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The First Neural Probe Integrated with Light Source (Blue Laser Diode) for Optical Stimulation and Electrical Recording

HyungDal Park, Hyun-Joon Shin, Il-Joo Cho, Eui-sung Yoon,
Jun-Kyo Francis Suh, Maesoon Im, Euisik Yoon, Yong-Jun Kim and Jinseok Kim

Abstract— **In this paper, we report a neural probe which can selectively stimulate target neurons optically through Si wet etched mirror surface and record extracellular neural signals in iridium oxide tetrodes. Consequently, the proposed approach provides to improve directional problem and achieve at least 150μm gap distance between stimulation and recording sites by wet etched mirror surface in V-groove. Also, we developed light source, blue laser diode (OSRAM Blue Laser Diode_PL 450), integration through simple jig for one-touch butt-coupling. Furthermore, optical power and impedance of iridium oxide tetrodes were measured as 200μW on 5mW from LD and 206.5kΩ at 1kHz and we demonstrated insertion test of probe in 0.5% agarose-gel successfully. We have successfully transmitted a light of 450nm to optical fiber through the integrated LD using by butt-coupling method.**

I. INTRODUCTION

THERE have been numerous efforts to understand nervous systems and develop treatments for its disorders. Patch clamp has been explored as an effective tool to record intracellular neural signals with high signal-to-noise ratio but the simultaneous access of multiple neurons is limited due to manual operation of single electrode [1]. Various MEMS neural probes have been introduced to simultaneously record as well as stimulate multiple-sites for studying central nervous system at the cellular level [2-4]. Optical stimulation has recently been reported as an alternative to electrical stimulation with potential advantages such as noncontact stimulation and investigated to selectively stimulate the specific nerves. Several methods have been tried to stimulate genetically modified neurons using an external light source such as laser coupled optics [5] or LED (light emitting diode) [6]. In these methods, neurons are directly stimulated from an external light source implemented in a separate device by optically focusing to target locations. However, this makes it difficult to record neural signals close to the stimulating region. Additionally, a recent report on optical stimulation still has a large gap between the stimulation and recording sites more than 0.4mm [7]. Also, conventional neural probe for optical stimulation coupled to external huge laser source

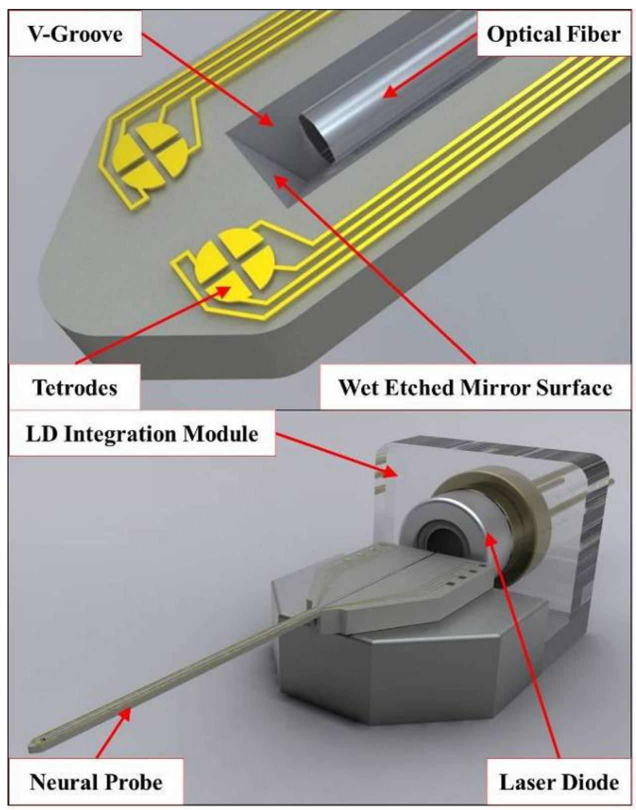

Fig. 1. Proposed neural probe structure integrated with light source, laser diode (LD), for optical stimulation and iridium oxide electrode array for electrical recording.

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HyungDal Park is with Center for Bionics of Korea Institute of Science and Technology, Seoul 136-791 South Korea and School of Mechanical Engineering, Yonsei University, Seoul 120-749, South Korea (phone: +82-10-5487-9181; fax: +82-2-958-6910; e-mail: phdpower@kist.re.kr).

Hyung-Jun Shin was with Center for Bionics of Korea Institute of Science and Technology, Seoul 136-791, South Korea (e-mail: kaiphy@kist.re.kr).

