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A Complementary Metal-Oxide-Semiconductor Vision Chip for Edge and Motion Detection with a Function for Output Offset Cancellation

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We have designed and fabricated a complementary metal-oxide-semiconductor (CMOS) vision chip by modeling cells of the human retina as hardware that are involved in edge and motion detection. There are several fluctuation factors which affect the characteristics of metal-oxide-semiconductor field effect transistors (MOSFETs) through the CMOS fabrication process and this effect appears as the output offset of the vision chip, which is composed of pixel arrays and readout circuits. The vision chip which detects edge and motion information from an input image is used for the input stage of other systems. Therefore, the output offset of the vision chip determines the efficiency of the entire system. In order to eliminate the offset at the output stage, we designed a vision chip utilizing the correlated double sampling (CDS) technique. The chip has been fabricated using a 0.6 μm standard CMOS process. With reliable output characteristics, this chip can be used at the input stage for various applications.

Key words: retina, vision chip, CDS, edge detection, motion detection

1. Introduction

In many image processing systems, the information about the edge of an object is an important clue in determining its characteristics. It can be utilized for an image processing system such as image recognition. Also, the motion information of an object is required for the system that responds to the movement of an object such as target tracking or robotic vision. The system architecture used for the edge and motion extraction of an object up until now was made of a charge coupled device (CCD) for image capturing and a personal computer for image processing. In a conventional image processing system, the image capturing and processing modules are viewed as two separate parts of the system.[1)] Therefore, several steps of signal processing and a high density system for extracting edge and motion information are required from the original image.

With remarkable advances in complementary metal-oxide-semiconductor (CMOS) process technology, a variety of vision sensors with signal processing circuits for complicated functions are actively being developed. In particular, as the principles of signal processing in human retina have been revealed, a series of vision chips imitating the human retina have been reported.[1–3)] Retinal cells perform edge and motion detection in the human retina where parallel signal processing is accomplished.[2)] Therefore, it is possible to reduce the system area and the power consumption by implementing both stages, image capturing and signal processing, on the same chip.

When a vision chip modeled from a human retina is implemented in the CMOS integrated circuits, the most serious factor limiting the performance is the mismatch of metal-oxide-semiconductor field effect transistors (MOSFETs), which happens during the CMOS fabrication process. The matching property of MOSFET is important especially in analog systems such as a signal processing circuit, digital to analog converter and voltage reference circuit. Generally, it is known that the threshold voltage(V_T), current factor(β), and the subthreshold factor(κ) are important model parameters that influence the matching characteristics of MOSFET. Among these factors, the change of the threshold voltage due to the change of the fixed oxide charge is the most important.[4)] The variation of the threshold voltage in a vision chip often results in an output offset, which affects the efficiency of the entire vision system. Recently, a vision chip that has a function of cancelling output noise has been reported.[5)] But it requires additional circuits including an operational amplifier and a sample and hold (S/H) circuit in each pixel, which limit the fill factor and resolution of this chip.

In our research, we designed a vision chip that imitates the edge and motion detection mechanisms in the human retina.[6)] In order to eliminate the output offset due to device mismatches, we used a simple circuit structure which is called the correlated double sampling (CDS) technique[7)] without any additional circuit in the pixel. The designed vision chip was fabricated using a 0.6 μm CMOS process and the characteristics were measured.

2. Model

2.1 The principle of edge detection

Generally, photoreceptors, horizontal cells, and bipolar cells are known to be involved in edge detection.[3)] An incident optical signal goes through all the other cells and is absorbed in a photoreceptor. The photoreceptor transforms the optical signal into an electrical signal. The output of the photoreceptor that was transformed from an optical signal is smoothed spatially in a horizontal cell. We can obtain a contrast-enhanced signal around the edge of an object by calculating the differences between these two signals. In a human retinal bipolar cell, the difference between the output

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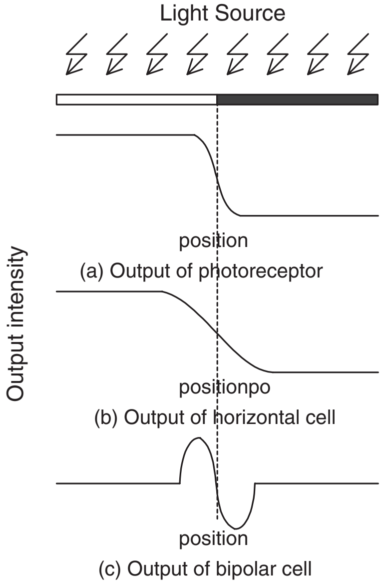


Fig. 1. The principle of edge detection. (a) When the object moves to the right. (b) When the object moves to the left.

of photoreceptor and the output of bipolar cell is calculated. Figure 1 shows the principle of edge detection.

