Report on Silicon Retina and Its Different Components, Including Circuitry

A neuromorphic device inspired by biological retina functioning to process visual information.

Layers that a biological retina contains -

- Photoreceptor : Photoreceptors are light sensitive cells. The two main types of Photoreceptors are rods and cones. The rods are extremely photosensitive cells and saturate easily; they provide vision in low light conditions known as scotopic vision (Scotopic vision is the vision of the eye under low-light levels). The cones are color sensitive cells that provide color vision above low light conditions. The retina consists of red, blue and green type cone cells. The outputs of these cells are in the form of transmission of neurotransmitter (Glutamate) but for emulation this can be modelled as a simple analog current or an analog voltage. In the given circuit only the rod inputs have been taken into consideration. The circuit employs photodiodes to generate a current based on input image to the sensor.
- Horizontal cell : The Horizontal cells connect laterally to an array of Photoreceptors and Bipolar cells and perform spatial filtering and smoothening of the input image. They integrate and regulate the input from multiple photoreceptor cells and hence assist in differentiating colors and detecting edges
- Bipolar cell : Bipolar cells connect the outer retina (Photoreceptors and Horizontal cells) to the inner retina (Ganglion and Amacrine Cells). They implement differential processing. Bipolar cells process visual information by generating a graded potential encoding the input luminosity in the output. The On type of Bipolar cell generates a positive graded potential in response to light incident on the cell. The Off-type bipolar cell generates a positive graded potential when the luminosity of light is lower than a threshold.
- Amacrine cell : Amacrine cells are cell that detect directional sensitivity. They are laterally connected to an array of bipolar cells and Ganglion cells. Amacrine cells modulate the signal that reaches the ganglion cells. There are a diverse types of amacrine cells and the exact working is still not known. Hence to abstain from complexity, the amacrine cells have not been included in the circuitry.
- Ganglion cell : The Ganglion Cell is the final cell in the retinal pathway. The Ganglion cells encode contrast information from the vision, the primary output of the cells are output spikes as opposed to graded potential, commonly known as action potential. The Ganglion cells spontaneously fire action potentials at a base rate while at rest. Excitation of retinal ganglion cells results in an increased firing rate while inhibition results in a depressed rate of firing. The baseline rate of fire is adjusted to scene

luminescence; thus, Ganglion cell is excited by a positive contrast(bright light) and inhibited by negative contrast(lack of light), the rate of firing is proportional to contrast . The output of the ganglion cells is sent to the cerebral cortex in the brain via the optic nerve fibers where further processing is done.

