A CCD image sensor and an imaging system with scene adaptability for DSC applications

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Abstract

A CCD image sensor and an imaging system, which can change their movements to adapt to various shooting conditions, have been developed by utilizing characteristics of human eyes as hints. They are a switchable system between Wide dynamic range mode, High sensitivity mode and High resolution mode. As a result of this, the most suitable mode for the shooting conditions can be selected, like human eyes.

I. Introduction

The number of pixels on an image sensor is often used as a convenient yardstick for image quality in digital camera market. We developed "Super CCD HR" image sensor which had small pixels to produce high-definition pictures[1]. To overcame S/N degradation caused by shrinking pixels, we improved photo-sensitivity of pixels by improving optical layers and reducing noise of an output amplifier and dark current in charge transfer paths. Also, in order to produce higher quality pictures, we developed "Super CCD SR" image sensor which produced pictures with rich gradation[2][3]. This sensor had high sensitivity S-pixels and low sensitivity R-pixels, which were placed on a chip. By combining information from S-pixels and R-pixels, this sensor produced wide dynamic range pictures.

On the other hand, we recognize that current digital cameras cannot respond to various scenes which require scene-by-scene performance. For example, landscape photography mainly requires high resolution. In contrast, indoor photography mainly requires high sensitivity, or high SNR, because of low-light condition. Also, there are scenes which mainly require wide dynamic range due to their high contrast. It is widely believed that high resolution, high sensitivity and wide dynamic range are tradeoff in designing imaging systems. Indeed, it is difficult to satisfy these characteristics with one system.

In contrast, human eyes are excellent sensors. They control cone cells which perceive color, and rod cells which only perceive brightness. In a comparatively bright place, human eyes make cone cells work to obtain color fidelity and high resolution. In a comparatively dark place, human eyes make rod cells work to preserve sensitivity instead of color fidelity and resolution. Thus, human eyes have optimal performances for daily life by changing its response adaptively according to neighboring brightness.

A CCD image sensor (named Super CCD EXR) and an imaging system presented here have been developed to offer a system which can change their characteristics depending on shooting conditions like human eyes. They operate in three modes; “Dual Capture mode” for wide dynamic range, “Pixel Fusion mode” for high sensitivity and “Fine Capture mode” for high resolution. The scene adaptability with the three modes is the concept of Super CCD EXR.

II. Design Points of Super CCD EXR

Fig.1 shows the block diagram of Super CCD EXR. It is based on a Super CCD (PIACCD[1]) technology. The structural change is a re-arranged color filter array. Fig. 2 shows the color filter arrangement of conventional Super CCD and Super CCD EXR. Super CCD EXR has a distinctive color filter arrangement that two Bayer arrangements are placed side by side as shown in Fig. 3. This new color filter arrangement and new driving methods described below allow the sensor to switch its characteristics. This is the key feature of Super CCD EXR.

Even more, it is also the feature to switch demosaicing processes according to the operating mode because of a difference of color arrangement in each mode. Each demosaicing process is optimized for each color arrangement. One is a demosaicing process same as a Bayer arrangement. This process is used in Pixel Fusion mode and Dual Capture mode. The color arrangement in Pixel Fusion mode is same as the Bayer arrangement by pixel binning as shown in Fig.4. In Dual Capture mode, two pixel planes, which are exposed for different periods of time described below, are merged as shown in Fig.5. Then, the merged data is treated as a color arrangement same as the Bayer arrangement. The other is a demosaicing process used in Fine Capture mode. It processes the distinctive color arrangement of Super CCD EXR, and is optimized to produce higher resolution pictures.

