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Characterization of a back-illuminated CMOS Camera for soft x-ray coherent scattering

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Abstract. A commercial scientific camera has been adapted and characterized at the SOLEIL Synchrotron with the aim to improve the acquisition capabilities on the soft X-ray coherent scattering experimental station at SEXTANTS beamline. This device is equipped by the last generation of back side illuminated scientific CMOS (BSI-sCMOS) of 2048 by 2048 pixels of 11 µm² able to acquire low noise images with a frame rate up to 48 Hz. The camera's performance measurements have been done and shows a good level of readout noise, a large full-well capacity, a medium dark current and a good homogeneity, respectively, 1.6 e- rms (in High Gain mode), 80 000 e- (in Low Gain mode), < 5 e-/pixel/s and ~ 1%. The quantum efficiency (QE) measurement has been performed at the soft x-ray branch of the METROLOGIE beamline and gives a relatively good agreement with the expected theoretical values. Finally, the demonstration of the camera's efficiency and of the gain in useful time measurement related to the high frame rate have been performed with a series of Airy patterns images compared with an image recorded using the standard BSI-CDD already in operation at the SEXTANTS beamline.

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INTRODUCTION

The advantages of the so-called scientific CMOS (sCMOS) sensor [1] used for the application in the visible range are widely known: large field, small pixel size below 10 µm, high frame rate exceeds 200 fps, high quantum efficiency (QE), low noise per pixel about one electron and high dynamic range of the order of 1:10000 e-. Today, these types of specifications have become a necessity in many fields of synchrotron radiation experiments. Indeed, manufactured sCMOS cameras are usually part of the indirect X-ray detector used in the hard X-ray tomography or ptychography experimental end-stations [2,3]. However many soft X-ray (with energy range of few ten of eV to 2 keV) applications as for example X-ray holographic imaging do not yet reap its benefits. In fact, the commercial sCMOS are mainly based on front-side illuminated structure using micro lens to improve the light collection but leading to disastrous quantum efficiency for X-rays below 1 keV. Currently, most of the soft X-ray beamlines, as the SEXTANT beamline [4] at SOLEIL synchrotron, use a commercial in-vacuum back-side illuminated CCD camera (for example the Princeton Instruments PI-MTE, 13.5 µm² pixel size) which insures a nice performance in term of signal to noise ratio with a high detection efficiencies but suffers from a severe readout speed limitation due to the charge transfer from pixel to pixel (typically 4 s for 16 bit depth image with 1 Mhz analog to digital converter). Anyway, we could relate some specific CMOS detectors using Silicon-On-Insulator (SOI) technology [5] for very high frame rate soft X-ray FEL application or PERCIVAL detector [6], a CMOS-MAPS (Monolithic Active Pixel Sensor) currently under development by a group of synchrotrons.

Recently, a new generation of Back-Side Illuminated sCMOS (sCMOS-BSI) has been developed [7] especially to optimize the QE deliver in visible (> 95% @ 550°nm) with 100% fill factor, the GSENSE4000BSI. This BSI-sCMOS with a large size (22.5 mm x 22.5 mm), small pixels (11°µm²) and quite high frame rate (49°Hz) is

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becoming a good alternative to the commonly used BSI CCD. In this paper, we report on the adaptation of a commercial camera to soft x-rays including in-vacuum compatibilities equipped with this BSI-sCMOS sensor. The modified camera was tested both in the SOLEIL detector laboratory using visible light but also using synchrotrons beams between 30 to 2000 eV respectively in the bending magnet METROLOGIE and undulator SEXTANTS soft X-ray beamlines. In particular, the quality of this sensor has been checked to measure: dark noise, temporal noise, spatial uniformity, linearity, electronic gains and quantum efficiency. Finally, a diffraction pattern image from pinhole and a sample dedicated to test the coherence of the beam has been performed to illustrate the capability to record soft X-ray hologram.

