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# Photoreceptor Circuit Based on Only Metal–Oxide–Semiconductor Transistors

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### WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *The basic functions of biological cells found in the retina are known. It is understood how these cells convert images into electrical signals. It is possible to design transistor-based electronic circuits that can mimic the function of photoreceptor cells and produce the same outputs as biological cells.*
- *One of the most significant problems encountered when designing circuits that mimic biological cells is minimizing their power consumption, and this study explains how this should be done.*

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## ABSTRACT

In this study, a photoreceptor circuit composed solely of MOS (metal–oxide–semiconductor) transistors was proposed. Currently, researchers in neuromorphic engineering are focusing on mimicking biological nervous systems using silicon devices. The challenges involved in mimicking biological systems are as significant as their potential. These challenges include circuit complexity, low power consumption, computational difficulty, and the challenge of integrating passive components onto a chip. Biologically, millions of neurons consume only a few watts of energy to process information. Therefore, the main reasons challenging researchers in silicon circuit design are reducing power consumption and making it entirely composed of transistors for applicability within the chip. In this study, the modified photoreceptor circuit holds promise due to its low power consumption and entirely transistor-based design. The circuit design was created in LTspice. Permission for real production in TSMC 90-nm technology was granted for the simulation results. The metal–oxide–semiconductor field-effect transistors used in the design were operated below their threshold. The modified circuit is approximately equivalent to the potential change in a biological photoreceptor cell. The modified circuit has been shown to consume approximately 23 times less power compared to the reference circuits. Furthermore, the modified circuit was analyzed under different background light conditions and was found to operate stably. The proposed circuit, composed entirely of MOS transistors, enhances its compatibility with chip designs. This feature reduces its size, which in turn helps lower costs.

***Index Terms*—**Complementary metal–oxide–semiconductor (CMOS), integrated circuit, LTspice, photoreceptor cell, silicon retina, spike generation

## I. INTRODUCTION

The retina's photoreceptors (rods and cones), which convert light incident on their pigments into neural electrical signals, are the most critical cells in the retina for vision. Photoreceptors subject light falling on the retina to specific differential processes and transmit it to horizontal cells and bipolar cells. The term "neuromorphic" was introduced into the literature by Carver Mead in 1990 and refers to a concept used to describe the design of electronic circuits that mimic the functioning of biological structures in the nervous system [1]. Neuromorphic engineering has evolved into a multidisciplinary field of research that combines mathematics, computer science, and analog electronics, drawing inspiration from the nervous systems of living organisms [2, 3]. In recent years, numerous studies have been conducted in neuromorphic research to mimic various biological sensory systems, drawing inspiration from biological synapses [4–6]. Many neuromorphic circuit designs incorporate memristor elements, which exhibit behavior similar to that of biological neurons due to their low power consumption, high operating speed, memory properties, and compact size [7–12].

In neuromorphic circuit designs, it has been demonstrated that using silicon neuron structures in analog circuits yields significantly lower power consumption than digital systems and substantially increases efficiency [13]. Neuromorphic circuits have become an essential field of study, attracting scientists because they offer advantages such as high efficiency and

**WHAT DOES THIS STUDY ADD TO THIS TOPIC?**

- *The fact that the proposed circuit consists solely of metal–oxide–semiconductor transistors increases its suitability for chip designs. This feature reduces the area it occupies, thereby lowering its cost.*
- *One of the most significant problems encountered when mimicking biological cells is their low power consumption. The power consumption of the electronic circuit proposed in this study is close to that of biological cells.*

low power consumption, similar to biological systems [1]. In the field of neuromorphics, the eye, which occupies an important place among sensory systems, has been the subject of numerous scientific studies, particularly focusing on the retina [2, 14–22]. Photoreceptors (rods and cones), horizontal cells, bipolar cells, and ganglion cells comprise the basic layers of the human retina. The work carried out by Misha A. Mahowald and Carver Mead, which pioneered the field of neuromorphics for scientists and successfully replicated three of the five cell types in the retina, was published in 1991 [23]. In studies aimed at developing a silicon retina in the field of neuromorphics, the term "retinomorphic" was first introduced by Kwabena Boahen [15].

