Proposal of New Organic CMOS Image Sensor for Reduction in Pixel Size

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Abstract

We proposed a new CMOS image sensor with a thin overlaid panchromatic organic photoelectric conversion layer as the best candidate for sensors with reduced pixel size. We experimentally made trial products of the proposed sensor, verified their potential capability, and proved the validity of the organic CMOS sensor.

1. Introduction

The history of imaging science and technology encompasses the history of Fujifilm, running together with that of Eastman Kodak. However, more than a hundred and a half years of history of silver halide photography based on organic materials has been replaced by several decades of history of the silicon technology based on inorganic materials. It is not unreasonable to assume that as we charge toward the future, the next historical chapter will consist of a hybrid technology of organic and inorganic materials that will overcome the present limits of each technology.

Silicon technology has been developing dramatically, and the smallest pixel size of 1.4 µm, which is nearly equal to 1/1000 of 1 mm, has now been achieved. Nevertheless, to meet the successive and strong demand of the market requiring an increasingly greater number of pixels within a limited chip area, it is necessary to continuously reduce the size of a pixel. Despite the tireless efforts to improve technologies for achieving smaller pixel size, the light capture efficiency and sensitivity of CCD and CMOS image sensors have been decreasing. Recently, many manufacturers have announced their development of back-illuminated CMOS image sensors[1] based on state-of-the-art silicon technologies, and the competition for achieving smaller pixel size is becoming fiercer and fiercer. However, the situation where many manufactures are faced with the major challenge in attaining higher sensitivity within smaller pixel size, has not changed.

We have been exploring the possibilities of developing a new image sensor which is not based on conventional technologies, by utilizing the features of an organic photoelectric conversion layer[2-4]. Fig. 1 shows a schematic cross section of the new organic CMOS image sensor, which we consider the most suitable structure for reducing pixel size. The sensor consists of a thin panchromatic organic photoelectric conversion layer and a CMOS signal read-out substrate. It is a hybrid structure comprising two layers: the upper layer for capturing light and converting it to electrical signals consists of organic materials, and the lower layer for outputting electrical signals consists of inorganic materials. In principle, the aperture for capturing incident light is 100%. The photoelectric conversion layer consists of a thin panchromatic organic photoelectric conversion layer sandwiched between a transparent counter electrode and pixel electrodes. Since the organic photoelectric conversion layer can be laid over the CMOS signal read-out substrate as a continuous film, it does not need any of the expensive micro-fabrication processes which are necessary for conventional silicon technology, and is suitable for reducing pixel size. Incident light is separated into three primary colors of blue, green and red by the micro-color filters, and signal charges generated by the absorption of each primary color in the thin panchromatic organic photoelectric conversion layer are read out by the signal charge read-out circuits in the CMOS substrate through via-plugs.

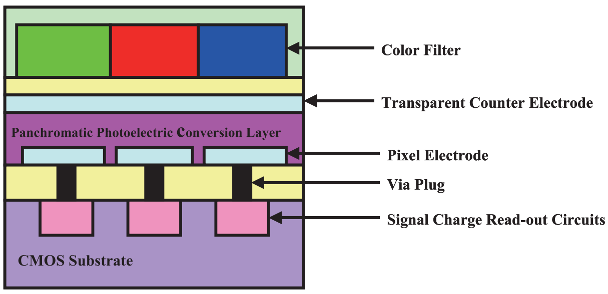

Fig. 1 Structure of the proposed image sensor with a thin overlaid panchromatic organic photoelectric conversion layer.

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As the organic photoelectric conversion layer has a large absorption coefficient in principle, it can absorb enough light in spite of its extreme thinness. Therefore, it is free from spectral cross-talk between tiny pixels when capturing slanting rays of light and does not need any micro-lenses conventionally used for gathering incident light. The spectral sensitivity of the organic photoelectric conversion layer can be freely controlled by designing organic materials and it is possible to achieve a panchromatic property which does not have sensitivity to infrared light but only to blue, green and red light as shown in Fig. 2. Therefore, it is not necessary to use a conventional infrared light cut filter and we can eliminate its problem, a change of infrared cut wavelength and color hue caused by a change of the angle of light incidence.

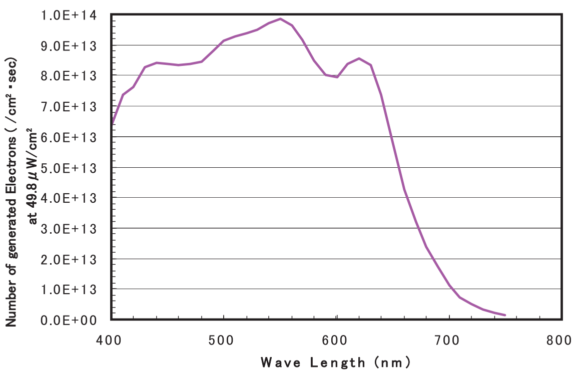

Fig. 2 Spectral sensitivity of the panchromatic organic photoelectric conversion layer.

We have made a trial product of the CMOS image sensor with an overlaid thin panchromatic organic photoelectric conversion layer in order to verify the potential capability of the new organic CMOS image sensor. The results of the evaluation are reported in this paper.

