A color x-ray camera for 2–6 keV using a mass produced back illuminated complementary metal oxide semiconductor sensor

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There are several reports in the scientific literature of the use of mass-produced charge coupled device or complementary metal oxide semiconductor (CMOS) sensors as x-ray detectors that combine high spatial resolution with significant energy resolution. Exploiting a relatively new especially favorable ambient-temperature back-illuminated CMOS sensor, we report the development of a spectroscopic x-ray camera having particularly impressive performance for 2–6 keV photons. This instrument has several beneficial characteristics for advanced x-ray spectroscopy studies in the laboratory, at synchrotron light sources, at x-ray free electron lasers, or when using pulsed x-ray sources such as for laser plasma physics research. These characteristics include fine position and energy resolution for individual photon events, high saturation rates, frame rates above 100 Hz, easy user maintenance for damaged sensors, and software for real-time processing. We evaluate this camera as an alternative to traditional energy-dispersive solid-state detectors, such as silicon drift detectors, and also illustrate its use in a very high resolution wavelength-dispersive x-ray fluorescence spectrometer (i.e., x-ray emission spectrometer) that has recently been reported elsewhere [W. M. Holden *et al.*, Rev. Sci. Instrum. **88**(7), 073904 (2017)]. Published by AIP Publishing. <https://doi.org/10.1063/1.5047934>

I. INTRODUCTION

The capabilities of a variety of x-ray techniques at synchrotrons, x-ray free electron lasers (XFELs), laser plasma facilities, and university-scale laboratories are heavily dependent on the characteristics of the x-ray detectors with which they are implemented. One technological regime of interest is that of pixel area detectors combining spectroscopic and spatial resolution with features such as high readout rate, large collection solid angle, and hardness to ionizing radiation and electromagnetic pulses (EMPs). The advent of time-resolved spectroscopy at synchrotron and x-ray free electron laser (XFEL) facilities has greatly expanded the need for this class of detectors.^{1–16} Similar needs are also present in laser-plasma physics, where entire spectra for fluorescence, x-ray band thermal emission, or inelastic scattering must often be collected in few-pulse or even truly single-pulse experiments.^{17–34}

While there is an impressive effort aimed at either improvement of existing state-of-the-art technology or *de novo* development of new ideas for truly advanced high-performance detectors,^{1–16,35,36} there is another route that requires consideration. Highly mass-produced, commercial multipixel sensors intended for primary use at optical wavelengths are, by the standards of x-ray science, already stunningly advanced sensors. For example, recent advances in the performance of mass-produced complementary metal-oxide-semiconductor (CMOS) image sensors, including readout rates above 200 Mpx/s and optical-wavelength quantum efficiencies exceeding 80%, significantly increase their potential for scientific applications. The direct application of such

sensors to the x-ray regime is limited mainly by the fact that their small pixel thickness leads to greatly decreased quantum efficiency for hard x-rays. That being said, the use of mass-produced CMOS image sensors in the x-ray regime has been explored in prior literature that has established them as viable spectroscopic imaging detectors having a favorable combination of low cost (a consequence of chip-level integration of all sensor functions), high framerates, and improved radiation hardness relative to comparable charge coupled devices (CCDs).^{37–41} By “spectroscopic,” we mean that the camera output contains sufficient information for the determination of both the energy and position of a photoabsorbed x-ray. Such devices are often referred to as “color x-ray cameras.” CMOS image sensors can also be operated at room temperature while still having low noise, which is beneficial in multiple ways. Without need for cooling, the cameras can be simpler and have a smaller footprint. Not having cooling also removes the need for shielding over the sensor to protect from condensation, which improves efficiency at lower x-ray photon energies where window material would be more strongly absorbing.

In a prior publication,⁴⁰ we presented an x-ray camera platform for the 2–6 keV photon energy range based on a legacy CMOS image sensor, the Aptina MT9M001. Here, we introduce a new camera that incorporates a modern back-illuminated CMOS sensor with significantly improved readout rates and finer spectral and spatial resolution. Specifically, we find an energy resolution of ~86 eV at 2 keV with saturation rates above 10⁶/s at ~80 Hz frame rate. These spectroscopic benefits are complemented by a spatial resolution of 2.9 μm and real-time processing of all results, but are constrained by a ~50% quantum efficiency at 2 keV that decreases to below 20% at 5 keV.

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This manuscript continues as follows. First, in Sec. II, we describe experimental details including the commercial hardware and its modification used in the present instruments, as well as the new software package that has been developed to support real-time spectral analysis and real-time energy-windowed imaging. A key point here is that it is not only the sensor but also the entire camera read-out system that is commercially available because of the high demand for extreme low-light sensitivity imaging for applications such as amateur astronomy. Next, in Sec. III, we present results and discussion, demonstrating the cluster-binning methods and also both energy-dispersive and photon-counting modes for the camera. This includes representative data from a wavelength-dispersive spectrometer whose design has recently been described elsewhere⁴² and also data from single-shot x-ray fluorescence measurements at a synchrotron light source. Finally, in Sec. IV, we conclude and provide future directions.

