IR/Color Composite Image Sensor with VIPS(Vertically Integrated Photodiode Structure)

Jeong-Ho Lyu, †Seok Choi, Jae Heon Choi, †Jung Hyun Nam, and †Jin Bok Jung

†*Miru Data System Co., Ltd.*
Maru LSI Co., Ltd.,
5F, Changhwa B/D, 1005-5, Yeongtong-dong, Yeongtong-gu, Suwon, Korea
TEL: +82-31-205-5786, FAX: +82-31-205-5784
E-mail: jlyu@marulsi.com

Abstract

The CMOS image sensor having VIPS(Vertically Integrated Photodiode Structure) was fabricated for the first time. By adding the high energy(~3MeV) ion implantation to the conventional CIS(CMOS Image Sensor) process, it was verified that the deep photo diode was successfully formed under the normal photodiode on a pixel. And it was observed that this image sensor can detect the visual image and near IR(Infra Red) image at the same time and distinguish the two images.

I. Introduction

It has several advantages for the image processing to obtain separate information of visible range and near IR range at the same time[1], especially in the surveillance system. For example, one can differentiate the patterns from the heated object or from the object which has a different IR absorptivity. Also, the IR cut filter which is implemented on the top of the lens can be removed from the commercial area image sensors. The NIR range below 1.1μm can be detected in the Silicon image sensors. But using the normal photodiode structures or layered photodiode, there is no way to distinguish the IR signal with the R,G, B signal[2], [3].

In this paper, the image sensor which can detect the near IR range is successfully integrated with the image sensor for the visible range detection using the conventional Si CMOS process. Though the basic idea of this structure was already patented[4], we combined it with the most advanced active pixel technology with on-chip color filter and it was realized practically on Si wafer for the first time. From this sensor which is called VIPS(Vertically Integrated Photodiode Structure), it is observed that the information about the visible range and IR range can be obtained simultaneously within a frame separately.

II. Design and Fabrication of the Sensor

As shown in Figure 1, the maximum wavelength that can be detected by Si CMOS type image sensor is about 1.1μm(λ_c cutoff wavelength) which corresponds to the band gap energy of Si. The absorption coefficient from 1.1μm to 1.5μm is almost zero. The absorption in the region longer than 1.5μm is well explained in the literature[5]. Also, considering the black body radiation of this λ_c, it will determine the temperature of the heated object that can be measured by Si CMOS image sensor. From the Figure 1, the minimum temperature is around 600K. To detect and differentiate the signal of the longer wavelength, the depth of the photodiode for IR signal should be deeper and wider than the normal photodiode. Figure 2 shows the schematic cross-section of VIPS. Compared to the normal image sensors, the pixel for the IR detection is added and the photo diode is located under the normal pixels. And the color filters for the R, G, B selection can be used as the normal color image sensors because the IR light can penetrate these filters. Because of this array type, the resolution of IR image will be a quarter of visible image. The depth and the width of the photo diode determine the spectrum range of detection. To measure the longer wavelength, the deeper and the wider photo diode should be implemented. But there is a limitation of the ion implantation with the Si CMOS process. Therefore the trade-off between the detectible range of light and the process compatibility should be considered carefully. In conventional Si CMOS process, the maximum projected range by the high energy ion implantation is about 2~3μm. Because the depth of normal photo diode is about 0.5μm, two different photodiodes can be integrated vertically and well isolated each other. In Figure 3, there is a pixel layout that we have fabricated. For normal area sensors, the Bayer pattern was used for a color filter formation. Already mentioned earlier, the IR pixel is located among the four normal pixels. And this IR pixel also have the TG(Transfer Gate) signal and the RG(Reset Gate) signal as same as the normal pixel. And the symmetry is maintained with the normal pixel array. In this paper, we have used the 4-transistor type normal image sensors which consists of TG, RG, SG(Source follower Gate), Sx(Source follower selection switch). Based on the pixel architecture and the array, the full chip was fabricated as in Figure 4. The total effective array number of active pixel is

640×480 for VGA operation. Each pixel size is 7.5μm ×7.5μm. The left vertical driver is for the operation of the vertical line of normal pixel array and the right vertical driver is for the IR pixel array. The operation of each vertical scanner can be selected by applying the synchronous signal separately and it will operate as a switch between IR image and visible image. The horizontal scanner is shared between two types operation. The output data from the each pixel is converted to the 10bit digitized data through the columnar ADC. The left and right vertical scanner should not operate at the same time, because the vertical signals are connected to each other to reduce the area consumption. In Figure 5, simplified circuit diagram of full chip is shown.