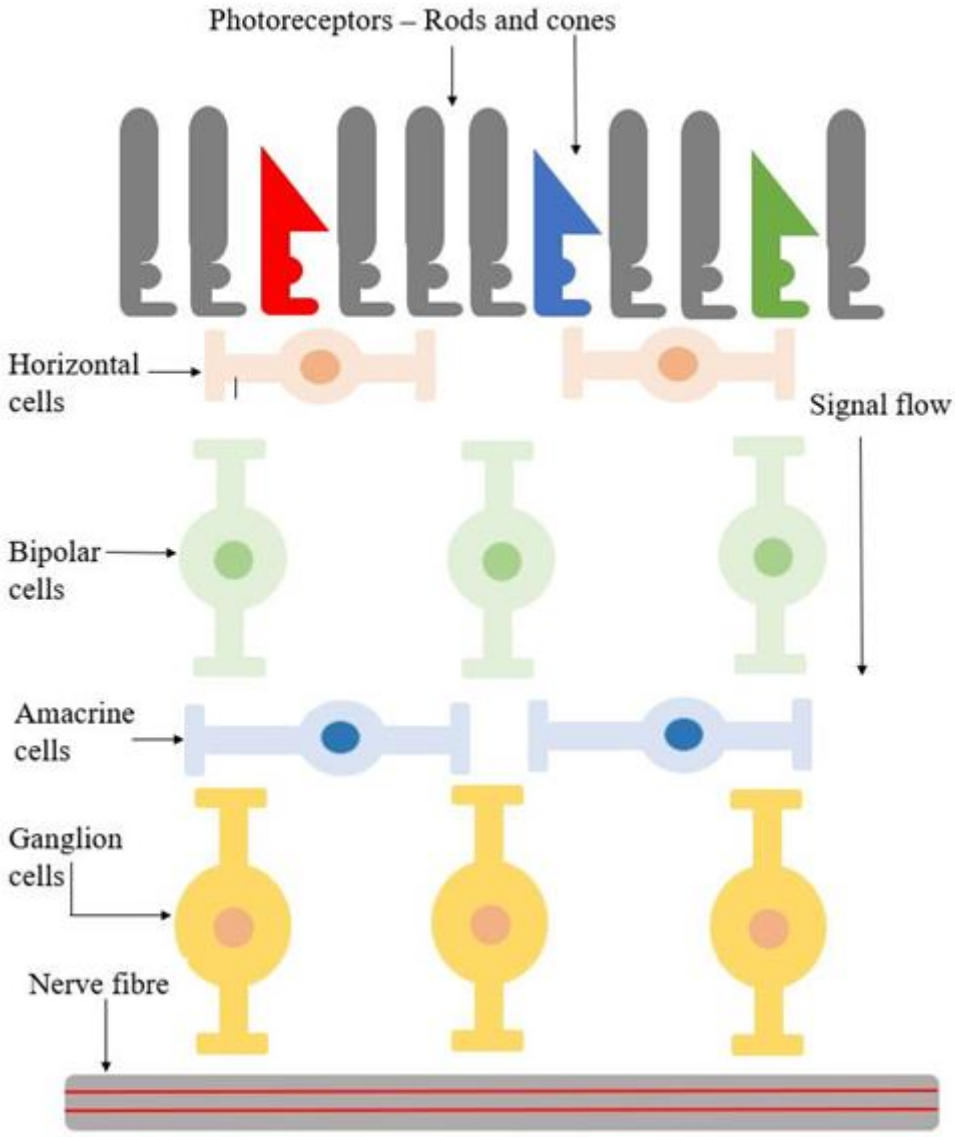

Fig : Structure of Retina

Photoreceptor

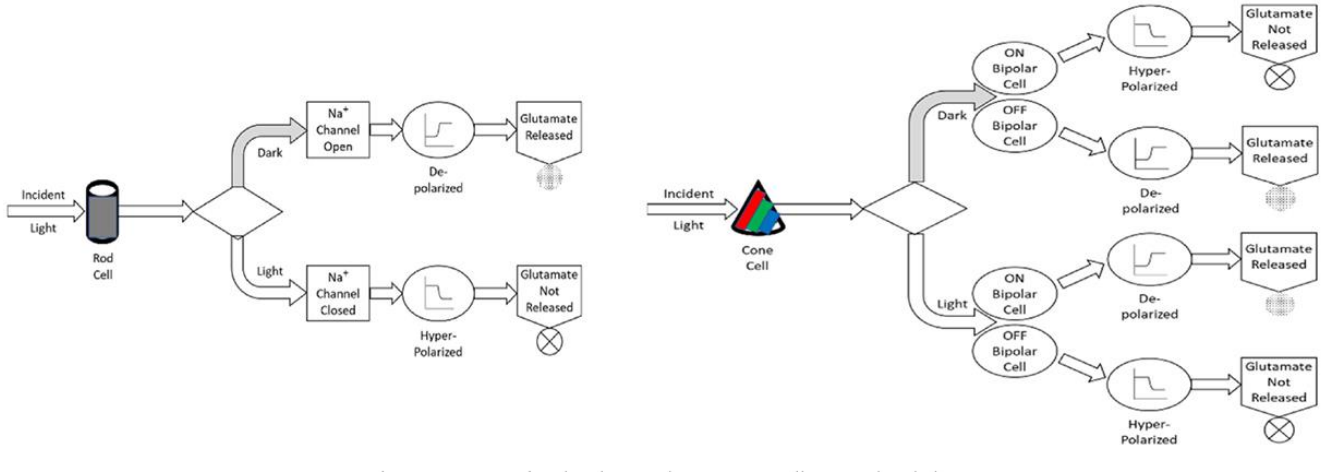

Fig : Response of Rod and Cone photoreceptor cells to incident light.

