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DOI
10.1109/CAS56377.2022.9934629

Publication date
2022

Document Version
Final published version

Published in
2022 International Semiconductor Conference, CAS 2022

Citation (APA)
French, P. J., Lawand, N., & Miralles, A. (2022). Advances in cochlear implants. In *2022 International Semiconductor Conference, CAS 2022* (pp. 87-90). (Proceedings of the International Semiconductor Conference, CAS; Vol. 2022-October). IEEE. https://doi.org/10.1109/CAS56377.2022.9934629

Advances in cochlear implants

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Abstract*—Cochlear implants restore hearing to many people around the world. These devices are hand-made and have limitations in terms of sound quality. The maximum number of electrodes at present is 22 and this means that the sound spectrum is divided into 22 blocks. Furthermore, the breadth of the implant limits penetration and thus lower frequencies are lost. Silicon based technology enables an increase in the number of electrodes and also a reduction in the cross-section of the probe. This will improve sound quality and reduce risks of damage during insertion. This paper shows the development of new technologies to improve the quality of cochlear implants. These involve a move to polymers which make use of silicon-based technology in their manufacture.

Keywords*—cochlear implant; Polymer devices; neural stimulation; implants.

1. Introduction

Present day cochlear implants use platinum electrodes incorporated in hand-made probes [1]. There is a clear need to develop probes that can be manufactured using techniques developed in the silicon industry. Present day cochlear implants consist three parts. The external part contains the microphone, power and transmission (of power and signal). Inside the body there is a unit which receives the signal and converts it into the signal required for the electrodes. The final part is the probe which is inserted into the cochlea which stimulates the nerves. The implant makes around 1½ turns in the cochlea which means that low frequencies are missed. Although the quality is limited, this implant restores hearing to the deaf with a quality where they can participate in conversation. The basic structure of the cochlear implant system is given in Fig. 1. Being handmade, the number of electrodes which can be included is limited and also miniaturisation of the electrodes is limited. One solution is to incorporate technologies developed in the silicon industry, which enables the number of electrodes to be increased. Although this technology allows a considerable increase in the number of electrodes, we still need to consider the maximum charge injection capabilities of the electrodes. Each electrode needs to deliver sufficient current to activate the nerves.

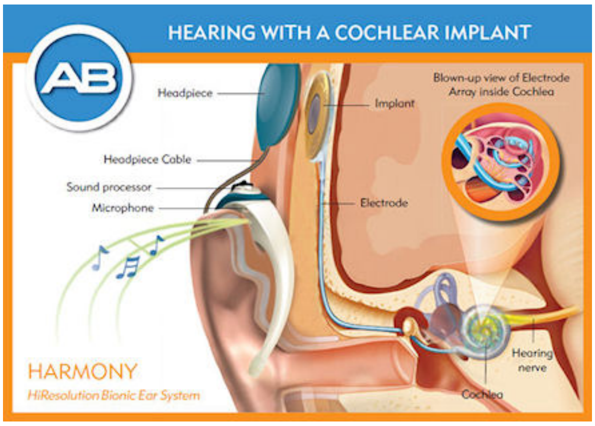

Figure 1 Cochlear implant. Reproduced with kind permission of Advanced Bionics.

2. Polymer based cochlear implant

Polymers offer new possibilities for cochlear implants. Polymers can be formed on a silicon substrate and removed at the end of the process to leave a polymer probe. The basic process is shown in Fig. 2 [2]. This uses a standard silicon wafer as base material on which SiO2 is grown and aluminium deposited (a). This is followed by the first polyimide layer (b). Then the Ti, TiN and Al layers are deposited. TiN was chosen as the

2022 International Semiconductor Conference (CAS) | 978-1-6654-5255-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/CAS56377.2022.9934629

electrode material since evidence shows that it is more stable than platinum in the this harsh environment. An example of a platinum electrode after use in a harsh environment is given in Fig. 3 [3].

After patterning, the probe is coated again with polyimide and then the windows are made over the electrodes. These devices have been fabricated and initial in-vivo measurements made. These showed the promise of this approach.

