Modular Assembly Concept for 3D Neural Probe Prototypes Offering High Freedom of Design and Alignment Precision

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***Abstract*— The new assembly technology developed in this research provides a means to extend planar intracortical neural probes with one-dimensional (1D) and two-dimensional (2D) electrode arrangements into complex three-dimensional (3D) neural probes. The approach is based on novel silicon stacking modules realized using microsystems technologies. With these microcomponents, 3D probes can be assembled flexibly and tailored to the demands of neuroscientific experiments. The manufacturing process of the stacking modules provides the possibility to adjust the electrode spacing in the stacking direction with micrometer precision. The assembly method is demonstrated with 32-channel systems comprising 7-mm-long and 50-µm-thin neural probes. The angular alignment between the neural probes and their stacking modules after assembly as well as the vertical electrode pitch were determined to be about 1° and 353±15 µm, respectively.**

I. Introduction

Neural probes based on silicon (Si) technologies for intracortical neural recording have established themselves as valuable tools for the *in-vivo* analysis of neural networks in the central nervous system. The penetrating probes afford recordings of extracellular biopotentials with the highest temporal and spatial resolution available so far. Further, the damage to the cortical tissue can be kept at a minimum even when the activity of small neuronal populations is monitored with many recording channels. The standard microfabrication processes used for MEMS devices can be utilized to create electrode arrays on slender silicon shafts with micrometer precision and a high-channel-count-to-volume ratio [1]. Especially when using silicon substrates, the co-integration with CMOS microelectronic circuitry yields the highest recording site densities [2,3].

The common fabrication schemes used for Si-based probes limit the arrangement of the microelectrodes to two dimensions. However, neuroscientific studies of three-dimensional (3D) neuronal networks demand similar 3D electrode arrangements to reveal the fine structure of the brain's electrophysiological activity. Assembly methods thus are necessary to extend the electrode arrays into the third dimension. Adapting the electrode configuration to the brain region under investigation is another demand [4]. Important characteristics of a fabrication technology for neural probe prototypes should be (i) cost-effectiveness and (ii) high design freedom for prototype configuration.

In recent years, various concepts for 3D neural probe arrays with high channel counts have been developed [5-8]. These mainly platform-based systems cover a low volume, which is advantageous for chronic implantation, e.g., in brain machine interfaces. The alignment of the probe shafts is normally accurate to a few micrometers. However, up to this point it has not been possible to reconfigure the channel count of such systems or change the distance between individual probe shafts without modifying the fabrication tools, e.g. the lithography masks. Our novel system approach relies on a modular concept offering high freedom of design in composing 3D neural probe prototypes by allowing to adjust the channel count of the neural probe and position of the microelectrodes in all dimensions with high precision.

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II. System Approach

A. 3D Assembly of Planar Neural Probes

Figure 1 schematically shows the components of the modular neural recording device and the 3D assembly concept. The planar probes and the highly flexible polyimide (PI) ribbon cables constitute fully functional neural recording devices with one-dimensional (1D) or two-dimensional (2D) electrode arrays of arbitrary shape. Novel dedicated stacking modules have been developed and tailored the probes' bases. In combination with these modules, multiple planar probes can be assembled into 3D electrode arrays by stacking.

The planar probes used in this study feature either 16 or 32 channels with recording sites distributed over one or more slender probe shafts [9]. The PI cables connect the electrode sites to the external instrumentation and mechanically de-

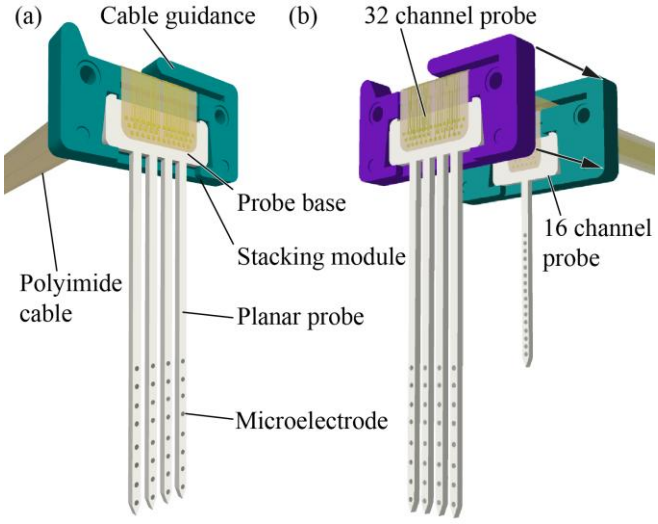

Figure 1. Schematic of (a) stacking module with inserted planar probe and (b) combination of differently sized 16 and 32 channel probes by stacking.

