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Advancements in Fabrication Process of Microelectrode Array for a Retinal Prosthesis using Liquid Crystal Polymer (LCP)

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***Abstract*— Liquid Crystal Polymer (LCP) has been considered as an alternative biomaterial for implantable biomedical devices primarily for its low moisture absorption rate compared with conventional polymers such as polyimide, parylene and silicone elastomers. A novel retinal prosthetic device based on monolithic encapsulation of LCP is being developed in which entire neural stimulation circuitries are integrated into a thin and eye-conformable structure. Micromachining techniques for fabrication of a LCP retinal electrode array have been previously reported. In this research, however, for being used as a part of the LCP-based retinal implant, we developed advanced fabrication process of LCP retinal electrode through new approaches such as electroplating and laser-machining in order to achieve higher mechanical robustness, long-term reliability and flexibility. Thickened metal tracks could contribute to higher mechanical strength as well as higher long-term reliability when combined with laser-ablation process by allowing high-pressure lamination. Laser-thinning technique could improve the flexibility of LCP electrode.**

I. INTRODUCTION

Retinal prosthetic devices for restoring partial vision of the blind patients suffering from retinal degeneration such as age-related macular degeneration (AMD) and retinitis pigmentosa (RP) have been widely investigated by a number of groups worldwide [1-6]. Those devices are targeting to elicit a sense of light via electrical activation of remaining retinal cells using microelectrode array inserted into the sub-retinal [4, 6], epi-retinal [5], or supra-choroidal space [1-3]. Retinal implants up to date generally consist of a flexible microelectrode array establishing a neural interface with retinal cells and a hermetic package made of metal or ceramic for encasing electronics. Such microelectrode array is required to be high-density, compatible with micro-fabrication process, long-term reliable, mechanically robust but minimized physical stress to the retina and the eye.

Thin-film retinal electrode arrays fabricated through photolithography have been developed based on various polymer materials such as polyimide, parylene and silicone elastomers [7-9]. While the safety and efficacy of those electrodes have been demonstrated in previous *in vitro* and *in vivo* studies, their long-term reliability still remains questionable mainly due to high moisture absorption rate of conventional polymer materials and the insufficient interlayer adhesion strength resulting in degradation and delamination under aqueous condition.

Recently, liquid crystal polymer (LCP) has been receiving increasing interest as an alternative biomaterial for implantable biomedical devices including retinal implant [3], depth probe [10] and intraocular pressure sensors [11]. LCP is biocompatible material which is mechanically stable and chemically inert, and can be thermally bonded to each other without use of adhesives. The moisture absorption rate of LCP (<0.04%), that is much lower than those of polyimide (~2.8%) and parylene-C (0.06~0.6%), is the most promising nature that could significantly improve the longevity of polymer-based implantable devices when properly processed. In the previous study, LCP encapsulation has been proven to provide superior long-term reliability than polyimide and parylene-C through accelerated soak test [12].

For these advantages of LCP, we are developing an all-polymer retinal prosthesis using LCP as substrate as well as packaging material in which all the components (electrode, coil, circuits) are monolithically integrated on the multilayered LCP substrate (See Fig. 1) [3]. Monolithic encapsulation technology can eliminate the need for feedthrough array (realizing “buried” feed through) greatly simplifying the device fabrication process. This novel LCP-based retinal implant is expected to achieve important improvements for development of retinal prosthetic devices in terms of miniaturization, monolithic fabrication and long-term reliability. A LCP retinal electrode array is a part of this project for achieving efficient and reliable neural interface with retinal cells.

