Optical characteristics of multi-storied photodiode CMOS image sensor with 3D stacking technology

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Abstract

We developed multiband imaging with a multi-storied photodiode CMOS image sensor (CIS), which comprises two photodiode (PD) arrays that capture two different images, that is, visible red, green, and blue (RGB) and near infrared (NIR) images, at the same time [1].

The sensor is able to capture a wide variety of multiband images at the same time and is not limited to conventional visible RGB images taken with a Bayer filter or to invisible NIR images. Its wiring layers, placed between two PD arrays, have an effect on the optical characteristics of the bottom PD array. The incident angle dependence of the bottom PD array shows that the thickness and structure of the wiring and bonding layers can act as an optical filter.

The CIS's wide range sensitivity and optimized optical filtering structure enable us to create images of specific bands of light waves in addition to visible RGB images without designated pixels for NIR images, thereby eliminating the problem of defective pixels for RGB images and the need for additional optical components.

Our sensor will push the envelope to capture a wide variety of multiband images

Introduction

There has been demand for a CMOS image sensor (CIS) that captures not only visible red, green, and blue (RGB) images but also invisible infrared (IR) images [2,3]. In the case of optical cameras, IR light is eliminated intentionally by inserting an IR cut filter in front of the surface of an image sensor to avoid color degradation. An IR signal, however, is suitable for getting additional information such as the veins lying beneath the skin because IR penetrates into skin more deeply than visible light [4,5].

Conventionally, RGB and NIR mixed images are made

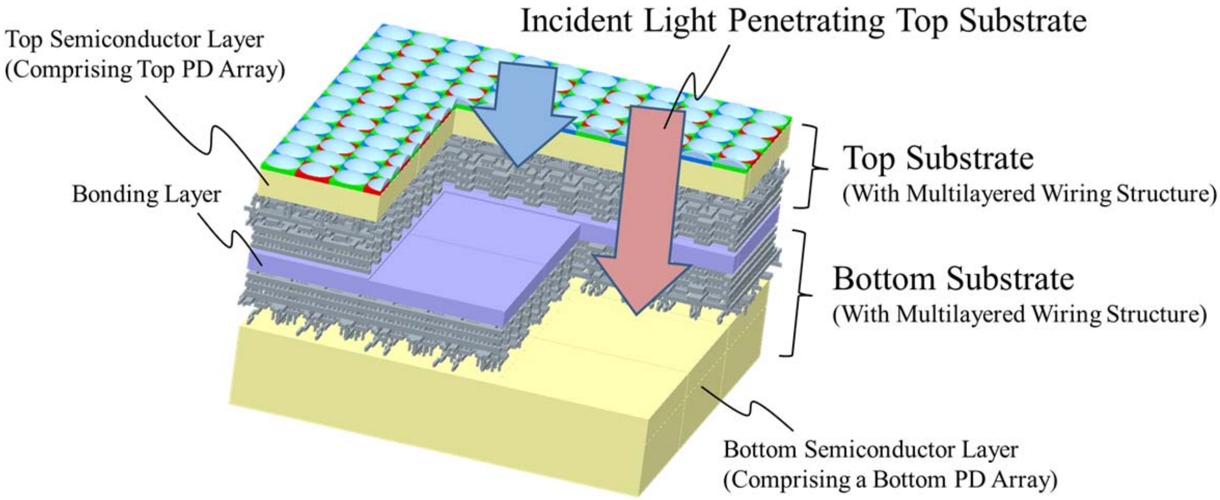


Fig. 1 Concept of multi-storied photodiode CMOS image sensor based on 3D stacking technology
The sensor comprises two semiconductor layers with PD arrays, one in the top and the other in the bottom semiconductor. The top PD array converts a part of incident light into corresponding signals and works as an optical filter for the bottom PD array. The bottom PD array converts light that penetrates through the top substrate, wiring layer, and bonding layer into signals, which means the top substrate acts mainly as a visible light sensor, and the bottom one acts as an invisible IR light sensor.

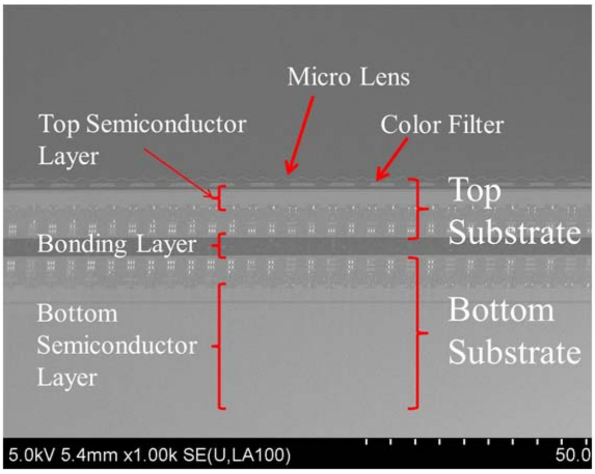
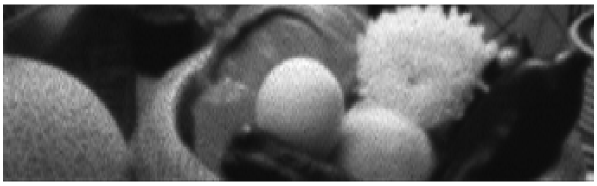


Fig. 2 Cross sectional SEM image of image sensor
Two substrates are bonded, and both have a semiconductor layer. Micro lenses and color filters lie on the top substrate. The thickness of the top semiconductor layer is 3 μm.

