Design of Retinal Ganglion and Bipolar Cell Exhibiting Near Biological Response

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***Abstract*—Neuromorphic engineering is multidisciplinary branch of biology, physics, mathematics, neuroscience, electronics engineering and computer science. Neuroscientists are working on mimicking retina, cochlea, motoring neurons etc. For the retinal systems, substantial research has been done due to which understanding of basic components, connection methods and computational processes becomes easier. There are various approaches like mathematical modeling, device modeling, circuit level and system level modeling by which retina can be mimicked. Still researchers get new challenging tasks due to new insights given by neuroscientists into retinal biological system. Due to adaptive nature of human brain, modeling of neurons and synapses is a challenging task. Generally, area, speed and power are the major tradeoffs in any VLSI (Very Large Scale Integration) circuits; however, degree of biological realism and robustness need to be considered in neuromorphic circuits. There are many research papers available in the literature related to modeling of bipolar and ganglion cells, however circuits giving near biological response are the most sought-after circuits. In this paper, spiking behaviour of combined bipolar and ganglion cell is mimicked considering novel averaging and multiplier circuit for bipolar cell, and comparator-based circuit for ganglion cell to mimic the best possible near-biological response. The circuit is implemented using TSMC 180nm technology using LTSpice.**

***Keywords*— Neuromorphic, retina, spiking ganglion cell, bipolar cell, LTSpice.**

I. INTRODUCTION

A. *Structure of retina*

The retina contains well organized three layers [1] as shown in Fig. 1. The information is entered in retina, first at the photoreceptors and then it passes through bipolar cells and ganglion cells i.e., through second and third layer of the retina respectively. In the second layer along with photoreceptors and bipolar cells, horizontal cells are also present which connects photoreceptor to another photoreceptor. Similarly, in the third layer amacrine cells are present at the interconnections of bipolar and ganglion cells. They take input from and give output to bipolar cells [1]. The different layers of retina are shown in Fig. 1.

B. *Signal flow through retina*

Among all cells present in retina, the photoreceptor, bipolar cells and ganglion cells play actual role in transmitting the visual information to the brain from eye. The horizontal cells affect the flow of visual inputs to bipolar cells by modulating the synaptic activity of photoreceptor cells. Similarly, the flow of visual inputs by ganglion cells is affected by synaptic activity of ganglion and bipolar cells modulated by amacrine cells [2], [3].

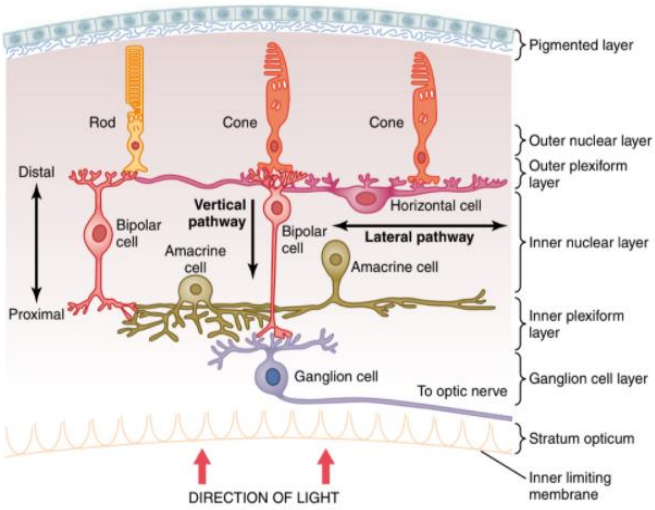


Fig. 1. Structure of Biological Retina [1].

The cells present in outer plexiform layer and amacrine cells respond with graded potential i.e. if the resulting current is large enough at their synapses, then neurotransmitter is released. Only the ganglion cells generate the action potential after recieving the signals [2], [3].

The rod photoreceptors are responsible for detecting monochromic and dim light and usally respond to relaitvely slow changes. The cones are responsible for detecting color and bright signals and respond to rapid light fluctuations. Thus, the images are decomposed into separate parts at rods and cones. The receptive fields of rods and cones are very narrow as both respond to light directly [2], [3].

