**A Disposable X-ray Camera Based on Mass Produced CMOS Sensors and Single-Board Computers**

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We have integrated mass-produced commercial complementary metal-oxide-semiconductor (CMOS) image sensors and off-the-shelf single-board computers into an x-ray camera platform optimized for acquisition of x-ray spectra and radiographs at energies of 2 - 6 keV. The CMOS sensor and single-board computer are complemented by custom mounting and interface hardware that can be easily acquired from rapid prototyping services. For single-pixel detection events, i.e., events where the deposited energy from one photon is substantially localized in a single pixel, we establish ~20% quantum efficiency at 2.6 keV with ~190 eV resolution and a 100 kHz maximum detection rate. The detector platform’s useful intrinsic energy resolution, 5-µm pixel size, ease of use, and obvious potential for parallelization make it a promising candidate for many applications at synchrotron facilities, in laser-heating plasma physics studies, and in laboratory-based x-ray spectrometry.

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The performance of a wide range of contemporary applications of x-ray methods are contingent upon the capabilities of x-ray imaging sensors. Examples include radiographic imaging across the full span of spatial resolutions in addition to both energy-dispersive and wavelength-dispersive spectroscopy in astrophysics[1-3](#_ENREF_1), plasma physics[4-6](#_ENREF_4), synchrotron science[7-11](#_ENREF_7), and laboratory-based x-ray spectroscopies[12](#_ENREF_12). The growing centrality of imaging detectors, especially those with significant single-pixel energy resolution, has led to a steady increase in commercial products and also niche-specific research efforts.

Here, we are most interested in a particular endpoint of these efforts, the possibility of mass-production of disposable x-ray spectroscopic cameras, i.e., those where each pixel has some significant energy resolution, having good performance for 2 – 6 keV photon energies. The ready availability of such sensors would be beneficial in several of the fields mentioned above while also serving as an easy test platform for new applications and as a convenient tool in education. We are not the first to consider these issues, and recent work in this subfield has demonstrated tantalizing potential for spectroscopic cameras based on standard, consumer-grade monochrome complementary metal-oxide semiconductor (CMOS) pixel arrays,[13-15](#_ENREF_13) such as regularly used in security cameras and other low-end imaging applications. This prior work establishes the viability of CMOS pixel arrays as spectroscopic imaging detectors of hard x rays and explores a host of performance characteristics, including linearity, radiation-hardness, and spatial response to single-photon interactions. The use of CMOS sensors, instead of charge-coupled devices (CCDs), is motivated by their lower cost due to chip-level integration of all sensor functions and the mature state of CMOS fabrication technology, as well as their typically much higher radiation hardness[16](#_ENREF_16)*.* These considerations are in some ways representative of other efforts where admittedly much more advanced and specialized CMOS sensors are making growing inroads. [17](#_ENREF_17)

Unlike prior work, here we investigate sensor performance below 6 keV photon energy. Our sensor platform design is driven by the goals of: (1) achieving a high saturation count rate, (2) generating single-photon spectra in real time, (3) ease of operation for new wavelength-dispersive spectrometer development in the laboratory setting[18](#_ENREF_18) and (4) developing simple sensor exchange to make the camera viable as a disposable detector for use in plasma physics experiments where experimental diagnostics are exposed to large electromagnetic pulses and to hazards from shrapnel from the laser-target interaction.

We consequently avoid commercial camera bodies and sensor evaluation boards, instead using a mass-produced CMOS sensor that can be easily and inexpensively replaced if damaged, a general-purpose single-board computer (SBC) having fast and flexible GPI/O capability as the principal hardware component, and a custom sensor board that has been designed in-house and fabricated by a rapid-prototyping printed circuit board service. To be specific, the sensor is an Aptina MT9M001 monochrome CMOS device with 1280 x 1024 resolution and a pixel size of 5.2 x 5.2 µm2. The sensor was chosen primarily because of its high near-infrared sensitivity, which indicates a relatively thick active layer. Before the chip’s installation its protective glass cover was removed, as it strongly absorbs x rays. The SBC is similarly a mass-produced component (BeagleBone Black SBC, Texas Instruments). The SBC is based on the AM3358 system on a chip, which contains an ARM Cortex A8 processor and a PRU-ICSS (Programmable Real-Time Unit Subsystem and Industrial Communication SubSystem) subsystem with two Programmable Realtime Unit (PRU) coprocessors. The SBC’s software interface to the sensor board consists of two PRU programs (implemented in PRU assembler) that perform the readout and communicate with a Linux user space program (implemented in C) that concurrently processes the resulting data stream (see Fig. 1). The PRUs operate at 200 million instructions per second (MIPS) and are configured for single-clock access to the GPI/O pins on the SBC that interface with the sensor PCB. This is sufficient for readout at 30 frames per second (fps), near the MT9M001’s maximum data rate. Our current implementation suffers from a memory bandwidth bottleneck that restricts frame rate to 10 fps, but this limitation can be removed by improving the PRU Linux kernel driver’s allocation and management of the ARM/PRU DDR buffer so that it exploits the ARM core’s CPU cache.



