A Medium-Format, Mixed-Mode Pixel Array Detector for Kilohertz X-ray Imaging

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Abstract. An x-ray pixel array detector (PAD) capable of framing up to 1 kHz is described. This hybrid detector is constructed from a 3-side buttable, 128×128 pixel module based upon the mixed-mode pixel array detector (MMPAD) chip developed jointly by Cornell and Area Detector Systems Corporation (Poway, CA). The chip uses a charge integrating front end for a high instantaneous count rate yet with single photon sensitivity. In-pixel circuitry utilizing a digital overflow counter extends the per frame dynamic range to $>4\times10^7$ x-rays/pixel. Results are shown from a base configuration of a 2×3 module array (256×384 pixels).

1. Mixed-mode PAD architecture

Pixel array detectors (PADs) can be classified according to the front end circuitry. Photon counting PADs [1,2] image with pulse height thresholding and an in-pixel counter. Dark noise is rejected but pixel count rates are typically limited to *ca.* 10^6 Hz. Analog PADs [3-6] use charge integration over the framing period. Since individual x-ray pulses need not be resolved, the maximum photon rate is increased substantially. Single x-rays can be detected if a small integration capacitance is used but well depth is limited to *ca.* 10^4 x-rays per pixel even for large capacitances.

An alternative approach is implemented in the mixed-mode PAD (MMPAD) (figure 1), developed in a collaboration between Cornell and Area Detector Systems Corporation [7-8]. When a comparator threshold is exceeded during integration, a charge removal circuit and an 18 bit overflow counter are triggered. This keeps the integrator in its operating region and extends the dynamic range by 2^{18}. A small integration capacitance gives high sensitivity to single x-rays. The average sustained photon rate is limited by the time required for a charge removal step, but that average rate is an order of magnitude higher than typical in a photon counting detector. Note the temporally bunched structure of a synchrotron beam can give instantaneous photon rates many orders of magnitude higher than the average rate (when ≥ 2 photons arrive from any single bunch). The MMPAD integrating architecture can correctly record 200 photons arriving instantaneously, limited by the charge removal step size.

2. Detector construction

This detector is constructed from 6 single-chip tiles arranged in a 2×3 array as seen in figure 2. Each 3-side buttable tile has 128×128 pixels with a 150 μm pitch. Each MMPAD chip is bump-bonded pixel-

by-pixel to a fully-depleted detector diode layer fabricated in 500 μm thick, high-resistivity silicon and biased to 150 V.
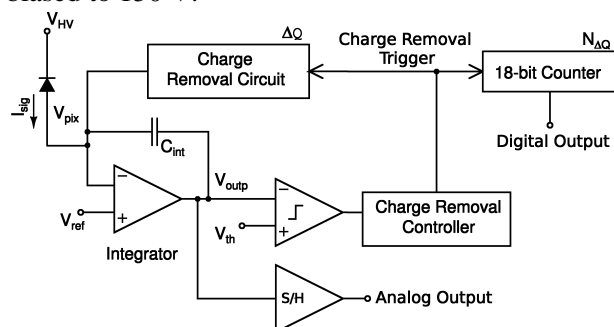
Figure 1. MMPAD pixel schematic. Comparator threshold, V_{th}, triggers counter and removes a charge, ΔQ, from the input. Digital counter and analog remainder are read at frame end.
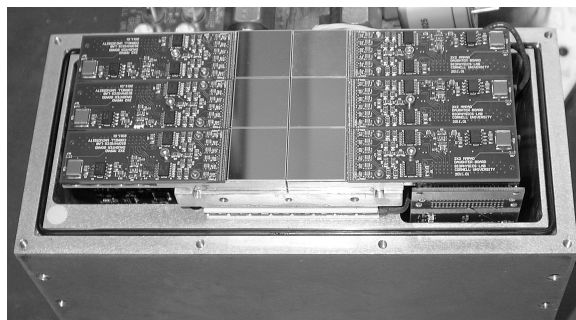
Figure 2. MMPAD 2×3 module assembly. 6-chip imaging array at center with 3 sets of circuit boards extending to each side and then downward. Shown with front vacuum window removed.

Each module assembly consists of a pair of small circuit boards mounted on a heatsink along with an MMPAD chip. The circuit boards provide signal buffering and analog-to-digital conversion. Six assemblies are aligned and mounted on a thermoelectrically controlled (-30 C) aluminum block. Module spacing is set nominally to be an integer number of pixels. A common backplane board provides vacuum feedthrough for all signals.

