

An Ultra-High-Speed Camera with an In-situ Storage Image Sensor

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Abstract

This article describes the structure and performance of an In-Situ Storage Image Sensor (ISIS) designed and manufactured at Philips Semiconductors in Eindhoven by members of the University of Applied Sciences in Osnabrueck. The camera for this ISIS was developed and built by the Shimadzu Corporation in Kyoto.

I. Introduction

Already in 1993, a questionnaire was distributed to Japanese scientists and researchers, who were potential users of high speed imaging systems (Etoh and Takehara, 1994). One result was, that the frame rates of available high-speed cameras at that time were not high enough. A camera with a frame rate of 1,000,000 fps and 100 consecutive images would satisfy 95% of the user requirements at that time. In a new questionnaire, distributed in early 2000, users of high-speed cameras requested an even higher frame rate. Now, 10,000,000 fps would cover 92.5% of the applications. To achieve a frame rate of 1,000,000 fps with 100 consecutive images, a concept, the "in-situ storage", is introduced to a high speed CCD image sensor. Each pixel has an own storage area adjacent to the pixel with memory size sufficiently large to reproduce a moving image. This storage is filled with image signals during the image-capturing phase. After the image-capturing phase, the read out of the sensor ensues.

The first successful application of the concept to CCD technology is a burst image sensor with "SPS (Serial-Parallel-Serial) storage" and an overwriting mechanism, presented by late professor Kosonocky in 1996. A camera which uses this sensor is now provided by Princeton Scientific Instruments and has a maximum frame rate of 1,000,000 fps with 32 consecutive frames.

The main problem with this design is the change of transport direction from the serial to the parallel storage. It is necessary to make two direction charge transfer during one integration cycle of the image capturing phase, which also limits the maximum frame rate. Another weak point of this sensor is the relative small number of consecutive frames.

To overcome the problem of direction changes, an ISIS structure with linear storage elements was introduced. The easiest way to produce such a sensor is to apply an additional lightshield to a standard CCD imager. The additional lightshield covers the storage CCD-elements and leaves small openings for the light sensitive CCD elements.

SMD, Silicon Mountain Design, first introduced an ISIS with linear storage to market (Howard, et al. 1997). The camera is now produced by DALSA. It reaches up to 1Mfps with 17 consecutive frames and a resolution of 240x240.

For the first tests of such a structure in Philips technology, the authors developed a camera with a sensor similar to the SMD one. The sensor is called ISIS-V1.

II. Structure of the system

A. Sensor

The "basis" for the ISIS-V1 is the Philips FXA1012 sensor. This sensor was chosen mainly because the pixels are quite small, 5.1 μm x 5.1 μm , and it has a full-well capacity of typical 45,000 electrons. It is a frame-transfer sensor using a 4-phase-clocking system and it has a resolution of 1616(H) x 1296(V) pixels.

The lightshield added to the light sensitive area of the FXA1012 is shown in Fig. 1. Below each opened light sensitive pixel, a covered area working as storage for the light sensitive pixel is

located. During integration, electrons are collected in the light sensitive pixels and then shifted down into the storage pixels below the light sensitive pixel. Because the FXA1012 is a standard frame-transfer sensor, a drainage of old pixel-information at the end of each storage

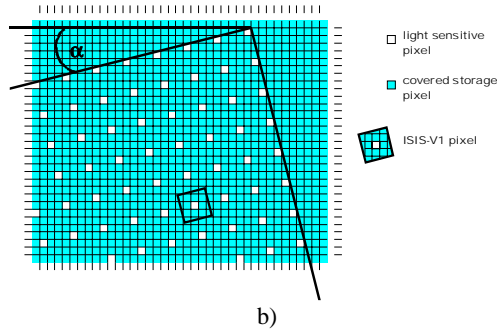
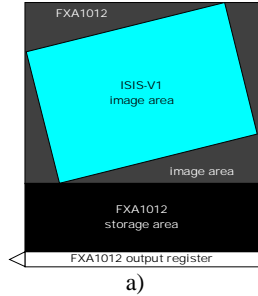


Fig. 1: ISIS-V1 punched lightshield, a) location on FXA1012, b) upper right corner

line is not possible. Integration must stop after the storage line below the light sensitive pixel is filled.