Photoreceptor design using MOSFET

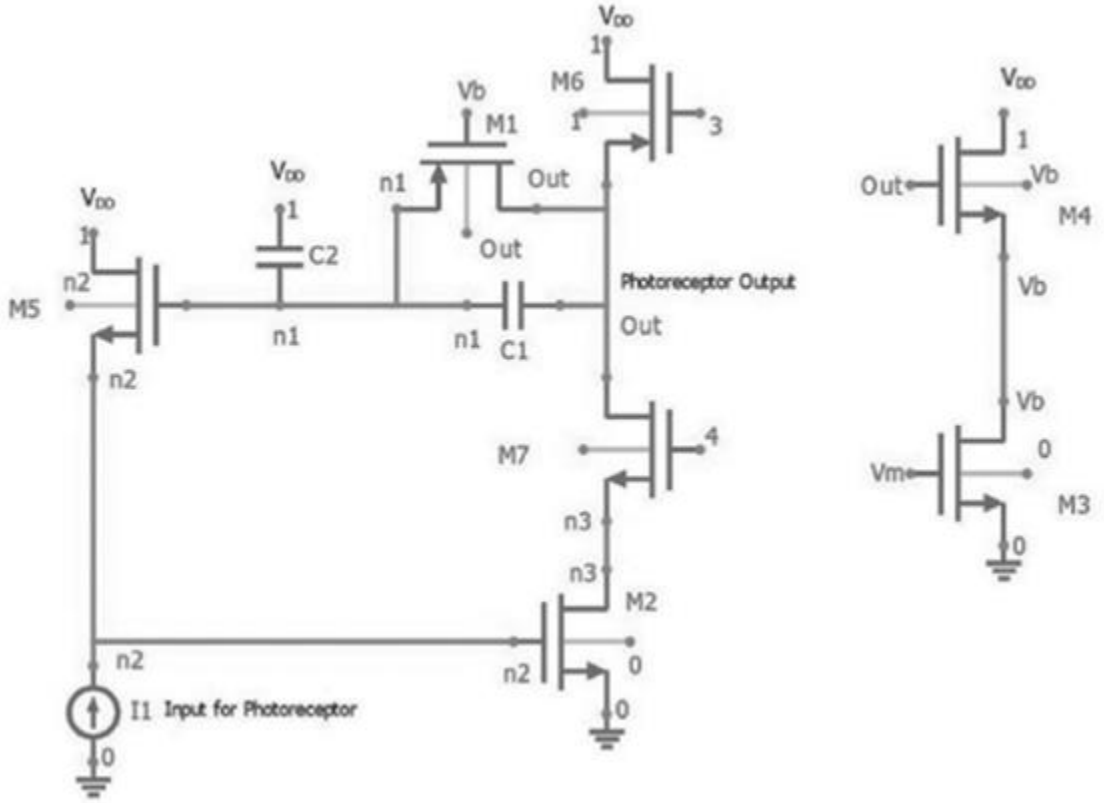

Fig : CMOS-based implemented photoreceptor circuit which matches with the biological response

Optimum Aspect Ratios (W) in the Photoreceptor Cell								
M1	M2	M3	M4	M5	M6	M7	C1	C2
2µ	900µ	1µ	180n	900µ	180n	50µ	180p	25n

