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Side-Illuminated Color Photo Sensor

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1. Introduction

Silicon sensors can detect light from the visible region to the near-infrared region, with a wavelength range of 400 nm-1100 nm. However, conventional silicon sensors themselves do not have the ability to distinguish colors. Therefore, for color imaging purposes, the Bayer method using a color filter is used in practical applications [1]. However, in the process of obtaining the color information, there are problems with the generation of false colors and moiré patterns. The Foveon method is another well-known color imaging method [2]. This method uses a pixel structure that alternately forms N-type, P-type, and N-type silicon layers on a P-type silicon substrate. In this method, color imaging is possible without using a color filter, and false colors and moiré patterns do not occur. However, because the signal electrode is not independent of each PN junction layer, an extraction operation is necessary to separate the color signals. Also, a special process is needed to form the three-layer NPN silicon region precisely. In this paper, we propose a side-illuminated color photo sensor which allows light to be injected from the side of the silicon substrate. The proposed method uses a standard silicon CMOS process, which reduces costs and enables color imaging without using color filters. Also, because each of the PN junctions is isolated from the others, the color information can be separated easily. To confirm the effectiveness of the proposed method, we fabricated a test chip and evaluated the color separation characteristics for visible to near-infrared light.

2. Side-Illuminated Color Photo Sensor

Figure 1 shows a cross section of the pixel structure of the proposed side-illuminated color photo sensor. Generated charges (electron-hole pairs) are collected in the depletion region which forms at the PN junction. On the surface of the P-type silicon substrate, four N-type silicon areas are formed in turn from the incident direction side of the light. Also, to minimize the attenuation of the incident light, the side area is removed to a depth *d*. It is also desirable that the width of the silicon from the chip side to the photodiode edge, denoted by *r*, is short.

All of the blue (*B*) + green (*G*) + red (*R*) + infrared (*IR*) light (signal value: α) penetrates the 1st area. Because the blue light, which has the shortest wavelength, does not reach the 2nd area, this area reacts to *G*+*R*+*IR* light (signal value: β). Similarly, in the 3rd area, this area reacts only to *R*+*IR* light (signal value: γ) because the *B* and *G* lights were absorbed by the 1st and 2nd areas. The 4th area reacts to the *IR* light only (signal value: δ). Therefore, *R* can be found by subtracting the *IR* value obtained in the 4th area from the γ value obtained in the 3rd area. Subsequently, *G* can be found by subtracting *R*+*IR* from the β value obtained in the 2nd area, and *B* can be found by subtracting *G*+*R*+*IR* from the α value obtained in the 1st area. The above arithmetic process can be summarized in matrix notation as eq. (1).

$$\begin{pmatrix} B \\ G \\ R \\ IR \end{pmatrix} = \begin{pmatrix} a_{11} & -a_{12} & -a_{13} & -a_{14} \\ 0 & a_{22} & -a_{23} & -a_{24} \\ 0 & 0 & a_{33} & -a_{34} \\ 0 & 0 & 0 & a_{44} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix} \tag{1}$$

In our proposed method, color information can be obtained easily using a single pixel and without a color filter.

3. Fabrication of a Test Chip

Figure 2 shows a microphotograph of the test chip, which was fabricated using a 1-poly 4-metal 0.35 μm CMOS process. The chip dimensions are 5000×5000 μm, and the silicon substrate thickness is 730 μm. Three types of line sensor circuit with varying margin *r* from the photodiode edge were placed in this test chip. The values of *r* in sensor circuits A, B, and C were 0.0 μm, 1.0 μm, and 2.0 μm, respectively. Each of these sensors was formed using a 128-pixel array with a pixel pitch of 9 μm. Also, the sensor surfaces were coated with a metal layer for shading. The sensors can therefore only detect the incident light from the side. Figures 3 and 4 show the pixel circuit and the layout, respectively. The lengths *L* for each of the 1st, 2nd, 3rd, and 4th photodetection areas are 0.7 μm, 0.7 μm, 2.0 μm, and 40 μm, respectively. The space between each of these photodetection areas is 0.6 μm. The metal layer used to shade the circuit also works as a mask when the side area is removed. The hatched area (side area) in the test chip shown in Figure 2 is 1000 μm wide and 5000 μm long. The area was etched to a depth of approximately *d*=80 μm by a combination of buffered hydrofluoric acid (BHF) and reactive ion etching (RIE) for the SiO_2 layer and a conventional deep-RIE for the Si substrate. Figure 5 shows a microphotograph of the test chip after the RIE process.