2.2 *The principle of motion detection*

The human being is not conscious of a stationary object. The human being recognizes the object and looks at it carefully or tracks it when the object is in motion. The motion data which is calculated in the retina and the visual nerve is utilized for important information such as selective attention. The mechanisms of motion detection that function in the visual nerve have not been determined in detail. However, motion information can be obtained by calculating the differences between the two time-delayed photoreceptor's outputs. In other words, we can obtain motion information from the variance of the same photoreceptor's output according to time variance.

Figure 2 shows the principle of motion detection. The output of the photoreceptor is transformed into an electrical signal corresponding to the incident optical signal as shown in Fig. 2(a). If the input pattern moves to the right, the output of the photoreceptor will also move to the right. The difference between the two sampled signals shows the motion information of the moved object. When the same pattern moves in the opposite direction, the output characteristic is shown in Fig. 2(b). The output of the bipolar cell should change its polarity to the opposite direction, as shown in Fig. 2(a). We can obtain motion information from the frame subtraction of signals which were sampled at present and one frame earlier.[8)]

3. Design

3.1 *Logarithmic photodetector*

A photodetector corresponds to the function of the input stage which transforms the incident optical signal into an electrical signal as does the photoreceptor in a human retina.

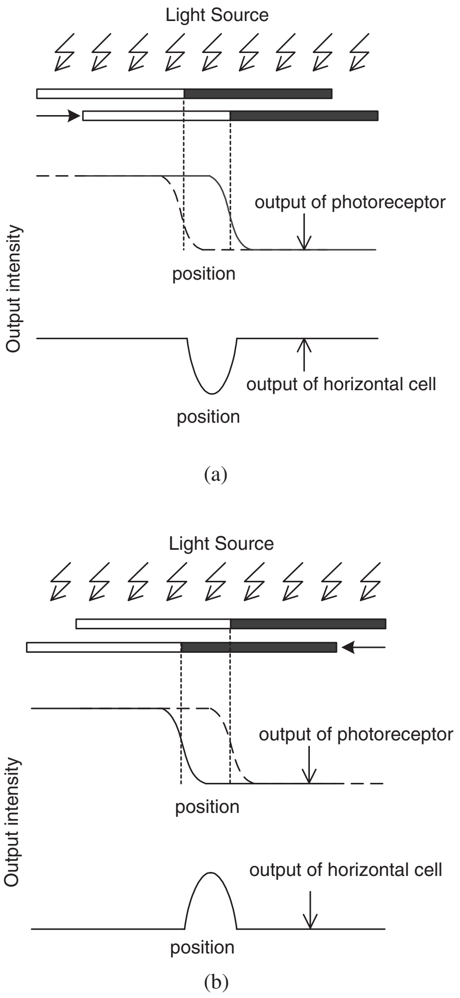


Fig. 2. The principle of motion detection.

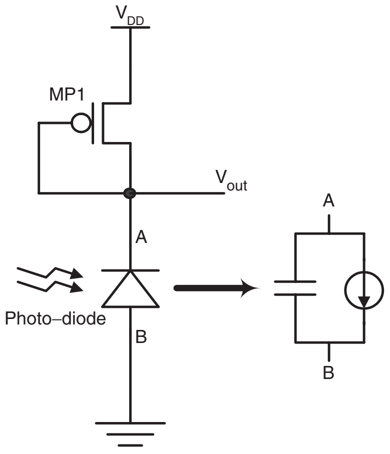


Fig. 3. Logarithmic photodetector.

Figure 3 shows the logarithmic photodetector circuit. It is composed of a diode-connected PMOSFET and a photodiode. The photodiode can be modeled by a parasitic capacitor and a current source for SPICE simulation.

