Imaging Hard X-Ray Compton Polarimeter SOI Sensor Prototype Specification

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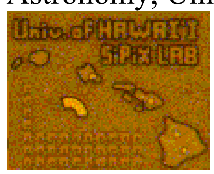

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ABSTRACT

This article describes the design specifications and proposed readout architecture for a future generation of silicon pixel detector for measuring hard x-rays for use in a future imaging Compton scattering polarimeter.

Keywords: X-ray detector, Compton Polarimeter, SOI detector

1. Introduction

The hard X-ray and gamma-ray bands have long been recognized as important windows for exploring the energetic universe. It is in these energy bands that non-thermal emission, primarily due to accelerated high-energy particles, becomes dominant. However, by comparison with the soft X-ray band, where the spectacular data from the XMM-Newton and Chandra satellites are revolutionizing our understanding of the high-energy Universe, the sensitivities of hard X-ray missions flown so far, or currently under construction, have not dramatically improved over the last decade. Clearly, the scope of discovery expected with much improved sensitivity for both point and extended sources is enormous.

Polarization measurements play key roles to study particle acceleration mechanisms in supernovae remnants, pulsars and back holes since synchrotron radiation, Compton scattering and bremsstrahlung are main photon processes and they produce distinct photon polarization features. An imaging polarimeter enables detailed polarization mapping in these objects and allows us to locate particle acceleration sites. Furthermore a measurement of polarization feature caused by General Relativity effect around Kerr back holes would provide THE definite proof of the back hole.

The HXICP will consist of a hard X-ray mirror and a focal plane detector. The basic IHXCP focal plane detector module's design is based on a Compton kinematics telescope[1,2]. The hybrid design of this module, illustrated in Figure 1, incorporates both silicon detectors and pixelated CdTe detectors. The silicon layers are required to cause at least one Compton scattering before a photo-absorption and also improves the angular resolution because of the smaller effect of the finite momentum of the Compton-scattering electrons (Doppler broadening) than CdTe. The Compton telescope consists of 10~20 layers of silicon detectors (double-sided silicon strip detectors or silicon monolithic pixel detectors) and 2 layers of thin CdTe pixelated detectors surrounded by 5 mm thick CdTe pixelated detectors. The telescope is surrounded by a BGO ($Bi_4Ge_3O_{12}$) shield units to reject backgrounds. The width of silicon strip or pixel depends on the requirement on the point spread function of the X-ray mirror. For a typical hard X-ray mirror, 0.5 arcminutes or better can be expected. We require each IHXCP event to interact twice in the stacked detector, once by Compton scattering in the Si or thin CdTe part, and then by photo-absorption in the CdTe part. Once the locations and energies of the two interactions are measured as shown in Figure 1, the Compton kinematics allows us to calculate the angle between the telescope axis and the incident direction of the event using the formula

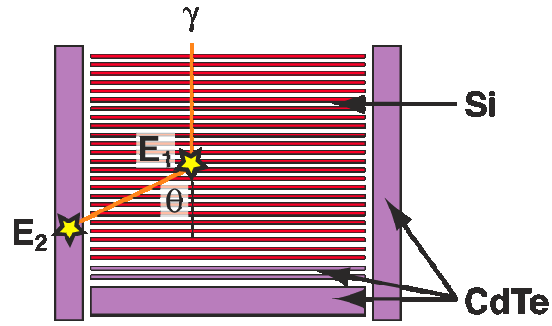

Figure 1: The Imaging Hard X-ray Compton Polarimeter (IHXCP) concept.

$$\cos\theta = 1 + \frac{m_e c^2}{E_2 + E_1} - \frac{m_e c^2}{E_2},$$

where θ is the polar angle of the Compton scattering, and E_1 and E_2 are the energy deposited in each photon interaction. The direction of the incident photon can be confined to be on the surface of a cone determined from θ and the two interaction positions. The fine energy resolution of the Si and CdTe devices help reduce the width of these "Compton rings". We can determine the location of point sources as intersections of multiple rings. The angular resolution is limited to ~8° at 100 keV due to the finite momentum of the Compton-scattering electrons, which is comparable to the FOV of the BGO collimators. Although the order of the events can be uncertain, we can use the relation that the energy deposition by Compton scattering is always smaller than that of the photo absorption for energies below $E_\gamma = 256$ keV ($E_\gamma = m_e c^2/2$).
The polarization can be measured by an azimuth scattering angle distribution as shown in Figure 2.

