MONOLITHICALLY INTEGRATED X-RAY DETECTOR ARRAYS FOR COMPUTED TOMOGRAPHY

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ABSTRACT

The design and performance of a high sensitivity monolithic X-ray detector array fabricated by depositing CdTe photodiodes on CdWO₄ scintillators for computed tomography (CT) are presented. CdTe photodiodes offer improved sensitivity due to the better match to the CdWO₄ scintillator emission spectrum than the Si photodiodes used in current CT scanners. A CdTe photodiode fabricated on glass mechanically stacked to a CdWO₄ scintillator showed 30% improvement in signal strength over Si photodiodes stacked to CdWO₄. Monolithic X-ray detector arrays were fabricated by depositing a CdTe photodiode structure on CdWO₄ using close-spaced sublimation technique. Preliminary results on the detector’s X-ray response, signal-to-noise ratio and the X-ray temporal response show that monolithic CdTe X-ray detectors are suitable for practical CT scanner applications.

INTRODUCTION

X-ray computed tomography (CT) is one of the important diagnostic tools in medical imaging. Current CT scanners use solid state detectors which consist of Si photodiodes mechanically stacked to scintillators. Although these detectors perform well, they are not ideal for CT applications. There is optical signal loss in these devices due to the spectral mismatch between the Si photodiode and the scintillator. For example, the emission peak of CdWO₄, a commonly used scintillator, is in the 480-500 nm wavelength range, a spectral region where the responsivity of Si photodiodes is relatively weak. Furthermore, the fabrication of X-ray detector arrays using Si photodiodes is complicated since precise stacking of photodiodes on scintillator is necessary. As a result, this approach is costly.

Monolithic X-ray detectors are desirable over the current Si photodiodes stacked on scintillator for a number of reasons. First of all, the process for fabrication of X-ray detector arrays is simplified by eliminating the need for precise stacking of photodiodes on scintillator. Secondly, the loss of optical signal due to the refractive index mismatch between the stacking glue and the scintillator is eliminated. Thirdly, the optical signal loss may be minimized by using a photodiode system that is matched to the emission spectrum of the scintillator. Finally, the cost of fabrication can be significantly reduced by inexpensive large area deposition methods. In this respect, monolithically integrated CdTe photodiode on CdWO₄ scintillator system is attractive for CT scanner applications. CdTe photodiodes offer a better spectral match to the
CdWO₄ scintillator emission is less photodetector efficiently used in CT scanners. In addition, the well-developed CdTe solar cell manufacturing technology using inexpensive and large area deposition techniques can be applied to develop commercially viable CdTe X-ray detector arrays for CT application. In this paper, we report the first demonstration of a monolithically integrated CdTe X-ray detector and its performance results.

EXPERIMENT

Figure 1 shows the device configuration. The photodiode consists of a CdS n-layer and a CdTe p-layer. The indium tin oxide (ITO) coating, a transparent conducting layer, on the CdWO₄ scintillator minimizes optical signal loss at the scintillator-photodiode interface due to its refractive index (1.8) match to the scintillator and acts as an electrical contact to the n-type layer of the photodiode.

In order to demonstrate that CdTe photodiodes have better spectral match to the CdWO₄ emission spectrum than Si photodiodes, we measured the external quantum efficiency in the 300–1100 nm wavelength range of a CdTe solar cell fabricated on a glass substrate with 12% efficiency and a Si photodiode, both separately stacked on a CdWO₄ scintillator. The spectral responsivity was calculated from the measured external quantum efficiency. The CdTe solar cell was obtained from the University of South Florida (USF). USF has been fabricating CdTe solar cells with the largest area, and they currently hold a world record for CdTe solar cell efficiency, 15.8%. Cell fabrication details are described in several journal articles. A 1000 A thick CdS layer was deposited by solution growth on ITO-coated glass substrates. After CdS deposition, 2 to 3 µm thick CdTe was deposited on CdS using close-spaced sublimation.

The X-ray response of a three element CdTe photodiode array built on a glass substrate and mechanically stacked on a CdWO₄ scintillator was measured at Analogic Corporation. A diagnostic X-ray source operating at 130 kVp and 40 mA was used for testing. A 0.8 mm Al and a 0.0002 inch thick Cu filter were used. A collimator with a beam half-angle of 14° was used in front of the entrance X-ray
separate signal was measured using Analogic read-out electronics. Signal-to-noise ratio was determined by acquiring data for more than 3400 samples at a rate of 2 Hz.