4. Measurement Results

A light irradiation experiment was performed on the test chip, and the color separation characteristics were obtained over the range of colors from visible to near-infrared light. A variable-wavelength type tungsten single color light source was used as the light source. The detection signals (α, β, γ, δ) from each photodetection area were converted into color information (*B*, *G*, *R*, *IR*) offline. The matrix parameters used were as follows: a_{11}=1.0, a_{12}=0.5, a_{13}=0.2, a_{14}=0.1, a_{22}=2.0, a_{23}=0.1, a_{24}=0.4, a_{33}=1.5, a_{34}=0.1, and a_{44}=0.8.

Because sensor circuit A was not operational, we used sensor circuit B. Figure 6 shows the measurement results for fixed pattern noise (FPN) and random noise (RN) for sensor circuit B before and after the removal of the side area. The fact that the results for both noise patterns remained largely unchanged after the RIE process indicates that little damage was caused during the RIE process.

Figure 7 shows the color separation characteristics obtained using sensor circuit B. Although there is expansion of the separation characteristics, the four colors can be separated. The peak wavelengths for *B*, *G*, *R*, and *IR* are 480 nm, 650 nm, 775 nm, and 925 nm, respectively. For both *G* and *R*, the peak wavelength shifted to the longer wavelength side of the real color range. This is because the photodetection areas designed in 0.35 μm CMOS technology are long and the spacing between each area is wide. Figure 8 shows simulation results for the color separation characteristics when using 0.18 μm CMOS technology, which can lower the size of these elements. The separation characteristics of *B*, *G*, *R*, and *IR* are better, and each of their peak wavelengths can be set appropriately to 480 nm, 570 nm, 640nm, and 810 nm, respectively. This simulation shows that better color separation characteristics could possibly be obtained if 0.18 μm CMOS structures are used.

5. Conclusions

We have confirmed that colors can be separated by the proposed pixel structure without the use of a color filter. This structure used multiple photodiodes placed along the optical path from the side. To obtain accurate color separation characteristics, it is necessary to design each photodetection area to be shorter and to be spaced more narrowly. The proposed method can only be used to form line sensors. However, an image sensor could be formed by first thinning the substrate used in the proposed sensor, and then laminating several sensors together to form an image sensor [3].

Acknowledgements

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References

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[2] Richard Billings Merrill, U. S. Patent 5,965,875, October 1999 (filed 1998).
[3] T.Ariyoshi, N.Uryu, A.Baba, and Y.Arima, Jpn. J. Appl. Phys. 51 (2012) 02BE01.

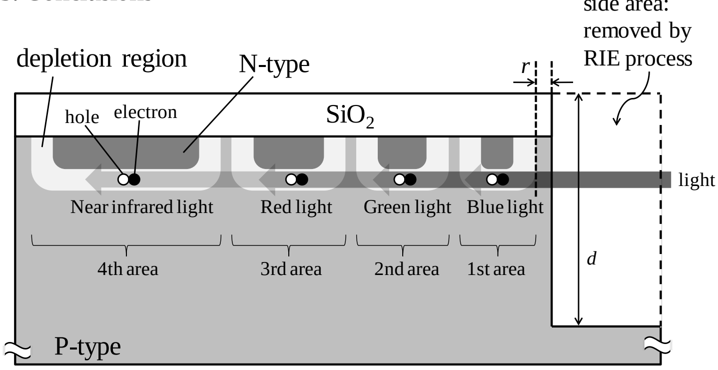

Fig.1. Cross-section of the proposed side-illuminated color photo sensor.