In the outer plexiform layer, the receptive field surround

effect of bipolar cell is produced by horizontal cells by filtering the responses of central photoreceptors on basis of responses of surrounding photoreceptors. The type of biploar cell is decided on basis of the stimulus condition which produces a depolarizing response. Bipolar cells are of 2 types, based on the responses to neurotransmitter called glutamate, which depolarizes off bipolar cells and hyperpolarizes on bipolar cells. Dark objects in lighter background are detected by off bipolar cells, while light objects in darker background are detected by on bipolar cells.

The ganglion cells have voltage-gated sodium channels. On depolarization by glutamate released by bipolar cells, they generate action potentials. The receptive field configuration of a retinal ganglion cell is determined by the receptive fields of bipolar cells with which retinal ganglion cell synapses. The retinal ganglion cells that synapse with off bipolar cells will have off-center/on-surround receptive fields and are called off ganglion cells. The response of ganglion cell would be exactly reverse when connected to on bipolar cells [2], [3].

Amacrine cells connect laterally with similar type of cells and vertically with ganglion and bipolar cells. These cells produce the movement sensitive response, enhance the center-surround effect in ganglion cell receptive fields and connect rod to cone bipolar cells, allowing ganglion cells to respond to the entire range of light levels [2], [3].

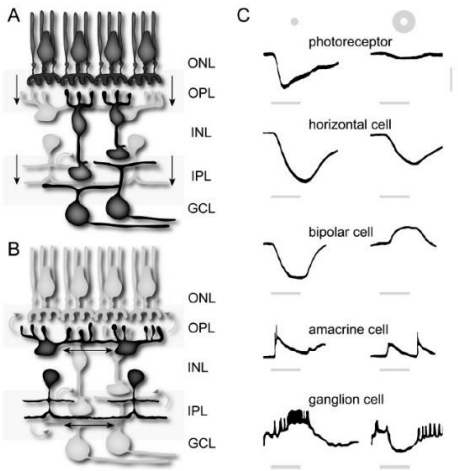


Fig. 2. Information flow in retina [5].

Fig. 2 shows the signal flow pathway in retina reported in [5]. In this, (A) depicts Vertical pathway. Signals flow through synapse formed by neurotransmitters in outer plexiform layer from photoreceptors to Bipolar to Ganglion Cells, feeding the retina output to brain. (B) depicts Lateral pathway. In the outer layer, Horizontal Cells are connected through gap junctions and collate visual signals laterally and then feedback to photoreceptors at Outer Plexiform Layer. In the inner layer, Amacrine Cells also collate laterally through electrical or conventional synapses and then feedback to Bipolar Cells or synapse to Ganglion Cells at Inner Plexiform Layer. (C) indicates graded and action potentials. Horizontal bar represents stimulus timing (500 to 1000ms), and Vertical bar is 5mV.

II. Literature Survey

Mahowald and Mead modeled the first silicon retina including modeling of out plexiform layer [6]. Silicon retina consists of transistors and photosensors made up of silicon mixed with impurities, wires and resistors made up of polysilicon and low-resistance wires made up of metal lines. The photoreceptor mimics the slow adaptive behaviour of cones in the biological retina using a photosensitive element and a feedback loop. The photosensor produces current in proportion of number of photons absorbed. The amplification of the difference between instantaneous photocurrent and its long-term average level is done through feedback loop. This circuit's output voltage is in proportion of logarithm of light intensity.

The Zaghloul and Boahen retina model [7] includes outer segments of cone that supply photocurrent to cone terminals and excite the horizontal cells. It modulates cone to horizontal cell excitation and cone gap junction through electric coupling of cone and horizontal cells to their neighbors by gap junctions. The narrow and wide field amacrine cell excitation is achieved by cone signals flowing from on bipolar and off bipolar cells to ganglion cells. The silicon retina outputs are a combination of behavior of on and off center wide field transient and narrow field sustained ganglion cells [8].

S. Usui formulated the ionic currents for bipolar cells [9]. This model utilized five different ionic currents identified in bipolar cells and described by mathematical formulation like the Hodgkin and Huxley equations [10]. In this, authors obtained voltage and current responses. It requires re-estimation of parameters for bipolar cells for mammals. Hence, reproduction of behavior of ganglion cell was experimental condition dependent.