2. Experiments

Table 1 shows the specifications of the trial product of a new organic CMOS image sensor, which has a structure as shown in Fig. 1. The CMOS signal read-out substrate was made by a 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 with a 3-transistor mechanism, which operates at 50 frames/sec as shown in Fig. 3. The ratio of the pixel electrode size to the pixel size is equivalent to the apparent aperture for capturing incident light. Fig. 4 shows an electron micrograph of the pixel electrodes on the CMOS signal read-out substrate of the trial product. The size of pixel is 3 µm and the size of pixel electrode is 2.76 µm, accordingly, the apparent aperture for capturing incident light is 85%.

The panchromatic organic photoelectric conversion layer, color filters and other materials were overlaid on the CMOS signal read-out substrate, and it was assembled as a package. We evaluated the S/N ratio, degree of image lag and other characteristics of an image sensor. Fig. 5 shows a photograph of an assembled chip of the new organic CMOS image sensor.

Table 1 Specifications of a trial product of the proposed organic CMOS sensor.

Process	0.18 µm, 2-Poly/4-Metal
Pixel Number	360 × 256 (QVGA)
Pixel Size	3 µm
Read-out Speed	50 frames/second
Signal Read-out Circuit	3-Transistor Mechanism
Photoelectric Conversion Layer	Panchromatic Organic Materials

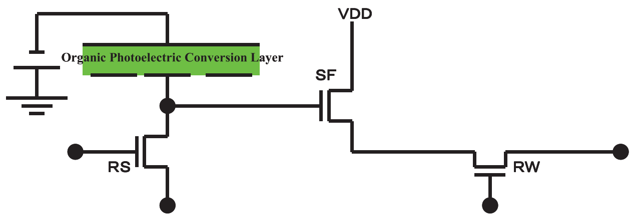

Fig. 3 Outline of signal charge read-out circuit with three-transistor mechanism for the proposed organic CMOS sensor.

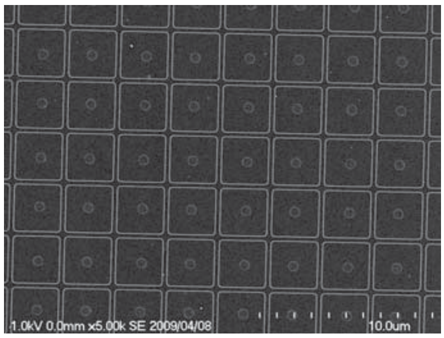

Fig. 4 Electron micrograph of pixel electrodes.

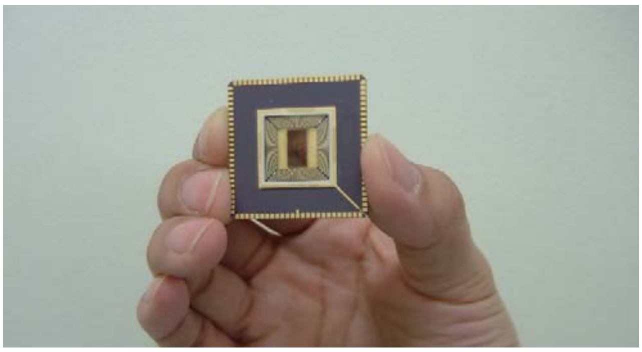

Fig. 5 Photograph of a trial product of the assembled organic CMOS sensor proposed in this study.

3. Results and Discussion

Fig. 6 shows an electron micrograph of a cross section of the trial product of a new organic CMOS image sensor. The thickness of the panchromatic organic photoelectric conversion layer is only 0.5 μm and extreme thinness is apparent when compared with the size of a pixel. Since the thin layer can absorb incident light well enough and convert it to electric signals, spectral cross-talk between pixels when capturing slanting rays of light can be reduced efficiently without using any micro-lenses.

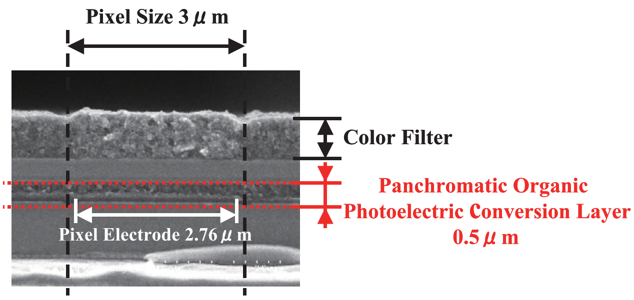

Fig. 6 Electron micrograph of the cross section of a trial product of the proposed organic CMOS sensor.

Fig. 7 shows a photograph of a resolution chart taken by the trial product of a new organic CMOS sensor without micro-color filters. Although the organic photoelectric conversion layer was laid over the CMOS signal read-out substrate as a continuous film without any structures, a resolution of 250 TV lines, which is the theoretical limit of resolution determined by the number of pixels in a column, was attained. This indicates that the new organic CMOS image sensor can achieve a resolution corresponding to the number of pixels without using any expensive and complicated micro-fabrication processes and be the best candidate for sensors with fine pixel size.

