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CdZnTe Array Detectors for Synchrotron Radiation Applications

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An X-ray linear-array detector was fabricated using high-pressure Bridgman-grown CdZnTe. The detector area was 175 × 800 µm and the pitch size was 250 µm. The measured dark current for the test 16-element detector was as low as 0.1 pA at 800 V cm^{-1} with excellent uniformity. Energy spectra were measured using a ^{57}Co radiation source. Both a small-pixel effect and charge sharing were observed. For the arrays, an average 5.8% full width at half-maximum (FWHM) at the 122 keV photopeak was obtained with a standard deviation of 0.2%. A large-area detector (1 × 1 cm) of the same material before fabrication exhibited a low-energy tail at the photopeak, which limits the photopeak FWHM to 8%, typically due to hole trapping. At energies below 60 keV, charge sharing between elements was observed. The charge sharing was greatly reduced by providing a path to ground for unwanted charges. A prototype readout electronic system for an eight-channel array detector was developed. A readout system intended for a multielement solid-state detector system was also used. The array detector will be used for high-energy diffraction and Compton scattering measurements at the Advanced Photon Source.

Keywords: detectors; CdZnTe; arrays; photopeaks; pixels; Compton scattering.

1. Introduction

The availability of high-intensity X-ray sources presents a technological challenge to fully utilize the photon fluxes available at such sources. This problem becomes more critical with the arrival of very bright photon sources like the European Synchrotron Radiation Facility, the Advanced Photon Source (APS) at ANL, and SPring-8 in Japan. One of the most challenging problems is the efficient detection of high-energy X-rays. There is a need for very fast X-ray detectors with high spatial and energy resolution able to operate near room temperature. Such detectors are of great interest for application in synchrotron radiation, astronomy and medicine. Several kinds of solid-state detectors are commercially available for X-ray detection applications. Si detectors are based on the most advanced technologies and their use is very common. However, the attenuation coefficient of Si is so low that the detector must be fairly thick in order to stop high-energy photons. As a result, the response is slow. Ge has a relatively large atomic number and seems to be a good choice. Since the intrinsic carrier density in Ge is large at room temperature, the detector has to be operated at cryogenic temperatures in order to increase the signal-to-noise ratio; thus the system becomes bulky.

In medical applications, sensitive, fast and large-area X-ray detector arrays which can display images in real time present a tremendous potential. II–VI semiconductors offer unique opportunities in terms of band-gap energies and optical and electronic properties. CdTe currently appears to be one of the most promising materials for the next generation of X-ray detectors. The band gap of CdTe is large and the intrinsic carrier concentration is low. In fact, with a high effective atomic number Z, it has a much higher stopping power than Ge and above all Si. The band gap of CdTe is large (1.6 eV) compared with Si and Ge, and therefore the intrinsic carrier number at room temperature is extremely small compared with Si and Ge. This translates to a higher sensitivity due to reduced noise. Dark current for CdTe at 300 K is several orders of magnitude less than for Si, whereas Ge detectors can only operate at low temperatures. Several research programs are being pursued by different groups directed towards the development of new materials for X-ray detectors. CdTe and CdZnTe seem to be the materials of choice for many of the applications when using hard X-rays. In recent years, groups in France and Japan have developed CdTe array detectors for use in medical and synchrotron radiation applications. These detectors were fabricated from bulk CdTe using lithographic and ion-etching techniques.

X-ray detectors based on CdTe/Si MBE-grown material, though exhibiting good performances, have to be improved

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in terms of energy resolution, sensitivity and speed. We believe that epitaxically grown CdTe position-sensitive detectors will be the detector of choice in the future when using X-rays in the 8–20 keV energy range (*e.g.* Yoo *et al.*, 1994, 1995, 1997), at high X-ray energies where Compton scattering experiments are performed (*e.g.* Sakurai *et al.*, 1992) or for medical imaging (*e.g.* Barber, 1996; Scheiber, 1996), where thin-film detectors are not efficient. One needs to fabricate array detectors from bulk CdTe or CdZnTe; they are more suitable for measurements above 40 keV. We are pursuing both directions in order to develop a third generation of solid-state detectors for X-ray applications. In this paper we present some results obtained with a CZT array detector fabricated in our laboratories.