Due to the attached lightshield, the axes of the ISIS image area are not orthogonal, the sensor has to be mounted slanted to the camera. The angle α in Fig. 1 b) is necessary to create squared ISIS-V1 pixels with the maximum fill-factor. The distance between two pixel rows must be the same as the distance between 2 pixel columns, else the image area would be non-rectangular.

For the ISIS-V1, each light sensitive pixel has 16 storage pixels, that means 17 consecutive frames can be taken (16 stored frames + 1 frame in the light-sensitive pixels). The angle of the image section is calculated with formula (1).

$$\alpha = \arctan \frac{1}{s} = \arctan \frac{1}{4} \approx 14.0^\circ \quad (1)$$

$s^2 = 16$: Number of storage pixels

With this angle, ISIS-V1 pixel size is about $21.0\mu\text{m} \times 21.0\mu\text{m}$. The number of storage pixels

is chosen to 16 to have good spatial resolution of at least $256(H) \times 256(V)$ pixels per frame and enough stored frames to create a short movie. The relation between the resolution of the FXA1012 and the ISIS-V1 can be seen in formulas (2) and (3).

$$H = Y + s(X - 1) + R_h \quad (2)$$

$$V = X + s(Y - 1) + R_v \quad (3)$$

$H = 1616$: FXA1012 horizontal resolution

$V = 1296$: FXA1012 vertical resolution

$X = 344$: ISIS - V1 horizontal resolution

$Y = 239$: ISIS - V1 vertical resolution

$R_h = 5$: unused pixel columns

$R_v = 0$: unused pixel rows

Fig. 2 shows an ISIS-V1 storage line for one light sensitive pixel. The pixel information of different frames for one ISIS-V1 pixel are located in the storage column right below the light sensitive pixel (see also Fig. 6).

The opening in the lightshield is chosen to the smallest guaranteed opening in the metal layer due to the production process. Also measurements on a test-sensor, produced before the ISIS-V1, showed that this opening is

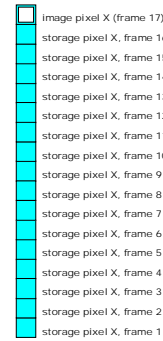


Fig. 2: ISIS-V1 storage line

satisfying to cover the pixels neighboring the light sensitive one. In this test-sensor, openings with different sizes were tested to measure the influence on neighboring covered pixels. The results can be seen in Fig. 3. The test sensor was illuminated and the charge collected in the covered pixels next to a light sensitive one was measured. The neighboring pixels in vertical direction collect much more charge than the ones in horizontal direction. The reason here is that a clock line is located between each FXA1012 pixel column. These clock lines block the light to the left and right next to the light sensitive pixel. There is no such block to the upper and lower

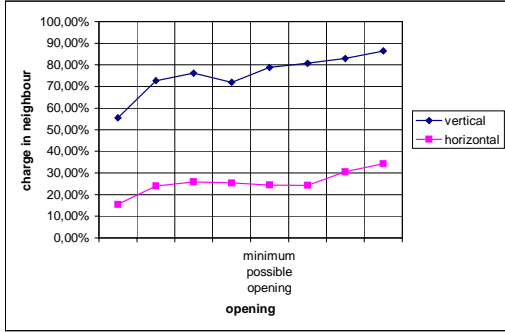


Fig. 3: Charge in covered pixels next to opened ones

pixel. The importance of light blocking to the sides is mainly given during the time the shutter of the camera closes (see B. Camera). In vertical direction, only the first or the last two frames might be over-illuminated, in horizontal direction, frames 4 and 13 might be over-illuminated. Thus, the blocking in horizontal direction is more important because frames from the middle of the movie might become unusable.

