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Tae Mok Gwon

A Polymer Cochlear Electrode Array: Atraumatic Deep Insertion, Tripolar Stimulation, and Long-Term Reliability

Doctoral Thesis accepted by
Seoul National University for the Degree of Doctor
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Supervisor's Foreword

Conventional cochlear implants have gained success through many scientific discoveries and engineering innovations and established their effect on impaired cochlear neural functions. Worldwide, there are tens of millions of people who need these implantable devices to hear sound and pursue basic life. And yet, in spite of technological advancements, current cochlear implants are too costly to expect all potential recipients to benefit. Therefore, a hope was there that some method will be available where economies of scale can apply and thus the most effective devices can be supplied at a cost low enough so all those in need can benefit. Current metal-based cochlear implants have limits in this aspect, and thus the search was on for a new type of cochlear implant using a new class of material and accompanying technology.

Polymers have been widely used in many biomedical applications due to their applicability to batch processing as well as their inherent material properties such as being flexible. Our group noted liquid crystal polymer (LCP), a class of thermoplastic polymer, as the one that can meet our needs for making low-cost neural prosthetic implantable devices. LCP's outstanding water absorption rate (<0.04%) is what makes it suitable for monolithic encapsulation of electronic components. As a polymer, the material allows easy passage of electromagnetic signals through it, which enables smaller, antennae-integrated implantable electronics package compared to that made of metals. LCPs are available in film form so that microelectronic fabrication techniques can be applied to neural interfaces that can be monolithically integrated with electronics on the same LCP substrate in a seamless way, thus enhancing long-term reliability as well as cost-effectiveness.

The work presented in this thesis is associated with the development of LCP-based cochlear electrode array for clinical use. The author has designed, fabricated, and evaluated LCP-based cochlear electrode array for an improved polymer-based cochlear implant. In this study, in contrast to a conventional cochlear implant which is composed of titanium-encased electronics and wire-based multichannel electrode array, the author aims to develop and evaluate an LCP-based cochlear implant using thin-film processes and microelectromechanical system (MEMS) technologies which are compatible with mass production. The thesis deals with three key topics: atraumatic deep insertion, tripolar stimulation, and long-term reliability. Atraumatic cochlear electrode array has become indispensable in state-of-the-art cochlear implants such as electric acoustic stimulation (EAS), wherein the preservation of residual hearing is significant. In this work, a novel tapered design of LCP-based cochlear electrode array is presented to fulfill such goals. Next, local tripolar stimulation using multilayered electrode sites are shown to achieve highly focused electrical stimulation to reduce channel interaction which should be avoided for high-density and pitch-recognizable cochlear implant. Lastly, this thesis addresses another vital issue of the long-term reliability of the polymer-based neural implants. After suggesting a new method of forming mechanical interlocking to improve polymer–metal adhesion, the author performs accelerating aging tests and analyzes comprehensive and systematic review to verify the method's efficacy.

These topics have been thoroughly examined through various in vitro and in vivo studies. Verification foretells the development of LCP-based cochlear electrode array for an atraumatic deep insertion, advanced stimulation, and long-term clinical implant. The new cochlear electrode arrays have been proven safe, effective, and reliable. The contents of this thesis contribute to expansion of use of LCP in implantable neural interfaces and are worthy of following in other biomedical application.

Seoul, Korea (Republic of) Prof. Sung June Kim
February 2018

Abstract

Biocompatible polymers have gained widespread interest for implantable biomedical applications owing to their flexibility and compatibility with micro-fabrication processes. A liquid crystal polymer (LCP) is an inert, highly water-resistant, and thermoplastic polymer suitable for the encapsulation of electronic components and as a base material for fabricating neural interfaces. LCP-based implantable devices have salient benefits in terms of performance and reliability owing to their extremely low water absorption rate (<0.04%) and applicability for monolithic integration in neural interfaces and electronics packaging. In this dissertation, a new design for LCP-based neural interfaces especially for cochlear electrode arrays is proposed and evaluated in terms of its fabrication process, functionality, and reliability. The following issues of an LCP-based cochlear electrode arrays were studied: atraumatic deep insertion, tripolar stimulation, and long-term reliability.

Flexible LCP-based cochlear electrode arrays have been studied, but no electrode structure has been designed for atraumatic insertion. An atraumatic cochlear electrode array has become essential for high-performance cochlear implants, such as electric acoustic stimulation (EAS), where the preservation of residual hearing is important. A new design for an LCP-based cochlear electrode array for atraumatic implantation that uses precise batch fabrication and a thermal lamination process is proposed, which is unlike conventional wire-based cochlear electrode arrays. Multilayered structure with variable layers of LCP films depending on the parts of the array was designed to achieve a sufficient degree of basal rigidity while maintaining a flexible tip, and a peripheral blind via was used to reduce the width of the array. The resultant electrode array was 0.3 and 0.75 mm in diameter at the tip and base, respectively. In vitro force measurements in a customized experimental setup revealed that the insertion force (with a displacement of 8 mm from a round window) and the maximum extraction force are 2.4 and 34.0 mN, respectively. Five human temporal bone insertion trials showed that the electrode arrays can be inserted from 360 to 630° without trauma at the basal turn. Electrically evoked auditory brainstem responses were successfully recorded in a guinea pig

model, which confirms the efficacy of the array. Hearing preservation and tissue reaction were investigated during implantation of the LCP electrode array and 4 weeks afterward.

