

Development of X-ray Pixel Array Detectors

Sol M. Gruner^{1,2}

¹Department of Physics, Cornell University

²Cornell High Energy Synchrotron Source, Cornell University

X-ray detector development has not kept pace with the exponentially increasing brightness and capability of synchrotron sources. The result is that experiments at synchrotron sources are very frequently more limited by the detector than the source. The reason detector development has not kept pace is because responsibility for detector development has traditionally been somewhere between the sources and the users: Detectors have most commonly been viewed as the responsibility of the user end of a facility. In consequence, the large resources that have been devoted to developing new synchrotron facilities have not involved adequate development of new detectors. But it takes the better part of a decade, a dedicated team of detector designers, and millions of dollars to develop a new detector technology. This requires resources and a commitment that are very unusual for user groups. At the same time, the market is sufficiently small, and the commitment of resources is sufficiently large, that it isn't very attractive to industry.

A CHESS goal has been to break this cycle in order to catalyze the introduction of new detector technologies for synchrotron experiments. In the mid-1980's CHESS teamed with Kodak (Rochester, NY) to install a novel image plate detector system. In the early 1990's CHESS teamed with my group, then at Princeton University, to install the first fiber-optically coupled CCD detectors for routine macromolecular crystallography. This evolved into a collaboration with Area Detector Systems Corp (ADSC; Poway, CA) and resulted in ADSC's very successful line of CCD detectors. Since the mid 1990's, my group, now at Cornell, has been developing x-ray Pixel Array Detectors

(PADs), a next generation detector technology.

In a phosphor-coupled CCD detector x-rays are absorbed in a thin phosphor layer resulting in visible light emission. The phosphor is deposited on fiber optics that conveys the light image to a CCD. This type of detector, while having many advantages, still suffers from a number of drawbacks: Phosphors are slow and have limited resolution, fiber optics distort the image, each x-ray results in a signal in the CCD that is barely above the intrinsic noise, the CCD read time is long, and the technology allows limited in-detector processing of information.

PADs can overcome all these limitations. In this context, a PAD consists of two silicon integrated circuits (ICs) bonded together (Fig. 1). The front layer, called the *detective layer*, is divided into pixels and is sufficiently sensitive throughout its ~500 μm thickness to stop most x-rays below roughly 20 keV. Each pixel of the detective layer is individually connected to its own

pixel of processing electronics in the back, or *CMOS layer*, via a small solder connection, or *bump*. Modern IC fabrication methods allow an incredible amount of processing power to be squeezed into each pixel. In a well designed PAD signals are conveyed to the processing layer in nanoseconds with amplitudes well above inherent noise, and with no signal spread beyond neighboring pixels. The processing layer can be designed not only to process signals, but also to read the information out very quickly.

PADs are of two general types: *photon counters* and *integrators*. Each type has advantages and disadvantages, depending on the experiment at hand. Photon counters process photons one at a time, generally taking a few tenths of a μs to do so. Consequently, photons that arrive at a pixel faster than the time required to process the signal from an x-ray suffer counting losses. In other words, photon counters are locally count-rate limited. At the same time, they can provide some level of photon energy

Diode Detection Layer

- Fully depleted, high resistivity
- Direct x-ray conversion in Si

Connecting Bumps

- Solder, 1 per pixel

CMOS Layer

- Signal processing
- Signal storage & output

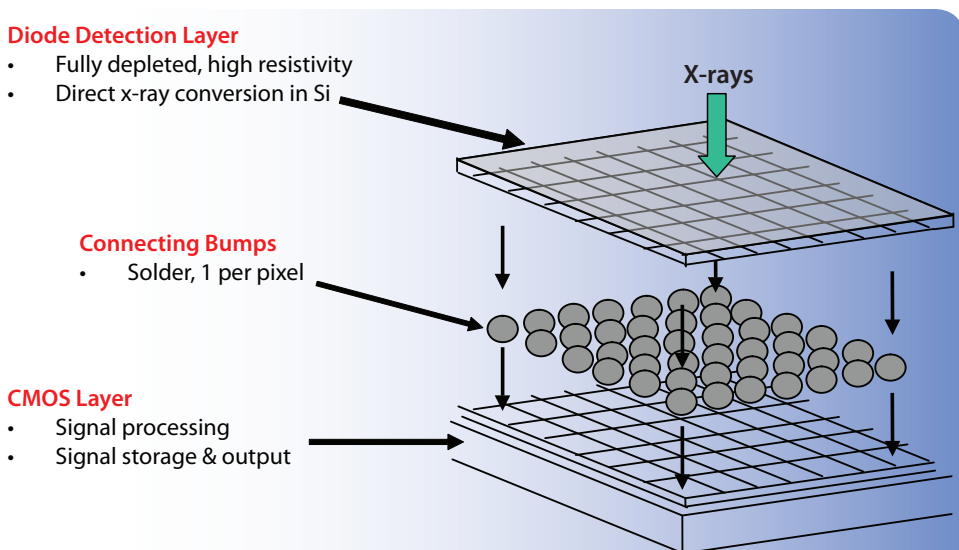


Fig. 1: A PAD, here shown in an exploded view, consists of two silicon ICs bonded together, pixel-by-pixel, with solder connecting bumps.

discrimination. Integrators sum the signal from arriving x-rays for later digitization and can, thus, avoid local count rate limitations, but they do not discriminate between photons of different energies. Our focus is on integrators, in part because there are competent efforts in Europe (such as the PILATUS PAD developed at the Swiss Light Source (now being vended by DECTRIS, Switzerland) focused on photon counters. Specifically, we have developed two distinct integrating PADs.