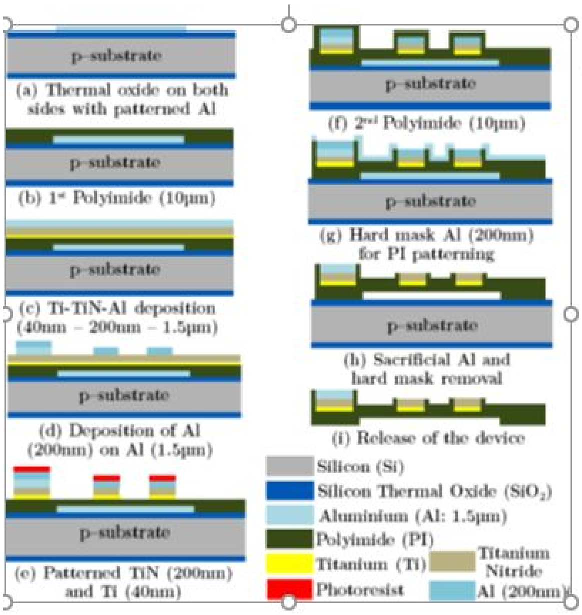

Figure 2 Processing for a polymer based cochlear implant

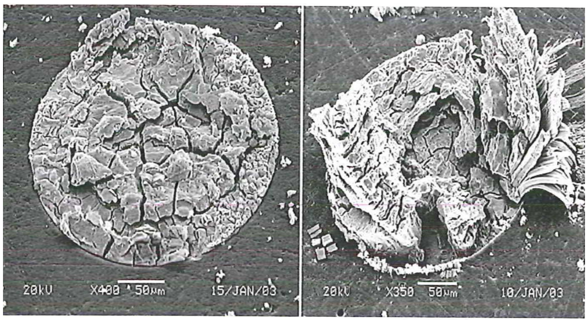

Figure 3 Platinum electrodes after exposure [3].

Although many issues can be addressed, there are still some remaining issues. As we increase the number of electrodes the numbers of tracks increase, which limited the maximum number of electrodes. The track will have to be very narrow and close together. This leads to an increase in resistance and the risk of capacitive interference between tracks. This can be addressed by adding multiplexing directly under the electrodes. A similar processing approach can be used, except that a thin layer of silicon is left at the end of the process. As shown in Fig. 4, the starting material is now a processed wafer with the electronics. The polyimide and metallisation (including the electrodes) are formed (b). Then the silicon is etched back to leave a thin silicon layer, which is flexible (c). Finally an additional layer of polyimide is used to coat the probe (d). This process does not require the removal of the probe from the silicon substrate, as shown in Fig. 2i. It has also been shown that TiN can be used as metallisation for a BiCMOS process [4], which can simplify the process. The would mean replacing the metallisation of the BiCMOS with TiN.

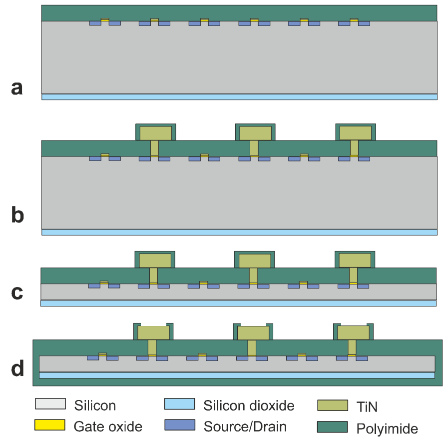

Figure 4 Basic process for polymer based probe with silicon electronics.

3. Polymer electrodes

The structure shown in Fig. 4 solves most of the issues with present day cochlear implants. The remaining issue is the charge injection limit. As mentioned above, this issue limits the number of electrodes which can be used. Traditional platinum electrodes has an injection limit of around 25-50μC/cm^2. TiN has a higher charge injection limit, but also has relatively high resistivity.

An option is to use conductive polymers, which can also simplify the process. An excellent candidate is PEDOT:PPS [5]. This is normally a conductive polymer, which makes it suitable for the electrodes, and it can be made insulating selectively with further processing. This further simplifies the process since a single layer can be used as both conductor and insulator. This work is focussed on the PEDOT:PPS material and its properties. Experiments have yielded, as deposited, a PEDOT:PPS conductivity of 230 Scm^{-1}, which is sufficient for the electrode. PEDOT:PPS can be made insulating in selective areas using standard lithography. Methods such as annealing, UV radiation [6] and NaOCl [7] treatment can be used. This work looks at using NaOCl to turn the conductive polymer into an insulating polymer. The advantage is that we can use standard lithography to make selected areas insulating. NaOCl causes a chemical oxidation of the PEDOT. In initial experiments NaOCl caused rapid reduction on conductivity in all exposed areas. However, surface damage could be seen, and is some cases caused delamination. Using under 0.05% wt. the conductivity was greatly reduced (to around 0.48 Scm^{-1}) within 60 seconds without damage to the layer. This is sufficient to use PEDOT:PPS as the electrode and the surrounding insulating layer. The change in conductivity after NaOCl treatment is given in Fig. 5.

