DOI: 10.2352/ISSN.2470-1173.2016.12.IMSE-264

Image Sensor with Organic Photoconductive Films by Stacking Red/Green and Blue Components

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Abstract

We present a novel single-chip color image sensor with a layered structure of three organic photoconductive films (OPFs), each one sensitive to only one primary color (red, green, or blue). First, we fabricate a red/green component consisting of two OPFs sensitive to red and green colors and transparent readout circuits on a glass substrate for red and green color imaging. Then, we fabricate a blue component consisting of an OPF sensitive to blue color and a transparent readout circuit on another glass substrate for blue color imaging. Finally, we stack the fabricated components in layers. As a result, we obtain color images with 128 × 96 pixels through a shooting experiment of the stacked structure.

Introduction

Complementary metal–oxide–semiconductor (CMOS) image sensors in mobile phone color cameras currently obtain images with a pixel size as small as one micron.[1-3] Photon shot noise in such a small photon is a major source of noise.[4] Sensors' quantum efficiency improves continuously by the introduction of advanced technological applications such as in backside illumination and noise reduction.[2,4] However, there is limited room for further improvement since the quantum efficiency can ideally reach a maximum at 100%.

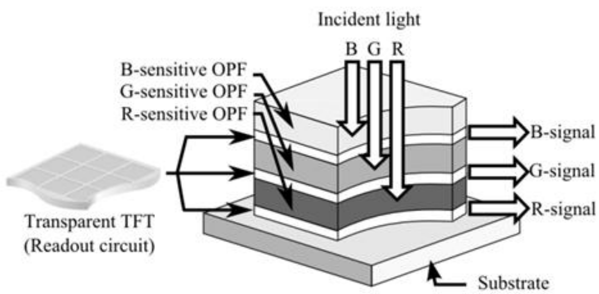

Fig. 1. Schematic of the proposed sensor's apparatus, comprising stacked OPFs layers. The sensor obtains signals of three primary colors from each pixel.

Here, we investigate a novel single-chip color image sensor with a layered structure of three organic photoconductive films (OPFs) sensitive to only one primary color each (red (R), green (G), or blue (B)) in order to reduce the photon shot noise drastically. Figure 1 shows a schematic of our proposed sensor with stacked OPFs. Each OPF absorbs only one of the three primary colors and converts it into an electron charge while transmitting the other two. These OPFs are alternately layered with transparent circuits, which read out charges generated in the individual OPF. Thus, our sensor obtains signals of three primary colors from each pixel. Compared with a conventional single-chip color image sensor with a color filter array (CFA), under the same conditions of sensor size and resolution of output images, the pixel size of our proposed sensor is two times larger than that of the conventional sensor for G color and four times larger for R and B colors (Fig. 2).[5] Therefore, the amount of light received in each pixel is increased, leading to a reduction of the photon shot noise.

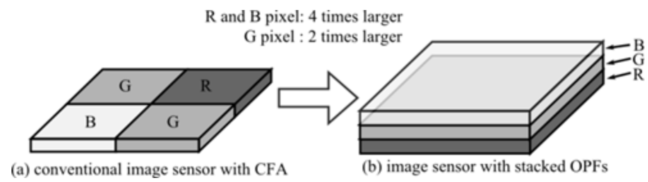

Fig. 2. Comparison between the pixel size in (a) a conventional image sensor with CFA and (b) an image sensor with stacked OPFs.