In this study, the electronic circuit of the photoreceptor cell found in the retina has been modified. Only complementary metal–oxide–semiconductor (CMOS) transistors were used in the circuit design. Using only CMOS transistors has made the chip design more cost-effective and smaller. Furthermore, since CMOS transistors operate below threshold, the power consumption is approximately 0.784 μW per pixel. This article begins by discussing the biological behavior of the photoreceptor. The application section describes the modified metal–oxide–semiconductor field-effect transistor (MOSFET)-based photoreceptor circuit. The simulation results section discusses power consumption, biological similarity, and stability under different background light intensities. The discussion and conclusion section presents a detailed comparison of the reference and modified circuits from multiple perspectives. The final section presents a discussion of the results, concludes, and outlines future work.

## II. RELATED WORK

### A. Biology of Photoreceptor

Photoreceptors are cells that convert light hitting the pigments of the retina into electrical signals. These cells are called rods and cones. There are many more rods than cones. There are approximately 120 million rods and 6 million cones. Rods are responsible for vision in low-light conditions, are stimulated by lower light intensities, and are less sensitive than cones [24]. Both rod and cone cells convert the absorption of a single photon into a meaningful electrical signal through a biochemical process involving a second messenger system. As shown in Fig. 1, this event is summarized as phototransduction. Phototransduction refers to the entire process by which light initiates a sensory response. The absorption of a single photon activates an enzyme that catalyzes the breakdown of cyclic guanosine monophosphate molecules (the type of second messenger in signal transduction pathways) [25].

Rods are not found in the central (fovea) retina. They are more often seen in the periphery (preferia). Cones, on the other hand, are found entirely in the central (fovea) retina. The areas where photoreceptors are located in the retina are shown in Fig. 2. Cones are responsible for color vision. There are three types of cone cells responsible for color vision: blue, green, and red.

