FIRST DUAL-COLOR OPTRODE WITH BARE LASER DIODE CHIPS DIRECTLY BUTT-COUPLED TO HYBRID-POLYMER WAVEGUIDES

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ABSTRACT

We report on the design, fabrication, assembly as well as optical, electrical and thermal characterization of the first MEMS-based dual-color optrode destined for neuroscientific research. The on-probe integration of bare laser diode (LD) chips emitting at 431 nm and 655 nm and directly butt-coupled to micromachined hybrid-polymer waveguides (WGs) enables highly compact systems for optogenetics. Co-integrated microelectrodes are aligned to the optical stimulation sites in application specific electrode arrangements. Temperature sensing elements embedded below the LD pads and at other selected locations along the probe shafts enable the temperature to be monitored during system operation. A large variety of probes has been realized.

INTRODUCTION

Neuroscientific research is interested in the investigation of brain function and dysfunction, neural patterns, and the interaction among brain circuits. Beside pharmaceutical treatment and functional electrical stimulation, optogenetics enable the direct control of neurons via light [1]. This approach offers millisecond precision and, in addition, cell type specificity and the opportunity to inhibit or excite action potentials using a broad range of wavelengths [2,3].

Over the past decade, a wide variety of approaches for light delivering neural tools have been published [4,5]. However the number of available devices lending themselves for experiments with freely moving animals requesting integrated light sources for an all-electrical control of the neural implant, is limited. Systems with light-emitting diodes (LEDs) [6–9] or LDs [10,11] have been introduced. The

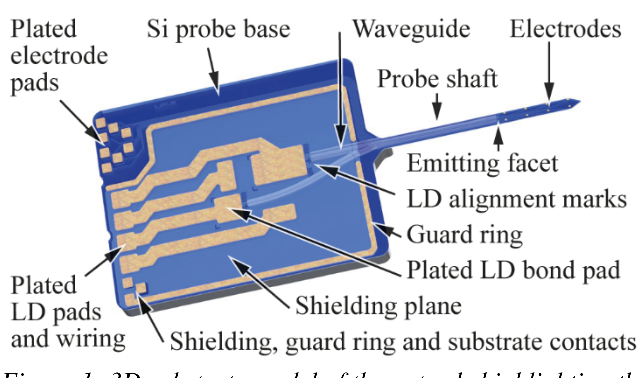

Figure 1: 3D substrate model of the optrode highlighting the implemented device features. Electroplated bonding pads at the rear of the probe base enable the interconnection of (i) electrodes, (ii) LDs, and (iii) shielding to the external instrumentation. Waveguides transmit the light emitted by assembled LD chips from the probe base along the implantable shaft. Recording electrodes are arranged close to the light emitting WG facet at the probe tip.

LEDs are either coupled to optical fibers [6,7] or implanted directly into neural tissue [8,9]. Main drawbacks are the non-efficient LED-fiber coupling, the non-hermeticity of LED encapsulations, and thermal issues due to the self-heating of the LEDs during operation. Miniaturized Si-based neural probes comprising recording electrodes combined with integrated LD chips and micromachined WGs are promising tools for advanced optogenetic studies in neuroscience [10,11]. Existing tools have so far been equipped only with red LDs [10] or relied on relatively bulky GRIN lenses for thermal insulation and easier alignment [11].

The present study demonstrates for the first time highly compact dual-color Si-based optrodes targeting opsins with different wavelengths [3]. The dimension of the optrodes are kept small by the direct butt-coupling of bare LD chips to micromachined hybrid-polymer WGs.

PROBE DESIGN

The probe design and its function is explained with the 3D model of the optrode substrate illustrated in Fig. 1. The probe consists of an implantable probe shaft and a probe base. The shaft carries recording electrodes at the tip, arranged in front of the light emitting WG facet. The electrodes are wired along the shaft to electroplated pads on the probe base. The pads enable the interconnection of the electrodes to the external instrumentation such as recording amplifiers and a wireless headstage. The light emitted by the LDs is transmitted from the coupling facet of the WGs on the probe base to their emitting facet on the shaft. Plated LD bond pads are positioned close to the WG coupling facets. Corresponding LD alignment marks are used for a highly precise alignment of the LD chips with respect to the WG center aiming for a high coupling efficiency. The electroplated LD wires and bond pads allow to keep electrical losses low. In order to minimize electrical artifacts on the electrode lines caused by the LD control current, we implemented a guard ring around the LD metallization and a shielding plane underneath. These metal structures as well the substrate can be connected using separate bond pads at the rear of the probe base. In some probe variants, we used the metallization of the shielding plane to embed temperature sensing elements directly underneath the LD bond pads and at several positions along the implantable probe shaft.

