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World's first 16:4:1 triple conversion gain sensor with all-pixel AF for 82.4dB single exposure HDR

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Abstract

A Triple Conversion Gain (TCG) sensor with all-pixel auto focus based on 2PD of 1.4 um-pitch has been demonstrated for mobile applications. TCG was implemented by sharing adjacent Floating Diffusion (FD) without adding other capacitor. TCG helps to reduce the noise gap or slow the noise increase as user gain increases. An image with a Dynamic Range (DR) of 82.4 dB through a single exposure can be obtained through intra-scene TCG (i-TCG). Through this, a wider range of illuminance environments can be captured in the image. In addition, a more natural image can be obtained by reducing the SNR dip in one image by using TCG.

Introduction

In the recent CIS market, high resolution, high image quality, 100% Auto Focus, and high dynamic range are required as key characteristics [1]. In order to obtain a high resolution image, the pixel pitch is getting smaller and this has to deal with the reduction of Full Well Capacitor (FWC), sensitivity, Signal to Noise Ratio (SNR), etc. [2]. This negatively affect images in dark environments.

In order to get a good image in a dark environment, it can be used like a big pixel by binning the signal of the surrounding pixels [3]. Although this method reduces the number of pixels of an image, it has the advantage of increasing FWC, sensitivity and DR and enabling all-pixel Phase Detection Auto Focus (PDAF) [4, 5]. However, as the number of pixels to be binning increases, the FWC and Dual Conversion Gain ratios increase, which leads to image quality degradation. A middle conversion gain is needed to slow this degradation.

In this paper, the triple conversion gain was designed by sharing the adjacent FD and its characteristics of binning mode were demonstrated. TCG reduces the height of the noise gap due to Conversion Gain (CG) changes and slows the increase in LSB noise, which increases as user gain increases. Especially in the intra-scene mode, the DR is extended to 82.4dB and the SNR dip is improved.

Technology

A. Pixel Architecture for Triple Conversion Gain

The conversion gain was adjusted by controlling the capacitance that converts the FD charge into the voltage applied to the SF gate. In order to have multiple conversion gains, a new physical capacitor or junction capacitor is usually added to adjust this capacitance of the CIS. However, in order to use the pixel space efficiently, simplify the process, and efficiently use the FD voltage swing range, we decided to share the surrounding FD to control the capacitance [6].

As shown in Fig. 1 (a), the unit pixel structure of the fabricated sensor is 2PD of 1.4um, and the color filter has a tetra pattern. This structure can read each pixel output to get a 50Mp image, and bin the 4 pixels of a tetra pattern with the sum of charges to get a 12.5Mp image. The capacitor of the High Conversion Gain (HCG) consists of only one FD of 2PD, and that of the Middle Conversion Gain (MCG) is configured by sharing the FD of the upper and lower two pixels. Low Conversion Gain (LCG) is designed to have larger capacitance by connecting FDs of different colors as well as FDs of the same color, as shown in Fig. 1 (c). Finally, a pixel with a TCG ratio of 16:4:1 was made. Fig. 1 (b) is the PTC graph of this image sensor, which proves that this sensor has a TCG and the ratio is 16:4:1.

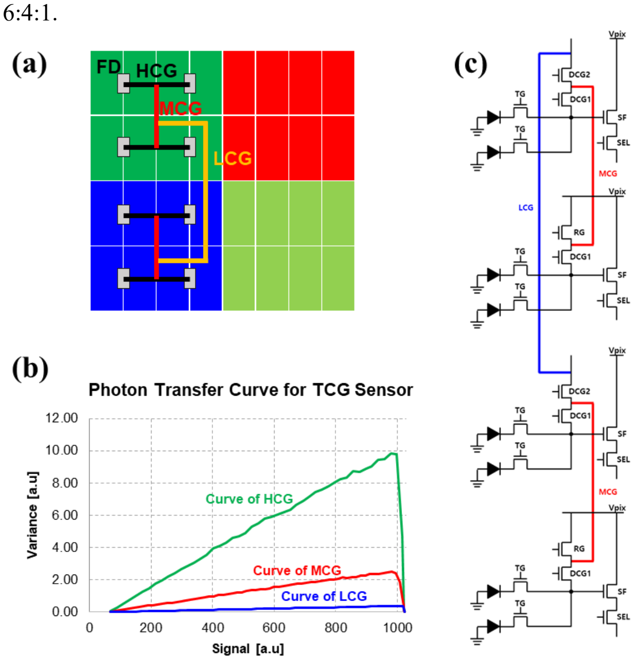

Fig. 1. (a, c) FD shared layout in tetra pattern based on 2PD and (b) Photon Transfer Curve of 16:4:1 TCG Image Sensor