To encode visual information, it is very important to understand response of ganglion cells [11]. In [12] authors presented on and off ganglion cell models that can capture intrinsic electrophysiological behaviors of ganglion cells. For example, on and off cells respond in opposite manner to increment or decrement in light intensity. However, authors have not suggested any way to stimulate on cells over off cells.

In [13], the researchers presented a continuum network model of retina, with active implementation of retinal ganglion cell tissue layer and passive implementation of deeper cell layers. First continuum multi-domain model for representing all main retinal ganglion cells was reported in [14]. It was limited only to specific types of ganglion cells. To match the theoretical models with real biological model, model with current activated through hyperpolarization was also reported in [15]. Tianruo Guo et al. suggested that biological responses can be recreated by on and off cells through morphological variations [16]. Use of morphologically realistic modelling would be helpful to study the propagation of action potentials through complex retinal ganglion cell's structure after intracellular stimulation [17].

Jonathan B. Demb et al. described the factors responsible for linear or non-linear response of ganglion cells [18]. The Y-ganglion cell receptive field contains two excitatory mechanisms: linear over narrow field (through input from bipolar cells), and nonlinear over wide field (through input from amacrine cells) [18]. The off inputs are typically dominant. The peripheral shift modulates the intensity of these inputs in opposite directions, enhancing the on pathway and diminishing the off pathway [19].

Table 1. shows biological output waveforms of retinal cells reported in literature, used for verifying the result of proposed system. Concluding from the published literature, it has been seen that most developed models work under typical conditions. For a large diverse conditions, adaptiveness of models is under research. For designing different biological models, trade-off involves efficiency, power consumption, speed, compactness, complexity, and biological exactness.

Considering the recent discovery of effect of TRP channel, modeling of bipolar cell action potential is under research. Design of combination of bipolar and ganglion circuit to imitate the firing dependent on surrounding light intensity and contrast is required [20]. Hence, from this the inspiration has been taken to design the circuit for bipolar and ganglion cell, which has characteristics of change in spiking rates with respect to change in light intensity of photoreceptor.

III. Proposed Structure of Bipolar and Ganglion Cell

The proposed structure to combine the bipolar and ganglion cell is shown in Fig. 3. There are seven photoreceptors, one would be at center and other six are surrounding it. They are modeled with current sources. This input is given to bipolar cell which contains averaging and multiplying circuits shown in Fig. 4 and Fig. 5. The output of bipolar cell (V_{out}) is given as input to ganglion cell comparator-based circuit. Input and output are in the form of current ranging from 100pA to 1µA for proposed current-based circuit.

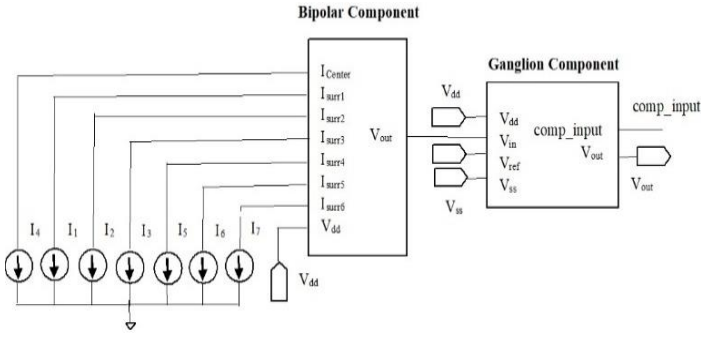


Fig. 3. Proposed combined structure of bipolar and ganglion cells

As discussed in introduction section, the input of the circuit is managed by photoreceptor and horizontal cell. Generally, the photoreceptor is mimicked with the help of photodiode. The output current of it is passed through horizontal cell to filter and feeds further to proposed circuit. Central photoreceptor is connected to six other photoreceptors through horizontal cell.

The bipolar circuit uses translinear principle given in [25] and consists of an average current computation circuit and multiplier circuit. The proposed circuits for average current computation and multiplier are shown in Fig. 4 and Fig. 5. Current from all seven photoreceptors are given to PMOS based current mirror circuits and added to a NMOS connected node. To this node, average value is generated through two current mirror circuits. To avoid non-linearities, high aspect ratio is kept for transistors. The current at output is,

$$I_{out} = \left(\frac{I_{in}}{I_{avg}}\right) * I_k$$

where I_{in}, I_{avg} and I_k are the currents from central photoreceptor, average and constant reference current (10nA) respectively. I_{out} is going to give the relative intensity of central photoreceptor. Width of all transistors shown in Fig. 4 is 2µm.