Monolithically integrated CdTe photodiodes on CdWO₃ substrates were fabricated using close-spaced sublimation techniques. The I-V characteristics and measured quantum efficiencies of the devices were measured. The devices were tested using a 120 kV, 20 mA X-ray tube at Analogic Corporation. The integral quantum and X-ray intensity dependent measurements were carried out at Picker International using X-ray tube currents ranging from 50 mA to 700 mA.

RESULTS AND DISCUSSION

One of the important properties for the X-ray detector is the photodiode's spectral responsivity. We calculated the spectral responsivity from the measurement of measured quantum efficiencies. Figure 2 shows a comparison of spectral responsivities of CdTe and standard W photodiodes and their relative usage in the CdWO₃ sublimation processes. The responsivity of the CdTe photodiode is higher than that of the W photodiode in the 500 to 800 nm wavelength range. The sensitivity to the shorter wavelengths can be further enhanced by depositing an even thicker target material, like CdWO₃, on the n-type layer of the device structure or by depositing the thickness of the Cd layer. The CdTe photodiode on a substrate showed 10% higher quantum X-ray response signal per volt than that of the W photodiode on a substrate. The signal-to-noise ratio (SNR) measured under identical conditions for these two devices was approximately equal. This result shows that the SNR is limited by quantum noise in the photodiode and not by the CdTe photodiode.

![Figure 2](image)

Figure 2 Comparison of spectral responsivities of CdTe/CdWO₃/Glass and standard W photodiodes.

We used the parameters originally developed for CdTe photodiodes fabricated on ZnO coated glass substrates to fabricate monolithically integrated CdTe photodiodes on CdWO₃ substrates. However, the electron beam system needed to be slightly modified to improve the sensitivity of CdTe photodiodes fabricated deposited on CdWO₃. Figure 3 shows the dark I-V characteristics of a CdTe photodiode monolithically integrated to a CdWO₃ substrate. Typically, a dark current density of 1.0×10⁻⁹ A/cm² was observed at 1 mA reverse bias. Given the 0.5 V bias, a device with lower current leakage may not yet have been developed for the CdWO₃ substrate; this must be very encouraging.

![Figure 3](image)

Figure 3 Comparison of spectral responsivities of CdTe/CdWO₃/Glass and standard W photodiodes.
For comparison purposes, we have measured the X-ray response of a monolithic CdTe detector (C) and two Si photodiodes (A and B). Device A is a regular arrayed detector module with mechanically isolated and optically bonded Si photodiodes on a CdWO₃ substrate. Device B is also a regular arrayed Si photodiode module but without CdWO₃ without optical isolation. Figure 4 shows the X-ray response of devices A, B and C. Device C has slightly higher signal than the average signal in devices A and B. This result may be explained by the differences in the device dimensions and light collection efficiency.

The SNR in devices A and C are approximately equal as shown in Figure 5. Note that the single elements of devices A and C have similar dark slope and of the standard module array A. This assumption is that the individual elements of devices A and C are not optically isolated from other and that crosstalk from a larger area of CdWO₃ substrate can be measured in the photodetector.

The quality of images will be affected by the thin-film preparation of the substrate. Figure 4 shows the response spectrum of the monolithic CdTe X-ray detector. The signal drops by 3 orders of magnitude when the X-ray source is moved off. However, there is still a small X-ray signal that persists up to 2 minutes. Improvements in the CdWO₃ substrates are believed to be responsible for this behavior and we are currently investigating ways to overcome this problem. Improved results will be reported in a future publication.

![Graph](image1)

![Graph](image2)

![Graph](image3)
A linear relationship between the X-ray intensity and the detector response is necessary for high quality medical imaging. Figure 7 shows the CdTe detector response for X-ray intensities ranging from 13 to 85 R/min. Note that an excellent linear relationship is observed in the measured range of X-ray intensities.
SUMMARY

We have demonstrated the first monolithic CdTe X-ray detector array that is suitable for CT scanner application. The preliminary results on CdTe photodetectors monolithically integrated to CdWO₄ scintillators show low dark current density (3.8±0.5 pA/cm² at 1 mV reverse bias) and high X-ray response comparable to or better than the performance of standard Si photodiodes coupled to CdWO₄. A good after-glow property of the X-ray scintillator is observed. A linear relationship between the X-ray intensity and the detector response is observed even at a 100-fold range of X-ray intensities. Optimization of device fabrication process and improved detector results will be reported in future publications.

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