Linkable Self-Coded CMOS Image Sensor with Serial Communication Interface for Compact Omnidirectional Lensless Cameras

Yuya Miyagi[1], Fuki Hosokawa[1], Tomoki Nakamura[1], Kiyotaka Sasagawa[2], Jun Ohta[2], and Tomoya Nakamura[3],
Keiichiro Kagawa[1]
[1]Shizuoka University, 3-5-1 Johoku, Nakaku, Hamamatsu, Shizuoka 432-8011, JAPAN
[2]Nara Institute of Science and Technology, 8916-5 Takayama-cho, Ikoma, Nara 630-0192, JAPAN
[3]Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, JAPAN
Email: kagawa@idl.rie.shizuoka.ac.jp

Abstract-This paper presents a self-coding omnidirectional lensless camera system using a dedicated CMOS image sensor with through-holes that act as a coding mask. Unlike conventional lensless cameras, the proposed system integrates the coding mask into the sensor itself, realizing a compact omnidirectional camera. We present the design and post-processing of the CMOS image sensor, including the formation of through-holes by deep reactive ion etching (DRIE). The measured full field of view (FoV) was about 20 degrees for the chip thickness of $50\mu m$. Experimental results demonstrated successful image reconstruction using a Wiener filter.

I. INTRODUCTION

Lensless cameras exploit advantages such as compactness, thinness, lightweight, and so on [1]. Instead of bulky lenses, a thin coding mask is used in most lensless cameras, which forms a spatially multiplexed image of the subject on the image sensor. Then, the original image is reproduced. However, conventional lensless cameras cannot solve a problem that they cannot see behind them. To overcome this problem, we have proposed a compact omnidirectional camera that uses a specially designed CMOS image sensor that works as a coding mask as well. In this study, we have designed and fabricated a dedicated CMOS image sensor with the linking function. We created through-holes in the silicon substrate and demonstrated an image reconstruction. This scheme has a great potential for applications in endoscopic imaging, wearable devices, and other areas where space and weight are limited.

II. PRINCIPLE OF SELF-CODED OMNIDIRECTIONAL LENSLESS CAMERAS

Lensless cameras are imaging systems that captures visual information without using a lens [2]. Instead of focusing light onto an image sensor using a lens, they use a coding mask consisting of many pinholes. Based on a computational method, an image of subjects is reconstructed from a captured optically multiplexed image. Thus, to build a lensless camera, we need an image sensor and a coding mask. In this paper, we use a new scheme where the coding mask is embedded in the pixel array of the image sensor, which has randomly placed through-holes working as pinholes. This new image sensor is referred to as a self-coded image sensor.

Fig.1 shows the principle of simultaneous imaging of both the front and rear objects by using a pair of self-coded image sensors [3]. When we capture the front scene, one works as an image sensor, while the other works as a coding mask. Because they have the same design, they can switch their roles to capture the scene behind them. By extending this observation scheme, we will be able to realize omnidirectional cameras. Fig. 2 shows conceptual drawings of a 360-degree or all-around camera composed of three pairs of self-coded image sensors.

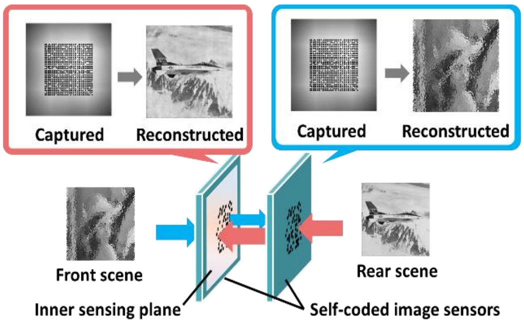


Fig. 1. Conceptual diagram of self-coded lensless camera.

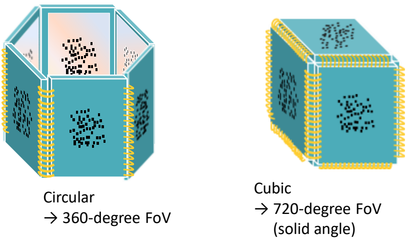


Fig. 2. Example of omnidirectional camera.

III. STRUCTURE OF PROPOSED CMOS IMAGE SENSOR AND PROCESSING FOR SELF-CODING

A. STRUCTURE

To connect multiple image sensors together for building an omnidirectional camera, the image sensor is equipped with the serial communication interface (SPI) and the ID fuse programmed using laser processing as shown in Fig. 3. This interface passes through the control signals of SPI and the image output signal. Only the chip whose ID matches the unique ID specified by the ID fuse is activated.