II. EXPERIMENTAL

A. Hardware

The hardware consists of a commercial amateur astronomy camera (ZWO Company) based on the Sony IMX291, a back-illuminated CMOS image sensor with a rolling shutter, with a pixel pitch of $2.9\text{-}\mu\text{m}$, pixel grid of 1936×1096 , and maximum framerate of 170 fps. The sensor features high sensitivity and dynamic range, with a 12-bit A/D converter and readout noise of $1e^-$ at maximum analog gain. The choice of the vendor and model was driven by the manufacturer's provision of a software application programming interface (API) allowing straightforward configuration and access to the sensor's uncompressed video stream; we note that other manufacturers offer products with similar feature sets.

We have modified the camera in two ways. First, the main camera board has been reworked by removing the IMX291 sensor and replacing it with a custom IC socket (Andon Electronics). This was done to more easily allow sensor replacement if radiation damage occurred. Second, the sensor itself has been modified by removal of the glass cover (Pacific X-Ray). A photo of the resulting camera is shown in Fig. 1. The blue 3-D printed plastic part is a simple clamp used to press the sensor against the socket contact pads.

B. Software

After the necessary hardware modifications, additional software was developed to process the sensor's output to optimize its performance with x-rays. First, a software package written in C was developed to efficiently parse the acquired frames, and second, a real-time processing pipeline was implemented to communicate with the camera, process the data, and allow for real-time data analysis.

When an x-ray photon is absorbed in the active layer of a sensor pixel, the charge separation results in a signal with expectation value proportional to the photon's energy. In the simplest case, wherein the entire charge cloud from an x-ray absorption event is concentrated in a single pixel, the detecting pixel has intrinsic sensitivity to the energy of the incident x-ray photon.^{39,40,43} In the majority of events, however, the charge

FIG. 1. Photograph of the modified camera. The original commercial product has been reworked to install an IC socket for the sensor and to remove the glass cover of the sensor. For scale, the outer diameter of the cylindrical package is 62 mm.

cloud spreads over a cluster of several adjacent pixels.^{39,40,43} To optimize the camera's quantum efficiency (QE) and spectroscopic sensitivity, it is essential to use this prior information to recover the energy and position of each detected photon on an event-by-event basis. To do this, we perform a "breadth-first" search⁴⁴ of every frame to identify sets of connected pixels with analog-to-digital converter (ADC) values above a user-specified signal threshold. For each cluster thus identified, the signal is summed over all member pixels and the event's position is inferred from the cluster's center of mass. This technique is similar to event-reconstruction algorithms used for the same purpose in prior literature, with the difference that we place no constraint on the size and shape of signal clusters.³⁹ The sensor's manufacturer-specified low noise floor (under $1e^-$ per pixel) allows the use of an aggressively low threshold level, resulting in a high level of signal.

To implement the above analysis, we developed a real-time data processing pipeline. It consists of a collection of several software components communicating with one another over ZeroMQ sockets. First, a customized version of the open source image capture program *oaCapture* controls the camera's readout, allowing the user to configure the camera's gain and per-frame exposure time. Event reconstruction, which requires the computational throughput of multiple central processing unit (CPU) cores for intense signals, is done by a pool of worker processes collecting frames from the capture application in a round-robin fashion. The resulting filtered frames from this parallel pipeline are aggregated on a sink node, which users can access with high-level functions for acquiring and visualizing the pre-processed camera data.

C. X-ray measurements

X-ray measurements for the direct characterization of the camera performance used a low-powered Rh-anode x-ray tube (Moxtek MAGPRO 12W). For quantum efficiency (QE) determination at different energies, the x-ray tube illuminated appropriate reference targets that generated elemental fluorescence at desired energies. The camera and a commercial silicon drift detector (SDD) (Amptek X-123SDD) were

alternately placed behind a pinhole that ensured equal illumination on each sensor. The ratio of detection rates, corrected for the SDD's QE, then allows the determination of the camera's QE. Saturation rate measurements involved direct illumination of the camera by the full broadband output of the x-ray tube, displaced several tens of cm away from the sensor to allow for a useful tube-current range before saturation.

