INVASIVE NEURAL ELECTRODES STRUCTURE FABRICATION BASED ON ALUMINUM WAFERS

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***Abstract* — Over the last two decades, many researchers have developed a variety of neural electrode types, taking full advantage of silicon microtechnologies. Silicon wafers became the raw structural material for the majority of the developed electrodes, and several techniques had to be studied and established in order to fabricate a feasible silicon-based neural probe. This paper shows an alternative raw material for the structure construction, the aluminum. With the same techniques used before (dicing and etching), it is possible to fabricate an array structure made from aluminum with 1.5 mm long needles, individually addressable. This structure presents a superior performance both mechanically and electrically, when compared to the silicon-based solutions. Furthermore, from the practical perspective, it ensures a more consistent fabrication procedure and a more competitive cost.**

***Keywords :* Neural electrode, invasive, microelectrodes, microneedle, wet-etch, dicing, aluminum, silicon,**

I – Introduction

Invasive neural electrodes are widely used tools in neuroscience to study the behavior and function of the central nervous system at cellular level. There is also a growing interest in the clinical application of stimulation and recording neural electrodes. Several successful applications of implantable neural prostheses, such as cardiac pacemakers, cochlear implants and deep brain stimulators, are commercially available. Many disorders can be treated with these neural prostheses (e.g. irregular heart rate, deafness and Parkinson's disease).

Intracortical microelectrode arrays can offer a selective access to individual nervous cell activity and also provide a greater spatial resolution than previously achieved with individual electrodes. Needle-shaped microelectrodes based on silicon that can be safely inserted into the brain have been reported [1–3]. In order to selectively stimulate and record from single or multiple neurons on the tips of the array, a biocompatible ionic transducer is deposited, (e.g. gold) while the remaining surface is insulated with a biocompatible material.

Despite the many advantages offered by silicon as the structural mechanical material [4], it still is a brittle material and needs to undergo doping processes to become a good electrical conductor. These characteristics increase the cost and fabrication complexity.

A more ductile material would provide greater energy absorption during insertion, avoiding breaking the needles. Another wishful characteristic would be to use an inherently good electrical conductor as bulk material. Generally, metals have both of these qualities, from which aluminum stands out as the most cost-effective with the mechanical and electrical characteristics needed for the present application

Therefore, in this paper, a neuronal electrode array structure fabrication process based on aluminum is presented.

II – Microelectrode array structure approach

The process starts with an aluminum wafer.

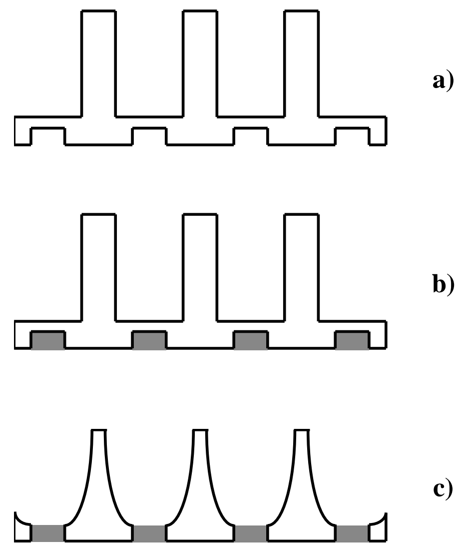

Figure 1*: Microelectrode array structure fabrication steps: a) Dicing; b) Adhesive filling; c) Wet-etching.*

In the first step, cuts are performed to define the electrode pillars and pad regions for the individual electrodes (Figure 1a). The pillars are designed with a high aspect ratio, as they should be thin (0.2 mm) and long (1.5 mm) in order to access deep brain regions, minimizing the damage on the surrounding tissues during insertion. In this first stage, the cuts should not go through the entire cross-section of the aluminum wafer in order to keep all the features in a single piece for the following stages.

In the second stage, a polymer adhesive is deposited in the back grooves around the electrode pads (Figure 1b).

Finally, the wafer undergoes an etching process in order to sharpen and to electrically individualize each pillar (Figure 1c). The needle shape facilitates the penetration of the electrodes in the neural tissue. As the etching process continues, it completely removes the thin connecting aluminum between needles. Due to the good adhesive and insulating properties of the polymer, this last process electrically individualizes each needle, while maintaining a good mechanical adhesion between them.

