An Ultra Low Power Silicon Retina with Spatial and Temporal Filtering

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Abstract

Retinas can process image information efficiently; consuming only 16.2 nW per ganglion cell. Here I describe novel and extremely efficient circuits that perform the spatial and temporal filtering attributed to the retinal layers between photoreceptors and ganglion cells. CMOS transistors of 90nm process compose the circuit, and when the circuit is integrated with photoreceptors and retinal ganglion cells, it can operate with a supply voltage of as little as 0.5 V and consumes less than $1/1000^{th}$ of the power consumption of previous neuromorphic designs. The power consumption per pixel (3.16 nW) is comparable to the mammalian retina.

1 Introduction

Retinal prosthesis is one of a hopeful cure for the age-related macular degeneration (AMD) and retinitis pigmentosa. Over the last two decades, many groups in the world have been researching on retinal prosthesis and retina itself. They have achieved some degree of success in developing retinal prosthesis, but still do not allow a sufficient level of vision recovery for patient to perform daily activities [1]-[5]. One of the main challenges we are facing is that retina prosthesis definitely need a large number of stimulating channels and a very low power consumption.

To achieve this, many retinomorphic chips have been developed [6]-[13], but their designs mimic either the sustained or transient ganglion cells, or had limitations in real-time image processing. Zaghloul and Boahen have developed a silicon retina that overcame these problems and limitations that others had, but its power consumption was almost a thousand times that of mammalian retina [14]-[17], so it is very difficult to be used in retinal prosthesis. Similarly, Kameda and Yagi developed a silicon retina that also produced both the sustained and transient responses, but was not suitable for retinal implant because of huge power consumption [18].

The silicon retina presented in this paper possess four types of ganglion cell inputs, which are on / off and sustained / transient cells, and has spatial filtering with adaptation to light intensity and temporal filtering. This silicon retina is designed mainly with current-based design in order to keep linearity and avoid a loss of information through processing pathways. In addition, the silicon retinal cells, which include cone terminals, horizontal cells, bipolar cells and narrow-field amacrine cells, consume only 3.16 nW, which is comparable with the mammalian retina.

In the next section, design of the silicon retina will be explained in detail with circuit schematics. In section three, simulation results will be provided. Finally, I will conclude the paper in section four.

2 System Description

The structure and function of the retina have been studied and are known to be not only pathways of image information processing but also efficient parallel image processor [20]-[23]. Many different types of cells cooperatively interact each other through excitatory and inhibitory gap junctions (Figure 1).

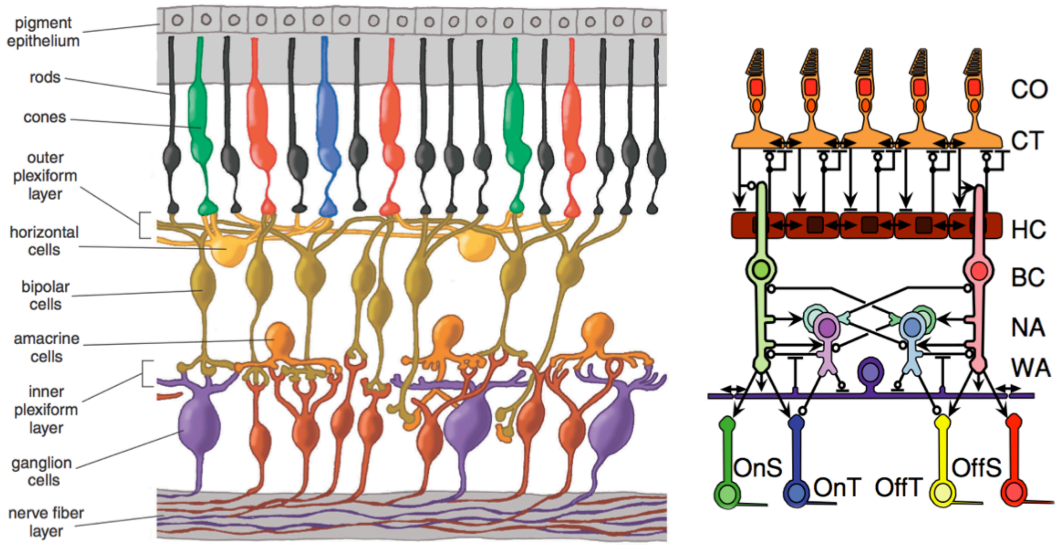

Figure 1: Simple anatomy of the retina [19] (left) and its corresponding structure of the silicon retina [17] (right). CO stands for cone, CT for cone terminal, HC for horizontal cell, BC for bipolar cell, NA for narrow-field amacrine cell and WA for wide-field amcrine cell. It also includes on/off sustained ganglion cells (OnS and OffS) and on/off transient ganglion cells (OnT and OffT).