(a) RGB image taken by image sensor



(b) NIR image taken by image sensor

Fig. 3 RGB and NIR images taken by image sensor

by combining two different images taken by two CISs with a dichroic mirror, which separates visible RGB light and NIR light. This combination method requires additional optical components and precise placement adjustment in order to make two images have the exact same frame. This method achieves the best quality possible for each type of image; however, the additional components increase the cost and difficulty of assembly. One method uses an NIR color filter in place of the RGB color filter, which means that the pixels with the NIR filter become defective pixels for RGB images [5]. This method can get RGB and NIR mixed images at the same time; however, pixel interpolation is needed to construct the RGB image.

As a sophisticated and effective way to capture a wide variety of multiband images, that is, RGB and NIR images, at the same time without any image degradation and additional optical components, we propose and demonstrate a multi-storied photodiode (PD) CIS that uses 3D stacking technology.

Concept and structure

The concept of the multi-storied PD CIS based on 3D silicon stacking technology is shown in Fig. 1. It comprises two layers of PD arrays to take RGB images and NIR images. The top substrate has a pixel array for mainly RGB images, and the bottom substrate has a pixel array for IR images. There are micro lenses and color filters, red, green and blue ones, on the top substrate. This means that the CIS splits incident light into six kinds of signals, that is, RGB signals in the top substrate, and in the bottom substrate, the other three optical signals passing through each color filter and the top semiconductor layer. Figure 2 shows a cross-sectional SEM image of the CIS. The distance between the bottom and top semiconductor substrates, which includes two wiring layers and one bonding layer, is 15 μm, and the thickness of the top semiconductor substrate is 3 μm. The PDs in the top substrate convert a part of incident light into corresponding signals, and the top semiconductor substrate, wiring layers, and bonding layer work as an optical filter for PDs in the bottom substrate. The bottom PDs convert light that penetrates through the top substrate into signals, which means that the top PDs act as a visible light sensor, and the bottom PDs act as an invisible NIR light sensor. An RGB image and NIR image taken with the CIS are shown in Fig. 3.

Measurement results and discussion

Figure 4 shows spectral sensitivities of PDs in the bottom substrate. Three types of color filters are arranged on the top substrate, and the incident light penetrates the color filter and the top substrate before reaching the bottom substrate. Then, there are three types of PDs in the bottom substrate: PDs under blue, green, and red color filters. The PDs in the bottom substrate are aligned with the PDs in the top substrate to be precisely located right under it, which means that incoming light for the PDs in the bottom substrate passes through the color filters and the top semiconductor layer. Measured and calculated normalized quantum efficiencies of the bottom PDs are shown by dots and dotted lines, respectively. The measured normalized quantum efficiencies show the

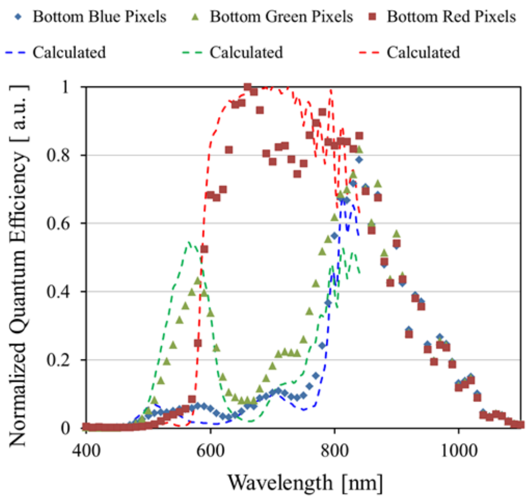
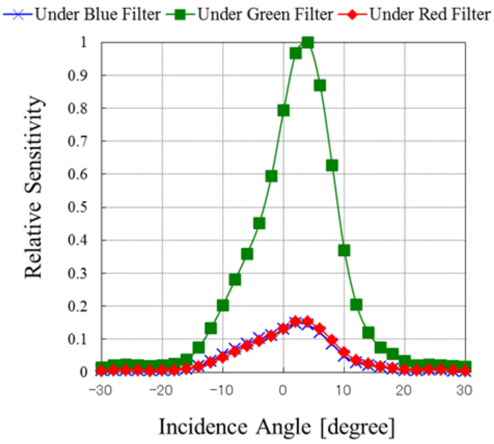


