Imaging with an ultra-high-speed video camera working at 20 mega-frames per second

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Abstract. An image sensor with 300,000 pixels capable of operating at 20 mega-frames per second (Mfps) is developed. The pixels on odd-numbered and even-numbered columns can be switched on and off independently. Therefore, the max frame rate is 40 Mfps when only half of the sensor is activated. The sensor is a backside-illuminated one for high sensitivity to support ultra-high-speed imaging. The structure, concept and operation of the sensor are presented. The sensor achieved doubled performance of the prototype which was developed in 2011 with 165 kpixels and 16 Mfps.In-situ storage for 107 signals is installed in each pixel which enables a simultaneous recording of signals at all pixels at ultra-high-speed. Video cameras equipped with earlier versions of these sensors were applied to imaging of high-speed phenomena which are essential in many industrial and scientific applications. In this paper, imaging of sudden crack propagation is shown for the performance test of the new video camera.

Keywords: high-speed, imaging, video camera, backside-illumination

1. INTRODUCTION

Since 2001, we have continuously updated the frame rate of high-speed video cameras: 1 Mfps in 2002 (Etoh et al., 2002), 16 Mfps in 2011 (Etoh et al., 2011). The sensitivity has also been increased by employing backside illumination to the sensor.

An image sensor with 300 kpixels operating at 20 Mfps is developed. The sensor can separately operate the pixels on the even-number and the odd-number columns. Therefore, the highest frame rate of the sensor at an interlace operation is 40 Mfps, though a half of the image signals in the consecutive two frames are common and the pixel count for the operation is 150 kpixels. The image sensor has pixels each of which has in-situ storage of image signals. The in-situ signal storage is a linear CCD elongating in a direction slightly slanted to the pixel grid from the photodiode of each pixel. Simultaneous recording of image signals at all pixels makes it possible to capture consecutive frames at a time interval for a signal packet to be transferred from the photodiode to the nearby one of the storage element of each pixel. The prototype was developed in 2011, which achieved 16 Mfps, 150 kpixels and very high sensitivity. The new one doubled the pixel count and slightly raised the frame rate.

The sensor is composed of the four same quadrants. The quadrants were symmetrically mirrored through X- and Y-axes. Each quadrant can be operated independently so that the sensor can work even when one or more quadrants are damaged. Unfortunately, a new sensor with all four working quadrants is not available for us at this moment, since, due to a low yield rate, a private company working with us on the camera has supplied the good sensors to their customers. Therefore, we applied the camera with the new sensor with at least one damaged quadrant to imaging of a rapidly propagating crack.

The test applications are also very important to accumulate know-hows necessary for the ultra-high- speed imaging, to develop supporting technologies of the imaging, and to create an advanced, comprehensive and, yet, user-friendly imaging system.

2. PLANE STRUCTURE AND FUNCTION OF THE SENSOR

Figure 1 shows the concept of the ultra-high-speed image sensor having 3x3 pixels. Each pixel has a large photodiode and a storage CCD which is attached to the photodiode and elongated in the slightly slanted direction to the pixel grid. The pixel center is the center of each photodiode, and the pixel pitch is the distance from the centers of the neighboring photodiodes.

In an image capturing operation, the image signals of the first frame generated in the photodiodes of all pixels are simultaneously transferred to the first element of the CCD memory attached to each photodiode. At the next image capturing, the image signals of the second frame are transferred to the CCD memory at once to the first elements. Therefore, the image signals of the first frame are transferred down to the second elements of the CCD memory automatically.

When all the memory elements of storage CCDs are filled with image signals, the image signals of the first frame are drained to drains attached to the end of each CCD memory, and the latest image signals are stored in the first element of each CCD memory. Therefore, the frame count, i.e., the number of consecutive frames, is the number of elements of each CCD memory. The operation continues until occurrence of a target event. Then, the image signals stored in the CCD memories are read out to the outside of the image sensor, and organized to produce a series of consecutive frames. This continuous overwriting operation by new image signals makes it easy to synchronize the image capturing with the occurrence of the target event.

The highest frame rate is 20 Mfps for a standard operation, and can be increased to 40 Mfps by operating odd- and even-column pixels with a time shift of a half of the frame interval.

3. CROSS-SECTIONAL STRUCTURE

Figure 2 shows a cross-section structure of the sensor. The sensor originally developed in 2002 was a front-side illuminated, FSI, image sensor. The fill factor, the ratio of the photo-receptive area to the pixel area, was only 15% to cover the CCD storage with a light shield. Loss of sensitivity is critical in ultra-high-speed imaging. Therefore, a special backside illumination, BSI, structure for the sensor concept shown in Figure 2 was invented and fabricated to assess the functionality.