These multiple conversion gains are selected and used according to the user gain in normal mode. Compared to 16:1 DCG having the same FWC and user gain range, using TCG has the advantage of reducing the noise gap that appears when CG changes according to UG. In case of using DCG, if it is set to switch from LCG to HCG at the point where the User Gain becomes 16, the LSB noise gap generated at this knee point is about 16.5 LSB. However, when 16:4:1 TCG is applied, one large noise gap becomes two noise gaps with a height of 3.2 LSB. Also, as in the graph of Fig. 2(a), it is possible to make the LSB noise smaller between the user gain 4 and 16 times. Fig. 2 (b) compares the case of 4:1 DCG and TCG with different FWC but the same ratio of adjacent CGs. When the user gain is 4, it changes from LCG to HCG and has one identical noise gap. However, in the case of TCG, there is one more noise gap, which slows the increase in LSB noise.

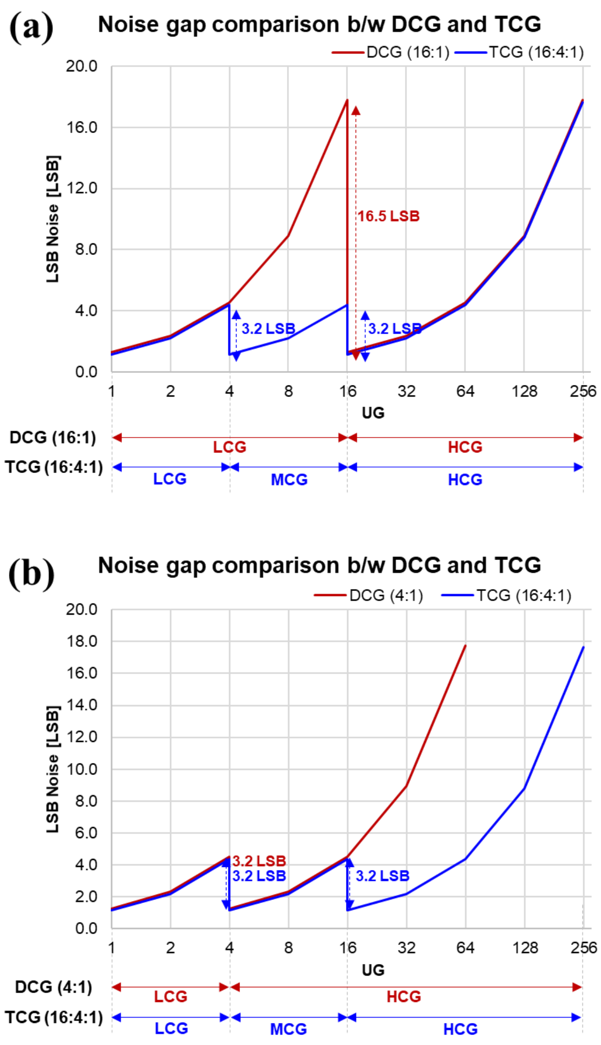

Fig. 2. (a) Comparison of noise gap 16:1 DCG and 16:4:1 TCG and (b) Comparison of noise gap 4:1 DCG and 16:4:1 TCG

B. Single Exposure High Dynamic Range

Intra-scene High Dynamic Range (HDR) is one of the best ways to take advantage of multiple conversion gains. Instead of selecting one conversion gain at a time, we can get all the images obtained with multiple conversion gains through a single exposure. Through i-TCG merger, these images are synthesized by multiplying the linearization coefficients suitable for each CG ratio. Finally, from three 10-bit images with different CGs, an image with 14-bit high dynamic range can be obtained, as shown in Fig.3. So the number of effective ADC bit can be increased from 10 to 14.