Fig. 1: Block diagram of the CMOS camera design.

Fig. 2: (a) An image of the camera, and (b) the camera’s quantum efficiency in single-photon counting mode as a function of x-ray photon energy, as established by comparison with a commercial Si drift detector. The glass cover of the CMOS sensor has been removed to allow direct x-ray detection.

Multiple steps in processing are all performed on the SBC, and processed data is stored on the SBC’s SD card before transfer to the control workstation. An exposure sequence accumulates the sum of all individual frames as a single image. Additionally, a spectrum is generated by binning the number of pixels per ADC channel. The finest energy resolution requires operating the sensor in the low-intensity single photon counting (SPC) regime where the mean period between photons incident on a given pixel is significantly larger than the frame time. Only x-ray events for which the entire charge cloud is concentrated in a single pixel are incorporated into the spectrum; this filtering step, which we refer to as cluster rejection, is well-established as necessary for optimal performance in pixel detectors used for SPC spectroscopy[13](#_ENREF_13), [19](#_ENREF_19).

In cluster-rejection mode the sensor’s saturation rate is 100,000 photons per second, but this can improved ~3-fold by resolving the aforementioned memory bottleneck. The quantum efficiency (QE) of the detector was characterized by measurement of the *K*-shell fluorescence spectra of chlorine, calcium, and several transition metals. This was done using a low-power laboratory x-ray tube source to excite 1*s* core holes of these elements in various solid samples. The intensity of resulting  and  emission registered by the detector was referenced to that recorded at the same position by a commercial Si drift detector (Amptek XR-100SDD) having known QE; results are presented in Fig. 2. Due to the small active layer thickness of the CMOS sensor, its quantum efficiency rapidly decreases from 19% at 2.6 keV (Cl emission) to ~1% at 8.0 keV (Cu emission). For imaging applications, such as use as a position-sensitive detector in wavelength-dispersive spectroscopy, it is clear that higher QE can be obtained by cluster identification, i.e., including information from events with some multipixel character. Our initial experience suggests a 50% increase in detected photon rate, but this requires further investigation. We expect that the QE will decrease below the Si *K*-edge because of the sudden increase in penetration length compared to the active layer thickness, but that some utility will remain below 1.5 keV. The present camera design is being modified for easier vacuum compatibility and the above issue will be investigated.

We now present detector performance in two representative applications. The radiograph in Fig. 3 (a) demonstrates the sensor’s use as an imaging detector, while Fig. 3 (b) presents a spectrum of Mn *K*-shell emission. No dark-field corrections are used here: the dark counts are negligible in this bin range. The FWHM of the sensor’s energy response function at Mn is 280 eV, approximately two times as large as in Fano noise-limited x-ray CCDs but still sufficiently small for the Mn and emission peaks to be resolved. The resolution generally scales as , where *E* is photon energy, for example showing 190 eV resolution at Cl  and 330 eV at Cu . The spectrum’s background below the Mn peak energy is due to incomplete collection of charge from photon events, even after filtering for single-pixel events.

The camera’s good QE below 4 keV suggests that few-keV x ray spectroscopy, whether in direct detection or as the position sensitive detector in a wavelength-dispersive instrument[9-11](#_ENREF_9), would be a particularly favorable venue. In this regime, the smaller pixel dimension of CMOS sensors similar to the MT9M001 is a significant advantage relative to conventional x-ray CCDs, as it enables the combination of short working distance, high collection solid angle, and high energy resolution.[10](#_ENREF_10), [20-22](#_ENREF_20) Additionally, such CMOS sensors’ much smaller (1% or under) cost, while not in itself a technical innovation, makes them promising candidates for disposable direct-detection spectrometers in laser plasma experiments, for high-resolution radiography in educational (instructional) settings, , and for versatile coverage of special scattering angles in synchrotron studies.



Fig. 3: (a) Radiograph of a flower petal. The grayscale is a representation of raw incident intensity. Improved spatial resolution would be achieved by selection of single-pixel events[14](#_ENREF_14). (b) X-ray emission spectrum of a Mn metal foil excited by a low-power laboratory x-ray tube source. The spectrum is based only on nominally single-pixel events.

In conclusion, we have reported the development of a flexible and surprisingly effective x-ray camera platform composed of standard commercial components merged with custom electronics that can be readily ordered from commercial prototyping services. The observed performance suggests an interesting range of future applications at photon energies of a few keV. This includes two aggressive possibilities: (1) large-area spectroscopic detectors formed by multiplexing large numbers of our cameras to reach net spectroscopic count rates useful for studies at the highest-intensity synchrotron beamlines or at x-ray free electron lasers, and (2) disposable detectors for use in the EMP-rich environments of laser plasma experiments.

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