MATERIAL AND SETUP

The detector used in our experiment is a TUCSEN Dhyana95 (Fig. 1.a) camera (http://www.tucsen.com) integrating the sCMOS back-illuminated GSENSE400BSI-TVISB sensor supply by GPIXEL Inc (http://www.gpixelinc.com). This 4 megapixels (2048 × 2048 resolution, 11µm² pixel size) high dynamic range sensor is based on standard 4T pixel architecture with two electronics gains (High gain and Low Gain) and a combined gain mode in order to achieve the so-called HDR (High Dynamic Range) mode. The Dhyana's sensor is cooled to -20°C by a thermoelectric Peltier module which able to reduce the dark noise down to 1.5 e-/s/pixel. The frame rate depends on the mode (Standard or HDR) and it's limited to 24fps (Full frame) by the digital interface (USB3.0) used. Dhyana95 camera was first evaluated in the visible range in Detector group Laboratory at SOLEIL with a LED light source (integrating sphere) used to expose uniformly the sensor without lenses. Figures of merits, such as Full Well Capacity, read out noise, linearity and homogeneity have been so evaluated.

To evaluate the GSENSE400BSI-TVISB X-ray response, Dhyana95 camera has been totally disassembled and reassembled with a home-made water cooling circuit designed to be compatible with standard in vacuum condition needed at soft x-ray beamline and keeping an optimal temperature of the electronic components (Fig. 1b). Up to now, without any specific optimization we have shown that the modified camera can be operated in a base pressure between 5 10^{-7} to 10^{-6} mbar. This vacuum compatible camera prototype (called DhyanaX in the rest of this paper) has been mounted in the reflectometer of the XUV branch of the METROLOGIE beamline [8] at SOLEIL (Fig. 1c). The METROLOGIE beamline allows to select an photon beam in the soft x-ray range (30 eV – 2000 eV) using several multilayer gratings combination and three mirrors to improve the X-ray beam efficiency and a series of thin filters available to reduce the harmonics in each configuration. The beam size could be adapted; and for our test experiment it was approximately 200 µm (H) by 150 µm (V). The reflectometer is equipped with different AXUV photodiodes (Optodiode IRD AXUV100) allowing measuring the incident X-ray beam flux for each selected energy.

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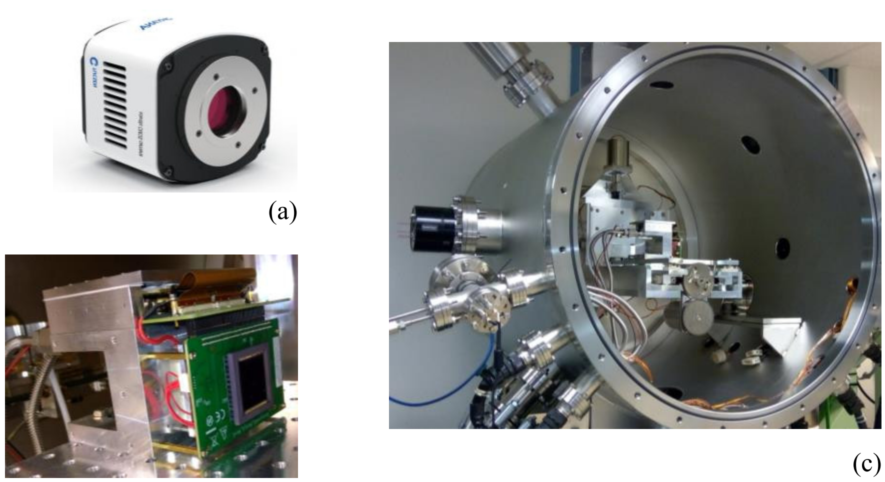

(a) (b) (c)

FIGURE 1. (a) Dhyana95 camera (original), (b) Vacuum compatible and water cooled DhyanaX assembly with GSENSE400-BSI, (c) DhyanaX camera mounted in reflectometer chamber at the METROLOGIE beamline.

The DhyanaX has also been installed on the end station at the SEXTANTS beamline in a dedicated high vacuum chamber after the RESOXS diffractometer [9].