To fabricate VIPS, 0.25μm Si CMOS standard technology with 1 poly and 3 metal was used. In this technology, the operation voltage is 5.0V, 3.3V for IO. And 0.25μm design rule was applied to the pixel design. For the logic design, 0.5μm design rule was used. In Figure 6, the process flow is summarized. Compared to the conventional CMOS process, deep NW(NWell) process is just added to form the deep photo diode for IR range. This deep NW is implanted with phosphorous ion as high as the energy of 3MeV. In Figure 7, the simulation result of the potential profile in the photo diode is shown. The peak of the normal photo diode is near the 0.4μm and the peak of the deep NW is located about 2.7μm depth and the depletion region is reached to the 4μm almost. After the ion implantation of photodiode, TG, RG ion implantation was followed to adjust the threshold voltage of transfer transistor and reset transistor. Then the remaining processes – gate patterning, source/drain formation, silicidation, contact formation and the 3 metal process are similar to the standard CMOS process. For the color area image sensor, the color filter process to make the R, G, B pattern was done on the metal 3 layer. Figure 8 is the photograph of the packaged chip after fabrication.

III. Results

The doping profile was investigated by SIMS as shown in Figure 9. Boron doping concentration on the surface area is about 6×10^{18} cm^{-3}, it was formed to prevent the injection of the defect from the surface dangling bond. And the background Boron doping concentration is about $2\times10^{15}cm^{-3}$. In case of Phosphorous doping profile, there are two peaks. The peak at the left side is for the visible range photodiode and the peak in the right side was formed from the process of deep NW with high energy ion implantation. Considering the background doping concentration of Boron and the peak doping concentration of Phosphorous, it can be confirmed that the double photo diode is well established. To take the image from this chip, the test board was configured as in Figure 10. In Table 1, the characteristics of R, G, B pixels of VIPS image sensor was summarized. The responsivity can be enhanced by the optimization of the floating diffusion area. The thermography characteristic was investigated as shown in Figure 11 with the variation of the target temperature. The IR pixel signal that was taken at 823K shows bright image of the hot zone from the hot plate in Figure 11(b). Because the thermal radiation can not penetrate the IR-cut filter, there is a dark area at the bottom of the image. As the temperature of the target is decreased, the signal becomes weak. And below 670K, it is not easy to detect the output signal as in Figure 11(c). It can be said that the temperature detection limit of the sensor is about 623K which is expected from Figure 1. Also, R, G, B pixels can detect the thermal radiation with lower thermal responsivity than that of IR pixels.

In Figure 12, there are three images which were captured without IR cut filter at three different modes - RGB only, IR only, and composite mode. In RGB mode, the thermal radiation(~773K) of the hot plate is not yet shown. But in IR mode, there is a bright white region on the hot plate as in Figure 12(b). Also, this hot zone is appeared in the composite mode image with the mixed RGB and IR signals of Figure 12(c). In this image, the R, G, B, IR signal can be modified by using the 3×4 color correction matrix. Also, if the images of Figure 12(a) and (b) are processed, it is possible to recognize the object along the different IR absorptivity.

IV. Conclusion

The Silicon CMOS image sensor having vertically integrated photodiode structure was successfully fabricated for the first time using the standard 0.25μm CMOS technology and it was observed that this sensor can differentiate the IR signal from the visible signal. Using this sensor, the thermography characteristic was investigated and the detectible limit was measured.