The initial material is a p^-/n^- double-epi layer on a standard p^{++} wafer, which is removed later. In the n^- epi-layer, a shaped p-well is created so that the concentration of the p-well is higher at the pixel boundary and gradually lowers to be zero toward the pixel center to make a p-well opening at the center. A signal electron generated by an incident photon near the backside is guided by an electric field created by the backside bias voltage and the shaped p-well to move around the p-well, to pass through the p-well opening, and to reach a collection gate at the center of the pixel on the front-side. In Figure 2, the photodiode in the original FSI design shown in Figure 1 is replaced by the collection gate.

The BSI structure provides a 100% fill factor and an about 80% quantum efficiency, making the net quantum efficiency 80%. In addition to the very high sensitivity, the BSI structure has another very useful advantage, "a higher frame rate", since metal wires to deliver the driving voltages can be placed on the front-side with more freedom without care for loss of fill factor and uniformity of the metal wiring on the pixels.

4. SENSOR AND CAMERA SPECIFICATION

Table 1 shows the specification of the sensors and the cameras of the prototype developed in 2011 and the currently developed one in 2016. The pixel count is almost doubled and the frame rate is increased. The frame rate is practically doubled, since increase of the pixel count results in higher capacitance C of the whole CCD area and higher resistivity R of wiring for delivery of the driving voltages, the frame rate is inversely proportional to RC, and the RC is proportional to the pixel count if the same process technology is applied. The increase of the metal layers from two to three (3P2M to 3P3M) contributed to the increase of the frame rate.

Table 1: Comparison of the prototype sensor (V16) and the new sensor (V40).

Sensor	Resolution	Frame count	Max. Frame rate	Fabrication process	Readout ports
ISIS-V16	362x456	117	16,000,000	3-Poly-2-	4

	(165k)			Metal	
ISIS-V40	446x672 (300k)	117	20,000,000	3-Poly-3-Metal	16

5. EXAMPLE APPLICATION – CRACK PROPAGATION

In this section, the developed ultra-high-speed video camera is applied to capture the images of the crack bifurcation in a transparent specimen, made of 3mm-thick epoxy resin. The geometry of the specimen is shown in Figure 3. Sharp initial crack with the length of 5mm was generated by the razor blade cut of 1mm length onto the machine saw-cut of 4mm length on the edge. Pin-loading is applied to the specimen in the tensile machine and the images of the rapid propagation and the bifurcation of the crack are captured with the frame rate of 5Mfps.

The overall experimental setup is shown in Figure 4. The continuous light beam emitted from an Nd-Yag laser is diverged into parallel beam and applied on the side of the specimen as the light source. The transmission image is captured by the ultra-high-speed video camera from the opposite side of the specimen. The electrical modulator is placed in the middle of the beam path to cut off the laser irradiation except the period of image capturing. The timings of the laser irradiation and image capturing are synchronized to the start of the rapid propagation of the crack with the aid of the laser synchronization system, so called laser trigger. In this trigger, thin laser beam is applied on the predicted crack propagation path in the transparent specimen beforehand, and the penetrating beam is received by a photodiode. Once the crack starts its propagation and the penetration of the beam is obstructed by the created new crack surface, the strength of the penetrating beam drops. Trigger system detects the drop, and send out the signal to the electrical modulator and the video camera through the function generator which enables to add the specified delay to the output signal of designed duration. First, images of rapid propagation and bifurcation of the crack, which occurred at the loading of 2.35kN, were captured at 5 Mfps. Nine images out of 107 captured images are shown in Figure 5. Bifurcation into three cracks occurred at the point, 40mm apart from the left edge of the specimen.

6. CONCLUDING REMARKS

An image sensor operating at 20 Mfps is developed. A video cameras equipped with the sensor was applied to take images of propagating cracks. Triply bifurcating cracks are also successfully captured at 5 Mfps. Through the preliminary applications, it was confirmed that the camera system is a powerful tool in scientific and industrial research.

ACKNOWLEDGMENTS

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REFERENCES

Etoh, T. G. et al. (2002), A CCD image sensor for 1Mframes/s for continuous imaging of 103 frames, *Technical Digest, International Solid State Circuit Conference 2002, San Francisco, CA,* 46–47.