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couple the probe from the skull during *in-vivo* application [10,11].

To improve handling as well as the assembly of the 3D probes, multiple PI cables can be bundled in the cable guidance at the back of the stacking module by bending them by 90°. This further results in a reduced device height.

Precise alignment of the planar probes and the stacking modules is guaranteed by cavities in the stacking module {Fig. 2 (a)}. The cavity deviates from the footprint of the probe base by a clearance of only 3 µm. In this way, the maximum theoretical angular offset between probe and stacking module is limited to 1.8°. Pins on the rear side of the stacking module and appropriately located receptacles on the front side guarantee the accurate alignment during stacking {Figs. 2 (a,b)}. The clearance between these alignment structures and the resulting maximum in-plane angular offset between two stacked components is 20 µm and 0.9°, respectively.

B. Adjustable Vertical Electrode Pitch

While the lateral dimensions of the electrode arrays and the stacking components are precisely defined by lithography masks, the vertical dimensions are set during their fabrication. This allows to adjust the vertical pitch between the electrode arrays in different stacking layers within a wide range.

Figure 3 (a) shows a schematic cross-sectional view of a stack as shown in Fig. 1 (b) according to the cut line defined in Fig. 2 (a). The thickness t_{sub} of the stacking modules is inherited from the Si substrate used for their fabrication. This value stays unchanged during the fabrication process. The pitch of the stacking modules is P_{mod}. Dry etching of the silicon substrate is used to create the topography of the stacking module and thus to define the value of P_{mod}. As long as the pins on the rear side of the stacking modules completely fit into the corresponding recesses of the subjacent module {Fig. 3 (a)}, the value of P_{mod} is only defined by t_{sub} and the height of the pins. The same is true for the pitch P of the electrode arrays on the stacked probes as the values of P and P_{mod} are equal {cf. Fig. 3 (a)}. This means that P can be controlled by adjusting the dimensions of the stacking modules.

One way of adjusting the vertical pitch is to alter the substrate thickness t_{sub}. A change of t_{sub} identically affects P_{mod} if the topography of the stacking module is unchanged {Fig. 3 (b)}. In addition, the etching parameters offer further

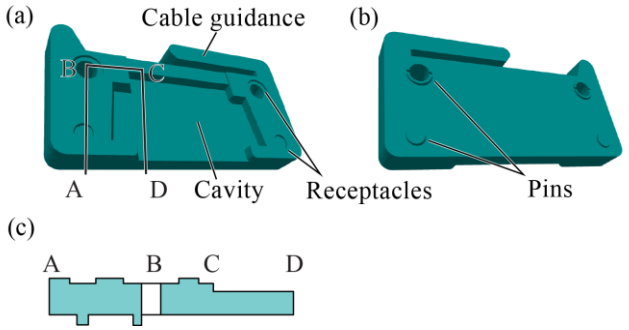

Figure 2. Schematic of the stacking module: perspective (a) front and (b) rear view; (c) cross-section along the line ABCD given in (a).

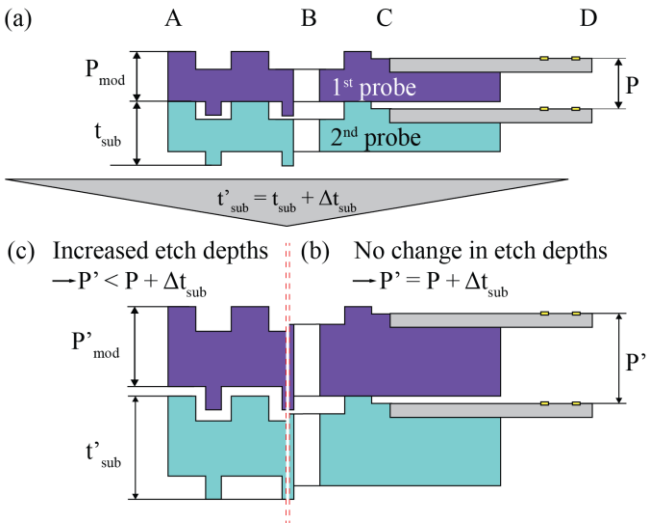

Figure 3. Schematic of a stack of two probes cut along the line ABCD indicated in Fig. 2 (c). (a) Stacking modules fabricated from substrates with thickness t_{sub}. (b) The vertical electrode pitch P can be increased by changing t_{sub} by Δt_{sub}. The increased electrode pitch is P'. (c) Smaller increase of P by adjusting the etch depth.