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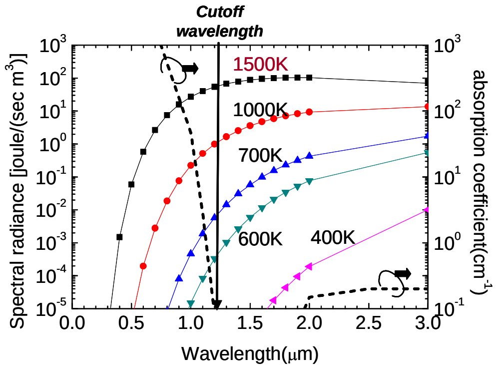


Fig. 1. Calculated Spectral radiance and absorption coefficient from the literature[4] along the wavelength.

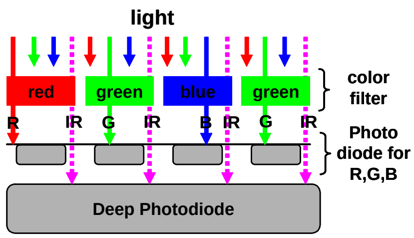


Fig. 2. Schematic cross-section of VIPS and the range of visible wavelength.

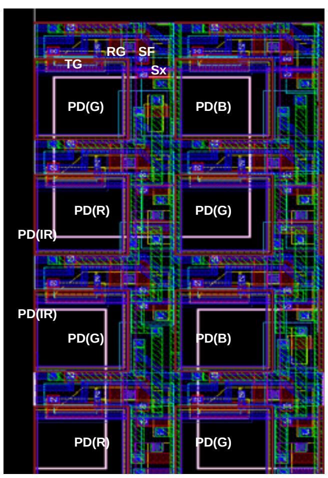


Fig. 3. Layout of pixel array.

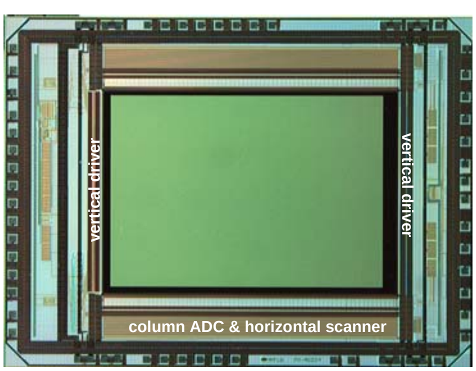


Fig. 4. Microphotograph of VIPS image sensor.

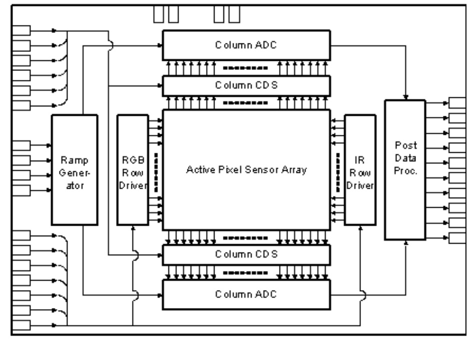


Fig. 5. Schematic circuit diagram of the area image sensor.

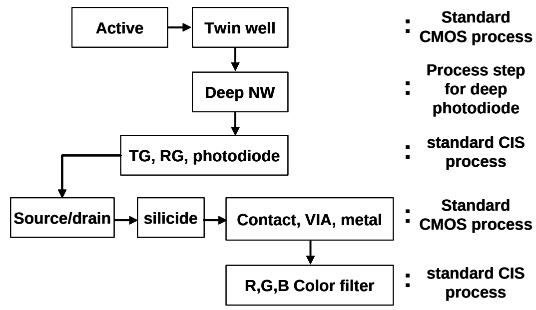
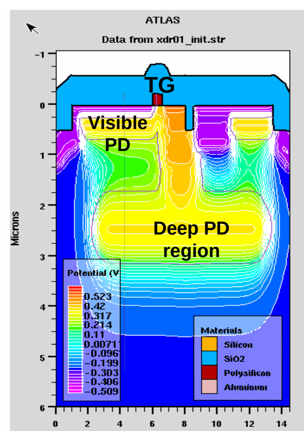


Fig. 6. Summarized process flow.



(a) 2-dimensional potential profile

Fig. 7. Simulated vertical potential profile of the pixel architecture.