Etoh, T. G., Nguyen, H. D., Dao, V. T. S., Vo, C. L., Tanaka, M., Okinaka, T. et al. (2011), A 16 Mfps 165kpixel backside illuminated CCD, *Technical Digest, International Solid State Circuit Conference 2011, San Francisco, CA,* 406–407.

Dao, V. T. S. et al (2010), Toward 100 Mega-frames per second: Design of an ultimate ultra-high-speed image sensor, Sensors, 10(1), 16-35

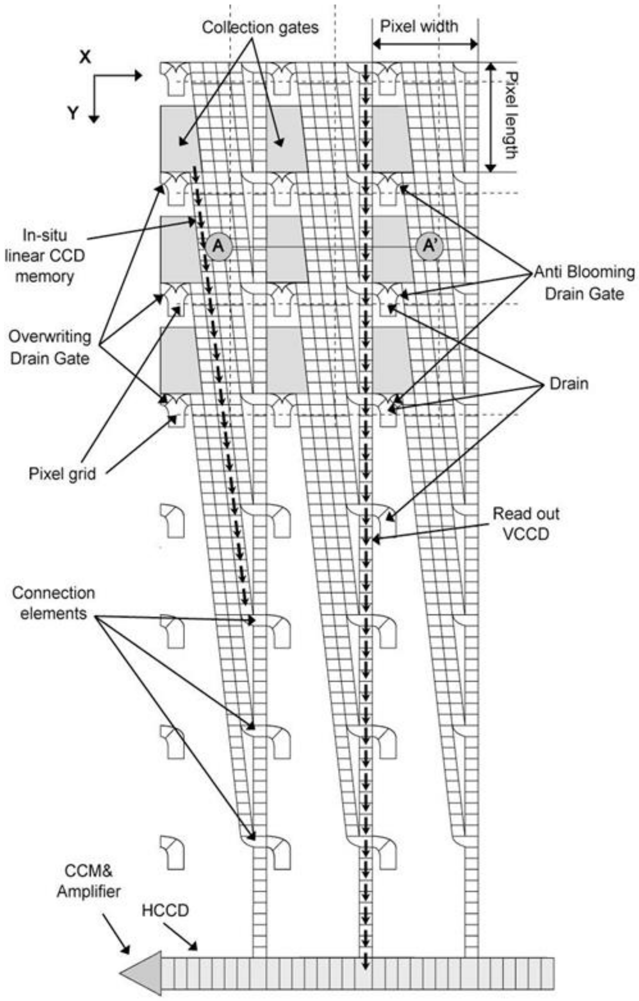


Figure 1: Plane structure of the image sensor with a slanted linear CCD memory in each pixel

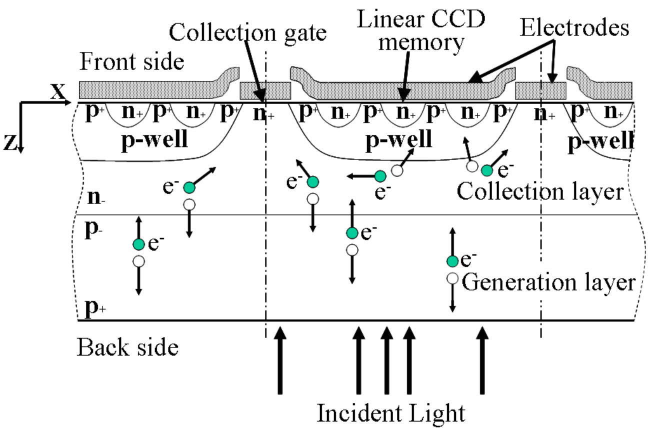


Figure 2: Cross-sectional structure of the image sensor.

