X-ray two-dimensional detector with a multi-port charge-coupled device for X-ray free electron laser experiments

We have developed an X-ray two-dimensional detector equipped with a multi-port readout charge-coupled device (MPCCD) [1,2]. The MPCCD detector was designed to meet experiments performed at the X-ray free electron laser (XFEL) facility SACLA [3]. The detectors are now providing reliable and high-performance X-ray imaging capability. Since user operations began in March 2012, the MPCCD detectors with up to eight-sensor array have been provided.

The design of the MPCCD detector is based on the character of the SACLA XFEL light source. The MPCCD detectors are currently running at a frame rate of 30 Hz, synchronizing to the repetition rate of the present SACLA operation. The detectors also demonstrated to fulfill the demands of recording from a single photon to thousands photons within a several femtosecond pulse and radiation hardness over a nominal annual fluence (1.6×10^{14} photons/mm^2 at a photon energy of 12 keV).

The CCD sensor is produced with an image format of 1024×512 and pixel size of 50 μm. This design value was determined by referring to the 3D device simulation and the point spread function measurement of the test sensor with a sensing layer thickness identical to the MPCCD sensor. The pixel size was optimized to be small while ensuring that the charge sharing effect is sufficiently suppressed.

Our study of the readout port based on the analytical circuit model yielded the fact that only eight readout ports is enough to operate at maximum frame rate of 60 Hz while achieving peak signal over 4 Me$^-$ and the system noise floor of less than 300 e$^-$ rms (these correspond to 2400 and 0.18 photons at 6 keV, respectively). This approach has sharply simplified the sensor architecture by reducing so many readout ports to just eight readout ports. The reduction does simplify the associated detector system through simple and robust calibrations, and moderate cooling requirement due to the lower heat dissipation of the sensor. The advantage of this concept was demonstrated by these MPCCD detectors [4].

The deployed detector performance is summarized in Table 1. Figure 1 shows the energy spectra of the Fe55 radiation source measured by the MPCCD detector. The first peak represents the distribution of the electrical noise in the MPCCD detector. The second peak is formed by the X-ray signals emitted from the Fe55 radiation source. The distinct signal from the noise suggests that the MPCCD detector is capable of detecting a single photon at a photon energy above 6 keV.

Table. 1. Performance of the deployed MPCCD detector

Description	Deployed performance	Unit
Pixel size	50 × 50	μm
Pixel number	1024 × 512	
Imaging area	51.2 × 25.6	mm^2
Sensing material	Epitaxial Silicon	–
Sensing layer thickness	50	μm
Sensor structure	Front-illumination	–
Image format	Full frame transfer	–
Operation temperature	0 ~ –30	°C
Quantum efficiency	80	% 6 keV
	20	% 12 keV
System noise	100-250	e$^-$
	0.06-0.15	photons@6 keV
Peak signal	4.1-5.0	Me$^-$/pixel
	2500-3000	photons@6 keV
Radiation hardness	> 3.2×10^{14}	photons/mm^2@12 keV
Frame rate	30	Hz
Number of readout port	8	–

In general, radiation damage affects the threshold voltage in the transistor and the dark current of CCD sensors. To reduce these effects, the MPCCD sensor has a radiation hardened structure in the gate. We evaluated the radiation hardness using beamline **BL29XU** of SPring-8. The resulting shift in the threshold voltage is sufficiently small to adjust for reliable operation of the MPCCD sensor after irradiation of the nominal annual X-ray dose. The increase in the dark current was also assessed with step irradiation of 3, 9, 30, 60 Mrad (1.6×10^{13}, 4.8×10^{13}, 1.6×10^{14}, 3.2×10^{14} photons/mm^2 at a photon energy of 12 keV) on to the single MPCCD sensor. The shot noise

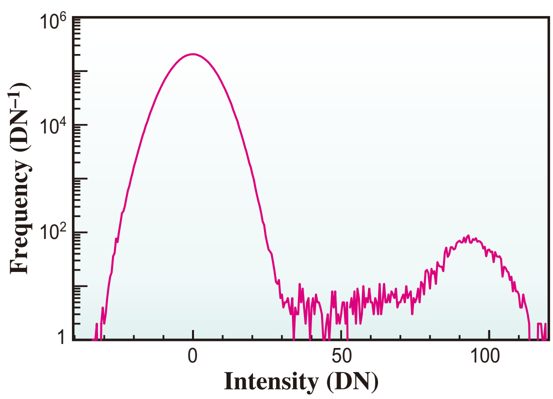


Fig. 1. Energy spectra of the Fe55 radiation source measured by the MPCCD detector.

