High-Speed Imaging at High X-ray Energy: CdTe Sensors Coupled to Charge-Integrating Pixel Array Detectors

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Abstract. Pixel Array Detectors (PADs) consist of an x-ray sensor layer bonded pixel-by-pixel to an underlying readout chip. This approach allows both the sensor and the custom pixel electronics to be tailored independently to best match the x-ray imaging requirements. Here we describe the hybridization of CdTe sensors to two different charge-integrating readout chips, the Keck PAD and the Mixed-Mode PAD (MM-PAD), both developed previously in our laboratory. The charge-integrating architecture of each of these PADs extends the instantaneous counting rate by many orders of magnitude beyond that obtainable with photon counting architectures. The Keck PAD chip consists of rapid, 8-frame, in-pixel storage elements with framing periods <150 ns. The second detector, the MM-PAD, has an extended dynamic range by utilizing an in-pixel overflow counter coupled with charge removal circuitry activated at each overflow. This allows the recording of signals from the single-photon level to tens of millions of x-rays/pixel/frame while framing at 1 kHz. Both detector chips consist of a 128×128 pixel array with (150 μm)^2 pixels.

INTRODUCTION

The introduction of Pixel Array Detectors (PADs) [1] revolutionized the way experiments in a variety of disciplines are performed at synchrotrons. By separating the processing layer (ASIC) from the sensor layer, both can be optimized independently. To date the most common sensor material is silicon, not only because of its availability and low cost, but also because of its excellent quality. However, the stopping power of silicon for x-rays limits the ability to efficiently absorb (and ultimately detect) x-rays of energies above approximately 20 keV.

In order to allow experiments at higher x-ray energies, we have replaced a standard silicon sensor of 500 μm thickness with Cadmium Telluride (CdTe) sensors of 750 μm thickness. This change increases the quantum efficiency of the sensors in the 15 to 100 keV range and beyond, as shown in Figure 1a.
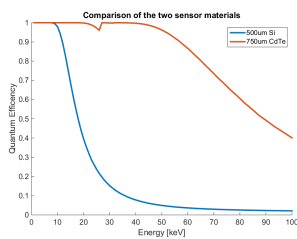
(a) Quantum efficiency of 500 μm silicon and 750 μm CdTe sensors.
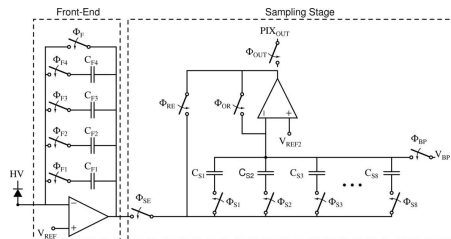
(b) Keck Pad block diagram.
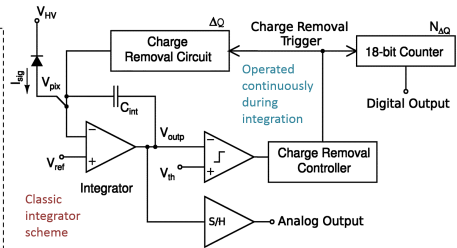
(c) MM-PAD block diagram.

FIGURE 1: Comparison of the quantum efficiency of sensors, as well as block diagrams of the hybridized chips.

Detector systems

Cornell University has developed integrating detectors, two of which, the Keck PAD and the MM-PAD (detailed below) have been selected for hybridization with CdTe sensors. Both ASICs are fabricated in TSMC 0.25 μm technology and feature 128×128 pixels of $(150 \text{ μm})^2$ per chip.

Both detector chips have been tiled to create 2x3 arrays, increasing the imaging area. The same custom built housing is used for both arrays, providing a thermally regulated vacuum environment, as well as support electronics.

Keck PAD

The Keck PAD [2, 3, 4], shown as a simplified schematic in Figure 1b, shares operating principles with past detectors [1, 5] like the analog integrating approach with in-pixel storage, which in turn inspired current day burst mode imagers like the AGIPD [6, 7]. Burst imaging at the 10 MHz level is possible (100 ns pulse separation) and the front-end conversion gain is set by the configuration of switches $F1$-$F4$, making it adjustable by a factor of up to 6.5.

Beyond their gain selection capabilities, the front-end capacitors (C_{F1}-C_{F4}) may also be re-addressed to add signal without reading out the device. Additionally, each in-pixel frame (a value stored onto C_{S1}-C_{S8}) may be built from temporally separated acquisition windows which allows for in-pixel averaging. In essence this feature allows the detector to work as a lock-in amplifier for x-rays.

