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Wireless retina implant with large visual field

Abstract: We present the concept of a novel epiretinal prosthesis, consisting of a foil-based, miniaturized electronics with wireless optical energy and signal transmission and integrated electrostimulation. The aim is achieving a wide-angle projection to create a large visual field. The implant having a diameter of 14 mm consists of a mosaic-like array of thinned silicon-based photodiodes combined with a polyimide foil. This thin implant, realized on a flexible foil for the first time, adapts to the curvature of the eye. Thin-film stimulation electrodes on the foil are electrically connected to the photodiodes. The influence of the electrode geometry on the electrical current density at the location of electrostimulation is investigated by computer simulations. First experiments towards realization of via holes in a 10 µm thick polyimide layer were successful and led to vias with inclined sidewalls and rounded openings. This shape is advantageous concerning uninterrupted conductor paths leading from the photodiodes to the stimulation electrodes.

Keywords: Retinitis pigmentosa, electrostimulation.

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1 Introduction

Worldwide, 3 million people suffer from a hereditary retinal disease [1]. Retinitis pigmentosa, the most common form, is a hereditary disease that leads to the slow death of the photoreceptors in the eye and often to complete blindness. The only therapy available so far is the implantation of an electronic retinal prosthesis [2]. These retinal prostheses convert the light entering through the eye lens into electrical impulses and lead to a depolarization of the remaining ganglion cells, which transmit the image signal directly to the brain [3]. However, previous retinal prostheses show considerable limitations with regard to visual field, resolution, cable-bound guidance into the eye for external energy supply, large extraocular components, long operation time and limited biocompatibility. The function that can be achieved at best is limited to orienting contour vision within a very small visual field radius [3].

We present the concept of a retinal prosthesis with a completely new technological approach, consisting of a foil-based, highly miniaturized electronic system with wireless optical energy transmission, wireless optical signal transmission and integrated electrostimulation. With this completely wireless solution, there are no wires leading to or into the eye. The thin pixel arrays, which are realized on a flexible foil for the first time, adapt to the curvature of the eye. The aim is to achieve the first ever wide-angle projection to create a large visual field (approx. factor 5 in relation to the state of the art).

2 Materials and Methods

2.1 Concept of the implant

The proposed implantable neurostimulator is highly flexible and closely adapts to the contour of the inner layers of the retina. Due to its foil structure, the implant fixes itself via the transretinal suction effect and does not require any special fixation. It is not necessary to fix the proposed implant exactly in place. A slight lateral shift plays no role for the topographic control of the ganglion cells to be stimulated.

The requirement to adapt to the contour of the eye is especially high for a large area retina implant. According to our concept the implant presented here has a diameter of 14 mm and consists of a mosaic-like array of thinned silicon-based photodiodes having a thickness of approx. 20 to 35 µm. Three photodiodes connected in series form one of the approx. 1,600 pixels per implant. To make the implant mechanically robust the array of photodiodes is combined with a thin polyimide foil which is put on top of the photodiode array. The top side of the polyimide foil,

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comprising the stimulation electrodes and all electrical contacts to the photo diodes, is directed towards the retina. The thin-film stimulation electrodes as well as the tracks are realized on the top side of the polyimide film by sputter deposition, while the photo diodes are located below the polyimide. The entire implant will be coated with special thin encapsulation layers to protect the photodiodes and the metal tracks from the humid environment in the eye, leaving only the stimulation electrodes open. To this end we intend to test several multi-layer coatings of DLC (diamond like carbon) and Parylene C. Opening of these encapsulation layers can easily be done by dry etching (RIE, Reactive Ion Etching) with oxygen as etch gas.

Projection glasses are used for data and energy transmission. They capture the image with an integrated CMOS camera and transmit it wirelessly and optically to the wide field implant via a diode laser and a scanner device. By amplifying the received image by laser projection, this approach achieves a high light intensity per pixel and permits simultaneous optical transmission of the image information and the energy required for electrostimulation.