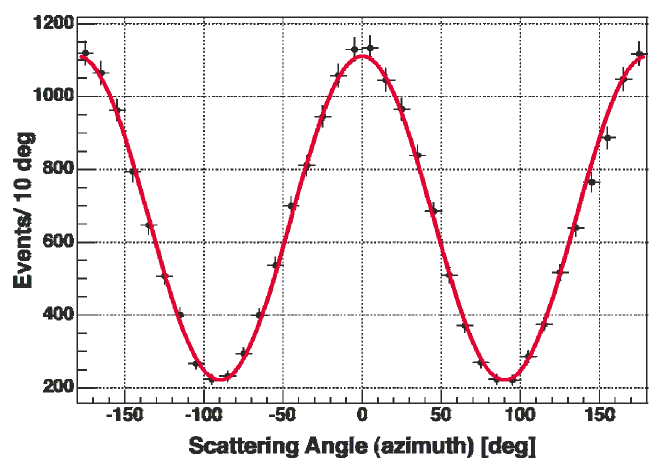

Figure 2: An example of polarization determination as a function of scattering angle.

In order to maximize the energy resolution, a low-noise pixel sensor is a natural choice.

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1.1. *Sensor specifications*

The specification for a pixel sensor to perform the energy measurements while operating in a self-triggered mode are listed in Table 1 below. Of note is the desire to minimize the power and to provide a low-noise, data-driven measurement of the Compton energy deposition.

Table 1: Specification for the IHXCP pixel sensor.

Pixel Size	200 x 200 μm
Pixel Array (Detector) Size	2.1 x 2.1 cm
Noise	<=10 e-
Global Trigger Rate	500 Hz
Single Pixel Rate	**10?** mili-Hz
Trigger Threshold	0.5 keV
Trigger Latency	1-2 μs
Power	200 μW/pixel
Total Array Power	2 W
ADC precision	12 bits

2. Architecture

A schematic view of the proposed architecture is found in Figure 3. The base pixel is 200 x 200 um. An array of 100 x 100 of these (2cm x 2cm) form the x-ray focal plane. In order to simplify the readout and provide efficiency in readout, the detector is segmented into 4 quadrants as shown. Within each of these quadrants, which are identical from a layout point of view, are a set of column and row electronics which perform the following key functions:

1. Hit detection and hit time encoding
2. Sample selection
3. Analog to Digital Conversion
4. Event hit word build
5. Queue and transfer data to DAQ