2.1 Designs for Outer Layer of the Retina

Cones and rods are photoreceptors in the retina. They sense the light, process the image information spatially forming receptive field by gap junctions between cone terminals and via horizontal cells, and then relay the light-dependent signals to bipolar cells. In addition, the size of the receptive field varies according to light intensity. As the light intensity increases, the receptive field becomes sharpened, meaning that the size of the receptive field shrinks [24].

Figure 2 shows the circuit schematic of a cone terminal and its gap junctions through horizontal cells and cone terminals itself. Cone input is current input from photodiode, which is not designed in this work, and is copied through a current mirror and delivered to bipolar cells via node voltage NB. The information is relayed from the cone terminal to the bipolar cell by current and not by voltage unlike the design of Zaghloul and Boahen [17], so linearity is improved and it has less information loss. Two negative-channel metal-oxide semiconductors (NMOSs) connected to just above the cone input are the gap junctions between cone terminals, which are modulated by the horizontal cell's activity. The other two NMOSs connected to HC are modeled for gap junctions via horizontal cells. Conductivity of the gap junctions is modulated by node voltage PB. As the light input increases, PB decreases and the conductivity of the gap junction decreases. As a result, the size of receptive field becomes smaller and sharpened.

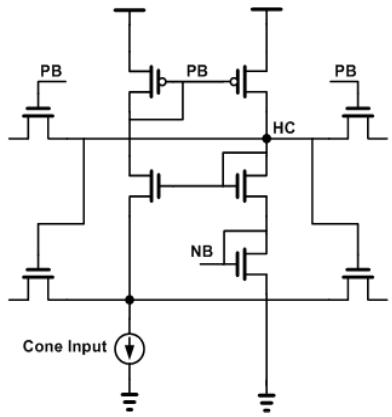

Figure 2: Circuit schematic of the cone terminal and the horizontal cell (HC)

Figure 3 is a one-dimensional structure of cone terminals and horizontal cells. It is easily expanded to two-dimensional model. The gap junctions are symmetrical; each gap junction on left and right sides has same conductivity not like the design of Zaghloul and Boahen [17].

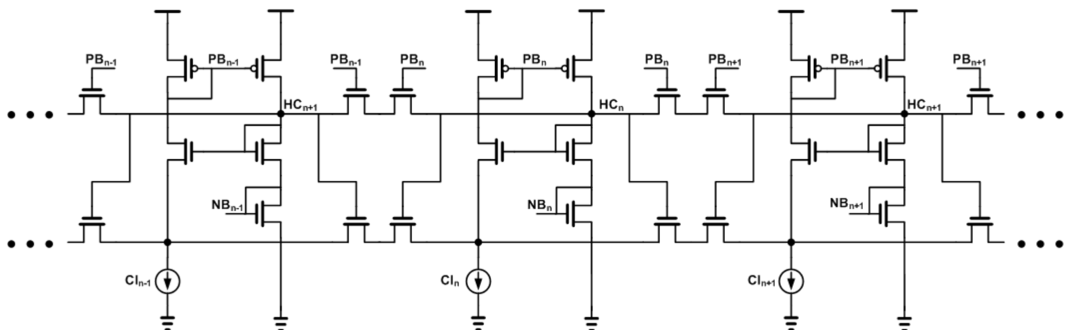

Figure 3: One-dimensional structure of cone terminals and horizontal cells

2.2 Designs for Inner Layer of the Retina

There are two kinds of bipolar cells: on bipolar cells and off bipolar cells. The circuit in Figure 4 generates on and off bipolar cell's response currents according to the light intensity. The threshold between on and off current can be controlled by the external voltage V_{REF}. If the input current from the outer layer of the retina is bigger than the threshold, I_{ON} flows proportional to the input current minus threshold current. I_{OFF} is inversely proportional to the input current when the input current is smaller than the threshold current made by V_{REF}.

