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CZT pixel detector modules for medical imaging and nuclear spectrometry

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Abstract

Detector modules for nuclear imaging have been assembled from $Cd_{1-x}Zn_xTe$(CZT) pixel-arrays and associated electronics. CZT crystals are grown by a specific crystal growth technique, which ensures a ready supply of large wafers, free of macroscopic defects. The pixel-arrays fabricated from these wafers exhibit good spectroscopic performance, manifested by the attenuation of the low-energy tailing of the spectrum, which is maintained even for contacts that strongly decrease the dark current. Such a performance might be explained by a dynamically-Ohmic behaviour of the contacts to thus grown bulk material. Coupled to the pixel arrays are ASICs, which perform analogue amplification and pulse shaping, followed by digital conversion of the gamma absorption event into energy and location information. These detector modules are thus optimized for nuclear imaging applications, of which Nuclear Medicine is the leading one. However, they may be operated in a mode, where the spectra measured by all the pixels in parallel is combined. Then those imaging modules become an effective nuclear spectrometer with a volume as large as one wishes, still maintaining the high spectroscopic qualities of a single pixel. Therefore, application such as in Nuclear Security and Nuclear Industry may profit from the strong motivation to meet the demands of the medical market.

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1. Introduction

$Cd_{1-x}Zn_xTe$ (Cadmium Zinc Telluride – or – CZT) has been proven to be the primary semiconductor for fabrication of room-temperature nuclear detectors. The practical applications of such detectors have recently been described in detail [(1)], where medicine seems to be the most immediate and market-driven application. However, there are many other fields, which might profit from the strong incentive to satisfy the needs of the medical market. Such are the fields of nuclear security, radioactive waste management (including verification), and astrophysics. For imaging applications the optimal configuration of those detectors is as pixel-arrays, where the pixel size is in the mm range, and the wafer thickness, when optimized for 140 KeV, is about 5mm. The emphasis of our present effort is to create ready industrial-scale availability of large area pixel-detectors. Only thus such detectors will be available in a cost that will be competitive with the present scintillator-photomultiplier technology.

2. Crystal growth technology

IMARAD is using a specific version of modified-horizontal-Bridgman technique to grow the crystals, of which the IMARAD detectors are fabricated [(2)]. These CZT crystals (with x ~ 8%) demonstrate good uniformity and are free of macroscopic defects. Thus this technique proves to be beneficial in comparison to both the Traveling-Heater-Method (THM) crystal growth technique [(3)] and the High Pressure Bridgman (HPB) technique[(4)]. The THM technique has been very slow and limited in the size of the crystals. The HPB technique is limited in its capability to produce large area monolithic pixel detectors, of spectroscopic quality, due to high density of macroscopic defects (cracks, voids, pipes, inclusions), and limited uniformity due to excessive polycrystallinity.

The spectroscopic performance of detectors fabricated from CZT crystals, grown by the IMARAD technique, is inherently different from detectors which are fabricated from material grown by other techniques. This difference stems from a combination of bulk and contact characteristics that are manifested by a unique photoluminescence behaviour, and high uniformity of the internal electric field [(2)]. Moreover, such pixel detectors exhibit high energy-resolution, with a strongly diminished low-energy-tail (and thus, high “peak-to-valley” ratios), which is achieved without any electronic pulse processing or geometrical compensation techniques. Figs (1) and (2) are the ^{57}Co and ^{137}Cs spectra, respectively, of such typical standard detectors. Such a spectral behaviour could not be explained merely by the small-pixel effect principle, however, it might be explained by a dynamically - Ohmic behaviour of the contacts to these detectors.

3. Contact characteristics and detector performance

The present contacts on the standard IMARAD detectors are based on evaporated indium. For such IMARAD CZT detectors, under an x-ray flux, we have observed that the induced photocurrent has been multiplied by a photoconductive gain of more than two orders of magnitude. Such a gain can be explained only by the ohmicity of the cathode (see Rose [(6)] for detailed description and explanation). In this case, the x-ray photons are absorbed, and the neutrality of the semiconductor bulk is violated, since the high-mobility electrons move fast towards the anodes and leave the positively charged hole-spheres behind, either slow-moving or trapped. The steady-state electrons injection from the cathode is the result, and the reason for the photocurrent gain.

