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A High Optical Performance 3.4 μm Pixel Pitch Global Shutter CMOS Image Sensor with Light Guide Structure

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Abstract – We describe a high optical performance 3.4 μm pixel pitch global shutter CMOS image sensor with multiple accumulation shutter technology and a large tapered light guide structure. The pixel achieves 1.8 e- temporal noise and full well capacity of 16,200 e- with charge domain memory in 120 fps operation. The sensitivity and parasitic light sensitivity are 28,000 e-/lx·s and -89 dB, respectively. Moreover, the incident light angle dependence of sensitivity and parasitic light sensitivity has been improved by the large tapered light guide structure.

I. Introduction

The Global Shutter (GS) function is strongly required in order to avoid image degradation caused by rolling shutter (RS) distortion. However, the GS CMOS image sensor (CIS) has generally been inferior to the RS CIS in performance, because it generally has more components than conventional CIS to implement GS function into CIS. Specifically, there are two common problems. Firstly, additional charge domain memory (MEM) limits saturation since the photodiode (PD) area and MEM area are shrunk. Secondly, additional light shield (LS) structure decreases optical performance since the PD aperture width is shrunk. These problems become particularly obvious with the small size pixel.

To solve these problems, we developed a new multiple accumulation readout procedure and a large tapered light guide (LG) structure in the 3.4 μm pixel pitch GS CIS.

II. Pixel Architecture

Fig. 1 shows a block diagram of the GS CIS and pixel circuit schematic. The chip comprises a photodiode array, column slope 12 bit ADCs with dual-gain amplifiers (SSDG-ADC) [1], column memories, signal processors and low voltage differential signaling (LVDS) interface. The pixel array consists of 2676 (H) x 2200 (V) pixels. A unit pixel is configured as two floating diffusion (FD) shared pixel structure with charge domain memories (MEM) and overflow gates (OG). GS is used for global charge transfer, TX is for rolling signal readout, and OG is used to discharge carriers which exceed a PD full charge capacity.

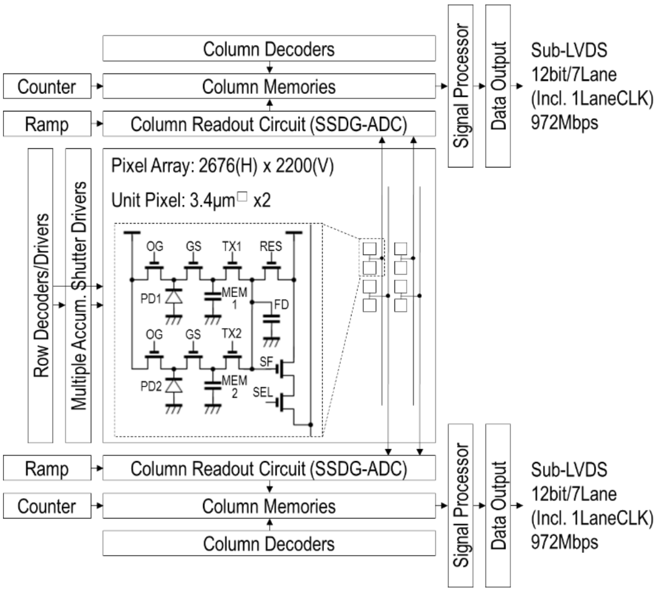

Fig. 1. Block diagram of the GS CIS and pixel circuit schematic

Fig. 2 shows the layout and cross section diagram of LS and LG structure. One of the optical isolation techniques used in this pixel is a tungsten LS wrapped around the MEM below the 1st metal layer to shield the MEM from incident light.

The top and bottom diameter of LG structure is 2.4 μm and 0.8 μm. Although the large tapered LG structure is difficult to make uniformly, we have developed stable formation process. This structure contributes to improve characteristic of sensitivity and parasitic light sensitivity (PLS).