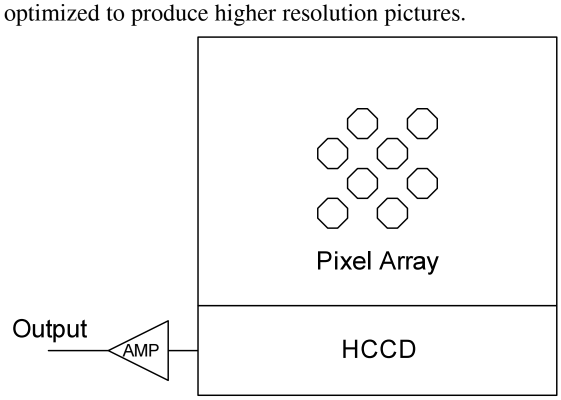

***Figure 1**. Block diagram of Super CCD EXR*

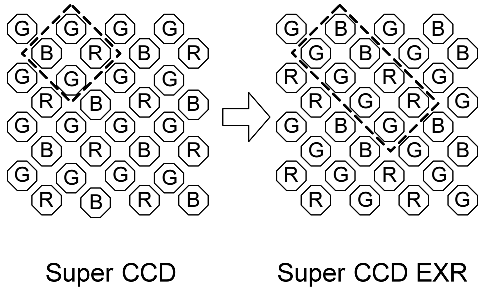

***Figure 2**. Comparison of each color filter arrangement*

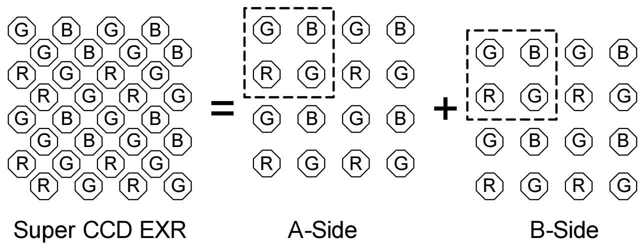

***Figure 3**. Feature of the color filter arrangement of Super CCD EXR*

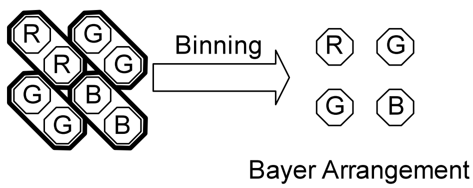

***Figure 4**. Pixel Fusion mode*

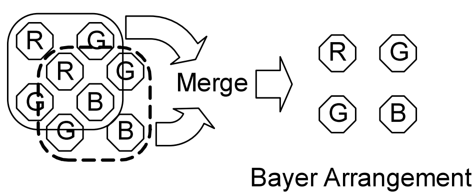

***Figure 5**. Dual Capture mode*

III. Details of each mode

Dual Capture mode

FIG. 6 shows the timing diagram of Dual Capture mode. Exposures of both A-Side pixels and B-side pixels are finished by closing a mechanical shutter. The exposure of A-side pixels starts at the end of electronic shutter pulses. On the other hand, the exposure of B-side pixels starts after applying a sweep-out pulse to transfer gates of B-side pixels. The sweep-out pulse transfers unnecessary electric charges accumulated in photodiodes of B-side pixels to VCCD. And the charges are drained out to a reset drain of an output circuit through HCCD.

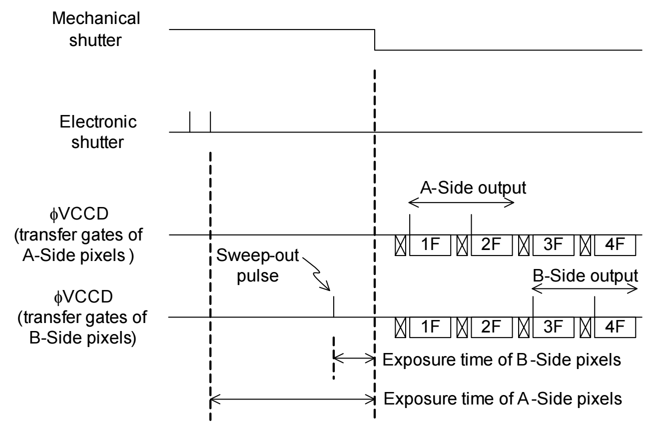

***Figure 6**.Timing diagram of Dual Capture mode*

Fig.7 is the schematic diagram of the sweep-out process of B-Side. Unnecessary electric charges in the photodiodes of B-Side pixels are transferred to VCCD through transfer gates of the pixels. This process is similar to an usual readout process of signal charges.

