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Noise Sources of a 16 Mfps Video Camera

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Abstract

We developed an ultra-high-speed and ultra-high-sensitivity image sensor operating at 16,000,000 fps at its highest frame rate with 165,000 pixels and capable of continuous imaging of 117 frames. The ultra-high-sensitivity is supported by Backside illumination and Charge Carrier Multiplication, CCM. Through evaluation of the sensor, we found problems such as hole accumulation at the backside, sensitivity adjustment along the center lines, direct intrusion of incident light to the in-situ memory area during mechanical shutter closing, etc... They obstructed the sensor performance, especially the ultra-high-sensitivity. These problems are summarized with sources of signal attenuation and other noises common to image sensors. In this paper, countermeasures to some of these problems are also proposed.

Keywords: ISIS, CCD, Ultra high speed, High sensitivity, Image sensor.

1. Introduction

We developed a CCD image sensor with 400 x 489 pixels capable of capturing continuous 117 images at 1,000,000 frames per second (1Mfps) [1]. We named the sensor “ISIS-V12”, In-situ Storage Image Sensor version twelve. ISIS-V12 is a first backside illuminated (BSI) image sensor mounting the ISIS structure and CCM on the front side. The CCM, combined with the BSI-ISIS structure and cooling, achieved very high sensitivity. Furthermore, the BSI structure increases frame rate by placing metal wires almost freely on the front side without care for less fill factor and non uniformity of the pixel design.

The prototype, ISIS-V16, was next developed by improving mostly the metal wiring of the ISIS-V12. The frame rate reached 16Mfps [2]. The performance of ISIS-V16 was evaluated. There are many problems obstructing further improvement of the ultra-high-sensitivity of the ISIS-V16 camera. They are listed as follows:

(1) Hole accumulation at the backside

(2) Sensitivity adjustment along the center lines

(3) - Leak current from the p/n junction at the mechanically dice edges

- Dark current generated by mechanical stress due to bumps for flip-chip mounting on a carrier substrate.
- Dark current from wide depletion layer

(4) - Direct intrusion of incident light to the in-situ memory area during mechanical shutter closing

- Migration of electrons to the fast and the last parts of the memory during mechanical shutter closing
- Migration of electrons to the amplifiers

(5) - Stability of voltage of the CCM electrode

- Stability and heat generation of driving

(6) - Readout noise (parallel readout)

- Random spike noise
- Electromagnetic noise due to high frequency/high power driving

(7) Infrared light generated by recombination of hot electrons generated in transistors of the amplifier with holes

2. ISIS-V16 design

Fig. 1 and Table 1 show the global planar structure and specification of ISIS-V16, respectively. We divide the ISIS-V16 structure into four blocks, each with a photo-receptive area (181 x 228 pixels), an HCCD, a CCM and an amplifier. The number of consecutive is 117. The maximum frame rate is 16 Mfps.

In Fig. 2, a signal charge packet is transferred from the collection gate to the memory CCD channel, carried downward, and drained from the drain at the end of the CCD channel. Each slanted linear CCD serves as a memory for each pixel. The simultaneous parallel recording operation at all pixels realizes the ultimate high frame rate. The drain allows continuous overwriting recording during the image capturing operation. When occurrence of the target event is detected, the overwriting operation is stopped, and the

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image signals stored in the CCD memories inside the image sensor are then slowly read out. The overwriting mechanism is essential to ultra-high- speed imaging to ease synchronization of the image capturing timing with occurrence of the target event.

Figure 3 shows a cross section of BSI-ISIS from A to A' of fig. 2. The incident lights come to the backside of the sensor and generate electron-hole pairs. The signal electrons come towards the collection layer and, then to the collection gate. The linear CCD memory is installed in a p-well in the n-epi layer on the front side of the sensor. The sensor must be thick enough to avoid unwanted incident light, with the wavelength higher than 700nm, coming directly to the CCD memory in the p-well.

