Thomas Velten*, Thorsten Knoll, Frank Stracke, Ronan Le Harzic, Tino Jaeger, Michael Rammensee, Oliver Kurz, Stephan Klesy, Kai Januschowski, Loic Sermeus, Peter Szurman, Yves Olsommer and Klaus-Peter Hoffmann

Wireless retina implant with optical energy supply

https://doi.org/10.1515/cdbme-2020-2007

Abstract: We present the first results of work towards a foil-based epiretinal prosthesis that can stimulate retinal cells. The prosthesis receives trigger signals and energy in the form of high intensity infrared radiation. Array-like silicon photodiodes with attached thin film electrodes convert the received infrared light into electrical stimulation signals, which are intended to stimulate ganglion cells. The photodiodes are arranged like stones in a mosaic on an only 10 µm thin and thus flexible polymer foil. Like this, the prosthesis can adapt to the curved shape of the eye and will have close contact with the retina.

The photodiode array is fabricated on silicon wafers. Etched trenches guarantee the electrical separation between the individual photodiodes and pixels. Spectral sensitivities of backside-illuminated photodiodes were measured for wafers thinned to different thicknesses. The thin polymer foil is realized by spin coating polyimide on the photodiode array followed by imidization. Via holes are etched into the polyimide film for contacting the pads of the photodiodes. First spin coating tests were performed using silicon wafers without photodiodes but with metal pads and with etched trenches to simulate the gap between individual photodiodes.

Although the thickness of the spin-coated polyimide layer was very inhomogeneous, we succeeded in realizing vias for connecting contact pads by thin film gold tracks crossing deep trenches. The realized via holes had inclined sidewalls as desired. Electrical measurements showed sufficient electrical contact between two connected pads.

Keywords: electrostimulation; retina implant; retinitis pigmentosa.

***Corresponding author: Thomas Velten**, Fraunhofer IBMT, Joseph-von-Fraunhofer-Weg 1, 66280 Sulzbach, Germany,
E-mail: thomas.velten@ibmt.fraunhofer.de
Thorsten Knoll, Frank Stracke, Ronan Le Harzic, Yves Olsommer and Klaus-Peter Hoffmann
Fraunhofer IBMT, 66280 Sulzbach, Germany
Tino Jaeger, Michael Rammensee, Oliver Kurz and Stephan Klesy, PREMA Semiconductor GmbH, 55129 Mainz, Germany
Kai Januschowski, Loic Sermeus and Peter Szurman, Augenklinik Sulzbach, Knappschaftsklinikum Saar, 66280 Sulzbach, Germany

Introduction

About three million people worldwide are affected by a hereditary disease of the retina [1]. The most prevalent form is retinitis pigmentosa, a retinal degenerative disease which can lead to complete blindness due to the loss of photoreceptors. The implanted electronic retinal prosthesis is so far the only available form of therapy [2]. This prosthesis is usually placed on the inner limiting membrane (epiretinal) or between the retina and pigmented epithelium (subretinal) and converts the light entering the eye into electrical signals. In case of epiretinal implants these electrical signals depolarize the still intact ganglion cells and the image information thus initiated is transmitted to the brain via the optic nerve [3]. The disadvantages of previous retinal prostheses are a severely restricted field of vision and the need for a power supply cable leading into the eye.

First approaches exist for the realization of wireless, purely optically powered retinal prostheses [4]. These use arrays of silicon photodiodes suspended by thin bars of silicon to give the prostheses a high mechanical flexibility.

Here, we describe a retinal prosthesis consisting of a two-dimensional array of light-sensitive pixels. Three thin silicon photodiodes connected in series form one pixel. Trenches separate adjacent photodiodes. A thin, continuous polyimide layer connected to the photodiodes holds the pixels together. The foil is the substrate for the stimulation electrodes. In addition, the electrical wiring between individual silicon photodiodes of a pixel is realized on the foil, which simplifies the processing of the silicon wafer. The implant realized on the flexible foil can adapt to the curved shape of the eye even if realized as a large-area implant, thus allowing a wide-angle projection to achieve a large field of view.

We present first results of the work on the foil-based epiretinal prosthesis. These include the fabrication of the silicon photodiode arrays, their integration with a thin polymer foil and the realization of feedthroughs and electrodes.