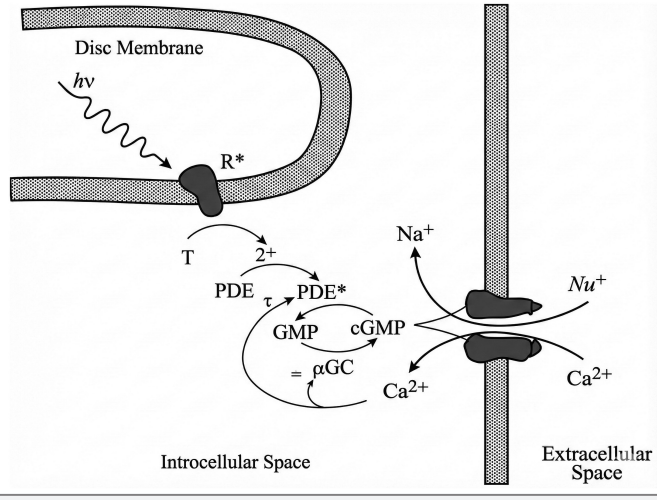



**Fig. 1.** Occurrence of phototransduction [25].

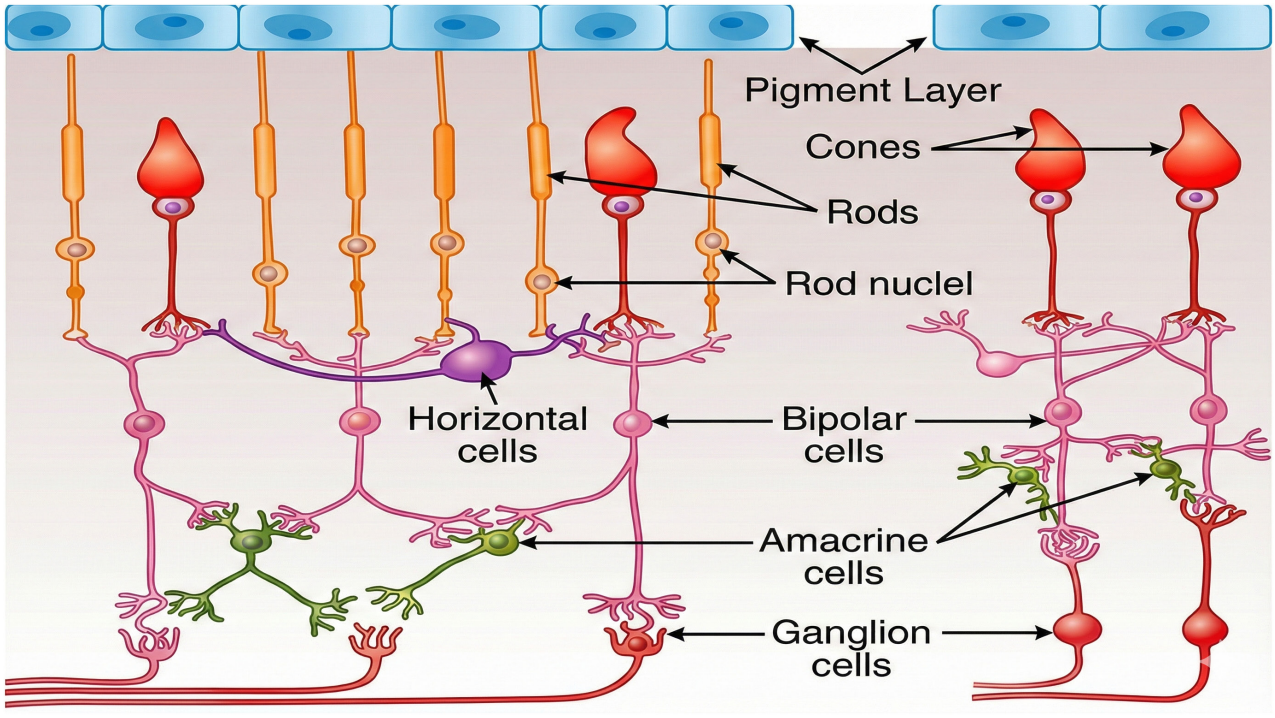



**Fig. 2.** Neural structure of the retina: The fovea area on the right, the peripheral area on the left [24].

### B. Reference Photoreceptor Circuit

The first adaptive photoreceptor circuit was introduced to the literature by Delbrück and Mead in 1995 [26]. The circuit designed by Shih Chii Liu was introduced to the scientific world, featuring improvements to the Delbrück circuit. The circuit is small and compact, capturing the transient and adaptive properties of photoreceptors and laminar layers in the fly eye structure [27].

The circuit shown in Fig. 3 was replicated by Vishnani and colleagues in 2021 using metal–oxide–semiconductor-(MOS) transistors [28].

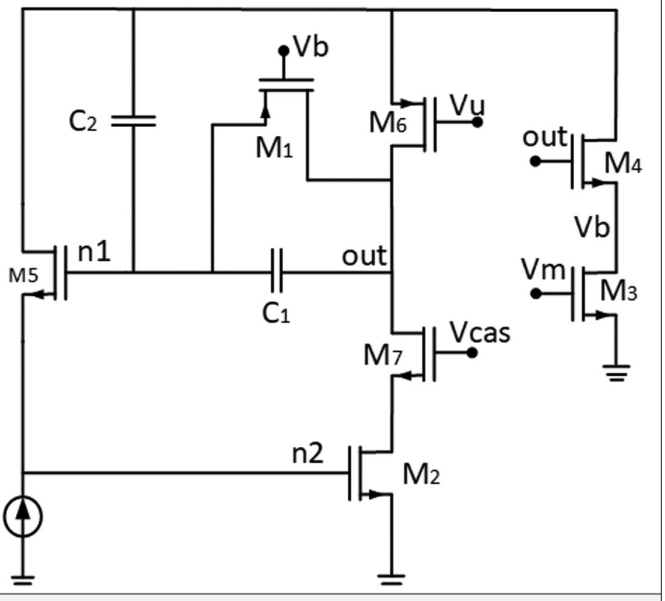



**Fig. 3.** Photoreceptor cell circuit using metal–oxide–semiconductor field-effect transistor [28, 29].

However, in this circuit, a square wave with a light source varying between 200 and 250 nA and a pulse width of 210 µs was used instead of a photodiode. Transistor $M_5$ was used as feedback. Transistors $M_3$, $M_4$, and $M_1$ were used to provide the circuit with adaptability. Transistors $M_3$ and $M_4$ form a feedback loop in the circuit, controlling transistor $M_1$ and enabling it to behave as an adaptive or learning element. Additionally, transistors $M_6$, $M_7$, and $M_2$ were used to invert and amplify the input signal. The $M_7$ transistor essentially functions as a cascode to eliminate the Miller capacitance between the gate and drain terminals of $M_2$.

