

Martin Deckert*, Michael Lippert*, Kentaroh Takagaki, Andreas Brose, Frank Ohl and Bertram Schmidt

Fabrication of MEMS-based 3D- μ ECoG-MEAs

DOI 10.1515/cdbme-2016-0021

Abstract: The microfabrication and packaging of novel, three-dimensional, polyimide-based, highly flexible, microscale electrocorticography multi-electrode arrays for enhanced epicortical recording of local field potentials is presented. A polyimide foil embeds metallic structures relating to 32 taper-type electrode sites, contact pads as well as interconnecting conductor paths which are integrated in the planar portion of the electrode substrate material. Circular exposed and, thus, active electrode sites are 50 μm in diameter and employed center-to-center pitches range from 250 μm to 1 mm, respectively. As-fabricated 3D- μ ECoG-MEAs provide taper heights of approximately 4 μm as well as 59 μm being distinguished by characteristic impedances of about 368.9 k Ω at 1 kHz measured in saline electrolyte. The applied packaging strategies favor flip-chip bonding and vapor phase soldering of the polymer substrates to customized printed circuit boards.

Keywords: electrocorticography; microelectrode; polyimide; SNR; three-dimensional.

1 Motivation

High-resolution extracellular recordings of specific cortical brain regions at the mesoscopic scale are of great interdisciplinary interest to microtechnological and neuroscientific research as well as clinical applications. The ideal neural interface for long-term applications is electrically, mechanically and biologically compatible as well as stable [1–3].

This research focuses on the fabrication of three-dimensional, microscale electrocorticography multi-electrode arrays (3D- μ ECoG-MEAs) for technically

improved, low impedance epicortical recording of local field potentials (LFPs) in respect of locally three-dimensional, tapered electrode site geometries with integrated sealing lips as well as micro- and nanoroughening of exposed electrode sites to optimize recorded signal-to-noise ratios by minimizing volume conduction in the meningeal space. At the same time, the cortical capillary system is encompassed to a certain extent depending on epicortical capillary diameters, capillary density and taper height to reduce electrode site crosstalk and, respectively, increase signal quality of recorded neuronal activity.

2 Material and methods

2.1 Design and fabrication

The design portfolio of developed and fabricated 3D- μ ECoG-MEAs in form polyimide (PI)/metal/PI sandwich structures incorporates different electrode spacings of 250 μm , 500 μm , 800 μm and 1 mm center-to-center pitches as well as varied electrode site distributions for versatile neuroscientific applications. The smallest electrode pitch is defined with 250 μm due to the highest reasonable MEA resolution for cortical, electro-chemical signal superposition in respect of LFPs [1, 3].

Hence, a for 60 s at 3000 rpm (LabSpin 6, SUSS) spun on and at 350°C for 1 h in vacuum atmosphere cured (plasma furnace VLO 20, Centrotherm) polyimide (PI-2611, HD-MicroSystems) foil substrate encloses sputtered (LS500ES, Ardenne), circular shaped, 450 nm thick chromium/gold/platinum (Cr/Au/Pt) electrodes with exposed site diameters of 50 μm . Feeding conductor paths are 10 μm in width and pitch. The metallization is patterned in a lift-off process.

The fundament of the presented 3D fabrication process is the successive spin-coating at 1500 rpm for 60 s, curing (350°C for 1 h in vacuum) and microroughening (RIE) for surface activation and interlayer adhesion optimization of three and nine PI-2611 multilayers elucidated in the result section. In compliance with the 3D-capable mask design, the highly anisotropic and

*Corresponding authors: **Martin Deckert**, Otto von Guericke University Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany, E-mail: martin.deckert@ovgu.de; and **Michael Lippert**, Leibniz Institute for Neurobiology, Brenneckestraße 6, Magdeburg, Germany, E-mail: michael.lippert@lin-magdeburg.de
Kentaroh Takagaki, Andreas Brose, Frank Ohl and Bertram Schmidt: Leibniz Institute for Neurobiology, Brenneckestraße 6, Magdeburg, Germany, E-mail: kentaro.takagaki@lin-magdeburg.de (K. Takagaki)

