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QVGA Color Image Sensor Comprising Blue/Green-sensitive Organic Films with ITZO TFT Readout Circuits Stacked on CMOS Image Sensor

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Abstract

In this paper, we describe a three-layer stacked color image sensor comprising two organic photoconductive films (OPFs) with thin-film transistor-based readout circuits and a CMOS image sensor (CIS). Color video imaging operation at 60 frames per second of a prototype sensor with 320 × 240 pixels and a pixel pitch of 20 μm was confirmed without a color filter array, and good color separation of the sensor was achieved owing to the combination of the CIS and the color-selective OPFs.

1. Introduction

Recently, the requirements for high-resolution imaging in video systems have increased, such as 4K and 8K resolutions. A CMOS image sensor (CIS) with a Bayer pattern color filter array (CFA) is mainly used in modern high-resolution cameras. From the viewpoint of the pixel arrangement, the use of a CFA reduces the resolution owing to the demosaicing process and some loss of incident light. For instance, a blue (B) pixel in the CFA can only detect B light and loses green (G) and red (R) light. To deal with these problems, a three-layer CIS comprising vertically stacked Si photodiodes was proposed and commercialized [1]. Moreover, a three-layer stacked color image sensor comprising two-layer stacked Si photodiodes on a Si substrate and an organic photoconductive film (OPF) for detecting G light above the Si photodiodes to improve the spectral characteristics was reported [2]. However, spectral crosstalk was still observed between the Si photodiodes for B and R light because of the nonselective absorption of Si in the visible light region.

Meanwhile, we have studied a new type of image sensor with a structure in which three OPFs sensitive to the primary colors and three thin-film transistor (TFT)-based readout circuits that transmit visible light are stacked alternately [3]. We have also prototyped a three-layer stacked sensor with OPFs that had 128 × 96 pixels with 50 μm pixel pitch, and it performed color separation in the vertical direction without a CFA [4].

In the present study, we developed a three-layer stacked color image sensor comprising two OPFs with TFTs and a CIS for the first time. This sensor has a high number of pixels of 320 × 240 (QVGA) and a small pixel pitch of 20 μm. The color video imaging operation of the sensor was confirmed, and low spectral crosstalk was achieved owing to the integration of the CIS and the color-selective OPFs.

2. Device configuration and fabrication

Fig. 1 shows the structure of the fabricated three-layer stacked sensor. The top, middle, and bottom layers are B-, G-, and R-sensitive layers, respectively. The B layer is an OPF that is sensitive only to B light, and the OPF was deposited on a glass substrate with an indium tin zinc oxide (ITZO) TFT array to read out the signal detected by the OPF. The G layer is a G-sensitive OPF that was deposited on a Si substrate, with the ITZO TFT array fabricated on a CIS.

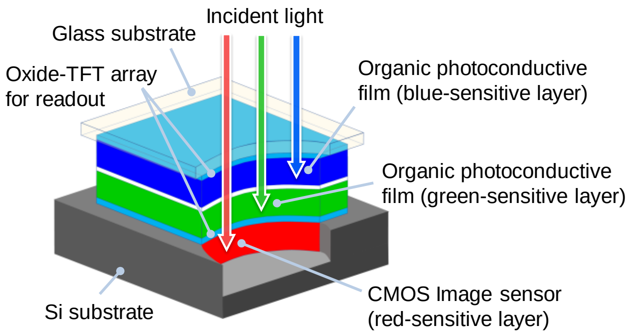

Fig. 1 Schematic of fabricated three-layer stacked image sensor.

We designed the TFT readout circuits in both the B and G layers to have the same architecture, with each pixel consisting of an indium tin oxide (ITO) pixel electrode and a TFT switch. We fabricated the bottom-gate staggered-structure TFT by the following six mask steps: patterning gate electrodes with a 50-nm-thick molybdenum (Mo) alloy, depositing a gate insulator consisting of a silicon oxide (SiO_x)/aluminum oxide (AlO_x) double layer with a total thickness of 150 nm, forming a 50-nm-thick ITO pixel electrode, patterning a 30-nm-thick ITZO semiconductor layer, opening via holes by reactive ion etching, and patterning source and drain electrodes with a 70-nm-thick Mo alloy. Finally, a spin-coated organic passivation layer with a thickness of 600 nm was formed. The channel width/length of the TFT was 4 μm/2 μm. Thereafter, a 200-nm-thick OPF and a 15-nm-thick aluminum (Al) counter electrode were overlaid on the TFT array to apply a bias voltage. Note that pixel separation in the OPF and counter electrode is not required owing to the high horizontal resistance of the organic film. The organic photoelectric conversion materials used for the B and G layers were a dinaphthothienothiophene (DNTT) derivative and quinacridone (QA):3',4'-dibutyl-5,5''-bis(dicyanovinyl)-2,2':5', 2''-

terthiophene (DCV-3T) mixed films, respectively.