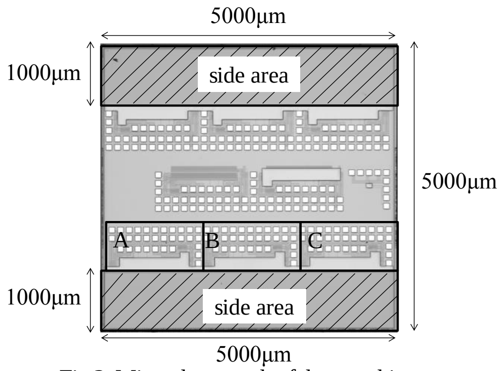

Fig.2. Microphotograph of the test chip.

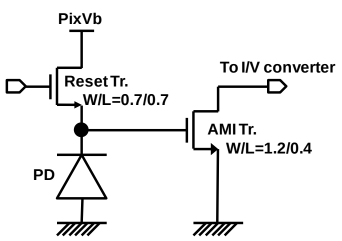

Fig. 3. Pixel circuit.

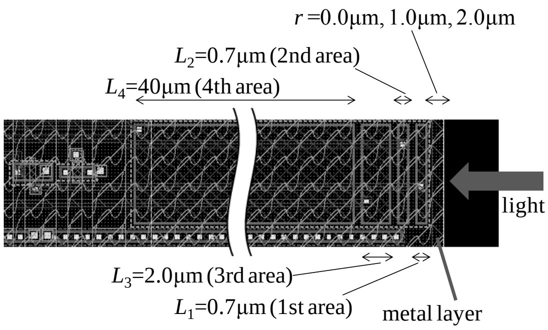

Fig.4. Pixel layout.

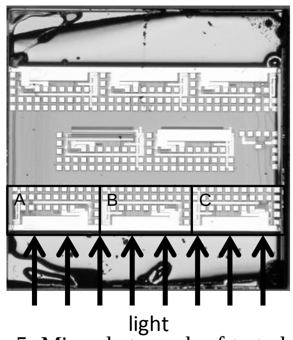

Fig.5. Microphotograph of test chip after RIE process.

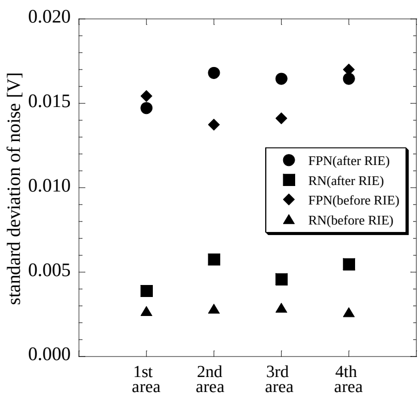

Fig.6. Measured noise.

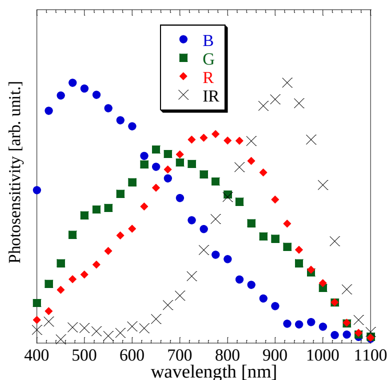

Fig.7. Measurement results for the color separation characteristics.

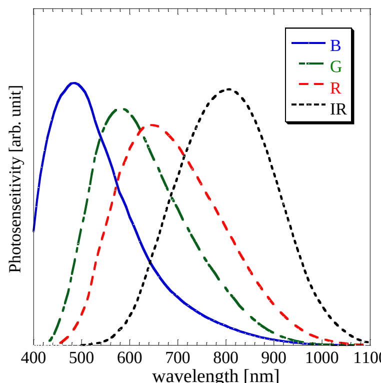

Fig.8. Simulation results for the separation characteristics when using 0.18 μm CMOS rule.