Performance improvements of polarization analyzing CMOS image sensor using multiple pixel array architecture and 65nm standard CMOS process

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Introduction

We have been developing polarization-analyzing CMOS image sensor with monolithically embedded polarizer [1, 2]. Differing from preceding works [3-5], we implement on-chip polarizers configured with a metal wiring layer available in standard CMOS technology. In the last workshop, we have demonstrated the polarization-analyzing functionality with a CMOS image sensor fabricated with 0.35 μm standard CMOS process. Figure 1 schematically shows the concept of polarization-analyzing pixel. We implemented an on-chip polarizer configured with metal wire structures. Owing to the on-chip polarizer, the pixel shows polarization-dependent sensitivity [1, 2]. The typical extinction ratio of the on-chip polarizer was 6.7 for line / space = 0.5 μm / 0.45 μm [1], and 2.03 for line / space = 0.6 μm / 0.6 μm [2].

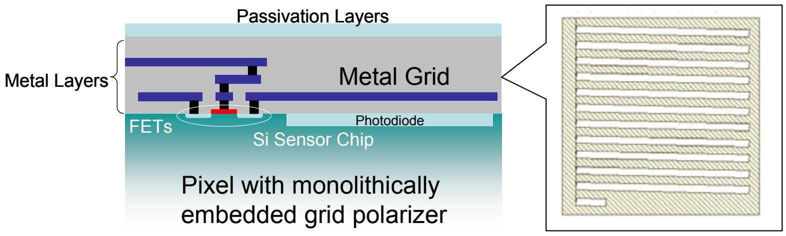

Figure 1. Structure of the polarization-analyzing pixel.

We designed variations of polarization-analyzing pixels with the polarization angles between 0 and 179 with 1 deg. step. An array of polarization-analyzing pixels was implemented on the polarization-analyzing image sensor [2]. Despite of the limited performance of the on-chip polarizer structure (extinction ratio smaller than 10) and the angular step of 1 deg., we succeeded to measure polarization angle of incident light with an accuracy of 0.04 deg [2]. In this work, we report two kinds of performance improvements of the polarization-analyzing CMOS image sensor.

Accuracy improvement with multiple pixel sets

As we reported [2], the sensor shows angular mismatch between designed and measured angular profile of the on-chip polarizers. The distribution of the angular mismatch was as large as σ = 1.03 deg. This distribution is considered to be one of the major factors that limit performance of the polarization-analyzing image sensor. To reduce the measurement error, we designed a new polarization-analyzing CMOS image sensor with multiple polarization-analyzing pixel sets. Figure 2 shows configuration of the polarization-analyzing CMOS image sensor with multiple pixel sets. Table I shows specifications of the sensor. We used 0.35 μm standard CMOS process, and the line / space of the embedded polarizer was 0.6 μm/0.6 μm. The sensor was equipped with an array of 64 x 64 polarization-analyzing pixels. As shown in Fig. 2, we implemented 9 sets of embedded polarizer with angles of 0-179 deg.

When the sensor was used for uniformly polarized light, we can use these pixel sets in parallel and obtain better performance in polarization measurement. Based on the placements of the embedded polarizer, any 20 x 18 set of the polarization-analyzing pixel includes a set of 0-179 deg. pixels. It provides another feature of the sensor, thus, a flexibility to choose the area to be measured. Figure 3 schematically shows the functionality of the polarization-analyzing CMOS image sensor. We can simultaneously obtain 9 polarization profiles using the partial pixel sets (left part), and one polarization profile measured with arbitrarily selected partial array (right part).