FABRICATION AND ASSEMBLY

The substrate fabrication is illustrated in Fig. 2. It starts with four-inch, 525-µm-thick, single-side-polished, and highly p-doped Si wafers. First, 1 µm of a stress compensated SiO_x/Si_xN_y layer stack is deposited using plasma enhanced chemical vapor deposition (PECVD) at a temperature of 300°C {cf. Fig. 2(a)}. A lift-off process patterns the first metallization (Ti/Au/Pt/Ti, 30/300/100/30 nm) into the electrode wiring, shielding plane and temperature sensing elements. This first metallization is passivated by a 1.5-µm-thick stress compensated SiO_x/Si_xN_y PECVD layer stack and a 200-nm-thick layer of a low temperature oxide (LTO) deposited at 425°C and acting as the lower WG cladding layer {cf. Fig. 2(b)}. Then, vias are opened using reactive ion etching (RIE) and the electrode material (Ti/Pt, 30/200 nm) is sputter deposited and patterned via lift-off {cf. Fig. 2(c)}. The second metallization consists of a 3-µm-thick electroplated Au layer patterned on a seed layer (Ti/Au, 30/300 nm) using a 10-µm-thick photoresist (PR) {cf. Fig. 2(d)}. After PR stripping, the remaining seed layer is wet etched using KI/I_2 and 1% HF {cf. Fig. 2(e)}. The WGs (ORMOCER®, Micro Resist Technology GmbH, Berlin, Germany) are spin coated and patterned by UV exposure. OrmoCore is spin coated at 4500 rpm resulting in a WG core height of 15 µm while OrmoClad is applied at 3750 rpm resulting in a 25-µm-high cladding layer. A 250-nm-thick OrmoPrime layer, deposited first, acts as an adhesion promoter {cf. Fig. 2(f)}. A 30-µm-thick AZ9260 photoresist masking layer enables the probe patterning via RIE of the dielectric layers and deep reactive ion etching (DRIE) of the Si substrate to a depth of 120 µm {cf. Fig. 2(g)}, in the first step of the so-called etch before grinding (EBG) technique [12]. A 2nd 30-µm-thick AZ9260 PR layer planarizes the surface and enables the 2nd EBG step, namely wafer grinding (DISCO Hi-Tec Europe GmbH, Kirchheim, Germany) and thus probe thinning down to a thickness of 100 µm {cf. Fig. 2(i)}. Grinding and PR stripping release the neural probes from the Si wafer {cf. Fig. 2(j)}.

