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CMOS Image Sensor with an Overlaid Organic Photoelectric Conversion Layer : Optical Advantages of Capturing Slanting Rays of Light

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Abstract

We prepared a trial product of a CMOS image sensor with a thin overlaid panchromatic organic photoelectric conversion layer and evaluated the dependences of its sensitivity and cross-talk upon the angle of incident light. We verified the optical advantages of the proposed sensor, which should enable the reductions in F-number and size of optical lenses.

1. Introduction

Persistent and tremendous efforts have been made to meet the strong demand of the market requiring the reduction in pixel size of solid-state image sensors. Recently, backside illumination (BSI) of CMOS image sensors is gathering keen attention, because it is free from the problems, which prevent conventional CCD and CMOS image sensors from being designed with smaller pixel size[1]. However, BSI of CMOS image sensors still has a problem for the reduction in pixel size owing to accompanying increase in spectral cross-talk for capturing slanting rays of light. Moreover, such processes as wafer-bonding and wafer-thinning are additionally needed for BSI of CMOS image sensors, and disadvantageous to it for enhancing production yield and cost performance.

We have proposed a new CMOS image sensor with an overlaid organic photoelectric conversion layer in order to overcome these problems[2]. Figure 1 shows a schematic cross-section of the proposed CMOS sensor. It has a stack-type structure, in which a panchromatic organic photoelectric conversion layer is overlaid as a continuous simple layer without any micro-fabrication process on a CMOS signal read-out substrate, and the pixel aperture for incident light is 100 % in principle. Incident light with each of three primary colors separately passes through a micro-color filter and is converted to signal charges in a panchromatic organic photoelectric conversion layer, which is sandwiched between a transparent counter electrode and pixel electrodes. The signal charges thus generated in the layer are read out by the signal read-out circuit in a CMOS substrate through a pixel electrode and a via-plug. Since the capacitors, which store signal charges in the proposed sensor, include an organic photoelectric conversion layer in addition to a pn-junction in a CMOS substrate, their electric capacity in total is larger than that of a corresponding CMOS sensor, and makes it possible to reserve the number of saturated electrons per pixel to achieve sufficient dynamic range when its pixel size is reduced.

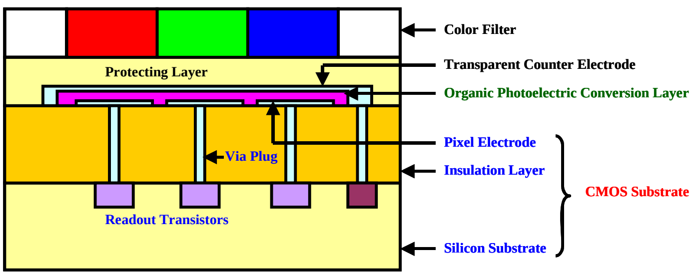

Fig. 1 Schematic cross-section of the CMOS sensor proposed in this study.

The absorption coefficient of the organic photoelectric conversion layer adopted in the proposed sensor is high enough to realize the reduction of its thickness, which does not deteriorate its light utilization efficiency without using micro-lenses for gathering light, and makes it possible to escape from the increase of optical cross-talk for capturing slanting rays of light. Since the signal charges migrate in a vertical direction of the organic photoelectric conversion layer according to the applied electric field between a transparent counter electrode and pixel electrodes, electrical cross-talk is also small. Since the confinement of the spectral sensitivity of the organic photoelectric conversion layer within visible range makes it unnecessary to use an IR-cut filter, the proposed sensor does not suffer from the change of color hue due to the change in the threshold wavelength of an IR-cut filter, which depends on the slanting angle of incident light. As a result, the proposed CMOS sensor admits incident light with a high chief ray angle and is expected to contribute to the increase in the sensitivity of devices by making it possible to use camera lenses with brighter F-number and to design thinner optical modules.