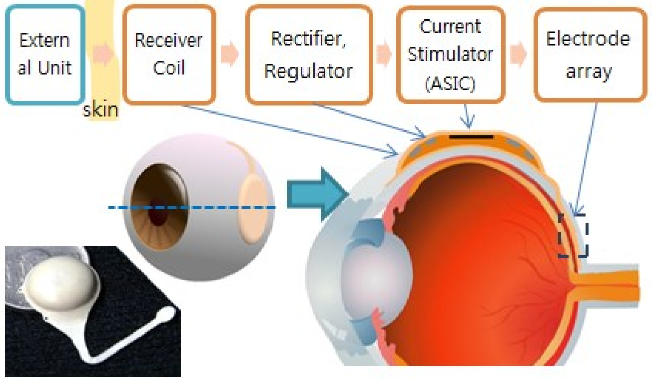

Figure 1. Schematic diagram of an all-LCP retinal prosthesis

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A fabrication method of a microelectrode array from LCP has been developed by Lee et al. using photolithography of evaporated gold film and fusion-bonding lamination of pre-drilled cover layer for site-window opening [13]. Although this LCP-based retinal electrode array has been shown to be long-term reliable through blister test and to effectively elicit cortical response from rabbit visual cortex via supra-choroidal stimulation, there is still room for improvements in its fabrication process for higher mechanical robustness and long-term reliability.

One limitation of the preciously developed electrode is the fragile metal tracks of a few hundreds nanometers in thickness. Such thin film metal layer lacks robustness against mechanical stress and cannot withstand high load pressure (>150kPa) during thermal lamination process. The higher load pressure is applied during fusion-bonding process, the stronger interlayer adhesion of LCP films is achieved, thus leading to improved long-term reliability. However, the maximum applicable pressure was limited in previous process for two reasons: 1) fragility of thin metal tracks and 2) narrowing down of site opening when the cover layer was fused and pressed. These issues could be resolved by line thickening via electroplating and site opening through laser-ablation of cover LCP layer.

Another drawback of previous process was the relatively high stiffness of electrode which is an unfavorable property for being inserted into soft, delicate and curvilinear retinal space. The LCP electrode thickness could not be less than 50 μm due to limited option of commercially available film products (A 25 μm-thick film is the thinnest). Despite the similar Young's modulus (2~4 GPa), LCP electrode had higher stiffness than polyimide- and parylene-based electrode of which thickness could be readily controlled in spin coating or vapor deposition process. Dry etching can be used, but it is a time-consuming task due to low etch rate (~0.25 μm/min reported in [14]). In order to enhance the flexibility of LCP electrode, we developed a fast and simple laser-ablation process to thin the 50 μm LCP electrode by precisely controlling the laser parameters.

In this research, we report the advancements of fabrication techniques for a LCP retinal electrode array, as a part of our LCP-based retinal implant, including electroplating, laser-ablation and laser-thinning in order to achieve higher mechanical robustness, long-term reliability and flexibility.

II. MATERIALS AND METHODS

A. LCP-based Retinal Prosthesis

The LCP-based monolithically encapsulated retinal prosthesis is illustrated in Fig 1. It consists of dome-shaped system package (15 mm diameter, 1.5 mm max. thickness) that conformally attached on eye-surface and electrode array to be inserted into supra-choroidal space. The package is encasing planar coil embedded in the package lid, 16-channel stimulating IC and surrounding circuit for generating biphasic current pulse to stimulate the retina via microelectrode array. All these components are monolithically integrated on the multilayered LCP substrate.

B. Electroplated LCP Electrode Array

The advanced fabrication process for LCP-based retinal electrode array using electroplating up to 5 μm and laser-ablation for site-window opening is schematically illustrated in Fig 2. First, seed layer of Ti/Au (50/100 nm) was evaporated onto 25-μm-thick LCP film (Vecstar series, Kuraray) (Fig. 2(a)) and gold-electroplated using patterned 10 μm-thick photoresist (AZ4620) layer as a mold (Fig. 2(b)-(c)). After removal of photoresist and seed layer (Fig. 2(d)), a cover LCP layer (25 μm -thick) was laminated by thermal bonding process (Fig. 2(e)) and site window was opened using UV laser-machining (Fig. 2(f)). Considering that LCP interlayer adhesion gets stronger with higher load pressure applied during thermal pressing (not published data), extended long-term reliability of the retinal electrode is expected when the metal tracks were thickened and laminated with greater force (>600 kPa).

