Technical Note SC-XRD 18

Advanced Large Area Indirect X-ray Detectors

There are two basic types of X-ray imaging detectors: direct and indirect. Both types have certain advantages and limitations. However, recent advances in detection technology including high-resolution scintillators and ultra-low noise pixel arrays now allow the design of photon-counting indirect detectors with unprecedented size and performance.

Indirect detection

Most commercially available X-ray imagers, including those used for medical radiography and non-destructive testing, are based on indirect detection, in which an X-ray is absorbed first in a scintillator and the resulting visible light is recorded in an attached sensor array [1].

Indirect detectors are preferred in many applications as they can be produced economically with large active areas without gaps and with high uniformity. An indirect detector can also achieve a high Detective Quantum Efficiency (DQE) over a broad energy range without loss of spatial resolution due to parallax.

However, indirect detectors have limitations, including relatively low quantum gain, which can degrade the sensitivity for weak signals, and scattering of light in the scintillator screen, which can degrade the spatial point spread function.

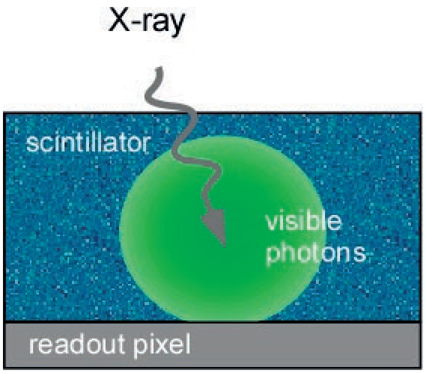

Figure 1. In an indirect detector, an X-ray is absorbed in a scintillator screen that produces visible photons. It is the visible photons that are actually detected by the readout pixel array.

The quantum gain of an indirect detector is limited by the relatively small conversion gain in a scintillator screen. For example, when a Cu-Kα X-ray is absorbed in a scintillator, it produces on the order of 400-500 visible photons, which in turn typically generates on the order of 300-400 electron-hole pairs in the silicon sensor array.

This is significantly lower than the quantum conversion gain in a typical direct detector, as described below. Thus, with conventional charge-sensitive readout electronics (with electronic noise on the order of a hundred electrons or greater), it is impossible to distinguish these relatively small signals reliably from the background noise. For this reason, indirect detectors typically have reduced sensitivity for very weak signals. Also, for the same reason, photon-counting pixel array detectors based on indirect detection have not been feasible.

Another limitation of indirect detectors is that the scintillation photons are scattered in the scintillator screen and thus the signal from a single X-ray is spread over several adjacent pixels. This in turn degrades the point spread function and thus the achievable spatial resolution in an indirect detector is typically lower than in a comparable direct detector.

Direct detection

In direct detectors X-rays are absorbed in a semiconducting sensor and the resulting photoionization charge is collected in a hybridized readout circuit, as shown in Figure 2 [1].

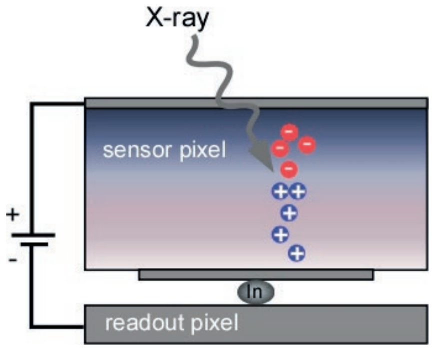

Figure 2. A direct detection pixel array. An X-ray is absorbed in a depleted semiconductor. The resulting charge cloud is detected in a separate, hybridized readout ASIC-CMOS.

One of the main advantages of direct detection is higher conversion gain. That is, when an X-ray is absorbed in, say, silicon, then each X-ray produces on the order of 2000 electron-hole pairs for a Cu-Kα X-ray. This is about a factor of 5 higher than in an indirect detector (as discussed above).

The electronic noise of a typical pixel array readout ASIC-CMOS is on the order of several hundred electrons (for example, 174 electrons rms for the Medipix3, 123 electrons rms for the PILATUS3, and 168 electrons rms for the PXD18k (HYPIX) [2]). Thus the signal-to-noise ratio is typically on the order of 10 or better and thus the signal from an X-ray is clearly distinguishable from the background noise by applying a threshold as shown in Figure 3. This allows these detectors to operate in photon-counting mode which gives superior DQE for very weak signals.

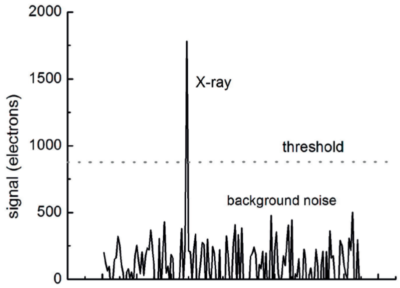

Figure 3. Direct detectors typically have a gain on the order of 2000 electrons for 8.1 keV X-rays while their electrical noise is on the order of a hundred electrons rms. Therefore, it is possible to apply a binary threshold to distinguish X-rays from the background noise with good statistical confidence. This allows these detectors to operate in a photon-counting mode.