Fig : Optimum aspects ratios

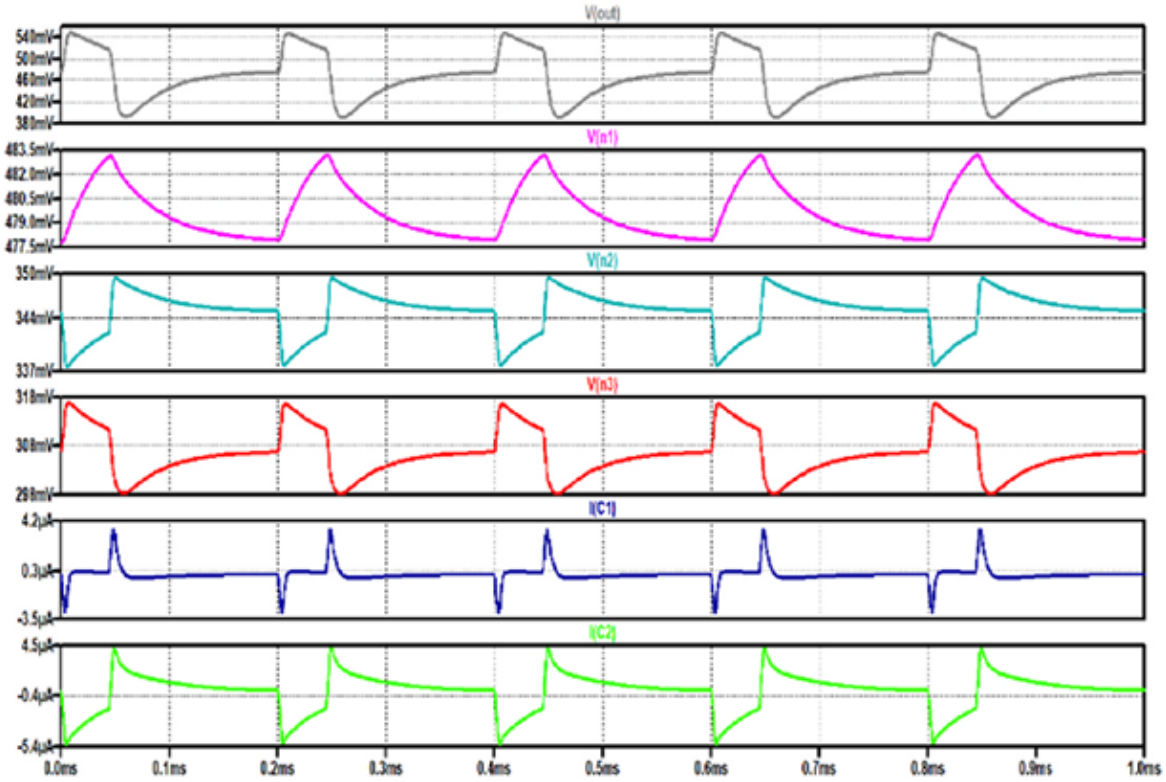

Fig : Output of the circuit

In the circuit input, is given through current source which should be replaced by photodiode. A square wave with an initial value of 250 nA and pulse value of 200 nA with pulse width of 210µs is considered as the input current waveform. Transistor M5 and photodiode (current source in this case) form the source follower receptive circuit. Transistors M3, M4 and M1 form the circuit known as the “adaptive element of the circuit”. This part of the circuit is responsible for predicting the output ahead of the input given to the circuit. Thus, transistors M3 and M4 form the feedback loop for the circuit which acts like an adaptive/learning element in the circuit. Further, transistors M6, M7 and M2 form the inverted Common Source Amplifier. Transistor M7 shown in this case essentially acts like a cascade device to cancel the effect of miller capacitance from the gate terminal to drain terminal of M2.

Bipolar cell

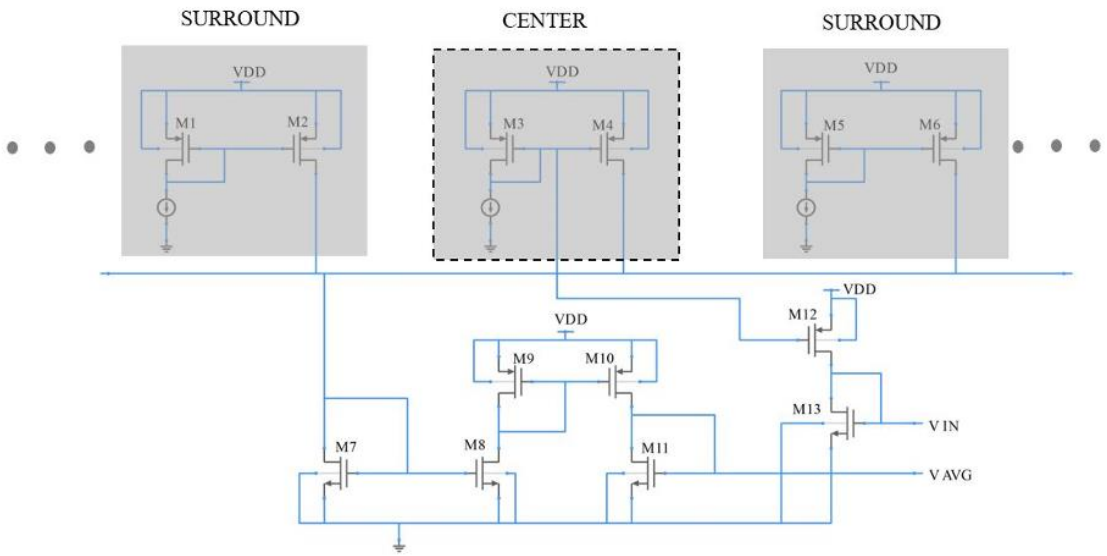

Fig : Bipolar circuit stage 1 (Averaging stage)