Mixed-Mode PAD (MM-PAD)

The MM-PAD [8, 9, 10] uses an integrating approach with counting features, as shown in Fig. 1c. Charge is accumulated on the integration capacitor until the output voltage of the front-end integration stage passes a programmed threshold, generally equivalent to a couple hundred 8 keV photons.

When the output voltage reaches this level, an in-pixel circuit removes a fixed amount of charge, typically also equivalent to a couple hundred 8 keV photons, from the integration capacitor. This charge-removal process can occur concurrently with the arrival of charge from stopped x-rays, i.e. the process incurs no dead-time.

An in-pixel digital counter records the number of times the charge removal circuit is triggered. At the end of the integration period, the in-pixel digital counter is read out, as well as the analog output of the front-end integrating amplifier. The analog output is digitized with off-chip electronics and is combined with the digital counter outputs to measure the total charge produced by x-rays absorbed in the sensor.

The MM-PAD achieves single x-ray sensitivity [11] and spans a dynamic range of $> 4 \times 10^7$ x-rays/pixel/frame (at 8 keV) while framing at > 1 kHz; this has proven to be very useful for coherent x-ray imaging [12].

CdTe Material

The CdTe material used for the sensor investigated here was produced by Acrorad Co Ltd., Japan. The sensors are In/Pt Schottky type, so the pixellated contact collects holes. Bump deposition and flip-chip bonding was performed by Oy Ajat Ltd., Finland. Module placement was performed in-house and wire-bonding, except for the HV wire, which was attached in-house, was done by Majelac Technologies LLC, USA. For the initial tests, a bias of +450 V and a temperature of +20° C were chosen, which will be reviewed after in-depth characterization of the produced modules.

RESULTS

The initial testing is intended to show functionality rather than an in-depth characterization of the material. These modules are the first of their kind, so we looked for problems along the production chain and a general measure of whether the new modules will be useful in scientific experiments. Results are presented for the Keck PAD chip only.

Imaging

All imaging tests were performed with illumination from an x-ray tube with a silver (Ag) anode operated at 45 kV tube voltage. In order to reduce the number of low energy photons the tube's output was filtered through 0.13 mm of copper. Two example images are shown in Figure 2.

Both sub-figures are dark-field corrected radiographs of objects and did not receive any corrections to account for pixel-to-pixel variations, neither gain nor flat field corrections. The figures show certain common features:
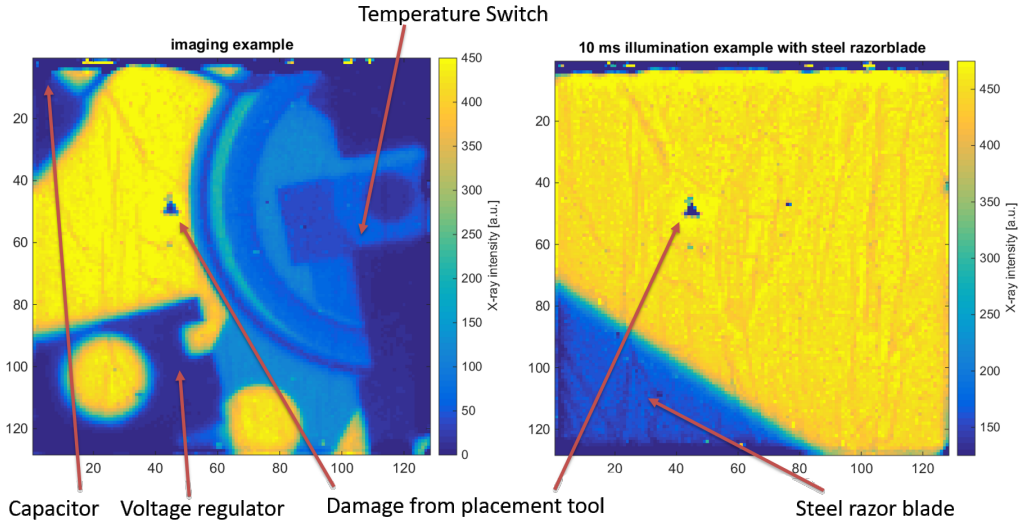
FIGURE 2: Radiographs. For a discussion of the observed features please refer to the main text.

First, there is a faint network of lines visible that modulate the signal. These lines are commonly observed in CdTe sensors, and their impact can be significantly reduced using flat field correction methods.

