# An analog VLSI chip calculating high-precision spatial and temporal derivatives of the vertebrate retina

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## 1 Introduction

The retina is a part of the central nervous system in the vertebrate and plays important roles in the early stage of visual information processing. Namely, images projected on a two-dimensional photoreceptor arrays are transduced into electrical signals, and important information required for the brain to express higher order visual functions is extracted by the retinal circuit. The computations carried out in the retina are far more complex than those of simple CMOS imaging devices, as is suggested by the variety of light-induced response types of neurons. However, one can find two distinct types of response. One is a sustained type in which cells respond continuously during illuminations, and the other is a transient type in which cells respond transiently when illumination is turned on or off. The sustained response is thought to be relevant to the perception of static images, and the transient response is thought to be relevant to the perception of moving objects.

Inspired by the unique algorithm and the architecture of the retinal circuit, analog CMOS VLSI circuits, the silicon retinas, have been fabricated[2, 3]. However, these silicon retinas have not yet reached practical engineering applications because of a low accuracy of outputs due to a low sensitivity to light and uncontrollable mismatches of transistor characteristics. Recently, we have fabricated a silicon retina having a one-dimensional Laplacian-Gaussion-like ($\nabla^2$G-like) receptive field[4]. This silicon retina can provide offset-suppressed outputs.

In the present study, a two-dimensional analog silicon retina was fabricated using the similar design of the one-dimensional chip. The chip emulates the two fundamental response types of the retinal circuit. The edge of moving object and the direction of motion were extracted in real time using the outputs of the chip.

## 2 Silicon retina

The silicon retina fabricated in the present study was designed after the model of the vertebrate retina constructed with detailed physiological observations. The chip emulates the two fundamental types of response in the vertebrate retina: the sustained-type response and the transient-type response. The output of the chip emulating the sustained response has a Laplacian-Gaussian-like ($\nabla^2$G-like) receptive field and therefore carries out a smoothing and a contrast-enhancement on input images. The output of the chip emulating the transient response is obtained by subtracting consecutive image frames that are smoothed in advance by a resistive network. Fig.1 A shows the circuit design depicting a single pixel. The chip consists of two layers of resistive networks, which have different tightness of electrical couplings between neighboring pixels. A subtraction of outputs of these two resistive networks generates a $\nabla^2$G-like receptive field. The photo sensor is an Active Pixel Sensor (APS) which consists of a photo-diode and a source follower circuit (Fig.1 B). The APS has a high sensitivity to light, at the same level as general CMOS imagers, by accumulating the photoelectron in the parasitic capacitor of the photo-diode. Furthermore, the dynamic range can be controlled by changing the accumulation time. Neighboring pixels are connected with MOS resistors at the first and the second resistive networks. The resistances of MOS resisters are controllable by external bias voltages. Nbuf and DSB are sample/hold circuits (Fig.1 C). The sample/hold circuits are embedded to compensate for the circuit offsets, which are the amplifier offset and the fixed-pattern noise in each pixel circuit due to the statistic mismatches of transistor characteristics[4]. Two fundamental types of image processing can be performed with the chip by controlling the external signals in different timings[1]. The silicon retina was controlled by

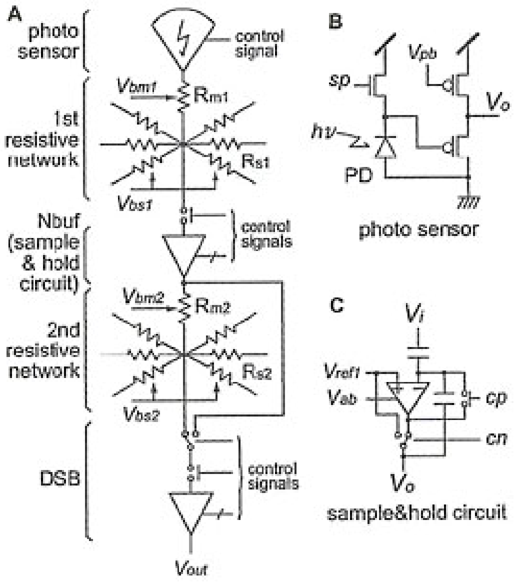


Figure 1: Circuit design of the single pixel.