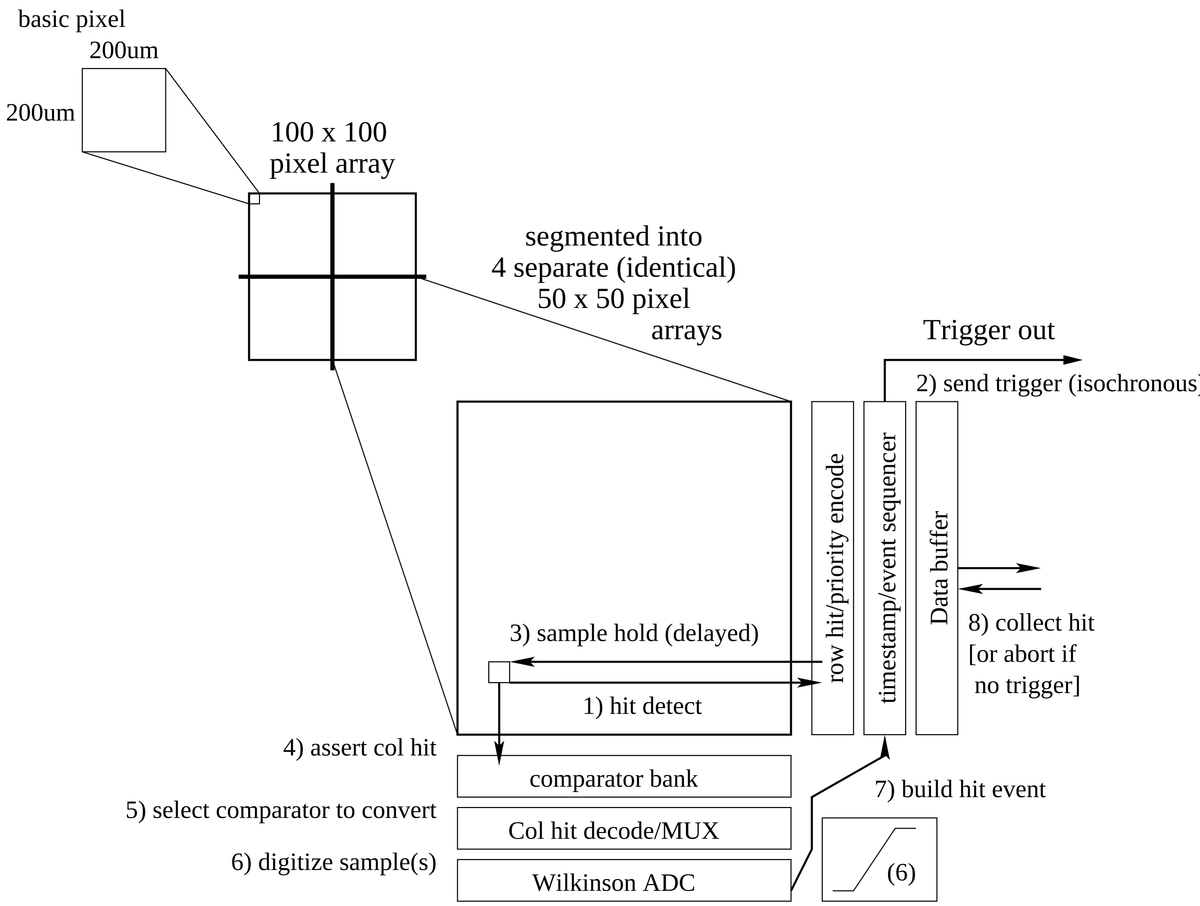

Figure 3: Overview of the readout architecture, illustrating the data-driven nature of the proposed scheme. A hit is encoded and collected as per the enumerated steps shown and described in more detail in the text.

2.1. Pixel level Detail

Key to obtaining the desired performance is the functionality contained within each pixel. A schematic representation of the simplest, baseline design is shown in Figure 2. Hold is common to an entire row, so column decoding is used to resolve actual hit channels. The basis of the signal sensing and storage is similar to that being developed for charged particle tracking applications [3].

