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Synchrotron Area X-ray Detectors, Present and Future

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Abstract. X-ray experiments are very frequently detector limited at today's storage ring synchrotron radiation (SR) sources, and will be even more so at future Energy Recovery Linac and X-ray Free Electron Laser sources. Image plate and phosphor-coupled CCD detectors that predominate at present-day sources were outgrowths of technologies initially developed for the medical and astronomical communities, respectively, with resultant limitations for SR. These limitations are enumerated. The growth of commercial silicon foundries and design tools enabling the production of large, customized integrated circuits is beginning to have a profound impact on SR detectors and is ushering in the age of "designer detectors". Novel area Pixel Array Detectors (PADs) are starting to appear in which each pixel has dedicated, complex circuitry capable of high speed and, in some cases, significant data processing power for specific applications. PADs now at, or near the horizon will be described. Integrated circuit methods continue to develop at a rapid pace. Implications for future x-ray detectors will be discussed.

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FILM, IMAGE PLATE, AND PHOSPHOR-COUPLED CCD DETECTORS

Synchrotron area, or imaging, x-ray detectors have undergone considerable evolution over the last three decades. Initially, the most commonly used detector was x-ray film. Film consists of roughly micron-sized grains of silver halide, each one of which is rendered "developable" upon absorption of a single x-ray. Film has excellent properties, including high spatial resolution, a very good capacity to integrate signals over a very long period of time, and non-volatility once developed. This is counter-balanced by low dynamic range, non-linear response, and difficulties involved in chemical development of the film. Film also has considerable noise resulting from "film fog", i.e., a stochastic distribution of about 10^5 photo grains/cm^2 that develop even at zero dose.

In the mid-1980's image plate detectors started to appear at synchrotron sources[1]. Image plates rely on the x-ray excitation of long-lived centers in solid-state media, such as BaFBr:Eu^{2+}. A signal proportional to the number of excited centers is then independently read out by scanning the media with a laser, resulting in de-excitation via emission of visible light that is detected with a photodetector. Image plates have good resolution (~50 μm, limited by light scatter in the polycrystalline BaFBr:Eu^{2+} film), are readily available in large areas, and have sufficient density of excitable centers to store x-ray signals for doses over many orders of magnitude. The high x-ray stopping power of the image plate media makes these detectors especially valuable for large area, high resolution detection with very hard (> 20keV) x-rays. However, the read out step is slow (seconds to minutes), there is slow thermal de-excitation in the excited centers, various ghosting phenomena, and drifts in the optical readout system that tend to limit calibration accuracies to roughly one per cent. Overall noise levels tend to be close to single x-ray detection, although this is rarely achieved in practice.

The introduction of phosphor-coupled CCD detectors in the early 1990's greatly enhanced quantitative x-ray imaging capabilities at synchrotrons[2, 3]. Phosphor-coupled CCD detectors are now pervasively used for synchrotron x-ray imaging. Although these detectors come in many variants, they most typically consist of a thin layer of phosphor that serves to convert the x-ray energy to visible light. The light is coupled via fiber or lens optics to a cooled CCD operating in an integrating mode. Integrating-mode CCDs, as developed especially by the astrophysical community, are extraordinarily sensitive and quantitative visible light image recorders. Phosphor-coupled CCD detectors may have nearly single x-ray quantum limited performance while still being able to store the

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signal from ~10^4 x-rays, are very stable and, thus, can be calibrated to a few tenths of a per cent. They have resolutions comparable to image plates, limited by light scatter in the phosphor and optical coupling system. Mosaics of fiber-optic taper-CCD modules may be assembled to cover large areas. The major drawbacks of CCD detectors include slow readout (frame) times on the order of a few seconds (although multi-port CCDs that frame at several Hz are becoming more common), and tails to the point spread function (PSF) that make it difficult to see small signals next to large bright ones. Most available CCD detectors also have poor efficiency for very hard x-ray imaging.

DIRECT DETECTION IN SEMICONDUCTORS

All of the detectors just mentioned involve a relatively complex sequence of signal quanta between the incident x-rays and a recorded electrical signal. For example, in a typical phosphor-fiber optic taper-CCD detector, an x-ray photon absorbed in a phosphor excites very complex luminescent phenomena that result in emission of only 10 – 20% of the energy as many optical light photons, some of which are captured and conveyed with considerable loss by a fiber optic taper to a glue joint, some of which then emerge and are then absorbed in the CCD, resulting in a stored electrical signal. The many steps in this sequence each have noise and introduce error, complexity, and opportunities for calibration drift. By contrast, x-rays may be "directly detected" upon absorption in reverse-biased semiconductor material, resulting in electron-hole pairs that constitute an immediate electrical signal. More importantly, the fidelity of direct detection is remarkable. For example, a 500 μm thickness of fully reverse-biased, commercially available silicon will absorb 97% of incident 10 keV x-rays. Each absorbed x-ray will yield 2740 ± 20 electron-hole pairs (Note that 20 is far smaller than $(2740)^{1/2}$) in a volume that is initially only about a micron in size. The electron-hole pairs can be collected with very nearly 100% efficiency in nanoseconds and with electronic noise levels that are far smaller than the signal from an individual x-ray. These characteristics make direct x-ray detection in silicon very attractive. Silicon has the drawback of relatively low stopping power for very hard x-rays. However, higher atomic number high-quality semiconductors are becoming more and more available.

