Implantable neuromorphic vision chips

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The implantable neuromorphic vision chips are analysed and implemented. These proposed analogue integrated circuits are to implement four cell functions of the retina for implant. These retinal cells are photoreceptor cells, horizontal cells, bipolar cells, and ganglion cells. All simulation results are successfully verified and consistent with researches on biological retinas.

Introduction: Nowadays high performance implantable electronic devices are popular and commonly used in the biomedical domain. Several biomedical electronics have been designed for neuro-prosthesis applications. These implantable electronics include cardiac pacemakers, cochlear prostheses, retinal prosthesis systems [1], and functional neuromuscular stimulation systems. For the nervous system of vision, over one million people worldwide are blind because of damaging the photoreceptor cells of the retina (cones and rods). The retinal prosthesis under our study is based on the concept of replacing retina function by using analogue integrated circuits. The implantable neuromorphic vision chips are to implement four cell functions of the retina for implant. These retinal cells are photoreceptor cells, horizontal cells, bipolar cells, and ganglion cells. In this Letter, these cell functions are implemented and proved through HSPICE simulation.

Vertebrate retina: According to researches [2–5], all the vertebrate retinas are organised in the same basic plan where two synaptic layers called outer and inner plexiform layers are intercalated between three cellular layers called photoreceptor nuclear layer, horizontal nuclear layer, bipolar nuclear layer, and ganglion cell layer. Light is transduced into electrical potential by the photoreceptors at the top. The primary signal pathway proceeds from the photoreceptors in the photoreceptor nuclear layer through the synapses in the outer plexiform layer to the bipolar cells, and then to the retinal ganglion cells, the output cells of the retina. The horizontal cells are located just below the photoreceptors, and they spread across a large area of the retina to form layers transverse to the primary signal flow. The property of the photoreceptor cells is response to the captured light only with graded hyperpolarising potentials. At the layer of the horizontal cells, the spatial lowpass filtering takes place, because the incoming excitation from each photoreceptor is spread into the adjacent region over this horizontal layer. Then the off-centre and on-centre bipolar cells come in pairs in the retina. These two bipolar cells can offer an added benefit: activity in paired populations falls on the opposite sides of a light–dark boundary, and thus signals a line edge. The recordings show that the ganglion cells have very similar receptive field organisation to that of the bipolar cells. Therefore, the on-centre ganglion cell and off-centre ganglion cell would receive most of its synaptic inputs from the bipolar cell terminals through excitatory synapses. Finally, the biphasic stimulus current for action potentials is generated by ganglion cells and transmitted through optical nerve to visual cortex.

Circuit design: The pixel structure of the implantable retinal circuit is shown in Fig. 1. The MOSs Mp1–Mp2, and a photodiode D_0 are designed as photoreceptor cells. The MOSs Mp3–Mp4, and photodiode D_0 with adjustable MOS resistors (Ms1–Ms4) are implemented as horizontal cells. Hence, the smoothing function of the horizontal cells is controlled by the gate voltage Vsmooth (VF). The MOSs Mn1–Mn6, and Mv1–Mv2 are designed as bipolar cells. The operation principle of bipolar cells could be divided into three parts; first, the extracted current is to subtract the current Iiso and Ismt, which are produced by photoreceptors and horizontal cells, separately. Therefore, it results in two positive current edges. Secondly, the extracted current is to convert into analogue voltage. By controlling bias voltages Va and Vb, it makes bipolar cells operate in the subthreshold region. If the positive current edge is entered, the drain voltage of MOS Mn5 is pulled down to a lower voltage level due to the positive current edge. Moreover, the controlling voltage Vth of MOS Mn6 is to adjust the extracted current with a threshold shift in order to avoid ambiguity under noise and disturbance. Then, the output signal of bipolar cells (Bipolar_out) is obtained. Finally, the other circuitry for ganglion cells is implemented. The circuit structure of ganglion cells can be divided into four components, including current-mode digital-to-analogue converter (Ma1–Ma13), current mirror (Mu1–Mu4), biphasic current controlling logic, and output stage (Mr1–Mr4). The ganglion circuitry could generate a maximum current of 1.8 mA through 1 KΩ load, which is the typical optical nerve impedance. The output stimulus current could be varied in 32 different steps ranging from 0 to 1.8 mA. Every step would be approximately 55 uA that requires a 5-bit resolution DAC for controlling the level of current. The transistors are placed in parallel or in series to make programmable current. The transistors could be considered as resistors that result in a 5-bit binary weighted current-source. Moreover, to maintain the stability and linearity of the output current is the main issue during VLSI design. To keep the source's linearity, we have to adjust the dimensions of DAC's transistors so that they produce the appropriate reference current. The reference generated by the DAC is amplified in the current mirror stage. Therefore, the current intensity could be adjusted suitably for the patient's need by controlling DAC. The stimulus pulses of ganglion cells are biphasic. Biphasic pulses could avoid ion-charge accumulation in tissues. Based on the biological property, the current direction through the optical nerve is determined using SIGN and UNSIGN inputs. The two terminals of the optical nerve are connected to electrodes (E1 and E2). Hence, with the switching between SIGN and UNSIGN, the current flows through one side of the PMOS transistor to the other side of the NMOS transistor which generates biphasic current.