Table 1 shows the specification of the prototype image sensor. Fig. 4 shows the configuration of the pixel array composed of 65×61 pixels. The coded mask region is placed in the center of the pixel array. The black pixels stand for through-holes, where the pixels have no photodiode or circuitry.

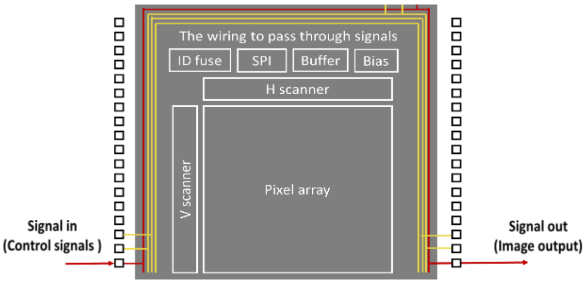


Fig. 3. Chip configuration.

Table 1. Specifications of proposed image sensor

Technology	$0.18\mu\mathrm{m}$ CIS
Pixel type	3T-APS
Chip size	$4.8 \times 4.8[\mathrm{mm}^2]$
Pixel pitch	$56 \times 56[\mu\mathrm{m}^2]$
Pixel count	$65(\mathrm{H}) \times 61(\mathrm{V})$
Aperture size	$40 \times 40[\mu\mathrm{m}^2]$
Fill factor	50%

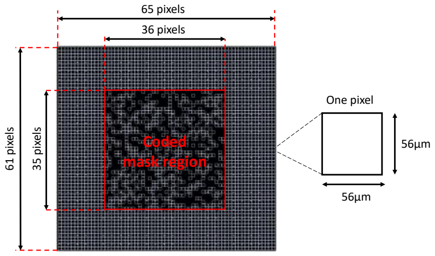


Fig. 4. Pixel arrangement

Black pixels are holes.

B. POST-PROCESSING

The through-hole formation process that enables self-coding was composed of three steps. First, the image sensor was thinned from 600µm to 50µm by back-grinding and hand polishing. Because there is a trade-off between the thickness of the chip working as coding mask and FoV, this process is necessary to increase the FoV of the lensless camera. Second, the photoresist pattern was formed on the backside of the image sensor by photolithography. Third, through-holes were made by DRIE, where passivation (forming a protective film) and etching are alternated.

Thus, side etching is suppressed, and therefore holes with high aspect ratios are formed. One cycle consisted of 12 seconds of etching and 8 seconds of passivation formation. 70 cycles were required to penetrate a 50µm-thick chip. Fig. 5 shows the microphotography of the chip after the processing.

To avoid the dark current generated around the through-holes, the photodiodes were formed in the deep N-well (Fig. 6).

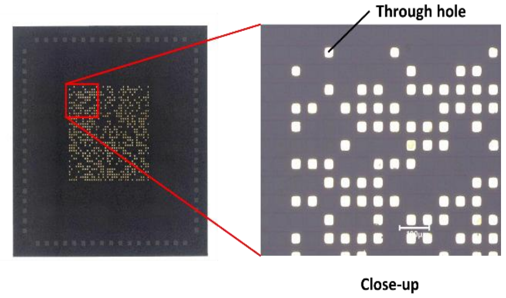


Fig. 5. Microphotography after through-hole formation process.

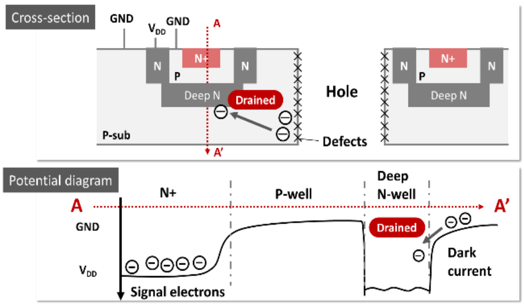


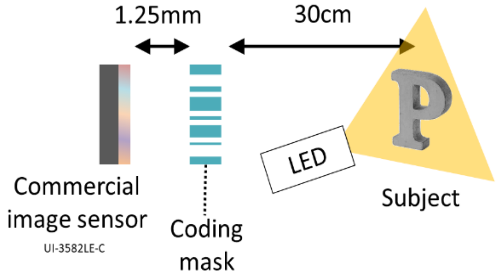
Fig. 6. Pixel structure with deep N-well to suppress the dark current by due to drilling.