The channel length-to-width ratios of the MOS transistors used are specified in Table I. Since the values of capacitors C1 and C2 are large, they are not suitable for production and are assumed to be connected externally to the chip. Fig. 4 shows simulations of the referenced circuit.

## III. IMPLEMENTATION

### A. Modified Complementary Metal–Oxide–Semiconductor–Based Photoreceptor Circuit

The photoreceptor circuit modified using only MOS transistors is shown in Fig. 5. The operating principle of the photoreceptor circuit uses an ideal current source to model a constant but intensity-varying light source. This current source will create a very high voltage at the gate of the $M_3$ transistor. Therefore, the $M_8$ transistor, which acts as a parallel resistor, is connected to pull the resulting voltage below the threshold. An external voltage source (Va = −0.3 V) was

**TABLE I.** OPTIMUM ASPECT RATIOS IN THE PHOTORECEPTOR CELL [29]

| $M_1$ | $M_2$ | $M_3$ | $M_4$ | $M_5$ | $M_6$ | $M_7$ | $C_1$ | $C_2$ |
|---|---|---|---|---|---|---|---|---|
| 2 µm | 900 µm | 1 µm | 180 nm | 900 µm | 180 nm | 50 µm | 180 pF | 25 nF |

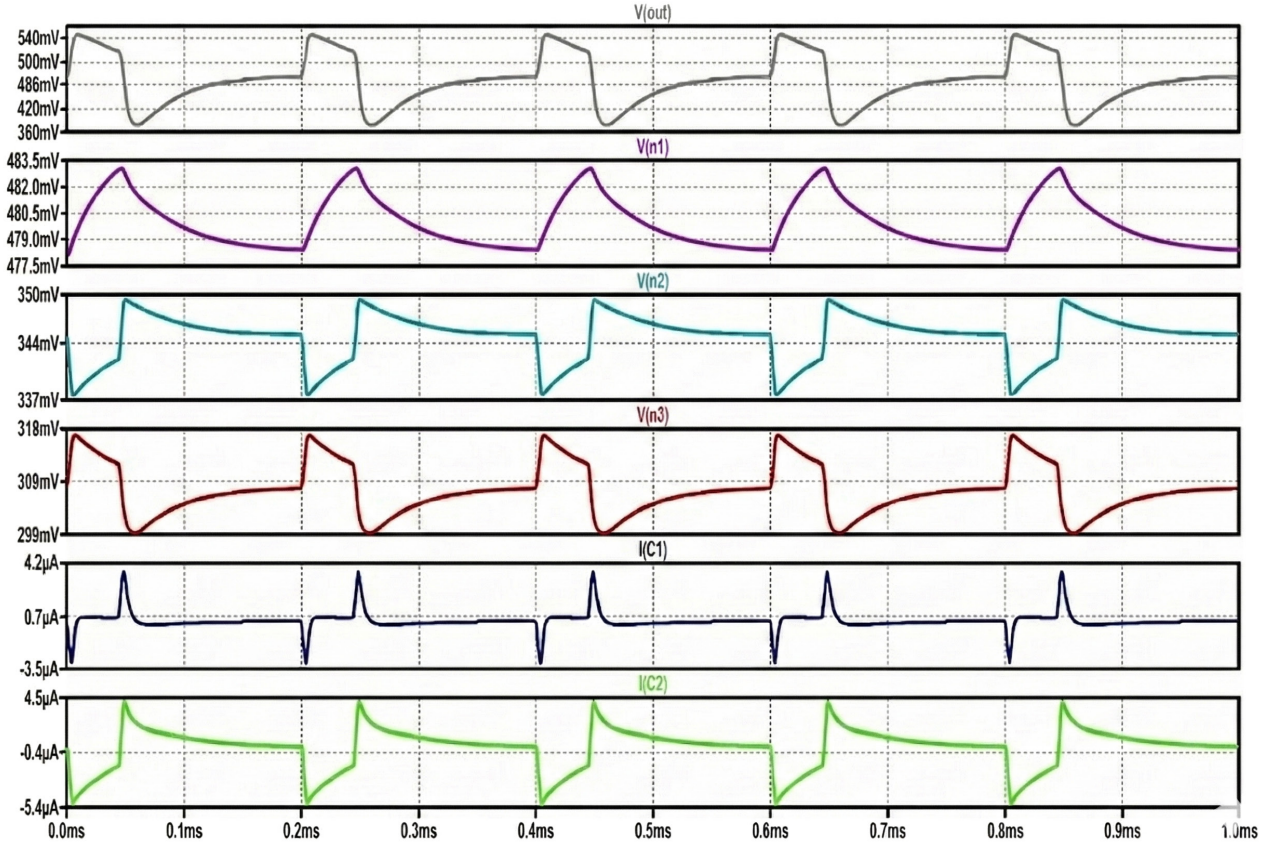



**Fig. 4.** Output of photoreceptor cell circuit using metal–oxide–semiconductor field-effect transistor [29].

used to drive the $M_8$ transistor. The $M_3$ transistor in the circuit was configured as a common-source amplifier, amplifying the signal at its output and introducing a phase shift. Therefore, it amplified the signal applied to its gate and provided a phase-shifted output. The signal from its output represents the photoreceptor circuit's output. The output of the photoreceptor circuit, like the photoreceptor cell found in the biological retina, becomes negatively charged