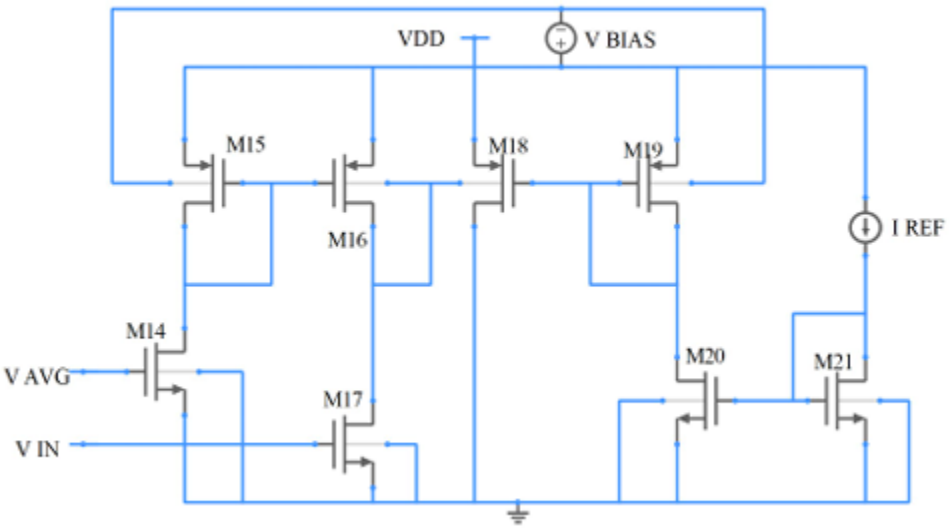

Fig : Bipolar circuit stage 2(Multiplier stage)