III – Microelectrode array structure fabrication

The cutting stages were performed on a Disco DAD 3H/6T dicing machine, equipped with Disco ZHDG blades capable of performing cuts 3 mm deep and 0.120 mm wide. The square aluminum substrate was 10 mm wide and 2 mm thick.

In the dicing stage, two cutting programs were prepared: one for the pillars cut and other for the pads region outlining. The pad region was the first to be performed and the program was set up to cut 1 mm wide, 0.3 mm deep squares. The 0.12 mm pad spacing is defined by the blade thickness. The pillars cutting program ensured vertical structure 1.5 mm long and 0.2 mm wide, with 1 mm spacing (Figure 2).

Cyanoacrylate was the polymer adhesive selected to cluster all the pillars in a single structure. This polymer offers good biocompatibility, adhesive properties and also ensures electric insulation. The polymer is deposited in the back grooves and the excess is removed through grinding and polishing.

In order to sharpen and individualize the pillars after the dicing procedure, the diced substrate is placed in a type A aluminum etchant at 50ºC [5]. Figure 3 shows the results after 30 minutes of etching, while in Figure 4, the electrically individualized needles are shown.

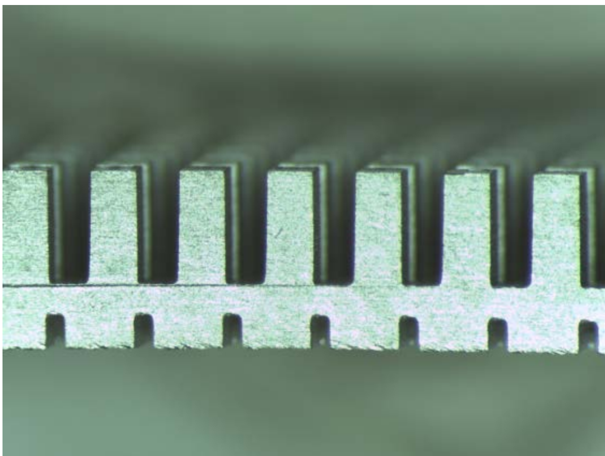

Figure 2*: Cross-section view of aluminum substrate cutting stage.*

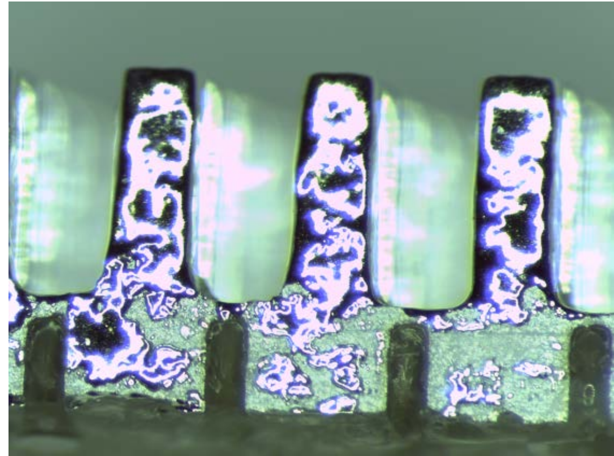

Figure 3: *Aluminum pillars submerged in a wet-etch solution at 50ºC, after 30 minutes.*

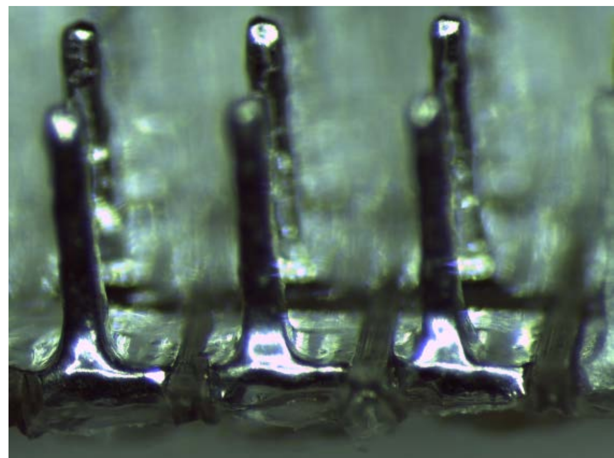

Figure 4*: Electrical and mechanical individualization of each needle after 100 minutes of etching.*

IV – Characterization

A. Structural

The aluminum structure demonstrates to be hard enough to withstand handling without suffering any damage. A concern on this technique is the alignment errors that may occur between the upper and back face of the aluminum wafer. It is visible on Figure *2* the cut misalignment between the two surfaces. Such alignment errors result from parallax errors, as the blade is optically positioned by the operator. The maximum deviation obtained in the several prototypes fabricated was 0.05 mm.