The CIS was designed to have an active-pixel and front-side illumination structure, and a CMOS wafer was fabricated with 0.18 μm 1-poly 5-metal CIS technology. The CIS layer is located at the bottom of the three-layer stacked structure and is the R layer of the sensor. When light enters the three-layer stacked sensor, the B and G components of the light are selectively absorbed by the OPFs placed over the CIS. On the other hand, the R component reaches the bottom CIS by passing through the OPFs and TFT circuits. Consequently, the bottom CIS acts as an R-sensitive layer.

The B layer was fabricated on the glass substrate and the G/R layers were fabricated on the Si substrate. The number of pixels and pixel pitch of the sensor were 320 × 240 and 20 μm, respectively. The device configuration is summarized in Table I.

Table I Configuration of three-layer stacked image sensor

Layer	Photoactive material	Pixel architecture	Pixel number / pixel pitch
Blue (top)	DNTT derivative	Passive pixel with ITZO TFT	320(H) × 240(V) / 20 μm
Green (middle)	QA:DCV-3T mixed	Passive pixel with ITZO TFT	320(H) × 240(V) / 20 μm
Red (bottom)	Si	Active pixel with 4 Si transistors	320(H) × 240(V) / 20 μm

The B layer was stacked mechanically on the G/R layers. When assembling the three-layer stacked sensor, each layer is required to be in the proximity of the other layers so that an optical image projected by a lens can be focused on all the layers. As shown in Fig. 2, the three-layer structure was fabricated by placing the glass chip, or the B layer, face down above the Si chip, or the G/R layers, and then the glass chip was approached as close as several tens of micrometers to the surface of the Si chip.

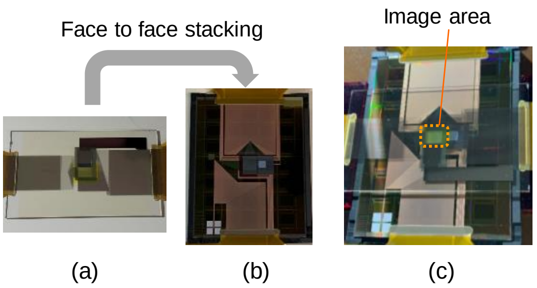

Fig. 2 Photographs of (a) B-sensitive sensor chip fabricated on glass substrate, (b) G/R-sensitive sensor chip on Si substrate, and (c) three-layer stacked image sensor fabricated by combining the two chips. When forming the three-layer stacked structure, the glass chip surface was placed face down on the surface of the Si chip.

3. Operation of three-layer stacked image sensor

To operate the sensor, the assembled Si and glass chips were connected to external driving circuit boards through flexible printed circuits (FPCs), and interconnections between these chips and FPCs were formed using anisotropic conductive films. The output signal that was read out outside of the pixel region of each layer was sampled by each off-chip analog-to-digital converter, then the signal was processed.

Fig. 3 shows the normalized spectral sensitivity of each layer of the three-layer stacked sensor. Monochromatic light entered from the top side, that is, the B layer, of the sensor and the photoresponses were measured. As shown in Fig. 3, the B layer had sensitivity in the B-light region. The G layer mainly had sensitivity in the G-light region. The G layer also showed limited sensitivity in the B-light region because not all the B light was absorbed by the 200-nm-thick B-sensitive OPF. The R layer consisting of the CIS only exhibited significant sensitivity in the R-light region, which was attributed to the almost complete absorption of B and G light by the two OPFs above the CIS.

Fig. 4 shows color images (320 × 240 pixels) taken by the fabricated three-layer stacked sensor at 60 frames per second (fps). We successfully confirmed the operation of the sensor at 60 fps, and the images captured by each layer were in focus because the layers were sufficiently close to one another.

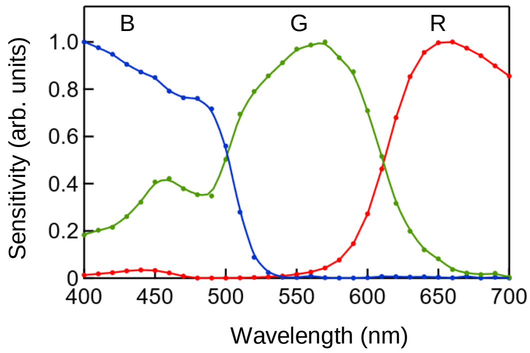

Fig. 3 Normalized spectral sensitivity of three-layer stacked sensor.

Fig. 4 Color images taken by fabricated three-layer stacked sensor.

4. Conclusions

We developed a three-layer stacked color image sensor comprising two OPFs with TFTs and a CIS for the first time. We also successfully fabricated a sensor that had a higher number of pixels (320 × 240, QVGA). Color video imaging operation of the sensor at 60 fps was confirmed without a CFA, and less spectral crosstalk than that of the previous sensor was achieved owing to the integration of the CIS and the color-selective OPFs.

References

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