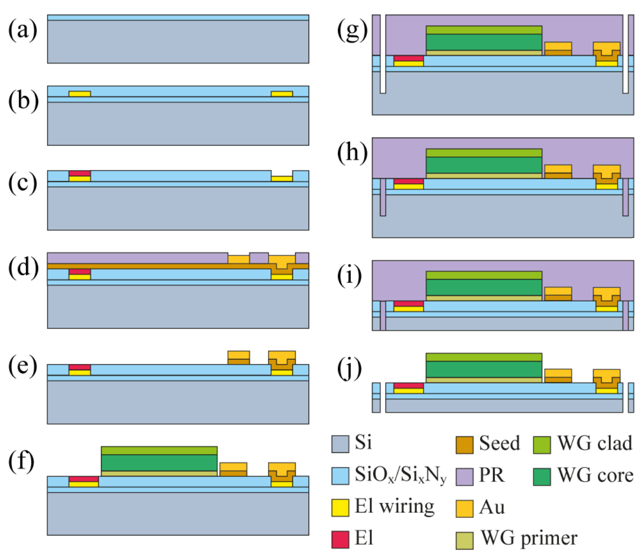

Figure 2: Fabrication process of Si-based optrodes with integrated LD chips, WGs, and Pt temperature sensing element. (a) Substrate passivation. (b) Pt lift-off to pattern metal lines, passivation. (c) RIE to open vias, electrode deposition. (d) Photoresist (PR) patterning, electroplating of Au on Ti/Au seed layer. (e) PR strip and seed layer etch. (f) Deposition of WG primer, core, and cladding. (g) RIE and DRIE for probe patterning. (h) Surface planarization using PR and (i) probe thinning by wafer grinding. (j) PR removal and probe separation.

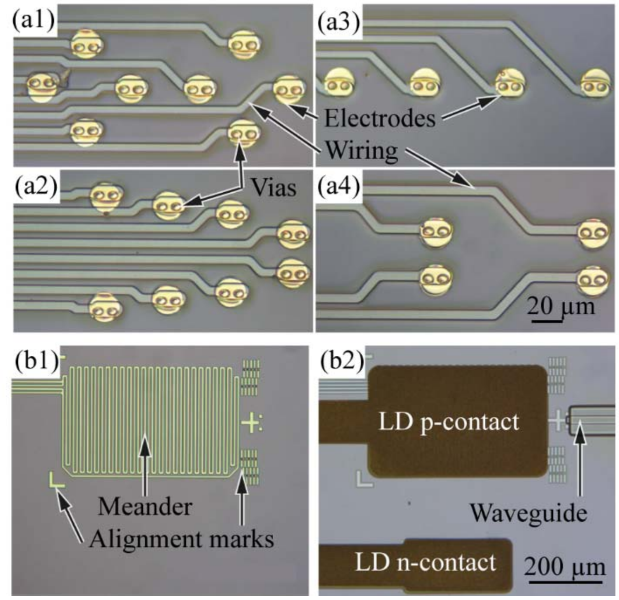

Figure 3: (a1-a4) Micrographs showing details of fabricated electrodes on Si based optrode substrates and vias to their respective wiring. (b1) 1st metallization forming a meander acting as temperature sensing element and LD alignment marks. (b2) 2nd metallization realizing LD contact pads and their wiring. LD p-contact pad is deposited directly on top of the Pt meander. Fabricated WG is aligned with respect to the LD alignment marks.

The micrographs in Fig. 3 show metal structures resulting from this process. Figures 3(a1-a4) show the electrode wiring (1st metallization) and the electrodes (2nd metallization) in various arrangements. The meander in Fig. 3(b1) serving as temperature sensing element is realized in the 1st metallization. In Fig. 3(b2) a similar meander is arranged directly beneath an LD p-contact pad enabling a temperature measurement during LD operation. Moreover, Fig. 3(b2) shows the fabricated WG directly in front of the LD p-contact pad.

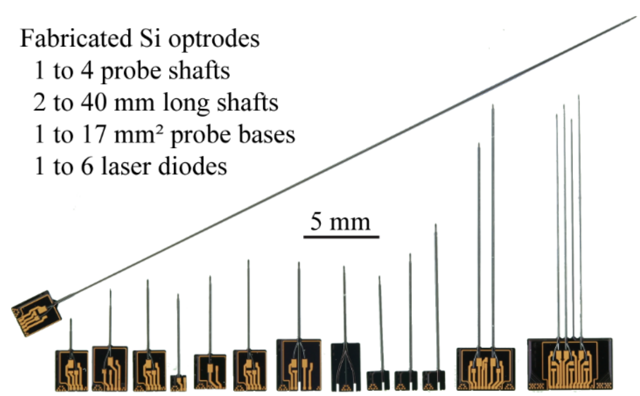

Figure 4: 14 out of 28 optrode variants with different shaft lengths, nos. of LDs and shafts, and base dimensions. Individual shanks are 100 µm wide and carry various arrangements of eight electrodes {cf. Fig. 3(a1-a4)}.

