Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1126-1127

A 37×37 Pixels Photoreceptor Chip with Switchable Photosensitivity Circuit for 3-D Stacked Retinal Prosthesis Chip

Hideki Naganuma[1], Takaharu Tani[1], Kouji Kiyoyama[2], and Tetsu Tanaka[1,3]

[1]Dept. of Bioengineering and Robotics, Graduate School of Engineering, Tohoku University
6-6-01, Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
Phene:+81-22-795-6258, Email:link@lbc.mech.tohoku.ac.jp
[2]Dept. of Electrical and Electronics Enginieering, Nagasaki Institute of Applied Science
[3]Dept. of Biomedical Enginieering, Gradute School of Biomedical Engineering, Tohoku University

1. Introduction

Effective medical treatments for diseases such as retinitis pigmentosa (RP) and age-related macular degeneration (AMD) have not been established yet. RP and AMD cause degeneration of photoreceptor cells in the retina, which converts incident light to electrical signals propagating in optic nerves. As photoreceptor cells degenerate, patients experience gradual vision loss. To restore visual sensation of blind patients suffering from RP and AMD, retinal prostheses have been developed by several research institutes [1,2]. We have been developing a fully implantable retinal prosthesis with three-dimensional (3-D) staked retinal prosthesis chip [3], as shown in Fig. 1. The 3-D stacked chip comprises a photoreceptor chip for converting incident light into electrical current, a visual information processing chip for edge enhancement, and stimulus current generator chip for generating appropriate electrical stimulation patterns, as shown in Fig. 2. These chips are vertically stacked and electrically connected by thousands of through silicon vias (TSVs).

Until now, we fabricated some kinds of prototype 2-D retinal prosthesis chips and evaluated photosensitivity. Fig. 3 compared photosensitivities between target characteristics equivalent for slightly modified human retina characteristics and 2-D retinal prosthesis chip. The target characteristics represented stimulus current pulse frequencies of 40 to 300 Hz determined based on electroretinogram measurements in accordance with incident light intensities of 4 to 400 lx in the eyeball, respectively. As a large difference existed between them, it is strongly required to realize identical characteristics. However, a photosensitivity slope of the retinal prosthesis chip depends mainly on the material properties of Si photodiode. In this study, we newly proposed a photoreceptor chip having switchable photosensitivity function. Both circuit design and evaluation results of fabricated chip were reported in detail.

2. Design and fabrication of a 37×37 pixels photoreceptor chip with switchable photosensitivity

We designed a 37×37 pixels photoreceptor chip with switchable two photosensitivities such as sunlight mode and room light mode. In the sunlight mode, the photoreceptor chip used photosensitivity suitable for incident light intensities between 50 and 400 lx. In the room light mode, similarly, photoreceptor chip used photosensitivity suitable for 4 to 50 lx. Patients can change the mode with outer switch by themselves, and obtain appropriate visual sensations as if they wear sunglasses when the sun is bright.

Fig. 4 shows the switchable photosensitivity circuit diagram of the photoreceptor chip. This circuit consisted of a large photodiode, *PD*, current mirror circuits with MOSFETs for amplifying photocurrent, and switching MOSFETs for changing operation mode. The incident light to a *PD* was converted into the photocurrent, I_{pd}, and the I_{pd} flowed through pMOSFET, M_{pd}. When the incident light intensity became larger than 50 lx, a positive voltage was applied to SW_A. Then, $0.7\times I_{pd}$ flowed through pMOSFET, M_A, because the current mirror ratio between M_{pd} and M_A was set to 0.7. And then, $0.7\times I_{pd}$ flowed toward the other chip via P_{out}. This is the sunlight mode. Similarly, when the incident light intensity became less than 50 lx, a positive voltage was applied to SW_B. The current $7\times I_{pd}$ flowed toward the other chip via P_{out}. This is due to the current mirror ratio between M_{pd} and M_B is 1 to 7. This is the room light mode.

In order to evaluate switchable characteristics, we fabricated the photoreceptor chip with 0.35-μm CMOS image sensor technology. Fig. 5 shows a photograph and a pixel layout of photoreceptor chip. This chip consisted of 37×37 pixels and three pixel circuits having stimulus current generators in addition to switchable photosensitivity circuit. The chip size is 3.2×3.2 mm^2 and a pixel size is 75×75 μm^2. The pixel includes a 30×50 μm^2 photodiode, current mirror circuits, and two TSV pads for 3-D stacking with other chip.

3. Evaluation of chip characteristics

Fig. 6 shows relationships between incident light intensity and output current of switchable photosensitivity circuit. The incident light intensity was changed from 1 to 1000 lx, which were identical to light intensities outside the eyeball from 3 to 3000 lx, respectively. The measured output current corresponded well with SPICE simulation results, verifying circuit design. Furthermore, Fig. 7 shows relationships between incident light intensity and stimulus current pulse frequency for sunlight and room light modes. The stimulus current pulse frequency was generated by a stimulus current generator with the output current from switchable photosensitivity circuit. In this measurement, cathodic pulse width, inter delay, and anodic pulse width are all set to 1 msec. As results, it is clearly demonstrated that we can obtain two appropriate photosensitivities in accordance with incident light intensities. Patient can use each mode by themselves.

