Softer, thinner and more complaint cochlear implants with liquid metal

Bei Wang [a], Hao Li [b], Sonal Prasad [c], Jing Xu [a], Anders Fridberger [c], Klas Hjort [a*]

[a] Microsystems Technology
Department of Materials Science and Engineering
Uppsala University, Uppsala, Box 35 75103, Sweden
[b] Department of Surgical Sciences, Uppsala university Hospital, Uppsala, 75185, Sweden
[c] Department of Biomedical and Clinical Sciences, Linköping, 58185, Sweden
e-mail: klas.hjort@angstrom.uu.se

A cochlear implant (CI) is an advanced implantable medical device that can restore sound perception for people with congenital or sensorineural hearing loss by delivering modulated electrical stimulation to auditory nerves through an electrode array inserted in the cochlea. It has been one of the most successful neural prostheses [1-3]. However, the electrode arrays consist of long wires and rigid platinum electrodes encapsulated in soft elastomer tubing. The high stiffness of this structure may cause intra-cochlear trauma during its insertion. In addition, current commercially available CI electrode arrays are all manually assembled, leading to relatively high cost when it comes to scaling massive manufacturing. Gallium-based liquid metal (LM) is liquid at room and body temperature, with excellent electrical conductivity and stability during stretching. Replacing solid wires, LM can enhance the compliance of the electrode array, contributing to less intra-cochlear trauma, but the LM pattern demands high-resolution. To reduce costs and increase precision, automated manufacturing for small series but larger total numbers like in printed circuit board (PCB) manufacturing would be sought for CI production.

This work introduces a PCB manufacturing technique for high-resolution LM-based cochlear implant fabrication. It consists of laser cutting and ablation, masked LM microscale spray deposition, lift-off, and encapsulation. The microscale deposition is capable of patterning uniform LM at high resolution by fine spraying a sonication-produced LM particle based ink [4]. A novel feature is that the laser-processable substrate is engraved when cutting the protective lift-off mask, avoiding mask transfer by lamination [5] and allowing for alignment, vias, and higher aspect ratio structures, at high resolution. This feature simplifies the whole process and improves the precision and yield, allowing for more complex circuits.

Figure 1 shows the process in more detail. The substrate material was carbon black (2 wt%) mixed with polydimethylsiloxane (cPDMS). The sacrificial mask was dyed polyvinyl alcohol (PVA). Both have similar energy absorption to laser energy. For the lift-off process, the PVA mask is dissolvable in water. With the high precision of the laser system, the lift-off PVA film, and the engraving of the cPDMS, an aspect ratio up to two was shown and the line width resolution was 30 µm.

The produced cochlear implant contains cPDMS, liquid metal, and platinum electrodes (Figure 2). The Young's modulus of PDMS is 1 MPa. It is stiff enough to be inserted into a printed guinea pig cochlea model. The micro-CT image shows the high-resolution liquid metal spatial distribution. The micrograph in Figure 3 exhibits the cross-section of the electrode hole, and the distance between electrodes is 1.3 mm. The impedance at 1 kHz is about 8 kΩ. The investigated impedance over the frequency also shows good performance. With these evidences, we believe the LM based CI will work in future animal experiments *in vivo* with more electrodes.

[1] A. Dhanasingh et al., Hearing Research. 356 (2017) 93-103.
[2] Y. Xu et al., IEEE Trans. Biomed. Engineer. 66 (2019) 573-583.
[3] A. Dhanasingh et al., PLoSONE. 14 (2019) e0222711.
[4] B. Wang et al, Adv. Mater. Technol. (2021) 2100903.
[5] B. Wang et al, Soft Robotics 6 (2021) 414.