Ganglion Cell

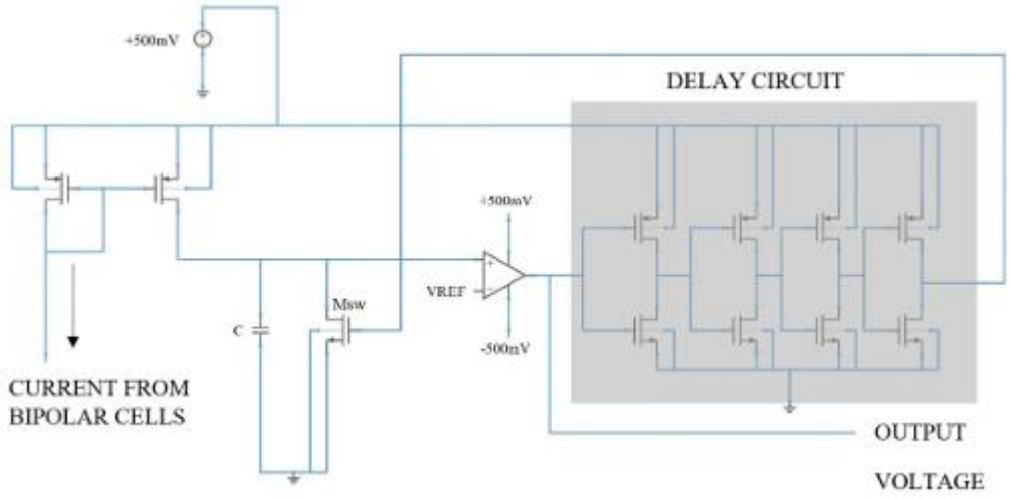

Fig : Ganglion cell circuit

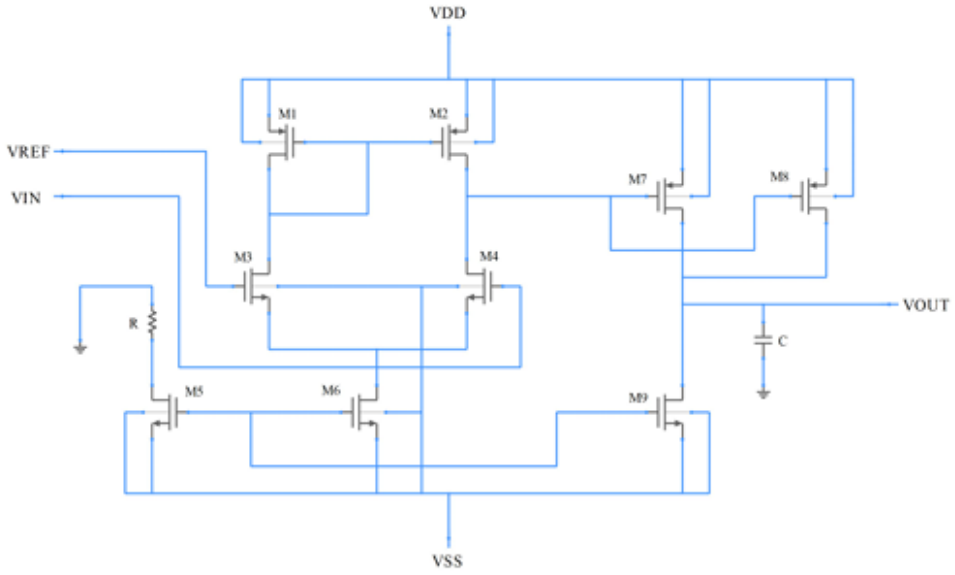

Fig : Comparator circuit that is used in the Ganglion cell circuit

Review of Bipolar and Ganglion Cell Modeling in Neuromorphic Retinal Circuits -

1. Abstract Neuromorphic engineering combines biology, neuroscience, electronics, and computer science to mimic biological systems. This paper reviews the proposed modeling of retinal bipolar and ganglion cells, focusing on spiking behavior and near-biological responses. The design employs novel circuits for bipolar cell averaging and multiplication, and ganglion cell spiking based on light intensity and contrast. Implemented using TSMC 180nm technology, the results demonstrate biologically accurate responses under specific conditions.

2. Structure of the Retina Key Layers: First Layer: Photoreceptors (rods and cones) process light stimuli. Second Layer: Bipolar cells transmit signals, influenced by horizontal cells. Third Layer: Ganglion cells transmit signals to the brain, influenced by amacrine cells. Photoreceptor Functions: Rods: Detect monochrome and dim light. Cones: Detect color and bright light. Synaptic Activities: Horizontal cells modulate photoreceptor activity. Amacrine cells modulate bipolar and ganglion cell synapses.

3. Role of Bipolar and Ganglion Cells Bipolar Cells: On Bipolar Cells: Detect light objects on dark backgrounds. Off Bipolar Cells: Detect dark objects on light backgrounds. Respond via depolarization or hyperpolarization depending on glutamate neurotransmitter activity. Ganglion Cells: Generate action potentials based on inputs from bipolar cells. On Ganglion Cells: Activated by bipolar cells; detect bright stimuli in dark regions. Off Ganglion Cells: Activated by off bipolar cells; detect dark stimuli in bright regions.

4. Literature Review Key Models: Mahowald and Mead: Silicon retina with photoreceptors mimicking adaptive cone behavior. Zaghloul and Boahen: Models cone terminals, horizontal cell coupling, and ganglion cell excitations. Usui: Ionic current-based bipolar cell model using Hodgkin-Huxley equations. Tianruo Guo et al.: Morphological modeling for retinal ganglion cell action potential propagation. Nathan B. Demb et al.: Linear and nonlinear ganglion cell receptive field responses influenced by bipolar and amacrine cell inputs. Key Insights: Most models mimic specific retinal cell functions under controlled conditions.

Adaptiveness for diverse biological scenarios is under research. Incorporating amacrine cells remains a significant gap.

5. Proposed Model Circuit Design: Bipolar Cell Circuit: Uses averaging and multiplier circuits based on translinear principles. Processes photoreceptor currents to compute relative light intensity. Ganglion Cell Circuit: Comparator-based circuit mimics spiking behavior. Spike frequency depends on bipolar cell output and surrounding light contrast. Implementation: Photoreceptor currents modeled as input from one central and six surrounding photoreceptors. Outputs are current based, ranging from 100pA to 1μA.

6. Results and Observations Bipolar Cells: On-center and off-center bipolar cells activate based on light intensity contrast between central and surrounding photoreceptors. Ganglion Cells: Mimic spiking behavior through capacitor charging and discharging cycles. Increased input current results in higher spike frequency, aligning with biological ganglion cell behavior. Output Verification: Output waveforms closely match biological responses reported in the literature.