Developments in imaging direct-detection semiconductor detectors are being driven by the rapid advancements in the integrated circuit industry. Pixel Array Detectors (PADs) consisting of two ICs bonded together are of particular relevance. A pixilated **detective layer** of ~0.5 mm thick high-resistivity silicon stops x-rays and produces the primary electrical signal. Lithographically fabricated metal connections (bump bonding) are used to connect each pixel to its own electronics in a corresponding **CMOS layer**. This layer is a pixilated CMOS Application Specific Integrated Circuit (ASIC) consisting of an array of electronic cells in one-to-one correspondence with the detective layer pixels. Each CMOS cell contains the signal conditioning, control, storage, and read-out electronics for one pixel. In effect, each pixel is its own complete detector. In principle, CMOS processing can be done on the backside of the detective layer, thereby eliminating bump-bonding. This technology is still very much in a R&D stage.

The CMOS layer is custom designed for the detector application. This allows precise tailoring of the functionality of the PAD for a given type of x-ray application. This is an enormous step forward in x-ray detection. Most detectors described in the prior section operate by acquiring a frame of data during an exposure period, after which the x-rays are shuttered off while the detector media is read out and reset for the next exposure. By contrast, clever design of the CMOS layer can endow the detector with great functionality. Individual x-ray photons can be counted and signals can be immediately processed.

PADs are generally either **photon counters** or **integrators,** each with advantages and disadvantages. Photon counters incorporate discriminators in each pixel to identify and count individual photons. Discriminators can be set to exclude lower energy fluorescent x-rays in monochromatic diffraction, which is very useful in improving the signal to background of many experiments. In most PADs, the charge cloud from an x-ray spreads to 20 – 40 μm upon traversing the detector layer, so an x-ray absorbed near the boundary between pixels contributes some charge to these adjacent pixels. Thus, photon counters require subtle setting of discrimination thresholds or complex communication protocols between adjacent pixels to avoid under- or over counting of photons shared between adjacent pixels. Photon counters have an intrinsic count-rate limitation because it generally takes ~100 ns to process the signal from each x-ray. This limits use when multiple x-rays arrive in pixel at ns rates, as for example, in many experiments planned for up-coming x-ray Energy Recovery Linac (ERL) or X-ray Free Electron Laser (ERL) sources. Even so, photon counting PADs are an advance that will have a huge impact on SR.

Integrators analog-integrate the signal incident in each pixel[4]. This allows enormously high per pixel count-rates without need to correct for photon events split between pixels. Well-designed integrators have high single photon signal-to-noise ratios, so the statistics of data collection are totally dominated by the shot noise in the incident x-ray signal (see next section). A disadvantage of integrators is that the absence of single photon discrimination precludes exclusion of lower-energy fluorescent radiation. Another disadvantage is that in very low-count rate applications integration of the signal competes with that of thermal dark current from the detective layer. This necessitates device cooling, which is a bother.

In the remainder of this brief note, we focus on integrating PADs under development at Cornell University.

EXAMPLES OF INTEGRATING PADS BEING DEVELOPED AT CORNELL

The Linac Coherent Light Source (LCLS) being commissioned at the SLAC National Accelerator Laboratory in California is specified to deliver pulses of x-rays at 120 Hz. Each pulse will be about 200 fs in duration and consist of about 10^{12} x-rays, typically at 8 keV. The goal of the Coherent X-ray Imaging (CXI) experiment is to perform imaging of single sub-micron particles. The x-ray pulse will destroy the sample; therefore, x-rays scattered by each pulse must be individually recorded. The CXI detector is a collaboration between Cornell and SLAC. Cornell is responsible for the development of the detector ICs and SLAC is responsible for the packaging of the detector and the electronic interface to the common SLAC data acquisition system. Detector specifications are given in Table 1. Data are digitized in each pixel for each frame, so only digital data is exported from the pixels. Descriptions of the PAD chips may be found in[5, 6].