Il-Joo Cho is with Center for Bio-Microsystems of Korea Institute of Science and Technology, Seoul 136-791, South Korea (e-mail: ijcho@kist.re.kr).

Eui-sung Yoon is with Center for Bio-Microsystems of Korea Institute of Science and Technology, Seoul 136-791, South Korea (e-mail: esyoon@kist.re.kr)

Jun-Kyo Francis Suh was with Center for Bionics of Korea Institute of Science and Technology, Seoul 136-791, South Korea (e-mail: jkfsuh@kist.re.kr).

Maesoon Im was with Center for Wireless Integrated Microsystems, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan, USA (e-mail: maesoon@umich.edu).

Euisik Yoon was with Center for Wireless Integrated Microsystems, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan, USA (e-mail: esyoon@umich.edu).

Yong-Jun Kim was with School of Mechanical Engineering, Yonsei University, Seoul 120-749, South Korea (e-mail: yjk@yonsei.ac.kr).

Jinseok Kim was with Center for Bionics of Korea Institute of Science and Technology, Seoul 136-791 South Korea (e-mail: jinseok@kist.re.kr).

[1, 8-9]. In this case, there is no advantage for ethological experiment because of coupled optical fiber.

In this paper, we report a new approach of optical neural probe by directly integrating optical fiber on the wet etched V-groove. The distance between the stimulation and recording sites can be accurately controlled within the tolerance of misalignment of photolithography. In this probe, effects of signal propagation with and without optical stimulation can be monitored from the integrated tetrodes.

II. Design & Fabrication

A. Optical Probe Design

Fig. 1. shows the schematic view of the proposed neural probe and light source integration. The optical fiber is integrated on V-groove and connected to blue laser diode (OSRAM Blue Laser Diode_PL 450, λ=450nm). The optical fiber and blue laser diode should be accurately aligned to minimize a coupling loss through butt-coupling. A V-groove is formed on the silicon substrate to secure a room for the optical fiber. We used additional simple jig for butt-coupling between the optical fiber and blue laser diode. It is composed one hole for blue laser diode fixing and plate for neural probe.

There are total 2 iridium oxide tetrodes, composed 4 individual electrodes, in the vicinity of the stimulation site to monitor extracellular neural signals during optical stimulation.

B. Fabrication

The Fabrication of the proposed neural probe is illustrated in Fig. 2. First, silicon nitride is deposited to form a layer for electrical insulation layer and backside wet etching mask layer. Next, titanium and iridium oxide were deposited and patterned for interconnections and recording electrodes. On top of the patterned titanium and iridium oxide layer, chrome and gold were deposited and patterned for wire bonding. Next, the second dielectric layer, low temperature oxide (LTO) is deposited for electrical insulation and wet etching mask. Using this LTO layer, V-groove is formed by KOH wet etching process. Next, iridium oxide of tetrodes and gold pad sites are opened by patterning and dry etching. And probe shank shape is patterned using Deep RIE. Next, backside Si was etched by KOH wet etching process. Finally, the probe is release by laser dicing. The SEM images of the fabricated neural probe are shown in Fig. 3. The length of the shank which will be inserted into a brain is 6 mm with 400μm width. The thickness of the shank is 400μm, which is determined by Deep RIE and KOH wet etching. Fig. 3(b). shows an enlarged view of the shank. There are total 2 iridium oxide tetrodes for signal recording around the optical stimulating site at the end of V-groove. And the optical fiber is mounted in the V-groove. Closed image of iridium oxide tetrode is showed in Fig. 3(c).