The first is a PAD made in collaboration with ADSC. It is designed to deliver images at up to a 1 kHz rate, with no dead time and with an extraordinarily large dynamic range per pixel ($\sim 2 \times 10^7$ x-rays/pixel/msec). Design of this detector was the principal focus of Dan Schuette's Ph.D. thesis when he was at Cornell (Dan was one of the first recipients of a Cornell G-line Fellowship. He is now a scientist at Lincoln Laboratory in Massachusetts.) Figure 2 shows an x-radiograph of a Canadian dime taken with this PAD. Figure 3 shows the extraordinary dynamic range and sharp point spread function (e.g., per pixel resolution) of this PAD.

Fig. 2:

X-radiograph of a Canadian dime. The back was sanded off to thin the coin.



The second PAD is being designed for the coherent imaging station at the Linac Coherent Light Source (LCLS) at SLAC. X-rays from diffraction patterns from the LCLS arrive at the detector with the time structure of the x-ray laser, e.g., ~ 100 fs. It would be impossible to count photons at these rates. So the PAD was designed to have very good single photon sensitivity, but to integrate the signal. In other words, the PAD will clearly be able to see signals as small as 1 x-ray per pixel, yet can receive up to 3000 x-rays per pixel. The entire detector will frame at the LCLS repetition rate of 120 Hz. Figure 4 shows a radiograph of part of U.S. dollar bill taken in Cu K α radiation. The contrast in the image is provided by the ink in the dollar bill. Pull out a dollar and look at the relevant feature to note the resolution.

Both PADs are now operational as single chip detectors about an inch across. Future work on both projects will be to make mosaics of chips to cover larger areas. In the meantime both PADs are being used for a variety of user x-ray experiments at CHESS and the APS, including coherent x-ray microscopy, time-resolved pulsed laser deposition growth of complex oxides, protein solution scattering, and time-resolved growth studies of carbon nanotube forests.

The future of PADs is very bright, indeed.

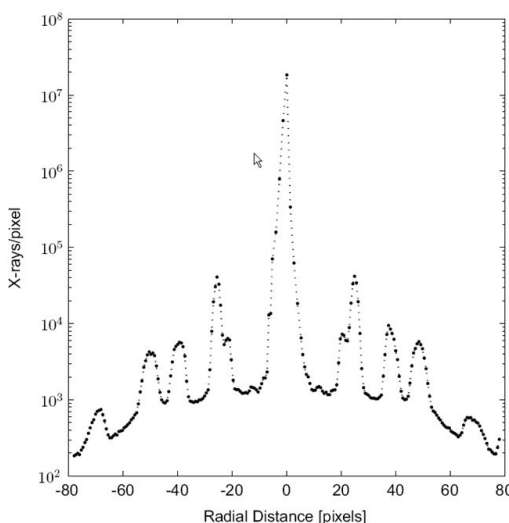
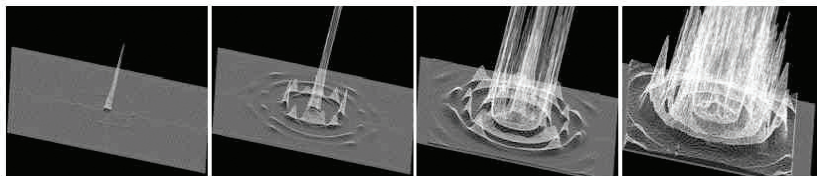
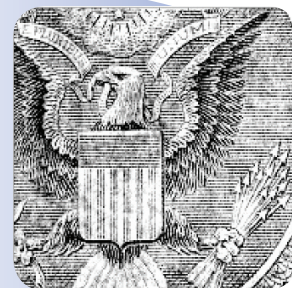


Fig. 3: (top) Diffraction from a large grain aluminum sample. The four panels are all of a single image taken at the CHESS F2 station at various display magnifications. No beam stop was used, which is why there is a large central peak. (bottom) A graph of intensity through the single image diffraction pattern. Note the logarithmic ordinate. Also note the small peaks about 10 pixels to the left and right of the central

main beam peak. These peaks are 25,000 times weaker than the central peak and less than a mm removed from it. This type of extraordinary dynamic range and sharp point spread behavior is not possible with a phosphor coupled CCD detector. From W. Vernon, M. Allin, R. Hamlin, T. Hontz, D. Nguyen, F. Augustine, S.M. Gruner, Ng.H. Xuong, D.R. Schuette, M.W. Tate, and L J. Koerner; "First Results from the 128x128 Pixel Mixed-mode Si X-ray Detector Chip", Proc. SPIE, Conference 6706, paper 29, U-1 to U-11 (2007).

Fig. 4: Cu K α radiograph of part of U.S. dollar bill. The display of the radiograph data has been adjusted to zoom in on the contrast variation coming from the green ink in the dollar.



Acknowledgements:

The PAD developments described in this article have been carried out by members of the Cornell detector group in my lab in the Cornell Physics Department, including Mark Tate, Hugh Philipp, Marianne Hromalik, Lucas Koerner, Kate Green and Dan Schuette (now at Lincoln Labs in Massachusetts). Darol Chamberlain (CHESS) has also been involved. PAD research in our lab is supported by DOE Office of Biological Research via grant DE-FG02-97ER62443. The ADSC project is a collaboration with Area Detector Systems Corporation via NIH grant RR-014613. LCLS PAD development is supported by the Department of Energy.