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STRETCHABLE MICRO-ELECTRODE ARRAY

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Abstract – **This paper focuses on the design consideration, fabrication processes and preliminary testing of the stretchable micro-electrode array. We are developing an implantable, stretchable micro-electrode array using polymer-based microfabrication techniques. The device will serve as the interface between an electronic imaging system and the human eye, directly stimulating retinal neurons via thin film conducting traces and electroplated electrodes. The metal features are embedded within a thin (~50 micron) substrate fabricated using poly (dimethylsiloxane) (PDMS), a biocompatible elastomeric material that has very low water permeability . The conformable nature of PDMS is critical for ensuring uniform contact with the curved surface of the retina. To fabricate the device, we developed unique processes for metalizing PDMS to produce robust traces capable of maintaining conductivity when stretched (5%, SD 1.5), and for selectively passivating the conductive elements. An in situ measurement of residual strain in the PDMS during curing reveals a tensile strain of 10%, explaining the stretchable nature of the thin metalized devices.**

Keywords - **Retinal prosthesis, PDMS metalization, Residual stress, Strechable microelectrode array**

I. INTRODUCTION

Millions of people suffering from diseases such as retinitis pigmentosa and macular degeneration are legally blind due to the loss of photoreceptor function [1]; however the neural cells to which the photoreceptors normally synapse remain viable, and electrical stimulation of these cells has been shown to result in visual perception [2]. These findings have generated worldwide efforts [1-5] to develop a retinal prosthesis device, with the hope of restoring vision to millions of patients. Two different approaches, subretinal and epiretinal, are being taken to develop the retinal implant. The subretinal device will be implanted in the photoreceptor region, the back of the eye (chow). This system is activated by light entering the eye, which will trigger a series of events that will lead to the stimulation of the appropriate retinal neurons. The subretinal implant is essentially taking over the function of the photoreceptors. The epiretinal device on the other hand is activated by an electrical signal. A miniature external camera captures the image and the information is transferred into the appropriate signal and sent wirelessly to the implant. The epiretinal device is implanted on top of the retina within the eye in direct contact with the ganglion cells.

With the advancement of microfabrication, integrated circuit, and wireless technologies, the once inconceivable goal of developing such a system now appears to be within reach. The cochlear implant is a working proof of the feasibility of this concept. The cochlear implant utilizes microelectrodes to stimulate auditory nerves allowing deaf patients to regain their sense of hearing (Rauschecker et al.). As part of a multi-laboratory research team to create an epiretinal prosthesis [5], we are developing an implantable, stretchable micro-electrode array using polymer-based microfabrication techniques. Technical approaches based on traditional silicon substrate are limited due to the mechanical rigidity and fragility of silicon, which makes it a hazard to be implanted into the eye. This device will serve as the interface between an electronic imaging system and the human eye in an retinal implant, directly stimulating retinal neurons via thin film conducting traces and electroplated electrodes.

Because the device is intended as a long-term implant that interfaces with delicate retinal cells, vital biological and physical design requirements must be met. The metal features are embedded within a thin substrate fabricated using poly (dimethylsiloxane) (PDMS), an inert biocompatible elastomeric material that has simultaneously very low water and very high oxygen permeability. The conformable nature of PDMS is critical for ensuring uniform contact with the curved surface of the retina. PDMS is able to withstand the chemical and physical conditions with out causing adverse side effects, making it an ideal material to implant within the eye. Robustness of the micro-electrode array is another important design consideration, as stretching and bending occur during fabrication and implantation of the device.

II. METHODOLOGY

1) *PDMS preparation and membrane thickness characterization*: PDMS prepolymer and its curing agent (*Sylgard* 184®, Dow Corning) were mixed at a 10:1 weight ratio and degassed to remove all air bubbles from the mixture [JO]. While in its liquid precursor state, PDMS is spun on gold-coated silicon wafers at spin rates varying from 500 to 7000 rpm for 20 and 90 seconds. The PDMS membranes were then cured at 66° C for 1 hour and the thickness was measured using a Tencor® P-10 surface profiler (Tencor Instruments) to determine membrane thickness as a function of spin rates. Fig. 3 shows the plot of membrane thickness versus spin speed.