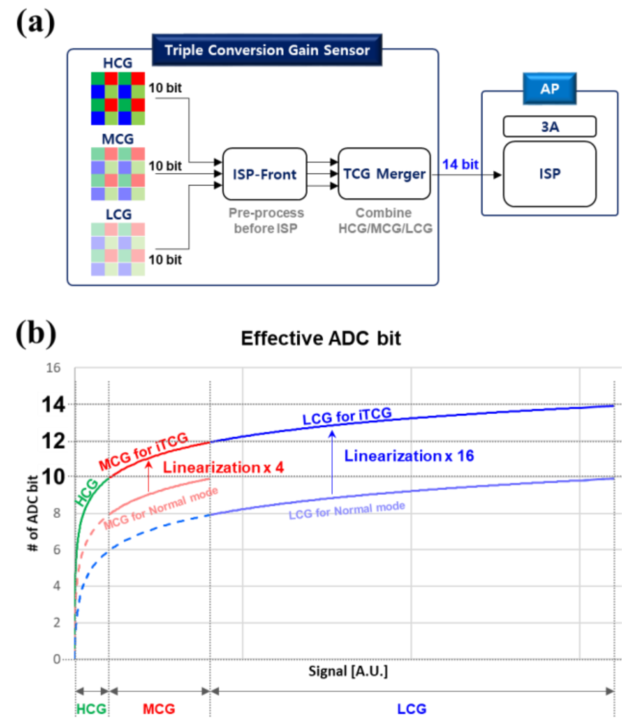

Fig. 3. (a) Merger for intra-scene triple conversion gain and (b) extension of effective ADC readout bit

As the effective ADC bit number increases, the dynamic range of the image also increases [7]. The 4:1 i-DCG has an effective 12-bit ADC readout and a dynamic range of 70.4 dB. When the FWC is extended, it can have a DR of 76.9 dB. And a 16:4:1 i-TCG with effective 14 bit ADC readout can have a dynamic range of 82.4 dB. Fig. 4 provides an intuitive understanding of i-TCG's dynamic range extension and SNR dip reduction.

Fig. 4 (a) shows the case with and without intra-scene mode. Fig. 4 (b) shows the 4:1 i-DCG and 16:4:1 i-TCG when ADCSAT is the same. A comparison with a 4:1 i-DCG with the same FWC can be seen in Fig. 4 (c). Since i-TCG has a larger number of effective ADC bits than i-DCG, quantization noise decreases and DR increases in the direction of the left arrow. So far, the dip of the SNR curve does not appear significantly. However in the case of a 16:1 i-DCG with the same FWC, as shown in Fig. 4(d), the SNR dip at the knee point where the HCG changes to the LCG occurs significantly. The 16:1 i-DCG has one large SNR dip of 2.4 dB, but the 16:4:1 i-TCG has two small SNR dips of 0.2 dB/0.7 dB.