2. Fabrication and electronics

Conventional photolithography was carried out on one side of a 1 × 1 cm CdZnTe (CZT) sample. The element area was 175 × 800 μm with 250 μm pitch size. After development of the photoresist, the contact area was slightly etched in 0.1% Br_2 in HBr, followed by electroless gold deposition. For the metalization on the opposite side of the sample, a photoresist was applied to protect the arrays, and then the whole sample was dipped into the etchant, followed by the electroless gold deposition.

After metalization on both sides, the sample was mounted on a graphite substrate using low-melting-point wax, then a photoresist was applied on the whole surface of the sample. This was necessary to protect the delicate surface of CdZnTe. The mounted sample was cut using a 125 mm-diameter stainless-steel wire saw and 16 μm boron nitride slurry. Extreme care was taken to avoid chipping the edge and minimizing damage on the wall; therefore, the cutting speed was extremely slow and took almost 1 h for one complete cut. The whole sample was dipped into 5% Br in methanol for 5 min to etch the damage done to the wall, followed by cleaning in trichloroethylene, acetone and methanol.

For connection to the pre-amplifiers, the array was mounted on a ceramic plate using silver paint. The ceramic plate was then glued onto a DIP chip socket. Gold pieces, which provide the bonding pads on the socket, were soldered onto pins. A new bonding technique using a thermosonic gold ball wire bonder, developed at UIC, allows successful bonding on the electroless gold layer on top of the CdZnTe surface. Since the bonding is performed at room temperature and without ultrasonic agitation power, this process does not damage the highly resistive CdZnTe surface and does not peel up the electroless gold. In a previous report, we confirmed that the leakage current of the detector elements corresponds to the resistivity of the sample.

Eight detector elements with 500 μm pitch were bonded to DIP pins of the socket and all the adjacent elements were bonded to the ground. The grounded elements serve as a guard ring and reduce the cross-talk between the sensing elements.

A prototype eight-channel charge-sensitive pre-amplifier was built on a standard PC board using commercial hybrid amplifiers. The amplifiers were closely placed at a spacing of 0.1 inch and significant cross-talk between amplifiers was found on the output. Therefore, each amplifier was carefully shielded using thin grounded Cu foils. The amplifier output noise was significantly reduced and uniformity confirmed for all the amplifiers. Surface-mounted ceramic capacitors of 1500 pF were soldered onto the pre-amplifier inputs for AC coupling to the array detectors and 100 MW resistors were connected to the ground for high-voltage bias to the array (Fig. 1). To test the complete electronics, a pulse was applied simultaneously to the test inputs of the pre-amplifiers and the output pulse heights of shaping amplifiers were measured. There was less than 5% variation of output pulse heights and this is within the variation of the capacitance of the coupling capacitors. After calibration of the shaping amplifier gain, the output pulse-height variation was reduced to 0.1%, and the measured spectrum FWHM of the pulse peak was 1.2% when the test pulse amplitude was adjusted for the output pulse height equivalent to a 122 keV photon from a ^{57}Co source.