In the case of a single-event, gamma-photon-absorption, this ohmicity of the cathode contact might be used to explain the unique behaviour of the IMARAD gamma detector. Ohmicity, in this case, is in the sense of Rose's definition: "An ohmic contact is one that supplies a reservoir of carriers freely available to enter the semiconductor as needed" [(6)]. Then, the single hole-sphere, left alone by the fast moving electrons, is a strong transient singular perturbation to the neutrality of the bulk, and the electrons supplied by the cathode will be moving towards this hole sphere, to recombine with the holes. Thus, their trajectories will compensate for the trajectories that the holes are not able to complete. In that way these readily available electrons eliminate the charge-loss which is usually associated with the holes [(7)].

This model describes the behaviour during the short time it takes the electrons to transverse the distance between the cathode and the anode (usually, between 0.2-0.5 μs). On this time scale the cathode might behave in an Ohmic fashion, even though the current-voltage (I-V) dependence of the detector is not necessarily linear [(8)]. This is not surprising since the I-V dependence characterizes a steady state situation, whereas the gamma-absorption event causes a major transient disturbance to this equilibrium state. That is demonstrated by the fact that the current induced by this event, during this short time, is usually larger than the steady-state dark current. As an example, Fig.(3) shows a very non-linear I-V behaviour of an IMARAD CZT detector with gold contacts (though it is definitely not the usual blocked-contact behaviour – the "hump" at low voltages probably indicates some kind of a tunneling effect). Still, the detection characteristics of this detector, as shown in Fig.(4), demonstrate the same performance as the detectors of Figs. (1) and (2) with the linear I-V behaviour, i.e., the spectrum has a well attenuated low-energy tail. Moreover, this spectrum is characterized by an energy resolution, which is better than a standard indium contact.

The dynamically-ohmic model is thus a possible explanation for the performance of the IMARAD gamma detector, and we are not aware of any other model that might describe its behaviour. Its performance cannot be explained by the "small pixel" effect alone [(8)], nor can it be explained by the model proposed by Shor et al. [(9)], which is an extension of the small-pixel principle [(5)]. Shor et al. predict that the Full-Width at Half-Maximum ((FWHM) of the spectrum, when measured as function of the bias voltage, should exhibit a local minimum at an intermediate bias value. We have carried out detailed measurements on the IMARAD detectors, and have observed that the FWHM of the spectra is rather a monotonically decreasing function of the bias voltage with no local minimum (as long as the increased dark current is not contributing to the broadening of the spectrum) [(8)].

The FWHM of the spectra of these detectors is still larger than expected if the usual noise contributions are taken into account [(10)]. We believe that this broadening is caused by the notorious “contact noise” contribution and it still can be improved. Preliminary experiments with a different surface treatment, before applying indium contacts to the same CZT material, do indeed show a remarkable improvement, as demonstrated by Fig. (5). However, these results are preliminary and would need much more developmental work to replace the present standard contact technology.

4. Electronics for pixel detectors

To obtain nuclear imaging capability it is essential to couple to the pixel detector an array of associated electronics, which individually perform for each pixel the usual chain of amplification and pulse processing. This multitude of electronic circuits is condensed into Application-Specific-Integrated-Circuits (ASICs). In the specific case of the IMARAD detector, with its 256 pixels, there are two ASICs [(11)] mounted on a board which serves to interconnect between the ASICs and the detector. Following analogue processing, there is digital conversion into energy (Pulse-Height-Analysis) and location information, for each pixel on the 40 mm x 40 mm module. This structure reflects the development, two decades ago, of the Z-structure for the infrared technology [(12)], keeping the whole amplifying and processing circuits limited to the vertical dimension. Thus, it allows to assemble a mosaic of those modules for imaging as large an area as needed.

5. Nuclear spectrometers

The original goal of these imaging modules (pixel detector coupled to ASICs) is the market of nuclear medicine. The performance of such modules has been tested by taking images, both on phantoms and clinically, demonstrating their superior energy and spatial resolutions. However, such modules can also be utilized as large-volume nuclear spectrometers. In this case, all the individual outputs of all the pixels are combined into one, after going through a gain correction to overcome the gain variation amongst the ASIC channels.

Fig. (6) demonstrates such a performance for a 20 mm x 20 mm x 5 mm (thick) pixel detector. The spectrum shown is of a combination of ^{241}Am, ^{133}Ba and ^{57}Co, and it is obvious that the combined spectrum is of the same spectroscopic quality as every one of the individual spectra. Thus, the volume of such a nuclear spectrometer can be made as large as one wishes, by assembling a multitude of modules (everyone of the IMARAD modules has an effective volume of 8000 mm^3). In such a way, it is possible to overcome the limit imposed by the use of single detectors, which, even when being used in a hemispheric configuration, can be made not much larger than 1000 mm^3 [(13)]This is most important for applications such as: in-the-field verification measurement of nuclear material. Even more so, this unlimited size of the detector, which ensures high overall sensitivity, is crucial for nuclear security monitoring devices.