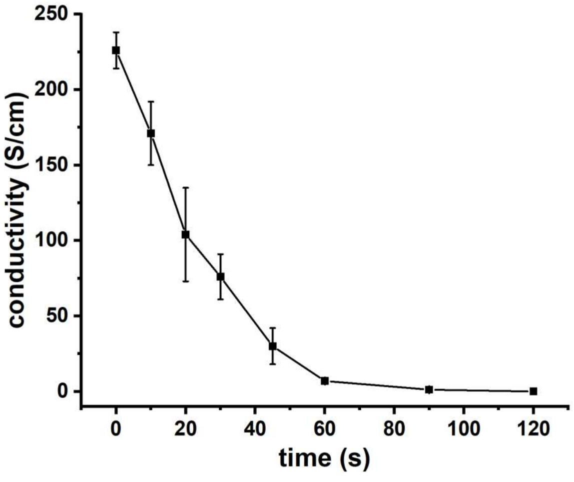

Figure 5 The reduction in conductivity as a function of exposure time to NaOCl.

A further minute of exposure led to a further (minor) reduction of conductivity. The PEDOT was converted into an effective insulator and the unexposed areas maintained their high conductivity. This means that a single layer can be deposited and non-conductive areas defined around the electrodes. The issue remains whether the devices can be sufficiently cleaned to remove any traces of NaOCl for this *in-vivo* application. The probes can be cleaned, but it still has to be tested whether this is sufficient for FDA approval.

Furthermore, studies have shown that PEDOT can be made biocompatibility [8-9], although the long-term stability for this application still has to be investigated.

The next issue is charge injection capacity. This is extremely important if we want to reduce the size of the electrodes in cochlear implants. If the electrodes are made too small, they are unable to inject sufficient current to stimulate the nerves. Experiments have shown that PEDOT:PPS has a charge injection capacity of 384μCcm^{-2}, compared to 25μCcm^{-2} for platinum, an increase of a factor of 15. This is shown in Fig. 6

This means that the electrode can be significantly reduced in size, while maintaining sufficient current injection. This will allow us to increase the number of electrode and retain sufficient charge injection. Therefore, with correct processing PEDOT can be used for both insulating layer and electrode material.

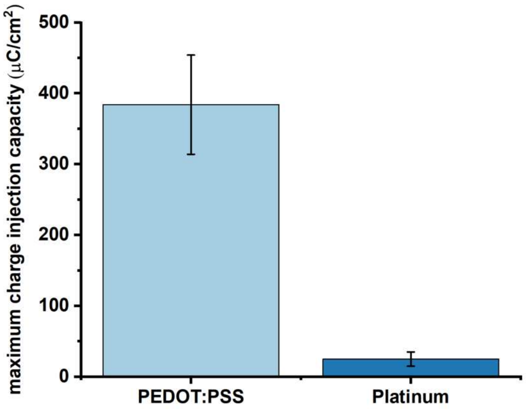

Figure 6 Maximum charge injection capacity of PEDOT:PSS.

If polymer electronics were to be included, this would lead to a completely polymer-based cochlear probes which will be cheaper and more effective than present day devices. It still has to be investigated on whether the PEDOT electrodes should be combined with silicon electronics or polymer electronics.

4. Conclusions

Modern cochlear implants restore hearing for many people around the world. However, there are limitations in the sound quality, due to the low number of electrodes. Furthermore, the cross-section of probe increases the risk of injury during insertion. This work has shown that the number of electrodes can be increased using polymers and silicon technology. The second level of limitation is the charge injection capacity of the electrodes. A move to conductive polymers in place of platinum yielded a 15 fold improvement in injection capacity. This allows a reduction in the electrode size. A polymer-based cochlear implant shows great promise for future cochlear implants.

Acknowledgments. The authors would like to thank The National Science Foundation (STW), who funded part of this work. Prof. Johan Frijns and Dr. Jeroen Briaire from Leiden University Medical Sensor for the collaboration and the in-vivo measurements and Advanced Bionics for their support and input throughout the different projects.

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