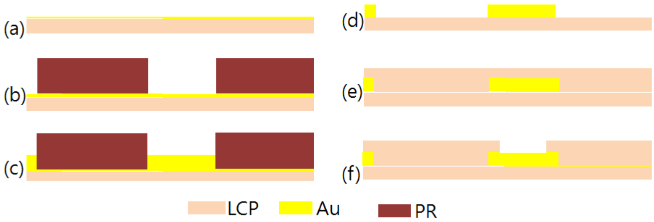

Figure 2. Schematic illustration of advanced fabrication process of LCP retinal electrode including electroplating and laser-ablation

C. Laser-ablation for site opening

Feasible techniques to open the site windows of LCP-based electrode include lamination of pre-drilled cover, dry etching and laser-ablation. The first one was developed in [13] and has been currently used, but in case of opening diameters in the range of sub-millimeter, shrinkage of opening tends to be significant as a result of reflow of fused cover layer when high pressure was applied in lamination process. The lamination pressure cannot be compromised as it is a critical factor for strong interlayer adhesion and thus for long-term reliability

An alternative is the use of laser-ablation to expose the metal site from the overlying LCP cover layer as in the Fig. 2(e)-(f). The key factor for successful ablation is to completely remove the overlying LCP layer but not to affect the surface morphology of underlying metal site. For that, we tailored the LCP ablation process using a 355 nm UV laser machine (Samurai system, DPSS, CA) by varying the factors of power, pulse rate, scan speed and pulse width. After the optimal pulse rate had been established that selectively etch away the LCP cover with minimized effect on metal surface, the amount of power (combination of power (%), scan speed, pulse width and repetition time) was determined for the complete removal of LCP cover layer.

To ensure the complete ablation of overlying LCP and to observe any adverse effect on the surface morphology of exposed gold site, the test sample was assessed through scanning electron microscopy (SEM) and electrical impedance spectroscopy (EIS) for comparison with an electroplated gold site without laser treatment.

D. Laser-thinning for higher flexibility

Grating patterns were engraved from the both face of the electrode using identical laser system as the site opening, in order to thin the LCP electrode down to the thickness of 20~30 μm which is comparable to conventional polyimide-based electrode arrays. Laser parameters along

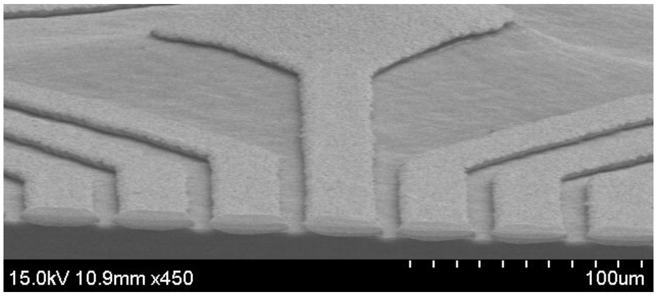

Figure 3. SEM image of fabricated metal tracks and pads on LCP using electroplating (before cover layer lamination).

Table I Laser parameters for ablation and thinning process

	Ablation	**Thinning**
Power (%)	0.1	80
Scan speed (um/s)	1000	100
Pulse rate (kHz)	65	20
Pulse width (us)	10	20
Repetition	5	1

with the grating pitch were optimized for precise control over the amount of etching.

The thickness of thinned electrode was measured through cross-sectional SEM images and enhancement of flexibility was quantitatively evaluated through force measurement in bending test as illustrated in Fig 6(a), following the experimental protocol presented in [10].

III. RESULTS

A. Electrode fabricated by electroplating and laser-ablation

A SEM image of LCP-based electrode array fabricated by electroplating of gold metal patters up to 5 µm is shown in Fig. 3 without cover layer. The line width and spacing are 25 µm and 10 µm, respectively.