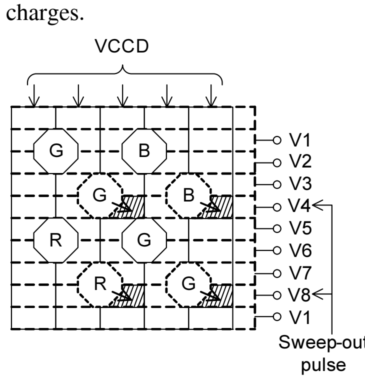

***Figure 7**. Schematic diagram of the sweep-out process*

FIG. 8 shows signal outputs of the imager when the exposure time ratio of A-side to B-side is set to 4:1. It shows that both outputs are linear to illuminance, and the output level of B-side is 1/4 of A-side while A-side output is not saturated. This means that unnecessary electric charges of B-side pixels are drained appropriately.

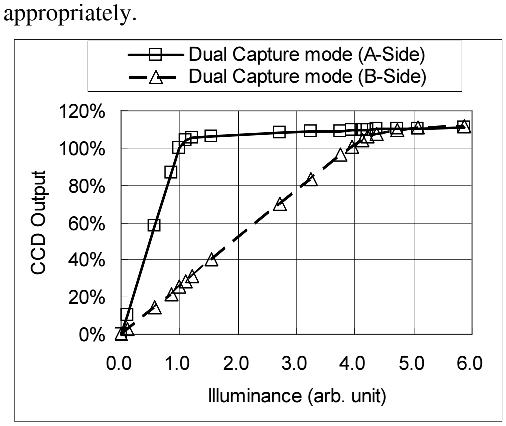

***Figure 8**. Signal outputs of Dual Capture mode*

FIG. 9 shows the SNR comparison between our conventional methods to expand dynamic range and Dual Capture mode of Super CCD EXR. Super CCD SR has two kinds of pixels, high sensitivity pixels (S) and low sensitivity pixels (R). Therefore the dynamic range expansion ratio is limited structurally. Super CCD HR expands dynamic range by shortening exposure time and adjusting gain curve. Thus, wider the dynamic range is, lower the SNR is. Therefore, the upper limit of the dynamic range expansion ratio depends on an acceptable SNR. On the other hand, Dual Capture mode of Super CCD EXR holds fixed SNR independent on the dynamic range expansion ratio because it is not necessary to reduce sensitivity of A-side pixels to expand dynamic range. Moreover, it can expand dynamic range more than Super CCD SR theoretically because it doesn't have the structural limit of the pixels.

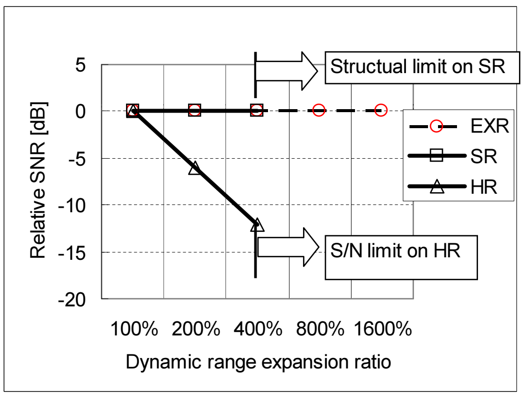

Figure 9. *Comparison of dynamic range expansion methods*

Pixel Fusion mode

Fig.10 shows the schematic diagram of Pixel Fusion mode. The left hand side of Fig.10 shows a read-out process of signal electric charges from photodiodes to VCCD, and the right hand side of Fig. 10 shows a binning process of the signal electric charges in HCCD.