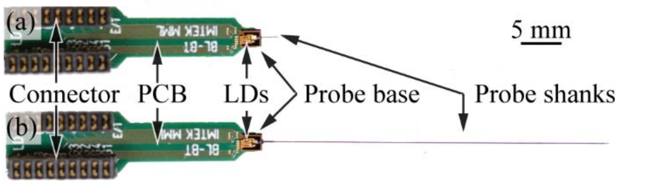

Figure 5: Assembled (a) 2-mm-long and (b) 40-mm-long optrodes attached and wire bonded to PCBs for electrical interconnection during acute experiments.

The wide variety of the fabricated optrode designs is illustrated in Fig. 4, with 14 out of 28 different designs fabricated for user-specific applications. Besides varying the electrode arrangements {cf. Fig. 3(a)}, probe dimensions, and number of shafts and LD chips, we also implemented designs enabling to combine Si-based probes with optical fibers. These latter combinations offer the users a wider range of light sources especially in view of the applicable wavelengths.

Examples for fully assembled optrodes with 2-mm-long and 40-mm-long probe shafts are illustrated in Figs. 5(a) and (b), respectively. The LDs are assembled using a flip-chip bonder. The previously published procedure [10] was improved in two respects. First, the implementation of LD alignment marks enabled an improved LD positioning {cf. Fig. 3(b1)}; secondly, a wider WG core aims for higher efficiencies of the LD-WG butt-coupling by lowering the required alignment accuracy. After the aligned flip-chip bonding of the LD p-contact to the corresponding substrate contact, the LD n-contact is wire bonded to the respective pad on the Si probe base. This is followed by adhesively (EPO-TEK 353 ND-T, Epoxy Technologies Inc., Billerca, USA) fixing the Si probe base to a rigid printed circuit board (PCB). Finally, the contact pads of the probe are wire bonded to the PCB. The interconnection to an external instrumentation is ensured via a strip connector. The rigid PCB was designed for acute animal experiments and also served for the device characterization.

OPTRODE CHARACTERIZATION

First, optical functionality tests of assembled optrodes were performed, as illustrated in Figure 6. The assembled blue (FhG-IAF, GN 6198 FE, Fraunhofer IAF, Freiburg, Germany) and red (LCU6505142, Laser Components GmbH, Olching, Germany) LDs are controlled by a custom designed current source applying the LD current at a of duty cycle (DC) of 1% at a frequency of 1 kHz. The blue LD in Fig. 6(b) couples into the straight WG in front of it, whereby light is guided to the probe shaft tip. The shining WG indicates some light loss due to scattering. Similarly, the assembled and operated red LD couples into the corresponding WG {cf. Fig. 6(d)}. Again, the light is guided along the WG and some light scattering along the WG is observed. However, in this example, the WG is bent with a radius of 2 mm.

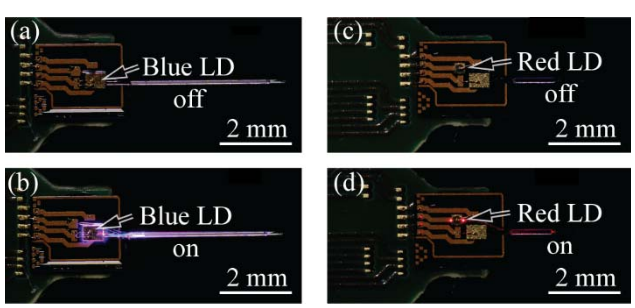

Figure 6: Optrodes with integrated (a,b) blue and (c,d) red LD chips. (b,d) Optical functionality test of the integrated LDs. Shining WGs indicate the successful coupling of light into the WG and transmission to the probe tip.

