

Silicon Active Matrix detector for diffraction and scattering at LCLS.Motivation

LCLS presents a unique problem for detector systems. The signal arrives in 100fs bursts at a rate of 100Hz. Thus, there is no possibility of counting individual photons. Given that we are forced to some type of integrating detector, the choice of system is limited. CCD, fully pixellated detector or, as we propose here, a monolithic active pixel matrix device. We believe that the latter is an ideal compromise between standard process but slow readout (CCD) and ultimate readout speed but challenging fabrication (fully pixellated). Since it is a monolithic device, it avoids the bonding of detector and readout chips (still a roadblock to such devices), but it requires non-mainstream processing, which requires some process development effort. Most of the applications anticipated require photon-limited data quality, which cannot be achieved using conventional optically coupled scintillator / visible light detector combinations. We propose two possible architectures for X-ray Active Matrix Pixel (XAMP) detectors. One has been prototyped, and shows promise, but comes with some difficulties. The second is an alternative way to achieve the same result which avoids the worst problems of the first type, but has not yet been prototyped. We will describe both below.

Proposed development

Pavel Rehak at BNL has proposed a solution ^[1] which is intermediate in complexity between CCDs and pixel detectors, the X-ray Active Matrix Pixel detector (XAMP). It has much in common with the flat-panel concept, except that it is a bulk silicon device which is fully depleted and therefore efficient. It is also monolithic, i.e. the detector element is formed from the same crystal block as the readout electronics. Thus no secondary bonding operation is required. It is capable of providing time resolutions of order 1 millisecond, while limiting the number of readout channels to thousands, rather than millions. This device is called an active matrix detector by analogy with the flat-panel displays used by personal computers. It is fabricated by connecting all of the individual detector pixels to a series of busbars via some type of charge switch, in such a way that the detector is read out row-sequentially, but column-parallel. This system effectively reduces the readout to a one-dimensional problem, with significant savings in complexity. The device is not a standard CMOS device, and so cannot be fabricated using standard commercial processes. The material that forms the actual detector elements must be high-resistivity silicon which can be fully-depleted and therefore becomes sensitive to x-rays through the full device thickness. In contrast, the charge gate located at every pixel of the array must be highly conductive when switched on. A technology has been developed which creates a low-resistivity layer (by ion-implantation doping) to serve as the conductive layer. This is not an industry-standard process, but has been demonstrated to be possible. Since the charge gate is a simple structure, these devices are much more radiation-hard than the complex circuitry in a typical CCD detector, and hence this whole device is essentially as radiation-hard as a simple photodiode.

We propose two structures which could serve as the pixel charge gate. The first is a standard JFET switch which connects the pixel charge storage capacitor to the column bus-bar. Figure 1 shows schematically a single pixel structure from such a device.

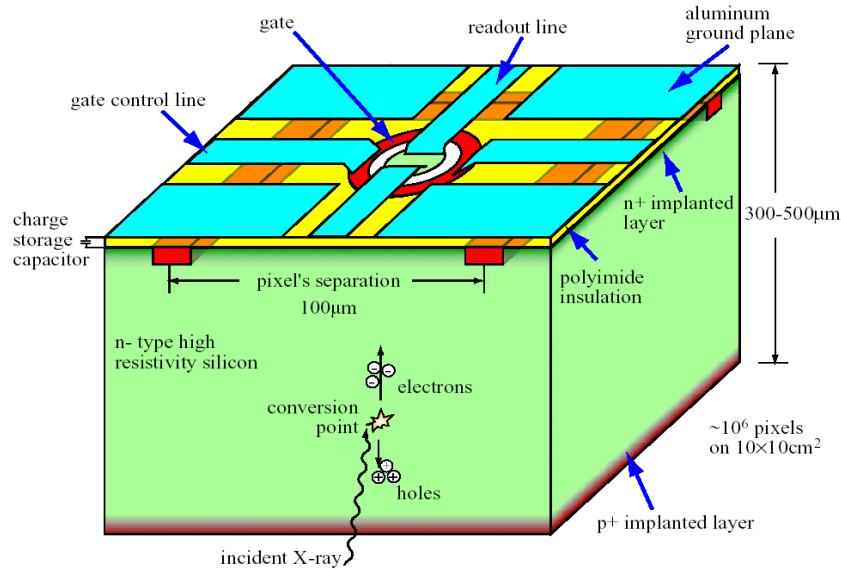


Figure 1. One pixel from an Active Matrix Pixel detector array. The device is fabricated by forming a low-resistivity silicon layer suitable for JFET switching devices on top of high-resistivity silicon optimized

Test versions of such a device have been made, and are functional. An unintentionally high-resistance contact caused the device to be slow to read out, but the basic concept was proved. Two facts push us away from this architecture. First, a significant problem in principle with such a structure is the use of a switching signal of several volts to turn on and off the pixel switch. Inevitably, charge is injected into the readout by the transients of this signal. It would be in principle possible to counteract this effect by injecting an opposite charge to compensate, but this has not yet been done. Second, using BNL in-house processing, it is difficult to fabricate this FET in a pixel smaller than $100\mu\text{m}^2$.

In light of these issues we propose a new, alternative architecture which is intrinsically balanced with respect to charge injections, only requires conventional p-n junctions to achieve the charge gating, and would allow pixels of smaller size, e.g. $50\mu\text{m}^2$. Figure 2 shows this architecture schematically.

In this architecture, the charge is trapped in a potential well created by the diffused regions around the charge collection electrode. When it is time to extract the charge, the bias potentials on each region is changed to allow the charge to flow to the collector. Since these bias potentials move in opposite directions, the charge induced can be made to cancel, thus minimizing any induced noise.