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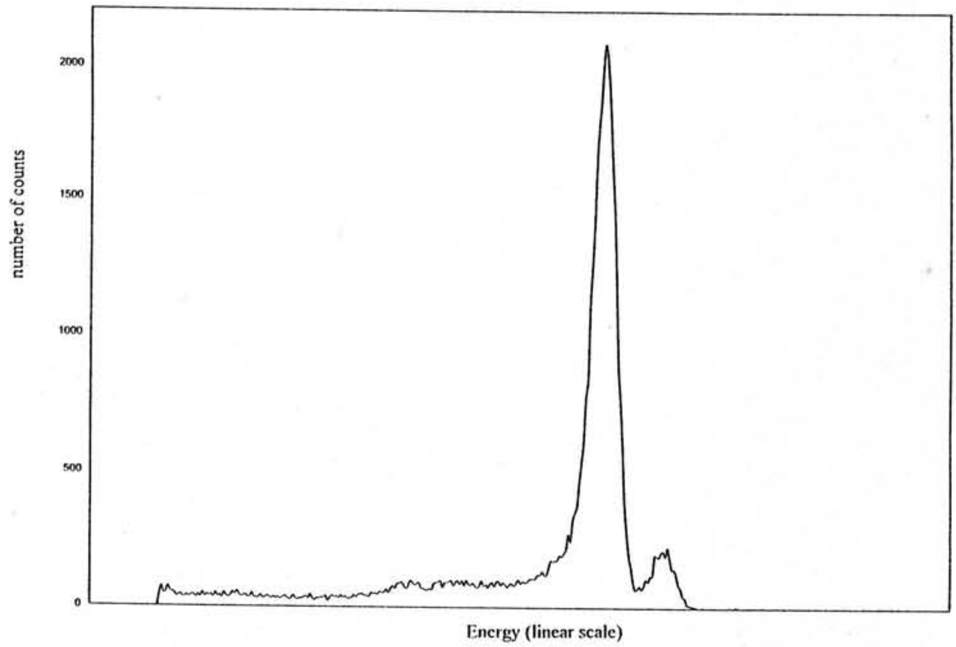


Fig. 1 ^{57}Co spectrum (122 keV and 136 keV) of one pixel (2.4 mm x 2.4 mm pitch) in a pixel-array with indium contacts (wafer thickness is 5 mm). The bias voltage is -600V, and the source is partially collimated (FWHM ~ 5.3%).

