Polarisation analysing complementary metal-oxide semiconductor image sensor in 65-nm standard CMOS technology


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Abstract: In the present study, the authors demonstrate a complementary metal-oxide semiconductor (CMOS) image sensor implemented with on-chip polarisers using 65-nm standard CMOS technology. The polariser is composed of metal wire grids made of metal wires fabricated by the CMOS process. An extinction ratio of 18.8 dB was obtained for a single pixel with an on-chip polariser, where the line/space widths have the finest pitch obtainable by 65-nm technology. Electrical crosstalk between pixels is reduced by over 25% using a guard ring structure. Polarisation imaging by the sensor was also performed.

1 Introduction
Integration of optical functional elements on a complementary metal-oxide semiconductor (CMOS) image sensor enables miniaturisation of optical measurement systems [1–6]. As an example, Tokuda et al. proposed an image sensor with an on-chip metal grid polariser composed of a metal wiring layer obtained using 0.35-μm standard CMOS technology [1]. Each polariser has a different angle and the sensor can measure the polarisation angle of incident light in real time without mechanical rotation. In our previous study, we placed a polarisation analysing image sensor in the path of a chemical microreactor system [7]. The system allows the reaction process of optically-active molecules to be monitored in real time. In order to improve the sensitivity of this system, a higher extinction ratio is required. The extinction ratio of the polarisation analysing CMOS image sensor in 0.35-μm standard CMOS technology is 3.3 dB [1]. The extinction ratio can be improved by narrowing the grid pitch. In the previous studies, we achieved an extinction ratio of 16.1 dB with fine pitch metal wire grids obtained using 65-nm standard CMOS technology [8, 9]. Based on this result, in the present study, we design and fabricate an image sensor with high-extinction-ratio polarisers using 65-nm standard CMOS technology.

2 Polarisation analysing CMOS image sensor
Figs. 1a and b show a micrograph and the pixel structure of the image sensor, and Table 1 shows its specifications. The pixel number on the image sensor is 32 × 32, and the pixel size is 20 × 20 μm. The photodiode is composed of n-well/p-sub-diode. The fill factor is 43.6%. The pixel readout architecture is that of a 3-Tr active pixel sensor [10]. The operating voltage is 3.3 V. The on-chip polarisers are designed with the bottom metal wiring layer above the photodiode. The line/space widths of the on-chip polarisers are the narrowest used in 65-nm technology, and are much lower than the visible wavelengths. The polariser angles are 0° and 90°, which are placed alternately in each column. Each photodiode is surrounded with a guard ring of n-well/deep n-well layers in order to decrease crosstalk by absorbing stray carriers between or under the pixels [11].

3 Characterisation of the polarisation analysing CMOS image sensor pixels
To measure the extinction ratio of an on-chip polariser, linearly polarised light was focused on a pixel, and the output was obtained as a function of polarisation angle. A single longitudinal mode 635-nm AlGaInP laser diode (LPS-635-FC, Throlabs Inc.) was used as a light source, and linearly polarised light was irradiated to the single pixel. The polarisation was controlled with half- and quarter-wave plates. The beam was focused on a pixel by an objective lens (40×). The guard ring voltage was set to 3.3 V. The outputs of the illuminated pixel and one of the neighbour pixels were measured. Fig. 2a shows the measurement results as functions of polarisation angle. The measured extinction ratio was 18.8 dB, which is similar to the result for single pixel reported by Shishido et al. [9]. Here, the extinction ratio is represented by the transmittance ratio of polarisations parallel and perpendicular to the metal wire grid. Using TM polarised light, which has high transmitted polarisation, the neighbour pixel output of −15.0 dB to the illuminated pixel was observed, despite a lack of illumination. Since the output of

![Image](https://example.com/image.png)
−15.0 dB is larger than that obtained under the illumination of TE polarised light, the effective extinction ratio of the present image sensor is limited by crosstalk. Fig. 2 shows the pixel outputs of the illuminated pixel and the five neighbour pixels. An output of −15.5 dB was obtained at the pixel next to the illuminated pixel. The output of the third pixel from the illuminated pixel was −22.8 dB. Since the extinction ratio of a single pixel is −18.8 dB, the pixels should be separated by approximately 40 μm in order to avoid crosstalk limitation.

To reduce electrical crosstalk, the pixel photodiodes are surrounded by guard rings. We measured the crosstalk reduction characteristics provided by the guard ring. The beam spot of TM polarised light is focused on a pixel, and the output from the neighbour pixels was measured. The guard ring voltage was set to 0, 1.1, 2.2 or 3.3 V. Fig. 3 shows the pixel outputs. A 7% decrease in output voltage at the illuminated pixel was observed, as the guard ring voltage was increased from 0 to 3.3 V, which indicates that a portion of the photo-carriers generated below a photodiode are collected by the guard ring rather than the photodiode. The output reductions of the non-illuminated neighbour pixels are >25%, which is higher than the illuminated pixel. This result shows that the guard ring is effective in order to reduce the crosstalk due to carrier diffusion. The results in Fig. 2 indicate that the crosstalk to the neighbour pixel for TM polarised light is higher than the extinction ratio of the polariser. Thus, the effective extinction ratio is limited by the crosstalk from the neighbour pixels and can be further improved by reducing this crosstalk. Figs. 2b and 3 indicate that the optimisation of the pixel pitch and the guard ring structure would be solutions for this problem. Optical crosstalk can also be the limitation of the extinction ratio [6]. However, further investigations on this subject are required.

4 Polarisation imaging

Imaging tests were conducted using the fabricated image sensor. A halogen lamp was used as a light source, and the guard ring voltage was set to 3.3 V. A dog figure was imaged using the developed sensor. Figs. 4a and 4b show the imaging results obtained with non-polarised and linear polarised light illuminations, respectively. Using the non-polarised light, a clear light intensity image was obtained, as shown in Fig. 4a. Using the linearly polarised light, the light reflected by the object is also polarised. Since the 0° and 90° polarisers are placed alternately in each column, a vertical stripe pattern appears in the polarisation image, as shown in Fig. 4b. This indicates the feasibility of polarisation imaging.

5 Conclusion

A polarisation analysing CMOS image sensor was designed and fabricated using 65-nm standard CMOS technology. The extinction ratio of 18.8 dB was obtained for single-pixel irradiation, which was similar to the result for a single pixel obtained in our previous study [9]. The crosstalk from the neighbour pixel, which determines
the effective extinction ratio of the image sensor, was $-15.0$ dB. A crosstalk reduction of 25% was achieved through the use of a guard ring structure. Polarisation imaging was performed using the fabricated image sensor.

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7 References