Second, a few localized spots seem to be less responsive to x-rays or even completely unresponsive. The big triangular region, labeled in Figure 2, has been identified as damage to the detector surface that was caused by the placement tool. The origin of the smaller point-like artifacts is still under investigation. Possible causes for theses artifacts include, but are not limited to, unbonded pixels and point defects or inclusions in the sensor material.

Last, the images look less sensitive towards the edges of the chip, especially towards the top, where the chip appears unresponsive. This behavior is most likely caused by the leakage current of the sensor, which is known to increase towards the edges of the sensor. High leakage currents flood the input capacitor and cause a large dark-field offset, which effectively reduces the well-depth of the pixel, in the worst case to zero. Reducing the operation temperature of the modules should reduce the leakage current of the sensor and thereby reduce this effect.

Characterization

These measurements used the tube with a monochromator and a tungsten pinhole mask with 75 μm pinholes on a 0.5 mm grid. The monochromator was adjusted so that the 22.16 keV K_α line of silver illuminated the pinholes. The pinholes ensured that only the pixel under investigation was centrally illuminated and surrounding pixels were dark.

The histogram in Figure 3a displays 30,000 individual events, each with an illumination time of 1 ms. The histogram shows a clear separation between the peaks of individual photons and allows determination of the pixel gain, approximately 5.5 keV/ADU, and a noise of approximately 6 keV rms. These values are in good agreement with values previously reported for Keck PAD modules with silicon sensors [3, 4], accounting for the difference in energy required to produce an electron-hole pair in CdTe and silicon (4.4 eV vs. 3.6 eV).

Figure 3b shows the saturation behavior of one of the storage cells in highest gain. The resulting well-depth of approximately 500 photons of 22 keV is also in agreement with results obtained previously using modules with silicon sensors [3]. The intensity was varied by increasing the integration time of individual exposures. All data points were dark-field corrected and are an average of at least 1000 individual measurements.

CONCLUSIONS AND NEXT STEPS

The results show that the sensor hybridization and module assembly were successful. Some damage due to the placement tool was observed and the process has since been improved to avoid this kind of damage in the future.

Although developed for use with silicon sensors, Cornell systems work with CdTe sensors. Gain and noise are comparable to versions using silicon sensors. No apparent drawbacks due to hole instead of electron collection were

(a) Single Photon sensitivity in highest gain.
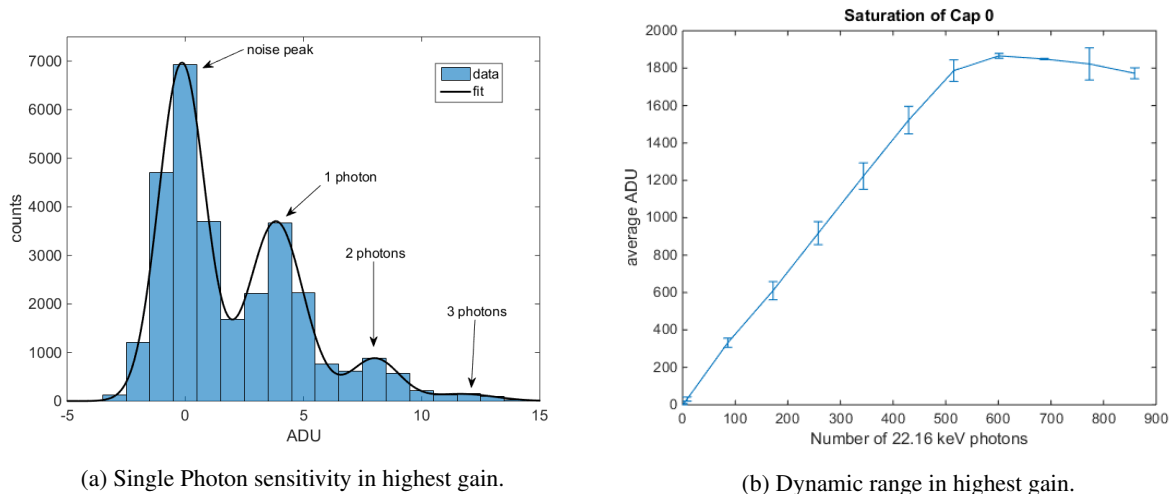

(b) Dynamic range in highest gain.

FIGURE 3: First results of the Keck PAD chip using CdTe sensors.

found. Detailed characterizations of both chips are on-going. Goals of the upcoming characterization campaign are to find optimum operating points in temperature and bias for both chips and to fully evaluate their performance.

ACKNOWLEDGMENTS

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