Tab. 1. Specification of ISIS-V16

	ISIS-V16
Frame rate	16,000,000 fps
Pixel Count	362 x 456 (=165,072) pixels
Full well capacity	22,000 e-
Pixel size	43.2 x 43.2 micron^2
Size of CCD Element	3.0 x 3.6 micron^2
Fill Factor	100% (1,866 micron^2)
Average QE	about 80%
Number of Frame	117 frames
Transfer Scheme	Four-phase transfer
Operation Temperature	-50 degree C
Sensitive Wavelength	350 ~ 650 nm
Overwriting Operation	Installed
CCM	Installed
Interlaced image	Installed

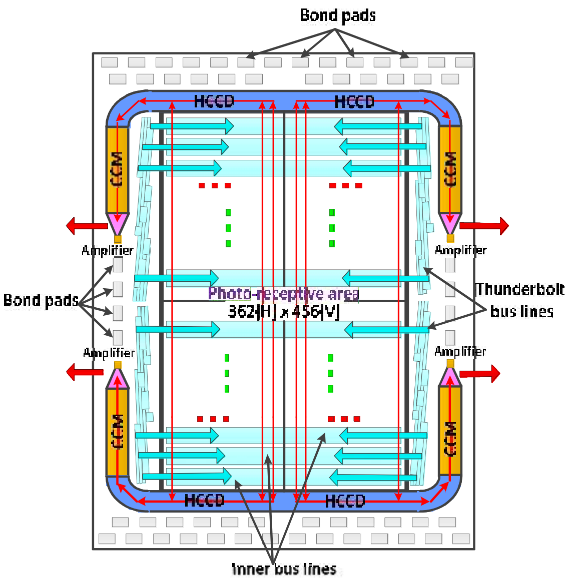


Fig. 1. The global planal structure of ISIS-V16

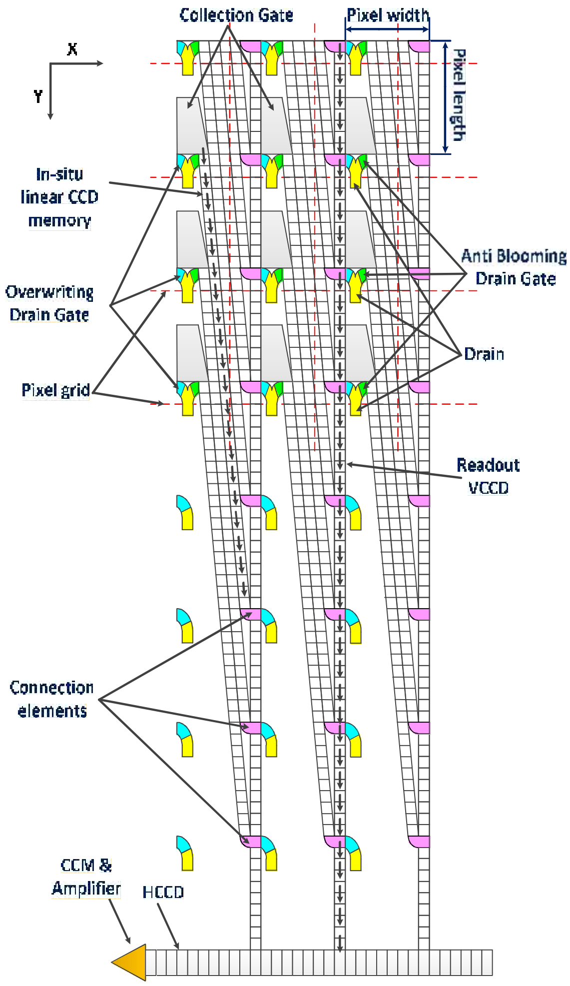


Fig. 2. Schematics diagram of the front side circuitry

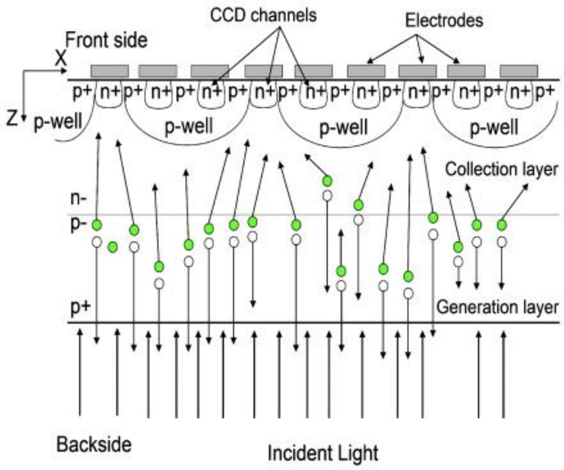


Fig. 3. Cross section (A-A' cross section in Fig. 2)