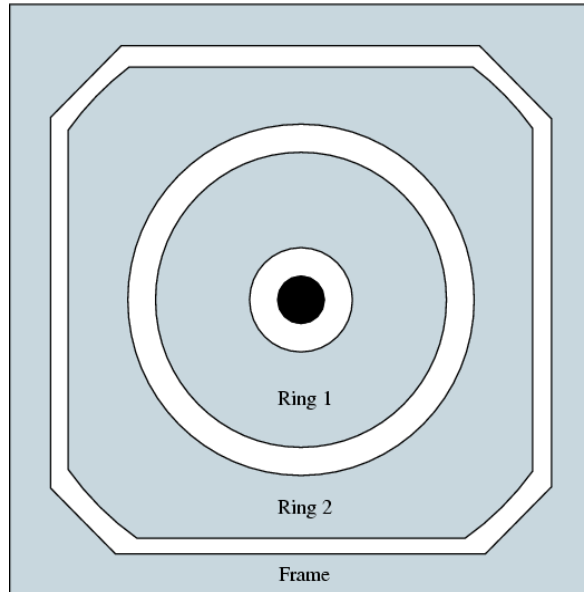


Figure 2. A new pixel structure which uses changes in bias level of Ring 1 and Ring 2 to either trap the charge below Ring 2 or allow it to flow to the central collector electrode. The bias levels change in opposite directions, so the spurious induced charge can be minimized.

One of the key features of direct-detection devices that makes them so widely applicable is the fact that the x-ray induced charge is large enough that the readout noise is significantly less than one x-ray photon equivalent. This arises from the fact that the charge deposited by an absorbed photon is around 3000 electrons, whereas the readout noise is around 1000. Thus, for applications in which the signal is a few photons per pixel per readout, the absolute number can easily be determined. This is typically the situation in, for example, an x-ray speckle experiment. The other side of this advantage is the fact that the total charge that can be stored on a pixel is limited by the maximum allowed voltage excursion on the pixel. For the device described here that limit is around 10^4 photons. Thus, reading the device every 1 millisecond would provide a capability of 10^7 photons per pixel per second. This is similar to the equivalent full-well performance of existing crystallographic CCD detectors which use a visible light CCD coupled via a fiber-optic taper to a scintillator screen. The key differences are that:

The CCD readout time is of order seconds, while the XAMP is read out every millisecond. Thus, a 1 millisecond exposure is 0.1% efficient for a CCD, but 50% efficient for an XAMP. When this detector is used in a streaming mode efficiency will approach 100%.

The detector readout noise is much less than one x-ray photon so consecutive reads can be accumulated without noise penalty. The situation for crystallographic CCDs is that the readout noise is typically a few photon equivalents.

CCDs used in direct-detection mode have good noise performance, but their full-well capacity only allows a few hundred x-ray photons to be detected, and since their active thickness is small, they are not very efficient above a few keV photon energy. Their readout time is also slow.

Another advantage of pixellated solid-state area detectors lies in the details of their spatial response function. The scintillator-based detectors (CCD and flat-panel) mentioned above suffer from significant lateral smearing of their images caused by scatter in the scintillator itself and by light leakage in the fiber taper and optical coupling layers. The point-spread function tends to be Lorentzian, with extended low-intensity tails. Thus, in order to provide adequate peak separation in a closely packed diffraction pattern, the detector resolution specification must be overstated. With all pixellated direct-detection devices, this does not happen, and the point-spread distribution function is essentially 1 pixel wide, limited by charge-sharing phenomena between adjacent pixels. Thus an XAMP with 0.1 mm pixels will perform as well as or better than a scintillator-based detector with a resolution of 0.05 mm

Although the scale of the readout system is reduced from that for a fully pixellated device, it is still non-trivial, requiring 1000 channels of high-speed ADC for fully parallel readout. As discussed in a previous section, this presents significant power dissipation problems, and there are doubtless other difficulties to be overcome to realize such a system, not least the average data rate. From a 2 k x 2 k detector read out at 16 bit resolution, the rate would be 8 Mb per frame at a 100Hz rate. This is close to 1Gb/s. The computer system required to absorb this data rate from the proposed device is large, but not impossibly so. The system will need some degree of parallelism with multiple high-speed connections between the detector and system memory. Fiber links having several gigabits/second capacity exist, so a relatively small number of these could handle the rate, with wide (64 or 128 bit) memory receiving the results. Digitizing the data will also be problematic. Fast ADCs are becoming available at a rapid rate as their use in high-frequency telecommunications gains popularity. For example, an 8 channel 10 bit device capable of conversion at 40 MHz is available now, with power dissipation around 1 W. Since a data row appears at the detector every 1 microsecond, each channel of such a device could in principle be multiplexed to several detector channels. One can thus envisage 64 chips, each with 8 ADC's, each multiplexed among 4 detector channels providing 2048 readout channels. The details of the readout system are not yet decided and this discussion should be regarded simply as a strawman example.

End-user software

The successful deployment of a new detector will only happen if the user can immediately benefit from its adoption. It therefore requires that the detector integrate smoothly with the user's existing experiment framework. Our proposal will request funds for manpower to perform this integration.

References.

[1] W. Chen, G. De Geronimo, Z. Li, P. O'Connor, V. Radeka, P. Rehak, G. C. Smith, B. Yu. IEEE Trans. Nucl. Sci. 49, (2002) 1006-1011.