

High Sensitivity Color CMOS Image Sensor with WRGB Color Filter Array and Color Separation Process Using Edge Detection

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ABSTRACT

We have developed a CMOS image sensor with a novel color filter array (CFA) where one of the green pixels of the Bayer pattern was replaced with a white pixel. A transparent layer has been fabricated on the white pixel instead of a color filter to realize over 95% transmission for visible light with wavelengths of 400-700 nm. Pixel pitch of the device was 3.3 μm and the number of pixels was 2 million (1600H x 1200V). By introducing the Bayer-like White-Red-Green-Blue (WRGB) CFA and by using the low-noise color separation process, signal-to-noise ratio (SNR) was improved. Low-illumination SNRs of interpolated R , G , and B values have been increased by 6dB, 1dB, and 6dB respectively, compared with those of the Bayer pattern. The false color signals at the edge have been suppressed by newly developed color separation process using edge detection. This new CFA has a great potential to significantly increase the sensitivity of CMOS/CCD image sensors with digital signal processing technology.

1 INTRODUCTION

A basic trend toward smaller pixels for CMOS image sensors allows a huge number of pixels (more than 10M pixels), but causes decrease of the photodiode area, resulting in decrease of incident photon number.

Moreover, in case of color CMOS image sensors, the color filter loses as much as 2/3 of incident energy.

Conventionally, the pixel area consists of 2 x 2 'unit blocks' that include two green pixels diagonally, one red pixel and one blue pixel (as expressed in Fig.1). This layout of the color filter array (CFA) is called 'Bayer pattern' [1]. The reason why twice as many green pixels are placed as red and blue pixels is that the human eye is most sensitive to green and the green pixel represents the luminance signal of the incident image. As for the YUV color space, luminance signal Y is expressed as follows:

$$Y = 0.59G + 0.30R + 0.11B \quad (1)$$

Here G , R , and B mean output digital value of green, red, and blue signals, respectively.

Since luminance signal Y depends greatly on G , Bayer layout has twice as many green pixels as red or blue pixels. However, the need for higher signal-to-noise ratios (SNRs) of red and blue signals is growing.

We developed a CFA including 'white pixels' and the pre-digital low-noise signal processing to process the output values from the CFA, which realize higher SNR of R , G , and B signals compared with the Bayer pattern [2].

2 BAYER-LIKE WRGB COLOR FILTER ARRAY

Figure 1 shows the Bayer layout and the newly developed Bayer-like WRGB layout. In a 2 x 2 unit block one of the two green pixels was replaced with a 'white' pixel. The red, green, and blue pixels have a color filter layer (colored resin film) over the passivation layer.

For the 'white' pixel, a transparent resin film was fabricated instead of a color filter to realize high transmission of visible light with wavelengths of 400-700 nm.

The white pixel was introduced because the incident light is not lost compared with a green pixel.

The reason why 'WRGB' CFA was adopted is that the color representation is maintained by having primary color pixels. Moreover, for complementary CFAs, a reduction is caused in SNR due to subtraction operation during the color conversion [3].

Microlenses are fabricated on each pixel.

The pixel pitch of the device is 3.3 μm and pixel number is 1600x1200 (2 megapixels).



Fig. 1. 2 x 2 unit pixel blocks of the Bayer Pattern (left) and the newly developed the Bayer-like WRGB Pattern (right).

Figure 2 shows the spectral sensitivity of each color pixel of WRGB CFA device. The white pixel has higher spectral sensitivity than any of the color pixels in the wavelength of 400-700nm.

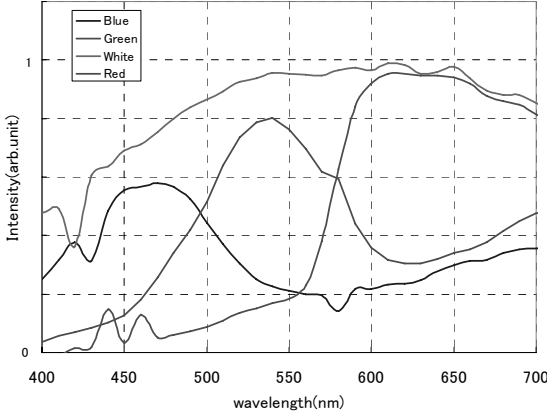


Fig. 2 Spectral sensitivity of each pixel in the Bayer-like WRGB CFA.