The other key advantage of direct detectors is superior point spread function. That is, after an X-ray is absorbed in the semiconductor the resulting charge cloud flows along the field lines with relatively little scattering. Thus the point spread function is typically superior compared to indirect detectors, at least at low X-ray energies where there is little parallax.

The main limitation of direct detectors is that it is expensive and complex to implement large active areas. Large direct detectors are therefore typically tiled together from smaller modules. Thus, this type of detector suffers from inactive gaps between modules. Also, the separate modules can have different operating characteristics which reduces the effective uniformity.

Another limitation of direct detectors, based on silicon in particular, is parallax at higher energies. Parallax causes reflections that are incident at oblique angles to be smeared over a number of pixels, as shown in Figure 4. This is a result of the relatively low atomic number of silicon, which in turn necessitates a very thick silicon sensor to absorb higher energy X-rays. For copper Kα, the parallax effect is relatively small, typically on the order of a pixel. However, for molybdenum Kα or high energies, the parallax can become severe (figure 4).

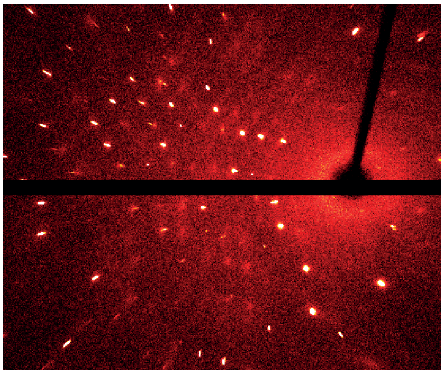

Figure 4. Parallax in a direct detection silicon pixel array detector operated with Mo-Kα radiation. Reflections at high resolution (high angles) are distorted due to the long absorption length of X-rays in the relatively low-Z silicon sensor.

Advanced indirect detectors: ultra-low-noise pixel arrays

Recent advances in both electronics and scintillator technology have now made it possible to produce indirect detectors with sensitivity and spatial resolution that rival the best direct detectors.

Historically, the very first photon-counting detectors used in X-ray diffraction were scintillator-coupled photomultiplier tubes (and these scintillation detectors are, of course, still in use today for some applications). They are true photon counters, able to count single photons with high DQE.

However, they are not, of course, imaging detectors. Could one make a pixel array in which the individual pixels would function just like a scintillation counter? With conventional pixel arrays this has not been feasible because the electronic noise is too high. Scintillation counters work because the photomultiplier tube has a high gain with essentially no electronic noise (because of avalanche charge multiplication). Thus, single photon detection is possible even with the relatively low light yield from a scintillator.

However, the readout electronics employed in a typical pixel array are certainly not noise-free. Rather, as noted above, they suffer from significant noise, typically on the order of a hundred electrons or more [2]. This has made photon counting with an indirect conversion pixel arrays detector infeasible.

More recently, advances in readout amplifier technology now make it possible to read out a pixel array at very high speed (tens of megapixels per second) with an extremely low noise on the order of 10-20 electrons rms, that is, about an order of magnitude lower than the charge-sensitive readout amplifiers used in current-generation direct pixel array detectors. For example, the latest generation Jungfrau 0.4 pixel array features a read noise of 27 electrons rms [3], while the H1RG pixel array achieves a read noise of 8 electrons rms [4].

These very low noise arrays were designed for direct detection with soft X-rays in the range of 1-5 keV. However, using such low-noise pixel array technology, it is also now possible to achieve signal-to-noise ratios on the order of 10 for higher-energy X-rays in the 8-20 keV range with indirect detection. It is thus feasible to do photon counting with an indirect detector [5,6]: such a detector is *essentially an array of miniature scintillation counters.*

With sub-20-electron read noise, the signal-to-noise ratio of an indirect pixel array detector rivals the best present-generation direct detectors, including, for example, the XPAD3, the Medipix3 or the PXD18k (HYPIX). This can be seen in Figure 5, which shows three single X-ray events recorded using an indirect detector [5]. The very low noise of the ray allows the events to be clearly distinguished from the noise background.