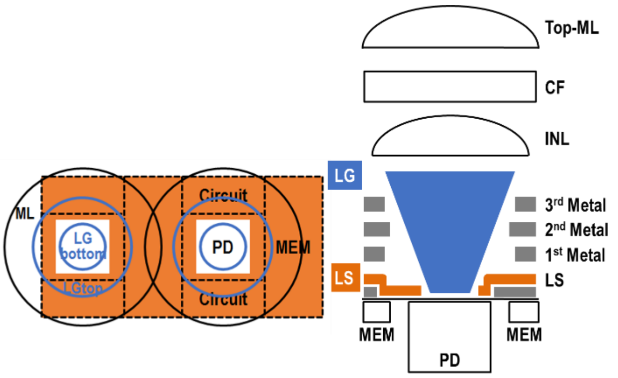

Fig. 2. (a)Layout and (b) cross section diagram of LS and LG structure

III. Multiple Accumulation Shutter Technology

Fig. 3 (a) shows the conventional signal readout procedure of the GS pixels. During the signal readout period ($T_{READOUT}$), signal charges generated in the photo conversion region corresponding to one frame exposure period are retained in the MEM. In this readout procedure, the time period for retaining the signal in the MEM (T_{RETAIN}) is as long as the $T_{READOUT}$. Besides, the signal transfer from PD to MEM is usually once in a frame. Consequently, the saturation signal of the GS pixel is determined by the PD saturation which is as much as that of the MEM.

Fig. 3 (b) shows the proposed multiple accumulation readout procedure [2], [3]. One of the feature of this procedure is that $T_{READOUT}$ can be configured at a fraction of the T_{RETAIN}. For example, the ratio ($=T_{READOUT}/T_{RETAIN}$) can be set as 1/2. In consequence of this contrivance, signal readout from the MEM of each pixel is completed much sooner than conventional procedures. Once the signal readout from the MEM is completed, the MEM is ready to receive signal charges of the next frame. Thus, we can transfer PD signal to the MEM at earlier timing. After this signal transfer, the MEM still can retain signal charge until next frame readout starts. As a result, the number of transfers from the PD to the MEM can be multiplied. In consequence, we can attain several times as much saturation signal as that of PD as a pixel saturation. In this readout procedure, light exposure and signal readout are performed simultaneously, hence the seamless signal accumulation can be carried out.

Fig. 3 (c) shows the timing diagram of non-seamless signal accumulation with multiple accumulation readout procedure. One of the feature of this procedure is that the frame rate is almost equal to $T_{READOUT}$ time. Therefore, this procedure is higher frame rate than seamless signal accumulation procedure without decreasing saturation signal.