EXPERIMENTAL RESULTS

sCMOS-BSI characterization results using visible light

The DhyanaX camera has been evaluated for its different mode following the standard described in the EMVA1288 [10] of the European Machine Vision Association. Firstly, the photon transfer curve [11] has been evaluated (Fig. 2a). The Full Well Capacity and electronic gain have been deduced from this curve. The fixed pattern noises, Dark Signal Non Uniformity (DSNU) and Photon Response Non Uniformity (PRNU), have been measured. And finally, the measurements of the dark current and the electronic readout noise (Fig. 2b) have been done. Furthermore, the linearity and the cosmetic (number of defected pixel) have been evaluated. The specifications given by TUCSEN and the measurement result are summarized in table 2 and also compared with the PI-MTE CCD (https://www.princetoninstruments.com) camera's specification.

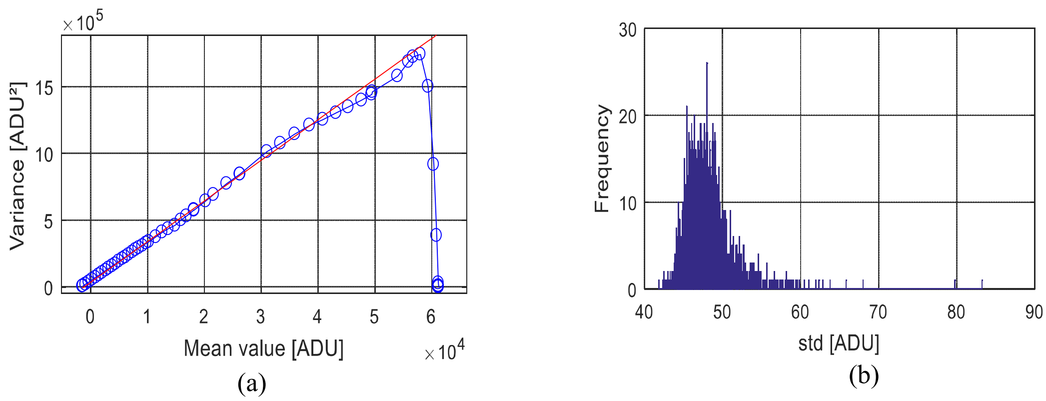

FIGURE 2. (a) Dhyana95 camera Photon Transfert Curve with High Gain mode. The gain evaluated is 30.4 ADU/e-. (b) Dhyana readout noise for High Gain mode measured from 100 dark images of 20 µs. The maximum value is obtained for 48.6 ADU, so 1.6 e- rms.

TABLE 1. Dhyana95 performance measurement results compared to the TUCSEN and PI-MTE camera specifications

	Dhyana95 specif.	**Dhyana95 measurements**			**PIMTE 2048B specif.**
		HDR	**High gain**	**Low gain**	
The overall gain	0.6 ADU/e-	0.87 ADU/e-	30 ADU/e-	0.62 ADU/e-	0.65 ADU/e-
Temporal dark noise (20 µs)	1.45 e-	3.5 e-	1.6 e-	57.5 e-	3 up to 12 e-*
Absolute sensitivity threshold	2 -	6 e-	2.7 e-	58 e-	-
Saturation capacity	90 000 e-	70 000 e-	1 907 e-	80 000 e-	100 000 e-
Maximum SNR	-	8 bits	5 bits	8 bits	-
Dynamic range	-	11 000	681	1 377	33 000 down to 8000*
Dark current**	1.5 e-/px/s	5 e-/px/s	2.7 e-/px/s	6 e-/px/s	0.02 e-/px/s
DSNU	0.6 %	2.5 %	0.09 %	0.09 %	-
PRNU	0.02 %		1.2 %		-
Defected pixels	-		0.01 %		-

* depend on ADC readout speed
** sensor temperature of -15 °C for Dhyana and -50°C for PI-MTE

The experimental results are in good agreement with TUCSEN specification, especially, the readout noise reaches 1.6 e- in the High gain mode and the full well capacity up to 80 000 e- in Low gain mode. The dark current