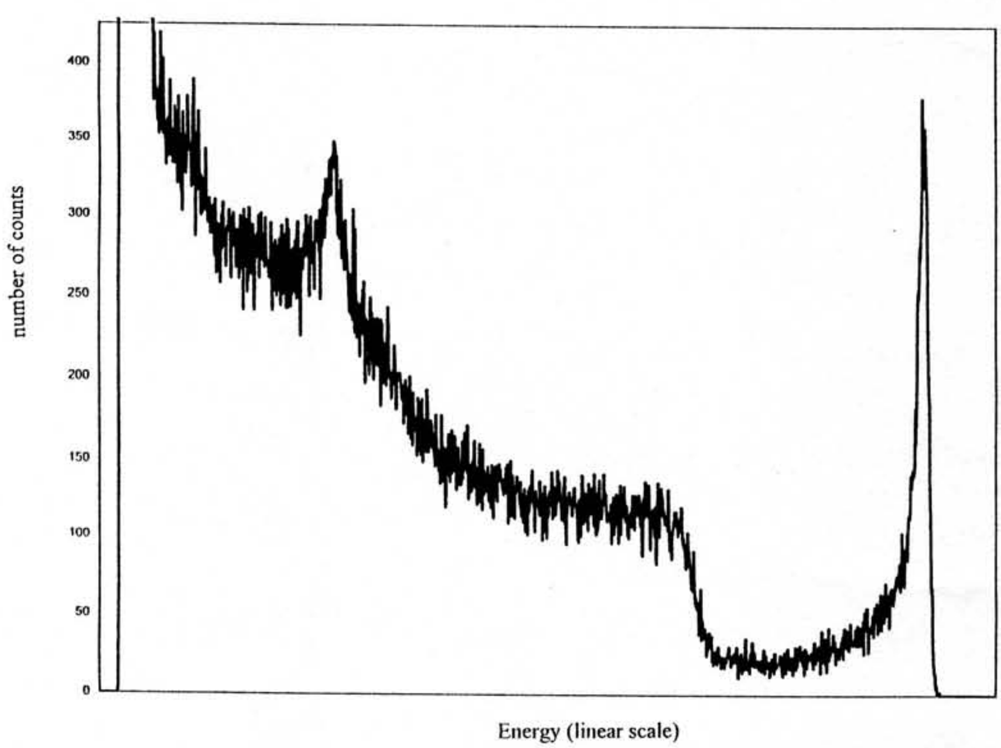


Fig. 2 ^{137}Cs spectrum (662 keV) of the same pixel as in Fig. 1. The bias voltage is -700 V and the source is non-collimated (FWHM ~ 1.7%).

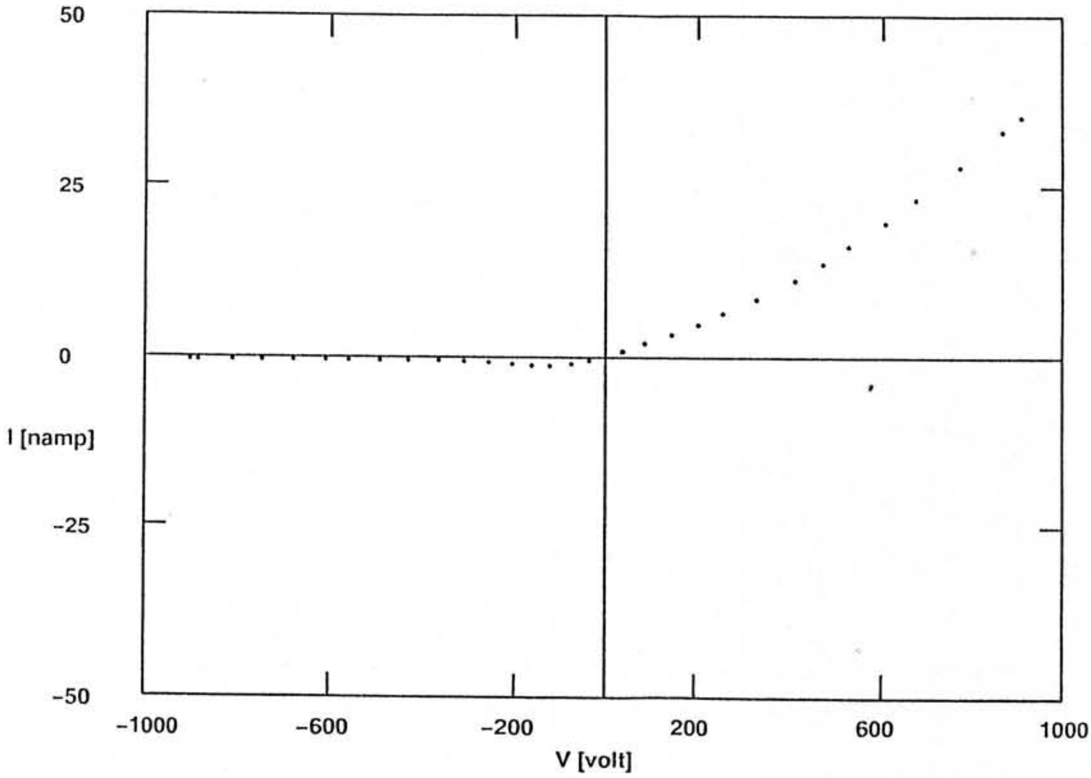


Fig. 3 I-V curve of a pixel in an array of a detector with gold contacts. The pixel size is 2.4 mm x 2.4 mm and the wafer thickness is 5 mm.