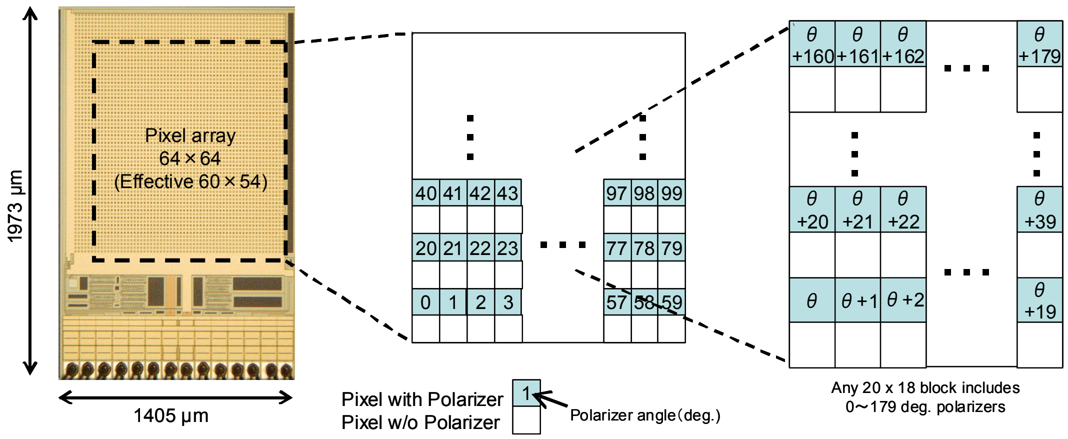

Figure 1: Configuration of the polarization-analyzing CMOS image sensor with multiple pixel sets

TABLE I: Specifications of polarization-analyzing CMOS image sensor

Technology	0.35 µm 2 poly 4 metal standard CMOS
Pixel number	64×64 (Effective 60×54)
Pixel configuration	3Tr - APS
Embedded polarizer	Line / Space = 0.6 µm / 0.6 µm
Pixel size	20 µm × 20 µm
Photodiode size	10 µm × 10 µm
Operation voltage	3.3 V
Chip size	1405 µm × 1973 µm

