A 128 x 96 Pixel Stack-Type Color Image Sensor with B-, G-, R-sensitive organic photoconductive films

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1. Introduction

Our group has been developing a new type of image sensor overlaid with three organic photoconductive films, which are individually sensitive to only one of the primary color components (blue (B), green (G), or red (R) light), with the aim of developing a compact, high-resolution color camera [1-6]. We confirmed the unique characteristics of organic photoconductive films, such as wavelength selectivity [3,4] and high resolution without pixel separation [5], and we observed the signal output voltage from an organic film on a CMOS readout circuit [6]. Takada et al. demonstrated monochromatic images from a CMOS image sensor overlaid with an organic photoconductive film [7], and Ihama et al. recently showed a color image taken through a color filter array by a CMOS image sensor overlaid with a panchromatic organic layer [8].

In this study, we produced a color image from a vertically-stacked image sensor with B-, G-, and R-sensitive organic photoconductive films, each of which had a zinc-oxide thin film transistor (ZnO TFT) readout circuit. The three elements of the sensor, each sensitive to B, G or R, were fabricated on the individual glass substrates and directly stacked. The number of pixels for each element was 128 x 96, and the pixel size was 100 x 100 μm^2. Fabricated image sensor produced a color image with a resolution corresponding to the pixel number. In addition, a continuous fabrication process from the bottom to the top layers was devised for reducing the total thickness of the sensor.

2. Experimental

2.1 Configuration of stacked image sensor

Figure 1 shows a schematic illustration of the developed stacked image sensor. The three elements of the sensor were individually fabricated on three separate glass substrates, each respectively composed of a ZnO TFT circuit/B-sensitive organic film/indium-tin-oxide (ITO) electrode, a ZnO TFT circuit/G-sensitive organic film/ITO electrode, and a ZnO TFT circuit/R-sensitive organic film/aluminum (Al) electrode. These elements were then directly stacked in the order of B, G and R from the side on which light is incident.

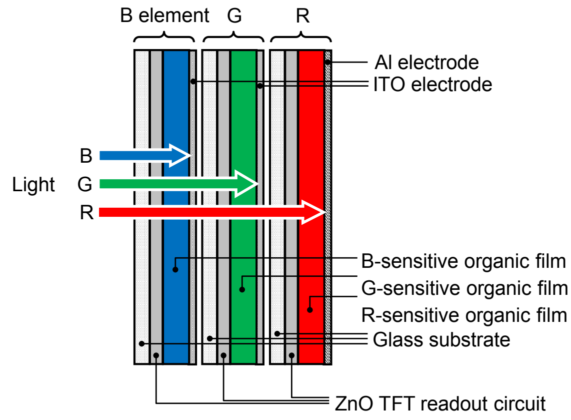


Fig. 1 Schematic illustration of stacked image sensor.

The principle of color separation in the stacked image sensor can be summarized as follows. When light is irradiated on the stacked imaging sensor, the B-sensitive organic film absorbs blue light and generates an electric charge corresponding to the amount of light absorbed in the film. This charge is read out through the ZnO TFT circuit constituting the B element. The green and red components of the incident light pass through the B element and reach the G-sensitive organic film. Similar operations are repeated for the G- and R-sensitive organic films. As a result, the stacked image sensor separates the incident light into three primary colors in the depth direction of the sensor, which is similar to what happens in photographic film.

2.2 ZnO TFT readout circuit

Figure 2 shows a schematic cross-section of a pixel in the B element of the sensor. The ZnO TFTs have a bottom gate configuration composed of a gate electrode made of Cr, a gate insulator with a SiO/SiN double layer, a channel layer with a 45-nm-thick ZnO, interlayer insulator made of SiN, a pixel electrode made of ITO, a signal line made of MoW, and passivation layer with SiN, fabricated on a 0.7 mm-thick glass substrate. The detailed fabrication process for the bottom-gate ZnO TFT is described elsewhere [9]. A microphotograph of a fabricated ZnO TFT array is shown in Fig. 3. The pixel pitch of the array is 100 μm and the width and length of a channel in the TFT are 60 and 12 μm, respectively. The number of the pixels is 128 (horizontal) x 96 (vertical), and the aperture ratio (i.e., the percentage of the photosensitive area in the whole active area of the sensor) is 53%. Since ZnO is a wide-bandgap (3.3 eV) semiconductor, the use of transparent conductive materials for the gate electrodes and signal lines will