3. X-ray fluorescence measurement

A test was performed with a single-element CdZnTe detector (10 × 10 × 1.5 mm^3) by measuring the X-ray fluorescence of various metals. To obtain the fluorescence spectra, the target metals were excited with the 75 keV synchrotron X-ray beam at the BESSRC 12 BM beamline at the APS. A double-crystal Si(111) water-cooled monochromator was tuned for a 25 keV primary X-ray energy. A 1 cm-thick Al slab was placed in the beam path to cut off the primary X-ray beam. Energy spectra of the beam scattered by cardboard were measured before and after placing the Al slab in the beam path and the results were

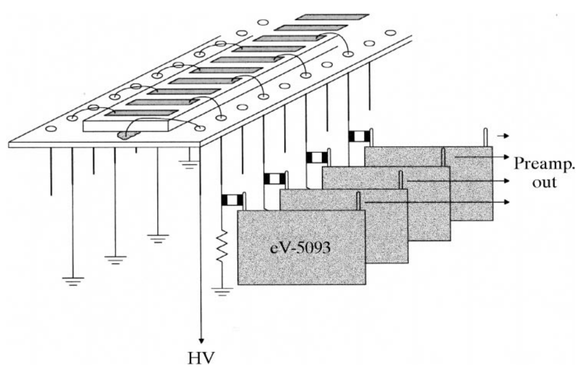

Figure 1
Schematic diagram of an eight-channel linear-array detector and its pre-amplifiers. High voltage (HV) is applied to the bottom contact of the array. 100 MW resistors are connected to each array element and 1500 pF capacitors were used for AC coupling to the pre-amplifiers.

compared. With the Al slab in the beam path, the primary-energy X-ray photons of 25 keV were greatly reduced but with a slight decrease for the third-harmonic-energy X-ray photons of 75 keV. The measured spectra of the scattered X-rays by Pd, Sn, Zr and Sn are illustrated in Fig. 2. The X-ray fluorescence X-ray energies were obtained from the calibrated spectrum. These measurements were performed at very high counting rates.

The fabricated linear array was tested using a 0.2 mCi ^{57}Co source placed 1 cm away from the linear array. A negative bias was applied to the common contact at the bottom, such that the charge collected at the top contacts are electrons. Since all the adjacent elements used for guard-ring contact were directly connected to the ground, the leakage current of the grounded elements contributed an additional voltage drop across the 100 MW resistor. The measured voltage drop across the resistor was as low as 4% of the applied voltage up to 600 V, indicating very low leakage current of the individual elements. After proper calibration of the amplifiers, the energy-resolution measurements for the eight-channel detectors were carried out simultaneously and the results are shown in Fig. 3. The photopeaks of 14.4, 122 and 136 keV are clearly visible on the spectra of all the elements. In general, for small detector elements, the generated charges are often shared by adjacent elements and an unexpectedly large number of counts is observed in the low-energy spectrum as shown in microstrip detectors (*e.g.* Matteson *et al.*, 1996; Macri *et al.*, 1996; Stahle *et al.*, 1996). This often causes poor energy resolution of the spectrum in the low-energy range or a very large background (*e.g.* Yoo *et al.*, 1996), or the disappearance of the photopeaks. However, the charge sharing was greatly reduced by grounding every other sensing element. This isolates the current path between the sensing elements, and only charges created near the sensing electrodes are shifted. As seen in Fig. 3, the background counts are as low as in a single-element detector and the 14.4 keV photopeak is greatly enhanced. In previous measurements on an array without the grounded elements, we observed the 14.4 keV photopeak superimposed on a high background.

In Fig. 3, we can easily see that the counts of some elements are slightly higher than others and we may suspect that there is an efficiency variation between elements. This is purely a geometrical effect. Suppose a radiation source with a small active area (1 mm diameter) is placed close to the array detectors (4 mm long); there should be a variation of the effective photon flux on each element. For example, the number of photons impinging on an element should be slightly less than on an element just beneath the source. The variation should be even greater when the source is placed on one side of the array or the angle variation to the source for each element is large. Charge sharing is low for this array because of the grounding elements used. The count rate gradually increases from one side of the array to the other. We carried out measurements by placing the source on the other side of the array and observed a similar response, slowly varying from one side to the other.