3 DIGITAL SIGNAL PROCESSING

3.1 Low-noise color separation process

Since the signal from the white pixel has much luminance information but no color information, we have developed a low-noise color separation process to separate W signal value into R , G , and B signal values by referring to color information of the red, green, and blue pixels surrounding the white pixel, as shown in Fig. 3. In detail, we calculated the 'color ratio' of the G signal value to the sum of the average of R , G , and B signal values: $G_{average} / (R_{average} + G_{average} + B_{average})$.

For example, $R_{average}$, $G_{average}$ and $B_{average}$ are made of the average values from two red pixels, four green pixels, and two blue pixels surrounding the white pixel, respectively. More pixels can be referred to for calculating each average value to decrease random noise in the color ratio. Next, we multiplied the signal value of the white pixel by the color ratio calculated previously, as follows:

$$R_w = W \times \frac{R_{average}}{(G_{average} + R_{average} + B_{average})} \quad (2)$$

$$G_w = W \times \frac{G_{average}}{(G_{average} + R_{average} + B_{average})} \quad (3)$$

$$B_w = W \times \frac{B_{average}}{(G_{average} + R_{average} + B_{average})} \quad (4)$$

where R_w , G_w , and B_w are newly obtained color signal values at the white pixel. In equation (2)~(4), W value stands for luminance and the color ratio part stands for chrominance.

This process assumes that the chrominance is homogeneous in the region of 3×3 pixel area when the color reference region is 3×3 pixel area. However, since luminance signal is obtained from the single white pixel, luminance resolution is not degraded.

Afterwards, the pixel interpolation process was performed with both the R , G , and B 'raw' signals and the newly obtained R_w , G_w , and B_w signals. Interpolation was performed by averaging the same-color signals in the region of each 3×3 pixel area.

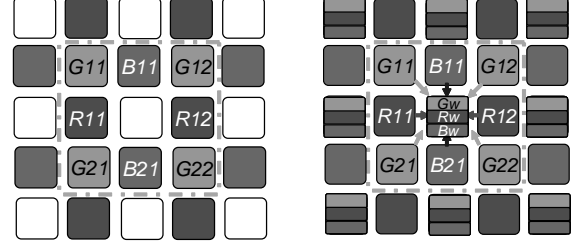


Fig. 3. Concept of the low-noise color separation process (5×5 pixel block of the WRGB CFA).

3.2 Edge detection process

The assumption that the chrominance is homogeneous in the color reference region is not correct for the high spatial frequency image. Therefore false color signal appears at the edge after the color separation process.

Edge detection was carried out in the 3×3 pixel area surrounding the white pixel, prior to the color separation process. Horizontal edge detection was performed by comparing $(G11+B11+G12)$ with $(G21+B21+G22)$, as shown in Fig. 4. If the difference between the two sum values is over the threshold value, horizontal edge is detected around the white pixel. Vertical and diagonal edges around the white pixel are also detected.

If an edge is detected, the color separation process is not performed. Instead only a green signal value is generated from white signal value. To coincide the sensitivity of the white signal with that of green signals, white signal value is multiplied by the coefficient α , obtained from the neighboring color ratio.

By branching off the signal process at the edge, we can suppress the false color signal due to the color separation process.

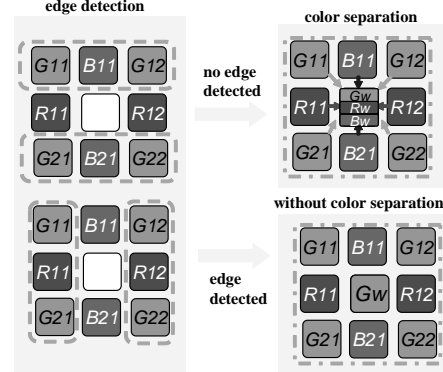


Fig. 4. Color separation process with edge detection.

4 RESULTS

4.1 SNR improvement in low illumination

We took raw data of the Macbeth chart[®] illuminated by halogen lamp with the color temperature of 6000K, by the image sensor chips with Bayer CFA and Bayer-like WRGB CFA. By using the neutral density (ND) filter (1/512), illumination was controlled to be 3lux.

For the WRGB-CFA data, R_w , G_w and B_w signals were calculated at each white pixel by the low-noise color separation process without edge detection.

