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High-aspect-ratio neural electrode array fabrication using thermomigration process

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Abstract

A novel fabrication process for a high-aspect-ratio recording and stimulation intracortical neural microelectrode array is described. Using a combination of dicing and KOH wet-etching, microspikes are formed on the surface of a *n*-type (100), 4 mm thick, silicon wafer. Deep 3 mm cuts are performed in order to produce sharped tip pillars of high-aspect-ratio (0.2x0.2x3 mm). Thermomigration is employed as a selective doping technique performing electrically insulated pillars due to the *pn* back biased junctions formed between each pair of *n*-type substrate and p^+ migrated trails. Gold is deposited over the spikes in order to have a good ionic interface with the neural tissue, while the remaining surface is passivated with a biocompatible layer of cyanoacrylate. The final result is a deep penetrating electrode array with potential new applications in neuroprosthetics' research field.

Keywords:Invasive neural electrode; Microelectrode array, thermomigration, silicon.

1. 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

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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).

Recent scientific advances in the neuroprosthetics therapies’ field and the need to gain scientific insights on how populations of neurons interact in the complex and distributed systems that generate behavior, triggered the development for long penetrating electrodes.

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. Many spike-shaped microelectrodes based on silicon that can be safely inserted into the brain have been successfully developed [1].

However, in order to selectively stimulate and record from single or multiple neurons each electrode in the array must be electrically independent from the others. A physical phenomenon known as thermomigration is used to selectively dope the silicon, creating conductive trails across the silicon wafer. After the doping procedure, a biocompatible ionic transducer is deposited over the electrodes’ tips, while the remaining surface of the array is insulated with a biocompatible material.

In this paper, it is presented a neuronal electrode array fabrication process based on the thermomigration technique.

2. Selective doping

Liquid droplets in a solid migrate in a thermal gradient because atoms of the solid dissolve into the liquid at the hot interface of the droplet, diffuse across the droplet, and deposit on the cold interface of the droplet. The resulting flux of dissolved solid atoms from the hot to the cold side of the droplet causes the droplet to migrate towards the hot end of the crystal [2].

This droplet movement applied to semiconductor and metal is often called thermomigration. The selective doping starts with the deposition of aluminum pads over an *n*-type silicon wafer. The aluminum pads deposited on the cold surface form droplets of silicon-aluminum liquid alloy, which tend to migrate along the temperature gradient towards the hot surface.

As the droplets move through the wafer, the silicon, now doped to saturation with aluminum, recrystallizes behind the droplets. Eventually the droplets traverse the entire thickness of the wafer, and deposit themselves on the hot surface. As aluminum is a *p*-type dopant, this process leaves a trail of p^+-type silicon in the *n*-type wafer [3].

Figure 1: Aluminum migration due to thermal gradient; a) Liquid alloy formation; b) Migration of silicon-aluminum liquid alloy towards hot surface.

(a) *(b)*

3. Fabrication procedure

The fabrication process starts by dicing 0.2x0.2x0.3 mm pillars on a 4 mm thick *n*-type (100) silicon wafer (*Figure 2b and Figure 3a*). In order to create sharp tips, the substrate with an array of pillars undergoes a KOH wet-etch process for 4 hours (*Figure 2c and Figure 3b*). The etching stage was performed with a 30 % KOH solution at 90 ºC.

On the following step, a thin-film of photolithographically patterned aluminum squares is deposited on the bottom surface of the silicon substrate (*Figure 2d)*. With a heat source underneath the substrate and a cooling convection system above it, a strong thermal gradient (0.02 ºC/µm [4]) is formed across the wafer and the thermomigration process starts. With a minimum of 660 ºC in the cold surface, the aluminum squares melt and form a silicon-aluminum liquid alloy which migrates through the silicon wafer's cross-section and establishes a conductive channel (*Figure 2e*).

A second dicing procedure is performed in order to create high-aspect-ratio 0.4x0.4x3 mm pillars with sharp tips (*Figure 2g and Figure 3c*). Because of the pillars' high-aspect-ratio and the silicon brittleness, the cutting speed needed to be below 1 mm/s. These pillars are electrically insulated from each other by the resulting back to back *pn* junction, which is formed between any pair of p^+ trails (*Figure 2f*).

Lastly the tips are coated with gold which is a good ionic transducer, and the remaining surface is passivated by depositing a biocompatible layer of cyanoacrylate (*Figure 2h*) [6].