when exposed to a light source. The $M_4$ transistor, which generates the output voltage, was used to balance the voltage at the photoreceptor cell's output. Since the gate voltage of the $M_5$ transistor is the output voltage, an increase in the output voltage increases the conductivity of the $M_5$ transistor, which in turn increases the gate voltage (Vx) of the $M_4$ transistor. Since the $M_4$ transistor is P-type, increasing the gate voltage will turn it off, decreasing the output voltage. Therefore, this method is used to balance the increase in output voltage. Conversely, if photoreceptor output decreases, the M4 transistor's gate voltage decreases, increasing its conductivity and causing the output voltage to decrease. This will ensure the photoreceptor responds more stably to light fluctuations.

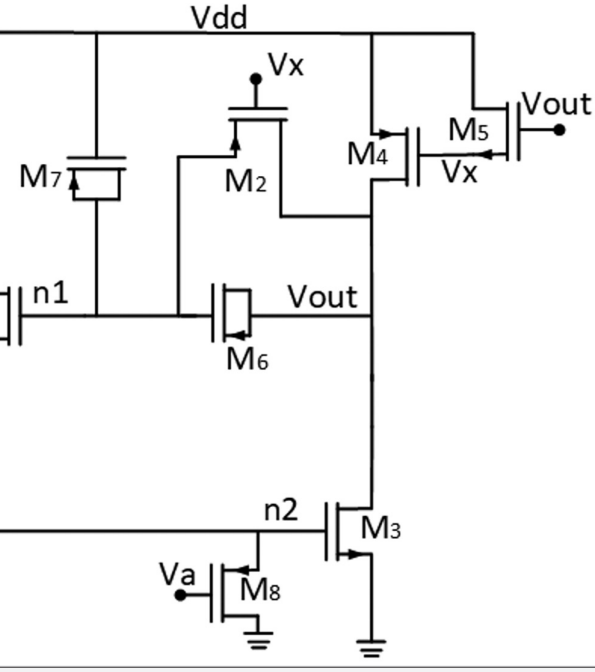



**Fig. 5.** Photoreceptor circuit modified using only transistors.

Transistors $M_6$ and $M_7$ were used as MOS capacitors in the circuit. Transistor $M_7$ was preferred over a capacitor to prevent noise. Transistor $M_6$ was used as a voltage divider in the circuit. Using transistors instead of capacitors offers the advantage of requiring less space and allowing the circuit to be integrated into the chip. The modified photoreceptor circuit uses the $M_1$ transistor as the feedback transistor. If there are sudden increases in the output voltage of the feedback transistor, the conductivity of the $M_1$ transistor increases due to the voltage applied to its gate. As conductivity increases, more current flows through it, raising the gate voltage of the $M_3$ transistor. The $M_3$ transistor's conductivity increases, resulting in a lower output voltage. Transistor $M_2$ was used as the adaptive