In this paper, we present the results of the evaluation of a trial product of the proposed CMOS sensor, particularly placing an emphasis on its optical advantages of capturing slanting rays of light.

2. Experiments

A CMOS signal read-out substrate with pixel electrodes was made by 0.18 μm, 2-Poly/4-Metal CMOS process. The pixel size is 3 μm and the number of pixels is 360×256 (QVGA). Each pixel has a signal read-out circuit of 3-transistor mechanism operating at 50 frames/sec. An organic photoelectric conversion layer was thermally evaporated on the CMOS substrate and a transparent counter electrode, a protecting layer and micro-color filters were overlaid sequentially in this order. The micro-color filters were arranged according to the usual Bayer-pattern with blue, green and red colors. After dicing a wafer, each chip was assembled in a package and evaluated from various technical aspects. Figure 2 shows the spectral external quantum efficiency of the panchromatic organic photoelectric conversion layer. As seen in this figure, the proposed sensor is characterized by the spectral sensitivity, which is confined within visible light region, and the external quantum efficiency, which is as high as over 80% at 550nm without any anti-reflection layer. Figure 3 shows an electron micrograph of the cross-section of a trial product of the proposed CMOS sensor. The panchromatic organic photoelectric conversion layer is as thin as only 0.5 μm owing to its high absorption coefficient and is much thinner than the pixel size of the proposed sensor.

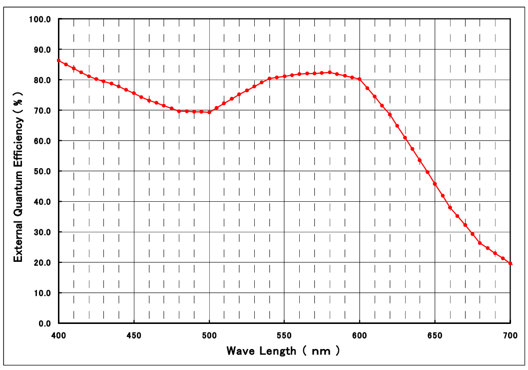

Fig. 2 Spectral external quantum efficiency of the panchromatic organic photoelectric conversion layer without any anti-reflection layer.

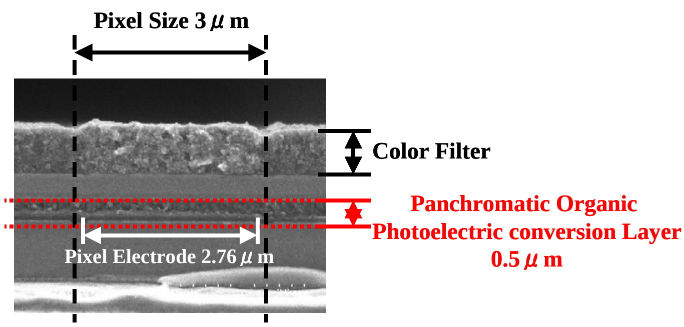

Fig. 3 Electron micrograph of the cross-section of a trial product of the proposed CMOS sensor.

3. Results and Discussions

(1) Evaluation of fundamental characteristics

Figure 4 shows a photograph of a resolution chart taken by a trial product of the proposed CMOS sensor without micro-color filters. Although the organic photoelectric conversion layer was laid on the CMOS signal read-out substrate as a continuous layer without any structure, a resolution of 250TV lines, which is the theoretical limit of resolution on the basis of the number of pixels in a column of the CMOS substrate used, was attained. This indicates that the proposed CMOS sensor could achieve a resolution corresponding to the number of pixels in the CMOS substrate without using any expensive and complicated micro-fabrication processes, and should be therefore the best candidate for sensors with reduced pixel size. Figure 5 shows a photograph of a resolution chart under a spotlight, which was as intense as approximately 300 times of a standard light. It is noted that such an intense light did not bring about any false signals such as smear and blooming. Figure 6 shows one of the frames in a movie taken by the proposed sensor at 50 frames/sec with an operating metronome as an object. The operating pendulum is clearly taken without exhibiting any lag.