An FPGA board (Xilinx Virtex-6 ML605) controls the chip clocking and data capture. Output is read through 48 analog and 48 digital output channels. Analog remainder values are digitized to 12 bits. The FPGA handles the necessary bit reordering, including passage of the 18 bit digital word through a look-up-table to decode the counter value from its pseudo-random shift register implementation [7,8]. The digital data is scaled and added to the analog data to form a 32 bit word. Data is transferred to the host computer via a CameraLink interface (Matrox Radient eCL). Frame readout occurs in 0.86 ms. Host PC software places tiles within the frame and performs background subtraction. A live display window and region of interest calculations are provided.

Integration timing is set using a 36-bit programmable counter in the FPGA. Framing modes include single frame, a set of *N* sequential frames, and continuous framing. Frames can be initiated via ethernet commands or an external hardware trigger. Sustained frame rates to 1100 Hz can be achieved to computer memory and up to 200 Hz for continuous storage to disk. Note the maximum signal/pixel for short integration times will be subject to the sustained count rate limit of $>10^8$ Hz/pixel.

Table 1. Detector performance parameters

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Pixel size	150 μm	Read noise (rms)	0.16 x-rays (8 keV)
Detector format (2×3 chip)	256 × 384 pixels	Full well	4.7×10^7 x-rays (8 keV)
Instantaneous count rate	$>10^{12}$ Hz/Pixel	Sustained count rate	$>10^8$ Hz/pixel
Read time	0.86 ms	Energy Range	1 – 20 keV

3. Detector Characterization

Detector characterizations (Table 1) were made using a low power copper x-ray source (Tru-Focus TCM-5000M) placed 40 cm from the detector to provide a uniform source of illumination. The x-ray spectrum was made roughly monochromatic by using tube biases below 14 kV along with a 25 μm thick nickel filter. An array of 75 μm holes at 450 μm pitch fabricated in 50 μm thick tungsten foil

was used to provide geometric calibration as well as resolution measurements. Each 8 keV x-ray produces an 2200 e⁻ signal in the diode. Illumination of a single pixel through a 75 μm pinhole produces a stepwise response according to the number of x-rays in a frame. Figure 3 shows a histogram of pixel values from 28000 frames with an average dose of roughly 1 photon per frame. The series of gaussian peaks at 0, 11, 22, 33, … analog/digital units (ADU) correspond to 0, 1, 2, 3, … photons per frame. The read noise is 1.9 ADU rms (0.16 x-ray at 8 keV).
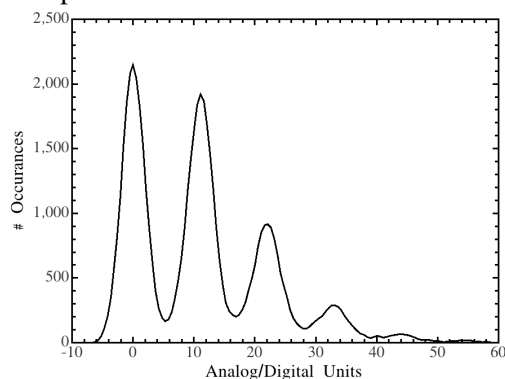
Figure 3. Photon histogram from a series of 28000 frames using low-level illumination of a single pixel. Peaks at 0, 11, 22, … ADU correspond to 0, 1, 2, … x-ray photons in a given frame.
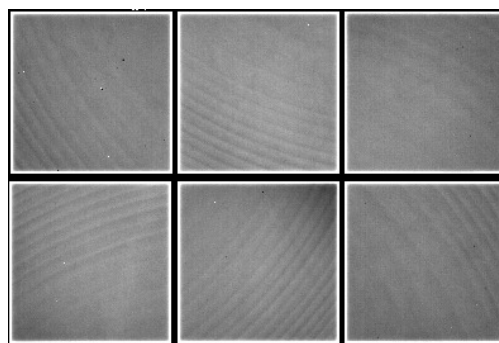
Figure 4. Flood illumination of array. Contrast is stretched to highlight arc-like features (1.5% peak-to-peak) due to diode wafer dopant variations.

