Evolution of ultra-high-speed image sensors
- Light-in-Flight imaging to Ultra-fast X-ray imaging -

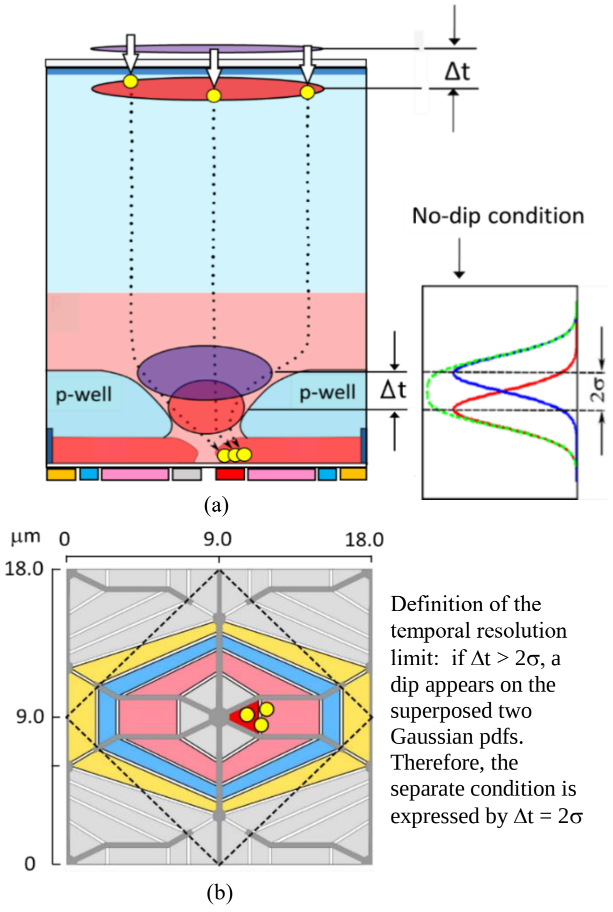
Kazuhiro Morimoto, Nguyen Ngo, Kazuhiro Shimonomura, Takeharu G. Etoh
Graduate School of Science and Engineering, Ritsumeikan University
1-1-1 Nojihigashi, Kusatsu, Shiga, 525-8577 Japan
E-mail: gr0397xr@ed.ritsumei.ac.jp

Abstract We proposed a backside-illuminated multi-collection-gate image sensor (a BSI MCG image sensor), and fabricated the test sensor with the frame rate of 100 Mfps, the pixel count of 600 kpixels, the frame count of 5 or 10, and the fill factor of 100%. Light in flight was captured by a single shot of the sensor without high-speed gating devices such as a streak camera or post data processes. This paper reports the achievement and further evolution of the image sensor for much higher frame rate toward the theoretical temporal resolution limit of 11.1 ps derived by the authors. New ideas ultra-fast X-ray imaging continuous digital recording are also presented.

Keywords: Ultra-high-speed, multi-collection gate, convex silicon pyramid, pyramid charge collector

1. Introduction

The authors proposed a sensor structure, backside-illuminated multi-collection-gate (BSI MCG) image sensor for ultra-high-speed imaging [1]. A test sensor was developed and evaluated [2]. The sensor can capture 10 consecutive frames of 300-kframe pictures at the frame interval of 10 ns. Light-in-flight was captured by the sensor. A driver circuit dedicated to the MCG structure was proposed and a chip mounting the circuit and being stacked to the BSI MCG image sensor was also fabricated and evaluated [3]. Another test sensor for 1,220 consecutive frames with a new function for in-pixel image signal accumulation was also developed [4]. The sensor is equipped with 4 collection gates at the center of each pixel, and a looped CCD memory is attached to each collection gate. The theoretical highest frame rate of silicon image sensors was theoretically derived, which is 11.1 ps [5]. This paper summarizes these prior achievements and new proposals to achieve the frame interval closer to the theoretical limit. The frame interval less than 100 ps can be developed for the burst mode with existing technology, and 1 ns may be possible for the digital continuous readout mode in the near future.