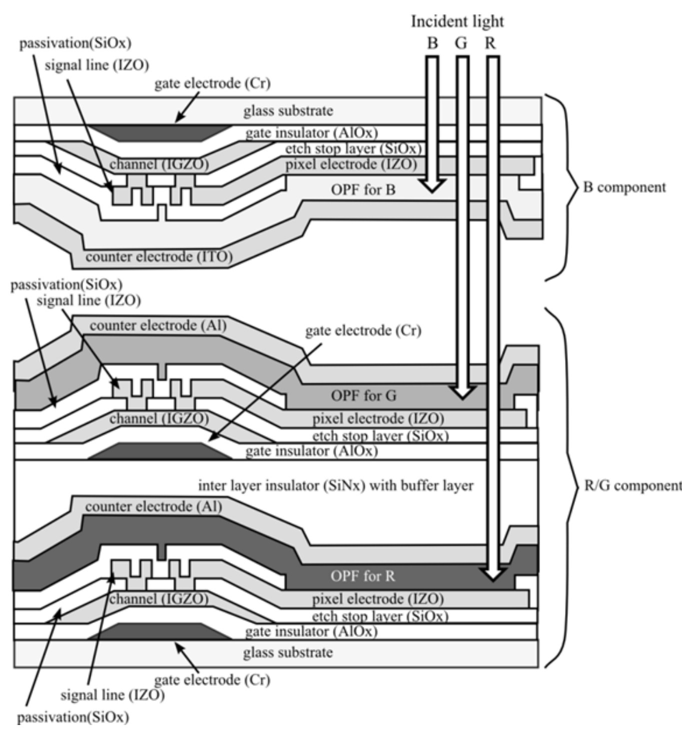

Fig. 3. Configuration of the fabricated sensor.

In previous studies, we confirmed the unique characteristics of OPFs, such as wavelength selectivity[6,7] and high resolution without pixel separation.[8] Applying thin-film transistors (TFT)

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with a transparent semiconductor of zinc oxide as transparent readout circuits, color images of 128 × 96 pixels were successfully obtained from the three stacked glass substrates on which the OPF for B, G, or R and the TFT readout circuit were fabricated, respectively.[9] To further improve the resolution of the output images, we attempted to fabricate a structure of three-layered OPFs separated by thin interlayer insulators before shrinking the pixel size and increasing the pixel number in order to close the OPFs within an optical focal depth.[10-12] We demonstrated that R, G, and yellow color images can be reproduced from a sensor with two stacked OPFs sensitive to R or G by applying In–Ga–Zn–O (IGZO) TFT circuits separated by a 10-μm-thick epoxy film as an interlayer insulator.[11] Furthermore, we fabricated a structure composed of three stacked OPFs, each sensitive to R, G, or B, with a thickness of 5.8 μm using 2-μm-thick silicon nitrides as interlayer insulators.[12] However, we could not obtain color images from this structure due to defects and fabrication yield loss. Here, we demonstrate a color image obtained by combining two components opposite each other: an R/G component for R and G color imaging, and a B component for B color imaging. This combination apparently improves the above drawbacks due to its structure, which contains three stacked OPF pairs and a readout circuit.

Experimental and Results

Image Sensor Configuration and Operation

Figure 3 presents a cross-section of a fabricated image sensor pixel. A B component for B color imaging was fabricated on a glass substrate, and an R/G component for R and G color imaging was fabricated on another glass substrate. Then, we stacked them opposite each other. Each component contains an OPF, which converts light to signal charges, and a transparent circuit, which scans the OPF and interprets signal charges from it. In addition, the readout circuit consists of an IGZO TFT acting as a switch element and a pixel electrode.

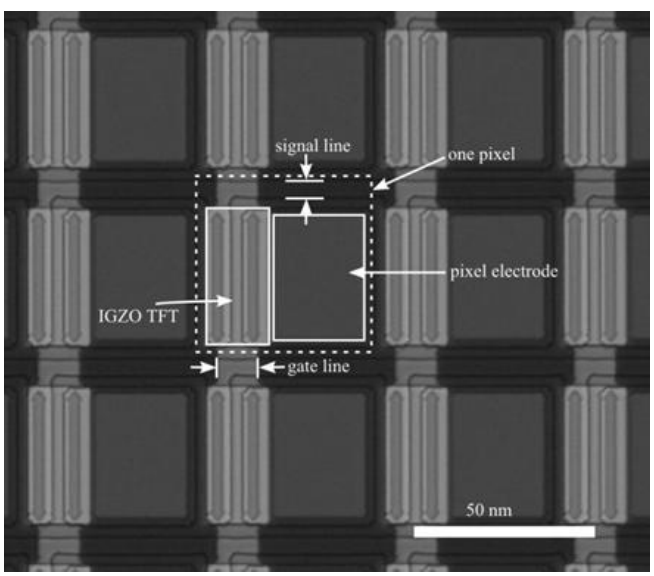

Fig. 4 Top view of the fabricated TFT circuit obtained through an optical microscope.