For the data of both of the CFAs, interpolation was carried out by using the same-color-signal values in the 3×3 pixel block to calculate the R , G , and B values at every pixel. Figure 5 shows low-illumination SNR comparison between the Bayer CFA and WRGB CFA devices. SNR was calculated by using the average and dispersion of values in the grayscale square of interpolated Macbeth images.

SNRs of G , R , and B were increased by 1dB, 6dB, and 6dB, respectively, for the WRGB CFA image. SNR increase of G is because of higher sensitivity of a white pixel than a green pixel, and the SNRs of R and B increased because of doubling of the effective R and B pixel number.

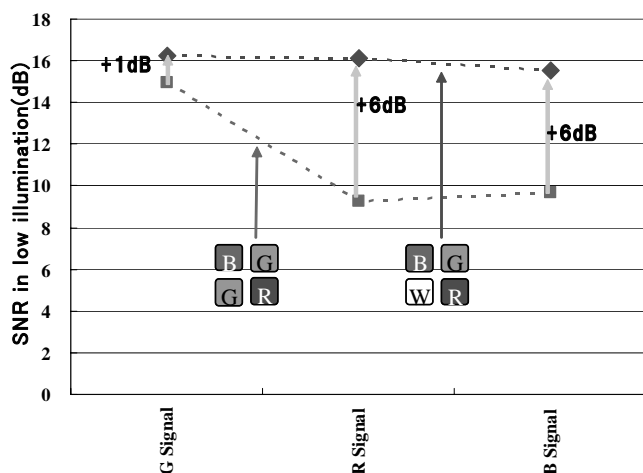


Fig. 5. Low illumination SNR comparison between the interpolated signal of the Bayer CFA and that of the Bayer-like WRGB CFA.

4.2 Color Representation

The Macbeth chart image and the color vector are shown in Fig. 6. Raw data was taken by both the Bayer CFA sensor and the WRGB CFA sensor under high illumination condition.

For the WRGB CFA data, the color separation process and interpolation by using the same-color

value of 3×3 pixel block were performed. The color vector was obtained from the third line of the Macbeth chart.

Since Bayer-like WRGB CFA has three primary-color pixels and the low-noise color separation process is based on the chrominance signal calculated by using the pure R , G and B values, color could be represented by WRGB CFA without any problem.

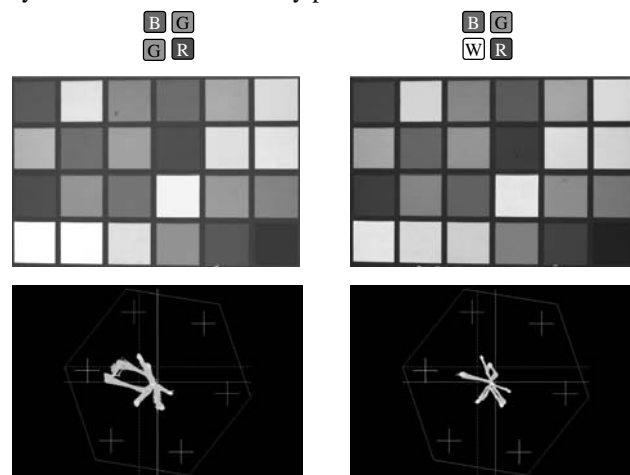


Fig. 6. Macbeth chart comparison between the Bayer-CFA sensor and the WRGB-CFA sensor, taken under a high illumination condition where halogen lamp (6000K) was illuminated onto the reflection-type Macbeth chart.

4.3 Resolution

The Circular Zone Plate (CZP) response was simulated. Color separation and interpolation were performed for the black-and-white CZP image. Figure 7 shows RGB color images after interpolation. Strong color moiré appears at the Nyquist frequency. This is because blue pixel and newly obtained B_w effective pixel form vertical lines at intervals of 2 columns after the color separation. After the interpolation and the RGB image synthesis, bright blue moiré pattern appears.

On the other hand, by using edge detection, the CZP response of the WRGB layout (Fig. 8) has become comparable to that of the Bayer layout (Fig. 9).

Figure 10 shows the comparison between the edges of Bayer CFA, WRGB CFA without edge detection, and WRGB CFA with edge detection. False color signal due to the color separation has been suppressed by using the edge detection.