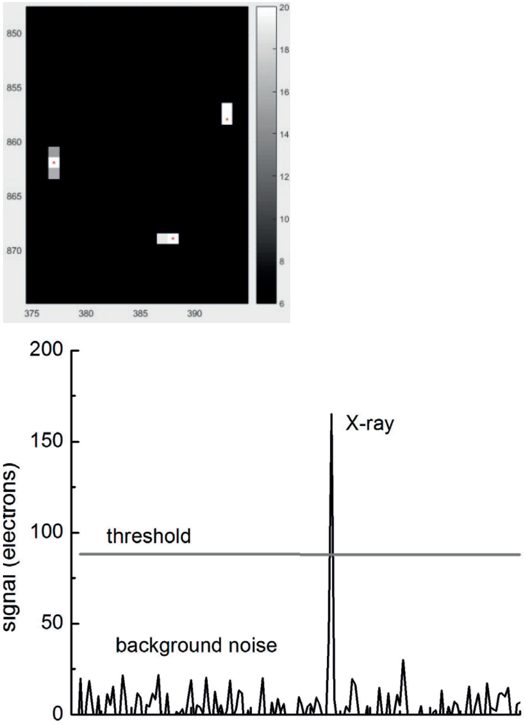

Figure 5. Three 8.1 keV X-rays absorbed in an indirect detector. Each X-ray produces a signal on the order of 200 electrons per pixel which is well above the background noise of 20 electrons. This makes it possible to distinguish unambiguously single X-ray events above the noise background.

Advances in scintillator technology: ultra-high-resolution scintillator screens

The other limitation of indirect detector technology is scatter of light in the scintillator screens. This scatter leads to tails on the point spread response from a single X-ray, which then degrades the effective spatial resolution. Because of this limitation, conventional indirect detectors based on standard scintillator screens cannot achieve the same spatial resolution as direct detectors.

However, there are now a number of new technologies to reduce or even eliminate the scatter in a scintillator screen and thus improve the spatial resolution. Thus, it is now possible to achieve spatial resolution with an indirect detector comparable to the best direct detectors.

The first approach is to use so called "structured scintillators", in which the individual scintillator crystals have a columnar structure as shown in Figure 6. This columnar structure guides the scintillation light to the sensor, similar in principle to a fiber optic faceplate. Available structured scintillators include CsI(Tl) and Lu2O3:Eu. Such structured scintillators are now the standard conversion technology used in the majority of medical X-ray imagers.

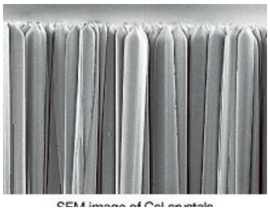

Figure 6. A structured CsI(Tl) screen. The needlelike geometry of the CsI crystallite channels light towards the sensor, improving spatial resolution. Ref. http://www.fujifilm.com.

Another approach is to use a micro-machined substrate to confine the scintillation light to a single pixel as shown in Figure 7. In this case, there is no lateral spreading of the light and a superior point spread function is achieved. However, this improvement in point spread is accompanied by a decreased quantum gain [7].

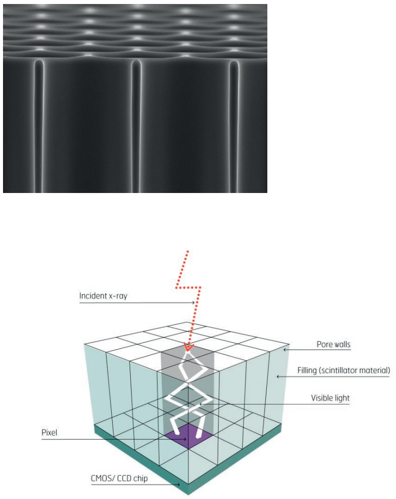

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Figure 7. Another approach to structured screens employs an array of pores micromachined into a substrate material, which are then filled with a scintillator. This traps all the light into a given pixel (ref. http://www.scint-x.com/)

PHOTON III: A large area photon-counting detector

The PHOTON III is a new detector that combines the best features of direct and indirect detectors to achieve unprecedented size and performance.

The PHOTON III incorporates a new, advanced scintillator to achieve very large active areas of up to 200 x 140 mm^2 with no gaps, very high uniformity, true single pixel spatial resolution and almost zero parallax at energies up to 30 keV.

The PHOTON III is the first detector available in the home laboratory which incorporates an advanced, ultra-low noise pixel array with read noise less than 20 electrons rms to achieve a single pixel signal-to-noise better than 10 for Cu-Kα photons. This equals or exceeds the best direct detectors and allows the PHOTON III to operate in photon-counting mode in order to accurately detect the weakest signals and to allow extremely long exposures with no dark current accumulation.

The PHOTON III is also the first laboratory detector that operates in the so-called mixed-mode (that is, photon counting mode for weak reflections and integrating mode for strong reflections) like other recent charge integrating pixel detectors for beamline application such as the Jungfrau or Mönch. This advanced mode eliminates both the charge-sharing noise and the count rate saturation seen in conventional photon-counting detectors [11].

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