Table (1). Specifications for the LCLS CXI PAD

Parameter	Goal
Energy Range	4 – 8 keV
Well-depth/pixel/frame	2500 8 keV x-rays
Continuous-duty frame-rate	120 Hz
Signal/Noise	> 3 per 8 keV x-ray
Detective Quantum Efficiency	> 90% @ 8 keV
Pixel size	110 μm x 110 μm
Detector format	1516 x 1516 pixels

FIGURE 1. Left: Histogram of ADU/pix from single pixel illumination. Peaks from zero, one, two, … five x-ray photons per acquisition are clearly seen. Middle: Radiograph of part of a U.S. dollar bill in Cu K_α radiation. The green ink of the dollar provides the contrast. Right: The spatial response of the pixel shows that charge is only shared when the beam is ~20 μm from a pixel edge. In part, from [5].

CXI imaging of single particles has more intense low angle diffraction, and very weak high angle diffraction. Hence, the detector must be capable of recording up to a few thousand x-rays/pix near the detector center yet be able to very accurately determine if even a single x-ray was incident in a given pixel towards the detector periphery. To accomplish this, each pixel may be programmed to operate in either a low- or high-gain mode. Figure 1 shows that in the high gain mode, the detector is easily capable of single photon imaging. In this test, 25 μm apertures were centered on pixels and short 8 keV exposures were acquired. Sometimes one photon/pix was recorded, sometimes two photons, etc., simply due to x-ray arrival statistics The 1-photon/pix,…, 5-photon/pix peaks are clearly seen. Longer exposures show clear peaks out to at least 27 photons/pix. Figure 1 also shows an image from the PAD and that charge is shared only near to a pixel boundary.

A second example is a mixed-mode PAD (MMPAD) designed collaboratively with Area Detector Systems of Poway, California [7]. Originally designed for crystallography, this PAD is proving especially useful for high count-rate radiographic and coherent imaging. The MMPAD operates by charge-to-voltage integration until the voltage crosses a threshold set by V_{th} (Figure 2). At this point a circuit is engaged that removes a unit of charge, ΔQ, from the integrator and the number of charge removal operations is recorded by an 18-bit in-pixel digital counter. The size of ΔQ may be programmed by V_{ref}, to be anywhere from the equivalent of a few, to a few hundred x-rays. This process has no dead-time, as new charge (I_{sig}) may be entering from the detection diode simultaneously with charge removal. At any point, the digital counter may be read out and any residual analog charge on the integrator may be digitized by circuitry at the edge of the chip. The effective well-depth is about $3x10^7$ x-rays/pix. The MMPAD frames at up to 1 kHz, thereby providing an enormous continuous duty count-rate. This is especially advantageous, for example in emerging lensless coherent ptychography imaging [8]. Ptychography has potential to image extended object at nanometer resolutions in 3-dimensions. It involves stepping a coherent micro-beam across a sample in overlapping regions. 3-D reconstruction involves tomographic procedures whereby the scans are repeated with a rotated sample; however, many thousands of high-flux images may be required, so present experiments are very detector limited. The MMPAD provides a solution.

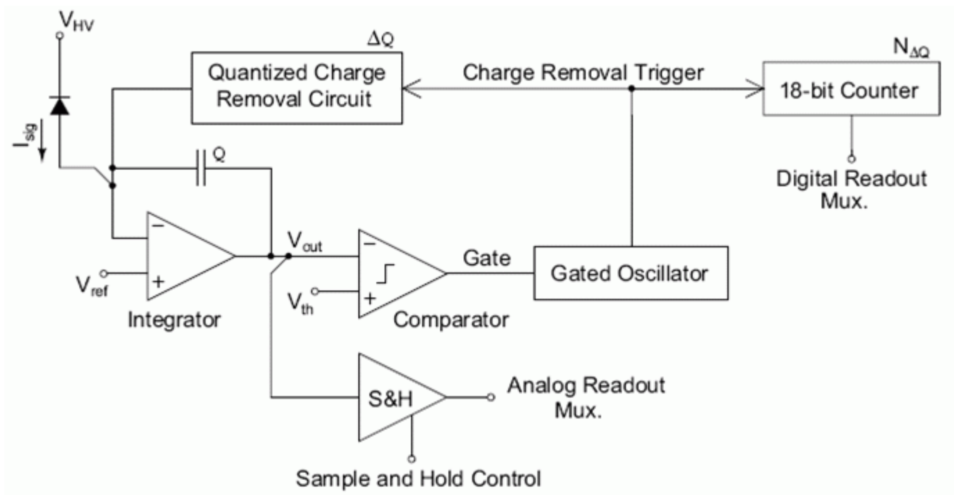

FIGURE 2: Simplified schematic of the MMPAD – see text. From [7].

This article is far too short to more than touch upon many new PAD developments [9, 10]. There is growing realization that PADs are opening new avenues for SR x-ray detection. Nor does this paper do justice to description of many other innovative x-ray detector technologies being pursued by the community, such as such as novel custom CCD architectures, CMOS imagers, superconducting detectors, MAPS devices, silicon drift detectors, etc.

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