In addition to the above tests, the camera is also used as a position-sensitive detector in a miniature wavelength-dispersive spectrometer, as described in the work of Holden, *et al.*⁴² This application makes heavy use of the camera's energy-resolving capability. By applying an energy window to the photon absorption events detected in each camera frame, stray scatter and fluorescence from the x-ray chamber are rejected and only the desired signal photons are summed into the final frame, allowing a low-noise spectrum to be obtained even for dilute samples with weak signal, such as in a recent study of S speciation in biochar by some of the present authors.⁴⁵

Finally, as a demonstration of the camera's ability to perform single-shot spectroscopy, measurements were also taken at the BioCARS beamline 14-ID-B at the Advanced Photon Source. The beamline was set to pink-beam mode, with the peak energy set to 13 keV, which provided pulses with energy 13 μ J. The small size of the camera allowed installation close to the sample, even amongst the existing beamline equipment, at a distance of ~ 8 cm from the sample. A 7.5- μ m thick Fe foil was exposed to the unattenuated beam in single-shot mode, and x-ray fluorescence spectra of the Fe foil for individual synchrotron pulses were recorded by the camera. The majority of exposures were captured in single frames, but due to the rolling-shutter operation of the camera, shots were occasionally measured over two subsequent frames.

III. RESULTS AND DISCUSSION

In this section, we address four aspects of the camera operation and performance: the cluster algorithm, energy dispersive operation, quantum efficiency, and finally single-photon counting mode for spectroscopically constrained imaging. First, a magnified view of a small region of a captured image is presented in Fig. 2, where single-photon signal clusters are readily identifiable. The distribution of cluster sizes is strongly

FIG. 2. Representative cropped region of a camera frame during direct illumination by a Rh anode x-ray tube source operating at 6 kV bias voltage. The total illumination results in the detection of 2×10^6 photons/s at an 80 Hz frame rate.

skewed; the largest clusters contain more than 10 pixels, while the mean number is 2.1.

Second, when operated as a spectroscopic sensor, the camera's user-visible output is a histogram of the number of events binned by per-event signal. This is demonstrated in Fig. 3(a), which shows the direct-illumination spectrum of a laboratory x-ray tube source. The ADC values have been converted to an energy scale using the identified spectral features. Note that the energy scale and the energy range detectable within the limit of the ADC depend on the user-selected gain value. The read noise of the sensor is lower with higher gain, so in practice, the gain is chosen to be as high as possible while avoiding signals in the region of interest saturating the sensor. The dominant components of the signal are the tube's continuous bremsstrahlung spectrum and Rh L-shell emission from the anode. Two detector artifacts are also visible. First, a peak at the energy of Si K α is generated by Si fluorescence photons emitted in the sensor that propagate far enough from their originating interaction sites to be registered as separate events. Second, the escape of Si fluorescence from the absorption sites of Rh L-shell fluorescence photons creates the so-called escape peak echoes of the Rh L peaks that are downshifted by 1.74 keV, the energy of Si K α . We find that the camera's energy resolution at the energy of P K α is 86 eV [Fig. 3(b)], close to the limit imposed by statistical fluctuations in the charge generated by an absorbed x-ray (i.e., Fano noise) of ~ 68 eV (calculated according to the work of Lumb⁴⁶ assuming no readout noise).

Third, the quantum efficiency (QE) of the detector is presented in Fig. 4. We note a maximum QE of 51% at the energy of P K α , a more than two-fold improvement over our previous camera and software.⁴⁰ Under x-ray uniform illumination at 6 kV accelerating potential, the observed count rates have

FIG. 3. (a) Energy dispersive spectrum from direct illumination of the camera by a Rh anode x-ray tube source operating at 6 kV bias voltage. The ADC channel at the peak of the Rh L emission contains 3.2×10^4 counts. (b) Energy dispersive spectrum of monochromatized P K α photons, showing a resolution of 86 eV full-width at half-maximum.

FIG. 4. The camera's quantum efficiency as a function of x-ray photon energy, established by comparison with a commercial Si drift detector. The measured energies are indicated by points which are joined by a smooth interpolating line as a guide to the eye.

only minimal deviations from linearity at 2×10^6 photons per second for a 80 Hz frame rate (see Fig. 5)—an impressive performance that is higher than the typical saturation rate of commercial silicon drift detectors. The exposure sub-region shown in Fig. 2 was captured at this count rate. Note that the photon clusters are still largely disconnected so that pile-up from cluster overlap is infrequent. The lower count rates for the CMOS camera compared to the SDD are a consequence of the camera's lower quantum efficiency at higher photon energies. The camera should retain the observed high saturation rate performance when illuminated with more monochromatic, lower-energy sources where its QE is higher.