IV. EXPERIMENTAL RESULTS

As a preliminary experiment, we performed image reconstruction using the processed chip and measured its FoV as a coding mask. We also measured the sensor output signal before the formation of through-holes.

A. IMAGE RECONSTRUCTION

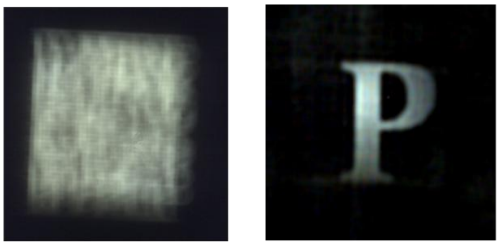
For imaging, we used the processed chip with through-holes working as pinholes and a commercial image sensor (iDS, UI-3582LE-C). Fig.7 shows the setup for imaging. We captured a multiplexed image and the point spread function (PSF). To reconstruct the object image, we used the Wiener filter. An object "P" was successfully reproduced as shown in Fig. 8.



Pixel count	1920(H) x 1920(V)
Pixel pitch	2.2 µm x 2.2 µm
Sensitive area	4.224 mm x 4.224 mm

Light source	White LED

Fig. 7. Schematic diagram of imaging of an object "P".



Captured coded image

Reproduced image with the Wiener filter

Reproduction	Wiener filter
Averaging	10 frames
Dark offset	subtracted

Fig. 8. Coding image and result of reconstruction.

B. FIELD OF VIEW

The imaging system using this experiment is the same as the previous one. To calculate the FoV, we captured and reconstructed a scale with 1cm-spaced lines. Fig.9 shows reconstructed images and the plots of the intensity profile. In terms of the full width at half maximum (FWHM), the FoV was 14.3 degrees when the chip thickness was 140µm, and 19.8 degrees when it was 50µm.

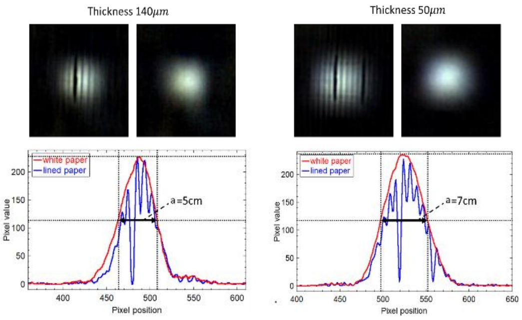


Fig. 9. Result of reconstructed images for measuring FoV and plots of intensity profile.

C. SENSOR OUTPUT

Fig. 10 shows an example of the sensor's output signal before the through-hole formation under three different illumination conditions. We have confirmed that the sensor was sensitive to light and was working properly. The sensor output signal went down at the pixels for the through-holes because there was no circuitry.

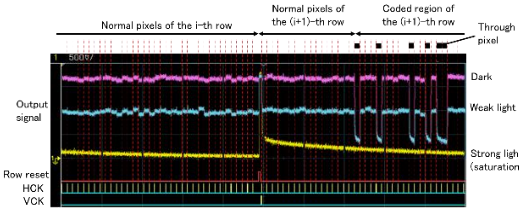


Fig. 10. Sensor output.

V. CONCLUSIONS

In this paper, we proposed a linkable self-coded CMOS image sensor with a serial communication interface for compact omnidirectional lensless cameras. Processing was performed on the fabricated sensors, including through-hole formation using deep reactive ion etching to function as a coding mask. Imaging experiments using the processed chip demonstrated successful image reconstruction with the Wiener filter, confirming the ability to identify objects. Furthermore, by capturing images of a ruler and measuring the FoV using FWHM, we verified the trade-off relationship between mask thickness and FoV.

VI. ACKNOWLEDGMENTS

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VII. REFERENCE

[1] V. Boominathan, “Recent advances in lensless imaging,” Optica, Vol 9, pp. 1-16 (2022).

[2] M. Salman Asif, “FlatCam: Thin, Bare-Sensor Cameras using Coded Aperture and Computation” IEEE Trans. Comput. Imaging, Vol 3, pp. 384–397 (2017)

[3] T. Nakamura, K. Kagawa, S. Torashima, M. Yamaguchi, “Super field-of-view lensless camera by coded image sensors,” Sensors, Vol. 19, Article 1329 (2019).