Dark charge is integrated along with the x-ray signal at a rate of 2×10^4 e⁻/s/pixel at -30 C. Even though a dark charge equivalent to 1 x-ray is accumulated in 0.1 s, the associated noise in the dark charge reaches a level of 1 x-ray only after 240 s. An optional post-processing step where short, low-dose images are thresholded in software serves to reject both read noise and dark noise by including only those pixels hit by x-rays [9,10]. Nearest neighbor pixels can optionally be included to record the full charge from events split between pixels. Summing multiple frames with this technique allows the recording of x-ray signal over long periods without the penalty of accumulating the dark noise.

Flood illumination shows arc-like features in the image with variations up to 1.5% peak-to-peak (figure 4); this is seen in all types of deep-depletion silicon detectors [11]. Dopant variations occurring within wafer manufacturing impose a pattern of lateral fields causing a local dilation in pixel area. Note, these features are not due to a pixel gain variation, and, as such, should not be corrected with a multiplicative gain factor as normally computed from a flood field. Notably, an area dilation does not affect the integrated intensity of an isolated feature such as an x-ray spot. The pixels at the outer edge of a module are about 50% brighter than the interior pixels. Fringing electric fields near the diode edge cause these pixels to collect x-rays from a correspondingly larger area.

Relative module placement was measured using the hole-array x-ray mask. A 6 pixel gap exists between the 2 rows of modules, with a 4 pixel gap between neighbors in a row (except for one 5 pixel gap in the lower left). Moire between the pixel pitch and the mask allow for fine measurement of module offset and rotation. Measured chip positions have an offset less than 0.2 pixel from the desired integer pixel spacing with a maximum rotation of any module of 0.1 degrees.

The lateral diffusion in the charge cloud from an x-ray limits the spatial resolution to about 20 μm for a 500 μm thick diode at 150 V, well below the dimension of a pixel. Signal from an x-ray spot centered on one pixel spreads less than 10^{-4} to nearest neighbor pixels. For x-rays hitting near a pixel edge, charge will be shared between pixels. The nature of the integrating front end assures that the total charge is recorded. Scans of a 25 μm pinhole across pixel boundaries show constant integrated charge to within 1% [7]. In contrast, a photon counting detector must be carefully trimmed at each x-ray energy to achieve good performance at the pixel boundaries.

4. Experimental examples

The versatility of this detector can be highlighted with several experimental examples. Figure 5 shows a 10 s accumulation from a ptychographic data set taken at beamline 2-ID-B at the Advanced Photon Source. The diffraction is from a Pt zone plate illuminated with a 150 nm wide beam at 2.5 keV, spanning 6 orders of magnitude in intensity. The quantum efficiency at 2.5 keV is about 0.5 due to dopant layers at the diode surface. The low signal per x-ray is not an issue since the integrating front end records the total charge per frame. Operation at energies below 1 keV should be possible.
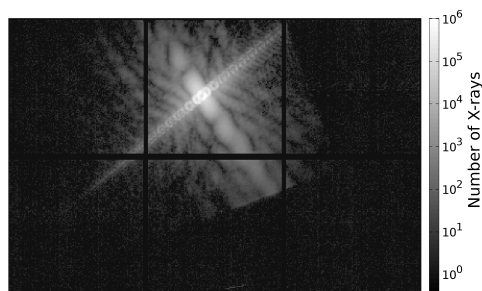
Figure 5. 10 s diffraction from Pt zone plate. 10^6 photons full scale
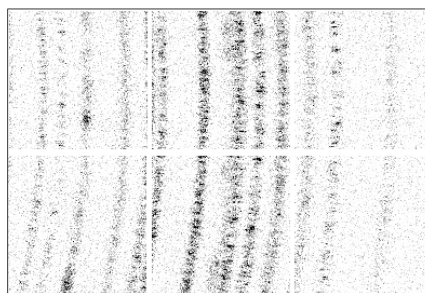
Figure 6. 2 ms diffraction from Al3Ni multilayer foil undergoing reaction. 0-5 photons full scale.

Shown in figure 6 is a 2 ms powder diffraction image from a time resolved sequence of a Al3Ni bilayer metal foil undergoing an exothermic mixing reaction. This image was taken at beamline A2 at CHESS with an x-ray energy of 15 keV. Here, most of the pixels have zero x-rays, with individual x-rays clearly distinguished in the image. To achieve the highest temporal resolution, low noise performance is essential. Thresholding of this image for photon hits allows the filtering of the nickel fluorescence x-rays as well.

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