A Multi-photodiode Array-based Retinal Implant IC with On/off Stimulation Strategy to Improve Spatial Resolution

Jeong Hoan Park, Shinyong Shim, Joonsoo Jeong, and Sung June Kim*

Abstract—We propose a novel multi-photodiode array (MPDA) based retinal implant IC with on/off stimulation strategy for a visual prosthesis with improved spatial resolution. An active pixel sensor combined with a comparator enables generation of biphasic current pulses when light intensity meets a threshold condition. The threshold is tuned by changing the discharging time of the active pixel sensor for various light intensity environments. A prototype of the 30-channel retinal implant IC was fabricated with a unit pixel area of 0.021 mm², and the stimulus level up to 354 µA was measured with the threshold ranging from 400 lx to 13120 lx.

Index Terms—Photodiode, neural stimulator, retinal implant, on/off stimulation, spatial resolution

I. INTRODUCTION

In conventional retinal implants, designed to restore of blind patients by electrical stimulation of surviving inner retinal neurons, the main focus has been on providing a large number of stimulation channels with detailed visual information [1-3]. To achieve many stimulation channels, the data rate between the stimulation IC and the electrode array must be maintained high with many interconnection lines. In such a design, the image processor unit and the stimulation pulse generation circuit are often separated [4, 5]. On the other hand, a multi-photodiode array (MPDA) based subretinal implant that employs photodiode array and image processor are integrated into the same IC with stimulation circuitry. Recently clinical trials using the subretinal implant with more than 1000 channels have been demonstrated where patients could perceive consistent light with basic tasks such as distinguishing grating patterns and characters [6, 7].
However, despite a large number of stimulation channels employed, visual acuity of the blind patients using the 1500-channel MPDA-based sub-retinal implant did not increase dramatically, even compared with that obtained from using epiretinal implant having only 60 channels. It may be due to the current spread elicited by the electrodes with increasing level of electrical stimulation. Maintaining the stimulus level at a moderate level is preferred to achieve higher spatial resolution.

In this paper, we propose a novel MPDA-based retinal implant IC with an on/off stimulation strategy which generates biphasic current pulses in response to incident light only above a designated intensity threshold, thus allowing excitation of retinal neurons with minimum current level to prevent unnecessary spread. The output voltage of the 4-tr APS (V_OUT,APS) decreases during TX, and this relation can be expressed as

\[ V_{\text{OUT,APS}} = V_{\text{IO}} - V_{\text{TH}} - V_{\text{ph}} \]
\[ = V_{\text{IO}} - V_{\text{TH}} - k \cdot L \cdot TX \quad (1) \]

Section II describes the detailed circuit of the proposed MPDA-based retinal stimulator. Experimental results and discussion follow in section III and IV, respectively.

II. CIRCUIT DESCRIPTION

Fig. 2 schematically represents the MPDA-based retinal implant IC and the flow of signals. The IC consists of a bias generator, a digital controller, and an array of multi-channel pixels. Each pixel has a photo sensor, a voltage-controlled current source (VCCS), and a biphasic current generator (BCG).

A 4-transistor active pixel sensor (4-tr APS) combined with a low power comparator (COMP) is adopted for the on/off stimulation strategy of the photo sensor. The 4-tr APS allows the change of photo-sensitivity via discharging time (TX) and provides excellent noise characteristics as compared with other types of CMOS image sensors. The output voltage of the 4-tr APS (V_OUT,APS) decreases during TX, and this relation can be expressed as
where $V_{\text{photo}}$ is a voltage induced by the photodiode, $L$ is a light intensity, $k$ is a responsivity ($V$/lx·s), and $V_{\text{TH}}$ is the threshold voltage of the MOSFET $M_i$. At the comparator (COMP), if $V_{\text{OUT,APS}}$ is below the reference voltage ($V_{\text{REF1}}$), digital signals (AN, CA) that control the switching of BCG pass through the SW[1:0], enabling biphasic pulse generation. Using this property and (1), the threshold light intensity ($L_{\text{threshold}}$) for generating current stimulus can be written as (2) and (3)

\[
V_{\text{REF1}} = V_{\text{OUT,APS}} = V_{\text{DD}} - V_{\text{TH}} - k \cdot L_{\text{threshold}} \cdot TX
\]
\[
L_{\text{threshold}} = \left( V_{\text{DD}} - V_{\text{REF1}} - V_{\text{TH}} \right) / \left( k \cdot TX \right)
\]

From (3), it is found that $L_{\text{threshold}}$ is inversely proportional to $TX$. Thus $L_{\text{threshold}}$ can be adjusted by varying $TX$, making this type of photo sensor uniquely applicable to various light intensity environments.

Furthermore, we propose an automatic $TX$ controller to control the light intensity threshold for efficient image processing of on/off stimulation strategy. In Fig. 2, it is also shown that the distributed photodiodes discharge the capacitor, decreasing the voltage. As the voltage is below $V_{\text{REF2}}$, the output of Schmitt trigger is changed to $V_{\text{SS}}$. The value of $TX$ is calculated with RST and the capacitor voltage via the AND gate. Thus the circuit in Fig. 2 can perform automatic control of the $TX$ value according to the average light intensity.

The VCCS based on the MOS resistor is used to control the current stimulus level efficiently [12]. An OTA retains drain voltage of $M_i$ to a fixed voltage of $V_{\text{FIX}}$ forcing $M_i$ to remain in triode region for acting as the MOS resistor. The telescopic OTA optimized using $g_{m}/h_{ij}$ methodology is operated in weak inversion region [13].