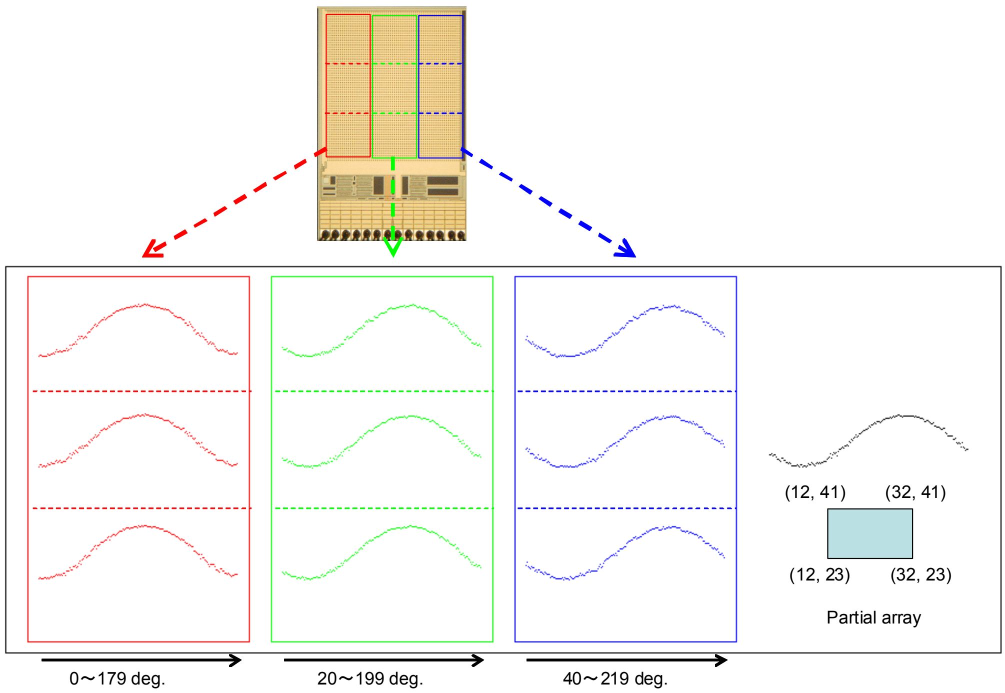

Figure 3: Functionality of the polarization-analyzing CMOS image sensor

Figure 4 shows temporal fluctuation of measured polarization angle observed in sequential measurements with static incident light with fixed polarization angle. We used full-angle scheme for the estimation of polarization angle [2]. The frame rate was 37.6 ±2 fps. Since the incident polarization was fixed, the traces in Fig. 4 show the temporal noise level in the polarization measurement. When we use single pixel set, $\sigma = 0.0067$ deg. ($3\sigma \sim 0.02$ deg.) with 10 inter-frame averaging, and $\sigma = 0.0036$ deg. ($3\sigma \sim 0.01$ deg.) with 100 inter-frame averaging. On the other hand, we obtained $\sigma = 0.0061$ deg. without inter-frame averaging, and $\sigma = 0.0031$ deg., and $\sigma = 0.0022$

deg. with 10 and 100 inter-frame averaging, respectively. The accuracy was clearly improved and the effect of the averaging the results from 9 partial pixel is comparable that by 10 sequential inter-frame averaging. The result suggests that we can combine temporal averaging and special averaging schemes with the present polarization-analyzing CMOS image sensor.

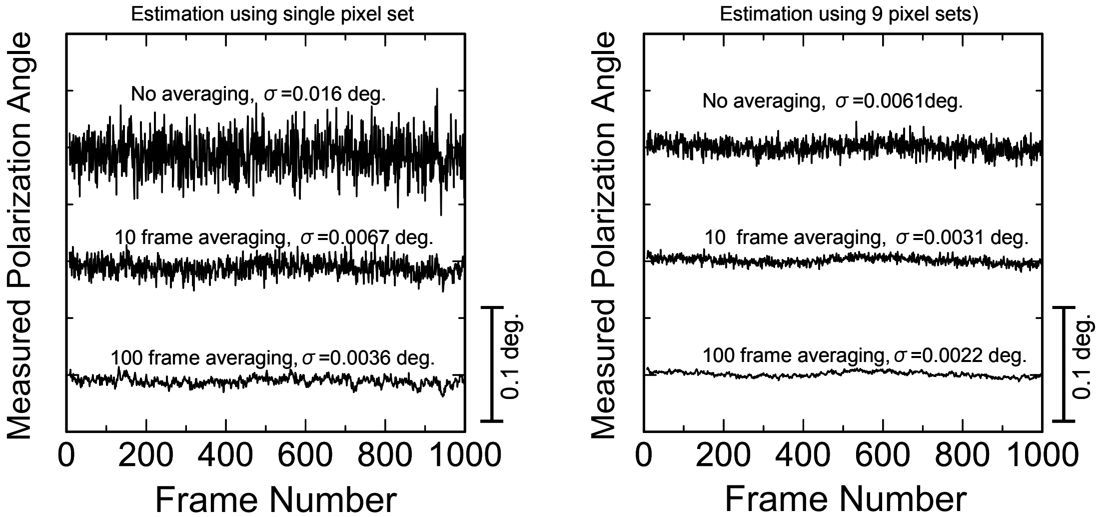

Figure 4: Temporary fluctuation of the measured polarization angle
(uniform, continuous illumination with fixed polarization)

Performance improvement of embedded polarizer using fine technology

The minimum grid pitch of the embedded polarizers fabricated with 0.35 μm standard CMOS process is approximately 1 μm, which is larger than the wavelength of visible light. It is the major reason of the small extinction ratio of the polarization-analyzing pixels [1, 2].

To improvement extinction ratio of the embedded polarizer, we adopted 65 nm standard CMOS process. Figure 5 shows layout of the polarization-analyzing pixel TEGs made with 65nm CMOS process. Table II shows specifications of the polarization-analyzing pixel TEGs.