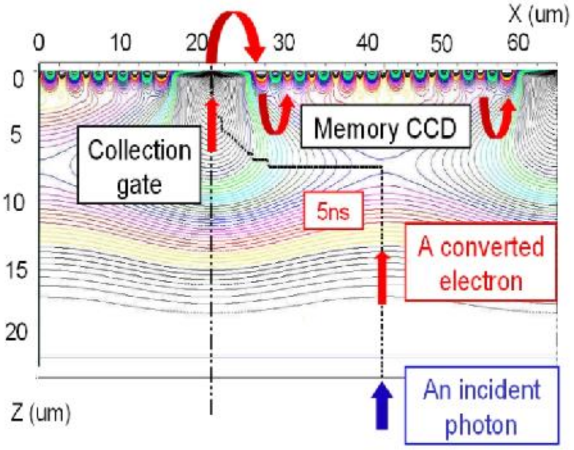


Fig. 4. Simulated electric field of X-Z section of a BSI-ISIS

Figure 4 is a simulated electric field of the X-Z section of the BSI-ISIS. The traveling time of an electron from the backside to the collection gate is about 5ns. The traveling time of an electron in to the collection gate is much less.

The total traveling time is as small as 6 ns, which is less than 10 ns. Thus, in the theory, we can achieve a very high frame rate up to 100 Mfps.

3. Evaluation system

3.1. ISIS-V16 evaluation camera

Figure 5(a) shows the ISIS-V16 evaluation camera. It consists of the camera head, a FPGA board and a power supply system.

In Fig. 5(b), the camera head is a vacuum container with two printed circuit boards, PCB, inside. One PCB is a CCD main board and the other one is a CCD clock board. The CCD sensor is mounted on the CCD main board. Many IC drivers are attached very close to the socket pins to send the driving voltages of the sensor as fast as possible. We use the CCD clock board not only to send the digital signals to the CCD main board to control all IC drivers operation, but also to receive the digital output signals of the sensor from the CCD main board before sending them to a computer to reproduce images.

The FPGA board is placed on a top of an empty box at the backside of the camera head. It operates as an interface board connecting the computer and the evaluation camera. To make the camera structure simpler, in the next step, we will combine the FPGA board and the CCD clock board in only one control board. The CCD technology is very flexible to adjust supply voltages to evaluate a sensor performance. Therefore, at the first step of the evaluation, we use many power supply sources to control voltages of the ISIS-V16 camera system. Finally, a power supply board are replaced to set all the voltages to the desired and stable states.