Simultaneous monopolar stimulation is used for reduction of the number of electrodes and for ease of scaling up the stimulation channels. The $N$-channel monopolar stimulation needs $N+1$ electrodes, compared with bipolar stimulation that needs $2 \cdot N$ electrodes. As most MPDA-based retinal implant IC’s include the stimulating electrodes [6, 7], reduction of the number of electrodes increases area an electrode can have. The electrode impedance is reduced to decrease the circuit compliance voltage for reduced power consumption.

As control signals are shared by all the pixels during simultaneous stimulation, it is possible to increase stimulation channels without modification of the digital circuit.

The BGA is designed to have two independent current sources, one for anodic phase and the other for cathodic phase, for safety reason [14]. In a structure that employs single current source, the monopolar, simultaneous multichannel stimulation, amplitudes of the biphasic stimulation pulses can be affected by the electrode-cell impedance. This can result in unsafe retinal stimulation due to excess charge used. Two independent current sources are designed to deliver predictable and safe stimulation to retinal neurons regardless of electrode-cell impedance.

### III. EXPERIMENTAL RESULTS

For verification of our design, a prototype of 30-channel MPDA-based retinal implant IC was fabricated using Towerjazz 0.18 µm CIS process. Fig. 3 shows the microphotograph of the fabricated prototype and the layout of a unit pixel. The pixel area is 0.021 mm², implying that 470-channel pixels can be integrated into a macular area of 10 mm².

<table>
<thead>
<tr>
<th>Table 1. The characteristics of the 4-tr APS</th>
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<td>Parameters</td>
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<tr>
<td>Size</td>
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<tr>
<td>Conversion Gain</td>
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<tr>
<td>Responsivity,Green</td>
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<tr>
<td>full well capacity</td>
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<td>Pixel noise floor</td>
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<td>Dynamic Range</td>
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A customized bench top test setup was configured to measure the IC performance, as shown in Fig. 4(a). The IC was connected with a PCB using wire-bonding and protected by transparent epoxy for light transmission. The digital controller was implemented with an FPGA (Spartan 3A, Xilinx Corp., USA). The light source was a digitally-controlled quartz tungsten halogen light lamp (66884, Newport, USA), and light intensity was measured by the light meter (TES 1336A, TES Corp., Taiwan). A resistor was connected as a load to the channel output. And then, current pulses as shown in Fig. 4(b) were measured using the oscilloscope (DPO4034, Tektronix Inc., USA) in various light condition.

Fig. 4(c) shows the measurement of the stimulation current pulse burst was measured while light with supra-threshold intensity was illuminated. Otherwise, no
biphasic current pulse was measured.

The dependency of the threshold light intensity ($I_{\text{threshold}}$) on the TX value was measured. Fig. 4(d) shows the measured data (in red lines) together with the design values (in blue lines). The device was designed to operate in the living room lighting condition of under 400 lx. However, the measured values were significantly higher than the design values. The discrepancy was found to be due to the abnormally large offset voltage in the comparator. This fault is under investigation and will be corrected in the next design. We can further increase the light sensitivity by increasing geometrical area used by APS for [15], perhaps using a 3-dimensional structure [16].

The biphasic currents in anodic and cathodic phases decreased for the increased LV (input voltage) values, as expected, and are shown in Fig. 4(e). Amplitudes of current in anodic and cathodic phase were measured to be within the range of 0-354 µA and 0-332 µA, respectively. The average current mismatch was 4.85 % with a standard deviation of 3.52 %. We thought that main reason for the current mismatch is in process variation, as well as in the channel length modulation that is caused by the drain voltage of the MOSFETs in the mirroring circuit. Thus, for safety concern, we added a short switch between CH and REF so we can remove the unwanted residual charge in the resting state.

The performance of the chip is summarized in Table 2.

<table>
<thead>
<tr>
<th>Process</th>
<th>0.18 µm CIS process</th>
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<tr>
<td>Stimulation strategy</td>
<td>Monopolar and simultaneous biphasic current stimulation</td>
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<tr>
<td>Supply voltage</td>
<td>$V_{DD} = 1.65 , \text{V}, V_{SS} = -1.65 , \text{V}$</td>
</tr>
<tr>
<td>Light intensity Threshold</td>
<td>400 lx @TX=12.5 ms, 13120 lx @TX=0.79 ms</td>
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<tr>
<td>Stimulus current level</td>
<td>0-354 µA ($I_{\text{A}}$), 0-332 µA ($I_{\text{C}}$)</td>
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<tr>
<td>Unit pixel area</td>
<td>0.021 mm$^2$</td>
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IV. DISCUSSION

In this study, we designed and verified a prototype of 30-channel MPDA-based retinal implant IC. On/off stimulation strategy with moderate current stimulus can reduce the stimulation level for a given incident light intensity. This can help reduce the inter-channel crosstalk which otherwise prohibits achieving desired spatial resolution in the retinal stimulation. The BCG with two independent current sources is used for monopolar, simultaneous multi-channel stimulation, which features the following advantages: 1) We can increase the number of stimulation channels without modifying the digital controller, 2) We can adjust the magnitude of biphasic current pulses regardless of the electrode-cell impedance, and 3) We can afford giving more area per pixel to achieve lower electrode impedance.

V. CONCLUSIONS

A novel multi-photodiode array (MPDA) based retinal implant IC was fabricated with on/off stimulation strategy and tunable light intensity threshold for the various light environments. The prototype of retinal implant IC was fabricated with an area of 0.021 mm$^2$ per unit pixel which can expand up to 470 channels in the macular area of 10 mm$^2$. Biphasic current pulse ranging from 0 µA to 354 µA was measured with the light intensity threshold from 400 lx to 13120 lx.

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REFERENCES


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