Stimulation concept

The image data and the energy required for electrostimulation are transmitted wirelessly to the implant by optical means using projection glasses. The stimulation electrode of each pixel has a radius of 35 µm while the active area of each of the three photodiodes forming one pixel is 315 µm by 85 µm. The photo diodes are assumed to have a sensitivity of 0.15 A/W at 905 nm wavelength. We aim at stimulation with passive charge compensation by using cathodic-first pulses of about 0.1 ms duration per phase and a current density of 0.2 mC/cm^2. Connecting three photodiodes of a pixel in series and illuminating the pixel with 905 nm light at 6.4 mW/mm^2 leads to the desired charge of 0.2 mC/cm^2 per pulse at the stimulation electrode. In order to avoid overheating of the retina during light pulses, the pulses must be limited in intensity. For pulsed exposure, the peak irradiance limit in the 0.05–70 ms duration range at a wavelength of 905 nm is described by the equation $285t^{-0.25}$, where t is the pulse duration in milliseconds and the result is in mW/mm^2 [4]. For 0.1 ms long pulses the permitted value is 507 mW/mm^2 and thus approx. 80 times higher than the light intensity assumed to be required for electrostimulation.

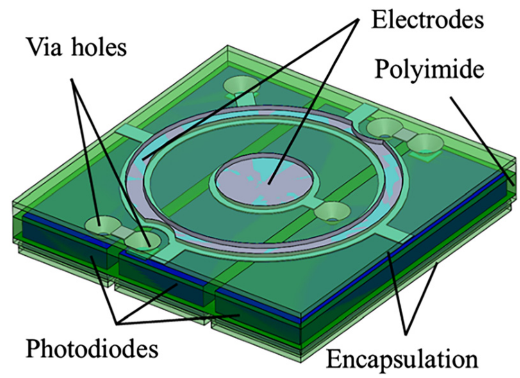

Figure 1: View of a pixel comprising three photodiodes. A thin layer of polyimide spans over all photodiodes and the 30 µm wide trenches between adjacent photodiodes. Electrodes are realized on the upper side of the polyimide layer. Interconnection of the photodiodes and electrical contacts to electrodes are realized by through holes in the polyimide and a metallization. Top and backside are encapsulated while electrodes are uncovered.

Materials and methods

Fabrication concept

The proposed foil-based retinal implant is designed to be highly flexible and to conform closely to the retina. The implant consists of a mosaic-like arrangement of approximately 1,600 square pixels with an edge length of 315 µm. The implant diameter is 14 mm. Each pixel comprises three thinned silicon-based photodiodes, which are initially not electrically connected to each other. Trenches with a depth greater than the thickness of the photodiodes and a width of about 25 µm are etched between the three photodiodes of a pixel as well as between the pixels. The individual pixels of the implant are held together by a thin polyimide film. The mechanical flexibility of this thin film contributes to the flexibility of the entire implant. The film is realized by spinning liquid polyimide onto the silicon substrates. After imidization, a thin film is formed which is directly connected to the photodiodes. The film is structured by lithography and dry etching and then metallized. After these process steps, the stimulation electrodes are located on the polyimide foil and the photodiodes underneath the foil. The individual photodiodes of a pixel as well as the pixels among each other are now electrically connected with each other by means of via holes in the polyimide and the applied metallization. Subsequently, the silicon substrate is thinned from the backside to the final thickness, which must be less than the depth of the trenches. After separating the implants, each implant is encapsulated while leaving the electrodes open (see Figure 1).

Realization of photodiode array

Photodiodes are fabricated in a bipolar semiconductor process using standard 150 mm wafers. An n-doped layer is spacial-selectively implanted right below the surface of the silicon wafer that is weakly p-doped. Thus, a pn junction is formed perpendicular to the surface. Both junctions, anode and cathode, are connected and wired with conducting and isolating layers coated and structured on top of the silicon substrate. Because the epiretinal implant requires backside illumination, the topside of the photodiodes is covered with a metal layer. This causes photons that are not absorbed when passing through the silicon to be reflected back to the pn junction. The metal layer is partly interrupted to release possible strain. Afterwards, deep trenches are etched between the photodiodes and wafers are thinned by chemical-mechanical polishing. A part of the surface of the photodiodes is shown in Figure 2.

Realization of via holes and their metallization

One of the most challenging processes in implant fabrication is the spin-on process for the polyimide and the realization of via holes. The trenches etched into the silicon wafer make it difficult to achieve a homogeneous thickness of a spin-on layer. Therefore, first tests were performed with test wafers comprising no photodiodes.