Laser parameters for opening the site window by ablation of overlying LCP layer as well as for laser-thinning process are tabulated in Table I. It has been found that the gold pad was barely affected by laser beam with higher pulse rate than 65 KHz by which could effectively ablate the LCP cover layer. The SEM image of ablated site opening of 200 µm diameter is shown in Fig. 4(a). The slope of laser-ablated sidewall was approximately 68°. In the test sample, the cover layer was intentionally weakly laminated and peeled off after site opening, in order to examine any adverse effect on the surface morphology of gold pad as a result of exposure to laser beam during the ablation process. As can be seen from the SEM image in Fig. 4(b), the laser-ablation process did not induce significant change in the surface morphology of electroplated gold site but minor residues which could be readily removed by oxygen plasma. The preservation of gold surface could be also confirmed through the comparison of impedance spectrum of laser-opened electrode with non-treated electroplated gold pad as shown in Fig. 5. The magnitude of impedance at 1 kHz increased from 7.6 kΩ of electroplated site as it is to 9.8 kΩ of laser-opened site. The

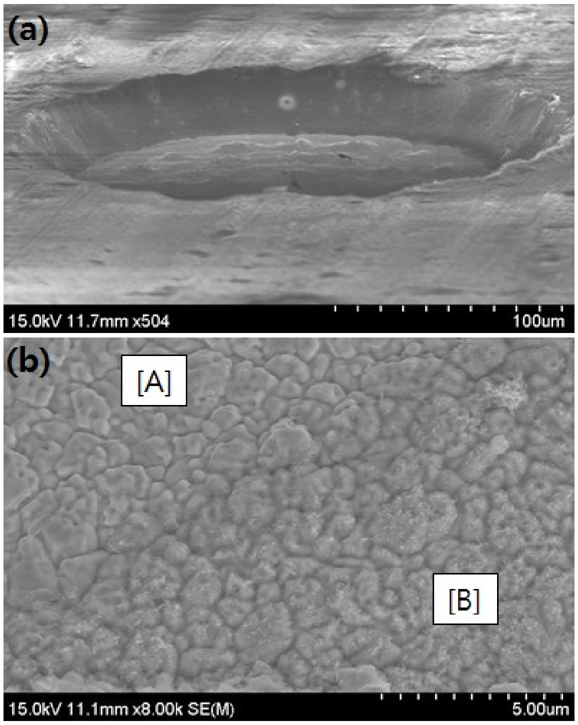

Figure 4. SEM image of site opening through laser-ablation (a) 200um-diameter electrode opening, (b) comparison between surface morphology of non-ablated [A] and ablated Au pads [B]

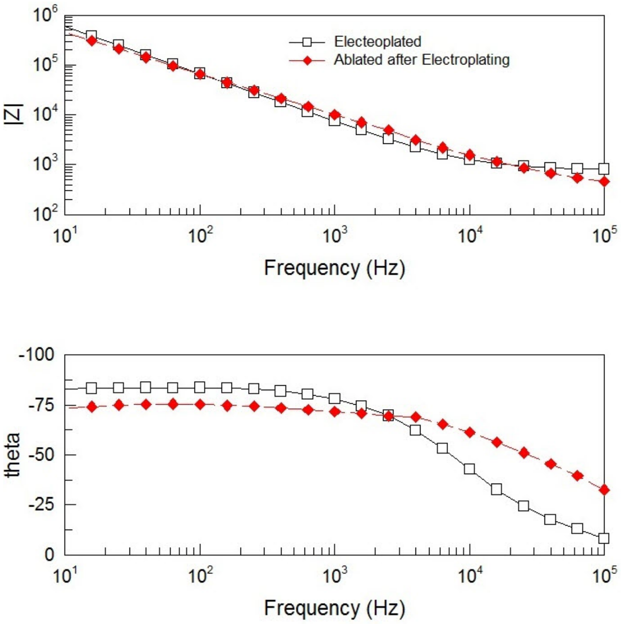

Figure 5. Comparison of impedance spectrum between laser-opened gold electrode and non-treated electrode just after electroplating: magnitude (top) and phase (bottom).

increased impedance is mainly attributed to the decreased roughness of laser-attacked gold site.