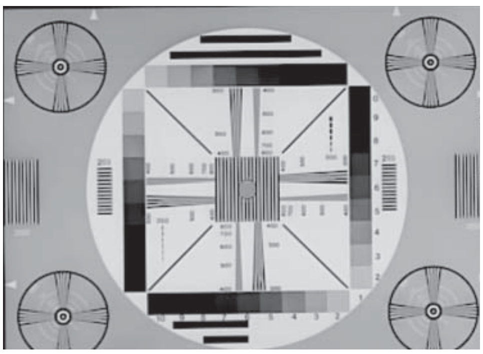

Fig. 7 Photograph of a resolution chart, which was taken by the trial product of the proposed organic CMOS sensor without micro color filters.

Fig. 8 shows a photograph under an intense spotlight approximately 300 times greater than standard light. There are no false signals due to the excessive light, such as smear and blooming, demonstrating that the new organic CMOS image sensor is free from these problems.

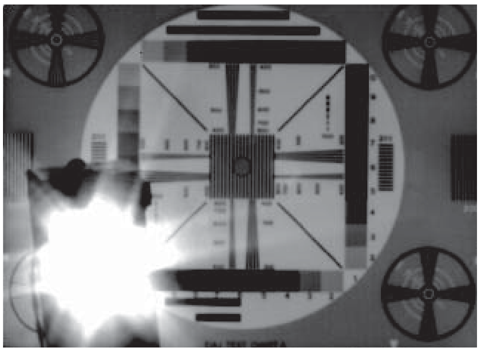

Fig. 8 Photograph of a resolution chart under intense light from a spotlight, which was taken by the trial product of the proposed organic CMOS sensor without micro color filters.

Fig. 9 shows one movie frame of operating metronome taken at 50 frames/sec. The moving pendulum is clearly taken and no image lag was observed.

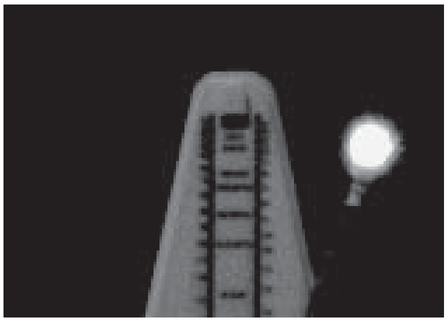

Fig. 9 Photograph of an operating metronome, which was taken by the trial product of the proposed organic CMOS sensor without micro color filters.

Fig. 10 shows a skin color comparison photograph taken by the trial product of a new organic CMOS image sensor with micro-color filters. This is the first color image in the world, which was taken by a single-board image sensor utilizing an organic photoelectric conversion layer. In a photograph of the 24 colors of Macbeth color chart, the average color difference from actual ones is 0.64, which can hardly be recognized by human eyes. Since the panchromatic organic photoelectric conversion layer is designed to be sensitive to only visible light, namely blue, green and red light, it can achieve such a negligible color difference without requiring any infrared light cut filters.

Fig. 10 Photograph of a skin color chart, which was taken by the trial product of the proposed organic CMOS sensor with micro color filters.

Table 2 shows the characteristics of the trial product of a new organic CMOS image sensor. The external quantum efficiency of photoelectric conversion is 65% at the wavelength of 550 nm corresponding to green light, and can be increased by adopting an anti-reflection layer for incident light. The number of saturation electrons is 40,000 per pixel and a wide dynamic range corresponding to 60 dB is achieved. The large number of saturation electrons gives a great advantage to the new organic CMOS image sensor with pixels of smaller size and contributes to the creation of images with rich gradation. Although the random noise per pixel is considerable (38 electrons), it is nearly equal to the kTC-reset noise inherent in principle of a 3-transistor signal read-out circuit. This random noise should be reduced by developing a new signal read-out circuit, which could decrease the kTC-reset noise for a 3-transistor mechanism. Although the dark current of the organic photoelectric conversion layer at 60°C is equal to about 7 electrons, it should be decreased further by the progress of research on the materials used for organic photoelectric conversion layer in the future.

Table 2 Characteristics of a trial product of the proposed organic CMOS sensor.

External Quantum Efficiency (550 nm)	65%
Conversion Gain	56 μV/e
Number of Saturation Electrons	40,000e
Smear & Blooming	Below Detection Limit
Lag	Below Detection Limit
Random Noise (RMS)	38e
Dynamic Range	60 dB
Dark Current of Organic Photoelectric Conversion Layer at 50 frame/second (60°C)	7e

4. Conclusion

We proposed a new organic CMOS image sensor, in which a thin panchromatic organic photoelectric conversion layer was overlaid upon a signal read-out CMOS substrate, as the best candidate for sensors with pixels of reduced size. This image sensor has a hybrid structure consisting of organic materials and inorganic materials. We have made the trial product in order to verify the potential capability of the sensor, and succeeded in experimentally proving that the panchromatic organic photoelectric conversion layer without requiring any expensive micro-fabrication processes could achieve high external quantum efficiency. We will continue our efforts to improve and develop this technology of a new organic CMOS image sensor, wishing to create a new milestone in the history of imaging science and technology.

References

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