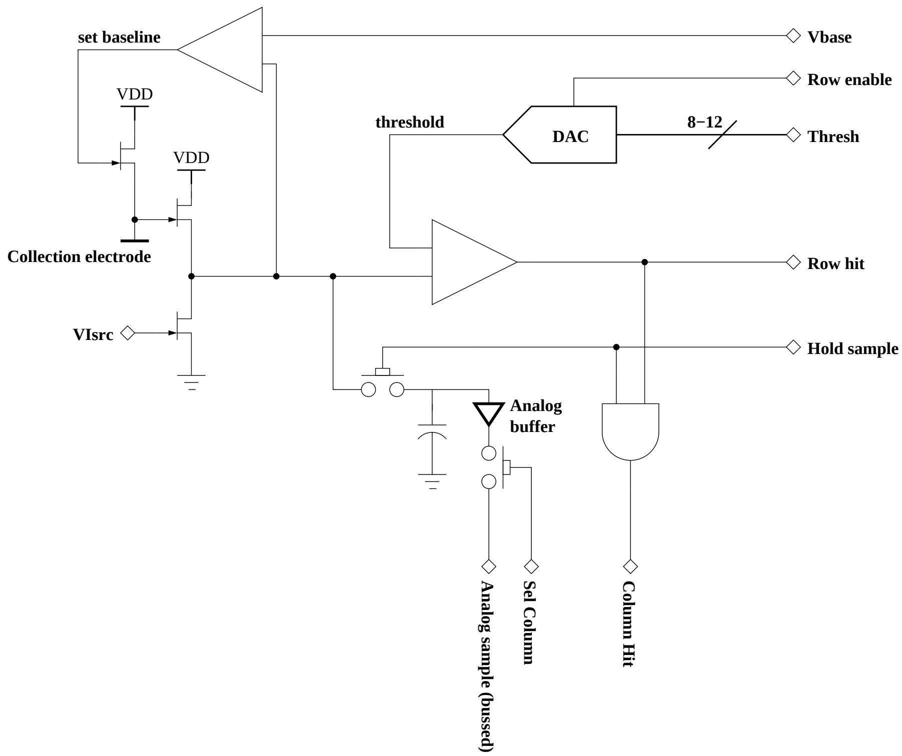

Figure 4: Essential elements of each pixel cell. A comparator is used to determine the crossing of a threshold set with an in-pixel DAC. A feedback loop is used to compensate for leakage current and restore the baseline after collection of an induced signal.

2.2. Data format

Each hit pixel is expected to produce a 48-bit data word: x-position (6-bits), y-position (6-bits), hit time (24-bits – 16s wrap-around to avoid timing ambiguities), and ADC value (12-bits). The details of this are not so important at this stage, merely to indicate that some type of serial shift-out of the data is possible given the low event rate and desire to minimize cabling and power.

3. Implementation Details

The choice of number of pixels is driven to match the expected reticle size. However this expectation is for the TSMC 0.25um process and may need to be revised. The quadrant architecture scheme shown can be extended to cover discrete die, in which 4 die could be fashioned together to form a larger array – or if there are issues with maximum reticle size.

3.1. Prototype proposal

At least a small array of pixels should be fabricated to explore the noise levels that can be expected. Also, it is desirable to implement as much of the peripheral control/sampling logic as will fit, commensurate with the shared real estate available on the first 5x5mm device. The primary issues to be addressed in evaluating the performance of this process are:

1. Noise
    a. Due to leakage current
    b. kT/C noise through storage capacitors
    c. fixed pattern noise/cross-talk
2. Uniformity
    a. Collection efficiency
    b. Shaping time

Basic test structures to address these issues seem an obvious choice. We would like to propose to make a very modest array of at least 3 different geometries:

1. 200 x 200 um – basic design
2. 100 x 100 um – to help understand leakage current scaling
3. 10 x 10 um – to evaluate architecture for low-energy "entrance window" x-rays

As a first check, it doesn't seem necessary to provide very extensive arrays, and perhaps a few variants will allow tests of systematic effects.

4. Open Questions

A component of the design and prototype study will be the obtainable performance. Certain design issues have been raised during the conceptual design process and are listed below.

4.1. Size of Pixel Sense Transistor?

The observed voltage shift due to the collection of electrons from e-h pair creation depends upon the size of the readout transistor chosen. One would like to make as small as possible to permit the maximum sensitivity (largest voltage shift) per collected electron. However, this needs to be matched to the needed dynamic range in a way that does not lead to saturation. **This will be studied**.

4.2. Force nearest-neighbor triggers?

For best energy resolution, it is desirable to collect small, but non-zero signal from neighbor pixels that may have been below threshold for forcing themselves to be read out. This becomes more critical if under realistic operating conditions, it is impossible to maintain a uniform and low threshold level. Such a forced readout is possible, at the expense of added complexity. **The tentative plan is to implement this feature.**

4.3. Correlated Double Sampling?

Optimal noise/SNR performance is always obtained with these type of Monolithic Active Pixel Sensor detectors if one takes advantage of multiple samples, correlated tightly in time (pre-sample and post-sample, separated by a us or two). It adds some complexity, but may be very much well worth doing or even necessary to attain the desired performance. **The tentative plan is to implement this feature.**

5.References

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