2.2 Computer simulations

Computer simulations were used to determine the optimal values for the dimensions and arrangements of the stimulation electrodes. The ganglion cells to be stimulated by epiretinal implants are located in a deeper level of the retina, having about 30 to 50 µm distance from the electrodes of an epiretinal implant. To concentrate the stimulation current at the center of each pixel of the retinal implant, a pair of electrodes is provided per pixel, consisting of a round central electrode and a ring-shaped electrode arranged around it (see **Figure 1**). The diameters of the inner electrode and outer electrode ring and the distance between the inner electrode and outer electrode ring were to be optimized in such a way that the stimulation current density in the plane of the ganglion cells is maximized. For this purpose, a 3D computer model was created and simulations were carried out using the finite element method with the aid of the simulation software ANSYS HFSS 2018.2. The radius of the inner electrode was varied in the range from 5 to 40 µm with steps of 5 µm. The radius of the outer electrode was varied in the range of 60 to 150 µm with steps of 10 µm. The width of the ring of the annular outer electrode was fixed at 10 µm in all simulations. The electrical voltage at the electrodes used for the simulations was set to 1 V. The computer model assumes that the electrodes are made of gold and all layers of the retina have the same properties as nerve tissue [4]. Of interest are only the changes of the current density values, which result from a variation of the electrode geometry (relative differences). For this consideration, and assuming linear behaviour, the assumption that the electrical properties of the retina are similar to those of nerve tissue does not lead to an error.

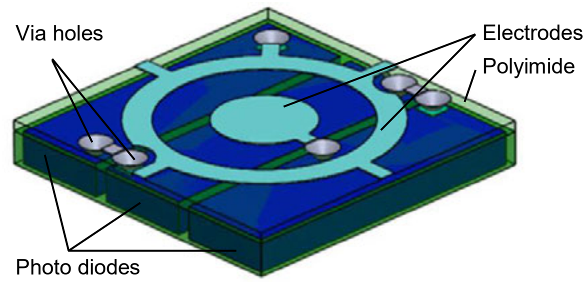

Figure 1: Oblique view of one pixel being composed of three photo diodes and separated by 30 µm wide gaps. A thin layer of polyimide spans over all photo diodes. Electrodes are located on top of the polyimide layer. Via holes in the polyimide are required for connecting three photodiodes in series and for connecting electrodes to photo diodes.

2.3 Realization of via holes

The photodiodes of each pixel are separated from one another by a gap of 30 µm fabricated by RIE at wafer level. Two thin layers of liquid polyimide (total thickness 10 µm) are spun on the wafer, cured and imidized in an oven over several hours at a maximum temperature of 350°. Platinum tracks connecting the photodiodes of a pixel electrically are realized on the thin polyimide foil which spans over the whole retina implant. Via holes are necessary for connecting the photodiodes located underneath the polyimide foil with the upper side of the foil where stimulation electrodes and tracks are located. The vias in the polyimide layer are fabricated by RIE using oxygen as etch gas.

Preliminary tests for the production of the film substrate on the silicon wafer and for the subsequent structuring of the film by RIE were carried out. The emphasis during etch process development was achieving via holes with inclined side walls and rounded upper edges to ensure that the entire sidewall and the edge of the via hole are coated with metal during the subsequent sputtering process. A 10 µm thick polyimide layer was used for the experiments. The layer applied to a silicon wafer was coated with an approx. 5 µm thick photo resist (AZ4562) and then lithographically structured. The holes produced in the resist with diameters between 25 and 50 µm were then transferred into the polyimide layer in a subsequent RIE process.

3 Results

3.1 Computer simulations

At small distances (normal to the electrode plane) from the electrodes the simulated current densities are highest for small diameters of the inner electrode (**Table 1**).

Table 1: Maximum current densities (A/m^2) at a distance of 20 µm from the electrode plane. R_i: radius of the inner electrode; R_o: radius of the outer electrode. The three highest values are highlighted.