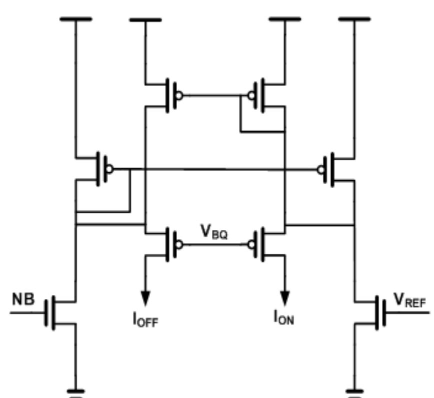

Figure 4: Circuit schematic of on and off bipolar cells

To stimulate sustained and ganglion cells, the circuit shown in Figure 5 generates sustained response and transient responses of the input current. The sustained output is simply modeled as a low-pass-filtered response, and the transient output as a high-pass-filtered response. As shown in Figure 5, the sustained output current I_{SUS} is low-pass filtered by current mirror with a capacitor. The transient output current I_{TRAN} is high-pass-filtered input generated by subtracting low-pass-filtered input from the input current. Those two sustained and transient output currents will be relayed to each type of ganglion cells. In total, this work can stimulate four types of ganglion cells, which are on and off sustained, and on and off transient ganglion cells.

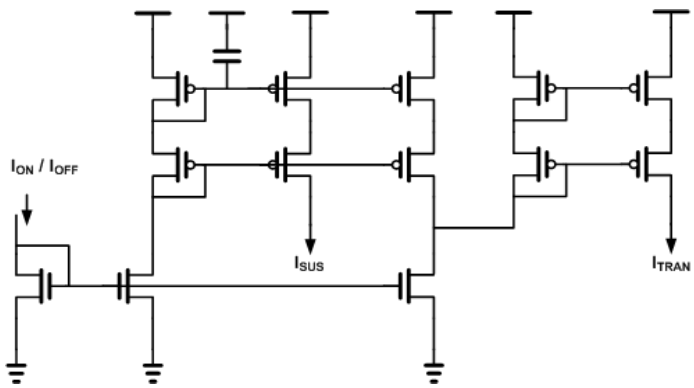

Figure 5: Circuit schematic of sustained and transient pathways to ganglion cells

3 Results

3.1 Spatial Filtering and Adaptation of Receptive Field

I simulated with one-dimensional thirteen complexes of cone terminals and horizontal cells connected each other like the one shown in Figure 3. Input to the cone #7 just in the middle among the thirteen cones in line is ten times larger than other cone's inputs. Figure 6 shows simulation results in which the spatial size of receptive field varies according to light intensity. Because of gap junctions working like a spatial low pass filter, outputs are smoothed through space. As light intensity increases, conductivity of the gap junctions becomes weaker and the receptive field becomes narrower.

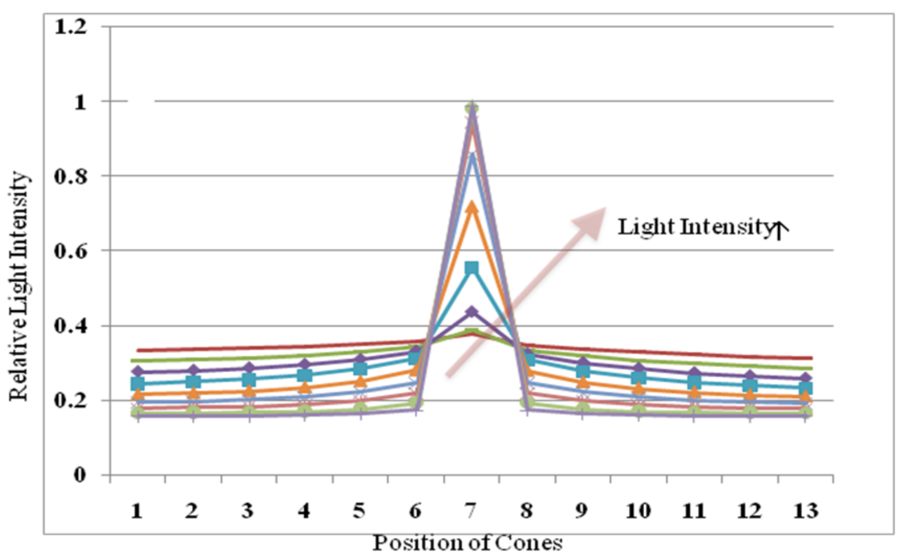

Figure 6: Simulation results for adaptation of receptive field according to light intensity