Aluminum is naturally a ductile material having a Poisson ratio of 0.35 [6], well above silicon. Its strength under compression is lower than silicon, with a Young modulus of 70 GPa [6]. Nonetheless, aluminum demonstrates to have the structural characteristics for the insertion forces involved in the penetration of an array into the brain [7]. Furthermore, it provides a bending range, which is desirable during insertion, avoiding needle breakage inside the neural tissue.

Alternatively, highly doped silicon has the mechanical characteristics needed for the insertion in the brain and the forces involved therein. Pure crystalline silicon has a Young modulus of 130 GPa [8] and a very variable Poisson ratio, being as little as 0.0064 up to 0.28 [8] due to the difference in the crystalline orientations. This means that silicon is brittle and strong under compression, although fragile while bending or while undergoing shear forces.

B. Electrical

Because monocrystalline silicon is not a good electrical conductor, a highly doped version must be used to provide a better electrical performance to it.

Boron doped P-type silicon can have a resistivity in the 0.1 Ωm range [2], while aluminum is an inherently good conductor, with electrical resistivity as low as 28 nΩm [9].

Aluminum offers an advantage in fabrication complexity, due to its good inherent electrical properties.

C. Comparison with silicon arrays

The use of aluminum as a bulk material offers advantages in the simplicity and number of fabrication steps when compared to silicon. Silicon-based arrays can be fabricated recurring to highly doped p-type silicon substrate either due to standard doping processes or alternative methods like thermomigration. Both of these approaches are challenge demanding.

Highly doped silicon can be etched with a mixture of HF and HNO_3, which is a hazardous acid, needing extra safety requirements.

The thermomigration approach requires a high temperature (in the order of 1400 ºC) furnace with the capacity to create a strong thermal gradient across the silicon wafer thickness (0.02 ºC/µm [10]). Besides not being available in the market, the experimental furnaces reported have the need of a great amount of maintenance [11]. Another disadvantage of thermomigration is the lack of precision and repeatability of the process [3], with a low production yield.

V – Functionalization

In order to make this electrode array functional, two fabrication steps need to be performed after the final etching stage.

First, the deposition of a non-oxidizing biocompatible electrical layer on the tip of the electrodes is required (e.g., titanium nitride, gold, iridium oxide, etc.). This thin-film is responsible for performing the interface between the biological domain to the electrical domain and vice versa. The aluminum only works as an electrical path to drive the signals between the electrode interface at the tip of the needle to the data acquisition electronics connected to the pad.

The other additional step is the passivation of the electrode's remaining surface. This passivation is achieved by depositing a thin layer of biocompatible coating. (e.g. Cyanoacrylate, Polyimide, Parylene-C, etc.). This coating is an electrical insulator, not only to avoid electrical interference from the surrounding tissues, but also to avoid the direct exposure of aluminum to the biological tissues.

VI – Conclusions

This paper proposed a different material for an electrode array bulk structure. With standard microfabrication techniques, it was demonstrated how aluminum may replace silicon wafers for the structural component of the electrode array.

With success, it was possible to fabricate an array with 1.5 mm long and 0.2 mm wide needles, fully individually addressable.

In comparison with the silicon-based solution, the proposed electrode structure provides a mechanical behavior fully compatible with the electrode's mechanical requirements. Although it presents itself as a more ductile material, it ensures the mechanical properties to withstand a safe insertion into the brain with less risks of needle breakage when compared to the silicon solution.

Electrically, the aluminum offers a highly conductive material from stock, avoiding the need for complex process of doping or thermomigration in order to establish conductive paths as the silicon case.

An aluminum bulk electrode can simplify the fabrication process of an electrode array, without neglecting its performance. Furthermore, with less number of processes involved, the proposed solution ensures a more consistent and reproducible fabrication process.

Acknowledgements

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