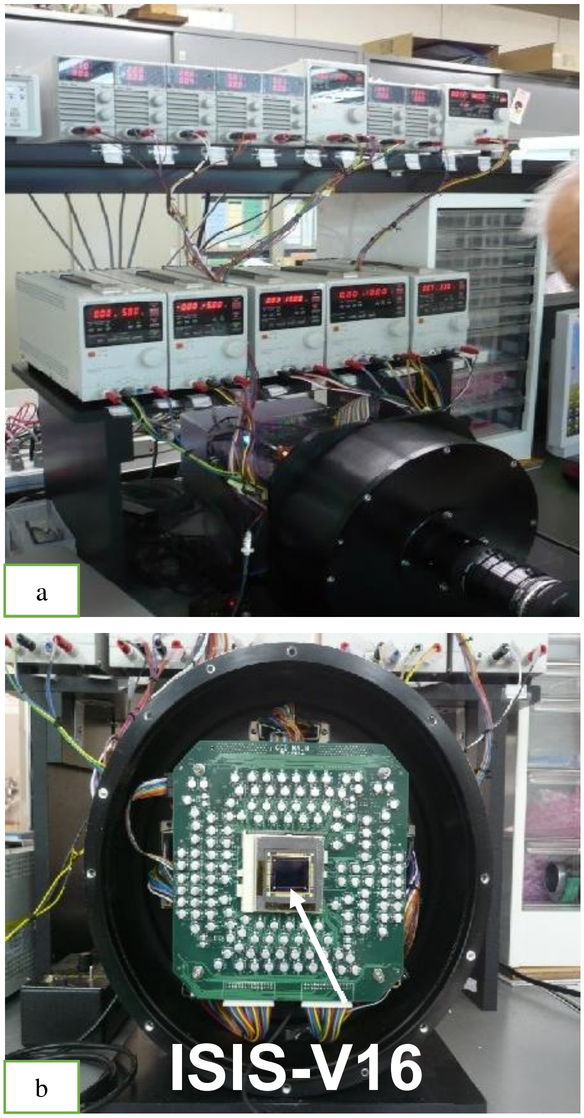


Fig. 5. (a) Evaluation camera and (b) camera head

A cooling rod is placed in the box and the head of the rod is attached to the backside of the package of the sensor. The standard operating temperature is -50 deg C. Although the sensor and the vacuum chamber can be cooled down to -80 deg C and -100 deg C respectively, most of ICs on the CCD main board in the camera head operate at the temperature higher than -50 deg C, according to their specifications.

3.2. Conversion rate of output amplifier and ADC

ISIS-V16 camera can operate with not only ultra-high frame rate but also extremely-high sensitivity. To get a better image quality, noise reduction must be required with very high priority. The ISIS-V16 camera uses 14 bits analog to digital converter (ADC). As the analog voltage range of this ADC in the CCD mode is one volt; the least analog to digital unit of the output from the ADC is equivalent to 61.03 microvolt. The output amplifier of the ISIS-V16 converts one electron to 40 microvolt. Therefore, one ADU measured as the output is equivalent to 1.53 (= 61.03/40) electrons.

4. Noise evaluation

4.1. Noise evaluation of ISIS-V16

We developed a CCD backside image sensor named ISIS-V12. This sensor was mounted in ISIS-V12 camera, which was made by Shimadzu Corporation. The total noise level is less than 10 e- at -50℃. Next, we developed a new sensor, ISIS-V16. The design is exactly the same as that of the ISIS-V12, excepting the metal wiring to increase the frame rate. However, since the ISIS-V16 camera was made by Kinki University at the first time with lack of experience, the total noise level is much higher than that of the ISIS-V12 camera. The noise evaluation results are summarized as follows:

- The average of the total noise level of the four blocks of the sensor is about 30 e- at -50 deg C.
- The noise levels of the four blocks significantly vary.
- They are independent of the frame rate.

Subsequently, the noise level of the ISIS-V16 camera is three times higher than that of the ISIS-V12 camera. The difference may be due to the camera system of the ISIS-V16 made by inexperienced engineers.

4.2. Hole accumulation at the backside

Incident photons generate electron-hole pairs in the thick p- generation layer at the backside. The electrons are collected at the collection gate on the front side. Holes are collected at the backside and drained to the outside of the sensor. To avoid the recombination of electron-hole pairs, holes should be drained as fast as possible. To enhance the hole draining, backside bias voltage of a proper fixed level is applied to the backside of the sensor, which also widen the depletion layer at the p-n junction and reduce thickness of the hole accumulation layer at the backside. These effects increases the quantum efficiency, QE. Unfortunately in the ISIS-V16, we found bonding to the backside to supply the bias voltage is not good so that the holes cannot be drained out perfectly. Therefore, a sensitivity of the ISIS-V16 is lower than the level expected in the design.

4.3. Readout noise

Figure 6(a) and 6(b) show the images taken at 1Mfps. They were taken at 20℃ (room temperature) and at -40 deg C, respectively. As shown in Table 1, the number of the pixel is 165,072 pixels and the number of consecutive frames is 117. Therefore, the number of all signals to be read out is about 20 million for full four blocks or 5 million for each block. The speed to read out the signals from each of the four amplifiers is quite slow. Thus, figure 6(a) has a very large dark current in the periphery area of the image. To improve this problem, in the next design, we will make the readout time much shorter by increase the number of the readout amplifiers and the readout rate of each amplifier.