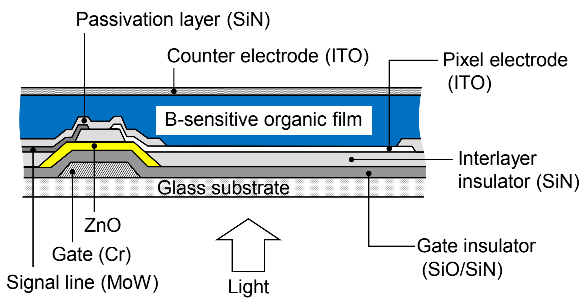


Fig. 2 Schematic cross-section of a pixel in the B-sensitive element of the sensor.

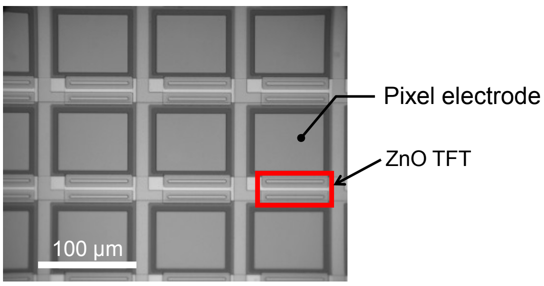


Fig. 3 Microphotograph of fabricated ZnO TFT array.

increase the aperture ratio of the sensor toward unity.

2.3 Organic photoconductive layers

Table 1 summarizes the organic materials used in this study and the structures of the B-, G- and R-sensitive films. The B-sensitive film consists of co-deposited photoconductive layers of coumarin 30 (an electron donor) and fullerene (C_{60}) (an acceptor), and a tris-8-hydroxyquinoline aluminum (Alq_3) layer (to provide an electron transport property). A

Table 1. Organic materials used in fabricated sensor structures.

Color	Structure
Blue	Glass / ZnO TFT / Coumarin 30 : C_{60} / Alq_3 / NTCDA / ITO
Green	Glass / ZnO TFT / NN'-QA / Py-PTC / NTCDA / ITO
Red	Glass / ZnO TFT / ZnPc / TiOPc / Alq_3 / Al

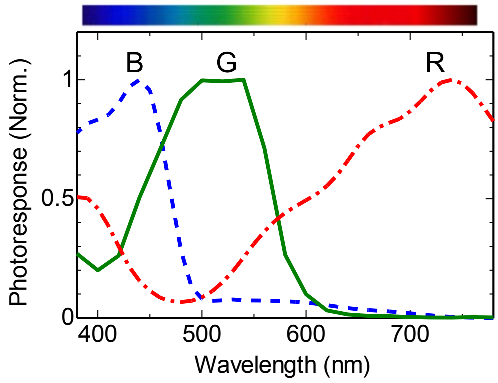


Fig. 4 Spectral photoresponse characteristics of the fabricated organic photoconductive films.

naphthalene tetra carboxylic anhydride (NTCDA) layer is deposited on the Alq_3 layer to prevent electrical shorting caused by depositing the counter ITO electrode. The photoconductive part of the G-sensitive film consists of a layer structure of the NN'-dimethylquinacridone (NN'-QA) and 2,9-di (pyrid-2-yl)-anthra[2,1,9-def:6,5,10-d'e'f'] diisoquinoline-1,3,8,10-tetrone (Py-PTC); these layers provide donor and acceptor properties, respectively. Zinc phthalocyanine (ZnPc) and titanyl phthalocyanine (TiOPc) were chosen as the R-sensitive photoconductive materials to provide electron donor properties, and Alq_3 was chosen as the electron acceptor and transport material.

Figure 4 summarizes the spectral photoresponse characteristics of the fabricated organic films as single structures (without stacking). Voltages of 5.0, 1.0 and 4.0 V were applied to the B-, G- and R-sensitive films, respectively. The films worked as wavelength-selective photoconductive films. The excellent wavelength selectivities compared with that of a silicon photodiode using a triple-well structure [10] is the most significant feature of organic photoconductive films.