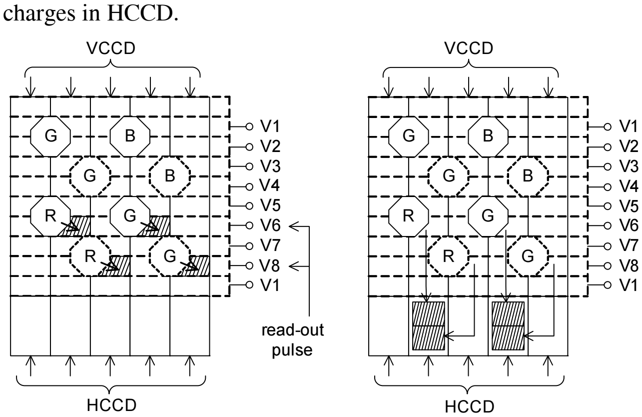

Figure 10. *Schematic diagram of Pixel Fusion mode*

Fig.11 shows signal outputs of the imager. The solid line indicates the output of Pixel Fusion mode, and the dotted line shows the output of Fine Capture mode for comparison. The output of Pixel Fusion mode is increased by 2 times over that of Fine Capture mode because the binning process is performed appropriately.

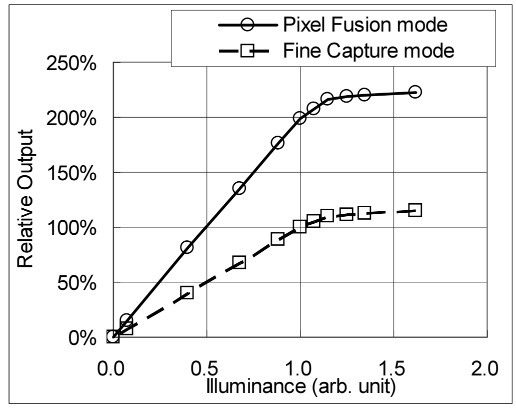

Figure 11. *Signal output of Pixel Fusion mode*

The SNR of Pixel Fusion mode is calculated as follows. Assuming that noise is consist of three parts: dark current electrons (Q_{dc}) generated in one photodiode and one VCCD packet, noise of an output amplifier (Q_{AMP}) and optical shot noise ($\sqrt{Q_S}$), the SNR improvement ratio of Pixel Fusion mode to Fine Capture mode is described as follows:

$$SNR\_improvement\_ratio = 2\sqrt{\frac{Q_{dc}^2 + Q_{AMP}^2 + Q_S}{2Q_{dc}^2 + Q_{AMP}^2 + 2Q_S}} \qquad (1)$$

Thus, the SNR improvement ratio is nearly 6dB if the signal and the dark current are little enough, and it converges to 3dB if the signal is large enough. On the other hand, the dark current in Pixel Fusion mode is smaller than that in Fine Capture mode, and this also contributes to improve SNR of Pixel Fusion mode. This is because the number of the output signals of Pixel Fusion mode is half of that of Fine Capture mode, and the dark current level depends on a signal transfer time. These SNR improvement effects don't depend on the color filter arrangement of the imager.

Furthermore, false color performance in Pixel Fusion mode is improved than that of conventional pixel binning method. The left hand side of Fig.12 shows the reproduced image captured by a conventional binning method with an imager which has a conventional color arrangement. The right hand side of Fig.12 shows the reproduced image captured by Pixel Fusion mode with Super CCD EXR. The false color decreases drastically in Super CCD EXR. This is because nearest-neighbor pixels are combined in Pixel Fusion mode, on the other hand, spaced-apart pixels are combined in the conventional method.