degrees of freedom to change P_{mod} independently from t_{sub}. By increasing the topography depth, the effect of an increased t_{sub} can be attenuated {Fig. 3 (b)}. In this way, it is possible to modify the vertical pitch of the electrodes over a wide range and with micrometer precision. Since it is simple to change the lateral dimensions of the 1D or 2D electrode arrays of the stacked probes, various 3D electrode arrays can be created with this concept.

III. Fabrication and System Assembly

A. Fabrication of System Components

The fabrication process of the stacking modules takes advantage of multiple deep reactive ion etching (DRIE) steps on the front and rear of 4" silicon substrates (Fig. 4). Photoresist and silicon oxide layers are combined as etching masks to create the stepped profile shown in Fig. 3. The average substrate thickness of the silicon wafers used in this study is 390 µm.

The process begins with the deposition of 4-µm-thick silicon oxide layers on both sides of the substrate by plasma enhanced chemical vapor deposition (PECVD) {Fig. 4 (a)}. The alignment pins on the rear of the stacking modules are defined by a photolithography process and transferred into the oxide by reactive ion etching (RIE) {Fig. 4 (b)}. The photoresist layer for patterning the oxide is stripped and a second photoresist mask defining the contour of the stacking modules is added {Fig. 4 (c)}. The two masking layers now allow to create a stepped profile by two successive DRIE steps, between which the resist mask is removed {Fig. 4 (d,e)}. The first etching step transfers the contour to a depth of 230 µm into the substrate. In the second step, the 35-µm-high pins are created.

The wafer front is patterned accordingly with adjusted etch depths to create the probe cavity and the receptacles {Figs. 4 (f-i)}. The final DRIE step suspends the stacking

modules to struts that allow their controlled release. Subsequently, the oxide layers on both sides of the wafer are removed by dipping in hydrofluoric acid {Fig. 4 (j)}. With these exemplary process parameters, a nominal vertical electrode pitch of 355 µm is realized in the final 3D array.

The fabrication processes for the planar probes and the PI ribbon cables are based on established procedures of our group [9,10]. Single-shaft and comb-shaped probes with a thickness of 50 µm and up to 32 platinum electrode sites created by sputter deposition can be used for the assembly [9]. Shaft lengths of several millimeters have been produced for the present assemblies. The highly flexible PI cables are 10 µm thick and 30 mm long [10]. Electrochemical deposition of gold is used to create bonding bumps at the proximal end of the cable. The bumps allow the electrical and mechanical connection to the electrode array by flip-chip (FC) bonding. For the connection to external instrumentation, a flexible printed circuit board (flex PCB) is soldered to the distal end of a cable.

B. Assembly of the 3D Electrode Array

The connection of the PI cables to the planar probes by ultrasonic FC bonding is the first step of the assembly [10]. At this point the probes can already be tested for their electrical functionality by electrical impedance measurement, as detailed in Section IV.B. Next, the probes are inserted into the cavities of the stacking modules either manually or with the assistance of the Fineplacer 96λ FC bonder (Finetech, Berlin, Germany). A biocompatible epoxy (EPO-TEK 301, Epoxy Technology Inc., Billerica, MA, USA) is then used to adhesively bond the probes to the stacking modules. After a thermal curing step at 60 °C for 1 hour, the PI cables can safely be inserted into the cable guidance. A guide bar made from Kapton (Kapton HN, DuPont de Nemours, Luxemburg) foil is slid into the guidance together with the PI cables to facilitates their threading. It also ensures the coarse alignment of multiple stackable probes {Fig. 5 (a)}. Then, a high-