The energy-dispersive mode of operation combined with the ability to measure high count rates with minimal saturation is appealing for single-shot studies at intense beamlines at synchrotrons and XFEL sources, where the extremely short pulse durations are a poor fit with SDD's, i.e., single-pixel detectors that can only detect one photon per incident pulse lest they suffer from pile-up. A synchrotron single-shot spectrum for a pulse energy of 13 μ J in pink-beam mode centered at 13 keV is shown in Fig. 6 for an Fe foil. With this intensity, about 4000 x-ray events were recorded in a single-shot frame, from which the $K\alpha/K\beta$ ratio can be determined to an accuracy of $\sim 10\%$. Higher count rates at, e.g., the Linac Coherent Light Source and/or parallelizing detection with the use of multiple x-ray cameras will allow much finer determination of branch

FIG. 5. Camera count rate as a function of incident photon intensity, controlled via current provided to an x-ray tube source directly illuminating the camera with a broadband spectrum [see Fig. 3(a)]. We compare to the same curves for a commercial SDD and digital pulse processing hardware having pulse shaping times optimized for count rate (short shaping time) or for energy resolution (long shaping time). The low efficiency of the camera is due to the large flux at higher photon energies where its QE is poor; see Figs. 3(a) and 4. Illumination at lower photon energies will retain the high saturation rates but give the improved QE of Fig. 4.

FIG. 6. Single shot energy-dispersive spectrum from an Fe foil at the APS beamline 14-ID-B.

ratios, or other quantitative aspects of x-ray fluorescence spectra in single-shot studies. In Fig. 6, one other detector artifact can be seen: a weak low energy tail that results from events in which an incomplete fraction of the total charge created during x-ray absorption is recorded. This effect has been previously reported,³⁹ and although relatively weak, it could be accounted for through further characterization if required, e.g., for fine determination of $K\alpha/K\beta$ ratios.

Finally, the camera's combination of high saturation count rates and small pixel dimension makes it a strong fit as a position-sensitive detector in dispersive x-ray emission spectrometer designs. The camera's spectroscopic sensitivity may be employed for background rejection (i.e., for rejection of photons with energies outside a pre-specified range), thus minimizing the need for shielding from stray scatter. Holden *et al.*⁴² have demonstrated this advantage in a novel compact wavelength-dispersive spectrometer design that incorporates the camera as its position-sensitive detector. In Fig. 7, we show a representative accumulation of camera exposures and the resulting spectrum. An energy region-of-interest (ROI) was set around the nominal S $K\alpha$ photon energy so that as each frame was captured, the detected x-ray events having energy outside of the ROI were filtered out and the resulting frames were added to the accumulation. The spectrometer's small dimensions, which are enabled in part by the camera's fine spatial resolution, give it a large collection efficiency which results in count rates in laboratory studies (using low-power x-ray tube sources) comparable to those at a third-generation synchrotron insertion device beamline. The instrument has thus far been demonstrated in the university-scale laboratory and at the synchrotron.

Before concluding, it is interesting to consider future directions for this instrument development project. First, while the present sensor manifests several benefits when compared to CCD detectors commonly used for spectroscopic imaging, the poor quantum efficiency at higher energies is a substantial drawback. Specialized production of CMOS sensors with thicker pixel active regions could be created to improve the QE, if supported by the obvious cost-benefit analysis. Second, the inherent modularity of the sensor strongly suggests future work to tile many such sensors to increase the net collection solid angle. This could be particularly useful at high-flux synchrotron beamlines at tender x-ray energies where fluorescence intensities quite typically saturate conventional SDD's, with common mitigations being to simply back up the detector to decrease its solid angle and/or to multiplex across

FIG. 7. Image of the sensor's output when serving as the position-sensitive area detector of a miniature wavelength-dispersive spectrometer (Ref. 42). The signal shown is a S $K\alpha$ spectrum. In order to reduce the background level, the camera was configured to reject all events with photon energies outside of a spectral region of interest centered at S $K\alpha$.

several such detectors. Given that these detection schemes are already effectively low efficiency (low solid angle), a high-solid angle multi-CMOS array with inherently lower quantum efficiency holds high potential to be competitive. Such a multi-CMOS array would obviously be aided by back-illuminated CMOS sensors with larger number of pixels, such as are indeed presently reaching the market, or sensors with much larger pixels (to decrease cluster size, thus enhancing count rates prior to pile-up). Third, whether for lower energy operation, where we have not yet tested the sensor, or for more convenient use at laser plasma facilities or some 2–3 keV end-stations at synchrotrons, it will be important to package this type of camera in a high-vacuum or even a ultra-high-vacuum compatible small chamber with a silicon nitride window. We have begun such an effort.

IV. CONCLUSIONS

In conclusion, we have reported the development of a spectroscopic x-ray camera based on a mass-produced consumer product. The observed performance suggests a range of potential applications as a spectroscopic detector capable of operating at ~ 100 Hz with fine spatial resolution and adequate quantum efficiency in the 2–6 keV photon energy range.

Among these applications, we have demonstrated the effective use of the camera as an energy-selective position-sensitive detector in a high-performance compact dispersive spectrometer. We see significant potential for use of this detector in the lab, at synchrotrons, at XFELs, and at laser plasma facilities.

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