The operation of the sensor is as follows. When light is irradiated from the glass substrate side of the B component, B color is absorbed from the incident light by the OPF of the B component and converted to a signal charge, which is proportional to the intensity of the B color. Then, the signal charge flows to the pixel electrode through a voltage, which was applied to the counter electrode and accumulated when the TFT was turned off. Turning on the TFT, the accumulated charge at the pixel electrode is output to the outer analog digital converter (Texas Instruments, DDC232) through the signal line. By scanning the gate lines of the TFT circuit, a B color image is reconstructed. The R and G color images are reconstructed in a similar manner.

Fabrication of R/G and B Components

Figure 5 shows an external view of the fabricated sensor components. First, we fabricated an IGZO TFT with a pixel electrode for an R-sensitive OPF on a glass substrate with a low alkali composition. It has a conventional bottom-gate configuration. The process followed was the same as that in our previous study.[12] The entire process was conducted at 150°C. Figure 4 shows the top view of the fabricated TFT circuit obtained by an optical microscope. The number of pixels was 12,288 (128 × 96), and the pitch was 50 μm. The width and length of the channel in the TFT were 36 and 6 μm, respectively. The aperture ratio of the pixel electrode area to the entire pixel area was 39%.

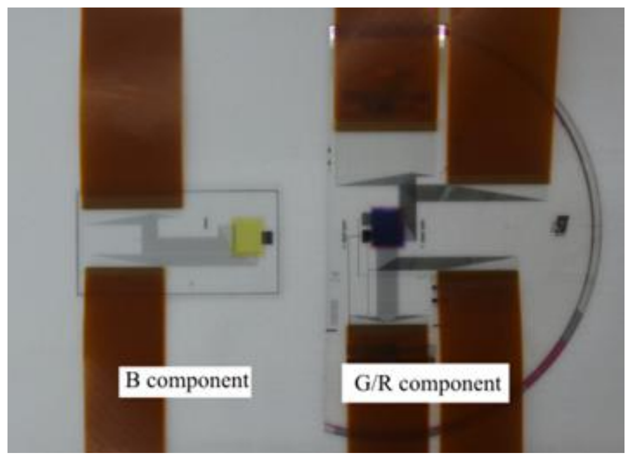

Fig. 5 External view of the fabricated components of the sensor.

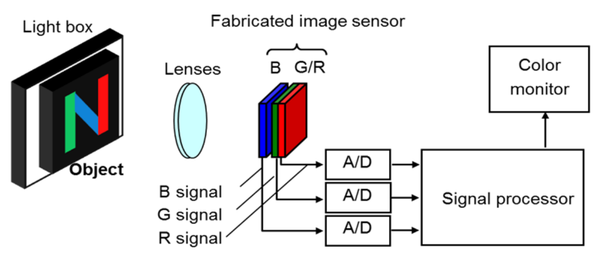

Fig. 6 Block diagram of the stacked image sensor shooting experiment.