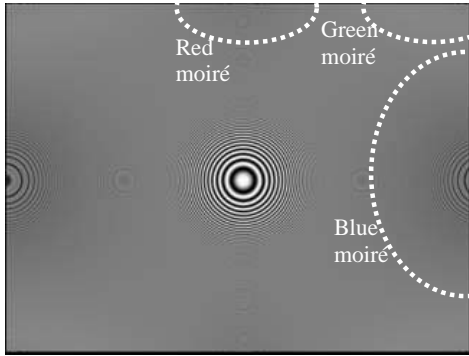


Fig. 7 Circular zone plate response of the WRGB layout without edge detection.

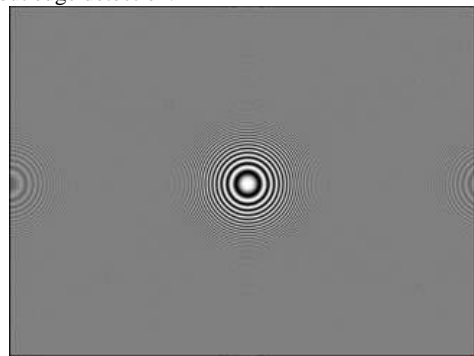


Fig.8 Circular zone plate response of the WRGB layout with edge detection.

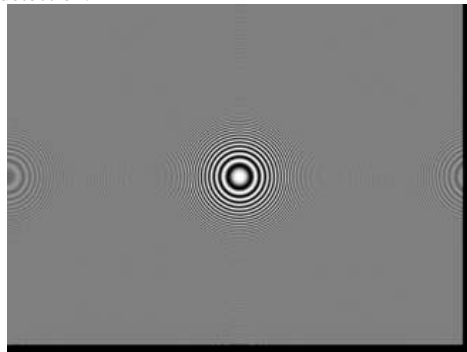


Fig. 9. Circular zone plate response of the Bayer layout.

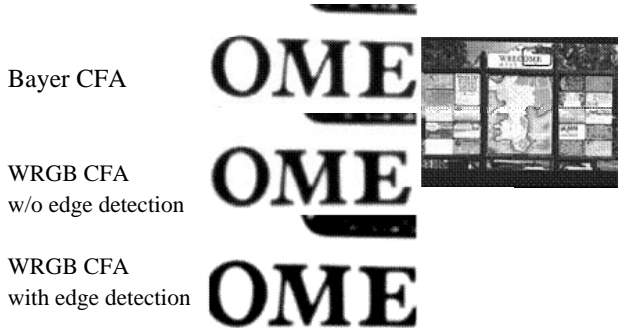


Fig. 10. Comparison between the edges of Bayer CFA, WRGB CFA without edge detection, and WRGB CFA with edge detection.

5 CONCLUSION

We have fabricated a CMOS image sensor with the Bayer-like White-Red-Green-Blue (WRGB) color filter array.

By introducing high-sensitivity white pixel and by using the low-noise color separation process, signal-to-noise ratios (SNRs) have been improved. Low illumination SNRs of the interpolated R, G, and B signal values were increased by 6dB, 1dB, and 6dB respectively, compared with those of the Bayer pattern.

There was no degradation of either resolution or color representation for the interpolated image.

The false color signals at the edge have been suppressed by newly developed color separation process using edge detection.

The issue of the color representation at the edge, where white signal value is regarded as green signal value, is to be solved by improving the color separation algorithm.

This new color filter array has a great potential to significantly increase the sensitivity of CMOS/CCD image sensors with digital signal processing technology.

ACKNOWLEDGEMENTS

The authors would like to thank G. Ito, K. Isogawa, K. Itaya, I. Fujiwara, H. Funaki and S. Uchikoga of the Corporate Research & Development Center, Toshiba Corporation, and T. Noguchi, H. Goto, F. Kanai, H. Kubo, T. Kawakami and N. Matsuo of Semiconductor Company, Toshiba Corporation, for encouragement and helpful discussion. They are grateful to N. Tanaka, M. Yanagida, M. Nakabayashi, Y. Higaki, and N. Unagami for help during various stages of this work.

REFERENCES

1. B. Bayer, "Color imaging array", United States Patent, No. 3, 971,065,1976.
2. H. Honda et. al., "A novel Bayer-like WRGB color filter array for CMOS image sensors", Electronic Imaging 2007, 2007 (to be published).
3. J. Nakamura, "Image sensors and signal processing for digital still cameras, pp. 62-63; 226-232, 2006.