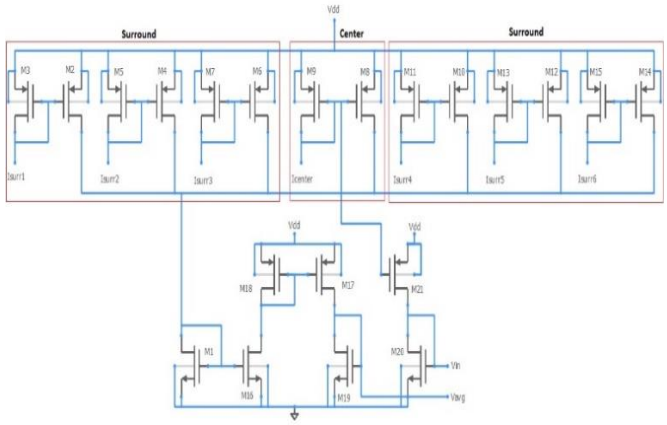


Fig. 4. Averaging stage of bipolar cell

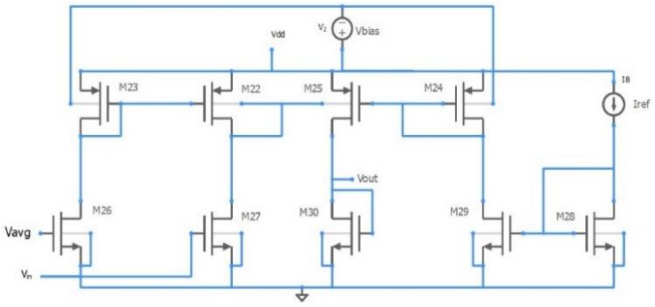
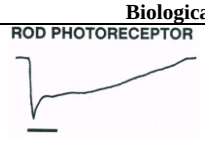
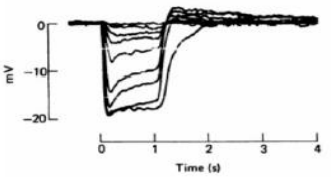
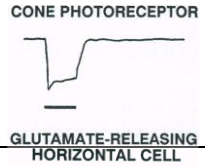
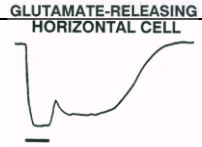
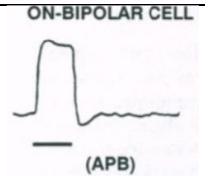
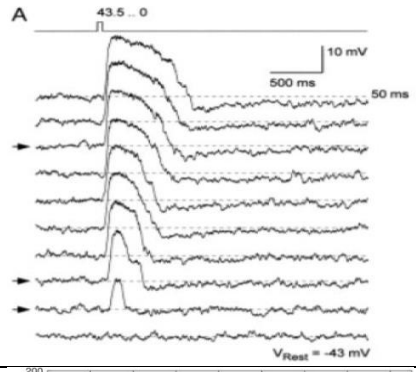
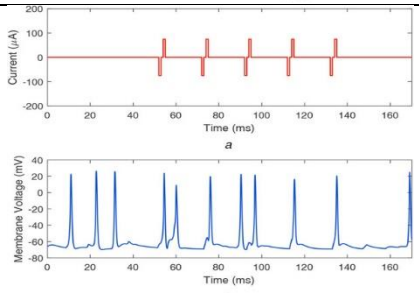
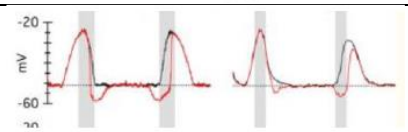