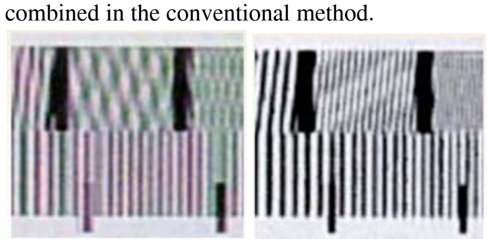

Figure 12. *Comparison of false color performances. Left: conventional binning method with a conventional imager. Right : Pixel Fusion mode with Super CCD EXR.*

Fine Capture mode

A reproducible frequency band of Super CCD is a diamond shape in monochrome, and this is suitable to reproduce natural scenes[1]. As for Super CCD EXR, the reproducible frequency band of Gray in monochrome is the same shape as that of Super CCD, as shown in the left hand side of Fig.13. But Super CCD EXR has the color filter arrangement which differs from Super CCD. The right hand side of Fig.13 shows reproducible frequency bands of Green which highly contributes to luminance. The band of Green of Super CCD EXR is equal to that of Super CCD in the horizontal and vertical direction, wider in the upper left and lower right direction, and narrower in the upper right and lower left direction. However, most scenes are comprised of intermediate colors rather than the three primary colors. Therefore, the spatial frequency response can be brought to that of Gray by utilizing a correlation between Red, Green and Blue.

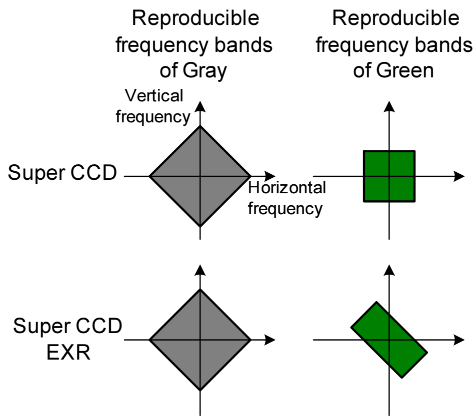

Figure 13. *Comparison of reproducible frequency bands*

Fig.14 shows the spatial frequency response of Full Capture mode of Super CCD EXR (12M pixels) applied the demosaicing process utilizing the inter-color correlation mentioned above. Horizontal axis shows the number of lines that the imager can resolve per picture height. The identical resolution limit of 12M pixels imager is 3000.

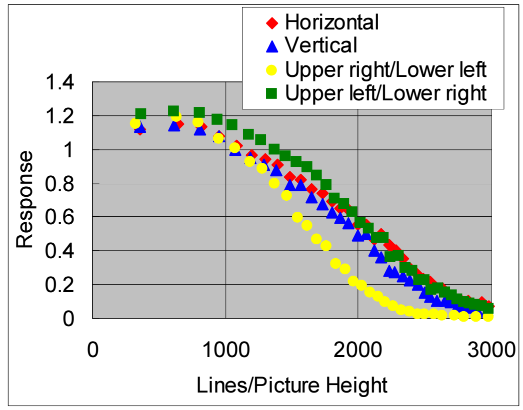

Figure 14. *Spatial frequency response of Full Capture mode*

This figure means that the resolutions except the upper right / lower left direction are close to the identical resolution limit. And, utilizing the inter-color correlation, the resolution in the upper right / lower left direction in which the reproducible frequency band is narrow is realized over 2000 lines.

Conclusion

An image sensor and an imaging system have been developed by utilizing characteristics of human eyes as hints. They are a switchable system between Wide dynamic range mode, High sensitivity mode and High resolution mode. As a result of this, the most suitable mode for shooting conditions can be selected, like human eyes.

References

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Author Biography

Makoto KOBAYASHI received the B.S. and M.S. degrees from Tohoku University, Japan, in 2000 and 2002, respectively. He joined Fujifilm Microdevices Co., Ltd. in 2002, and Fuji Photo Film Co., LTD. in 2004. He has been engaged in the research and development of solid-state image sensors.