3.2 On and Off Pathways

The bipolar circuit divides input current into two different output currents, which are on current and off current shown in Figure 7. When the input is below a certain input threshold~~,~~ of 0.3nA, which can be adjusted by input range, on current is very low and off current is inversely proportional to the input current. When the input current is over the threshold current, on current is increasing as the input current increases and off current is near zero.

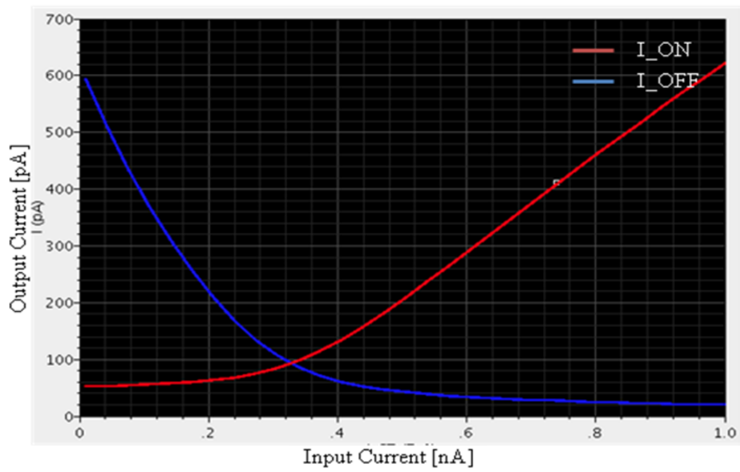

Figure 7: Simulation results of on and off currents versus input current to the bipolar circuit

3.3 Temporal Filtering: Sustained and Transient Pathways

Figure 8 and Figure 9 show~~s~~ simulation results for temporal filtering. In figure 8, the input is 100Hz square wave, whose amplitude is 1nA. In figure 9, the input is 200Hz sine wave with 1nA amplitude. On and off currents are generated according to the inputs. The sustained output shows low-pass-filtered response while the transient output has a high-pass-filtered response according to the on and off currents.