Fig. 4 Measured and calculated normalized quantum efficiency of bottom PD array

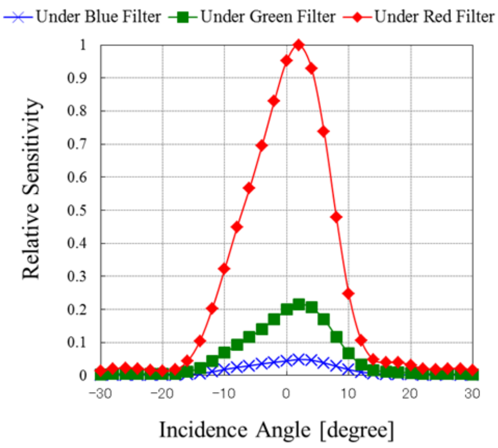
NIR signals are detected by the bottom PD array, which comprises three types of pixels corresponding to the color filters on the top substrate.

same tendency as calculations with the optical constants of the filters and the substrate materials. The CIS comprises six kinds of PDs whose spectral sensitivities depends on the thickness of the top semiconductor layer and the color filters.

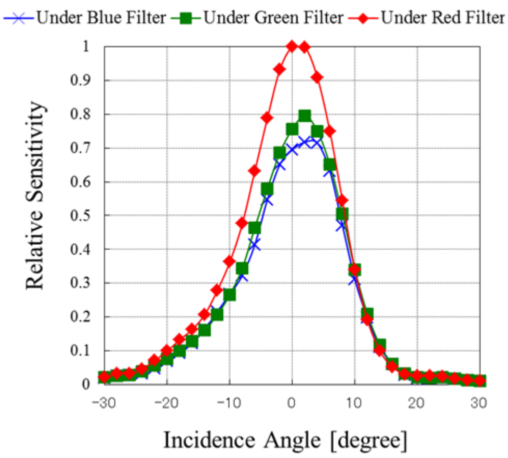
Figure 5 shows the incident angle dependence of the normalized sensitivities of the PDs in the bottom substrate measured with 560-, 640- and 800-nm wavelength light, respectively. The two substrates were aligned precisely within an accuracy of 0.2 μm, and both pixel sizes were 3.8 μm. Their sensitivity strongly depended on the incident angle of light because the wiring layers between both substrates also work as a kind of filter and the total thickness of the wiring layers and the bonding layer was 15 μm. Figure 6 shows a cross-sectional schematic diagram of the CIS. The incident light after penetrating the top semiconductor layer, two wiring layers, and bonding layer, reaches the bottom PDs. The incident light angle for the bottom PDs is less than 14 degrees because of the geometries of the wiring layouts. The measurement results show a relatively low sensitivity of over 10 degrees because the incident light is screened by the wiring layers. This means that we can design and control the incident angle characteristics of the bottom PDs by modifying the wiring layer layouts and structure along with the optical design to meet specifications. In this case, our CIS has as much as six layers of metal wiring, which limit incident light angle as shown and degrades the sensitivity of the bottom PDs. It is possible to improve the sensibility by as much as twice by reducing the number of



(a) with 560-nm wavelength light



(b) with 640-nm wavelength light



(c) with 800-nm wavelength light

Fig. 5 Angle dependence of normalized sensitivity of bottom PDs with 560-, 640-, and 800-nm wavelength light

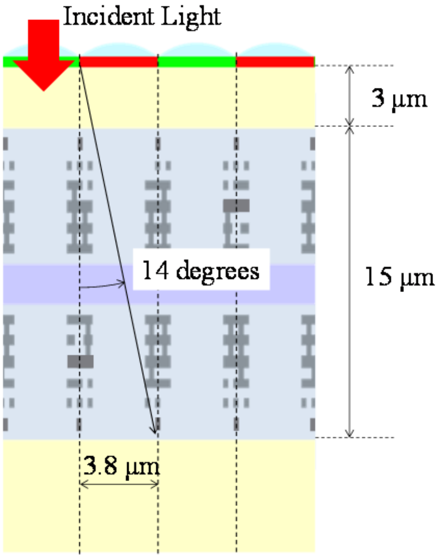


Fig. 6 Cross-sectional schematic diagram of CIS
Incident light penetrates the top semiconductor layer, two wiring layers, and bonding layer and reaches the bottom PDs.

wiring layers to three layers in each CIS and broadening the incident light angle limit.

Conclusion

We demonstrated multiband imaging with a multi-storied PD CIS, which comprises two individually functioning layered devices in different substrates bonded by our 3D technology. The sensor was confirmed to capture a wide variety of multiband images at the same time without additional optical components. We showed that the incident angle characteristics of the bottom PDs can be modified by adjusting the wiring layer layouts and structure.

This multi-storied PD array concept will push the envelope to achieve not only multiband imaging but also other functions like distance measurement or phase difference detection for lens focusing.

References

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