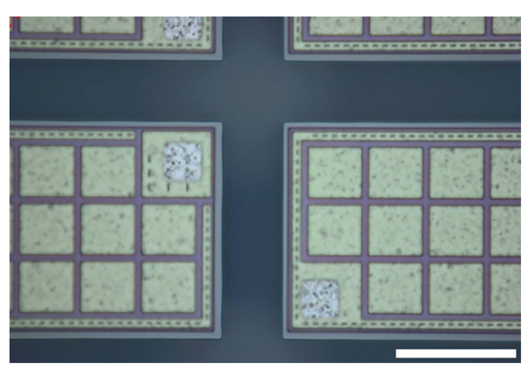

Figure 2: Microscope image taken after etching trenches between the photodiodes. Scale bar: 50 µm.

An etching mask made of the positive photoresist AZ 4562 was first lithographically structured. Subsequently, trenches were etched into the silicon with a reactive ion etching (RIE) process using O_2 and CF_4 as etch gas. Due to the chosen etching process and the geometric boundary conditions, an etching depth of 40 µm with a trench width of 15–20 µm was achieved on the test wafers. After etching the trenches, the test wafers were coated with polyimide. The coating was applied in two subsequent spin-on steps, resulting in a total polyimide thickness of 10 µm. A 30 µm thick layer of the positive resist AZ 4562 was lithographically patterned and used as etch mask for etching via holes into the polyimide by RIE for 110 min using oxygen as etch gas. A metal layer (300 nm gold on 10 nm platinum) was sputter deposited for realizing the contacts between vias and between vias and electrodes. Patterning of the metal was done by lift-off using the photoresist AZ nLOF 2035. The photolithographic masks also comprise additional test structures with bigger contact pads which facilitate measurements of the electrical contact between connected vias. A conventional multimeter was used for these measurements.

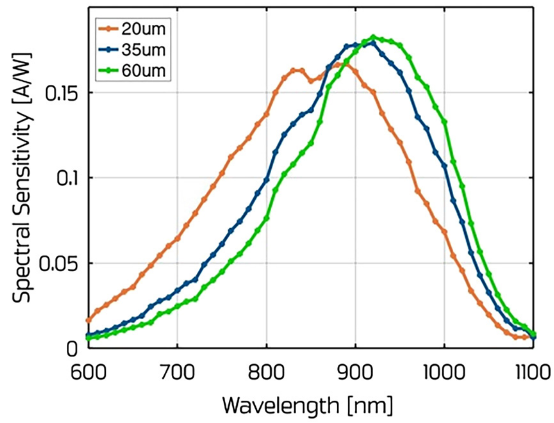

Figure 3: Spectral sensitivity of backside-illuminated photodiodes with a thickness as labelled.

Results

Spectral sensitivity of thinned and backside-illuminated photodiodes

The spectral sensitivity of thinned and backside-illuminated photodiodes was determined experimentally. Therefore, wafers with comparable photodiodes were mechanically back-grinded to wafer thicknesses of 20, 35 and 60 µm. Without any additional treatment singulated photodiodes were illuminated by a tunable light source and compared to a known reference sample. As it is illustrated in Figure 3 the maxima of the spectral sensitivity shift with the thickness of the photodiode. Interestingly, the spectral sensitivity was still about 35% of the value for frontally illuminated photodiodes. Additional measurements also showed that photodiodes without metal cap exhibit a reduced spectral sensitivity [5].

Realization of via holes and their metallization

It was possible to spin on the polyimide layer without creating streaks or air bubbles. Figure 4 shows the wafer after via holes had been etched in the polyimide by RIE and after metallization with a thin gold layer which was patterned by lift-off. Contacts between neighbouring via holes and a contact to one of the electrodes are realized. It is quite obvious from the photograph that the polyimide layer has an inhomogeneous thickness. The realized via holes have slightly inclined sidewalls as desired. SEM images (see Figure 5) show that the trenches are sufficiently filled with polyimide and gold tracks running from one side of the trench to the other have no interruptions. Electrical measurements on special contact pads confirmed that the two via holes and the metal layer connecting these via holes provide good electrical contact. The resistance measured between two contact pads was about 1.5 Ω.