R_o (µm)	R_i (radius of inner electrode (µm))					
	15	20	25	30	35	40
80	735	763	747	713	723	648
90	730	754	742	719	707	683
100	728	813	746	737	707	682
110	721	739	706	682	640	618
120	719	703	728	682	677	610
130	718	741	716	715	673	602
140	710	795	689	667	667	598

At larger distances from the electrode plane, the current densities are highest for larger diameters of the inner electrode (**Table 2**). For distances of 30 to 50 µm (plane of the ganglion cells) the highest current densities are obtained for radii of the inner electrode of 30 to 40 µm.

Table 2: Maximum current densities (A/m^2) at a distance of 50 µm from the electrode plane. R_i: radius of the inner electrode; R_o: radius of the outer electrode. The three highest values are highlighted.

R_o (µm)	R_i (radius of inner electrode (µm))					
	15	20	25	30	35	40
80	127	155	203	196	234	233
90	151	182	205	229	237	243
100	133	167	190	235	221	224
110	133	164	192	207	244	250
120	136	169	191	210	221	229
130	154	171	216	213	244	226
140	155	169	194	231	243	228

In the relevant tissue layers with distances of 30 to 50 µm from the electrodes, the values of the current densities are maximal under the inner electrode (see **Figure 2** as an example). A comparison of **Figure 2** with **Figure 3** shows that the strength of the current density also varies with a variation of the radius of the outer electrode. The current density changes most in the area between the inner and outer electrode, i.e. not in the area of the maximum current density.

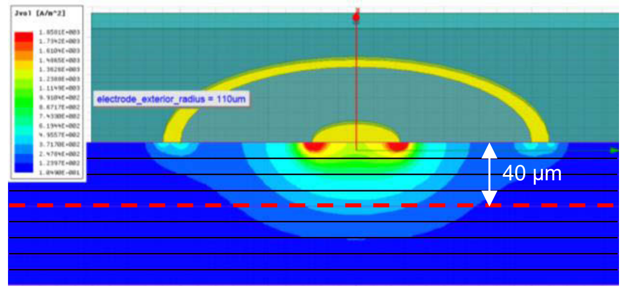

Figure 2: Distribution of the current density in the retinal tissue below the electrodes (dark blue colour: 0.105 A/m^2; dark red colour: 1.858 kA/m^2). Inner electrode with radius 25 µm and outer electrode with radius 110 µm.

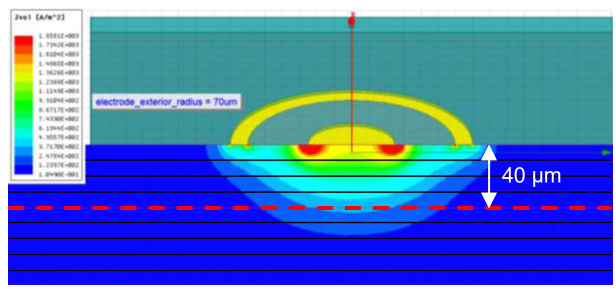

Figure 3: Distribution of the current density in the retinal tissue below the electrodes (dark blue colour: 0.105 A/m^2; dark red colour: 1.858 kA/m^2). Inner electrode with radius 25 µm and outer electrode with radius 70 µm.

The curves in the diagram of **Figure 4** show that for an inner electrode with a radius of 35 µm the maximum current densities for outer electrodes with radii in the range from approx. 80 to 140 µm are almost constant.

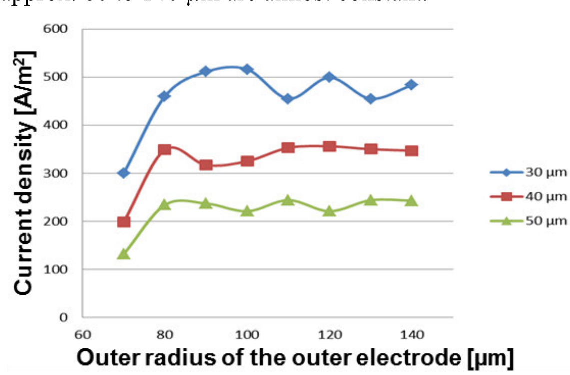

Figure 4: The three curves show the simulated maximum current densities below the inner electrode at distances of 30, 40 and 50 µm from the plane of the electrodes.