Then, we evaporated zinc phthalocyanine (ZnPc) on the fabricated TFT under a pressure of 10^{-4} Pa with an evaporation rate of about 0.5 Å/s. The thickness of the ZnPc was 200 nm. Next, we evaporated lithium fluoride with a thickness of 1 nm, aluminum with a thickness of 7.5 nm, and gold with a thickness of 7.5 nm in a sequence as a counter electrode. The transmittance of the counter electrode was about 70% that of light with a wavelength ranging from 500 to 700 nm. Then, we formed an interlayer insulator

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DOI: 10.2352/ISSN.2470-1173.2016.12.IMSE-264

consisting of a buffer layer and a SiNx layer. The buffer layer coating had a thickness of 400 nm for panelizing the surface undulation. After curing the buffer layer at 150°C, a 2-μm-thick silicon nitride layer was deposited by plasma-enhanced chemical vapor deposition. Subsequently, we fabricated a TFT for a G-sensitive OPF following the same procedure as that for the R-sensitive OPF.[12)] As a G-sensitive OPF, 2,7-bis(9-carbazolyl)-9,9-sspirobifluorene (Spiro-2CBP) with a thickness of a 30 nm and quinacridone with a thickness of 100 nm were evaporated. By evaporating a 12-nm-thick Al counter electrode, we completed the fabrication of the R/G component.

We similarly fabricated the B component for B color imaging on another glass substrate. In the B component, an Alq3 and C30/C60 co-deposited film was used as the OPF for B color and indium–tin–oxide was used as the counter electrode.

Shooting experiment of stacked image sensor

A diagram of a shooting experiment with the stacked image sensor is presented in Fig. 6. An optical image was focused on the stacked image sensor using lenses. The B, G, and R output signals from the signal lines of the IGZO TFT readout circuits were converted to a color video signal by an analog-to-digital (A/D) converter and a signal processor, and the reproduced image was displayed on a color monitor. The gate voltage in the on- and off-state of the three IGZO TFTs were set from 6.0 to −6.0 V, 2.1 to −6.1 V, and 2.0 to −5.5 V for the B , G, and R components, respectively. The applied voltages of the organic films were set at 3.6, 6.3, and 4.5 V for the B- , G-, and R-sensitive films, respectively.

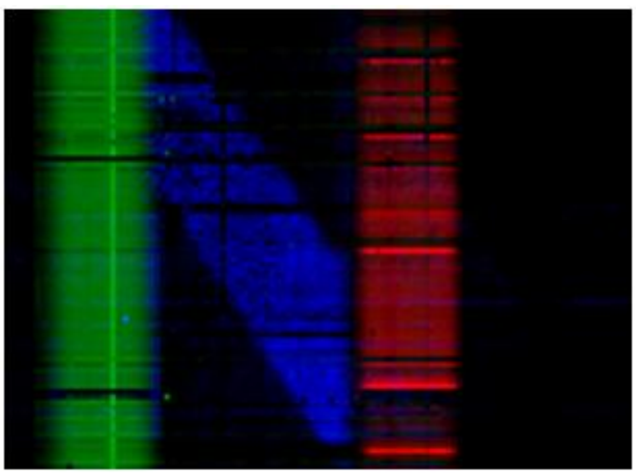

Fig. 7 Reproduced image taken with the stacked image sensor.

Figure 7 shows a reproduced image taken with the stacked image sensor at a 10-fps readout frame rate. The color image was obtained without conventional color separation optical systems such as a CFA or a prism, clearly demonstrating vertical color separation and signal output using only an alternately stacked structure of wavelength-selective organic films and IGZO TFT circuits.

Conclusions

A stacked image sensor with R/G and B components facing each other was fabricated. The number of sensor pixels was 128 × 96 for each color, and the pixel size was 100 × 100 μm^2. The stacked image sensor produced a color image at 10 fps with a resolution corresponding to the pixel numbers. We successfully improved the defects and fabrication loss in the structure with three stacked pairs of an OPF and a readout circuit.

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DOI: 10.2352/ISSN.2470-1173.2016.12.IMSE-264

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Mamoru Furuta (M'06) received the B.E. and M.E. degrees from the University of Electro-Communications, Tokyo, Japan, in 1988, and the D.Eng. degree from the Nara Institute of Sciences and Technology, Nara, Japan, in 2003. He is currently a Professor with the Center for Nanotechnology in Research Institute, Department of Environmental Science and Engineering, Kochi University of Technology, Kami, Japan..