Others have reported that energy resolution greatly improves when the size of the pixel area is smaller than the thickness (Barret *et al.*, 1995), or the electric field near the charge-collecting electrode is modified, such as of coplanar contacts of a large-area detector. This is related to the electric-field distribution between anode and cathode and is no longer linear as commonly observed in large-array detectors. The electric field is more enhanced near the

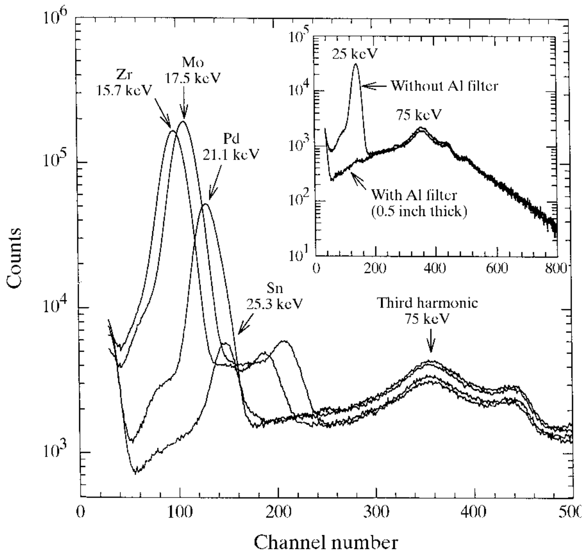

Figure 2
Energy spectrum of scattered X-rays from various metal targets measured by a large-area CdZnTe detector. The targets were excited by third-harmonic-energy X-rays (75 keV) of the synchrotron beam. Note that the primary-energy X-ray photons were decreased by a Al filters.

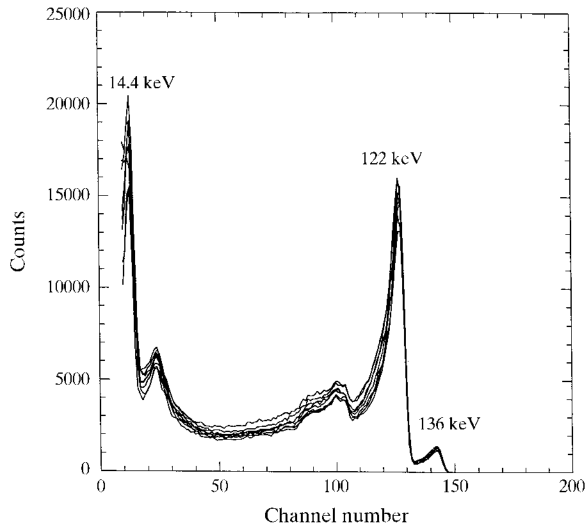

Figure 3
Energy spectrum of eight-channel linear-array detectors measured by ^{57}Co. Note the photopeaks at 14.4, 122 and 136 keV. Eight-channel CZT linear array (HB-4); 1.2 mm thick; 175 $\times$ 800 µm area; 500 µm pitch; V = $-$400 V. 0.2 µCi ^{57}Co. 0.25 µs shaping; $\times$100 gain; 20 h counting.

small-area pixel detector electrode. With a positive high-voltage bias on the pixel element, the collected charges are mostly due to the high-mobility electrons and the charge-collection efficiency is relatively insensitive to the hole trapping, which is commonly observed for large-area CdZnTe detectors. This small-pixel effect is more pronounced when the pixel size is far less than the detector thickness such as in the case of our detector. For this reason, we observed excellent energy resolution from the linear array. The measured energy resolution was as low as 5.8% at the 122 keV photopeak with excellent uniformity (0.6% standard deviation) which is far better than the FWHM (10.5%) obtained from the same material before the array fabrication. For this comparison, the same electronics were used for both the large-area and the linear-array detectors. However, less bias was applied to the large-area detector because of the relatively large leakage current. In fact, the CdZnTe material used for the fabrication of the array detectors is of poorer quality. However, when a small-area detector such as the linear array is fabricated from this material, the performance improves greatly over the large-area detector.