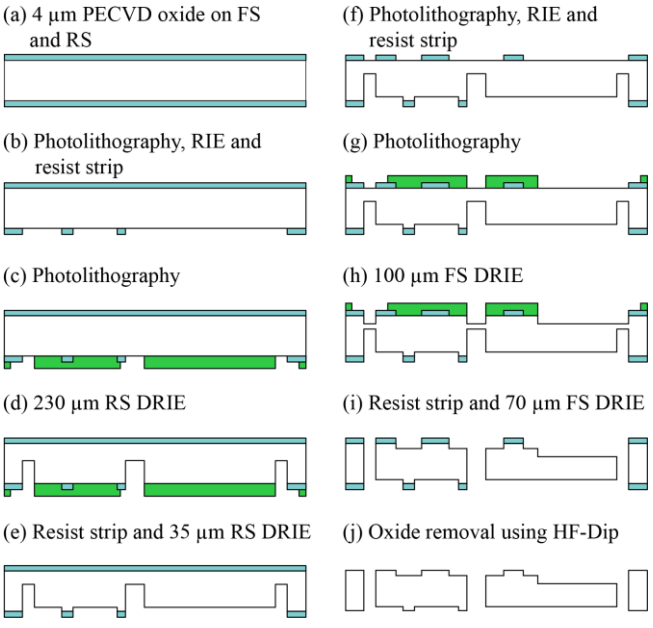

Figure 4. Fabrication process of the stacking modules (FS = front side, RS = rear side)

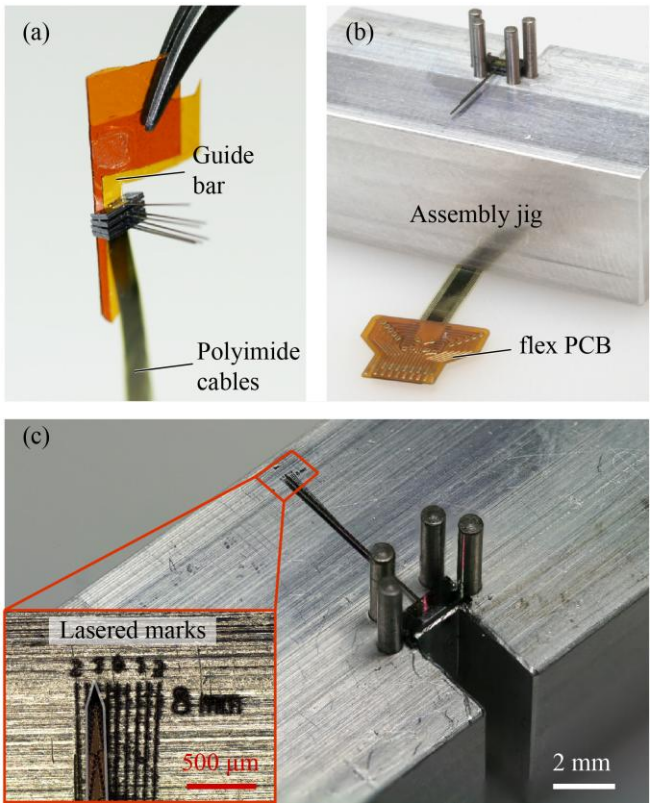

Figure 5. Photographs of (a, b) assembly procedure of four stackable probes with 7-mm-long shafts and (c) probe in assembly jig during alignment; the inset shows a micrograph of laser-structured marks that are used to measure the angular alignment of the probes.

viscosity biocompatible epoxy (EPO-TEK 353ND-T, Epoxy Technology Inc., Billerica, MA, USA) is dispensed into the gaps between the stacking modules. The stack is then placed in an assembly jig and the guide bar is removed {Fig. 5 (b)}. The alignment structures at the front and rear of the stacking modules are used for the fine alignment. As they interlock, the gaps between the stacking modules are closed. A micro-optical inspection can be performed at this stage to verify the alignment {Fig. 5 (c)}. The stack is then transferred into an oven together with the jig for thermal curing. The curing takes 10 min at 100 °C.

The procedure was successfully applied to assemble 3D electrode arrays with a total channel count of 32. Different electrode pitches have been implemented to demonstrate the versatility of this assembly concept {Fig. 6}. The array shown in Figs. 6 (a,b) features four 7-mm-long shafts with a nominal vertical pitch of 710 µm. An additional spacer module has been used to increase the pitch to twice 355 µm. The system in Fig. 6 (c) features three shafts and a stacking period of 355 µm.

IV. Characterization

A. Alignment

The clearance between the alignment structures of the stacking components (cf. Section II.A) that are necessary for the assembly can introduce angular misalignments and positional shifts between the electrode arrays in the different stack layers. While the positional shifts are limited to a few

micrometers and thus negligible in most practical purposes, the angular misalignment in the plane of the electrodes can cause more significant deviations of the electrode positions due to the shaft lengths. The actual angular misalignment between a probe and its stacking module was measured during the stack assembly using the laser structured marks on the assembly jig. It was determined to be lower than 1°. The maximum error occurring during stacking has been extracted from the realized dimensions of the pins and receptacles of the stacking modules. Its average absolute value is about 0.9°. In the worst case, the angular offset between two successive probes in a stack can thus be 2.9°.

