurements was 0.66µm. Measurements of most of the 100 electrodes were made at four different planes: at 127, 500, 825, and 1150µm above the silicon substrate. However, at some planes, small localized bubbles in the glass made measurements of some of the electrode diameters impossible.

RESULTS

Because of the micromachining processes we have used to make these arrays, the electrode cross sectional shape at all heights was square with rounded corners. Figure 3 is a scaled drawing of a side view of the average electrode showing the four planes at which measurements were made. The average size and standard deviation of the measured electrode diameters was calculated for each plane. It was found that the average electrode diameter +/- standard deviation was 86.3 +/- 5.5µm at 127µm, 62.6 +/- 4.8µm at 500µm, 53.4 +/- 3.9µm at 825µm and 39.9 +/-3.7µm at 1150µm.

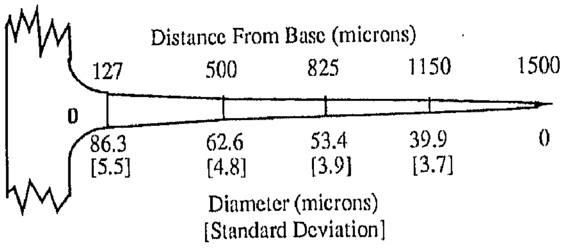

Figure 3: A scaled drawing of an electrode side view. The vertical bars represent the average electrode diameter at the four planes where measurements were made. Listed at each plane is the average electrode diameter and standard deviation.

In all the planes measured, there was a trend toward larger electrodes in the corners of the array. These corner electrodes averaged 17% larger than the overall electrode average diameter, while the center electrodes had the smallest diameters in the array. Figure 4 shows a plot at all four planes of the diameter of electrodes along a single row near the center of the array as a function of the location of the electrode across the array. It can be seen that the electrodes near the edge of the array are slightly larger in diameter. Figure 5 shows the same plot for a row of electrodes running diagonally from one corner of the array to the other. Again it can be seen that the electrodes in the corners are larger than those in the center of the array.

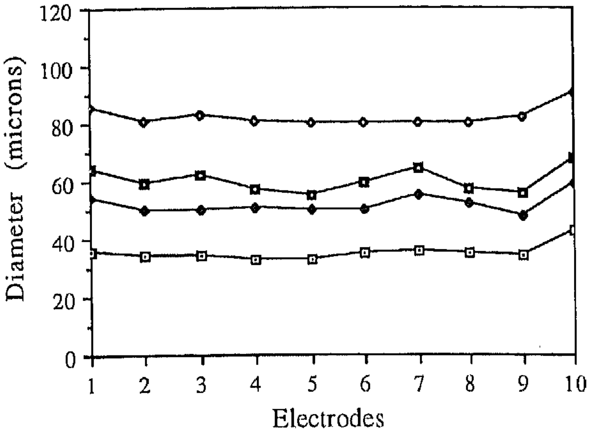

Figure 4: A plot of electrode diameters for a row of ten electrodes running through the center of the array. The four curves represent, from top to bottom, planes of measurement 127, 500, 825 and 1150µm from the silicon substrate.

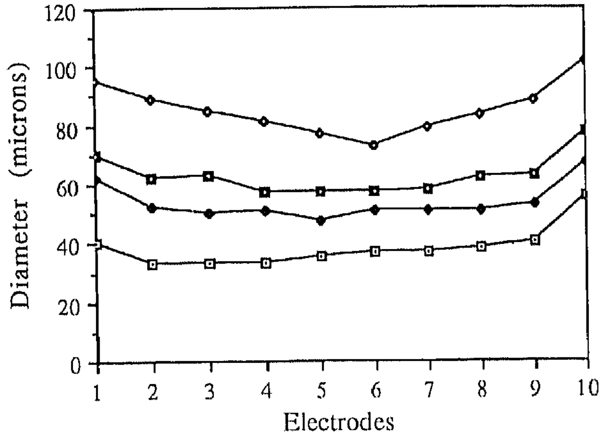

Figure 5: A plot of electrode diameters for a row of ten electrodes running diagonally through the center of the array. The electrodes on either end represent the corner electrodes. The four curves represent, from top to bottom, planes of measurement 127, 500, 825 and 1150µm from the silicon substrate.

DISCUSSION

Effects of structural non-uniformity

As can be seen in figures 4 and 5, the electrodes we have fabricated manifest variations in their dimensions. These variations in electrode diameter are more pronounced when viewing along the diagonal of the array as in figure 5, where the corner electrodes are significantly larger than the center electrodes. These observed diameter variabilities occur due to edge effects in the wet etching steps of the micromachining process, and additional work is ongoing to address that problem.

Since the major variations are confined to the electrodes at the perimeter of the array, these problems could be corrected by creating an array with an extra ring of electrodes surrounding the central electrodes, and then removing the edge electrodes following the wet etching process. To illustrate the consequences of this in achieving more uniform electrode diameters, we have reanalyzed the data of figures 4 and 5 but we have restricted our analysis to the central 64 electrodes. At the four planes measured for the central 8 x 8 electrodes, it was found that the average electrode diameter +/- standard deviation was 83.3 +/- 3.5μm at 127μm, 60.2 +/- 2.7μm at 500μm, 51.5 +/- 2.3μm at 825μm and 38.7 +/-2.6μm at 1150μm. The average standard deviation of electrode diameters for the center 8 x 8 electrodes is 38% less than the average standard deviation of all the electrodes. A corresponding increase in electrode uniformity for a 10 x 10 electrode array should occur if a 12 x 12 array was made, and the edge rows of electrodes were removed.

Another technique could be used to reduce the variability in the dimensions of the electrodes in our arrays. Again, the largest electrodes are found along the perimeter of our arrays. Clearly, etchant access to the columns along the perimeter of our arrays is compromised. This problem could be mitigated by making the dicing saw kerf around the perimeter of the columns larger than normal, to allow an increased flow of etchant at the perimeter of the array. We have not yet verified this simple solution.

CONCLUSIONS

This study has described a relatively simple and inexpensive method which can be used to produce a unique electrode array geometry. These electrodes should be particularly well suited for stimulating neurons or for recording the electrical activity of neurons with processes that are lying 1.5mm deep within the cortex. However, the method does not allow us to produce individual electrodes which are completely uniform across the entire electrode array. We have proposed two simple additional steps which should reduce the dimensional variability to within acceptable limits.

REFERENCES

(1) Anderson, D.J., Najafi, N., Tanghe, S.J., Evans, D.A., Levy, K.L., Hetke, J.F., Xue, X., Zappia, J.J. and Wise, K.D.. "Batch-Fabricated Thin-Film Electrodes for Stimulation of the Central Auditory System". IEEE Trans Biomed Eng., 1989, 693-704.

(2) Anthony, T.R. and Cline, H.E. "Deep-Diode Arrays". J. Appl. Phys., 1976, 47(6), 2550-2557.

(3) Campbell, P.K, Jones, K.E., Huber, R.J., Horch, K.W. and Normann, R.A. "A Silicon Based Neural Interface: Manufacturing Processes for a Three Dimensional Intracortical Electrode Array". In Preparation. 1990.

(4) Edell, D.J., McNeil, V.M. and Clark, L,D. "Microfabrication Technology for Development of Chronic Neural Information Transducers". Proceedings of the International Electron Devices Meeting, 1986, 180-183.

(5) Prohaska, O.J., Olcaytug, F., Pfundner, P. and Dragaun, H. "Thin-Film Multiple Electrode Probes: Possibilities and Limitations". IEEE Trans. Biomed. Eng. BME-33(2), 1986, 223-229.