(a)

Definition of the temporal resolution limit: if Δt > 2σ, a dip appears on the superposed two Gaussian pdfs. Therefore, the separate condition is expressed by Δt = 2σ

(b)

Fig. 1 One pixel of a BSI MCG image sensor
(a) A cross section
(b) A structual pixel area (a colored structure) and an optical pixel area (the dashed lines): gray, collection gates; red, collecting gate (with VH); pink, storage gates; blue, barrior gates, yellow readout transfer gates

2. BSI MCG image sensor and camera

Fig. 1 shows one pixel of the BSI MCG image sensor [1] and Table 1 is the specification of the test sensor [2]. Fig. 2 shows the test camera and a test result. The temporal resolution of 10 ns is confirmed.

Table 2 Specifications of the test BSI MCG image sensor

Structure	a BSI MCG image sensor
Frame and pixel counts	5 frames for 512x576x2 pixels 10 frames for 512x576 pixels
Shortest frame interval	10 ns (100 Mfps)
Fill factor	100%
pixel size	12.73x12.73 um^2

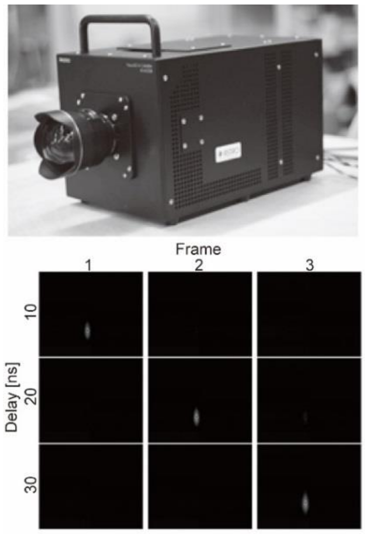


Fig. 2 The test camera and an evaluation result

Each row shows the first 3 frames from consecutive 5 frames taken by one shot. In the first shot, a short-pulse LD is applied to only to the first frame; in the second shot only to the second frame, and so on. The frame interval is 10 ns. Only one LD image appears in each shot, which proves the temporal resolution of 10 ns.

3. Light-in-flight imaging

Fig. 3 shows the last 5 frames from 10 frames of flying light captured by the test camera.

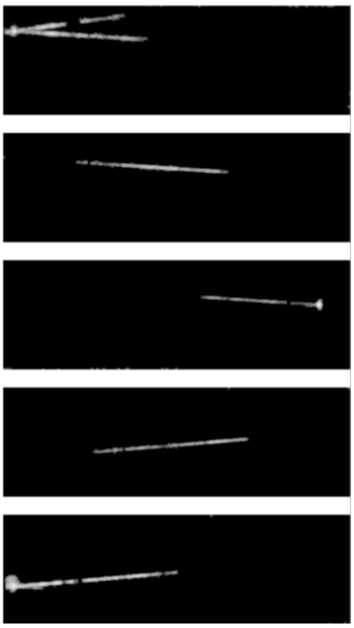


Fig. 3 Light-in-flight imaging with the test BSI MCG image sensor

Last 5 frames from the consecutive 10 frames. The distance of two mirrors is 7.43 m.

4. Suppression of horizontal motions of electrons

Fig.4(a) and (b) shows electron trajectories for the BSI MCG image sensor shown in Fig. 1, and the travel depths from the backside and the travel times to reach the depths. The temporal resoplution is defined by the spread of the arrival time. The figure shows that the major cause of the spread is the horizontal motion of electrons to the pixel center over the p-well.

The horizontal motion is perfectly suppressed, if the incident light is exactly focused at the pixel center and the generated electrons are guided to the front side through a silicon pipe with the infinitesimal diameter. We derived the expression of 2σ of the arrival time by considering only vertical mixing due to the distribution of the light penetration depth and electron veritcal diffusion [5]. The limit for the silicon image sensor is 11.1 ps.

Practical methods to suppress the horizontal motion are compared in Table 2 and Fig. 5. The convex pyramid charge collector can achieve 87.5 ps with the 100% fill factor, which is also can be used for X-ray imaging.