The transistor MP1 is working in the subthreshold region because the photocurrent corresponding to the incident

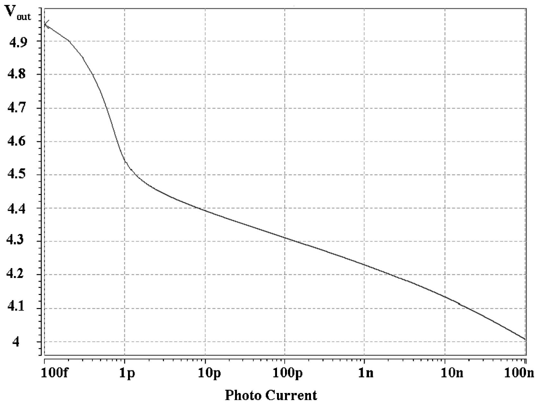


Fig. 4. The response of the logarithmic photodetector.

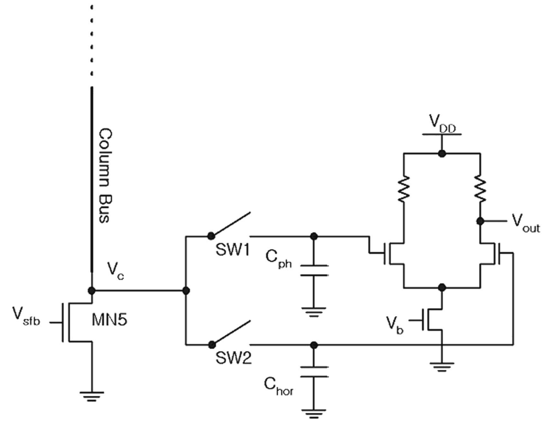


Fig. 6. CDS circuit for output offset cancellation.

optical signal is very small, from several hundred pico-amperes (pA) to several hundred nano-amperes (nA). The photocurrent flowing in the transistor MP1 can be expressed as eq. (1). Therefore, the output of the logarithmic photodetector is compressed into a log-scale and has a wide dynamic range over 100 dB,[9)]

$$I_{\mathrm{ph}} = \frac{W}{L} I_{D0} \mathrm{e}^{\frac{V_{\mathrm{out}}}{Ut}\frac{1}{n}} \tag{1}$$

$$V_{\mathrm{out}} \propto \log I_{\mathrm{ph}}, \tag{2}$$

where I_0 is the reverse bias leakage current when the light input does not exist, n is a subthreshold factor, and Ut is a thermal voltage which can be represented as kT/q.

Figure 4 shows the simulated result of a logarithmic photodetector. When the photocurrent varies from 100 fA to 100 nA for 6 order, the output of the photodetector is almost linear.

3.2 *Unit pixel circuit and CDS circuit*

We designed a CMOS vision chip for edge and motion detection based on a biological mechanism. The equivalent circuit of a unit pixel is shown in Fig. 5. The photodiode transforms input light into an electrical current as does the photoreceptor in a human retina. MP2 and MP3 work as resistors and connect neighboring pixels. They perform the role of the horizontal cell which smoothes the output signal of the photodetector. The source follower which consists of MN1 and MN2 and the level shifter which consists of MP4 and MP5 supply a proper gate bias to MP2 and MP3. Transistor, MN3, which has the variation of threshold voltage according to pixel position constitutes a source follower circuit with MN5 shown in Fig. 6. The variation of the threshold voltage of MOSFETs in the vision chip often results in an output offset and thus limits the performance of the entire vision system. We used the CDS technique to eliminate the output offset at the readout circuit. The CDS circuit is shown in Fig. 6. It is composed of two sampling switches and a differential amplifier.

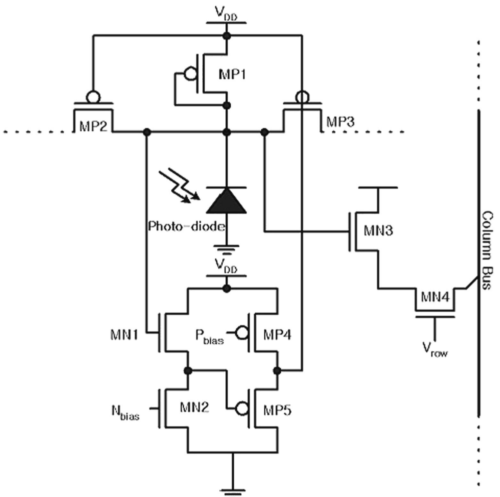


Fig. 5. Equivalent circuit of unit pixel.