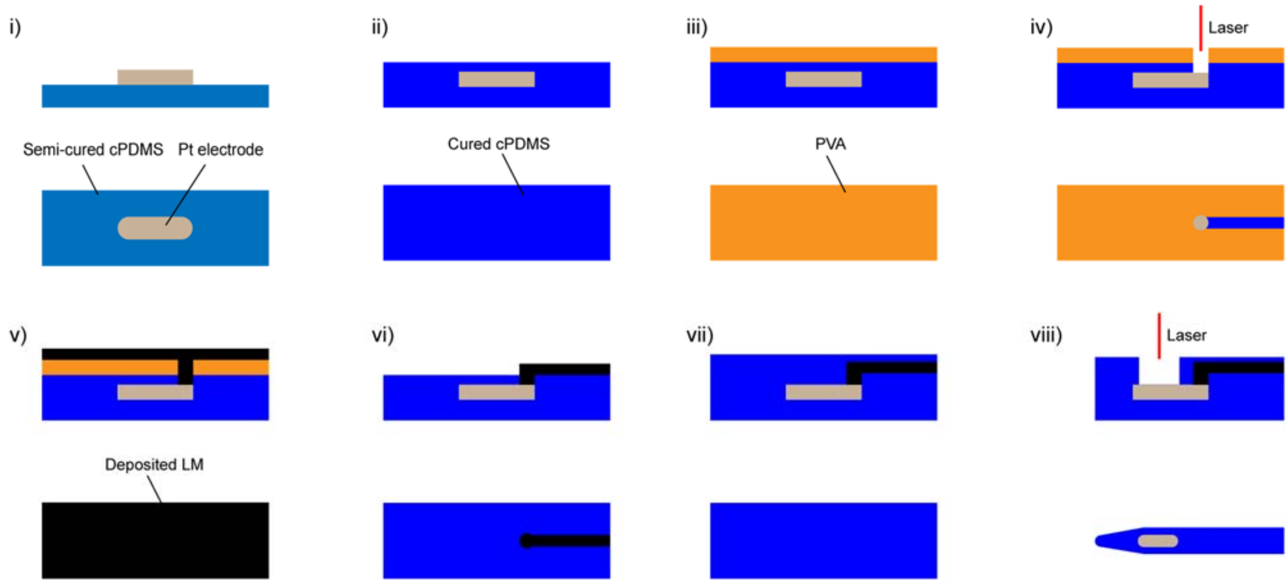

Figure 1. Illustration of the manufacturing process (Cross-section view on top and top-view at the bottom). i) Pick and place platinum electrodes on the sticky substrate of semi-cured cPDMS. ii) Cover another layer of cPDMS and fully cure. iii) Laminate PVA (polyvinyl alcohol) film. iv) Laser pattern the circuit and ablate a via hole to the electrode below. v) Microscale deposition of a layer of LM. vi) Lift-off the mask in the water, and expose the circuit. vii) Encapsulate the circuit with another layer of cPDMS. viii) Ablate the hole for electrical stimulation, and cut the CI shape (Assume here is the end of CI).

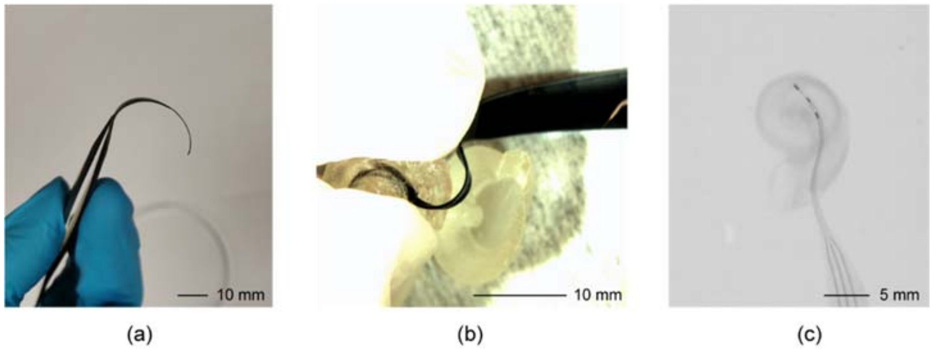

Figure 2. Photograph of a manufactured three-electrode cochlear implant with 1.3 mm pitch (a) and a top view when inserted into a 3D-printed cochlea model (b), and a micro-CT image (c).

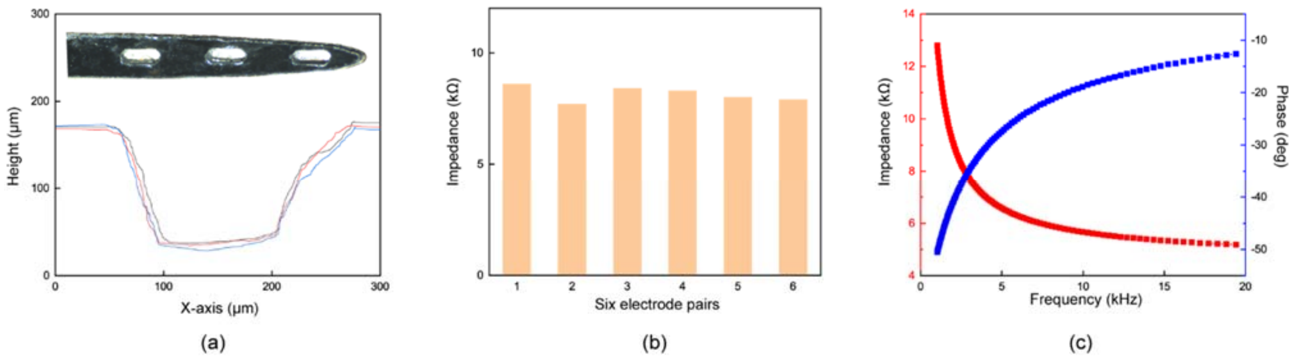

Figure 3. Cochlear implant characterization. (a) The cross-section of the electrode hole. The insect is the micrograph of the apical. (b) The impedance of six electrode pairs. (c) Frequency-dependent impedance spectrum.