Imaging with an ultra-high-speed video camera operating at 20 Mfps for 300 kpixels

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Abstract
An image sensor with 300 kpixels operating at 20 Mfps is developed. Pixels on odd-number and even-number columns can be independently operated. The highest frame rate is 40 Mfps when a time shift of a half of the shortest frame interval is introduced to the operation of the odd and even pixel columns. The sensor is backside-illuminated one for high sensitivity to support the ultra-high-speed imaging with fewer photons. The concept, the structure and the operation scheme of the image sensor are presented. The pixel count and the highest frame rate of the prototype which was developed in 2011 were 165 kpixels and 16 Mfps. Therefore, the new image sensor achieved doubled performance. In-situ storage for 107 image signals is installed in each pixel. Simultaneous recording of image signals at all pixels makes it possible to capture consecutive 107 frames at a time interval for a signal packet to be transferred from the photodiode to the nearby storage element of each pixel. Video cameras equipped with these sensors are applied to imaging of high-speed phenomena such as electric spark discharge and sudden crack propagation for the performance test.

Key words: High-speed, Imaging, Diagnostics, Video camera, Atomization

1. Introduction
Since development of a digital high-speed video camera for the first time in the world in 1991, we have updated the frame rate of high-speed video cameras: 4,500 fps in 1991 (Etoh, 1992), 1 Mfps in 2002 (Etoh et al., 2002), 16 Mfps in 2011 (Etoh et al., 2011), and 16.7Mfps in 2013 (Arai, 2013). The sensitivity has also been increased by employing backside illumination to the sensor. All these cameras are capable of capturing consecutive more than 100 frames, which reproduces images at 10 fps for more than 10 seconds. The images look sufficiently smooth and are long enough to activate dynamic recognition of human beings.

Other important achievements in this field include the cameras capturing (1) 30 consecutive frames at 300 kfps with 32.4 kpixes (Kosonicky et al., 1996), (2) 128 consecutive frames at 10 Mfps with 100 kpixels (Tochigi et al., 2013), and (3) 180 consecutive frames at 2 Mfps for 700 kpixels (Crooks, et al., 2013).

This paper reports a recently-developed image sensor with 300 kpixels operating at 20 Mfps. The pixel configuration of the sensor is similar to that of the sensor operating at 16 Mfps with 165 kpixels developed in 2011. The number of the metal layers were increased from two to three to reduce the resistivity of the metal wires to deliver driving voltages from
the outside of the sensor, which doubled the pixel count and further increased the frame rate.

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. One quadrant was designed and reversed or rotated and pasted to other quadrants. 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 camera with a prototype good sensor was applied to capturing electric spark discharge.

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. Pixels in the figure are 3x3. 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.

Fig. 1 A conceptual explanation of the plane structure of the IS-CCD with a slanted linear CCD memory in each pixel

Fig. 2 A conceptual explanation of a cross section of a Backside Illuminated image sensor with in-situ storage in each pixel
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 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-section 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 Fig. 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 Fig. 2, the photodiode in the original FSI design shown in Fig. 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 2015. The pixel count is almost doubled and the frame rate is slightly 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 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>
<thead>
<tr>
<th>Sensors</th>
<th>Year</th>
<th>Pixel Count (pixels)</th>
<th>Frame Count</th>
<th>Frame Rate</th>
<th>Process</th>
<th>Readout Pads</th>
<th>EM-CCD Cooling</th>
<th>Qmax/Noise (e-) bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISIS V16</td>
<td>2011</td>
<td>362x456 (165 K)</td>
<td>117</td>
<td>16 Mfps</td>
<td>3P2M</td>
<td>4</td>
<td>On</td>
<td>12,000/15</td>
</tr>
<tr>
<td>ISIS V40</td>
<td>2015</td>
<td>446x672 (300 k)</td>
<td>107</td>
<td>20/40 Mfps*</td>
<td>3P3M**</td>
<td>64</td>
<td>No</td>
<td>9,000/30</td>
</tr>
</tbody>
</table>

* 40 Mfps: Operation with time shift of a half frame interval of odd- and even-column pixels.
** 3P3M: A semiconductor process with three polysilicon layers and three metal layers.
5. Double-trigger

Operation at the very high frame rate generates sudden heat in the image sensor and the driver chips, which may damage the circuits. For ultra-high-speed imaging, a CCD has an advantage that the signal charges are directly stored without any electrical conversion which takes some additional time lowering the frame rate. On the other hand, the CCD in-situ memories consume much higher power than CMOS-type memories, since all the elements of a CCD memory are capacitors, which simultaneously operate to store one new signal charge packet in each pixel.

Targets of an ultra-high-speed imaging might also be damaged by strong illumination. For example, A living cell such as a sperm might die under focused strong illumination through a condense lens of a microscope during the ultrahigh frame rate imaging.

Therefore, some ways to minimize accumulation of heat must be incorporated with any ultra-high-speed imaging apparatus. One effective method is “Double-trigger system”, which is devised in the test camera. The concept is shown in Fig. 3 and also explained later by using the application to imaging of an electric spark discharge.

The double-trigger system is a timing control system to avoid heat-up due to the high operation rate, as follows:

(1) at the turn-on of the camera, the camera starts to run at a slow operation rate, “Idling rate”,
(2) at detection of a precursor of the target event, the operation rate is suddenly raised at “Image capturing rate”
(3) at detection of the target event, the operation stops and a readout operation starts, and
(4) at “Time-out”, after a certain specified time with no precursor, the operation rate returns to the idling rate.