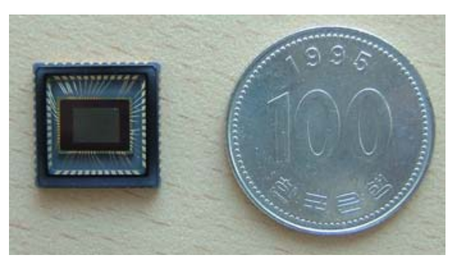


Fig. 8. Packaged chip photograph compared to Korean coin.

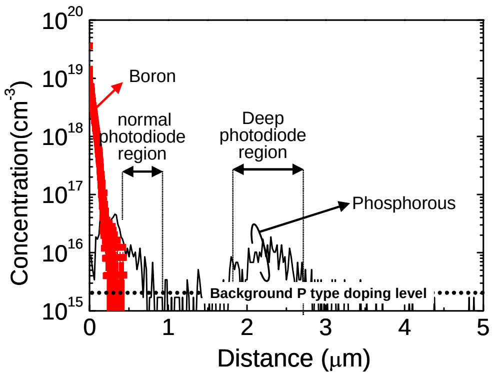


Fig. 9. Doping profile of Boron and Phosphorous in the photo diode region.

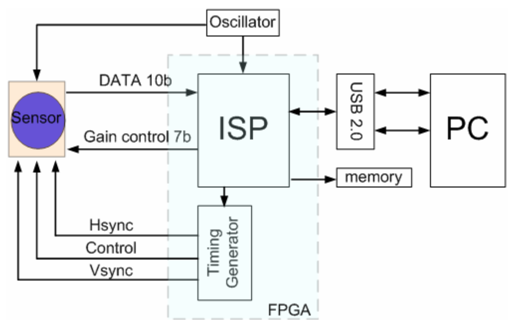
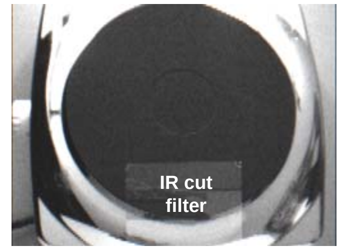


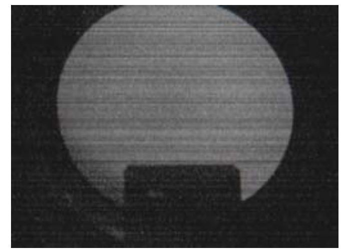
Fig. 10. Simplified schematic of the image test board.

Table. 1. Specification and characteristics of VIPS.

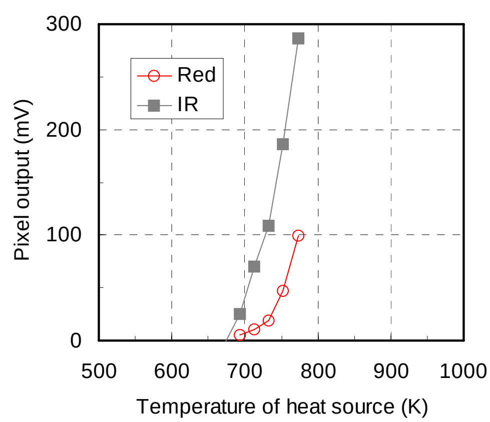
Process technology	0.25μm, 1P3M, CMOS
Optical format	1/3 inch
Pixel size	7.5μm × 7.5μm
Effective pixel array	640 × 480
saturation	1400mV
Responsivity	2.4V/lux·sec
Dark current	< 10mV/sec @ 20°C



(a) Image of hot plate at 300K

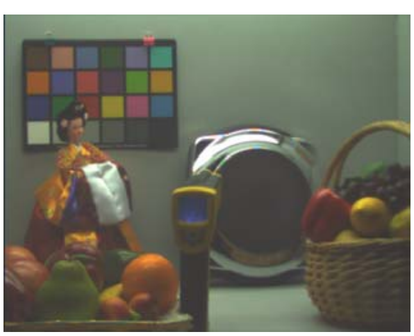


(b) Image of hot plate at 823K under zero lux



(c) Thermal responsivity

Fig. 11. Thermograph of hot plate and the thermal responsivity.



(a) normal RGB mode image

(b) IR mode image

(c) RGB + IR composite image

Fig. 12. Captured images with high temperature(773K) hot plate in RGB, IR, and composite mode without IR cut filter.