The electro-optical characterization measurements include *U-I* curves, spectral emission and radiant flux measurements of the optrode with its LDs and WGs using a of duty cycle (DC) of 1% at a frequency of 1 kHz. The applied optrode voltage U as a function of LD current I is shown for the blue and red LD chips in Figs. 7(a) and (b), respectively. The spectral emission is measured using a spectrometer (USB4000, Ocean Optics, Ostfildern, Germany). Peak emission at the WG, coupled to blue and red LD chips, are at 431 nm and 655 nm, respectively. The radiant fluxes of the assembled optrodes are measured using an integrating sphere (ISP-50-I-USB, Ocean Optics) and the spectrometer by placing the optrodes with their light emitting WG facets directly in front of the aperture of the integrating sphere. The lasing threshold current of the exemplary blue LD is determined to be $I = 58$ mA at an optrode voltage $V = 7$ V, whereas the lasing threshold current of the exemplary red LD is determined to be $I = 23$ mA at an optrode voltage of 2.15 V. Since the measured radiant fluxes (blue and red circles) in Fig. 7 are time averaged and the WGs cross-section is 15×25 µm², a time averaged radiant emittance of 13 mW/mm² corresponds to a radiant flux of 5 µW. Ultimately, due to time averaging at 1% DC, single pulses with a length of 10 µs have a 100× higher radiant flux and thus an emittance of 1300 mW/mm².

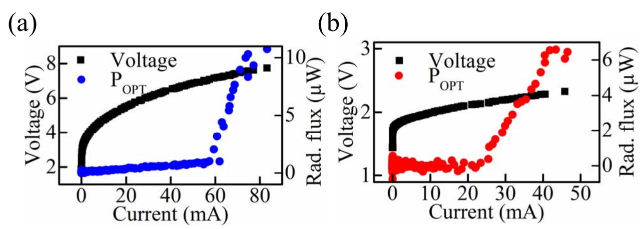

Figure 7: Electro-optical characteristics of (a) blue and (b) red LDs operated at 1% DC and a frequency of 1 kHz assembled in front of hybrid-polymer ORMOCER® waveguides. I-U curves describe LD behavior (black squares); Radiant flux measurements (blue and red circles) are given for WG cross-sections of 15×25 µm².

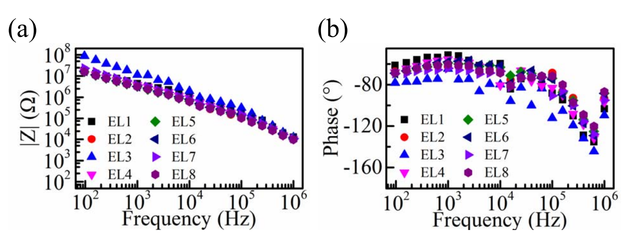

Figure 8: (a) Measured absolute impedance |Z| and (b) phase of the eight Pt electrodes with a diameter of 20 µm.

The electrodes of one optrode sample containing eight Pt electrodes with a diameter of 20 µm are characterized in Ringer's solution using an impedance spectrometer (CompactStat, Ivium Technologies, Eindhoven, The Netherlands) in a three-electrode configuration. Figures 8(a) and (b) illustrate the absolute value $|Z|$ and phase of the impedance of eight electrodes as a function of frequency. Electrode EL3 shows an increased impedance due to a damaged wire bond. The average impedance of the other seven electrodes at 1 kHz is 3.5±0.42 MΩ.

CONCLUSION

This paper presented a dual-color optrode with integrated bare LD chips. The presented 3D design was successfully fabricated, assembled, and characterized. It is designed for optogenetic experiments with freely behaving animals. In total 28 different probe designs cover shaft lengths between 2 mm and 40 mm and probes with up to four shafts. The optrodes offer various numbers of electrodes (8 to 32) and LDs (1 to 6). The probe base areas range from 1×1 mm^2 for a single shank optrode to 3.2×5.25 mm^2 in case of a four-shaft comb-type probe. The optrode fabrication using the EBG technique has been successfully demonstrated to thin optrode shafts and release the optical probe. Blue and red LDs emitting at center wavelengths of 431 nm and 655 nm are integrated by flip-chip bonding to electroplated Au pads on the probe base with an accuracy of better than ±5 µm relative to the WG facet. Time averaged radiant fluxes of assembled blue (I = 70 mA, 1% DC) and red (I = 35 mA, 1% DC) LDs transmitted via 1-cm-long WGs are measured to be 1.376 µW and 8.142 µW, respectively. This corresponds to radiant emittances of 3.7 mW/mm^2 and 21.7 mW/mm^2 at the WG emitting facet, above typical optical stimulation thresholds of 1-10 mW/mm^2. The absolute impedance value of the 20 µm Pt electrodes at 1 kHz was measured to be 3.5±0.42 MΩ.

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