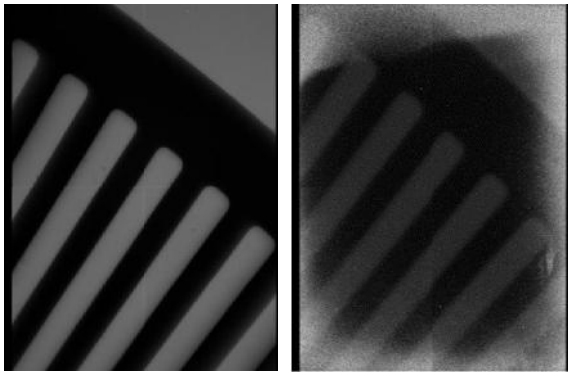


Fig. 6. Laser beam chopper: the 51st image taken at 1Mfps (Readout time: 20s) at (a) 20 degree C and (b) – 40 degree C

4.4. Leak current from the p/n junction at the mechanically diced edges and mechanical stress due to bumps

Mechanical dicing of the double-epi-wafer exposes a p/n junction on the rough dicing edge which causes strong leak current [3]. As shown in figure 7, large noise appears along the edges, and decreases toward the center. By cooling, this noise is reduced depending on the temperatures.

Figures 7(a) to 7(d) show the relationship between temperature and noise levels along the horizontal center line. From the figures, the noise characteristics are summarized as follows:

- The noise is much smaller at the center of an image.
- The noise level increases at higher frame numbers.
- At -40 deg C, the noise levels are almost constant.
- At the temperature below -60 deg C, the noise level becomes higher.

The noise is caused either by the leak current from the p/n junction at the edge or the mechanical stress generated by bumps for flip-chip process placed around the periphery of the sensor chip. For the former problem, the stealth dicing is effectively applied [3]. For the latter, introduction of smaller bumps distributed all over the sensor area is effective. This countermeasure also works for heat transfer when the sensor is cooled. Recently, for the commercial backside illuminated image sensors, even a no-bumps flip-chip technology is being applied.

The reason why the constant noise level along the center line at -60 deg C may be excessive cooling of the parts of control circuits in the vacuum chamber, since, according to the specifications fo the parts, operation temperatures of most of them are higher than – 50 degree C.

4.5. Electromagnetic noise due to high frequency/ high power driving

Figure 8(a) shows an image taken at 1Mfps, -50 deg C with no incident light. The brightness and the contrast of the image are adjusted to see clearly the noises. Figure 8(b) shows the enlarge images of the areas enclosed with rectangles in the blocks of Fig. 8(a). The figures show that:

- The noise shape is a stripe one.
- The noise levels of the first and the fourth blocks are similar. The noise levels of the second and the third block are also similar.
- The noise levels of the first and the fourth blocks are from 15 e- to 20 e-. The noise levels of the second and the third are from 35 e- to 40 e-, as seen in Fig. 9.

Stripe noise does not stay in one place. It moves at the constant rate when the frame number increases. A stripe-like noise is not caused by imaging device. The most possible cause is electromagnetic noises generated by the control circuits made by the author at the first time and operating at a very high frequency.