Table 1 shows the summary of the fundamental characteristics of a trial product of the proposed CMOS sensor. The number of saturated electrons per pixel is as many as 40000 and contributes to the realization of a wide dynamic range by the proposed sensor. Although the random noise per pixel was not low enough (i.e., 38 electrons), it was nearly equal to, and therefore arose from the kTC-reset noise, which was inherent in principle in a 3-transistor signal read-out circuit as adopted in the proposed sensor. It is necessary to develop a new signal read-out circuit with reduced kTC-reset noise.

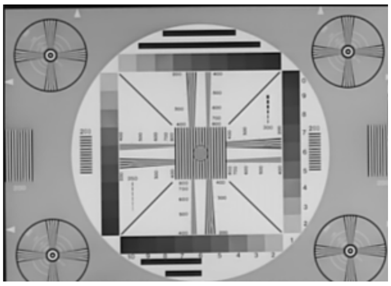

Fig. 4 Photograph of a resolution chart, which was taken by a trial product of the proposed CMOS sensor without micro-color filters.

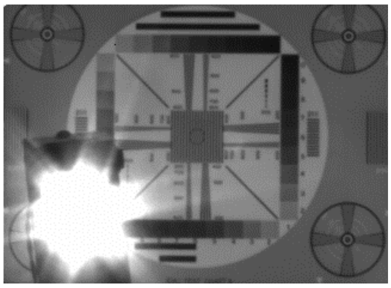

Fig. 5 Photograph of a resolution chart, which was taken under an intense spotlight by a trial product of the proposed CMOS sensor without micro-color filters.

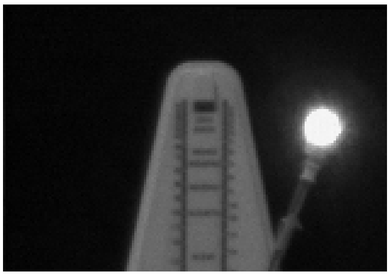

Fig. 6 Photograph of an operating metronome, which was taken by a trial product of the proposed CMOS sensor without micro-color filters.

Table 1. Summary of characteristics of a trial product of the proposed CMOS sensor.

Conversion Gain	56 μV/e
Number of Saturated Electrons	40000 e
Smear & Blooming	Below Detection Limit
Lag	Below Detection Limit
Random Noise (RMS)	38 e
Dynamic Range	60 dB
Dark Current of Organic Photoelectric Conversion Layer at 50 frames/sec. (60℃)	1 e

(2) Optical advantages of capturing slanting rays of light

Figure 7 shows the spectral sensitivity of a trial product of the proposed CMOS sensor. Since the spectral sensitivity of the panchromatic organic photoelectric conversion layer was confined within visible light region, the spectral sensitivity in Figure 7 could be attained without any IR-cut filter. Figure 8 shows a photograph of a Japanese doll together with a Macbeth chart, which was taken by a trial product of the proposed CMOS sensor with micro-color filters.

Figure 9 shows the output voltage of the blue, green, and red pixels in the proposed sensor on exposure to green light with wavelength of 550nm as a function of its incident angle. Over such a

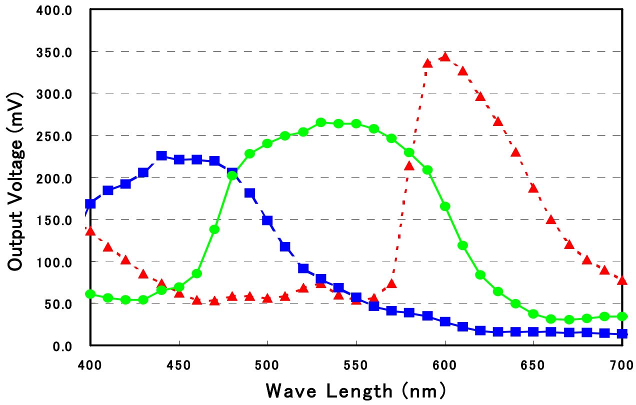

Fig. 7 Spectral sensitivity of a trial product of the proposed CMOS sensor with micro-color filters.