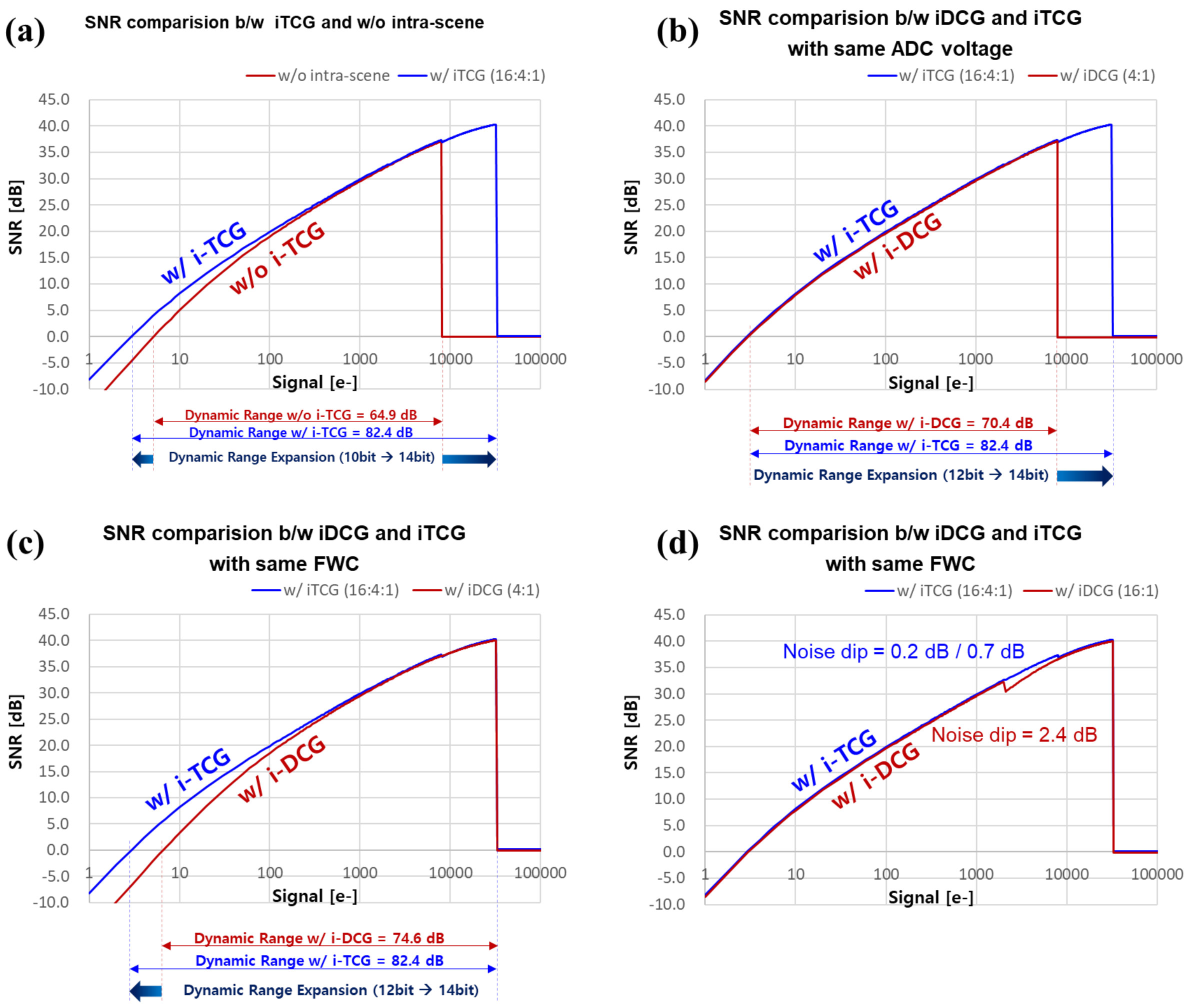

Fig. 4. (a) SNR comparison between no intra-scene and 16:4:1 i-TCG, (b) between 4:1 i-DCG and i-TCG when ADC voltage is the same, (c) between 4:1 i-DCG and i-TCG when FWC is the same , and (d) between 16:1 i-DCG and i-TCG when FWC is the same

Results and Discussion

Using the manufactured image sensor, images were obtained while changing the conversion gain under the same imaging conditions, and that is shown in Fig. 5. In HCG, it can be seen that the image output signal quickly saturates either on a relatively bright LED plate or in the center of the image. At the same time, detailed information in dark places such as the shadowed part on the right side of the wine bottle is sufficiently obtained. In the case of LCG, it is possible to obtain detailed information on bright areas such as the LED plate or the center of the image. But the information in the dark areas is not enough. Since one CG is selected in normal mode, low DR images with this limited information are obtained. However, the i-TCG images obtained through merging contain all the details of the highlights and shadows in one image. The contrast of the wall behind the object is gradually changing, but due to the small SNR dip, there is little or no degradation in quality.

Fig. 5. (a) Image obtained by HCG, (b) Image obtained by MCG, (c) Image obtained by MCG in normal mode, and (d) i-TCG image obtained through TCG Merger

Conclusion

An image sensor with an adjacent FD-shared triple conversion gain was fabricated. By connecting FDs of the same color and FDs of different colors, the ratio of HCG:MCG:LCG is 16:4:1. The TCG sensor reduces the LSB noise gap to 3.2LSB at the point where the CG changes according to the user gain and slows the noise increase. 3 images from single exposures with different CGs are combined into one i-TCG image via TCG merging. It has the effective 14-bit ADC readout in intra-scene mode for single exposure, and DR can be extended to 82.4 dB. TCG extends DR by increasing the FWC or lowering the QN, and makes the SNR dip smaller to provide users with a more natural image quality. The use of Multiple Conversion Gain does not end with Triple, but can be extended to Quadra-, Penta-, etc.

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Author Biography

ChangHyun PARK received his Ph.D. in physics from University of Yonsei in Korea and Université of Bordeaux in France (2020). Since then, the author has been developing CMOS image sensors at Samsung Electronics Co., Ltd.

Table 1. Comparison of characteristics of 4:1 DCG and 16:4:1 TCG sensor

Characteristics		Unit	4:1 DCG (1)	4:1 DCG (2)	16:4:1 TCG
Linear Full Well Capacity	at 50 Mp	e-	2,500	10,000	10,000
	at 12.5 Mp	e-	10,000	40,000	40,000
Random Noise		e-	2.0	2.0	2.0
Sensitivity (G)		e-/lux·sec	7,000	7,000	7,200
Cross talk		%	16.3	16.3	16.1
AF contrast		-	4.5	4.5	3.6(H), 2.3(V)
intra-scene Dynamic Range		dB	70.4	76.9	82.4