Fig. 5. Multiplier stage of bipolar cell

TABLE I. BIOLOGICAL OUTPUT WAVEFORM OF DIFFERENT RETINAL CELLS REPORTED IN LITERATURE

Types of cell	Biological response	Observations
Rod photo receptor		Rod response when a bright light is flashed for 1s. The maximum amplitude of response is 15-20mV and exceeds the stimulus.[21]
Cone photo receptor		The input stimulus is a step light flash of 620nm with incident flux of 8.3*10^3 photons per micrometer square for a duration of 1s [22]
		Cone response when a bright light is flashed for 1s. The hyperpolarization potential is around 10mV.[21]
Horizontal cell		The response is for duration of 1s stimulus. It has peak value of 45mV combining the features of rod and cone [21]
Bipolar cell		Bipolar cell response for duration of 1s stimulus. The depolarization is roughly around 10mV.[21]
		The bipolar cell responses are for various intensities. When the light is flashed for a duration of 50ms, the max depolarization peak reached is between 3.9mV to 26mV and the lowest hyperpolarization peak is between -1mV to -11.5mV.[23]
Ganglion cell		Output of ganglion cell for input current of 60μA.
Amacrine cell		Output of amacrine cell reported in [24], the typical values observed are A=-50mv, B=-50 to -25mv

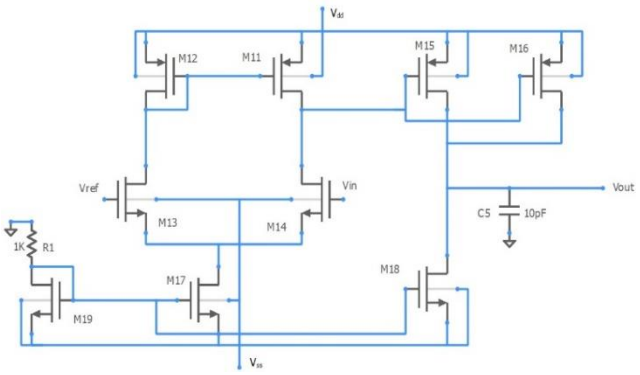


Fig. 6. Ganglion cell comparator circuit

TABLE II: TRANSISTOR ASPECT RATIOS FOR FIG. 6

Transistor	Aspect Ratio (Width/ Length)
M11, M12	7.2µm / 6.6 µm
M13, M14	5.4µm / 6.6 µm
M19	22.2µm / 6.6 µm
M17	5.4µm / 6.6 µm
M15, M16	29.7µm / 6.6 µm
M18	22.2µm / 6.6 µm

The output of bipolar stage is given as input to comparator circuit shown in Fig. 6. The ganglion circuit is shown in Fig. 7. As it is assumed that capacitor is initially not charged and constant V_{ref} is given to inverting terminal, the initial output of the comparator is low. As the gate input of bleed MOSFET is low, with its off state and contrast encoded current I_b, the capacitor will charge. The spike frequency will be

$$T_{spike} = dt = \frac{I_b}{CV_{ref}} \text{ as } q = CV \text{ and } I_b = C\frac{dv}{dt}$$

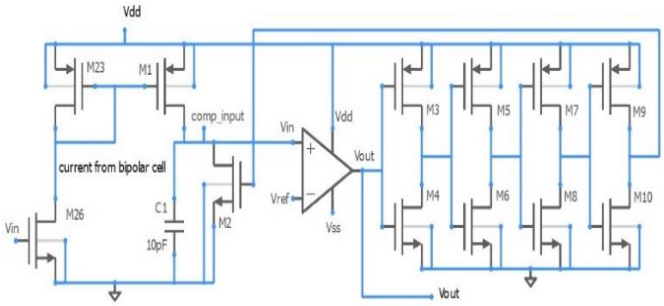


Fig. 7. Circuit for ganglion cell

IV. RESULT AND DISCUSSION

The input of photoreceptor is a current obtained by converting visual information. The current from seven photoreceptors is then given to horizontal cell which consist of cluster of photoreceptors, one photoreceptor is at center and rest six are surrounding it. The activation or threshold current of bipolar cell is the current obtained by averaging the currents in the cluster of cells. The diffusion of current would be on center or off center.

The central current is reduced as current is diffused, if the current transmits from center to neighboring cells through horizontal cells, if the central photoreceptor has high photocurrent and the outer cells have low intensity. İf diffused current exceeds the threshold then it gets depolarized resulting in activation of on-center bipolar cells. Similarly, off-center bipolar cells get activated in case of low intensity at central photoreceptor cell compared to outer cells. This function of cell is shown in Fig. 8.