4. Conclusion

We designed and fabricated the 37×37 pixels photoreceptor chip with switchable photosensitivity circuit. The switchable photosensitivity circuit has two photosensitivities such as sunlight mode and room light mode. As measurement results, we successfully switched between two appropriate photosensitivities accordingly with incident light intensities. This photoreceptor chip can be integrated with edge enhancement chip and stimulus current generator chip, and can offer a high quality of life to the patients.

Acknowledgements

The work is supported by VLSI Design and Education Center (VDEC), the University of Tokyo, in collaboration with Cadence Design Systems, Inc, Mentor Graphics, Inc, and Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research "Grant-in-Aid for Scientific Research (A)", No. 22246045.

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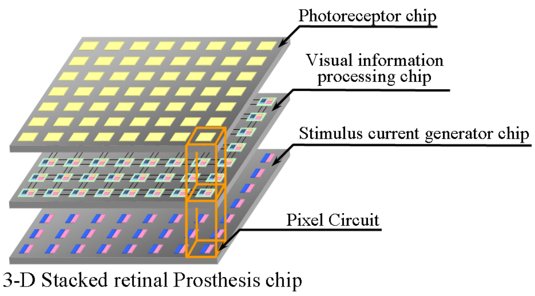

Fig. 1. Conceptual drawing of 3-D stacked retinal prosthesis chip.

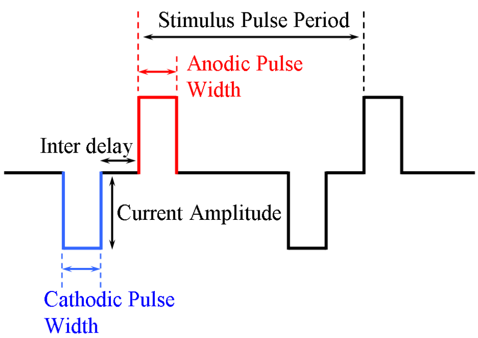

Fig. 2. Waveform of biphasic stimulus current pulses.

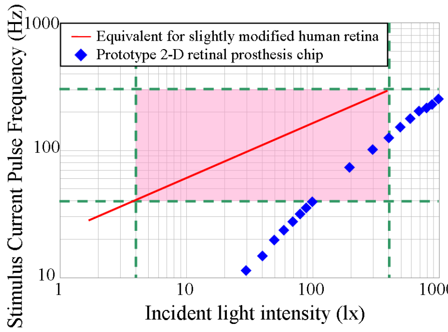

Fig. 3. Comparison of photosensitivity between target characteristics equivalent for slightly modified human retina and prototype 2-D retinal prosthesis chip.

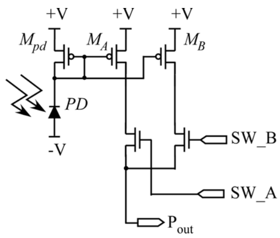

Fig. 4. Switchable photosensitivity circuit diagram of photoreceptor chip.

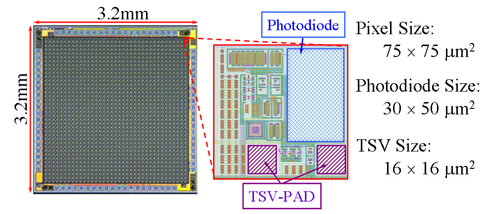

Fig. 5. Photograph and pixel layout of 37×37 pixels photoreceptor chip

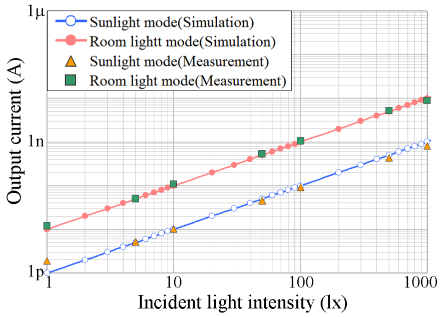

Fig. 6. Relationships between incident light intensity and output current of switchable photosensitivity circuit.

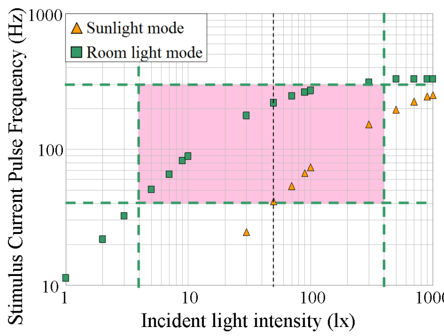

Fig. 7. Relationships between incident light intensity and stimulus current pulse frequency for sunlight and room light modes.