B. Camera

The camera for the ISIS-V1 must follow a special scheme of integration and read-out, shown in Fig. 4. The normal scheme for an FT-sensor is consecutive integration and read-out.

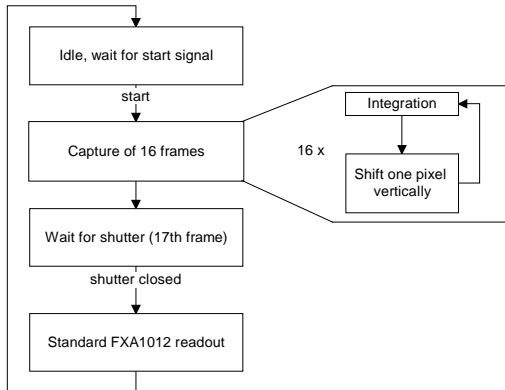


Fig. 4: ISIS-V1 imaging cycle

For the ISIS-V1, a start signal has to be set short time before target action happens. After that, 16 frames are taken and stored in the storage area below the light sensitive pixel. The speed of the shift to the storage is variable, maximum speed is $1\mu\text{s}$ (1,000,000 fps). Before read-out ensues, a mechanical shutter has to darken the sensor because it is read out through light sensitive pixels. During the time the shutter closes, the 17th frame is taken in the light sensitive pixel. After read-out, the pixels have to be sorted to

create 17 single pictures (Fig. 6, 7, 8). These pictures then can be combined to a movie.

C. Supporting technologies

The shortest integration time for the FXA1012 is recommended $1/120\text{s}$. If the frame rate of the ISIS-V1 is set to 1,000,000 fps (integration time $< 1\mu\text{s}$), this sensor needs about 8400 times more light to deliver the same signal. It is necessary to support the camera with a special strobe which has a high intensity and a short tail (to avoid over-illumination during shutter-closing).

III. Example Images and Associated Problems

Fig. 5 shows the lower left corner of the complete ISIS-V1 image area. The holes here represent the light sensitive pixels. In Fig. 6, pixel information of that part can be seen.

A complete ISIS-V1 picture before sorting is shown in Fig. 7. The marked triangular parts at the sides and at the top of Fig. 7 have light sensitive pixels with different openings in the

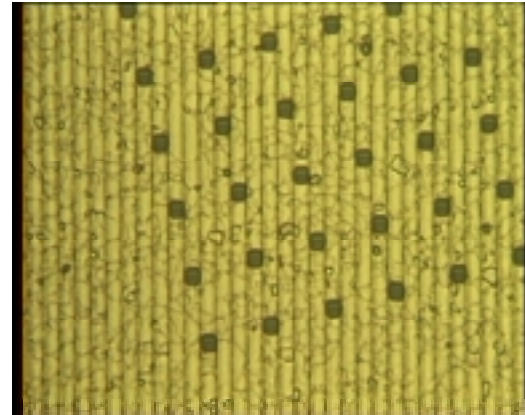


Fig. 5: ISIS-V1 lightshield with holes (lower left part)

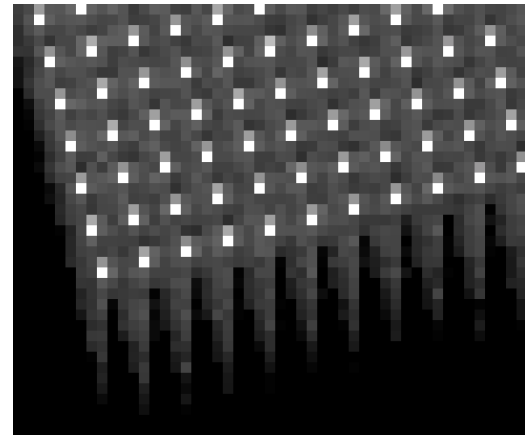


Fig. 6: ISIS-V1 image before sorting (lower left part)