Figure 6 shows the angular profile of the fabricated polarization-analyzing pixel with embedded polarizer. The 65 nm polarization-analyzing pixel shows the extinction ratio over 40, which is significantly larger than that obtained for the 0.35μm polarization-analyzing pixel [1, 2]. In the case of the polarization sensing with 0.35 μm sensor, we need to adopt the full-angle scheme to estimate the polarization angle [2]. On the other hand, using 65 nm CMOS technology, we expect to achieve an acceptable estimation performance with 4-angles estimation scheme [2]. It means that polarization imaging with a significantly higher resolution will be realized since we need only four polarization-analyzing pixels (0, 45, 90, and 135 deg.) to estimate the polarization.

Currently, we are working on the image sensor fabricated with the 65 nm CMOS process, and it will be reported in the workshop, too.

Conclusions

Two kinds of performance improvements of the polarization-analyzing CMOS image sensor were realized. By an implementation of the multiple sets of the polarization analyzing pixels, we obtained a reduction of random noise in polarization estimation. Intra-frame averaging using 9 pixel sets provides an improvement of the estimation stability as effective as 10 inter-frame averaging. We also successfully improved the extinction ratio of the embedded polarizer by adopting 65nm standard CMOS process. An extinction ratio over 40 was obtained with a 65nm polarization-analyzing pixel.

Acknowledgements

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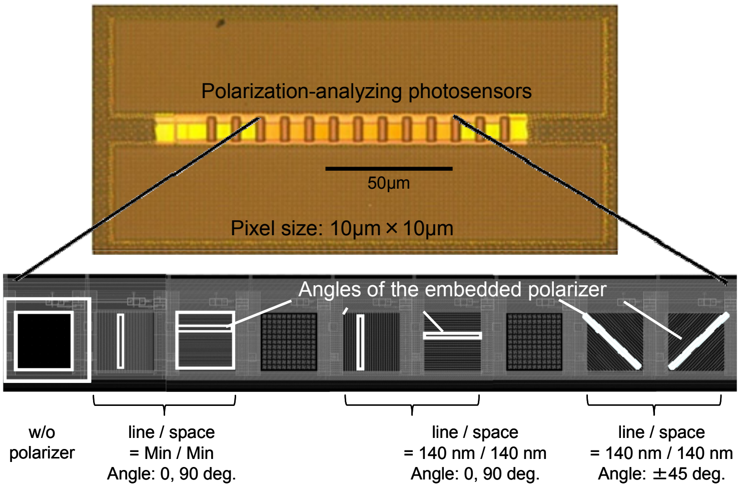

Figure 5: Layout of the polarization-analyzing pixel TEGs made with 65nm CMOS process

TABLE II: Specifications of polarization-analyzing pixel TEGs

Technology	65 nm standard CMOS
Wiring layers	7 (1 Al, 6 Cu)
Pixel configuration	3Tr - APS
Pixel size	10 μm × 10 μm
Fill factor	49 %
Pixel number	9×1

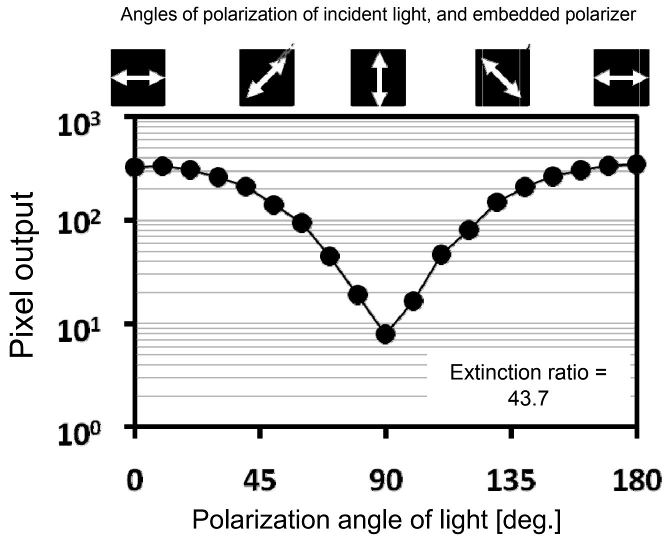

Figure 6: Performance of the embedded polarizer with 65 nm process

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