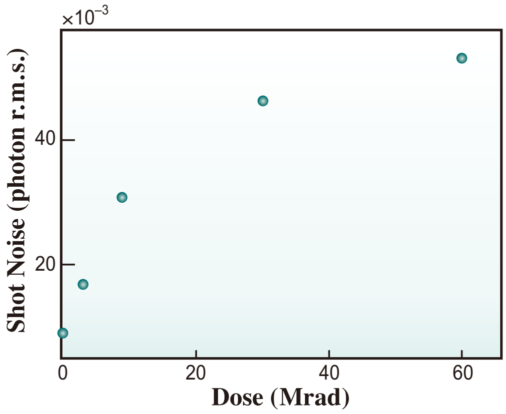
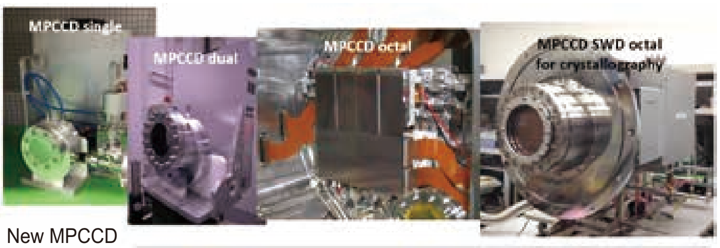


Fig. 2. Dose dependence of the shot noise induced by the dark current of the MPCCD detector. The temperature of the sensor is cooled to be –30°C.

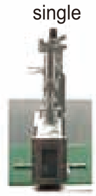
induced by the dark current increases as described in Fig. 2 at a sensor temperature of –30 degree. Even if the accumulated radiation dose to the MPCCD sensor is over two nominal annual dose (>3.2×10^{14} photons/mm^2 at a photon energy of 12 keV), the effect of the dark current increase on the noise performance is negligible compared with the typical value of the MPCCD system noise of 0.15 photons at a photon energy of 6 keV.

Currently, five kinds of the MPCCD detectors are deployed in user operations at the SACLA as shown in Fig. 3. They have different camera head structures and image formats, depending on the number of mounting sensors. The MPCCD single and dual with a beryllium window are used in atmospheric conditions. The MPCCD octal is frequently coupled to a user vacuum chamber for coherent diffraction imaging. To deliver high intensity signals close to the diffraction center downstream, a square aperture is equipped in the center of the eight-sensor array. The aperture size is adjustable with up to 8 mm square in a vacuum. Crystallography experiments utilize the MPCCD short working distance (SWD) octal for wide-angle signal measurements. The projecting structure from the base flange permits the sensor array to be close to the sample, allowing the beryllium window to shield the sensor array from contamination arising from sample loading and illumination of optical laser pulses.

At present, the total deployed pixel number is 19.4 Mpixels. The number is scheduled to be increased to 34.1 Mpixels for adequate provision of both the **BL3** and the newly constructed **BL2**, which starts user operations in 2015 (Fig. 3). In summary, the variant camera heads have been stably utilized since user operations began in March 2012 and cover a wide range of the XFEL applications. So far 75% of accepted user proposals at the SACLA utilize the MPCCD detectors as primary data collection apparatus.



New MPCCD single



	MPCCD single	MPCCD dual	MPCCD octal	MPCCD SWD octal
Total deployed number (at present)	9	2	2	1
Total deployed number (Dec. 2015)	9	4	3	3

Total deployed pixel number (at present): **19.4 Mpixels**
Total deployed pixel number (Dec. 2015): **34.1 Mpixels**

Fig. 3. Summary of the deployable MPCCD detectors.

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References

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