2) P*atterning PDMS for electroplating*: The desired handle wafer for these fabrication processes was a silicon

wafer with gold sputtered approximately 2mm in from the perimeter. The gold coating on the silicon is needed as a seed layer for the electroplating process and also allows the membrane to be easily removed from the wafer later, but the ring left on the edge secures the PDMS membrane from lifting off during processing. Photoresist (AZ®PLP 100XT, Clariant) was spun onto the handle wafer and baked at 60° C for 30 minutes. The photoresist was then UV exposed using a high-resolution transparency as the photomask (Imagesetters, Pleasanton Ca.). Once the pattern was developed (AZ 400K: H_2O 1:3 ratio) PDMS was spun on for 90 seconds at a rate that produces a thickness less than the photoresist features. PDMS is kept at room temperature for 15 minutes or until streaks disappear before curing. Once cured, the tops of the photoresist features were gently swabbed to remove excess PDMS before stripping the photoresist. This ensures the removal of the photoresist and the complete clearance of the vias formed. Platinum was then electroplated through the PDMS layer to form an array of electrical stimulators.

3) *PDMS metalization through lift-off*: After electroplating thru the vias in the PDMS membrane, photoresist (AZ®PLP 100XT, Clariant) was spun on and baked at 60° C for 30 minutes. Prior to spinning on the photoresist the wafer was placed in an oxygen plasma (Barrel Etcher Branson/IPC, Smithkline Company) to oxidize the surface, resulting in an increase of surface energy. This eliminates the beading and ensures the formation of a smooth and uniform coat of the photoresist on the PDMS surface. It was put in the oxygen plasma for 1 minute at an RF power of 100 watts and oxygen flow at 1 torr. The features were then exposed and developed as previously described and placed for a second time in the oxygen plasma to treat the surface of the exposed PDMS to promote the adhesion of the metal. Gold was then evaporated onto the wafer (electron beam Boc coating technology) using titanium as the adhesion layer. Once gold is deposited the lift-off process was performed; the wafer was placed in acetone to remove excess metal and photoresist. The wafer was then prepared for passivation by rinsing with ethanol and drying gently.

4) *Electrode passivation*: Oxygen plasma treatment was performed again before passivation to ensure adhesion of the second layer. After rinsing with ethanol and drying the wafer was placed in oxygen plasma as described previously. A stencil-like mask was then applied, and the second PDMS layer was spun onto the substrate. The stencil was removed prior to curing, exposing the traces in regions where electrical connections will be made.

5) *Strain measurements in metalized PDMS*: PDMS was spun onto a handle wafer at a thickness of 70 μm and metalized as described previously. A micrometer is used to measure elongation, and resistance of the metal trace was monitored as the sample is stretched, with failure corresponding to an open circuit.

6) PDMS membrane stress measurements: A 47 μm thick film of PDMS was spun onto a gold-coated 4 inch silicon wafer. A Tencor FLX-2320 Thin Film Stress Measurement instrument was then used to monitor stress in the PDMS over time as it cured at 60° C and at room temperature after curing. Both single and 2-sided wafers were used. The Tencor instrument optically measures wafer curvature and residual stress is calculated from the Stoney equation [7]:

$$\sigma_{PDMS} = ET^2/[6t(1-v)] * (1/R_{PDMS} - 1/R)$$

where σ_{PDMS} is the stress in the PDMS (positive for tensile), E is Youngs modulus of the substrate, T is substrate thickness, t is film thickness, v is the Poissons's ratio of the substrate, and R and R_{PDMS} are the measured wafer radii at the start of and during PDMS cure.

III. Results & Discussion

To fabricate the device, we developed unique processes for metalizing PDMS and selectively passivating the conductive elements. An extension of the technique described by Duffy *et al.* [6] is used to create PDMS membranes with patterned vias that serve as electroplating forms for the metal electrodes. Platinum is then electroplated through the PDMS layer to form an array of electrical stimulators. Fig. 1a-f shows the fabrication process and associated images. Selective passivation of the metal traces and micro-electrode array is achieved with a second PDMS layer.