The detector readout electronics used were conventional. Each detector element has a charge-sensitive preamplifier, followed by a model 9615 spectroscopy amplifier. For the single-element detector, the amplifier is connected directly to a model 9635 successive approximation analog-to-digital converter (ADC) and thence to a model 556 acquisition interface module (AIM). The multielement detector is used with a separate amplifier for each element, then an analog multiplexer to connect the outputs of each group of four individual amplifiers to a single ADC. The system is controlled over the ethernet interface from a PowerMacintosh computer.

4. Synchrotron X-ray measurements

Energy spectra using monochromatic synchrotron X-rays were measured with the linear array. When the synchrotron X-ray energy was monochromated using an Si(111) crystal monochromator, odd-numbered harmonic X-ray photons are expected to exist in addition to the primary-energy photons. However, the energy spectrum when a large number of photons are present, such as is the case for synchrotron X-rays, is often difficult to measure. This is caused by pulse pile-up due to the relatively slow signal processing of the amplifying electronics. Therefore, this results in a poor energy spectrum and often misleads interpretation of the high X-ray photon energies. In this case, the synchrotron X-ray beam should be greatly decreased such that the pulse pile-up is negligible. An alternative is to measure the spectrum with a small-area detector. In this case the impinging photons should decrease by a factor determined by the detector area and the pulse pile-up is prevented or reduced. A 20 keV X-ray beam was scattered from an Al plate, and the energy spectra were measured with both the large-area detector ($1 \times 1 \times 0.15$ cm^3) and the linear array (Fig. 4). For this experiment, the synchrotron beam size was collimated to 2×2 mm and the same electronics were used. Both detectors show photopeaks at 20 keV, third harmonic at 60 keV and other energies where it is believed to be due to scattering by other materials inside the hutch. For the large-area detector, the spectrum is very broad with a large background. As the photon energy increases, the photon count slowly decreases and extends to higher energy. However, for the linear array, the energy resolution is greatly improved, so that significantly narrower photopeaks are observed. Also observed was a decrease in detection efficiency for very high energies.

5. Conclusions

We have demonstrated the feasibility of fabricating a linear-array detector with high efficiency and high-counting-rate capabilities. CZT is shown to be the material of choice for detectors when working with high X-ray energies (above 40 keV). Larger arrays can be fabricated using the same methodology, a project we are presently addressing. We strongly believe that this type of array detector will find a wide range of applications in the synchrotron radiation community as well as in medical applications. The combination of energy discrimination, high efficiency and position sensitivity is highly desired by researchers in these communities.

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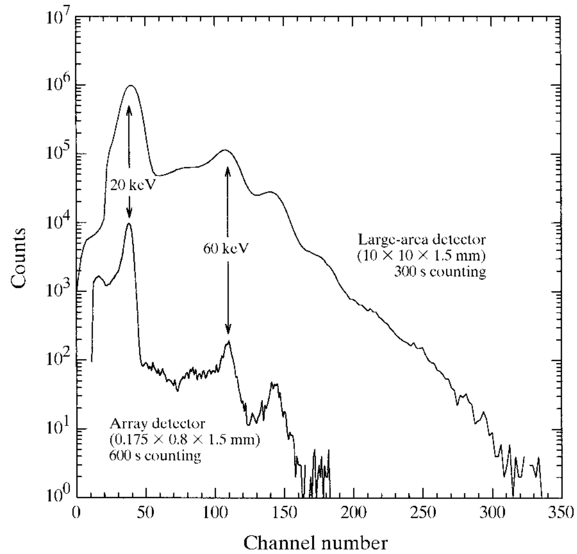

Figure 4
Energy spectra of both large-area and linear-array detectors are compared. For this comparison the same electronics were employed. Note the improved energy resolution for the linear-array detector. Monochromator X-ray energy = 20 keV. Integration time = 600 s.

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