To characterize the actual electrode pitch, the thickness of the probes and the topography of the stacking modules were measured using an optical profilometer (Hyperion, OPM Messtechnik GmbH, Ettlingen, Germany). The actual vertical electrode pitch is 353±15 µm.

B. Functionality Testing

The 3D electrode array shown in Fig. 6 (c) was tested with respect to its electrical functionality using an electrical impedance characterization setup. To do so, the electrodes on the probe shafts were immersed into 1 M Ringer's solution and characterized in a three-electrode-setup using an impedance analyzer (Ivium CompactStat, Ivium Technologies B.V., Eindhoven, The Netherlands). The impedance was measured in the frequency range between 100 Hz and 1 MHz. Figure 7 shows the results of the electrical impedance measurement performed on the 32-channel array. Each of the two 16-channel probes exhibits one non-functional channel. Their increased impedances indicates an open circuit probably located at the interface between the probe metallization and the gold bumps of the PI cable.

V. Conclusion

A new concept for the assembly of 3D electrode arrays has been demonstrated. It allows to flexibly configure 3D probes for recording or stimulating neuronal activity in the brain. The 3D arrangement of the microelectrodes can be adjusted in all directions with micrometer precision. The approach is based on the stacking of planar neural probes and novel stacking modules. The stacking modules are fabricated from silicon using a dual-sided multi-step DRIE process that allows to adapt the vertical electrode pitch of the stacked electrode arrays. This is achieved simply by adjusting the process parameters. A modification of the mask designs is not necessary, which effectively reduces the costs of fabrication.

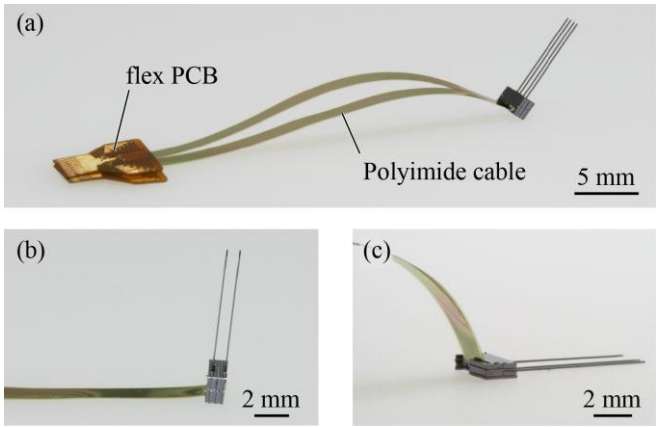

Figure 6. Photographs of 32-channel 3D neural probes with (a,b) four 7-mm-long probe shafts; (a) complete system and (b) side view of proximal end (nominal vertical electrode pitch 710 µm); (c) three-shaft-system (nominal vertical electrode pitch 355 µm).

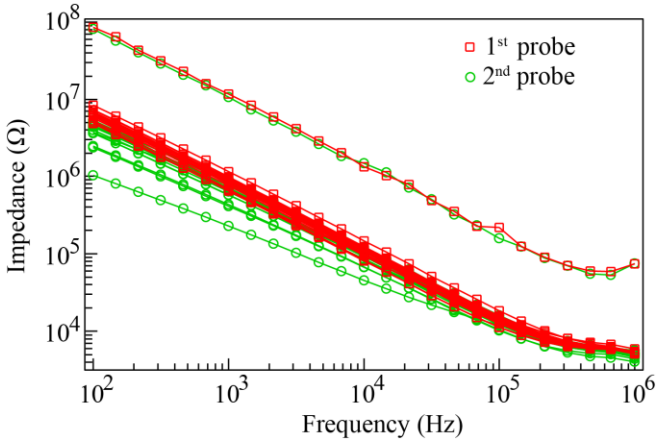

Figure 7. Impedance spectra of the 32 platinum microelectrodes (Ø 35 µm) of the 3D electrode array shown in Fig. 6 (c). One electrode of each probe is not electrically connected to the impedance analyzer probably due to a defect FC bond. The designation "1st probe" and "2nd probe" is consistent with that shown in Fig. 3 (a).

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