Pixel array detector for X-ray free electron laser experiments

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ABSTRACT

X-ray free electron lasers (XFELs) promise to revolutionize X-ray science with extremely high peak brilliances and femtosecond X-ray pulses. This will require novel detectors to fully realize the potential of these new sources. There are many current detector development projects aimed at the many challenges of meeting the XFEL requirements [1,2]. This paper describes a pixel array detector (PAD) that has been developed for the Coherent X-ray Imaging experiment at the Linac Coherent Light Source (LCLS) at the SLAC National Laboratory [3]. The detector features 14-bit in-pixel digitization; a 2-level in-pixel gain setting that can be used to make an arbitrary 2-D gain pattern that is adaptable to a particular experiment; the ability to handle instantaneous X-ray flux rates of 10^{17} photons per second; and continuous frames rates in excess of 120 Hz. The detector uses direct detection of X-rays in a silicon diode. The charge produced by the diode is integrated in a pixilated application specific integrated circuit (ASIC) which digitizes collected holes with single X-ray photon capability. Each ASIC is 194×185 pixels, each pixel is 110 μm × 110 μm on a side. Each pixel can detect up to 2500 X-rays per frame in low-gain mode, yet easily detects single photons at high-gain. Cooled, single-chip detectors have been built and meet all the required specifications. SLAC National Laboratory is engaged in constructing a tiled, multi-chip 1516×1516 pixel detector.

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1. Introduction

XFELs with femtosecond X-ray pulses with peak brilliances many orders of magnitude over 3rd generation synchrotron sources are promising to revolutionize X-ray science. This paper presents a pixel array detector (PAD) module developed for the coherent X-ray imaging (CXI) experiment at the Linac Coherent Light Source (LCLS). The PAD was made by fabricating custom CMOS electronics using a commercial 0.25 μm process[1] and mating it, at the pixel level, to a high-resistivity 500 μm thick silicon diode. X-rays absorbed in the diode are directly converted to electron–hole pairs and the holes are conveyed to the CMOS through pixel-level bump bonds. The pixel size is 110 μm × 110 μm and each CMOS ASIC is 192×185 pixels. Testing results shown are from single module (one ASIC) detector. SLAC has assumed responsibility for making fully tiled detector comprising 64 ASICs mated to 32 pixelated diodes.

2. Pixel-level description

A high-level block diagram of the electronics in each pixel is shown in Fig. 1. The front-end integration stage features a two-level gain adjustment controlled by in-pixel memory; a sample and hold stage; and an analog-to-digital converter. The adjustable gain expands the effective dynamic range of the detector. The capacitance of the integrating stage feedback loop with and without cap2 (Fig. 1) is 565 and 75 fF, respectively. A smaller capacitance in the feedback loop increases the charge to voltage gain and improves the signal to noise ratio for low-flux measurements allowing for high-fidelity single-photon detection. The larger feedback capacitance can be used for higher flux measurements of up to approximately 2500 8-keV photons. In-pixel memory allows independent pixel-level control of the front-end gain so an arbitrary, two-level gain map can be programmed into the detector to match the anticipated profile of incident X-rays.

