Two Dimensional Metallic Microelectrode Arrays for Extracellular Stimulation and Recording of Neurons

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ABSTRACT

In this paper, a novel, inexpensive and reproducible technique is presented for the realization of metallic microelectrode arrays. Arrays of sixteen microelectrodes have been fabricated using bulk silicon etching technology and photosensitive polyimide processing. The arrays are fabricated on a silicon substrate using nickel as the structural material and gold as the exposed material at the neural recording sites. Silicon nitride serves as the insulating material for the shaft of the electrodes. Individual electrodes are 15 μm thick, 25 μm wide, 1.1 mm in length, and have a probe-to-probe spacing of 75 μm. The process used to fabricate the microelectrode arrays is compatible with standard integrated circuit fabrication technology. The arrays have successfully undergone repeated insertion into the olfactory bulb of laboratory rats.

INTRODUCTION

Over the past several decades, scientists and engineers have devised a variety of innovative techniques to make microelectrodes that can detect extracellular neural signals or stimulate neurons at specific sites. By using these devices to map brain function and to probe the dynamics of complex networks of neurons, we have increased our knowledge of the nervous system thus leading to applications in neural prostheses including the partial reactivation of paralyzed limbs, limited control over organ and gland functions, and auditory aids for the deaf. Some of the earliest work in the area of extracellular recording involved the use of individual metallic microelectrodes fabricated using small diameter wire [1,2]. The tips of these electrodes were formed using electrochemical sharpening techniques and insulated by immersing the electrodes in a lacquer-based solution. The electrode recording sites were established at the tip by removing the insulative layer using a high voltage discharge. Since the area of the recording site is a primary factor in determining the electrical characteristics of metallic microelectrodes, this technique often led to significant differences in the characteristic impedance from one electrode to the next due to variations in the recording site area.

The first microelectrodes fabricated using micromachining techniques were constructed of gold electrodes supported on thin silicon support beams [3]. The length of the electrode shafts were in the range of 10 μm to 50 μm with silicon dioxide serving as the electrode insulating material. Later, this process was revised to include multichannel probes fabricated on silicon shanks [4] with the integration of signal amplification and multiplexing circuitry [5-8]. Similar work has been performed by others, including multielectrodes which use polyimide as the electrode insulating material and use plasma etching to define vias in the polyimide for recording site areas [9]. Other microelectrodes fabricated using micromachining techniques include the diving-board electrode [10] for chronic *in vitro* recording and stimulation, electrode arrays fabricated on metallic substrates [11], the cone electrode [12] and various others [e.g. 13,14] for chronic applications in which nerve regeneration is required.

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ELECTRODE STRUCTURE

In this paper, a novel and inexpensive technique is demonstrated for the fabrication of passive microelectrode arrays using conventional microelectronics materials and cleanroom equipment. The technique demonstrated enables metallic arrays of probes to be fabricated on silicon substrates using a process which is compatible with standard IC fabrication technology. This allows for future integration of the signal processing circuitry into the same substrate housing the microelectrode structures. Present arrays utilize electroplated nickel as the structural material and a layer of electroplated gold for recording site and bonding pad areas. The process is also compatible with other, more biocompatible materials. The probe shafts are prismatic with cross sections varying from 15 x 20 μm^2 to 15 x 50 μm^2 and have a length of approximately 1 mm. This allows insertion deep into cortical tissue with minimal damage. The probe shafts are completely insulated with silicon nitride, a material which is superior to silicon dioxide and polyimide for chronic implantations where the insulating material must be impervious to ionic migration in saline environments [9]. The recording sites are defined using standard photoresist technology so that repeatable areas can be defined to insure minimal variation in the characteristic impedance of the array's electrodes. These microelectrode arrays will be investigated for use in acute and chronic nerve stimulation and recording applications.

INSERTION FORCE

To determine the critical load of a single buckled electrode shaft, the basic differential equation for the deflection curve of a beam is used [15]. The equation holds for the case in which the material is homogenous, the deformation of the shaft is elastic, and all rotations of the electrode shaft are small.

$$\frac{d^2 v}{dx^2} = -\frac{M}{EI}$$

where v is the lateral deflection of the shaft, $\hat{x}$ is the direction along the unbuckled electrode shaft, M is th bending moment induced by buckling, and EI is the flexural rigidity of the beam. For the case of insertio of the electrodes, the applied force is assumed to be axial and the probe shafts are modeled as rigidly supported on one end and pinned at the other end. Tl boundary conditions for this case are $v(x=0)=0$ ar $v(x=L)=0$ so that the solution to the above equatio becomes

$$P_{cr} = \frac{n^2 \pi^2 EI}{L^2} \text{ for } n = 1,2,3...$$

where n is the buckling mode and L is the length of the electrode shaft. Assuming typical values for microelectrode arrays fabricated to date, i.e. a probe shaft length of 1 mm, cross-sectional dimensions of 1 μm by 25 μm and a value of E equal to 210 GPa for the case of nickel as the structural material [15], the critical loading for an individual electrode, P_{cr}, is calculated to be 14.6 mN.

