An Application of Pulse Frequency Modulation Photosensors to Sub-retinal Artificial Retina Implantation
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ABSTRACT
In this paper we discuss an application of CMOS photo-sensor array chip using pulse frequency modulation (PFM) to sub-retinal implantation to recover human vision. PFM with integration mode as photo-sensing circuit is used to realize enough dynamic range and compatibility with signals in real retina. To effectively stimulate the retinal cells, we have designed a PFM circuit with limited bandwidth of output pulses and two kinds of pulse shaping circuits with digital waveform memory and pixel-level output amplitude tuner. We have fabricated a PFM photo-sensing test circuits with a standard 0.35 µm CMOS technology to measure its basic characteristics, and have demonstrated a large dynamic range of around 40 dB.

Keywords: retinal prosthesis device, CMOS vision chip, pulse frequency modulation

1. RETINAL PROSTHESIS DEVICES
Retinal prosthesis using a silicon photodetectors chip has becoming one of the most promising methods to partially regain visual perception in a patient with retinal degenerative diseases. For the purpose, several teams are studying various types of retinal prosthesis devices mainly in the U. S. A. and Europe [1-5]. In this paper, we propose an application of CMOS vision chip, or photo-sensor array chip with additional signal processing circuits, using pulse frequency modulation (PFM) to implanting it in a subretinal space. Figure 1 shows the schematic diagram of implantation. In subretinal approaches, a photodetectors array buried underneath the retina converts light distribution of the image projected on a retina surface to electric signals, and stimulates the retinal cells such as bipolar cells.

Figure 2 shows the block diagram of the proposed implanted vision chip. Although photodetectors have been used without any bias voltage due to its simple configuration without a power supply in subretinal approaches, we believe that power supply is inevitable to obtain high photosensitivity and enough amount of charge injection to the retinal cells, and to realize additional on-chip processing such as tuning the intensity of electric stimulation. In Fig. 2, a photodiode is used with integration mode to gain high photosensitivity, which is a general setup in conventional image sensors. The retinal cells are stimulated with the electric pulses some of whose parameters such as amplitude and frequency are modulated. The processing circuits convert the incident light intensity according to a kind of pulse modulation. The pulse shaper generates the electric pulses with a suitable waveform for stimulation. The pulses are

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Fig. 1: Retinal prosthesis using a vision chip in a subretinal approach.
applied to the retinal cells through the electrode and electrolytes in retina after amplification.

2. PULSE FREQUENCY MODULATION (PFM)

2.1 Basics
We use a pulse frequency modulation for coding the light intensity into electric pulses[8, 9]. In this modulation, the light intensity is converted to the frequency of digital pulses with the same amplitude. Namely, weak light is converted to low frequency pulses, and strong light to high frequency. The advantages of PFM are compatibility with neuron cells, a large dynamic range, asynchronous and low-voltage operation, and compatibility with digital logic circuits. Because each pixel works independently without global lines (except power lines), it can be separated each other in space. This configuration enables us to bore holes in the chip to flow the nutrition fluid in between. In addition, tuning the stimulation parameters after implantation can be easily implemented with mixed signal techniques because it is easy to connect the PFM to digital circuits.

The circuit indicated in Fig. 3 is a basic PFM circuit composed of two inverters and a pmos reset transistor. When

![Fig. 2: Block diagram of the proposed implanted vision chip.](image)

![Fig. 3: Pulse frequency modulation.](image)
the cathode voltage of the photodiode $V_{PD}$ is charged up to $V_{dd}$, the output of the Schmitt-trigger inverter is low (L). $V_{PD}$ goes down according to photo-generated currents. When $V_{PD}$ reaches the threshold voltage of the Schmitt-trigger inverter $V_{th}$, the output voltage of the Schmitt-trigger inverter turns to high (H). After intrinsic delay $t_d$, the reset transistor becomes on, and the photodiode is charged again. Then, the Schmitt-trigger output becomes L, and the reset transistor turns off after $t_d$. The output pulse frequency $f' (=t_f/1)$ is represented by

$$f' = \left( \frac{C_{PD} (V_{dd} - V_{th})}{I_{ph}} + 2t_d \right)^{-1},$$

where $C_{PD}$ and $I_{ph}$ are parasitic capacitance and photocurrent, respectively.