Channel interaction is an important consideration for high-density, pitch-recognizing cochlear implants. There have been efforts to increase distinct stimulation channels using advanced focused current stimulation methods, including tripolar stimulation. In this dissertation, structural considerations on electrode sites are discussed for locally focused stimulation. A three-dimensional (3D) arrangement of electrode site in multilayered structure can be fabricated because differently patterned LCP layers can be merged into one substrate using thermal compression bonding. The 3D electrode site structures for locally tripolar stimulation are simulated about an electrical field distribution using the finite element method. An LCP electrode array of center stimulation channels with sidewall auxiliary channels for tripolar stimulation is fabricated based on the result of simulation. Compared to conventional monopolar and tripolar stimulation, locally tripolar stimulation on the proposed electrode site structure is more focused through in vitro measurements, which show the spreading of electrical stimulation in electrolytes.

Device reliability is one of the most significant issues in polymer-based neural prostheses. Two technical strategies are suggested in this dissertation. One strategy adopts a mechanical interlocking structure at the metal–polymer interface, which was started by J. H. Kim. This study extends his work and analyzes the impact of the strategy in terms of device reliability. The polymer–metal interface is vulnerable to water penetration that causes device failure. The goal is to suggest a feasible fabrication method using mechanical interlocking to improve polymer–metal adhesion in polymer-based neural electrodes and evaluate its impact on device reliability quantitatively through in vitro measurements. After the metal patterns with undercut profile cross sections are fabricated using a dual photolithography process and electroplating, the LCP interlocks with the metal during the lamination process. In a 180° peel test, the average maximum adhesion force of the samples with and without mechanical interlocking was 19.24 N and 14.27 N, respectively. In vitro accelerated soak tests that consist of interdigitated electrode patterns and a customized system for measuring the leakage current show that samples with and without interlocking fail to function after 224 days and 185 days, respectively, in a 75 °C saline solution. Scanning electron microscopy revealed that the interlocked LCP–metal interfaces remained intact after water leakage.

The other strategy is to use dielectric materials in LCP-based neural implants. Dielectric materials, such as silicon dioxide and silicon nitride, have been used in neural implants to prevent water and ion penetration. In addition to these features, dielectric materials can maintain metal patterning during the lamination bonding process, which causes migration of metal patterning on the LCP substrate. Preliminary tests—including a peel test to compare LCP–dielectric interface adhesion strength to that of an LCP–LCP interface, and thermo-compression bonding of LCP and dielectric materials with metal patterning to observe metal migration—were performed with consideration to the role of dielectric materials in

the LCP-based device and their effects on device reliability. The LCP–dielectric interface is more adhesive than the weakly bonded LCP–LCP interface, and there is no metal migration after the lamination process (295 °C, 1 MPa). The results confirm the feasibility of the strategy.

Finally, a review of the long-term reliability of LCP-based neural prosthetic devices, including recently developed enabling technologies, demonstrated prototype devices, their performance capabilities, and theoretical fundamentals, is presented. Verification shows the possibility of the development of cochlear electrode arrays for atraumatic deep insertion, advanced stimulation, and long-term clinical implants.

Keywords: Polymer-based neural prosthesis · Cochlear electrode array · Liquid crystal polymer · Atraumatic insertion · Focused stimulation · Long-term reliability

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Parts of this thesis have been published in the following articles:

Some parts of this dissertation are extracted and adapted from the journal publications which were published during the course of this study:

- Tae Mok Gwon, Kyou Sik Min, Jin Ho Kim, Seung Ha Oh, Ho Sun Lee, Min-Hyun Park, and Sung June Kim, “Fabrication and evaluation of an improved polymer-based cochlear electrode array for atraumatic insertion,” *Biomedical Microdevices*, 17(2), 2015.
- Tae Mok Gwon, Jin Ho Kim, Gwang Jin Choi, and Sung June Kim, “Mechanical interlocking to improve metal-polymer adhesion in polymer-based neural electrodes and its impact on device reliability,” *Journal of Materials Science*, 51(14), pp. 6897–6912, 2016.
- Tae Mok Gwon, Chaebin Kim, Soowon Shin, Jeong Hoan park, Jin Ho Kim, and Sung June Kim, “Liquid crystal polymer (LCP)-based neural prosthetic devices,” *Biomedical Engineering Letters*, 6(3), 2016.

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Contents

Abbreviations

ABR	Auditory Brainstem Response
ASIC	Application Specific Integrated Circuit
CSCc	Cathodic Charge Storage Capacity
CVD	Chemical Vapor Deposition
DAC	Digital to Analog Converter
DBS	Deep Brain Stimulation
EABR	Electrically evoked Auditory Brainstem Response
EAS	Electric Acoustic Stimulation
EIS	Electrochemical Impedance Spectroscopy
FEM	Finite Element Method
FIB	Focused Ion Beam
FPC	Flexible Printed Circuit
ICP	Inductively Coupled Plasma
IDE	Interdigitated Electrode
ISO	International Organization for Standardization
LCP	Liquid Crystal Polymer
MEMS	Microelectromechanical System
MRI	Magnetic Resonance Imaging
MTTF	Mean Time To Failure
PBS	Phosphate Buffered Saline
PCB	Printed Circuit Board
PFOA	Perfluorooctanoic Acid
PTFE	Polytetrafluoroethylene
PWM	Pulse Width Modulation
RF	Radio Frequency
SEM	Scanning Electron Microscopy
SPL	Sound Pressure Level
TEM	Transmission Electron Microscopy

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