Comparative Performance Evaluation of Silicon and CdZnTe Photon Counting Sensors in a MiniPIX Timepix3-based Portable XRF System

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1. Introduction

In portable X-ray fluorescence (XRF) systems, Silicon Drift Detectors (SDD) have traditionally been used. SDDs offer excellent energy resolution of about 130 eV at the Mn Kα line (~5.9 keV), enabling clear separation of characteristic X-ray peaks for different elements [1]. However, because SDDs operate using analog integration, they exhibit background noise due to thermal noise and dark current, and they are prone to signal saturation and pile-up when count rates become high [1]. In particular, when weak fluorescence signals are accumulated over long durations, electronic noise is also accumulated, which limits improvements in the signal-to-noise ratio (SNR) [1]. Moreover, since SDDs consist of only one large detector element, achieving spatially resolved imaging is difficult, and the detection efficiency for high-energy X-rays (e.g., >30 keV) drops sharply [1, 8].

To overcome these limitations, photon counting (pixel) detector technology has been developed. Photon counting detectors individually count incident X-ray photons and record them as digital signals, thereby minimizing noise and providing high linearity [2]. That is, because the detector itself has no dark current and the electronic readout noise approaches zero during readout, the continuous background in the resulting XRF spectrum is dramatically reduced [2]. Consequently, even minor elemental peaks can be identified with a significantly higher SNR than before, thus enhancing detection sensitivity [2]. In addition, since each pixel has its own dedicated measurement channel in the hybrid pixel structure, each pixel can handle count rates up to ~10^6 counts per second (cps), which results in an overall very high dynamic range and prevents signal saturation even under high X-ray flux [2]. Furthermore, the multi-pixel array, with pixel sizes of several tens of micrometers, also captures positional information of the XRF signal, enabling an innovative analysis that obtains both elemental distribution images and spectra simultaneously from a single measurement [2].

ADVACAM's MiniPIX Timepix3 module is a compact X-ray camera that leverages this photon counting technology. It combines a 256×256 pixel array with 55 μm pixels and a Timepix3 readout ASIC [4]. In this study, we compare the XRF performance of two sensor materials – Silicon and CdZnTe (CZT) – integrated in this module. Although both the Silicon sensor and the CZT sensor operate as photon counting XRF detectors based on Timepix3, their energy responses differ due to the intrinsic characteristics of the sensor materials. In the following sections, we compare the energy resolution, signal-to-noise ratio (SNR), and sensitivity of the two sensors, and additionally discuss other performance metrics such as effective energy range and escape peaks.

Figure 1 shows the external appearance of the ADVACAM MiniPIX Timepix3 based photon counting XRF sensor module used in this study.

Fig. 1. ADVACAM's MiniPIX Timepix3 based photon counting XRF sensor module

2. Methods and Results

2.1 Sensors and Equipment

In this study, two types of sensors embedded in ADVACAM's MiniPIX Timepix3 module were compared. One is a Silicon (Si) sensor with a thickness of 500 μm, and the other is a CdZnTe (CZT) sensor with a thickness of 1000 μm [4]. Both sensors feature a 256×256 pixel array (55 μm pitch) and use the Timepix3 readout ASIC, where each pixel records a pulse width proportional to the arrival time and energy of the incident X-ray photon [4].

2.2 Experimental Setup

For XRF measurements, a compact portable X-ray tube capable of outputting up to 50 kV/100 μA was used. The fluorescence X-rays emitted from the sample were directed to impinge directly on the photon counting sensor, and thick lead shielding blocks were positioned to reduce unwanted scattered X-rays. Measurements were performed on standard samples with various elemental compositions (e.g., single-element foils), and metal filters were placed in the primary X-ray path to selectively excite Kα and Kβ lines of specific elements for energy calibration of the sensor [5]. The Timepix3 sensor's ToA–ToT data for each photon event was processed via software to reconstruct the energy, and XRF spectra were generated in histogram form.

2.3 Performance Evaluation

To compare the performance of the two sensors, the following metrics were measured:

- **Signal-to-Noise Ratio (SNR):** Defined as the ratio of the signal peak to the adjacent background in the spectrum.
- **Energy Resolution:** Measured as the full width at half maximum (FWHM) of the main fluorescence peaks (e.g., Fe Kα peak) using a single-element standard sample.
- **Detection Sensitivity:** Qualitatively compared by assessing the ability to identify minor elemental peaks and detect elements at low concentrations.

Additionally, parameters such as effective energy range and the escape peak phenomenon were also evaluated. All measurements were repeated at least three times to ensure reproducibility, and data analysis was performed using in-house Python-based software [5, 8]. The table below summarizes the key specifications of the two sensors. The energy resolution was measured by the manufacturer and is reported based on the use of a single-energy gamma source at 60 keV. The radiation source employed is generally assumed to be Am-241.

Table I: Summery of Timepix3-based Photon Counting XRF Sensor Specifications

Type	Silicon (Si)	CZT (CdZnTe)
Thickness	500 μm	1000 μm
Energy Resolution	0.5–1.0 keV (FWHM)	1.1–3.6 keV (FWHM)
Sensitivity Range	3–20 keV	5–80 keV
Min. Det. Energy	~3 keV	~5 keV
Pixel array	256 × 256 (55 μm pitch)	
CPS	~ 106 cps/Pixels (Timepix3)	

3.Results and Discussions

In terms of the signal-to-noise ratio (SNR), the photon counting measurements showed an improvement of more than two times compared to conventional SDD measurements [2]. Even during long-duration counting, the photon counting detector did not exhibit an increase in background noise, and the experimental results confirmed that, in theory, the SNR improves in proportion to the square root of the count number [2]. Although this study did not directly calculate the actual quantitative SNR, the method for defining adjacent background in SNR calculations for the MiniPIX TPX3 involves selecting low-energy and high-energy regions adjacent to the signal range, modeling background values through polynomial fitting, and using this approach to derive net signal and noise levels