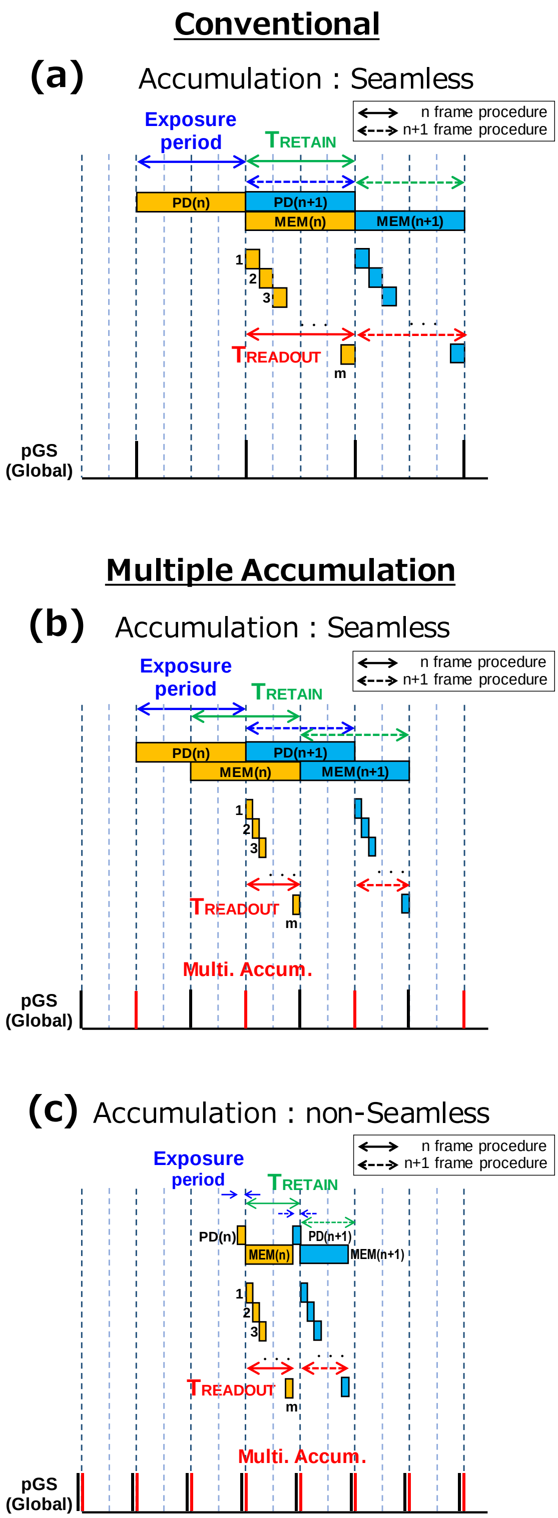

Fig. 3. Timing diagram of signal readout procedure

IV. Experimental Results

Fig. 4 shows the measured photoelectric conversion characteristics of the GS pixel with non-seamless signal accumulation procedure at 120 fps. The results shown in red line is measured by single (x1) charge accumulation from the PD to the MEM. The saturation signal was 8,100 e$^-$. The results shown in green line is measured by double (x2) charge accumulation from the PD to the MEM. In this experiment, the saturation signal of 16,200 e^- has been achieved. In addition, the sensitivity, the dark temporal noise and the PLS are 28,000 e^-/lx·s in green pixel, 1.8 e^-_{rms}, and -89 dB, respectively. The measurement was implemented using CIE light source A (2856 K).

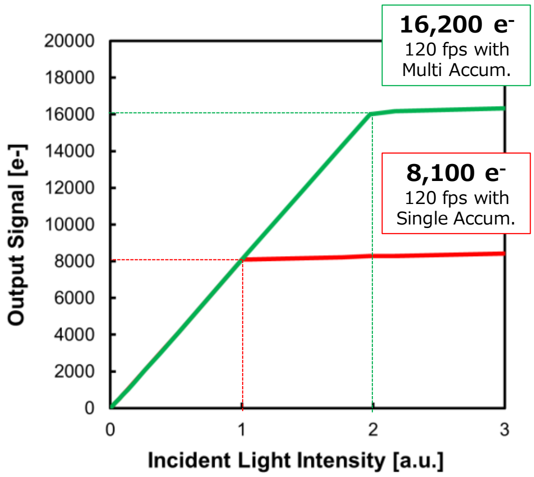

Fig. 4. Measured output characteristics

Fig. 5 shows the quantum efficiency (QE) spectrum of red, green, blue, and white pixel. The sensitivity of red color region is sufficient in spite of the narrow LG bottom and LS aperture.

Fig. 6 shows the PLS of incident light wavelength dependence. Although the PLS curve generally drops off at the longer wavelength region, the developed GS pixel keeps higher PLS even in the NIR region. This result is important for the automotive, industrial, and other emerging applications.

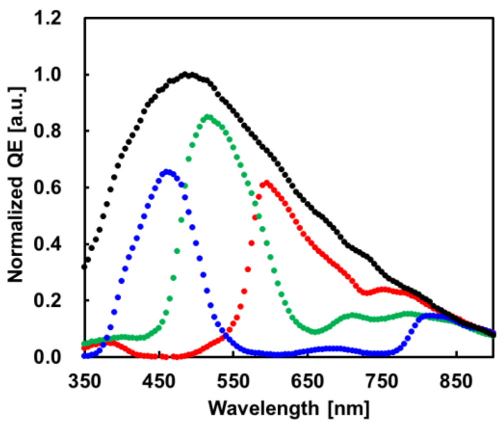

Fig. 5. QE spectrum of red, green, blue, and white pixel

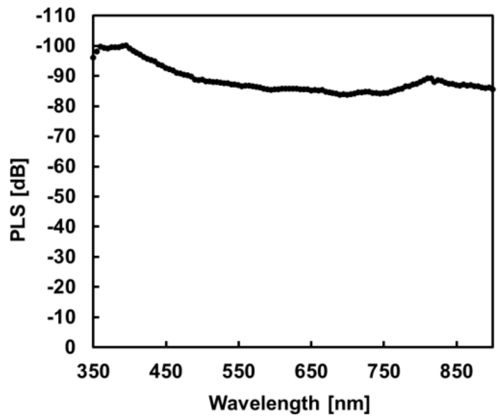

Fig. 6. Wavelength dependence of PLS

Fig. 7 (a) shows the simulated light intensity profiles of 15° incident light angle. Fig. 7 (b) shows the measured and simulation results of the incident light angle dependence of sensitivity with and without LG structure normalized to sensitivity of perpendicular light. These results indicate that the ratio of 15° incident light to the perpendicular light has been improved from 21% to 62% as the effect of the LG structure. Fig. 7 (c) shows the measured and simulation results of the incident light angle dependence of PLS with and without LG structure normalized to PLS of perpendicular light. These results indicate that the ratio of 15° incident light to the perpendicular light has been improved from 16.7x to 3.1x as the effect of the LG structure.

