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A self-reset CMOS image sensor for high signal-to-noise in-vivo imaging

Pakpuwadon Thanet[1], Mark Christian Guinto[1], Makito Haruta[1], Hironari Takehara[1], Hiroyuki Tashiro[1,2], Kiyotaka Sasagawa[1], and Jun Ohta[1]

[1] Graduate School of Science and Technology, Nara Institute of Science and Technology
8916-5 Takayama, Ikoma, Nara 630-0192, Japan
Phone : +81-743-72-6050 E-mail : sasagawa@ms.naist.jp

[2] Faculty of Medical Sciences, Kyushu University
3-1-1 Maidashi, Higashi-Ku, Fukuoka 812-8582, Japan

Abstract

In this research, we propose a CMOS image sensor for investigating small intensity signals such as a hemodynamic reaction or neural activities in the mouse brain. To achieve a high signal-to-noise ratio (SNR), this image sensor is integrated with the self-reset circuit in each pixel. This function prevents saturation and allows imaging at high light intensity conditions. The prototype was fabricated by a 0.35-μm CMOS process. By optimizing the design, it was achieved to the effective SNR over 70 dB.

1. Introduction

In order to study the brain function, monitoring the neural activity in natural habiting is a key to understand more deeply into its mechanics. Optical imaging methods for neural activities such as hemodynamics imaging or voltage-sensitive dye imaging require high SNR (at least 60 dB). Hemodynamic imaging does not use any dyes as a label [1]. In the case of an implantable device, the size and heat condition also need to be concerned in terms of the implantable device [2].

Commonly, the SNR is determined by the photon shot noise that is proportional to the square root of the incident photons. Thus, the maximum SNR of an image sensor is limited by the full well capacity of the pixel. It is difficult to achieve over 60 dB with the usual pixel size.

One of the solutions is an image sensor with an in-pixel self-reset circuit [3, 4]. Fig. 1 shows an experiment diagram performs with the self-resetting CMOS image sensor. The self-reset function increases the effective full well capacity by recycling the well. As a result, the imager has enough capacity for the flooded electron generated from high-intensity illumination. Thus, the imager will be able to collect the image with a wide dynamic range and high SNR. This self-reset function is realized by applying of the low-voltage driven Schmitt trigger [4], which is designed for reducing the power consumption. The well-managed thermal condition made it suitable for an implantable device.

In previous work, we successfully observed the intrinsic signal by using an implantable sensor. However, still frame averaging was required because of insufficient SNR.

In this study, we developed the self-reset CMOS imager with effective SNR over 70 dB. The full well capacity was increased by modifying the photodiode structure. Also, the reset noise level has been improved.

2. Chip design

Pixel circuit

In this pixel, the photodiode type is P+/N-well/P-sub. This structure increases the capacitance of the photodiode in comparison with N-well/P-sub structure, which is usually used in 3-transistor APS pixels. The estimated full well capacity was 1.24 Me-. The high capacitance reduces the sensitivity of the pixel but gives a better noise performance. In this study, our target is to observe high-intensity light. The pixel resets itself when the in-pixel circuit detects the voltage drop caused by the illumination is exceeding the threshold value. Thus, the pixel can maintain its sensitivity in a wide range or even in the high light intensity. The pixel size is 15 × 15 μm^2.

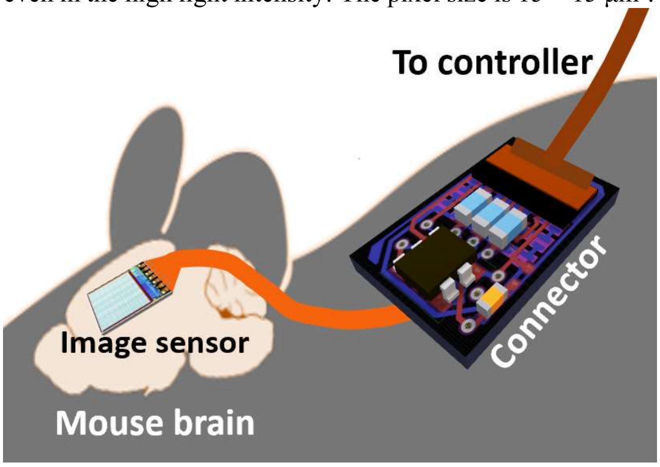

Fig. 1 Diagram of an implantable self-reset image sensor for detecting an intrinsic signal from hemodynamics reaction