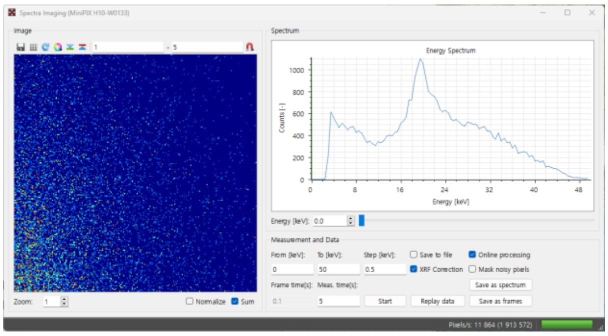

Fig. 2. The captured spectral image and energy spectrum of the energy of 50 keV source with **Silicon** based MiniPIX

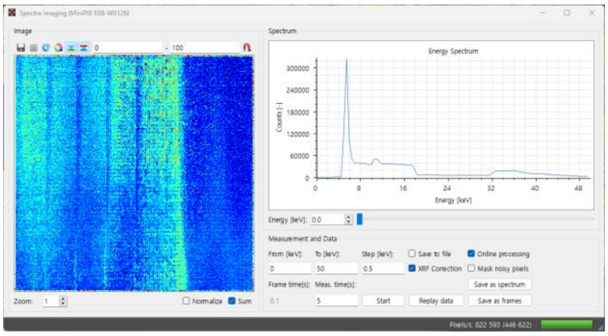

Fig. 3. The captured spectral image and energy spectrum of the energy of 50 keV source with **CZT** based MiniPIX

Regarding energy resolution, both sensors demonstrated lower resolution compared to SDDs; however, the Si sensor exhibited better energy resolution than the CZT sensor. (Fig2&3) Although the resolution was 5–10 times broader than that of an SDD, with appropriate calibration and filtering, many elemental Kα–Kβ peak separations (exceeding several keV) can be adequately resolved [8]. Nonetheless, for very closely spaced peaks (e.g., Pd Lα vs. Ag Lα), further refinement in calibration and spectral decomposition techniques is necessary [7, 8].

In addition, differences in the effective energy range between the two sensors were observed. (Fig2&3) The Silicon sensor provided high efficiency in the ~3–20 keV range but showed a steep decline in sensitivity for high-energy X-rays above 20 keV. In contrast, the CZT sensor effectively detected X-rays from as low as 5 keV up to above 80 keV [5]. However, due to the inherent characteristics of the material, the CZT sensor exhibits higher sensitivity, and its use must be optimized based on the measurement conditions.

Finally, as both sensors employ an identical 256×256 pixel array, their spatial resolution is the same. A one-dimensional scanning experiment confirmed that the elemental distribution within a sample could be imaged [5]. These results suggest that sensor selection can be appropriately made based on the range of elements to be analyzed and the required energy resolution, or by using a strategy that combines both sensor types. (Fig4) For reference, the bright area on the left side of the CZT image occurred during the process of matching the same conditions as the Silicon image. This area is exposed to X-rays and can be interpreted as showing that the CZT visualizes a greater amount of energy.

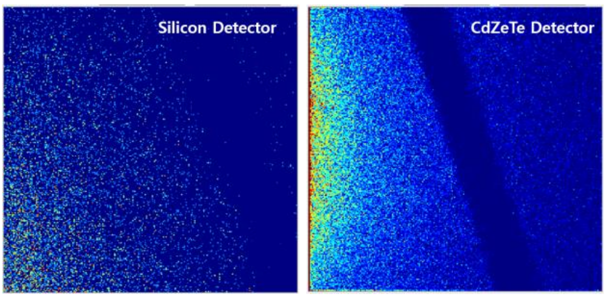

Fig. 4. 2D XRF image samples acquired under conditions where a long, thin material obstructs the sensor surface.(left Silicon, right CZT)

When compared with the experimental results of other researchers, the XRF system utilizing a photon counting 2D sensor showed improved performance over conventional SDD-based systems in several aspects. In terms of detection sensitivity, the ability to detect trace elements was greatly enhanced. For example, in samples at approximately 0.1% (1000 ppm) concentration—where identification was challenging due to background noise with SDDs—a clear peak was observed using the photon counting sensor [2]. This is because the photon counting method operates with digital counting, which inherently minimizes electronic noise and yields an extremely low background count rate, allowing even weak peaks to stand out clearly [2].

4. Conclusions

This study compared and analyzed two types of sensors—Silicon and CZT—embedded in ADVACAM's MiniPIX Timepix3 based photon counting XRF sensor module. The experimental results confirmed that the photon counting method provides advantages over traditional SDDs, including enhanced detection sensitivity for trace elements, improved signal-to-noise ratio, and simultaneous acquisition of spatial information [2]. In particular, while the Si sensor exhibits superior energy resolution in the low-energy region, making it favorable for light element analysis, the CZT sensor offers higher sensitivity and efficiency in the high-energy X-ray region [5, 8]. Depending on the range of elements to be analyzed and the required energy resolution, a strategy of selecting one sensor or using both in parallel is suggested. It is considered essential to establish a system layout for a portable 2D-XRF device capable of simultaneously performing light element analysis based on silicon detectors and heavy metal or high-density material analysis based on CZT detectors. With future improvements in energy calibration algorithms and sensor material quality, the photon counting based XRF system presented in this study is expected to significantly enhance the practicality of next-generation portable elemental analyzers.

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