**TABLE II.** CHANNEL WIDTH AND CHANNEL LENGTHS OF THE COMPLEMENTARY METAL–OXIDE–SEMICONDUCTOR TRANSISTORS IN THE MODIFIED PHOTORECEPTOR CIRCUIT

| Circuit Element | Parameters (W/L µm) |
|---|---|
| $M_1$ | W/L = 100/1 |
| $M_2$ | W/L = 1 /1 |
| $M_3$ | W/L = 1/10 |
| $M_4$ | W/L = 1/3 |
| $M_5$ | W/L = 5/1 |
| $M_6$ | W/L = 250/250 |
| $M_7$ | W/L = 1/1 |
| $M_8$ | W/L = 1/4 |
| Vdd | 0.9 V |

L, length; W, width.

circuit element. Since the gate of the $M_2$ transistor is connected to the output voltage, if there is a decrease in the output voltage, the gate voltage (Vx) of the $M_2$ transistor will decrease, and its conductivity will increase, causing the output voltage to increase. As a result, a circuit model capable of adapting to different light conditions reaching the human eye was proposed. This circuit enables rapid adaptation to both very bright and shadowy conditions. The CMOS parameters for the photoreceptor circuit are given in Table II. The power consumption per pixel for the modified circuit is shown in (1).

$$Vdd = 0.9V \qquad Ii \approx 871.93nA$$

$$P = Vdd * Ii = 0.9 * 871.93 * 10^{-9} \approx 0.784\mu A \tag{1}$$

The Vdd value given in (1) is the source voltage, and $I_i$ is the approximate current value provided by the source.

## IV. SIMULATION RESULTS

Simulations of the modified photoreceptor circuit are shown in Fig. 6. Here, since the biological output is too small to be measured with silicon-based circuits, the waveform shape has been matched [30]. As shown in Fig. 6a, the instantaneous power consumption of the circuit during the applied 50-nA light pulses was measured in Fig. 6e. While a similar circuit in the referenced literature consumed 18 µW, the average power consumption in this proposed design was reduced to below 1 µW (approximately 0.784 µW) by operating all transistors in the subthreshold region. This represents an approximately 23-fold increase in energy efficiency. The output response of the modified photoreceptor circuit is shown in Fig. 6b. Biological photoreceptor cells hyperpolarize and lower their membrane potentials when exposed to light. As shown in the graph, the proposed circuit successfully mimics biological hyperpolarization, decreasing the output voltage as the input current increases. Furthermore, the transient responses to signal changes demonstrate that the feedback loop rapidly stabilizes the circuit at a new operating point. To analyze the circuit's stability, the internal node voltages (Vn1 and Vn2) are shown in Fig. 6c and 6d. In particular, the voltage change at