FABRICATION

The microelectrode arrays are fabricated using established micromachining techniques. The process utilizes silicon as the substrate upon which the cantilevered metallic probes are electroplated. Initially one side of a <100> oriented silicon wafer is heavily doped with boron (> 10^{20} atoms/cm^3) using high temperature thermal diffusion to form a 4 - 6 μm p^+ layer. Next, 3000 Å of silicon nitride is deposited on both sides of the wafer using plasma-enhanced chemical vapor deposition, PECVD. The Si_3N_4 on the undoped side of the silicon wafer is then patterned and etched (using photoresist as a mask and CF_4 plasma to etch the unmasked silicon nitride) to define both the area of the individual silicon die upon which the electrode arrays are fabricated and the area over which the cantilevered electrode bodies will be

positioned. After patterning the Si_3N_4 layer, the exposed silicon is anisotropically etched using bulk silicon etching techniques [16]. In particular, a 20% solution of potassium hydroxide is heated to 56°C, resulting in a <100> silicon etch rate of approximately 17.5 μm/hr. The p^+ boron layer serves as an etch stop for the silicon etching [17-19], resulting in a thin sacrificial membrane upon which the length of the metallic electrodes are fabricated and subsequently released. When the anisotropic etching of silicon is complete, a metal system consisting of adhesion layers and an electroplating seed layer is evaporated on the insulating Si_3N_4 film, Figure 1a. The metal system consists of 250 Å of titanium for adhesion between the Si_3N_4 and the overlying seed layer, 1500 Å of copper (or appropriate metal) as the electroplating seed layer, and 1500 Å of chromium as an adhesion layer between the seed layer and the overlying molding material used to electroform the microelectrode array. After deposition of the adhesion and seed layers, 20 μm of commercially available negative photosensitive polyimide (PSPI) is spun on the surface of the etched silicon wafer [20]. The polyimide is patterned into electroplating molds using G-line exposure (435 nm wavelength) to crosslink the unmasked regions and γ-butyrolactone-based developer to remove the unexposed regions, Figure 1b. The electroplating molds of the electrode shafts are positioned over the membrane regions for release later in the process. Next, electroplated metal is deposited into the molds using conventional electroplating technology, Figure 1c. Due to the superior chemical and thermal stability of polyimide, a wide variety of electroplating metals or combinations of metals can be deposited. To date, polyimide electroplating molds have been used to fabricate structures composed of gold, silver, nickel, copper and selected combinations of the four. Extending the list to include biocompatible metals such as platinum and palladium for chronic applications seems reasonable. Once the electroplating is complete, the polyimide is removed using a 30 wt% solution of KOH heated to 70°C. The seed and adhesion layers are then etched. When the molding is removed, the top and sides of the electrode structures are exposed so that an insulating layer of PECVD Si_3N_4 can be deposited on these surfaces. Photoresist is then used to define the electrode recording site areas along the length of the probe shafts or at the tip of the shafts. The silicon nitride is removed from the defined areas using CF_4 plasma, thus exposing the metallic conductor at the bonding pads and the recording sites. A sacrificial copper layer is then deposited, covering the top side of structure. Next, the p^+ membrane and the Si_3N_4 are removed from the membrane regions by etching from the backside of the wafer. As a result, the shafts of the electrodes are released and freely suspended, projecting outward from the silicon-base support. To complete the process, Si_3N_4 is deposited on the underside of the suspended electrode shafts and the

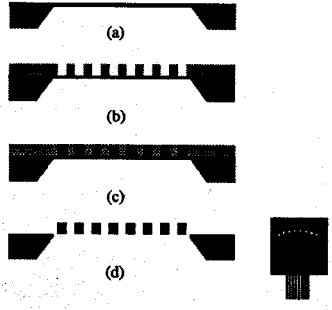

Figure 1. Microelectrode array fabrication procedure. (a) Create silicon membrane using the high temperature p+ doping, deposit an insulating layer of silicon nitride, and deposit the electroplating seed and adhesion layers, (b) Spin-on and pattern the photosensitive polyimide, (c) electroplate the microelectrode structures, (d) remove the seed and adhesion layers, deposit and pattern the overlying silicon nitride layer; plasma etch the p+ membrane and finish encapsulating the released probe shafts with silicon nitride.

sacrificial layer of copper is removed. The finished structure, Figure 1d, consists of an array of metallic microelectrodes which are supported by a silicon substrate and are completely insulated with silicon nitride except at the recording sites and the bonding pads.