In the edge detection mode, the bias voltage, N_{bias}, in Fig. 5 is set to 0 V and the resistance of the MOS resistor is on the order of several hundred mega ohms. Under those conditions, the output voltages of the logarithmic photodetector are sampled in the capacitor, C_{ph}, in Fig. 6 through the SW1 that consists of a simple transmission gate. Then, we provide proper bias voltage at the node of N_{bias} for image smoothing. The smoothed signals by the resistive network are stored in the capacitor, C_{hor}, through the SW2. Finally, the differential amplifier calculates the difference between the sampled signals in the capacitors C_{ph} and C_{hor}. These sampled signals which have the same signal path through the readout circuit in each pixel have equal value of threshold voltage. Therefore, the output noise caused by the variation of threshold voltage will be minimized using S/H and differential amplifier circuit. This shows that the output noise generated by device mismatches can be eliminated using the CDS circuit. When it is applied to the vision chip, we can obtain edge information without offset. We can also obtain motion information of an object by fixing the N_{bias} to 0 V. As a result, the edge and motion information of an object is obtained in a similar fashion as the mechanisms of the human retina.

4. Results

The designed vision chip for edge and motion detection

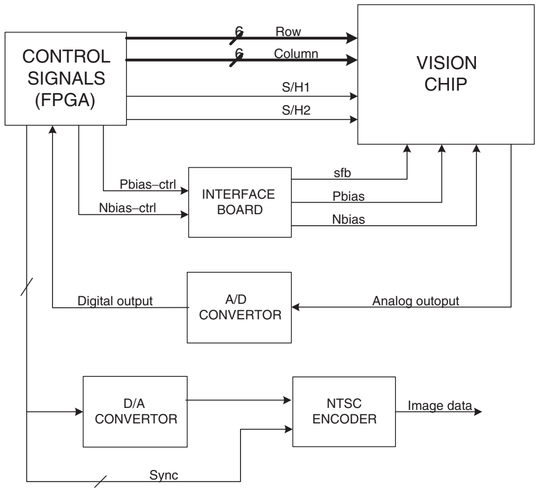
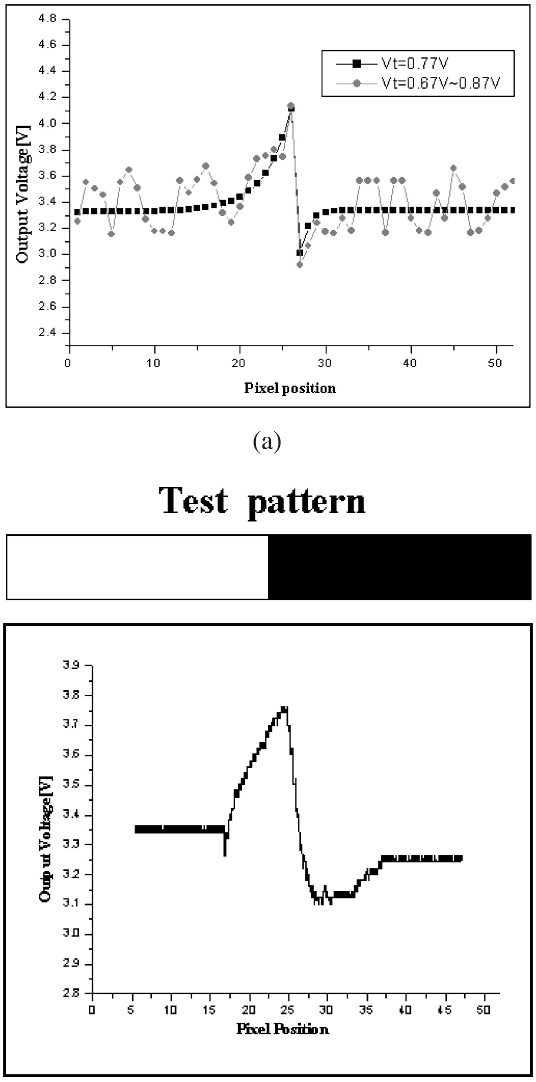


Fig. 7. Block diagram of the circuit for generation of control signal and image signal processing.



(a)

Test pattern

(b)

Fig. 8. Output characteristic of the fabricated vision chip for edge detection. (a) Simulated results. (b) Measured results.