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is clearly more important than a high cooled BSI-CCD but it could not have a large impact in the total noise due to the short exposure time, typically of 10 to few 100 of ms, used in soft x-ray elastic scattering experiment at state of the art soft x-ray undulator beamlines.

sCMOS-BSI X-ray Quantum Efficiency measurement

The Quantum Efficiency (QE) of GSENSE400-BSI has been evaluated in soft X-ray range in METROLOGIE beamline, 30 eV to 2000 eV. QE is the ratio of the number of photons detected by the sensor to the number of incident photons and could be express as the equation 1.

$$QE = \frac{N \times G / t_{expo}}{E / 3.65 \times \Phi} \tag{1}$$

where N is the sum of image pixels values (ADU) irradiated by X-ray beam, G is the camera's gain (e-/ADU), t_{expo} is the exposure time (s), E is the X-ray beam energy (eV), 3.65 eV is the electron–hole pair creation energy for X-ray absorption in silicon, Φ is the X-ray beam flux (ph/s).

For each step of energy (10 eV), an accumulation of 10 images of the X-ray beam with a exposure time of 0.4 ms, an equivalent dark image (no X-ray beam) and the X-ray beam flux given by the photodiode current have been successively acquired. The dark-corrected images have been averaged and the pixels values have been summed. Furthermore, 15 full energies scan QE measurements have performed the resulting average is reported in Fig. 3 with an error bar corresponding to the standard deviation in these series. The result is compare with a theoretical model knowing the thickness and coating materials (passivation and anti-reflected layers, SiO 7.5 nm and SiN 63 nm) and the Si-Epi used in GSENSE400-BSITVB (Si-Epi layer of 10 µm). Therefore, the theoretical QE_{theo} can be express as the part of X-ray travelled through the series of coated material layers and absorbed in Si-Epi and given in equation 2.

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$$QE_{theo} = T_{SiO} \times T_{SiN} \times (1 - T_{Si-EPi}) \tag{2}$$

where T_{SiO},T_{SiN} and $T_{Si\text{-}Epi}$ are the transmission of a X-ray photon through material and depending of the X-ray energy.

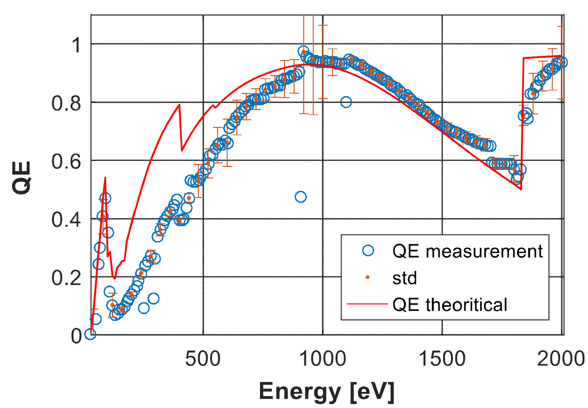
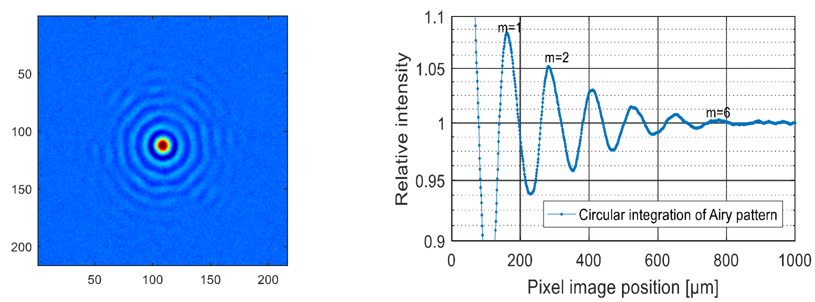


FIGURE 3. DhyanaX Quantum Efficiency measurement compared to the simple theoretical model given by coating and Si-Epi absorption (SiO 7.5 nm, SiN 63 nm and Si-Epi of 10 µm)