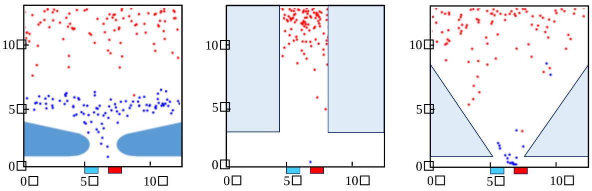
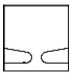
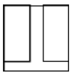
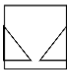
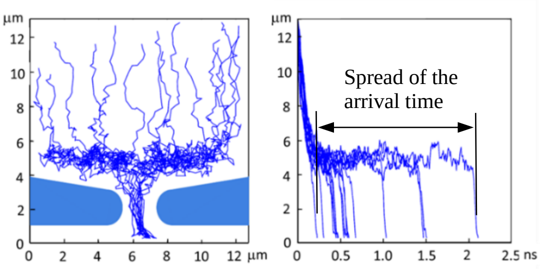


Fig. 5 Monte Carlo simulation results (Red and blue dots: 0 sec and 200 ps after the instant of incident light)

Table 2 Structures for charge collection and potential separation for BSI image sensors

pixel size, 12.73 µm; thickness, 13.1 µm, voltage amplitude to drive collection gates, 2 V; width of the light-electron guide pipe (square), 4 µm; outlet of the pyramid (square), 3 µm

Structure	p-well	Light/electron guide pipe	Convex silicon pyramid
Cross section			
Temporal resolution 2σ	990.0 ps	49.0 ps	87.5 ps
Fill factor	100%	10%	100%
Vertical field	5 kV/cm	25 kV/cm	25 kV/cm
Collection ratio	100%	100%	95%
Dark current	less	middle	large
X-ray	Applicable	Low efficiency	Ideal
Technical feasibility	Already applied	Existing technology	Process improvement



(a) (b)

Fig. 4 Electron trajectories for the BSI MCG image sensor shown in Fig. 1

5. Cascade Pipeline configuration for digital output

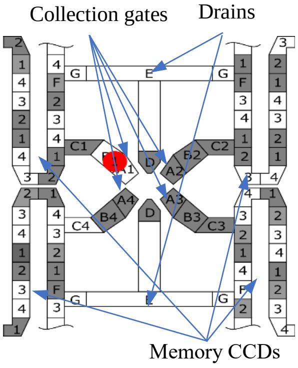


Fig. 6 The Central part of the MCG ISAS

A folded and looped CCD memory is attached to each of four collection gates

Fig. 6 shows a central part of the multi-collection-gate image signal accumulation sencer (MCG ISAS [4]). One Folded and looped CCD is attached to each of four collection gates. After capturing the first image signal (a red circle) by the collection gate A1, during collection of the second to the forth signals by A2 to A4, the first signal is transferred to the memeory CCD attached to A1. Therefore, the operation rate of the memory CCDs is 1/4 of that of the collection gates. If this pipe line configuration is repeated two more times, the operation rate of the last-stage CCDs is reduced to 1/64 of that of the collection gates. When the collection gates operate at 1 ns (1 Gfps), the third-stage CCD works at 64 ns (15.6 MHz). Then, the AD conversion is possible by a small-size ADC. The cascade can be done with MOS transisters. However, the noise level is high. So, the last stage cascade may be replaced by the MOS transister circuits. This may be the ultimate high-speed silicon image sensor.

References

[1] T. G. Etoh, et al., Toward One Giga Frames per Second - Evolution of in-Situ Storage Image Sensors. *Sensors*, 13(4), 4640–4658 (2013). [2] A. Q. Nguyen, et al., Toward the ultimate-high-speed image sensor: from 10 ns to 50 ps, *Sensors*, 18(8), 2407 (2018). [3] C. Zhang, et al., Pixel parallel localized driver design for a 128 x 256 pixel array 3D 1Gfps image sensor, Proc. SPIE 10328, 10328-07 (2017). [4] V. T. S. Dao, An Image Signal Accumulation Multi-Collection-Gate Image Sensor Operating at 25 Mfps with 32 × 32 Pixels and 1220 In-Pixel Frame Memory, *Sensors*, 18(9), 3112 (2018). [5] T. G. Etoh, et al., The theoretical temporal resolution limit of silicon mage sensors, *Sensors*, 17(3), 483 (2017).