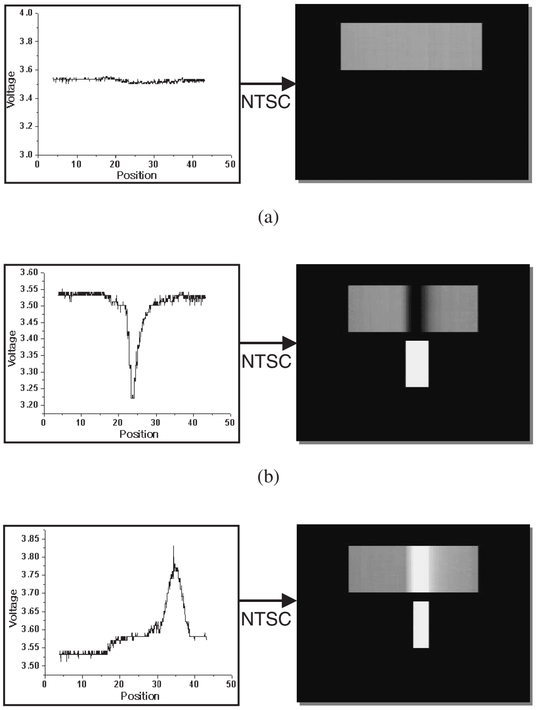
has been fabricated using a 0.6 µm standard CMOS process. The fabricated chip was tested to verify the function of edge and motion detection in indoor illumination. Figure 7 shows the setup of the vision system; it is composed of FPGA, an A/D converter, a D/A converter, an interface board, and a NTSC encoder. The control signals of the vision chip are generated by FPGA. A proper bias voltage is generated in the interface board. The output of the vision chip is reloaded to FPGA through an A/D converter and is saved in memory for other signal processing such as target tracking. The NTSC synchronous signals are also generated in FPGA and are applied to the NTSC encoder with input signals which are converted to an analog signal in the D/A converter.

Figure 8 shows the simulated results and the experimental results of the designed vision chip respectively. Simulation has been performed when the threshold voltage of the MOSFET in the source follower is constant at 0.77 V and when it is varied from 0.67 V to 0.87 V randomly. The simulated results clearly show that the random variation of the threshold voltage causes the output offset due to device mismatches. As shown in Fig. 8(b), the measured result is asymmetric compared to the output characteristics of the edge detection principle because the diffusion length of a resistive network composed of MOS-resistors varies with input light intensity. However, the measured results clearly exhibit the edge detection capability of the fabricated vision chip with a function of output noise cancellation. The output characteristics of other chips fabricated in the same batch were almost identical due to the CDS circuit.

Figure 9 shows the captured results when an object is in motion. When the object moves to the right, the output becomes a lower value compared to the average voltage at the position of the center that appears at the boundary of the test pattern in the motion detection mode as shown in Fig. 9(b). If the same pattern moves to the left, the output peak values change to the opposite side as shown in Fig. 9(c). Figure 9(a) shows the measurement results of the vision chip when there is no motion of the object. Images taken from the output of the vision chip in the motion detection mode are shown on the right side of Fig. 9. The analog signal formatted in the NTSC signal from the output of the vision chip is displayed in the gray level at the upper side and binary data obtained by a simple threshold operation from the output of the vision chip is also shown below.

5. Conclusion

We designed a vision chip which has an edge and motion detection function by imitating the mechanisms of the human retina. In order to implement the vision chip, we modeled human retina cells that are known to be involved in edge and motion detection. We used a logarithmic photodetector composed of a PMOSFET and a photodiode to transform the optical signal into an electrical signal. A MOS resistor was used as a horizontal cell in the human retina which smoothes the output of the photoreceptor spatially. In order to eliminate the output offset due to device mismatches



(a)

(b)

(c)

Fig. 9. Measurement results of the fabricated vision chip for motion detection. (a) When the object is motionless. (b) When the object moves to the right. (c) When the object moves to the left.

such as threshold voltage variation, we applied the CDS technique to the readout circuit of the vision chip. The designed vision chip was fabricated using a 0.6 μm CMOS process. Experimental results showed the edge and motion detection capability of the chip. The output characteristics for other chips fabricated in the same batch were almost identical due to the function of the offset cancellation by the CDS circuit. Therefore, this vision chip could be used in the input stage for actual applications where edge and motion information is needed, such as target tracking and fingerprint recognition. Since this vision chip is robust for device mismatches and has an inherently simple biologically motivated structure for edge and motion detection, a reliable and versatile operation of the whole vision system can be expected.

6. Acknowledgment

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