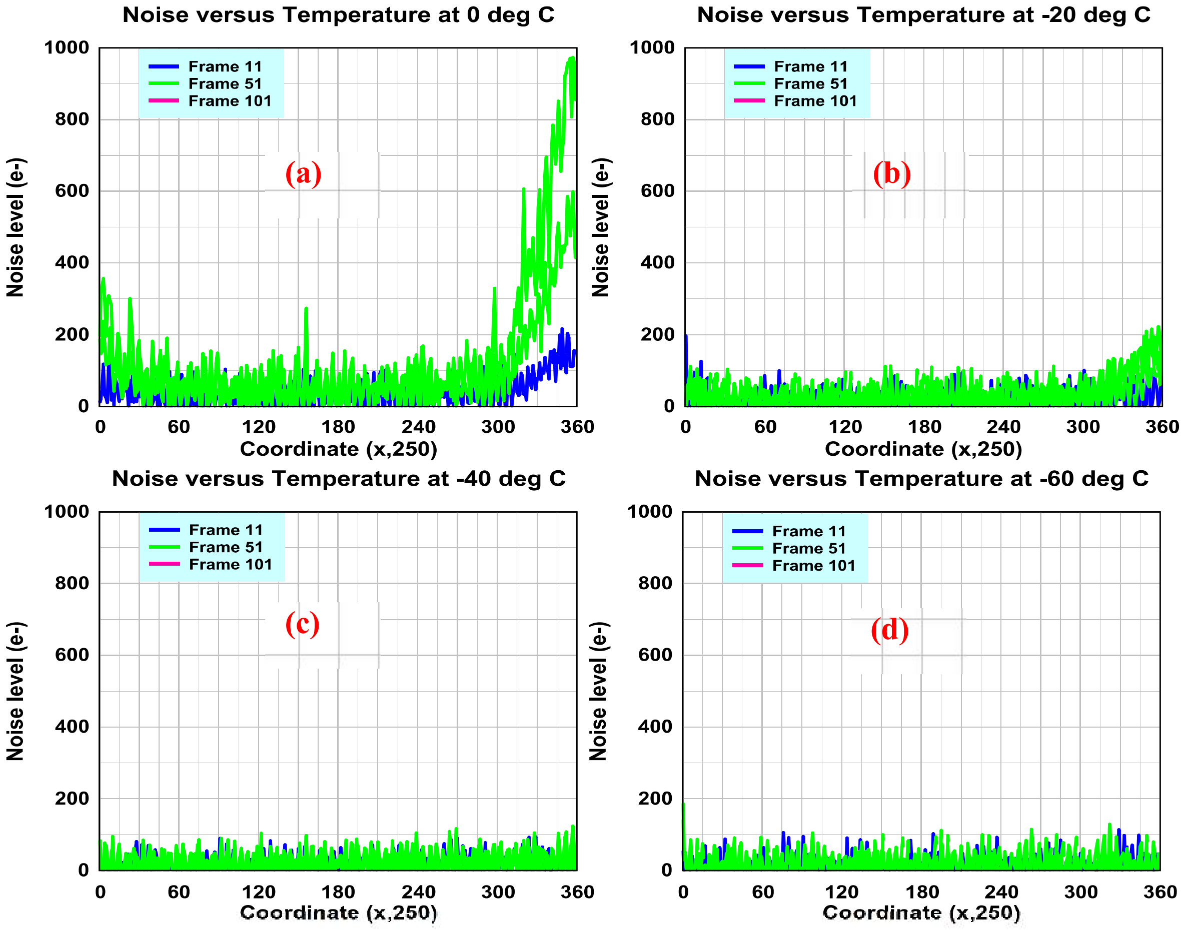
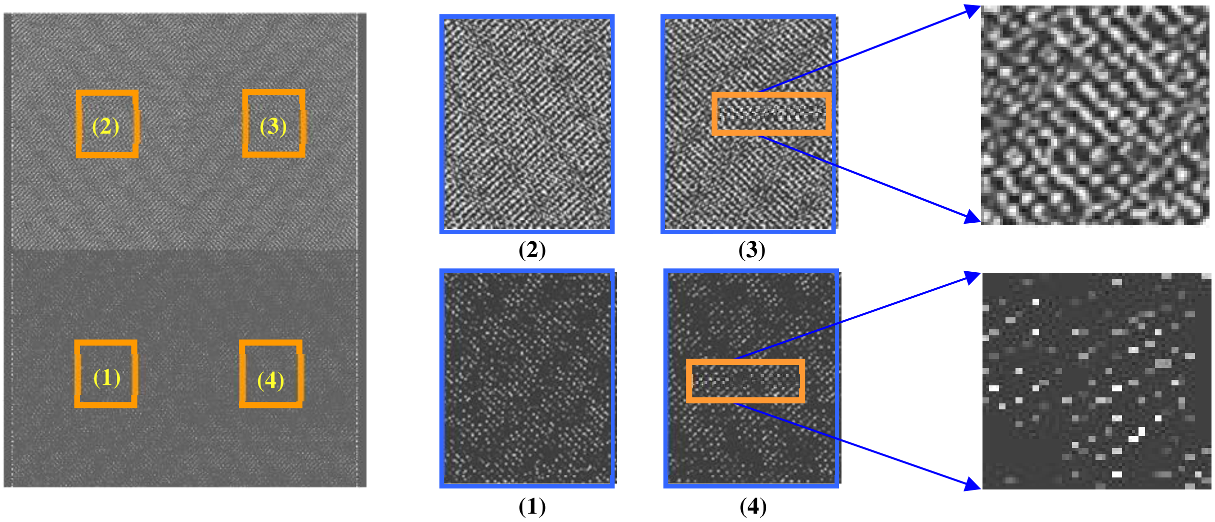