Figure 2: Fabrication steps; a)Silicon substrate; b) Diced micropillars; c) Etched micropillars; d) Aluminum deposition; e) p+ trails due to thermomigration; f) Interelectrode insulation due to back biased pn junction; g) Diced sharped pillars; h) Gold deposition and polymer coating.

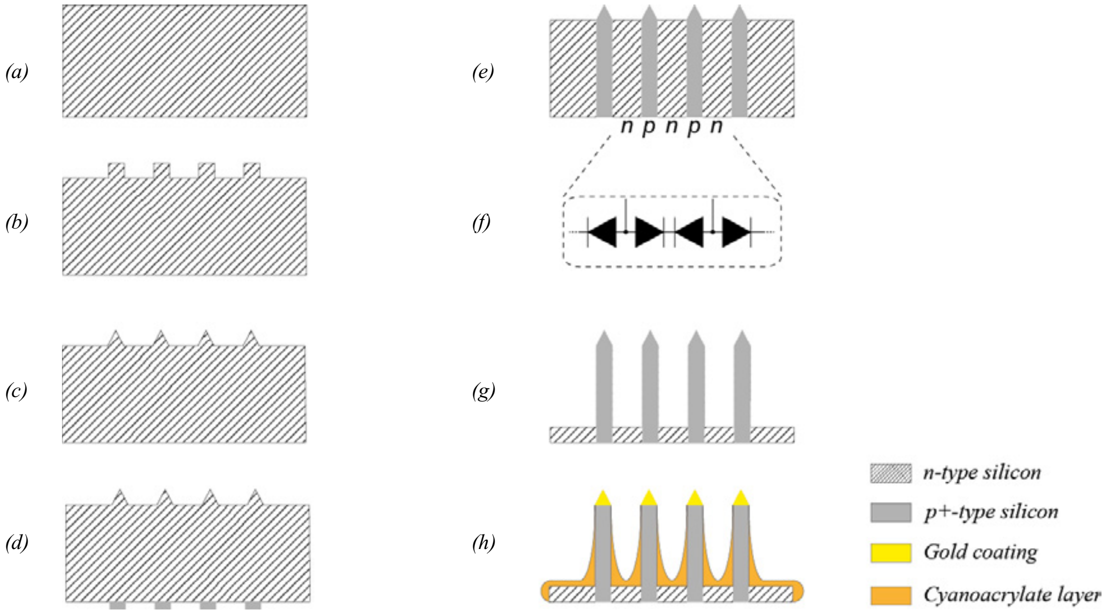
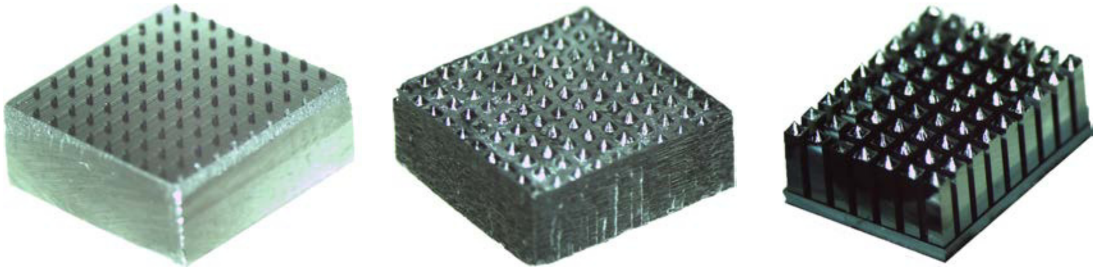


Figure 3: Photos of the fabricated prototype; a) Diced micropillars; b) Etched micropillars; c) Final electrode array.



(a) *(b)* *(c)*

4. Conclusion

A process to fabricate an invasive microelectrode array that enables deep reaching and individually addressable electrode has been presented. The fabrication procedure ensures a final structure with high-aspect-ratio electrodes. The presented approach of multi-dicing steps and thermomigration provides a consistent method of high-reproducibility. The method requires KOH as etchant instead of a HF, HNO_3 mixture, a hazardous acid, needing extra safety requirements, commonly used for etching highly-doped *p*-type silicon wafers.

The thermomigration phenomenon enables not only the definition of local conductive paths across the wafer for the biopotential signal drive, but also the formation of *pn* junctions for interelectrode insulation. The conductive channel uniformity is highly dependent on the temperature conditions that the wafer is subjected to. An evenly distributed heat below the wafer will practically eliminate irregularities in the doped trails, leaving behind only minor deviations.

The presented technique is a strong alternative for microelectrode array fabrication by combining KOH wet-etch and silicon dicing on a high-yield process.

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