B. Laser-thinning of a LCP electrode array

Engraving 50 µm-pitch gratings with laser parameters of Table 1, a 50 µm-thick LCP electrode could be evenly thinned down to approximately 30 µm thickness as shown in Fig. 6(b). The enhancement of flexibility was quantitatively measured

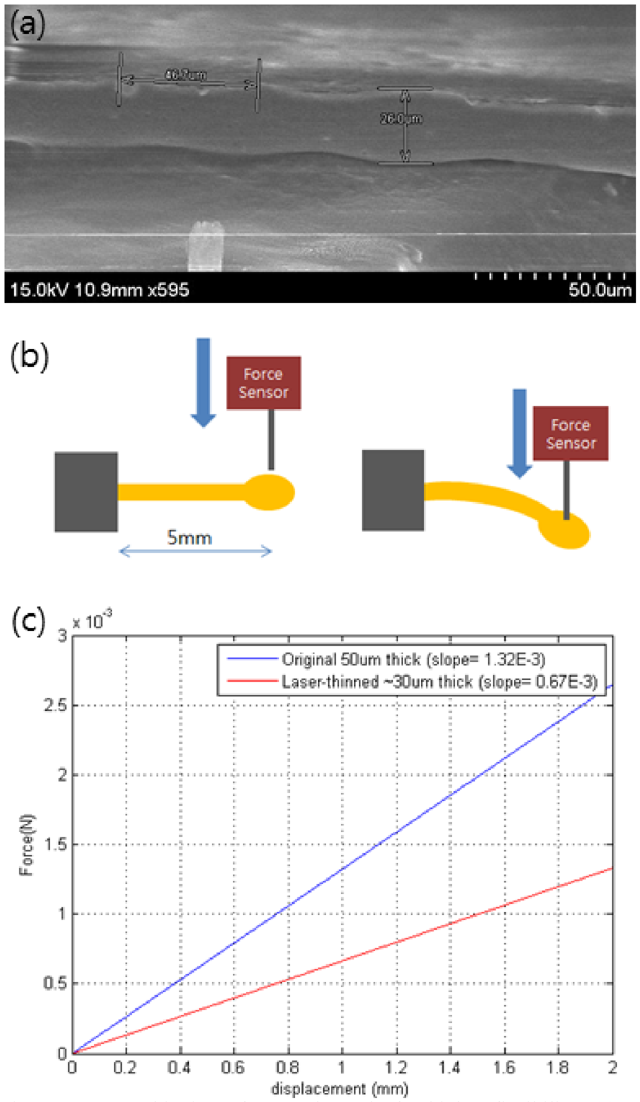

Figure 6. Laser-thinning of LCP electrode for higher flexibility: (a) a cross-sectional SEM image of thinned electrode down to ~30 µm thickness; (b) the experimental setup for force measurement from bending test; (c) comparison of bending force measurement between original 50 um-thick electrode and 30 um-thick thinned electrode.

through force measurement in bending test and its result was plotted in Fig. 6(c) which represents the measured force required to bend the test electrode with one end clamped. The acquired data was fitted with polynomial of degree 1 using Matlab. By comparing the slopes of fitted lines reduced from 1.3 mN/mm (original) to 0.67 mN/mm (laser-thinned), it could be confirmed that bending force decreased by about half using laser-thinning process which suggests improved flexibility of LCP electrode.

IV. DISCUSSION AND CONCLUSION

In this research, we developed advanced fabrication process of LCP-based retinal electrode array using electroplating, laser-ablation and laser-thinning techniques in order to achieve higher mechanical robustness, long-term reliability and flexibility. Thickened metal lines enhanced mechanical robustness and are expected to improve long-term reliability when combined with laser-ablation process by allowing lamination with higher pressure. Higher flexibility of the electrode by means of laser-thinning is expected to minimize the trauma of surrounding cells in chronic retinal implantation.

Our future plans are to verify those advantages of new fabrication processes through long-term experiments including accelerated soak test to evaluate long-term reliability and chronic implantation of electrode into animal retina for more than a year to examine any tissue damage. We are also developing electrodeposited iridium oxide (EIROF) layer onto the electroplated gold sites for higher charge capacity and lower impedance at neural interface.

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