FPGA (Field Programmable Gate Array). Fig.2 shows a block diagram of the pixel arrangement. The photosensors (shadowed squares in Fig.2) are arranged on a hexagonal grid. The chip has 40 x 46 pixels. The chip was implemented with a 0.6 um, double-poly, three metals, standard analog CMOS technology and the die size was 8.9 x 8.9 $mm^2$.

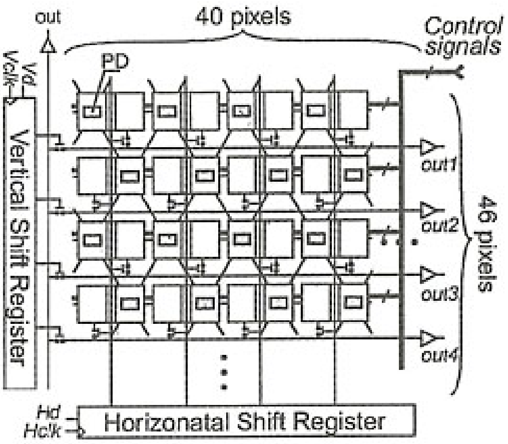


Figure 2: Block diagram of the chip

Fig.3 A shows the output of the silicon retina responding to a hand obtained by the sustained-type response mode. The hand on a black and white background was presented in front of the lens. The experiment was carried out under indoor illumination (0.36 $W/m^2$). The accumulating time of the photo sensors, which is equal to a read out time of one frame, was 33.3 ms. The contour of the hand as well as the border between black and white was enhanced. These outputs have extremely low noise because of the sample/hold circuits. Fig.3 B shows the image of the same scene obtained with the transient-type response mode. The moving hand was extracted, but the black and white background was removed from the scene. The outputs had an extremely low noise because the circuit offsets were compensated by the sample/hold circuits and the high-frequency spatial noise components were suppressed by using the smoothed images.

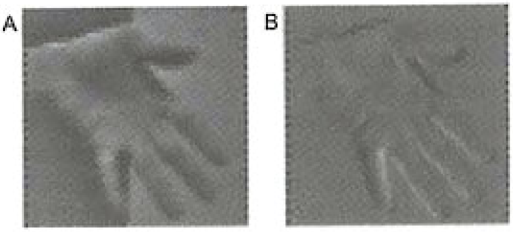


Figure 3: Responses obtained from the silicon retina

## 3 Extraction of direction of motion

Using these two responses from the silicon retina, we executed extraction of motion direction in real time. Fig.4 shows the overview of silicon retina system using FPGA. The silicon retina's analog responses were fed into the FPGA through an high speed A/D converter. Fig.5 shows the extracting images of motion direction on horizontal axis. The experiment was carried out under the same condition as in Fig.3. Fig.5 A shows the response when the hand was moved from right to left, and B shows the response when the hand was moved from left to right. The white pixel means left move and the black means right. As shown in the Fig.5, the direction of the hand is extracted in time with the hand moving independent of the black and white background.

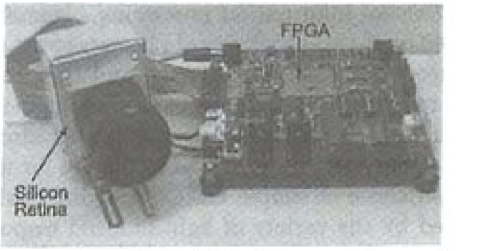


Figure 4: Overview of the silicon retina system.

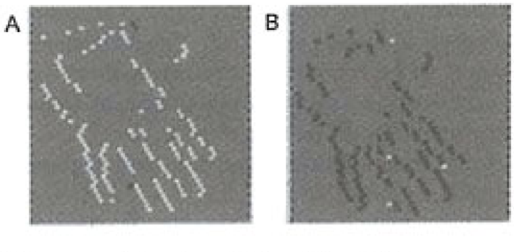


Figure 5: Outputs obtained from the system.

## 4 Conclusions

In the present study, a silicon retina that can provide two types of output mimicking the sustained response and the transient response of the vertebrate retina was fabricated. The chip was applied to the real time extraction of the motion direction under an indoor illumination. The silicon retina developed in the present is useful for various engineering applications, e.g. a robot vision, an automatic car navigation and etc.

## References


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