Dissociation of electron-hole pairs generated by photons at the interface between donor/acceptor interface is known to occur, and this results in an increase in the quantum efficiencies (QE) of the organic photoconductive film. For example, Fig.5

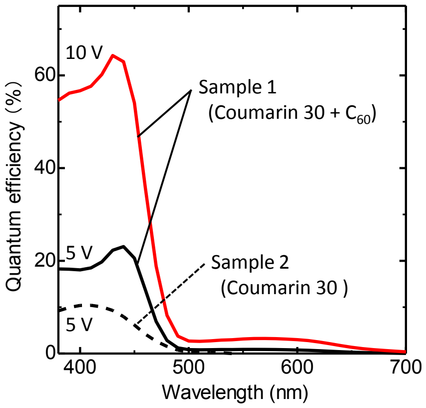


Fig. 5 Quantum efficiencies of B-sensitive films.

shows the QE of B-sensitive film with (Sample 1) and without (Sample 2) the electron acceptor (C_{60}). In an applied voltage of 5 V, the peak QE of Sample 2 was 10%, while the QE of sample 1 was 23%, i.e., more than twice that of Sample 2. The QE of Sample 1 increased with increasing applied voltage and reached 64% at 10 V [11].

3. Reproduced image of stacked image sensor

Figure 6 shows a diagram of a shooting experiment with the stacked image sensor. An optical image was focused on the stacked image sensor by using a set of lenses. The B, G and R output signals from the signal lines of the ZnO TFT readout circuits were converted into a color video signal by using an analog-to-digital (A/D) converter and signal processor. The gate voltage at the on-state and off-state of the three ZnO TFTs were set at 8.0 V and -8.0 V, respectively. The applied voltages of the organic films were set to 5.0, 1.0, and 4.0 V for the B-, G-, and R-sensitive films, respectively.

Figure 7 shows a reproduced image taken with the stacked image sensor at a read-out frame rate of 10 fps. The color image was obtained without conventional color separation optical systems such as a color filter array or prism, clearly demonstrating vertical color separation and signal output by using only an

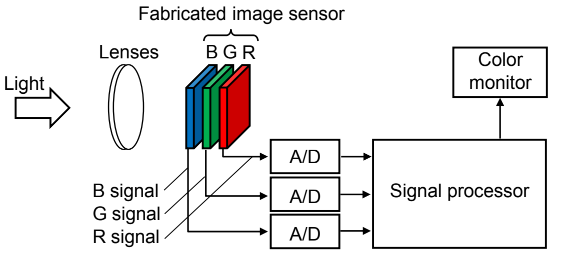


Fig. 6 Block diagram of shooting experiment of the stacked image sensor.

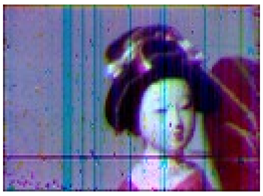
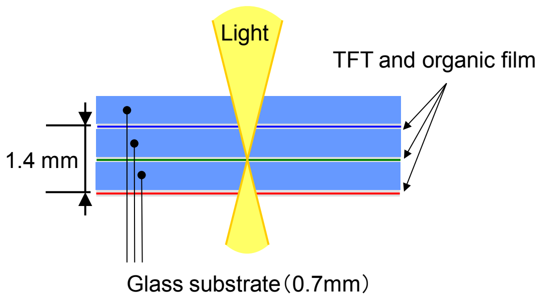


Fig. 7 Reproduced image taken with the stacked image sensor.

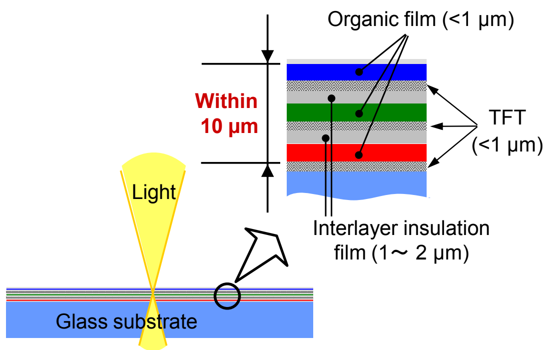
alternately stacked structure of wavelength-selective organic films and ZnO TFT circuits. The limiting resolution, as evaluated with a resolution chart, was almost 100 TV lines; this corresponded to the resolution limit of the sensor, namely, a vertical pixel number of 96 pixels.