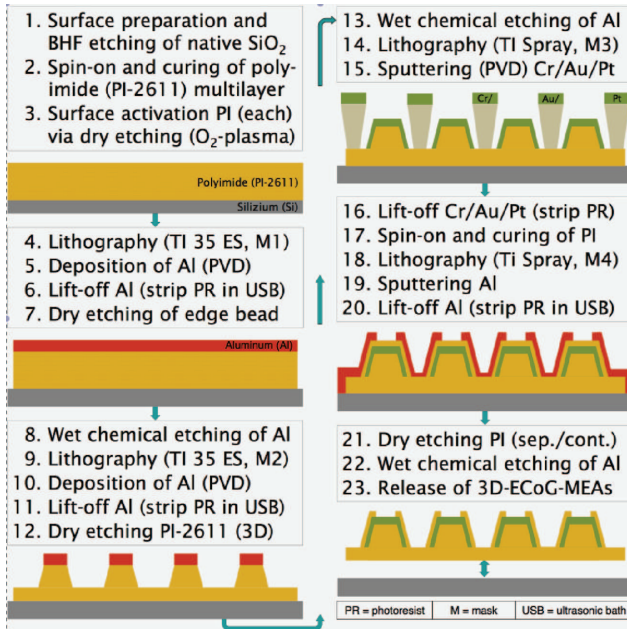


Figure 1: Process flow for 3D- μ ECoG-MEA microfabrication.

relatively high-pressure (95 mTorr) reactive ion etching (RIE; PlasmalabSystem 100, Oxford Instruments) of the multilayered PI substrate foil in an oxygen plasma enables for 3D- μ ECoG-MEA implementation and, consequently, entails the potential of improved signal-to-noise ratios (SNR) on the basis of a locally taper-type electrode shape incorporating sealing lips on the top faces of electrode sites as well as micro- and nonporous electrode site surfaces for impedance optimization (see Figures 3–5).

Subsequent to the sputter deposition and pattern generation of the metallization layer via lift-off, a repetitive and encapsulating cover layer made of PI-2611 is spun on at 5000 rpm for 60 s and cured at standard processing conditions in the plasma furnace at 350° for 1 h in vacuum atmosphere. Pattern transfer for electrode separation and cavity formation (integrated through wholes) is generated via RIE before electrode release in a manual peel-off process. The process flow for the MEMS-based fabrication of 3D- μ ECoG-MEAs is schematically illustrated in Figure 1.

2.2 Packaging

Investigated packaging strategies for electrical and mechanical junction of 3D- μ ECoG-MEA foil substrates onto customized printed circuit boards (PCBs), designed in CadSoft Eagle, employed flip-chip bonding (FINEPLACER[®] pico, Finetech), adhesive bonding and

aerosol jet direct writing (OPTOMECA M3D, Optomec) as well as wire bonding (wire bonder 5310/5330, F&K Delvotec) with globe top for passivation. The dimensions of customized PCBs are $1.41 \times 1.01 \times 0.6 \text{ mm}^3$ in length, width and height, respectively.

In respect of wire bonding a 25 μm aluminum wire was utilized and the epoxy EPO-TEK H77 (Epotec) served as passivation material. Adhesive bonding of 3D- μ ECoG-MEA substrates to PCBs was achieved with the epoxy Polytec EP 601-LV (Polytec) and a curing step at 150°C for 1 h. Subsequently, aerosol jet direct writing of UTDaG25TE (UT DOTS) silver ink cured at 200°C in nitrogen atmosphere (VLO 20, Centrotherm) for 1 h allowed for electrical contact between electrode and PCB. Pin transfer and curing of the polyimide resist SX AR-PC 5000/80.2 (Allresist) in vacuum at 170°C for 30 min passivated the electrical connection to withstand humid biological environments. Flip-chip bonding was carried out with the isotropic conductive adhesives EPO-TEK H20E-FC (Epotec) and ACURA E8074 from Resin Designs. Due to superior yield, second generation flip-chip bonding favored the lead free solder paste SN96.5AG3CU0.5 from Heraeus reflowed in the vapor phase soldering oven SLC 304 (IBL) for 3D- μ ECoG-MEA packaging to the manufactured PCBs and SX AR-PC 5000/80.2 passivation (see Figure 2).

Ethical approval: The conducted research is yet not related to either human or animals use.

3 Results and discussion

The PI-2611 based micromachined 32-channel neural implants integrate total electrode site diameters of 155 μm which allow for novel 3D- μ ECoG-MEA fabrication, since mask-based microfabrication of conductive paths along almost vertical side walls is technically not feasible. Taper-type electrode sites with base taper side wall angles of about 95° elevate the exposed electrode areas of 50 μm in diameter from the substrate foil level adjacent to active cortical neuronal tissue and potentially optimize achievable signal-to-noise ratios.

