# Organic CMOS Image Sensor with Thin Panchromatic Organic Photoelectric Conversion Layer : Durability and Performance

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## Abstract

We have developed a new organic CMOS image sensor with a thin overlaid panchromatic organic photoelectric conversion layer as a candidate for sensors in the next generation. The high durability of the organic photoelectric conversion layer, which satisfies a variety of requirements by customers, was attained by the usage of new organic molecules with high glass transition temperature and the application of a new inorganic protecting layer to it. The wide dynamic range, which is four times higher than that of conventional CMOS image sensor, was attained by the incorporation of a new storage node with large capacity in a signal read-out circuit.

## 1. Introduction

We proposed a hybrid CMOS image sensor with a thin panchromatic organic photoelectric conversion layer (organic CMOS image sensor) as a candidate for sensors in the next generation<sup>1),2)</sup>. The schematic structure is shown in Fig. 1. Passing through micro color filters separately, incident photons with three primary colors are absorbed by the 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 CMOS signal read-out circuits through pixel electrodes and via-plugs.



Fig.1 Schematic structure of the organic CMOS image sensor with a thin panchromatic organic photoelectric conversion layer.

A pixel aperture for incident light is 100% in principle since whole the organic photoelectric conversion layer is uniform and free from pixel division upon a CMOS signal read-out substrate.

This structure makes the external quantum efficiency at the wavelength of 550nm as high as over 80% (Fig. 2). Owing to a high absorbance of the organic photoelectric conversion layer, its thickness is as thin as only 0.5 um. Therefore, the sensitivity as a function of the incident angle of light is nearly equal to the theoretical limit predicted by the cosine rule and the optical cross-talk with slanting rays of light is negligibly small as verified by a trial product with 3 um pixel size (Fig. 3).



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



Fig.3 Output voltage of the blue-( $\blacksquare$ ), green-( $\bigcirc$ ), and red-( $\blacktriangle$ ) sensitive pixels with 3 um pixel size on exposure to green light with wavelength of 550 nm as a function of its incident angle. Solid line is the theoretical limit predicted by the cosine rule.

In this paper, we present recent advancements of the organic CMOS image sensor, which cover an improvement of the durability of the organic photoelectric conversion layer, an enhancement of the dynamic range, and a reduction of the noise in the signal read-out circuit.

#### 2. Durability

It is necessary for a sensor to have a high durability which satisfies a variety of requirements by customers. The durability of the organic photoelectric conversion layer was reinforced by the usage of new organic molecules with high glass transition temperature and the application of a new inorganic protecting layer to it. The protecting layer is composed of two sub-layers with aluminum oxide (AlO<sub>x</sub>) and silicon oxinitride (SiON). The first AlO<sub>x</sub> sub-layer with a thickness of 30 nm was deposited on the transparent counter electrode by the method of a thermal atomic layer deposition with a sequential self-terminating gas-solid reaction of trimethylaluminum and water<sup>3)</sup>. The AlO<sub>x</sub> sub-layer is dense, highly conformal and nearly pinhole-free film, which has ideal barrier characteristics against the permeation of O<sub>2</sub> and H<sub>2</sub>O<sup>4</sup>). Fig. 4 shows a transmission electron micrograph of the cross-section of an interface between the transparent counter electrode and the first AlO<sub>x</sub> sub-layer. The interface has a very distinct feature without any protrusions. It could be also confirmed that an interface between the transparent counter electrode and the organic layer was smooth.



Fig.4 Transmission electron micrograph of the cross-section of an interface between the transparent counter electrode and the  $AlO_x$  sub-layer.

However, the  $AlO_x$  sub-layer itself has a large tensile stress and does not have a resistivity against alkaline solutions. The second SiON sub-layer with a thickness of 200 nm was deposited on the  $AlO_x$  sub-layer by the method of a plasma-enhanced chemical vapor deposition and compensates a tensile stress of the first sub-layer. As a result of adopting this two-layered structure, the organic photoelectric conversion layer could have a high resistivity against mechanical and chemical damages and the permeation of  $O_2$  and  $H_2O$ .

The spectral external quantum efficiency and the response speed to rectangular light pulse of the organic photoelectric conversion layer before and after a variety of durability tests are shown in Fig. 5 and Fig. 6, respectively. There were no changes in sensitivity and response speed with a wide variety of temperature, high humidity and irradiation of light. The dark current measured at  $60^{\circ}$ C was also kept to be as low as  $100 \text{pA/cm}^2$  under these conditions. It is anticipated that the organic photoelectric conversion layer would be durable against severer conditions.



Fig.5 External quantum efficiency of the organic photoelectric conversion laver before( $\bigcirc$ ) and after ( $\blacktriangle$ ) durability test. for 1000hr under operating (a) 90 ℃ condition, (b) -45 °C for 1000hr under and 90% operating condition, (c)  $60^{\circ}$ C humidity 1000hr, relative for (d) Irradiation of light at 1000lx for 1000hr under operating condition.



Fig.6 Response speed of the organic photoelectric conversion layer to rectangular light pulse before(-) and after (--) durability test.

(a) 90 °C for 1000hr under operating condition, (b) -45 °C for 1000hr under operating condition, (c) 60 °C and 90% relative humidity for 1000hr, (d) Irradiation of light at 1000lx for 1000hr under operating condition.

### 3. Performance

We have developed a new organic CMOS image sensor with 3 um pixel size, which was fabricated by a 1 Poly 3 Metal 110nm CMOS technology. The pixel circuit consists of three transistors: a reset transistor (TR1), a select transistor (TR2) and a source follower amplifier transistor (TR3). In order to make the saturation level as high as possible, a storage node of large capacity is newly incorporated as shown in Fig. 7. The storage node allows charge accumulation up to the breakdown voltage of the node junction, which is realized by optimizing the impurity profile. Thus, the input of TR3 can be swung to the level of the power supply voltage, giving rise to a much wider dynamic range. The chip architecture is shown in Fig. 8. We note that the column noise canceller circuit consisting of a negative feedback loop reduces the kTC noise of TR1 down to less than 3 electrons by cancelling the noise itself. A transmission electron micrograph of the cross-section of the new organic CMOS image sensor is shown in Fig. 9.





Fig.7 Schematic diagram of the pixel circuit of the organic CMOS image sensor.

Fig.8 Chip architecture of the organic CMOS image sensor.



Fig.9 Transmission electron micrograph of the crosssection of the organic CMOS image sensor with 3 um pixel size.

The sensitivity curve of the developed organic CMOS image sensor with 3 um pixel size is shown in Fig. 10 with the supply voltage of TR3,  $V_{SF}$ , as a parameter. The total amount of saturation charges is maximized to be 77,000 electrons with  $V_{SF}$  of 5.0 V. This level is four times higher than that of conventional CMOS image sensor. The bright image taken by this sensor is essentially shot noise free giving impression of very still and high reality of objects. The overall chip performance is summarized in Table 1. The organic CMOS image sensor is expected to give a strong impact on any kind of applications such as digital still cameras, single-lens reflex cameras and mobile phones.



Fig.10 Input-Output characteristics of the organic CMOS image sensor with 3 um pixel size.

Pixel size	3.0µm
Input voltage of TR3	5.0V
The number of pixels	990 (H) × 630 (V)
Saturation charge	77,000e-
Sensitivity	35,500e <sup>-</sup> /lux · s
Read-out noise	2.9e-
Dynamic range	88dB
Image lag	Under detection limit

Table 1 Chip performance of the organic CMOS image sensor with 3 um pixel size.

## 4. References

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