Self-resetting circuit

Fig. 2 shows the schematic of the self-reset pixel in this proposed CMOS image sensor. In this design, pMOS-transistors have been used at M_{SEL}, M_{RST}, M_{SF}, M_{ST}, and also in the Schmitt trigger. The low power consumption Schmitt trigger is achieved by optimizing VDD2. The pMOS-transistor M_{ST} is added to stabilize the self-reset operation. M_{SF} is a part of the first stage source follower to read the pixel output. This is also a pMOS-transistor, although an nMOS-transistor is usually used in a CMOS image sensor pixel. This is because the threshold voltage of self-resetting is reduced as a result of the reduction of supply voltage for the Schmitt trigger inverter.

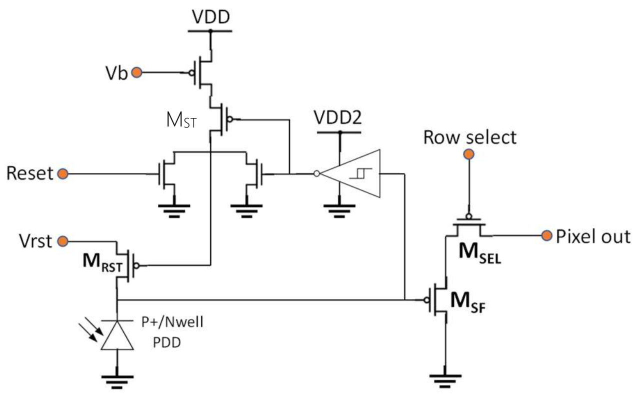

Fig. 2 Schematic of the self-reset pixel in this proposed CMOS image sensor (3 transistors active pixel sensor with Schmitt trigger).

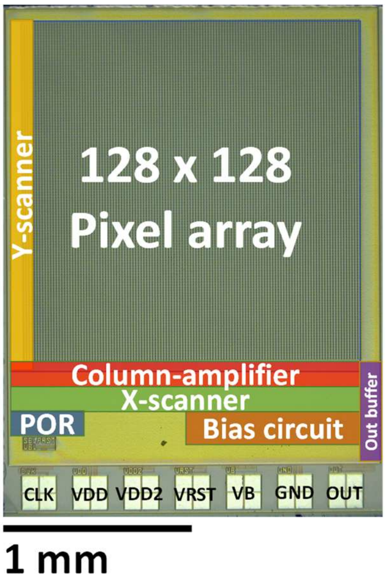

Fig. 3 Photograph of the self-reset image sensor

Table I Specifications of the chip

Technology	TSMC 0.35 µm 2-poly 4-metal std, CMOS process
Chip size	2.7 × 2.1 mm^2
Pixel size	15 × 15 $µm^2$
Photodiodes	P+/N-well/P-sub
Full-well capacity	1.24 Me^-
Fill factor	30 %
Pixel number	128 × 128
Operating voltage	3.3 V
Pixel type	3-Tr active pixel sensor with 4-Tr Schmitt trigger inverter for self-resetting

3. Image sensor

Chip design

The image sensor has been fabricated with the proposed pixel. The layout of the CMOS image sensor is shown in Fig 3, which are both diagrams and chip appearance just after the fabrication. We used the TSMC 0.35-µm 2-poly 4-metal standard CMOS process. The specification is shown in Table I. The fabricated chip achieved an effective SNR over 70 dB with a self-reset count of 20.

Fig. 4 Example image of hand taken by the self-resetting image sensor.

Imaging demonstration

Fig. 4 shows the image by the proposed imager only in 1 frame. As an example, an image of a hand was obtained. When the light intensity reaches the threshold, the imager reset itself and still can sense the light. Thus, it appears as the boundary of the fringe pattern in the image since the in-pixel self-resetting function in the highlight areas was reset several times. As shown in Fig. 2, the pixel circuit does not have any counter of self-resetting. This is no problem in our purpose that is to observe small intensity change by the intrinsic signal. Also, the normal image can be reconstructed by comparing with a reference image[4] or estimating algorithm[5].

4. Conclusion

We succeeded in designing and fabricating the image sensor with a self-resetting system using Schmitt trigger inverter, which has SNR reaches over 70 dB. The sensor chip was fabricated by a 0.35-µm standard CMOS process. These features are eligible for in-vivo imaging of intrinsic signals in the brain.

Acknowledgments

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