Fig. 8 Photograph of a Japanese doll with a Macbeth chart, which was taken by a trial product of the proposed CMOS sensor with micro-color filters.

wide range of incident angle as ±45° , the dependence of the output voltage of the green pixel upon the incident angle was nearly equal to the theoretical limit predicted by the cosine rule. The output voltage of the blue and red pixels exhibited the incident angle dependence similar to that of the green pixel, indicating that they were brought about by the green light, which passed through the blue and red filters. It is noted that any phenomenon indicative of the increase in spectral cross-talk by the increase in the incident angle of the green light was not observed. This result means that the pixel aperture for incident light is nearly 100% without increase in spectral cross-talk for capturing slanting rays of light. These characteristics originate from the fact that the panchromatic organic photoelectric conversion layer is very thin, and should therefore exist clearly in sensors with smaller pixel size.

These results indicate that the proposed CMOS sensor makes it possible to design optical lens modules and cameras, which bear large chief ray angle to a focusing plane. Figure 10 illustrates the conditions of rays of light when the sensitivity of devices is increased by using a lens with brighter F-number (a), and when thin package is achieved by using a lens with a short focal length (b).

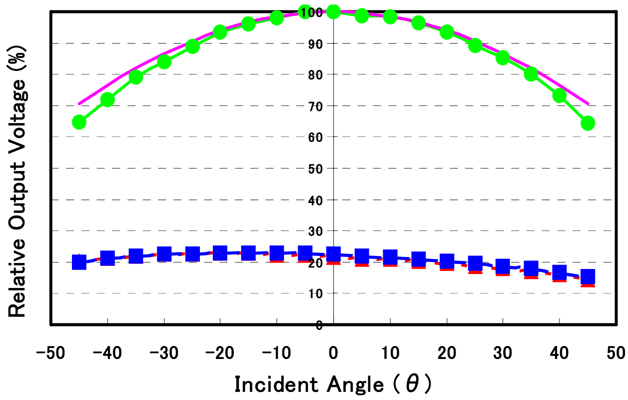

Fig. 9 Output voltages of the blue(■), green(●) and red(▲) pixels on exposure to green light with wavelength of 550nm as a function of its incident angle. Solid line is the theoretical limit predicted by the cosine rule.

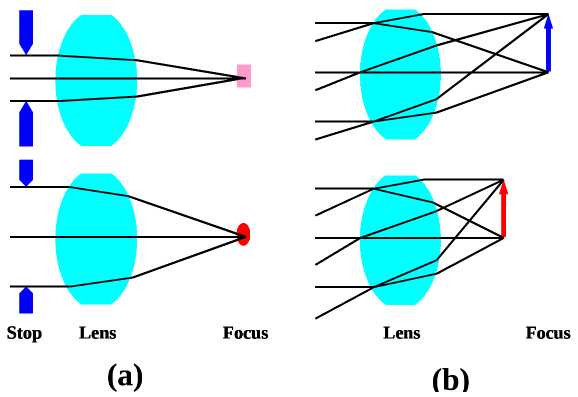

Fig. 10 Schematic optical example for (a) enhanced sensitivity by using a lens with brighter F-number, (b) reduction in package thickness by using a lens with a short focal length.

4. References

(1) 2009 International Image Sensor Workshop, Symposium on Backside Illumination of Solid-State Image Sensors, Bergen, Norway (2009)

(2) M. Ihama, T. Mitsui, K. Nomura, Y. Maehara, H. Inomata, T. Gotou, Y. Takeuchi, 2123, The 16th International Display Workshops, Miyazaki, Japan (2009)