Large Format CMOS-based Detectors for Diffraction Studies

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Abstract. Complementary Metal Oxide Semiconductor (CMOS) devices are rapidly replacing CCD devices in many commercial and medical applications. Recent developments in CMOS fabrication have improved their radiation hardness, device linearity, readout noise and thermal noise, making them suitable for x-ray crystallography detectors. Large-format (e.g. 10 cm x 15 cm) CMOS devices with a pixel size of 100 μm x 100 μm are now becoming available that can be butted together on three sides so that very large area detector can be made with no dead regions. Like CCD systems our CMOS systems use a GdOS:Tb scintillator plate to convert stopping x-rays into visible light which is then transferred with a fiber-optic plate to the sensitive surface of the CMOS sensor. The amount of light per x-ray on the sensor is much higher in the CMOS system than a CCD system because the fiber optic plate is only 3 mm thick while on a CCD system it is highly tapered and much longer.

A CMOS sensor is an active pixel matrix such that every pixel is controlled and readout independently of all other pixels. This allows these devices to be readout while the sensor is collecting charge in all the other pixels. For x-ray diffraction detectors this is a major advantage since image frames can be collected continuously at up 20 Hz while the crystal is rotated. A complete diffraction dataset can be collected over five times faster than with CCD systems with lower radiation exposure to the crystal. In addition, since the data is taken fine-phi slice mode the 3D angular position of diffraction peaks is improved.

We have developed a cooled 6 sensor CMOS detector with an active area of 28.2 x 29.5 cm with 100 μm x 100 μm pixels and a readout rate of 20 Hz. The detective quantum efficiency exceeds 60% over the range 8-12 keV. One, two and twelve sensor systems are also being developed for a variety of scientific applications. Since the sensors are buttable on three sides, even larger systems could be built at reasonable cost.

1. Introduction
The availability of large format (10 cm x 15 cm) CMOS devices enables the construction of imaging systems with large area, reasonable pixel size, excellent dynamic range and fast readout speed. Another advantage is the reduced cost of these systems compared to CCD and direct pixel based systems. Hasegawa et al1 in 2009 used a single large CMOS device to demonstrate the advantages of these devices for x-ray crystallography detectors. We have now developed a second-generation CMOS chip that has an active area of 9.4 mm x 14.76 mm and with a pixel size 100 μm x 100 μm. The radiation hardness, readout noise, device linearity and readout speed have all been improved. In
addition they are buttable on three sides so they can easily be combined into a large area single
detector system (e.g. 28.2 cm x 29.5 cm). A special feature of CMOS chip readout is that they can be
readout continuously while data is acquired in other pixels with a deadtime of only 33 nsec. The chips
can be readout with a frame rate as fast as 20 Hz. The dynamic range of the system is 14 bits in
standard mode and 16 bits in extended readout mode.

On top of the light sensitive surface of the chip is glued a 3 mm fiber optic plate to prevent
radiation damage and on top of the plate is a GdOS:Tb scintillator plate that converts the incoming x-
rays to optical photons that are measured by the CMOS chip. This direct coupling of the scintillator
plate to the CMOS chip gives high conversion efficiency to the system. For example, one 12 keV
photon produces approximately 400 electrons in the chip. The readout noise of the chip is about 180
electrons and the dark accumulation rate of the cooled detector is about 25 electrons/pixel/sec.

2. Diffraction System Configuration
We have fabricated a system for use at synchrotron-based diffraction facilities. The system is a 2 x 3
array of chips to give an active area of 28.2 x 29.5 cm. The chips are cooled to below -20°C and the
complete system with associated electronics is mounted in a 50 cm x 50 cm x 10 cm aluminum box as
shown in Figure 1. The system is able to acquire and store images at up to twenty frames/sec.

3. Detector Performance
The detector has been tested at beamline 4.2.2 of the Advanced Light Source. The spatial distortion
was measured by placing a large brass plate with 0.72 mm holes spaced uniformly in a 2.54 mm grid
just in front of the detector, and using a thin gold foil as an x-ray fluorescence source. The absence of
spatial distortion is shown in Fig. 2. Gold foil fluorescence was also used to flood-field calibrate the
dose response and linearity of each pixel, by taking a series of images at different exposure times and
then comparing the response to that calculated from the position and shape of the fluorescent x-ray pattern. The linearity of response was found to be better than 0.5% for all pixels. A program was developed to rapidly correct images that can be processed by standard diffraction programs (d*TREK, XDS, and HKL2000).

The detector performance was evaluated by collecting diffraction data from a series of protein crystals. In the conventional style of data collection, 180 images were taken with a crystal rotation of 1° per image, at 1 frame/second. Exposures were timed with an x-ray shutter. We obtain data of quality that are directly comparable to that which are obtained by conventional CCD detector systems. Figure 3 shows a typical 1 sec crystal diffraction pattern taken in the standard mode.

![Image](image1.png)

**Fig 2 Spatial Distortion using a brass plate**

**Fig 3 Protein crystal diffraction with 1 sec/frame**

Since the detector can be readout during acquisition, the detector is typically used in shutter-less mode in which the shutter is not closed between frames and the crystal rotates 1°/sec with a detector frame speed 10 frames/sec so that a complete 180 degree dataset is acquired in 180 sec. The features of this data acquisition mode have been recently described by Mueller et al. They used a Pilatus detector to take shutter-less data for a large number of crystals. The Pilatus detector is a photon counting detector which has the advantages that it can count at very high data rates and it has a low energy discriminator on every pixel to reduce background from x-ray scatter. It has the disadvantages of gaps between the readout chips which reduce the sensitive area by 8% while the area coverage of the CMOS system is continuous. The Pilatus 6M system has 6.2 M pixels with a pixel size of 172 um while the CMOS has 8.3 M pixels with a pixel size of 100 um. They have similar detector efficiency and similar readout speed per frame. The CMOS system is much lower cost than the Pilatus system.

Another mode of taking data with the CMOS system is available in which pairs of diffraction sets are taken where a fast rotation dataset is acquired (e.g. 5°/sec) to analyze the strongly diffracting peaks and a slow scan (e.g. 0.5°/sec) is used for the weakly diffracting peaks.

### 4. Summary

Large area CMOS detectors with 100 µm x 100 µm pixels have been developed which are suitable for diffraction experiments at synchrotron facilities. In comparison to conventional CCD systems they
provide better spatial uniformity, higher readout speed and comparable diffraction results. In comparison to direct photon counting pixel detector system like the Pilatus they can both be used in a shutter-less mode. They may especially useful to upgrade many diffraction facilities at reasonable cost so that they can take data in a shutterless mode to obtain better diffraction data with less radiation damage and higher crystal throughput.

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