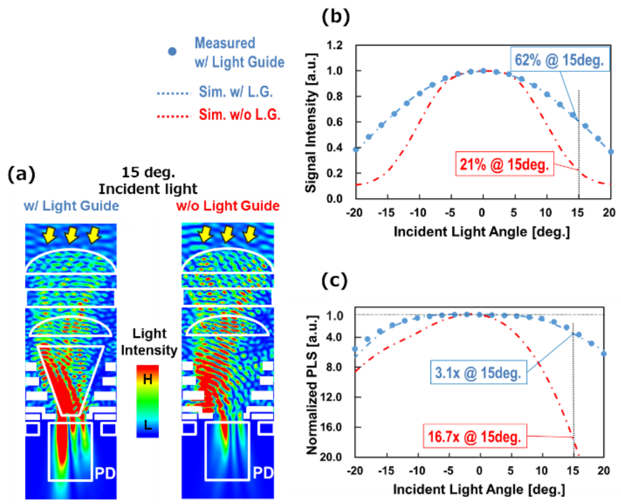

Fig. 7. (a) Simulation of the light intensity profile, (b) incident light angle dependence of sensitivity, and (c) PLS

V. Conclusion

The developed GS pixel attains 1.8 e^- temporal noise and 16,200 e^- full well capacity in 120 fps operation with multiple accumulation shutter technology. The sensitivity and PLS are 28,000 e^-/lx·s and -89 dB. Moreover, the large tapered LG structure is effective for the incident light angle dependence of sensitivity and PLS. A chip microphotograph is shown in Fig. 8 and the size of optical format is 2/3 inches. Table 1 shows a performance comparison among [3], [4], [5].

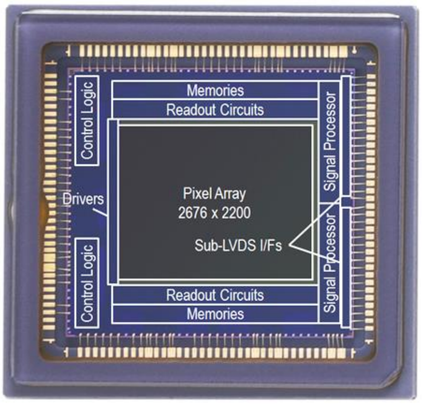

Fig. 8. Chip microphotograph

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Table 1. Summarized specifications and characteristics comparison

	Unit	This work	[3] IEDM 2016			[4] VLSI 2016	[5] IISW 2013
Shutter Function	-	GS	GS			GS	GS
Process Technology	-	130nm CMOS 1P4M+LS	180nm CMOS 1P4M+LS			90nm CMOS 1P5M+LS	180nm CMOS 1P4M+LS
Optical Format	-	2/3"	Super 35mm			Super35mm	2/3"
Pixel Pitch	μm	3.4	6.4			5.86	5
Number of Effective Pixels	-	2592 x 2054	4046 x 2496			3840 x 2160	1920 x 1080
Maximum Frame Rate	fps	120	30	60	120	480	240
Full Well Capacity	e^-	16200	70000	38000	19000	30450	15000
	e-/um2	1380	1700	930	460	890	600
Sensitivity	e^-/lx·s	28000	80000			17500	54250
Temporal Noise	e^-_{rms}	1.8	1.8			4.6	4
Dynamic Range	dB	79.0	92.0	86.0	80.0	76.3	71.5
Parasitic Light Sensitivity	dB	-89	-78			-100	-70
Power Consumption	W	0.45	1.5			5.23	1.1
Figure of Merit 1	e^-·nJ	1.27	8.91	4.46	2.23	6.04	8.84
Figure of Merit 2	e^-·pJ	0.14	0.23	0.21	0.21	0.92	2.36

FoM1= Power[W] x DRN[e^-] x 10^9 / (FPS[s^{-1}] x Num. of Eff. Pixels)
FoM2= Power[W] x DRN[e^-] x 10^{12} / (FPS[s^{-1}] x Num. of Eff. Pixels x DRU); **DRU**=FWC[e^-] / DRN[e^-]