7. Conclusion and Future Scope Achievements: Designed a novel circuit mimicking ganglion and bipolar cell behavior. Successfully simulated light intensity-dependent spiking. Limitations: Subthreshold operation deviations need optimization. Photoreceptor and horizontal cell stages are currently assumptions and require actual designs. Amacrine cell integration is essential for comprehensive modeling. Future Work: Incorporate amacrine cells for better biological realism. Optimize circuits for enhanced adaptiveness and accuracy. Extend the model for diverse biological conditions.

Key Findings

1. Bipolar and ganglion cell circuits can mimic retinal signal processing with near-biological accuracy.

2. On-center and off-center cells demonstrate expected activation behaviors.

3. Spiking frequency in ganglion cells varies proportionally to light intensity and contrast.

4. Future models should include amacrine cells and address subthreshold deviations for better performance. This review consolidates findings to aid further advancements in neuromorphic retinal modeling.

CMOS In-Pixel Optical Pulse Frequency Modulator -

1. Abstract Developed a CMOS pixel readout circuit integrating a frequency conversion feature. Designed an 8×8 array of pixels with on-chip frequency modulation for improved dynamic range and reduced size. Achieved a dynamic range of 58.828 dB and output frequencies from 12.341 kHz to 10.783 MHz. Simulation results confirmed linearity between photocurrent and output frequency.

2. Introduction Purpose: Convert analog optical signals to electrical signals for digital processing. Advantages of CMOS over CCD: Smaller size and fewer ICs required. Integration of additional circuitry for signal processing. Key Features: Pulse frequency modulation preferred over ADC for reduced pixel size and power consumption. Designed pixels with a maximum size of 30 × 30 μm 2 30×30μm 2 .

3. Methodology Pixel Design: Integrated a photodiode, Schmitt trigger, and capacitor in each pixel. Designed for 30 × 30 μm 2 30×30μm 2 area to accommodate an 8×8 array. Used AMS 350 nm process with a 5V supply voltage. Photodiode: n+-p+/p-substrate diode with low parasitic capacitance (3 fF). Calculated photocurrent based on photon flux density, quantum efficiency, and diode area. Integration Capacitor: Poly1-poly2 capacitor with 200 fF capacitance designed for optimal frequency modulation. Frequency Modulation Circuit: Utilized a Schmitt trigger for compactness and variable threshold voltage. Array Design: Included row and column select shift registers for individual pixel output.

4. Circuit Design Components: Photodiode: Converts light intensity into photocurrent. Integration Capacitor: Discharges as photocurrent flows to ground. Schmitt Trigger: Generates high/low pulses when voltage crosses thresholds. Reset Transistor: Resets capacitor after discharge cycle. Functionality: Photodiode and capacitor charge to $V\ D\ D$ V

DD . Discharge rate depends on photocurrent. Schmitt trigger output toggles, generating a frequency proportional to photocurrent.

5. Simulation Results Key Observations: Simulation confirmed linear relationship between photocurrent (10 nA to 10 µA) and output frequency. Achieved a dynamic range of 58.828 dB, exceeding an 8-bit ADC resolution. Verified schematic and layout functionality using Cadence Virtuoso. Output Behavior: Higher photocurrent results in higher frequency. Frequency ranged from 12.341 kHz to 10.783 MHz.

6. Conclusion Achievements: Designed a compact CMOS pixel with integrated frequency modulation. Achieved wide dynamic range and linear photocurrent-to-frequency relationship. Layout verified and ready for fabrication. Future Scope: Decrease pixel size further by optimizing component layout. Increase photodiode area to enhance photon absorption and dynamic range. Address dark current effects for improved accuracy at low frequencies. Explore applications in high-speed CMOS photodetectors and biosensing technologies. Key Findings Innovative Pixel Design: Integrated on-chip frequency modulation reduces size and power consumption. Capable of replacing ADCs with compact imaging systems. Dynamic Range: Achieved 58.828 dB, surpassing traditional ADC resolutions. Linear Output: Strong linear relationship between photocurrent and frequency (10 nA to 10 µA). Compact Array: Designed and simulated an 8×8 pixel array with individual pixel selection logic. This research demonstrates a novel approach to CMOS-based image sensors, emphasizing compactness, efficiency, and high dynamic range. It holds significant potential for advancing imaging and sensing technologies

References –

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