QE measurement honorably matches to the expected QE given by the simple model. The different absorption peaks from silicon, nitrogen and oxygen, 1830 eV, 410 eV and around 550eV, respectively, are clearly visible. Similarly, the transient rise efficiency around 90 eV corresponding to the X-ray beam transmission through the coated thin layer (Si0 and SiN) is seen. The efficiency offset observes for low X-ray energies < 1000 eV may be due to sensor contamination (surface oxidation and/or carbon contamination), in fact, any precautions were taken to store the detector once disassembled and no cleaning was performed before the measurements. This difference has not been analysed further. Thus, DhyanaX and its GSENSEBSI400 sensor is quite efficiency in the X-ray domain to be used by soft x-ray beamline scientist as the coherent scattering application.

sCMOS-BSI soft X-ray holographic images

A first tests was performed a classic Young experiment with a simple pinholes of 5 µm diameter positioned at 10 cm in front of the GSENSE400-BSI prototype camera on the reflectometer in METROLOGIE beamline. The pinhole is irradiated with a X-ray beam of 186 eV, a large series of diffracted pattern images with a 100 ms exposure time was recorded to finally obtained a cropped summation of these dark-corrected images as presented in Fig. 4a.

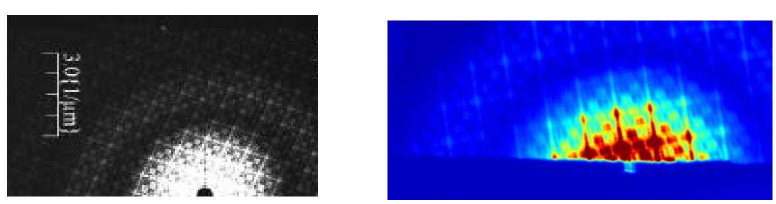


(a) (b)

FIGURE 4. (a) DhyanaX pinhole diffraction image at 186 eV on METROLOGIE Beamline (100 accumulation of 100 dark-corrected images), (b) Circular integration of pinhole diffraction image.

The Airy disk presented a nice first result with this non-dedicated setup. The Fig. 4b shows the result of circular integration around the concentric circular ring and the good camera dynamic able to visualize the order 6 of the maxima.

A second demonstration has been performed in SEXTANTS beamline to compare a previous results obtained with PI-MTE CCD camera during the beamline commissioning [4]. In this experiment a test mask consisting of eleven 200 nm diameter holes was irradiated by the X-ray beam. The following figure compared the image obtained with PI-MTE camera during previous experiment (Fig. 5a) and the image from DhyanaX prototype camera obtained in SEXTANTS beamline with an X-ray energy of 700eV (Fig. 5b).



(a) (b)

FIGURE 5. Test mask X-ray diffraction images.(a) SEXTANTS PI-MTE image (b) SEXTANTS DhyanaX image (Energy 700 eV, acquisition integration of 100 ms. Accumulation of 50 images)

Only half of the image is visible here. It's due to the very large beam-stopper used for the first test (complete dark part on the right of Fig. 5b). The image quality was not compared to the PI-MTE or to the theory. The setup used here doesn't allow us to give any quantitative result. Only the acquisition time could be compared. In fact, the DhyanaX image was obtained with accumulation of 50 images of 100 ms (exposure time) and the total time acquisition is less than 10 s (necessary time to record image in the computer disk) which has to be compared with the few minutes typical needing with PI-MTE for the same acquisition.

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SUMMARY

The firsts results achieved here seems really promising. The characteristics measured on DhyanaX camera matched with the scientific beamline requirements and needs. The quantum efficiency is quite sufficient for large panels of application in the soft X-ray domain and the frame rate allows to dramatically reducing the acquisition time for imaging application. The demonstration of simple X-ray diffraction measurement performed in this paper will be completed with a second version of high vacuum compatible camera under development by the design and engineering group at SOLEIL. Finally, the DhyanaX will be integrated in the new experimental set up of the SEXTANTS beamline, in SoftiMax beamline at MAXIV and probably in HERMES beamline at SOLEIL.

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