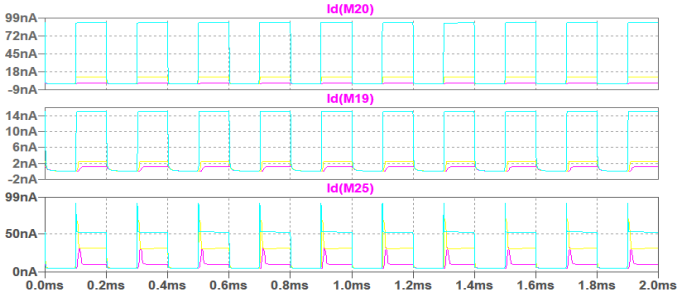


Fig. 8. Output (transient analysis) of bipolar cells with 1nA, 10nA and 100nA central photoreceptor current.

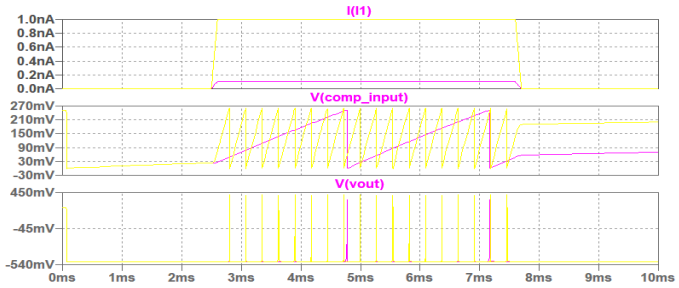


Fig. 9. Output of ganglion cell with 1nA input current

As discussed earlier, charging and discharging of capacitor V_c is responsible for spiking behaviour of ganglion cells. When input of 1nA is given to ganglion cell as shown in Fig. 9, as capacitor is kept constant, it starts charging. Due to negative step given by comparator, the nMOS is off. The nMOS will be on and capacitor will discharge as soon as the comparator gives positive voltage when voltage reaches to threshold voltage. This process continues till source is off. The selection of threshold voltage is done such that the chosen value is less than the lesser than the maximum depolarized voltage. To avoid the circuit operation in meta-stable stage small delay is added. The increment in input value results in increment in charging speed of capacitor and achievement in multiple spikes in same amount of time. Hence variation on frequency of spikes is possible in accordance with functioning of retinal ganglion cell. The output of combined bipolar and ganglion circuit is shown in Fig. 10. The ganglion cell gives more pulses when output of bipolar cell is high, and it gives less pulses when output of bipolar cell is less as shown in Fig. 10.

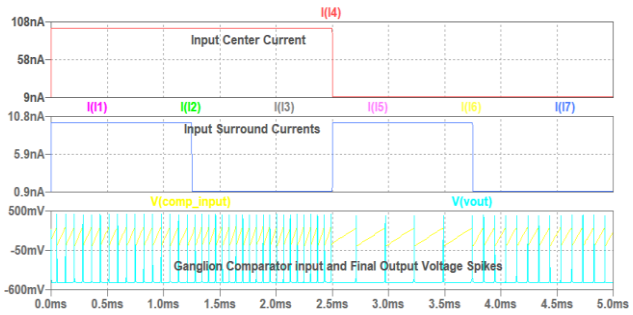


Fig.10. Output of combined bipolar and ganglion cell circuit

V. Conclusion and Future Scope

A novel circuit is designed and simulated for firing ganglion cells depending on surrounding light intensity and contrast. The output waveforms are verified with the waveforms related to biological functioning of ganglion and bipolar cell reported in literature. Near biological response has been obtained by using the proposed circuits for bipolar and ganglion cell.

The designed circuit can mimic one of the biological properties of retina, firing ganglion cells depending on surrounding light intensity and contrast. But for getting better near biological response, the range and deviations present in the circuit due to subthreshold region operations need to be considered. The assumptions are made for photoreceptor and horizontal cell stages, which also need to be designed. Also, as working of various amacrine cell is not known completely, most of the time it is ignored in design of retinal signal pathway. Amacrine cell should also be considered for correctly mimicking the behaviour of biological retina.

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