Figure 3 (top) depicts the as-fabricated 3D- μ ECoG-MEA incorporating conformal sealing lips manufactured out of three PI-2611 layers to form the polymer substrate base taper structure. A 16 μm high taper etched in as-deposited multi-layered PI foil with lift-off patterned Cr/Au/Pt metallization is shown in Figure 3 on the lower left. In the next steps of the fabrication process, the second and embedding PI-2611 layer was spun on and cured



Figure 2: Flip-chip bonded 3D- μ ECoG-MEA to PCB with SAC305.

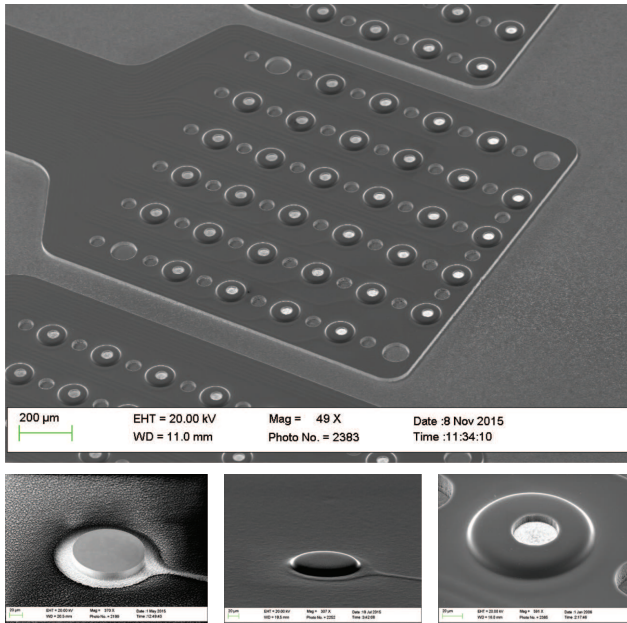


Figure 3: SEM pictures of 3D- μ ECoG-MEA with 16 μ m base taper.

encapsulating the electrode structures (Figure 3, middle). Subsequently, next to electrode separation and through whole structuring, active electrode sites are exposed via reactive ion etching and PI sealing lips are integrated on the top faces of each taper as shown in Figure 3 (lower right). Therefore, crosstalk between electrode sites can be reduced. The overall electrode thickness is 30.4 μ m and the planar section of the 3D- μ ECoG-MEA is 19.1 μ m thick, measured with the digital microscope VHX5000 from Keyence.

The SEM images of Figure 4 illustrate a 3D- μ ECoG-MEA fabricated with nine PI-2611 multilayers in order to realize elevated aspect ratios of integrated tapers carrying the exposed electrode sites. As a result, 59 μ m high tapers are implemented and shown in Figure 4 (top). To the initially 69 μ m base taper structure depicted (middle left), an equalizing PI layer had to be deposited at 1500 rpm for 60 s to smoothen surfaces in order to allow for later metal lift-off (middle right). This intermediate process step was required since the evolved surface roughness did not allow for acceptable lift-off results. Thereby, the taper height was

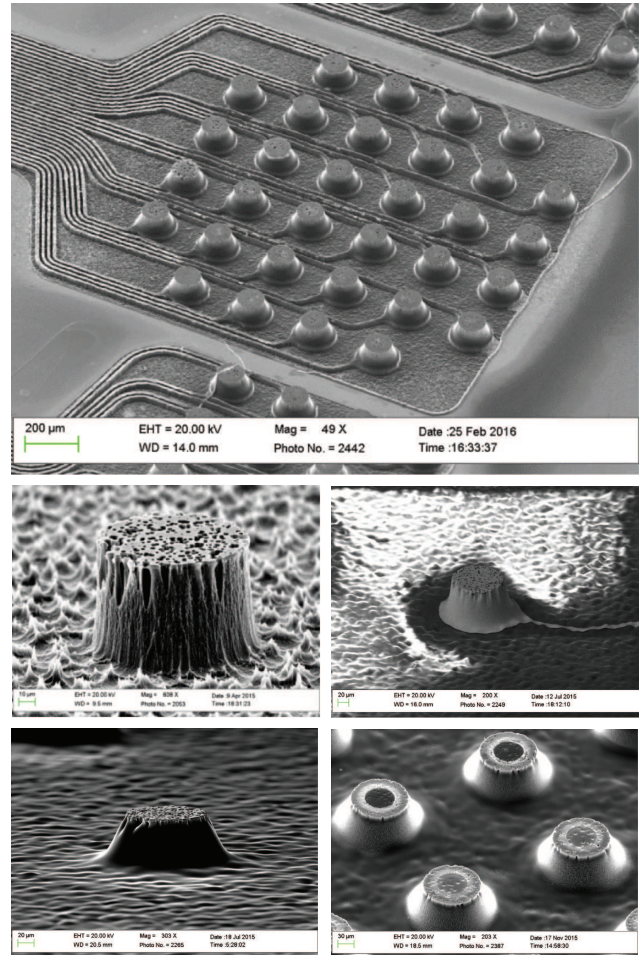


Figure 4: SEM pictures of 3D- μ ECoG-MEA with 69 μ m base taper.