4. Continuous fabrication technology to overcome a focal problem

Figure 8 (a) shows the schematic cross-sectional view of the fabricated image sensor. The thickness of the glass substrates in the intermediate layer of the image sensor could cause images at each organic film to be out of focus. The acceptable focal depth is roughly estimated to be shorter than 20 μm when the pixel pitch of the sensor is 5 μm and the lens iris is F2.0. To solve this focal-point problem, it is necessary to use a continuous fabrication process from the bottom to the top layers, that is, the process for



(a) Structure in this study.



(b) Structure using continuous fabrication in the future.

Fig. 8 Schematic cross sectional view of vertically-stacked image sensor.

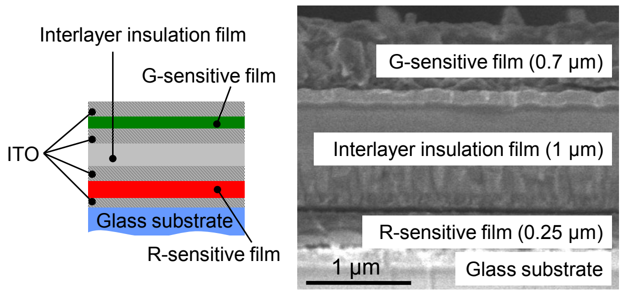


Fig. 9 Cross section of fabricated color sensor with double layer.

fabricating the interlayer insulation film and TFTs circuits on the organic photoconductive layers. By replacing the intermediate glass substrates with interlayer insulation films such as SiO_2, SiN, or organic insulators, the total thickness of the photoconductive part of the stacked image sensor could be reduced to within 10 μm (Fig. 8(b)). In this case, the insulation film and TFTs have to be fabricated at a temperature lower than 200 °C because organic materials are easily affected by heat. As a step toward the goal, we fabricated and tested a color sensor with double-layer (G- and R-sensitive films) of organic photoconductive films separated by a SiO_2 interlayer insulation film.

Figure 9 shows a cross section and microphotograph of the fabricated color sensor. The ITO electrode, R-sensitive film, ITO electrode, SiO_2 interlayer insulation film, ITO electrode, G-sensitive film, and ITO electrode were formed consecutively on a glass substrate. The 1.0 μm SiO_2 insulation film was deposited by using low-temperature chemical vapor deposition with a maximum temperature of 150 °C.

The spectral photoresponse characteristics of the fabricated color sensor are summarized in Fig. 10. Light was radiated on the G-sensitive side. The sensor

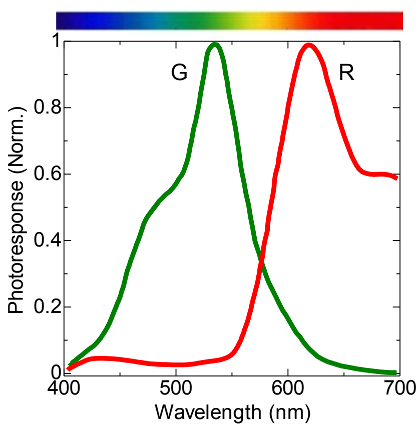


Fig. 10 Spectral photoresponse characteristics of the fabricated color sensor.

was able to separate the incident light into green and red components, indicating that R-sensitive film worked even after depositing a SiO_2 insulation layer on the film. The SiO_2 insulation layer had a dielectric strength voltage of at least 50 V.

5. Conclusion

We fabricated a vertically-stacked color image sensor with B-, G-, and R-sensitive organic photoconductive films, each having a ZnO TFT readout circuit. The stacked image sensor produced a color image with a resolution corresponding to the pixel number. This result clearly shows that color separation is achieved without using any conventional color separation optical system such as a color filter array or prism.

Acknowledgements

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