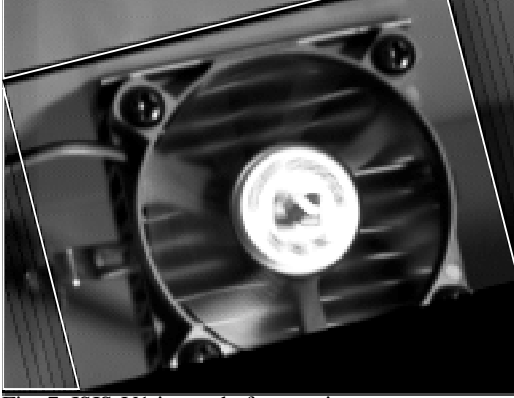


Fig. 7: ISIS-V1 image before sorting

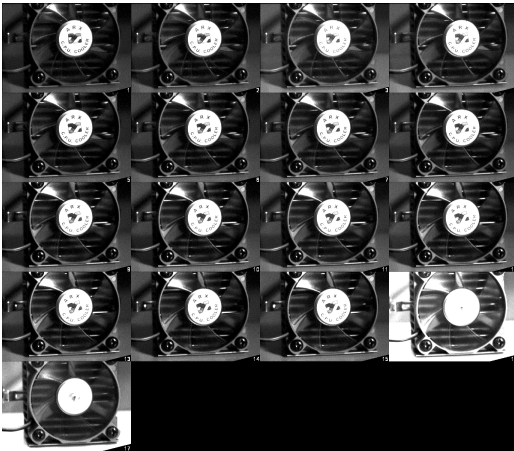


Fig. 8: ISIS-V1 image after sorting

lightshield and are used only for tests. Fig. 8 shows the sorted 17 frames. The last two frames, 16 and 17, are over-illuminated while the first image is normally illuminated. The flashlight during capturing of this sequence was located lower than the captured object, so the 16th frame was more illuminated.

The weak points of ISIS-V1 are:

- low light sensitivity
- low fill factor (about 3%)
- small number of consecutive frames
- no overwriting mechanism

To overcome these problems, a new sensor, ISIS-V2, was developed by the authors.

IV. ISIS-V2

The lightsensitive pixels in the ISIS-V2 are about 50 times larger than the storage pixels, so they are much more sensitive and a much better fill-factor is achieved. An overwriting mechanism is added at the end of each storage column. The number of consecutive frames is 105. Fig. 9 shows a scheme of the ISIS-V2, lower left corner. During integration, the storage area is filled up to the overwriting pixel. There, old

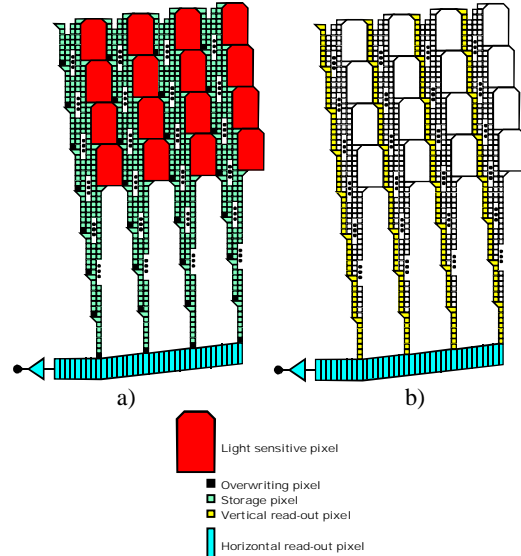


Fig. 9: ISIS-V2 sensor scheme a) integration b) read-out

pixel information is drained. During read-out, a part of the storage pixels act as a vertical register (see Fig. 9 b). It is clocked independently from the other storage pixels. The vertical register pixel information is shifted to the horizontal register and then read out, pixel information in the other storage pixels is not shifted during that time. After the vertical register is emptied, it is filled again from the storage pixels and then again read out. This ensues until the sensor is read out completely.

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