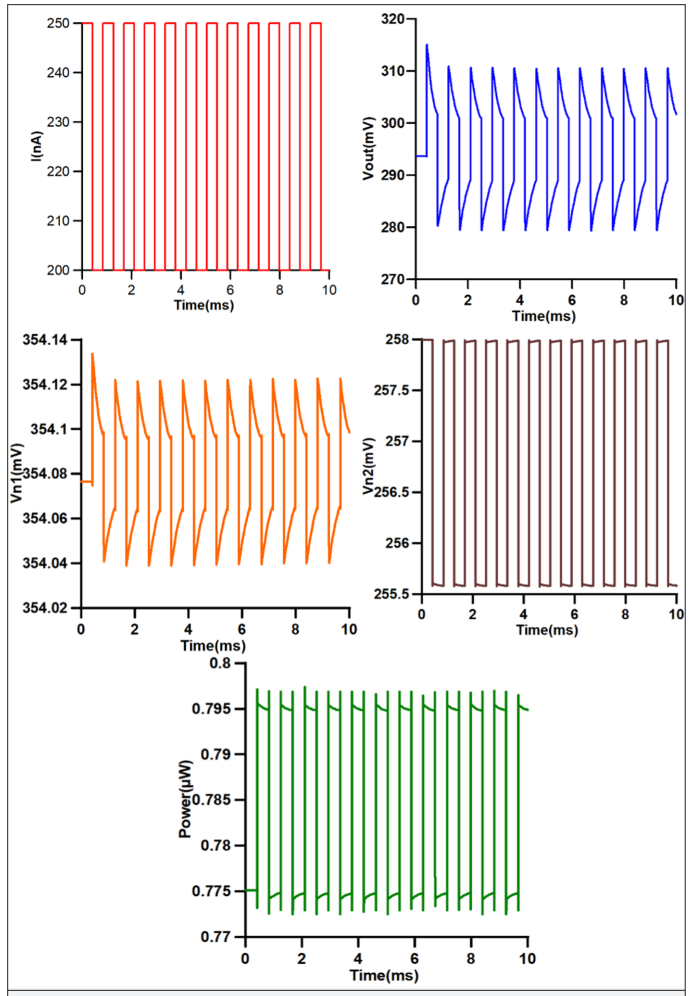



**Fig. 6.** Simulations of the photoreceptor circuit modified using only transistors. a) Applied input current values. b) Output voltage. c and d) Internal node voltages. e) Power consumption.

the Vn1 node, the key point of the feedback loop, remains below 0.1 mV despite large changes in the input signal. This demonstrates the circuit's adaptability.

Fig. 7 illustrates that the modified circuit is adaptable to various illumination conditions. In the simulation, a constant-amplitude light pulse was applied to three different background current levels (Idc = 50 nA, 200 nA, 350 nA).

### A. Adaptation

As seen in Fig. 7, as the background light level (Idc) increases (from 50 nA to 350 nA), the circuit's output voltage is automatically pulled down (from the blue line to the black line). This feature operates in the same manner in biological photoreceptor cells [30]. This behavior demonstrates that the circuit's negative feedback mechanism is functioning effectively. The circuit prevents the output from saturating by shifting the operating point as light intensity increases.

### B. Sensitivity Preservation

Even though the background light increased 7-fold (50 nA to 350 nA), the circuit's response to instantaneous light changes (pulse amplitude) remained distinct and strong. Examining the black curve

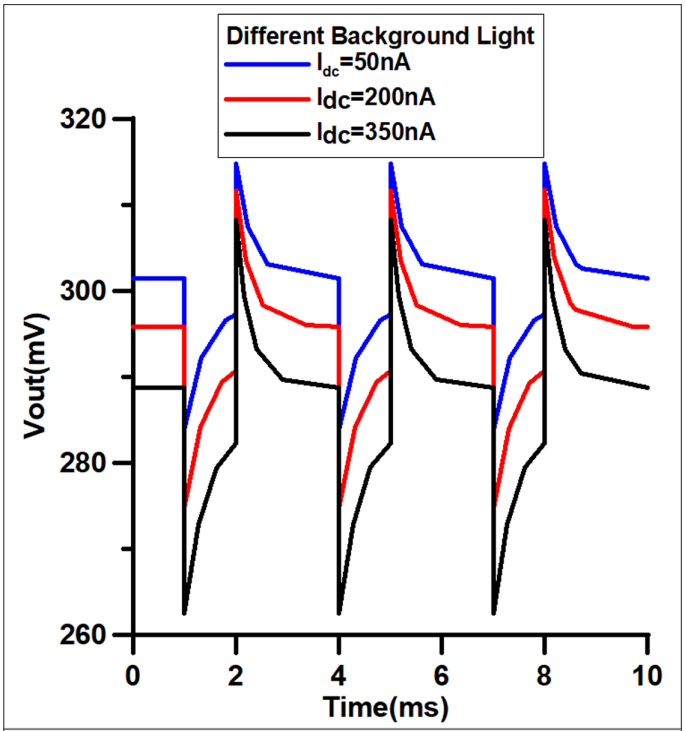



**Fig. 7.** Adaptation of the circuit to different background light levels.

(350 nA) shows that the signal remains undistorted even under high light. This confirms the circuit's Wide Dynamic Range capability and contrast detection ability.

### C. Fast Response and Stability

The rise time and fall time of the waveforms obtained at different light levels are consistent. Furthermore, no oscillation or ringing was observed during sudden changes. This demonstrates that the circuit can successfully track rapid changes in light, as biological photoreceptors do.