RESULTS

The microelectrode arrays fabricated to date include those electroplated from gold cyanide electroplating solutions and low stress Watt's nickel baths [20]. Figure 2 shows an array consisting of sixteen individually isolated electrodes. Each electrode is 15 μm thick and 25 μm wide with a probe-to-probe spacing of 75 μm. The suspended portion of the electrode shaft has a length of 1.15 mm. The microelectrodes have been fabricated using nickel as

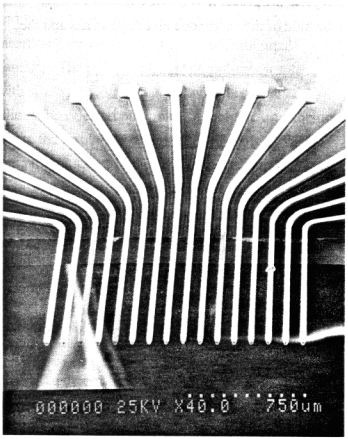

Figure 2. Scanning electron micrograph of a completed microelectrode array. The probes are 25 μm wide, 15 μm thick, 1.15 mm long and have a probe-to-probe spacing of 75 μm.

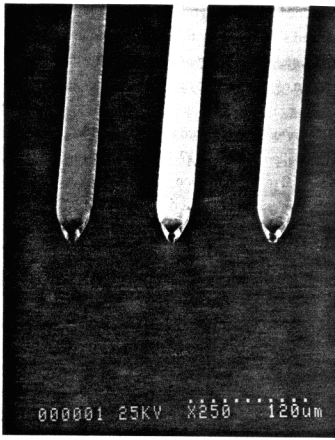

Figure 3. Scanning electron micrograph of the probe tips, revealing the sharp tips obtainable with the photosensitive polyimide process. The probes are 25 μm wide and 15 μm thick.

the primary structural material with a thin layer (2 μm of gold electroplated on top of the nickel. The electroplated gold layer serves several purposes. Firs gold has a low exchange-current density in biological fluids [3]. Secondly, the gold serves as a bonding layer for wire bonding between the microelectrode array and the package. Lastly, gold electrodes have been used extensively in previous studies [3,5-9]. Nickel is used as the primary structural material due to its high yield stress, so that during insertion of the probes the probability of inelastic bending is reduced. Also, as can be seen from Figure 2, the released electrode shafts are approximately straight due to the very low residual stress present in the electroplated nickel. Figure 3 shows a close-up of the electrode tips. The probe tips have been designed to minimize the insertion force needed to penetrate the pia mater, a

membrane closely adherent to the brain's surface. In Figure 4, the length of the electrode shaft is staggered in order to reduce the required insertion force for the array and for use in specialized experiments. The recording sites defined in the insulating layer of Si_3N_4 are 5 μm by 5 μm.

Metallic microelectrode arrays fabricated using this process have successfully been inserted into the olfactory bulb of laboratory rats. For testing purposes, the electrode shaft widths were varied from 20 μm to 40 μm. Arrays of sixteen electrodes with identical shaft lengths were then inserted into the olfactory bulb of laboratory rats. Electrode arrays of all widths were successfully inserted. In fact, the electrodes could be used repeatedly without evidence of deformation during insertion or upon inspection after withdrawal. Electrodes arrays with shaft widths greater than 30 μm caused a 2 - 3 mm inward depression of the pia mater before penetration of the membrane.

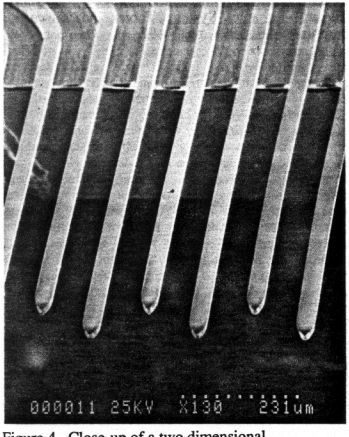

Figure 4. Close-up of a two dimensional microelectrode array with recording sites located at the tips of the staggered probe shafts. The stagger of the electrodes is 100 μm.

CONCLUSION

A technique has been presented for the realization of inexpensive metallic microelectrodes for the extracellular stimulation and recording of neurons. Microelectrode arrays composed of sixteen isolated nickel / gold electrodes were fabricated using a combination of bulk silicon etching technology and the photosensitive polyimide electroplating technology. The electrodes were insulated with Si_3N_4 for chronic applications where long term resistance to saline electrolytes is required. Neural recording sites were defined in the Si_3N_4 using a repeatable photoresist process to insure minimal variation in the electrode impedance's. Electrode arrays with varying electrode widths were repeatably inserted into rat olfactory bulb. Insertion forces of less than 14.6 mN / electrode were required.

ACKNOWLEDGEMENTS

The following groups deserve acknowledgement for the support necessary for the complete this research: International Society for Hybrid Microelectronics, Ciba Geigy Corp., Brewer Science Inc., OI-NEG TV Products Inc., and Silicon Quest Inc.

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