To route signals on the micro-electrode array, we have developed a PDMS metalization process for producing robust traces capable of maintaining conductivity when stretched. Uniaxial tensile tests performed on metalized PDMS substrates demonstrate that the traces remain continuous for strains of 5% (σ = 1.5). A micrometer was used to measure elongation, and resistance of the metal trace was monitored as the sample was stretched, with failure corresponding to an open circuit. Even after stretching to failure, the metal leads eventually reestablished continuity when the load was released, likely due to the viscoeleastic nature of PDMS.

Two factors contribute to the durability of the conducting traces. First, the PDMS is in a state of tensile residual strain resulting from the fact that it is constrained by a rigid substrate while it undergoes a volume contraction associated with the curing process. This strain was calculated to be 10% based on *in situ* measurement of the substrate curvature during curing (Fig. 2). The final residual stress in the PDMS film is 0.10 to 0.15 MPa, corresponding to a residual strain of 10% (stress = strain x biaxial modulus of PDMS). This result is consistent with 5% strain before failure of the metal traces in the uniaxial tensile measurements. Second, the metal film is deposited in a state of compressive residual stress, causing it to wrinkle slightly on the PDMS layer. When released from the substrate, the PDMS contracts, enhancing the compressive stress in the metal layer, and resulting in visible wrinkling of the metal lines as seen in the optical image in Fig. 1e. Thus, the traces remain in a state of compression even when

subjected to considerable tensile strain, consistent with the uniaxial tensile test results.

ACKNOWLEDGMENT

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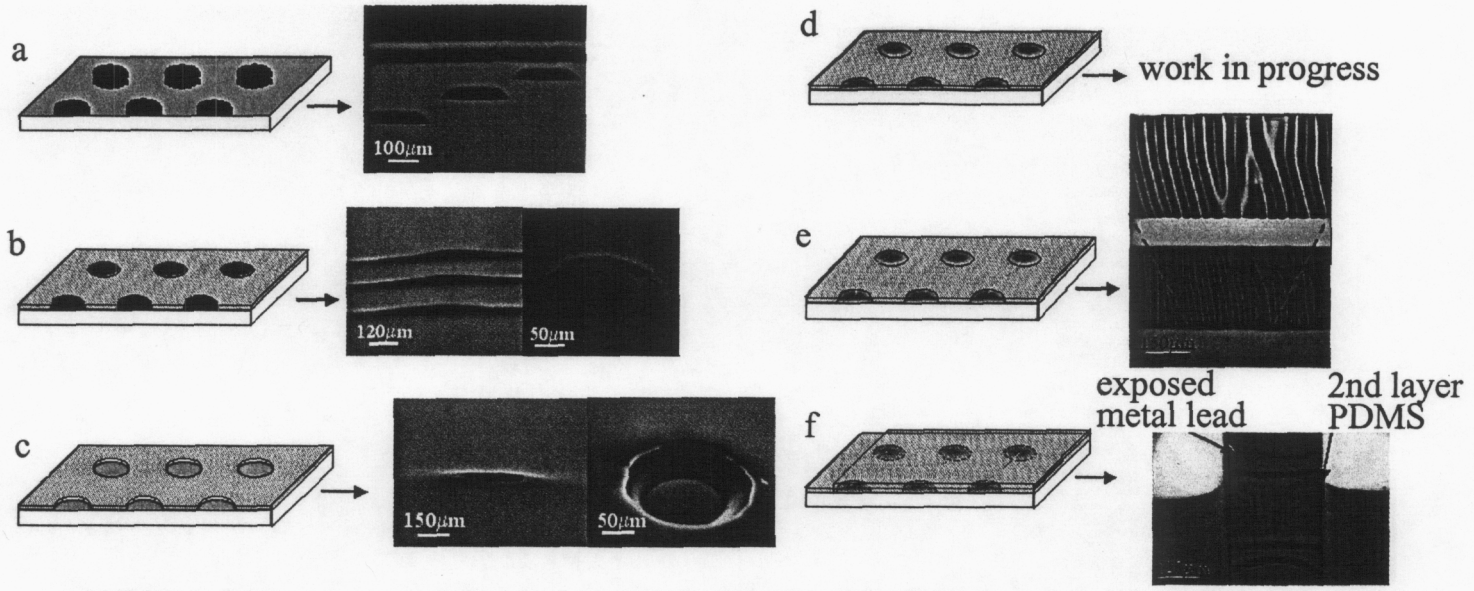