## V. RESULTS AND DISCUSSION

Photoreceptor circuits constitute a crucial structure in retinal design, and numerous researchers have proposed various circuit designs [23, 26, 27, 29]. Each of these circuits has different advantages and disadvantages. However, in summary, biological realism, power consumption, and minimum chip area coverage are among the most critical parameters in designing such circuits. In this paper, based on the existing design in [29], the circuit was improved by enhancing its features and eliminating its negative characteristics, resulting in a circuit that provides all the mentioned features. Subsequently, all necessary analyses were performed, yielding successful results. This section compares the reference circuit with the modified photoreceptor circuit, clearly demonstrating the improvement in results. The dynamic power consumption was calculated for both the reference and altered photoreceptor circuits. The power consumption was estimated at approximately 18 µW for the reference MOSFET-based circuit and approximately 0.784 µW for the proposed circuit. The fact that the modified photoreceptor circuit consists solely of MOS transistors is also crucial to its applicability. The capacitors used in the reference circuit are too large to be placed appropriately in the chip design. This directly affects the optimal operation of the designed circuit. Therefore, this disadvantage has been eliminated in the modified circuit. In summary, a detailed comparison between the modified and reference circuits is presented in Table III. As shown in Table III, the proposed circuit outperforms previous studies across all aspects. Reducing the number of power supplies to one, updating the technology parameter from 180 nm to 90 nm, and lowering power consumption to below 1 µW are crucial in circuit design. Furthermore, since the disproportionate transistor sizes are undesirable, the transistor sizes in the modified circuit have also been appropriately selected.

## VI. CONCLUSION

There are various photoreceptor circuits in the literature, each with different advantages and disadvantages. Circuit designers consider minimum power consumption, minimum chip area coverage, and the use of only MOS transistors/capacitors in photoreceptor circuit design. However, circuits in the literature that possess all of these features simultaneously are rare, and the circuit used as a basis is only one of them. To this end, one of the circuits in the literature has been redesigned using 90-nm TMSC CMOS parameters, aligning with the three essential criteria mentioned above, and some of its features have also been enhanced. Power consumption has been significantly reduced. Since the capacitor values in the reference

**TABLE III.** DETAILED COMPARISON OF THE REFERENCE CIRCUIT AND THE MODIFIED CIRCUIT

| Circuit Components | Reference Circuit [29] | Proposed Circuit |
|---|---|---|
| Power consumption per pixel (µW) | 18 | 0.784 |
| Number of transistors | 2 PMOS, 5 NMOS | 5 PMOS, 3 NMOS |
| Passive circuit components used | $C_1$ = 180 pF, $C_2$ = 25 nF | – |
| Number of external voltage sources used | 3 | 1 |
| CMOS dimensions (W/L µm) | $M_1$ = 2/1, $M_2$ = 900/1, $M_3$ = 1/1, $M_4$ = 0.18/1, $M_5$ = 900/1, $M_6$ = 0.18/1, and $M_7$ = 50/1 | $M_1$ = 100/1, $M_2$ = 1/1 $M_3$ = 1/10 $M_4$ = 1/3, $M_5$ = 5/1, $M_6$ = 250/250, $M_7$ = 1/1, $M_8$ = 1/4 |
| Technology parameters | 180 nm PTM | 90 nm TSMC |
| Vdd | 1.5 V | 0.9 V |

CMOS, complementary metal–oxide–semiconductor; L, length; W, width; PTM, Predictive Technology Model; TSMC, Taiwan Semiconductor Manufacturing Company.

circuit are high, they cannot be integrated into the chip design and must be connected externally. This disadvantage has been eliminated with the design presented here. The transistor sizes used in previous designs were disproportionate, leading to various imbalances. This problem has also been eliminated by selecting reasonable values. The circuit that is proposed is approximately equivalent to the potential change in the photoreceptor cell. Thanks to this feature, the biological intracellular potential change has been mimicked. Furthermore, the modified circuit has been analyzed under various background light conditions and has been found to operate stably.

**Data Availability Statement:** The data that support the findings of this study are available on request from the corresponding author.

**Artificial Intelligence Usage Statement:** The authors declared that no Artificial Intelligence Tool was used in the preparation of the manuscript.

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**Author Contributions:** Concept – M.M., Y.B.; Design – M.G., Y.B.; Supervision – M.G.,Y.B.; Resources – M.G.; Materials – M.G., Y.B.; Data Collection and/or Processing – M.G., Y.B.; Analysis and/or Interpretation – M.G., Y.B.; Literature Search – M.G.; Writing – M.G., Y.B.; Critical Review – M.G., Y.B.

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