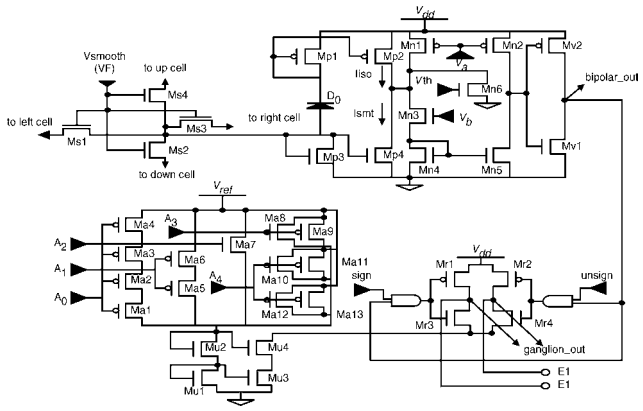

Fig. 1 *Pixel structure of implantable retinal circuit*

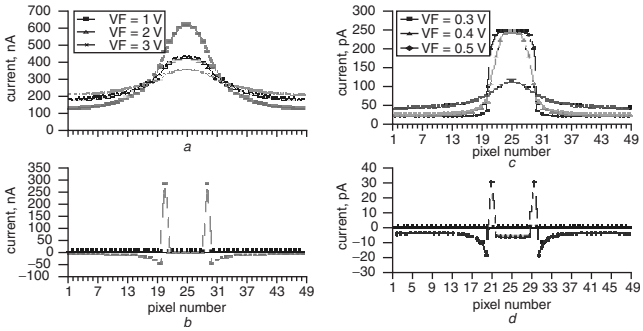

Fig. 2 *Smoothing and extracted function*

a Smoothing function of horizontal cell for induced photocurrent 25 nA
b Edge extracted function of bipolar cell for induced photocurrent 25 nA
c Smoothing function of horizontal cell for induced photocurrent 10 pA
d Edge extracted function of bipolar cell for induced photocurrent 10 pA

Results: All simulation results are based upon the device parameters of 0.35 µm 1P4M CMOS technology with 3.3 V power supply. First, it is applied in one-dimensional array to verify the smoothing function of horizontal cells and the edge extraction function of bipolar cells as shown in Fig. 2 with 50 pixels considered. The light is incident on the 20th to the 30th pixels. Secondly, to verify the function of high dynamic range, the induced photocurrent is simulated in 25 nA, and 10 pA, respectively. The Figures below imply that the circuitry of horizontal cells has good performances for high dynamic range as vertebrate retina. Comparing Figs. 2*a* and *b*, *c* and *d*, the main difference between them is the smoothing voltage (VF). If the incident

lighting were larger, the photosensor of the retinal circuit would induce greater current. Therefore, the resistance of the smoothing network, could be smaller because of the suitable scale of voltage variation in the smoothing network, i.e. if it is in dimming–illumination environment, the induced current is smaller. Therefore, it needs greater resistance to function as expected. The MOS resistance in the subthreshold region can be expressed as