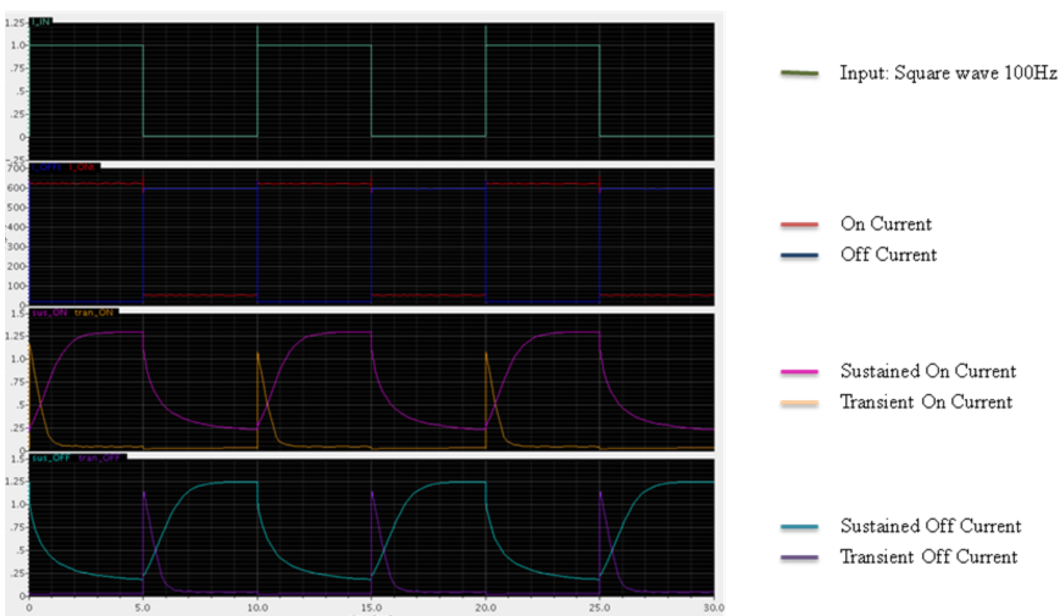

Figure 8: On/off sustained and transient responses from 100Hz square wave input

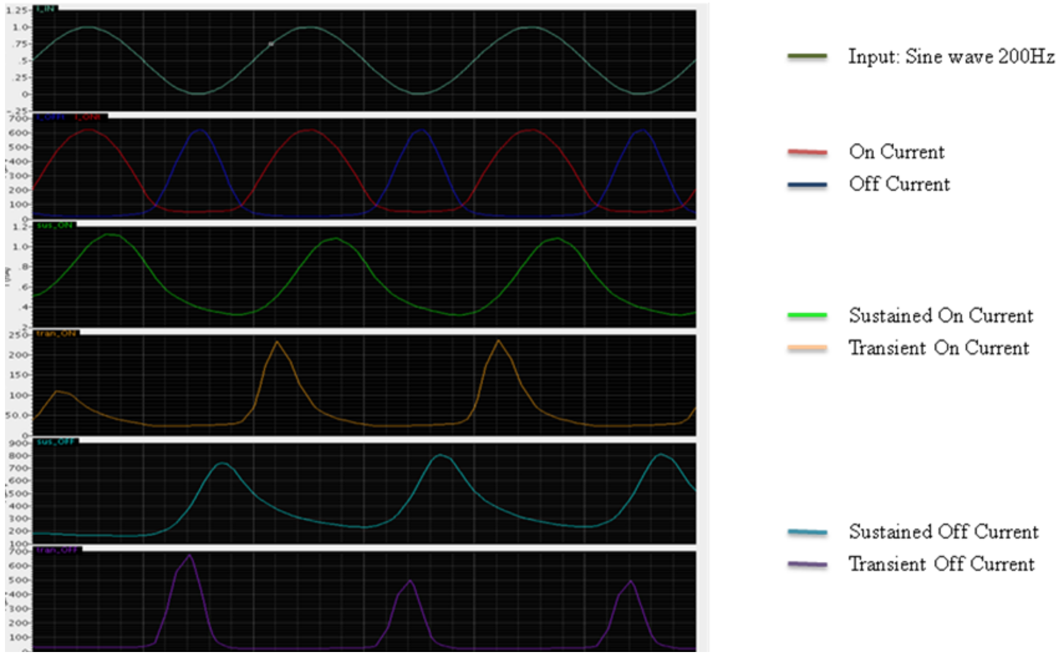

Figure 9: On/off sustained and transient responses from 200Hz sin wave input

3.4 Power Consumption

This work is designed with IBM 90nm Low Power CMOS process. Because all circuits operate in subthreshold region, high supply voltage is not necessary. To save power consumption, 0.5V was chosen as the supply voltage for this work.

This work models cone terminals, horizontal cells, on/off bipolar cells and narrow-field amacrine cells, and consumes only 3.16 nW per one set of all kinds of cells. As shown in Table 1, microprocessor consumes 2.2mW to simulate one ganglion cell including one set of other retinal cells, and the chip of Zaghloul and Boahen consumed 17 uW [17], which consumed more than 1,000 times than the power consumption of this work. If a ganglion cell could be designed with less than 13 nW, the total power consumption would be similar or less than the power consumption of the real retina.

Table 1: Comparison of power consumption per ganglion cell

Microprocessor	Conventional Retina Chip [17]	Real Retina	This Work
2.2mW	17uW	16.2nW	3.16nW

4 Conclusions

A silicon retina that can generate four types of ganglion cells with spatial and temporal processing and consumes only 3.16 nW, which is less than the mammalian retina, was designed and verified with simulations. The circuit of the silicon retina models the outer and inner layers of the retina. It has spatial low-pass filter with adaptation to light intensity, on and off pathways and temporal filters generating sustained and transient responses. Because its power consumption and information processing pathways are similar to the mammalian retina, it can be implanted as a part of retinal prosthesis in the future.

Acknowledgments

I would like to thank Gert Cauwenberghs, Jeffrey Bush and other classmates in BENG 260 for helpful discussions and feedback.

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