Analog-to-digital conversion is done in-pixel in a massively parallel fashion via in pixel comparison of a globally transmitted ramp and the sample-and-hold stage output. The comparator enables or disables an in-pixel counter which is clocked in unison with the ramp. After conversion, the counter is switched into shift-register mode and the values of the pixels are read. The pixel output is digital and eliminates the need for high-speed analog multiplexing, reducing demands on the external electronics.
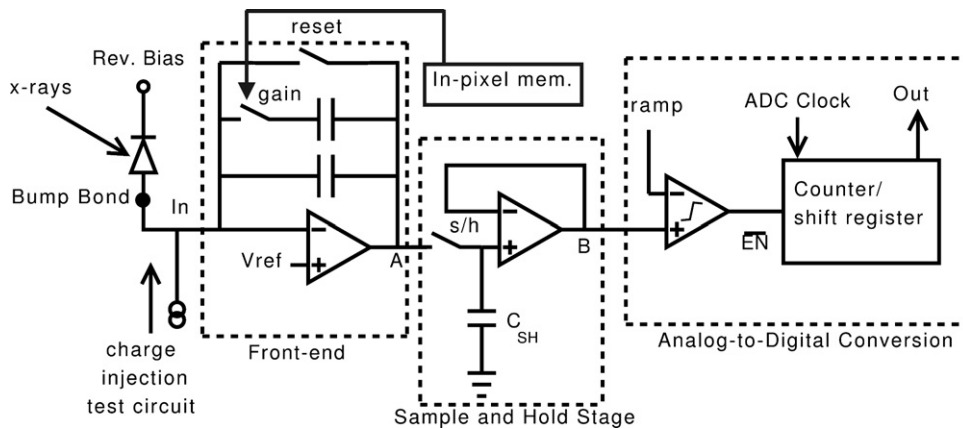
Fig. 1. High-level schematic of the pixel showing the major functional components. Figure reproduced with permission from Ref. [4] (2009, IOP Publishing LTD).
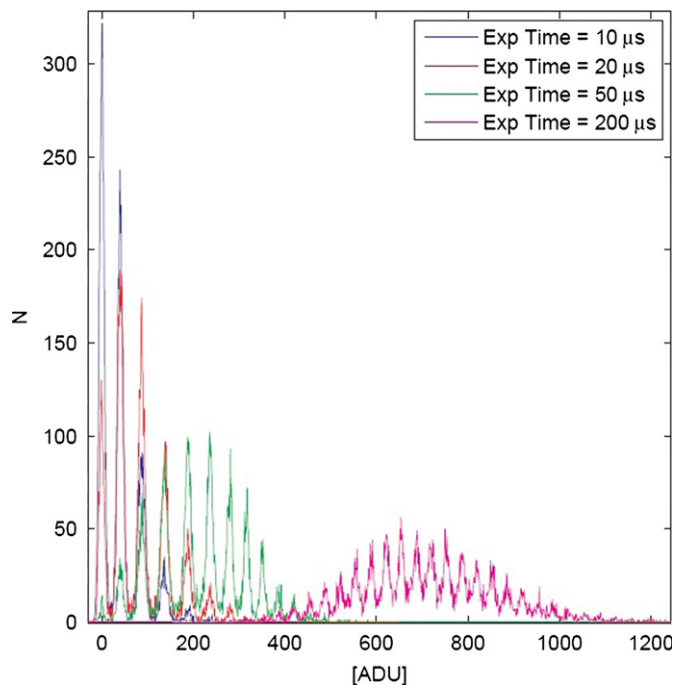

Fig. 2. Histogram of a single pixel masked by a 25 µm pinhole and illuminated with monochromatic 8-keV X-rays over many frames. The left most peak corresponds to zero photons. Subsequent peaks correspond to an integer number of photons. The x-axis is in analog-to-digital conversion units. More than 27 peaks are distinguishable.

Table 1
Detector specification summary.

Pixel size	110 µm × 110 µm
Array size	Single ASIC: 185 × 194
	Tiled detector: 1516 × 1516
Frame rate	120 Hz in operation at LCLS
Pixel saturation	2700 8-keV X-rays (low-gain)
	350 8-keV X-rays (high-gain)
Quantum efficiency	0.97 8-keV X-rays
	0.89 12-keV X-rays
	0.48 18-keV X-rays
Signal-to-noise	7 for 8-keV X-ray (high-gain)
(rms)	2 for 8-keV X-ray (low-gain)

integration time and the height of the peaks in the histogram trace out the expected photon counting Poisson distributions (Fig. 2). A summary of detector specifications is given in Table 1.

4. Conclusion

This detector is presently being assembled into tiled arrays by SLAC and will be used for the Coherent X-ray Imaging (CXI) experiment at the LCLS. A tiled version has already been installed on the LCLS X-ray pump-probe (XPP) beamline. This detector represents one of the first detectors specifically designed for these new sources that has been completed to the stage of large scale tiling and imminent installation on an X-ray Free Electron Laser beamline. The ability to distinguish single photon events and also integrate thousands of photons at extremely high count rates will be critical for many X-ray free electron laser experiments.

3. Single photon measurement and detector performance

This detector is (Fall, 2010) being assembled into tiled arrays by SLAC for Coherent X-ray Imaging (CXI) and X-ray pump-probe (XPP) experiments at the LCLS. These detectors will be among the first installed detectors specifically designed hard X-ray XFELs. The ability to reliably measure low-flux single-photon and multiple-photon conversions in a pixel is essential for the CXI experiment. Fig. 2 shows a histogram of a single pixel over thousands of frames. For the data shown, peripheral regions of the pixel, where charge sharing with adjacent pixels is significant, were masked off by centering a 25 µm pinhole over the pixel of interest. X-rays at 8 keV were produced by a copper anode X-ray tube run at constant current and voltage. The integration time was varied between 10 and 200 µs to produce the distributions shown. The average number of photons measured by the pixel increased with

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