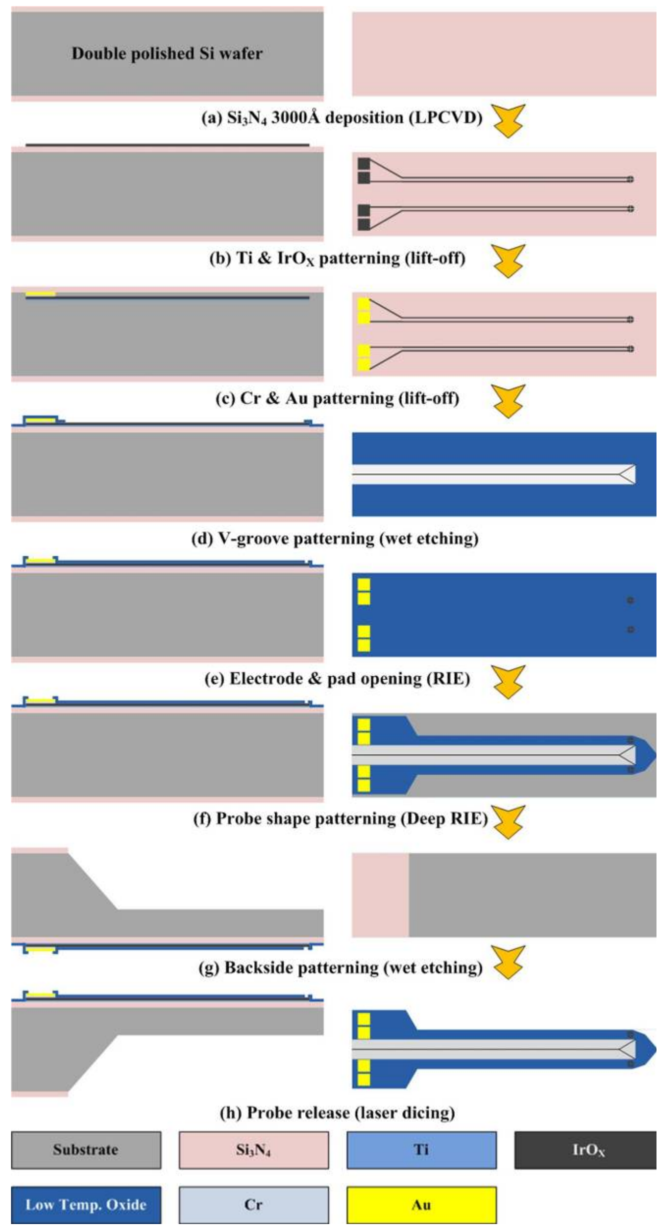

Fig. 2. Fabrication process flow: (a) silicon nitride deposition, (b) titanium and iridium oxide deposition and patterning, (c) chrome and gold deposition and patterning, (d) V-groove patterning, (e) electrode and pad opening, (f) probe define, (g) backside patterning, (h) release by laser dicing.

C. Light Source Integration

There are various optical coupling methods to extend optical transmission structures. Butt-coupling is the simple way to optical coupling. Also, coupling efficiency of butt-coupling has been calculated for different emitter and fiber type combinations [10].

In the case of laser diode, coupling efficiency has a variation between 29.4% and 58.6% which were depended on core size of optical fiber as shown in Table 1.

Table 1. Theoretical values for fiber butt-coupling efficiencies

Emitter			Fiber		η (Efficiency)
Type	Dimension	Θ_{SOURCE}	Φ_{CORE}	NA	
Laser diode	1 X 100μm	30°X10°	50μm	0.22	29.4%
			62.5μm	0.22	36.8%
			100μm	0.22	58.6%

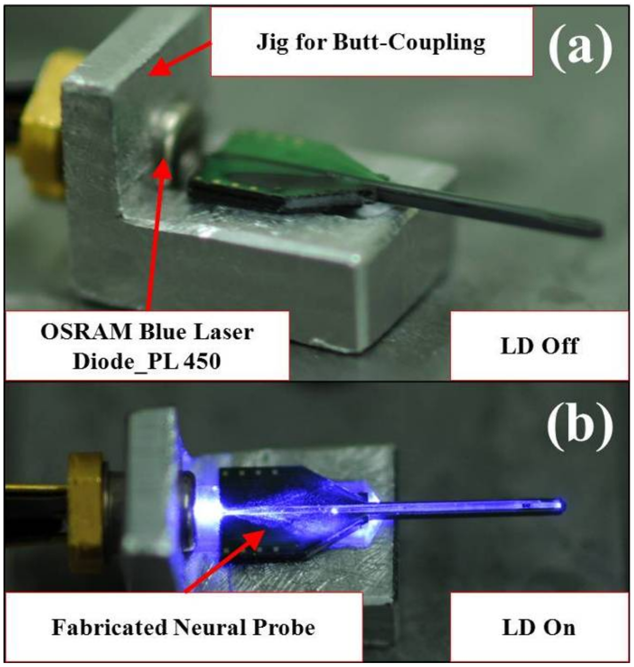

Fig. 4. Images of light source (blue laser diode) integration through butt-coupling: (a) when LD is turn-off, and (b) LD is turn-on.

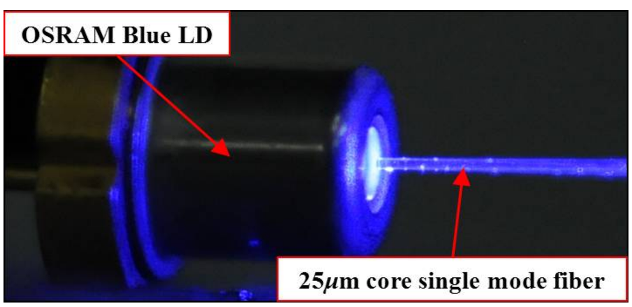

Fig. 5. Image of butt-coupling between blue laser diode and optical fiber (25μm core size).