### 2.2 PFM with limited bandwidth of output pulses frequency

We designed a PFM where the bandwidth of output pulse frequency is limited (lower and upper limits are represented by $f_{min}$ and $f_{max}$). $f_{min}$ is dominated by the lowest frequency at which human beings do not sense blinking of light caused by electric stimulation, which is supposed to be about tens of hertz. $f_{max}$ is restricted by mobility of ionic currents in retina, which is around tens of kilo-hertz. Figure 4 shows the schematic diagram and its layout of the PFM.
with limited output-pulse bandwidth. \( f_{\text{min}} \) and \( f_{\text{max}} \) are controlled by a nmos current sink discharging the photodiode and a switched capacitors filter composed of \( C_1, C_2 \), and two transmission gates working complimentarily. Pmos current source charges the photodiode to cancel its dark current. When the dark current is negligible, \( f_{\text{min}} \) and \( f_{\text{max}} \) are represented by the following equations, in which \( T \) represents the switching interval of the transmission gates:

\[
\begin{align*}
    f_{\text{min}} &= \left( \frac{C_{PD} (V_{dd} - V_{th})}{I_{\text{leak}}} + 2t_d \right)^{-1}, \\
    f_{\text{max}} &= \frac{C_1}{C_2 T}.
\end{align*}
\]

(2) 

(3)

Fig. 6: Schematic diagram of programmable pulse shaper using digital waveform memory.

Fig. 7: Programmable pulse shaper with tunable output intensity: (a) schematic diagram and (b) operation timing. TG means transmission gate.
Figure 5 shows the simulation result of photocurrent vs. output pulse frequency. We can successfully achieve to limit the lower and upper frequencies.

2.3 Pulse shaping circuit with digital memory and pixel-level stimulation intensity control

A biphasic output is required to obtain charge balance of the total amount of injected charge to the retinal cells. In addition, to effectively stimulate the retinal cells, controllability of pulse parameters such as anodic and cathodic duration times and the amplitudes, and interphase delay is required. Figure 6 shows the schematic diagram of a pulse shaper with digital waveform memory. Triggered by the PFM output, this circuit puts out an arbitrary waveform stored in the digital memory consisting of 7 3-bit-long words. A D/A converter follows this circuit. When a pulse from the PFM puts in, the cyclic shift registers start to rotate to the right. When all-0 datum, which is a special word meaning "STOP ROTATION," is detected at the output stage, this circuit stops putting out the stimulation pulse. Then, it stands by for the next PFM pulse.

Figure 7 shows the schematic diagram of a biphasic pulse generator with pixel-level stimulation amplitude control. For example, a gap space between the electrode and the retinal cell varies pixel by pixel. Therefore, the required amount of the injected charge differs for each pixel. To compensate the variations, pixel-level control of stimulation amplitude should be implemented on the implanted vision chip. This circuit has four amplitude levels, which can be selected by the contents of the latch memory. This circuit is composed of an inverter and bi-directional cascaded
diodes (diode-connected transistors) to reduce the amplitude. The inverter works as both current source and sink, so that this circuit effectively charges and discharges the retinal cells. In this circuit, voltage $V_b$ on the silicon chip is identical to the ground level of the retinal cells. As shown in Fig. 7(b), $V_b$ is put out when $p_2$ is high. When $p_1$ is high, the inverter generates a biphasic pulse. Figure 8 shows the simulation result of the biphasic outputs for different numbers of diodes. In the simulation, we assumed a standard 0.6µm CMOS process.

3. EXPERIMENTAL RESULTS

We have designed and fabricated a PFM pixel circuit without output-pulse bandwidth control using a 0.35µm CMOS technology to measure its fundamental characteristics. Aperture and junction sizes of the photodiode are 1µm×1µm and 2µm×2µm, respectively. Figure 9(a) shows relationship between the incident light intensity and the output pulse frequency. As a light source, a metal halide lump was used. From the experiment, dynamic range around 40dB was obtained at the low voltage. In the experiment, $V_{dd}$ was set to 1V; while the ordinary voltage of the power supply for the process was 3.3V.

4. CONCLUSIONS AND FUTURE WORKS

In this paper, we proposed an application of CMOS photo-sensor array chip using pulse frequency modulation (PFM) to sub-retinal implantation to recover human vision. To effectively stimulate the retinal cells, we have designed a PFM circuit with limited bandwidth of output pulses and two types of pulse shaping circuits with digital waveform memory and pixel-level output amplitude control. We have demonstrated a large dynamic range of around 40 dB using a PFM photo-sensing test circuits fabricated with a standard 0.35 µm CMOS technology. Operation of the fabricated implanted vision chip will be verified by in-vitro experiments using living retinas. As an intermediate goal, an implanted vision chip with 32 ³ 32 pixels which can be used in in-vivo experiments will be fabricated.

REFERENCES


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