Fig. 7. Temperature vs. Noise along the horizontal center line



(a) An original image

(b) Magnified images in the blue frames of the original image

Fig. 8. Electro-magnetic noise from control circuitry

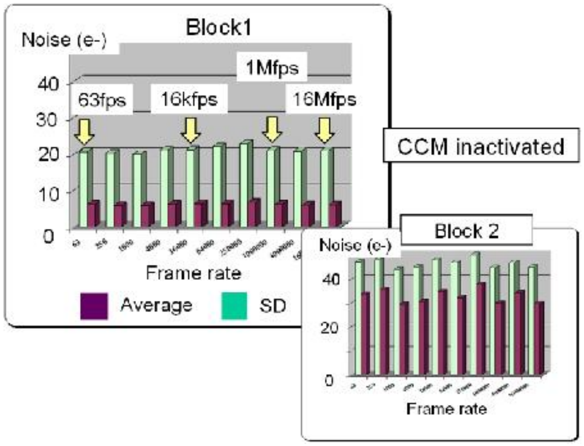


Fig. 9. Noise vs. Frame rate at block 1, 2

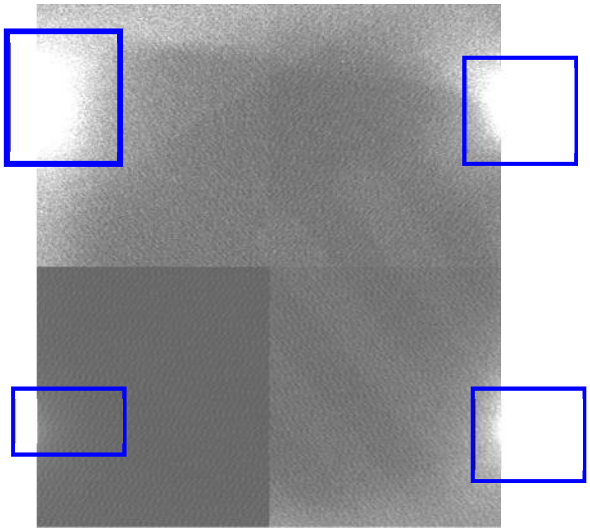


Fig. 10. Near IR emission from amplifiers (CCM is activated)

4.6. Light generated by hot electron generated at the amplifiers

Figure 10 shows an image taken with the CCM activated at 25 deg C (room temperature). Very weak light comes to the camera, generating small amount of electrons. These electrons are amplified by CCM before transferred to the output. As seen in the fig. 9, the image has several problems:

- The brightness of block four is darker than that of the others.
- There are four brighter parts near the corners of the four blocks. The brighter parts appear independent of temperature.

The first problem may be due to instability of the CCM gain. The second one occurs at the amplifier area. Transistors in the amplifiers utilize strongly-doped n type sources and drains. The strong n doping and the strong electric field inside the transistor increase velocity of electrons and generate high-speed electrons, so called “hot electrons”. Collision of hot electrons with the silicon generates secondary electrons, which recombine holes to emit near-infrared light.

The countermeasures are as follows:

- Lightly doped drain (LDD): To reduce the electric field at the rain area, a local light p-doping is commonly introduced.
- Reduction of readout time by increasing the number of output amplifiers and the readout rate of each amplifier.

5. Conclusion

For the ultra-high-speed and ultra-high-sensitivity image sensor developed by Etoh *et al.* in Kinki University, causes degrading the SN ratio are listed up. For some of them, evaluation data are presented. The possible countermeasures are also proposed as follows:

Design of the control circuitry by experienced engineers. Especially, for the CCM drivers, a very stable voltage and temperature control is essential.

Increase of the numbers of the output amplifiers and the readout rate of each amplifier.

Introduction of the stealth dicing or other methods to decrease the leak current from the diced edges.

Introduction of smaller bumps distributed all over the sensor area or non-bump flip-chip technology.

Effective backside contact to drain holes.

Design modification of the drain area of the amplifiers, such as introduction of the LDD.

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