Figure 4 (a) shows a frequency distribution of delay time from turn-on of the spark generator to occurrence of a discharge event measured before the imaging test of the spark discharge. The delay time is measured with an oscilloscope from the turn-on signal sent from the spark generator to detection of an electromagnetic noise. The delay widely distributes up to 150 ms. In this case, the idling rate is 8 “k” fps, and the image capturing rate is 4 “M” fps or 8 “M” fps, which is 1,000 times faster than the ideling rate. In the case, the precursor of the spark discharge is the turn-on signal of the spark generator. The duration for the time-out is set at 150 ms based on Fig. 4 (a).

Figure 4 (b) shows an example of a voltage fluctuation pattern due to electromagnetic noise generated by a spark discharge and detected by the oscilloscope. The pattern is composed of two stages: in the first part, the voltage ranges between 1 V to 5 V, and, in the second one, a huge voltage change appears.

The delay time is from turn-on of the spark generator to detection of the first noise signal, in the case of Fig. 4 (a), at - 2 μs. Therefore, the first trigger signal is the turn-on signal of the spark generator, which is the precursor in the case. The second trigger signal can be either the first part or the second part of the electromagnetic noise. In the experiment, the rising signal of the second one was employed.
with the threshold value for the detection, 10 V.
At the first trigger, the camera starts a continuous overwriting image capturing operation at a planned frame rate. At
the second trigger at 0 μs, the camera stops the image capturing operation, after waiting for the end of the whole spark
discharge process for 5 μs. Then, image signals stored in each pixel are read out. If the electromagnetic noise is not
detected during 150 ms, the camera operation returns to the idling operation.

6. Example application 1: Spark discharge

Figure 5 and Fig. 6 show the camera, and the spark generator and a handmade cage as an electromagnetic noise
barrier, utilizing a puppy cage. Fig. 7 and Fig. 8 show example images of the electric discharge.
The camera used in the imaging of the discharge is the one with the prototype sensor ISIS V16. Both the camera and
the spark generator are covered with electromagnetic noise barriers made with dog cages covered with metal nets and
grounded to the earth. A probe of an oscilloscope is attached to the cage to detect the spark discharges. After the spark
generator is turned on, a spark discharge occurs in 20 ms to 150 ms as shown in Fig. 4.

A spark discharge process is composed of two stages: in the first stage, a leader discharge proceeds from one of a
cube electrodes to another one step by step, creating a zigzag route, and, at the instance when the leader reaches the
opposite side, a sudden very bright spark begins by the short circuit and the second stage of the spark charge process
proceeds. In the second stage, the charge passes along the zigzag route which had been developed by the leader.
The development process of the leader in the first stage is shown in Fig. 7. The images were captured at 8 Mfps (the
time interval of 125 ns).
(1) The propagation begins at the 23rd frame, and ends at 50th frame,
(2) from the 50th frame to the 100th frame, current continuously flows between the electrodes, heating the route, which
may be the second stage, and
(3) the route gradually becomes vague and wide, which may reflect the diffusion of the heated air or plasma after the stop
of the current.
In this case, the first stage continues about 3 μs (0.125 x (50-23)).

Figure 8 shows a sudden strange phenomenon observed during the second stage captured at 4 Mfps.
(1) At the 58th frame, a local back flush can be observed near the end edge of the route,
(2) at the 60th frame, a net-like spark discharge suddenly spreads in the wide area, and
(3) it ends in one frame (250 ns), leaving some trace of the areal spark.

7. Example application 2: Crack Propagation

In this section, the developed ultra-high-speed video camera is applied to capture the images of the crack bifurcation
in the transparent specimen, made of 3mm-thick epoxy resin. The geometry of the rectangle specimen is shown in Fig.
9. Sharp initial crack with the length of 5mm was generated by the razor blade cut of 1mm length onto the machined
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 5M and 10Mfps.
The overall experimental setup and the optical system are shown in Fig. 10 and 11, respectively. The continuous light beam emitted from 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 2.35 kN, were captured with frame rate of 5Mfps. Nine images out of 107 captured images are shown in Fig. 12. In 107 images, time at the first image is set to be zero, and time at following images is set with 0.2 micro second interval in sequence. Bifurcation into three cracks occurred at the point, 40mm apart from the left edge of the specimen.

Images of the bifurcation, captured with the frame rate of 10Mfps, are shown in Fig. 13. From captured 107 images, Twelve images at every 0.4 micro second from 3.1 to 7.5 micro seconds are shown in this figure. Time at each figure is
decided in the same manner as the previous case, while the time interval is 0.1 micro second. Rapid propagation of the crack started at 2.13kN in this specimen. Bifurcation into three cracks occurred at points, locating 40mm, 43mm and 46mm apart from the left edge. Branched cracks at the previous two points stop in the middle, and the branched cracks at the last bifurcation point leads the fracture of the specimen.

8. Concluding remarks

An image sensor operating at 20 Mfps is developed. Video cameras equipped with the sensor and the prototype previously developed were applied to take images of spark discharges and propagating cracks. A double-trigger system is introduced to the camera and applied to avoid strong illumination for the ultra-high-speed imaging before and after the imaging period. Propagation of the spark discharge were captured at 4 Mfps and 8 Mfps. Triply bifurcating cracks are also successfully captured at 5 Mfps and 10 Mfps. Through the preliminary applications, it was confirmed that the camera system is a powerful tool in scientific and industrial research.
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