FIGURE 1. Fabrication process for the flexible micro-electrode array, with illustrations on the left and SEM and optical images of the features formed in each step on the right. a) Thick photoresist features are patterned on a handle wafer that has been pre-coated with a metal seed layer. b) A PDMS film is spun onto the wafer and cured in such a way that it does not form a continuous layer over the photoresist. c) Striping the photoresist in a suitable solvent results in a patterned PDMS film with vias through to the underlying seed layer. d) Platinum is then electroplated through the PDMS to form an array of electrical stimulators. e) Metal traces are deposited onto the PDMS to serve as an electrical interface to the micro-electrode array. f) Selectively encapsulating the micro-electrode array and the leads with a second PDMS layer for electrical passivation.

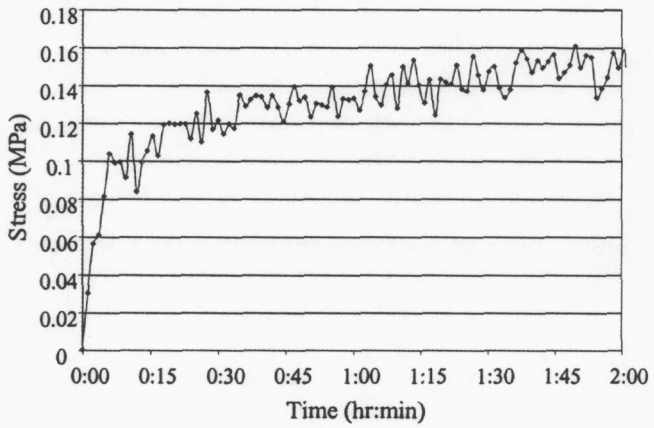

FIGURE 2. Evolution of residual stress during curing of PDMS at 60° C. A 47 μm thick film of PDMS was spun onto a gold-coated silicon substrate. A Tencor wafer curvature instrument was then used to monitor stress in the PDMS over time as it was cured at 60° C. The final residual stress in the PDMS film is 0.15 MPa, corresponding to a residual strain of 10% (stress = strain x biaxial modulus of PDMS). This result is consistent with 5% strain before failure of the metal traces in the uniaxial tensile measurements.

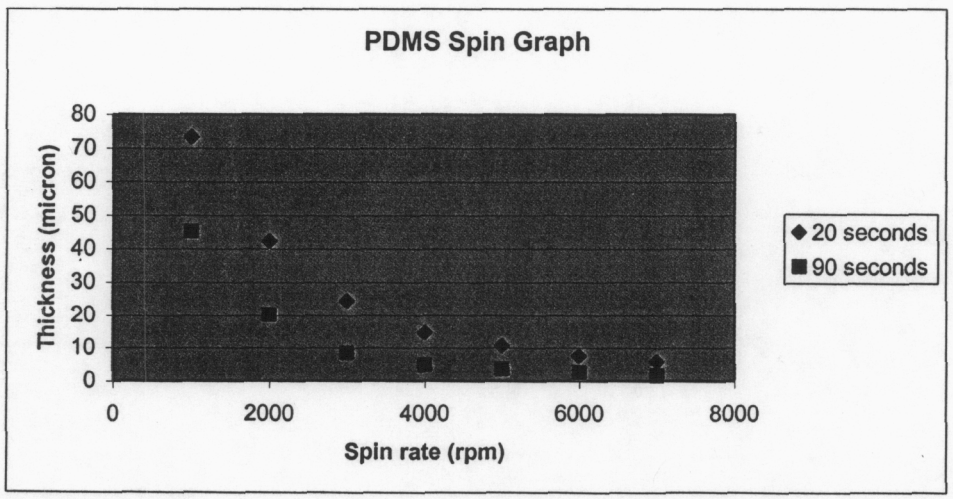

Figure 3. PDMS spin graph.