reduced to 61 μ m. The final and encapsulating PI-2611 thin film was spun on at 5000 rpm for 60 s (lower left) and results in a final taper height of 59 μ m for the displayed and patterned 3D- μ ECoG-MEA on the lower right of Figure 4. The overall electrode thickness for the higher aspect ratio 3D- μ ECoG-MEA is 94.2 μ m and the planar section of the electrode is 34.8 μ m thick (digital microscope VHX5000, Keyence).

Hence, a spin-on at 5000 rpm and given curing conditions leads to a PI thickness of about 2.6 μ m, whereas, spin-coating at 3000 rpm produces 4.1 μ m thick PI-2611

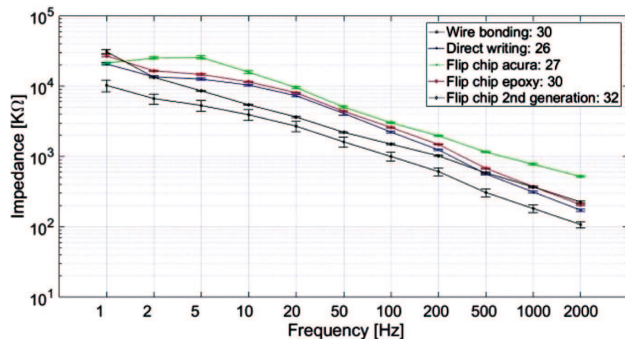


Figure 5

layers and, respectively, 1500 rpm involve PI thicknesses of about 8.4 μm .

The overall yield of 3D- μ ECoG-MEA fabrication applying the documented packaging strategies for first generation did not extend 46% and, therefore, was not satisfactory from the technological point of view. Second generation packaging is distinguished with a yield of approximately 97% and, thus, is suited for first *in vivo* tests.

The impedance measured with the impedance tester Nano Z (Neuralynx) in saline electrolyte was determined to be about 368.9 k Ω . An impedance plot illustrated in Figure 5 compares first and second generation packaging solutions. Further electrode characterization and *in vivo* validation of elevated SNRs is to be implemented in the following 3D-ECoG-MEA development steps.

4 Conclusion

Novel, three-dimensional, polyimide-based, highly flexible, microscale electrocorticography multi-electrode arrays of two different aspect ratios for enhanced epicortical recording of local field potentials are fabricated with standard MEMS and packaging processes. Final taper heights

of approximately 4 μm and 59 μm are accomplished. As a result, taper-type electrode shapes elevate the exposed electrode sites in respect to the substrate base level to make closer contact to the signal source and, thus, the cortical tissue. This entails the potential of improved signal-to-noise ratios (SNR) on the basis of incorporated tapers with sealing lips on the top faces of electrode sites as well as micro- and nonporous electrode site surfaces for impedance optimization. As-fabricated 3D- μ ECoG-MEAs are distinguished by characteristic impedances of about 368.9 k Ω at 1 kHz measured in saline electrolyte. Applied packaging strategies favor flip-chip bonding and vapor phase soldering of the polymer substrates to printed circuit boards.

Author's Statement

Research funding: The work has been funded by the Priority Program 1665 of the DFG with the support code "DFG/OH 69/11" and by the BMBF in the framework of Forschungscampus STIMULATE with the support code "03FO16102A" as well as by the state of Saxony-Anhalt (sup. code "I 60"). **Conflict of interest:** Authors state no conflict of interest. **Material and Methods:** Informed consent: Informed consent is not applicable. **Ethical approval:** The conducted research is not related to either human or animal use.

References

- [1] Obien MEJ, Deligkaris K, Bullmann T, Bakkum DJ, Frey U. Revealing neuronal function through microelectrode array recordings. *Front Neurosci.* 2015;8:1–30.
- [2] Ordonez J, Schuettler M, Boehler C, Boretius T, Stieglitz T. Thin films and microelectrode arrays for neuroprosthetics. *MRS Bull.* 2012;37:590–8.
- [3] Buzsáki G, Anastassiou CA, Koch C. The origin of extracellular fields and currents – EEG, ECoG, LFP and spikes. *Nat Rev Neurosci.* 2012;13:407–20.