3.2 Realization of via holes

A RIE process was used to etch via holes into a 10 µm thick polyimide layer. An approx. 5 µm thick patterned photo resist was used as etching mask. After an etching time of 90 min, the resist was completely removed by the etching process. From this point on, the entire surface of the polyimide was attacked by the etching gases leading to a reduction of the polyimide layer thickness to about 3.5 µm. The SEM image of **Figure 5** shows that inclined side walls and rounded upper edges can be achieved with this processing.

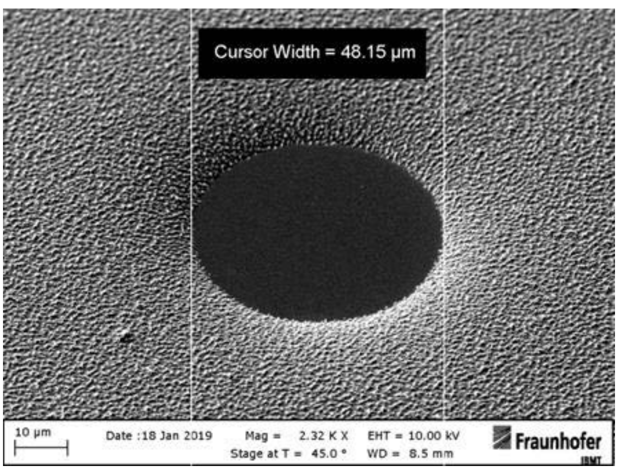

Figure 5: Scanning electron microscope images of RIE-etched via hole (diameter: 48 µm) in a thin polyimide layer. The rounded edges of the polyimide are clearly visible.

4 Discussion

In order to achieve the goal of a large area retinal implant, we opted for the concept of a foil-based implant where a mosaic-like array of silicon photodiodes is applied to a thin polyimide substrate. In contrast to silicon, polyimide is not brittle and is known to be mechanically robust, even at low thicknesses. Although we have not yet investigated this experimentally, polyimide, in contrast to silicon, is unlikely to splinter in the event of a fracture.

Computer simulations were performed to optimize the dimensions and arrangements of the stimulation electrodes concerning the highest stimulation current density at the location of the ganglion cells, i.e. about 30 to 50 µm below the stimulation electrodes. The computer model of the retinal tissue does not take into account any variation of the electrical parameters of the retinal tissue with depth, as these data do not appear to be available. Nevertheless, we assume that the obtained simulation results give good indications about the optimal electrode arrangement.

Using a round central electrode and a ring-shaped electrode per pixel and looking at a distance of 30 to 50 µm under the electrodes the values of the current densities are maximal under the inner electrode. For a fixed width of the ring of the annular outer electrode of 10 µm the stimulation current density at a depth of 30 to 50 µm under the centre of the central electrode is maximal for a central electrode diameter of about 35 µm and an outer radius of the outer electrode of about 80 to 140 µm. Nevertheless, the highest current densities do not occur at a depth of 30 to 50 µm but close to the edges of the electrodes. These are the locations of axons of the ganglion cells. It needs to be determined experimentally to which extent the axons of the ganglion cells will be stimulated by the proposed epiretinal implant.

First experiments for etching via holes into a 10 µm thick polyimide layer were carried out using photo resist as etching mask. During the etching process the entire resist layer was removed leading to a reduction of the thickness of the polyimide layer from 10 to 3.5 µm. The via holes have inclined side walls and rounded upper edges und are assumed to be suited for realizing uninterrupted conductor paths leading from the photodiodes underneath the polyimide layer to the stimulation electrodes on the polyimide.

Author Statement

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