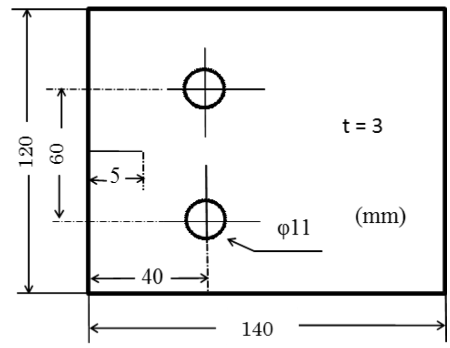


Figure 3: Geometry of the specimen

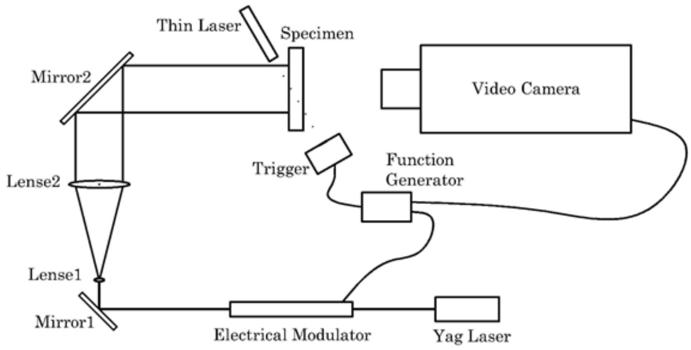
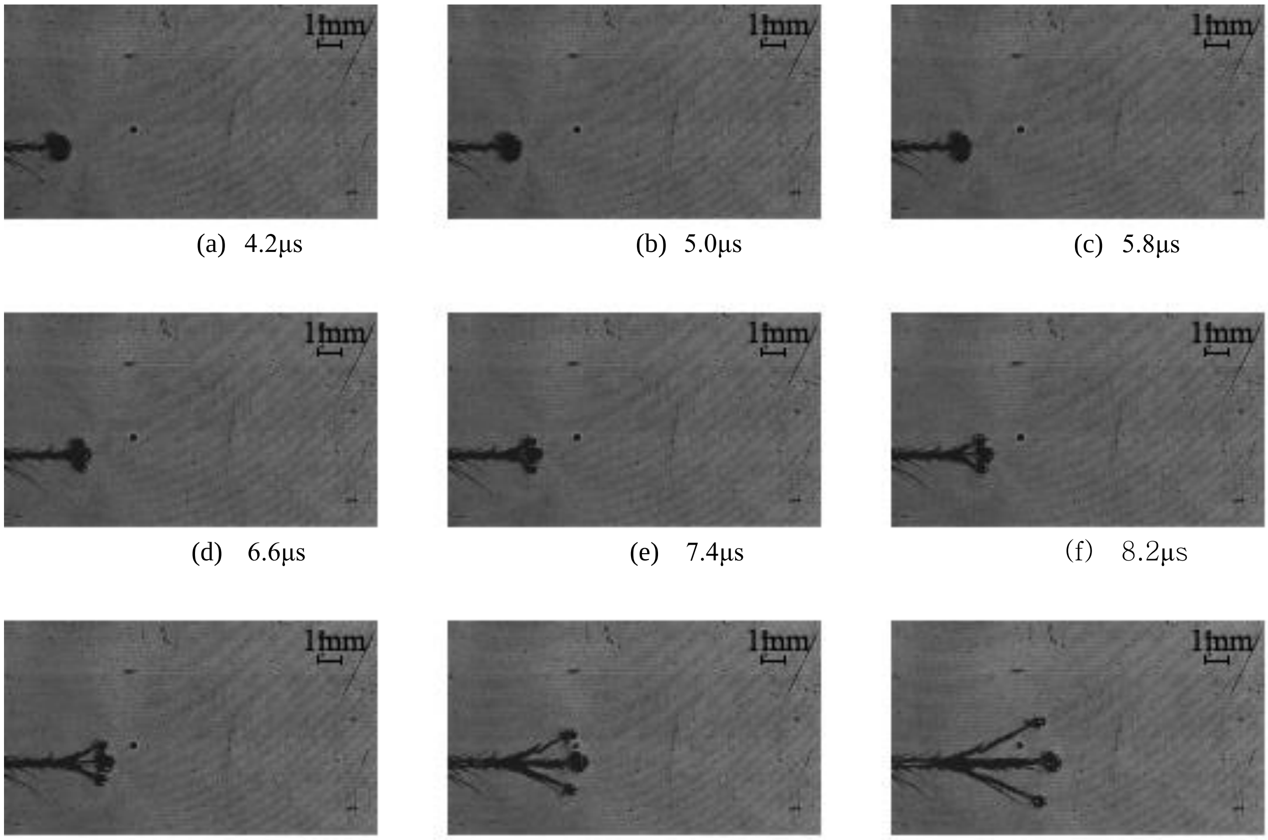


Figure 4: Overall experimental setup



(a) 4.2μs (b) 5.0μs (c) 5.8μs

(d) 6.6μs (e) 7.4μs (f) 8.2μs

(g) 9.0μs (h) 12.0μs (i) 15.0μs

Figure 5: Bifurcation captured with the frame rate of 5M fps