$$\mathrm{Rd} = \left[K_x \frac{W}{L} \exp\left(\frac{VF - V\mathrm{th}}{nv_t}\right)\right]^{-1} \quad (1)$$

where K_x depends on process parameter, W/L is the geometric ratio of the MOS, Vth is the threshold voltage of MOS, vt is the thermal voltage and is given by kT/q, and n is the subthreshold swing parameter. As seen from (1), Rds is tunable by VF. Thus the smoothing characteristics of the retinal circuit can be adjusted by VF. In these simulation results as mentioned above, this proposed circuit could be operated in different lighting environments, and at least it could have four orders of magnitude of light intensity. Finally, we apply this implantable retinal circuit into a two-dimensional 32 × 32 array, and simulate the incident static image to verify the function of bipolar cells. Fig. 3*a* shows the input pattern-A with noise, which is a zero-mean random noise with a standard deviation of 60% of induced current. Fig. 3*b* shows the output response of bipolar cells for spatial edge extraction. Therefore, it also shows good bipolar function for spatial edge extraction as vertebrate retina. Owing to the smoothing network of horizontal cells, this simulation also shows good performance of noise immunity in this proposed circuit. Fig. 3*c* shows the biphasic stimulus current of the ganglion cell. The biphasic pulse duration is 300 μs and pulse frequency is 20 Hz. All simulation results are successfully consistent with researches on biological retinas [2–5].

Conclusion: Implantable neuromorphic vision chips have been analysed and implemented. In the proposed architecture, this pixel structure includes photoreceptor cells, horizontal cells, bipolar cells, and ganglion cells for implant. Owing to the smoothing network of horizontal cells, these simulation results show the good functions of noise immunity and high dynamic range as vertebrate retina. The edge extraction functions for bipolar cells are also proved to operate correctly. Finally, the stimulus current of the ganglion cell is biphasic, the pulse duration is 300 μs and the pulse frequency is 20 Hz. All simulation results are successfully verified and consistent with researches on biological retinas.

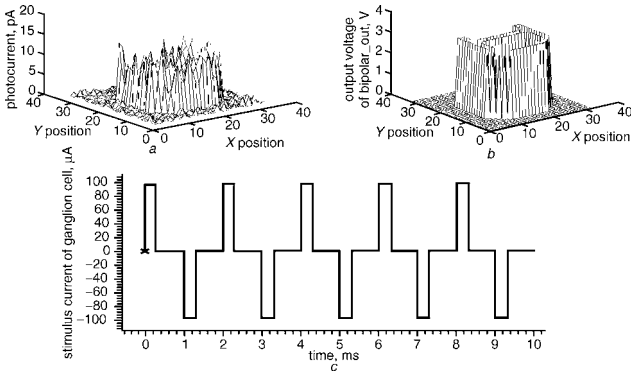

Fig. 3 *Input pattern-A with noise; output response of bipolar cells; biphasic stimulus current of ganglion cell*

a Input pattern-A with zero-mean random noise: standard deviation 60% of induced current, induced photocurrent 10 pA
b Bipolar output (Bipolar_out) with spatial edge extraction for input pattern-A on impalpable retinal array
c Biphasic stimulus current of ganglion cell

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References

1 Liu, W., Vichienchom, K., Clements, M., and Greenberg, R.: 'A neuro-stimulus chip with telemetry unit for retinal prosthetic device', *IEEE J. Solid-State Circuits*, 2000, **35**, pp. 1487–1497
2 Rodieck, R.W.: 'The vertebrate retina: principles of structure and function' (W.H. Freeman, San Francisco, CA, 1973)
3 Werblin, F.S.: 'Control of retinal sensitivity: II Lateral interactions at the outer plexiform layer', *J. Gen. Physiol.*, 1974
4 Dowling, J.E.: 'The retina: an approachable part of the brain' (Belknap Press of Harvard University Press, Cambridge, MA, 1987)
5 Carlson, N.R.: 'Foundations of physiological psychology' (Allyn & Bacon, 1988)