From above calculation results, we developed one-touch butt-coupling jig as shown in Fig. 4. Proposed jig is composed of a hole for LD fixing and plate for neural probe.

III. Measurement Results

For light source integrated optical characterization, butt-coupled optical fiber is connected to a detector of optical power meter like as Fig. 5. and the light has been successfully coupled to optical fiber as shown in Fig. 4(b). The wavelength (blue light) was chosen to effectively stimulate channelrhodopsin-2 (ChR2) expressed neurons [5].

Optical loss of the butt-coupling was measured using optical power meter as shown in Fig. 5. In this experiment, we successfully demonstrated optical coupling through blue laser diode integrating to end of the probe body by using butt-coupling with power source of 5mW. The output power measured at the end of the optical fiber was measured around 0.2mW, which is sufficient to optically stimulated neurons [4].

The electrical characteristics of the iridium oxide tetrodes have been measured as shown in Fig. 6. The neural probe is packaged on the PCB with bonding wires connected for measurement. The probe shank has been loaded in a 0.9% PBS solution and the electrode impedance has been measured according to frequencies. The average impedance was 206.5kΩ with a small variation between 190.1kΩ and 235.8kΩ at 1kHz as shown in Table 2. and Fig. 6.

Table 2. Impedance measurement at 1kHz.

Electrode No.	1	2	3	4	5	6	7	8
Impedance (kΩ)	205.4	201.6	200.6	190.1	222.7	235.8	205.6	205.6
Average of Impedance				206.5kΩ				

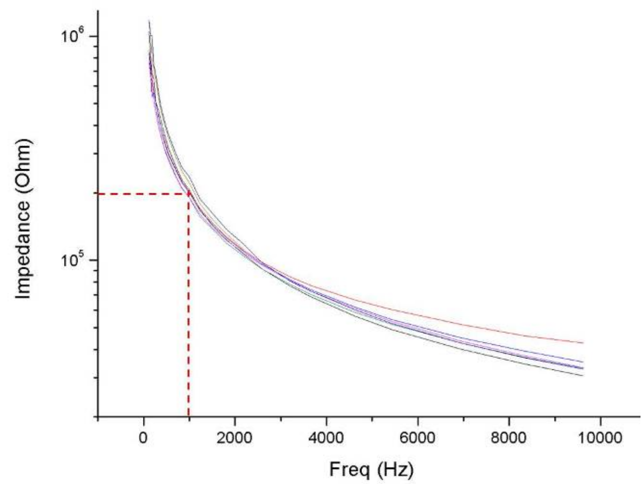

Fig. 6. Impedance measurement of 2 iridium oxide tetrodes in a PBS solution.

To verify insertion ability of proposed neural probe, insertion test have demonstrated in 0.5% agarose-gel as shown in Fig. 7. Also, probe was penetrated 0.5% agarose-gel

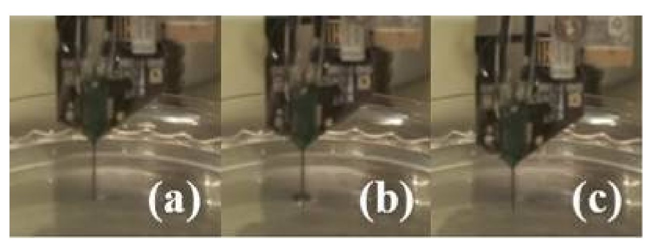

Fig. 7. Probe insertion test in 0.5% agarose-gel: (a) before insertion, (b) during insertion, and (c) after insertion

by 2mm/sec. In this test, proposed neural probe was easily inserted in.

IV. CONCLUSIONS

We have developed optical neural probe with V-groove for optical fiber integration, iridium oxide tetrodes for electrical signal recording, and light source (blue laser diode) integrating to end of the neural probe body through one-touch butt-coupling. The proposed neural probe can maintain the shank thickness below 400μm. The distance between the stimulation site and the recording electrodes can be precisely controlled to monitor neuronal behavior before and after optical stimulation. The output power measured at the end of the optical fiber was measured to be 0.2mW. And, The average impedance was 206.5kΩ with a small variation between 190.1kΩ and 235.8kΩ at 1kHz also we demonstrated insertion test of probe in 0.5% agarose-gel successfully. In the fabricated neural probe, consequently, we have successfully transmitted a light to the stimulation site through optical fiber from light source integration.

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