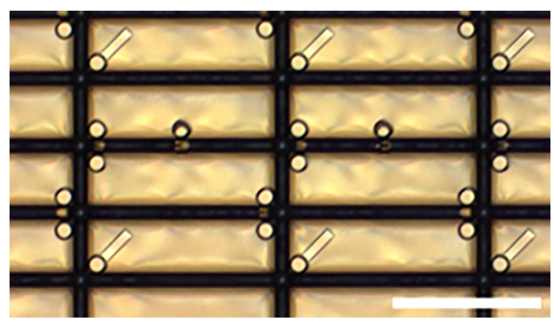

Figure 4: Microscopic image of the test wafer after metallization of the etched via holes. Scale bar: 500 µm.

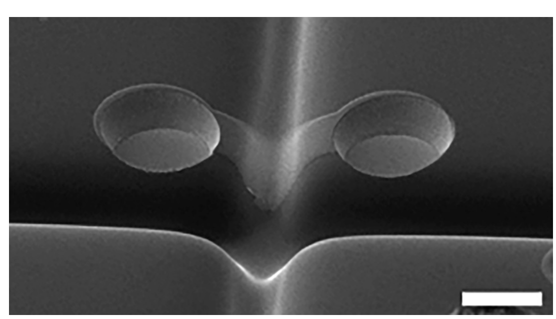

Figure 5: SEM image of two neighbouring via holes, which are electrically connected by a thin gold layer. The gold layer crosses the trench between the two via holes. Scale bar: 20 µm.

Discussion and outlook

To achieve a relatively high light sensitivity of backside-illuminated photodiodes we use thinned photodiodes. Despite the limited penetration depth of light into silicon, at photodiode thicknesses between 20 and 60 μm a significant amount of light generates photoelectrons that reach the pn junction at the front-side of the photodiode. As expected, penetration depth increases with wavelength. For a wavelength of 905 nm a silicon thickness between 20 and 35 μm leads to maximum sensitivity. Thin photodiodes are not only the preferred choice concerning photosensitivity but also due to the required mechanical flexibility of the implant. Due to the limit on aspect ratio imposed by the etching technique when etching trenches, shallower trenches would allow a reduction in trench width. This would not only enable to bring the photodiodes closer together but also reduce the challenge in realizing a thin polyimide foil on the patterned silicon wafer. The polyimide layer applied by a spin-on process has an inhomogeneous thickness due to the trenches in the silicon wafer. This effect is well known for spin-on processes applied to substrates with deep trenches. Although the thickness of the spin-coated polyimide layer was very inhomogeneous, we succeeded in realizing vias for connecting contact pads by thin film gold tracks crossing deep trenches.

The next step will be transferring the established processes to silicon wafers with realized photodiodes. Deep reactive ion etching (DRIE) will be used to realize trenches in order to reduce both, the trench width and the challenge in spinning on the polyimide. A statistical measurement of the resistance between the vias will be done to determine if the used fabrication process is reliable enough for being implemented into a real implant production. Further, the performance of the retina implant will be tested. A read-out system based on an explanted (human or mammalian) retina and suited for electrophysiology measurements (electro retinograms) with full nutrient and oxygen supply is already available for such tests. The implant will be placed in front of the cultured retina and illuminated with near infrared light patterns produced by a MEMS scanner.

Acknowledgment: The authors thank Micromotive GmbH, Mainz, for etching of the trenches between the photodiodes.

Research funding: The project, on which the work presented here is based, was funded by the German Federal Ministry of Education and Research under the number 16ES0783. The author is responsible for the content of this publication.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Competing interests: Authors state no conflict of interest.

Informed consent: Informed consent was obtained from all individuals included in this study.

References

1. Friedman DS, O'Colmain BJ, Munoz B, Tomany SC, McCarty C, De Jong PT, et al. Prevalence of age-related macular degeneration in the United States. Arch Ophthalmol 2004;122:564–72.
2. Shepherd RK, Shivdasani MN, Nayagam DA, Williams CE, Blamey PJ. Visual prostheses for the blind. Trends Biotechnol 2013;31: 562–71.
3. Walter P. Sehprothesen. Der Ophthalmologe 2016;113:175–89.
4. Mathieson K, Loudin J, Goetz G, Huie P, Wang L, Kamins TI, et al. Photovoltaic retinal prosthesis with high pixel density. Nat photonics 2012;6:391.
5. https://prema.com/index.php/en/assps-en/photo-diodes [Accessed 13 Jan 2020].