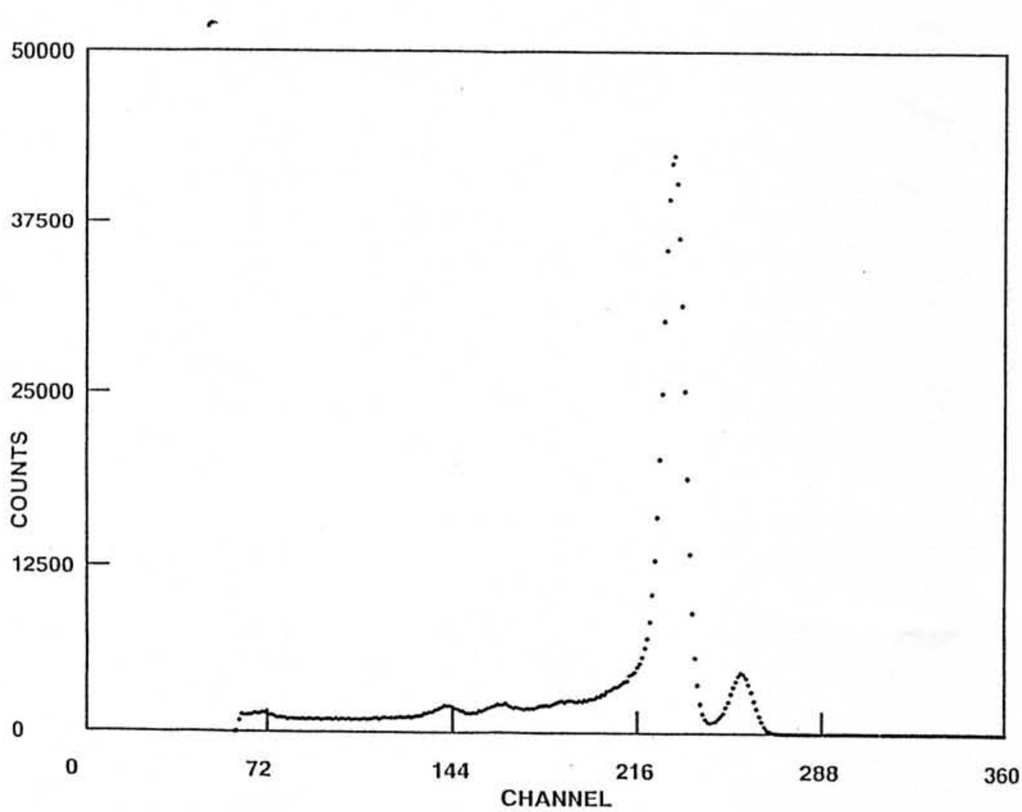


Fig. 4 ^{57}Co spectrum of the detector described in Fig. 3. The bias voltage is -750V on the cathode; shaping time is 0.5 μs; the source is partially collimated; (FWHM ~ 4.5%)

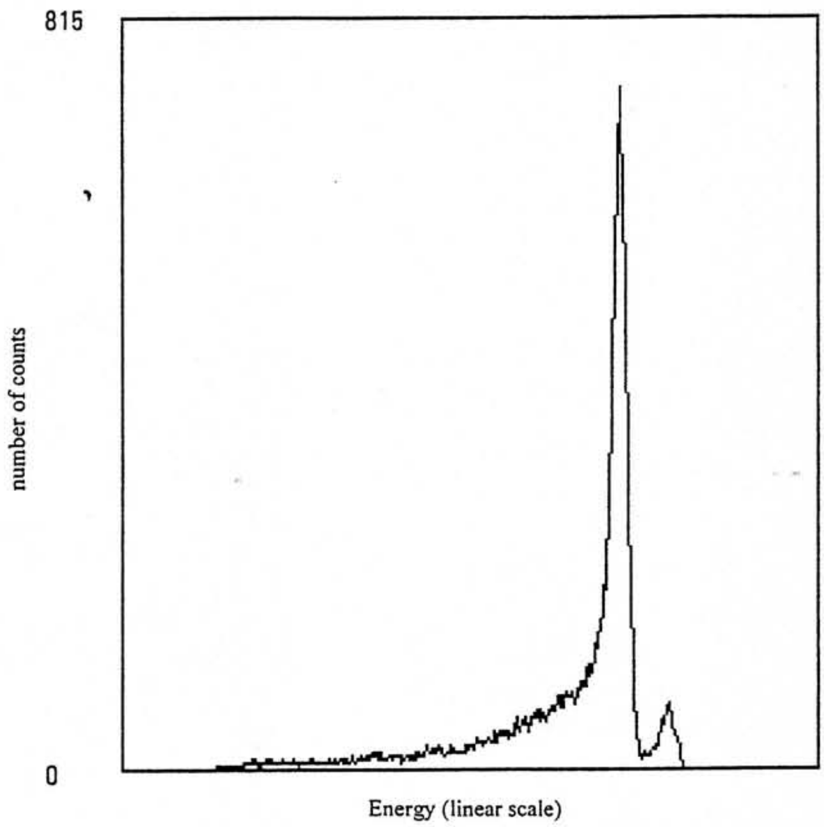


Fig. 5 ^{57}Co spectrum of one pixel (2.4 mm x 2.4 mm) in a pixel array with modified indium contacts (wafer thickness is 5 mm). The bias voltage is -600 V, and the source is non-collimated; (FWHM ~3.5%).

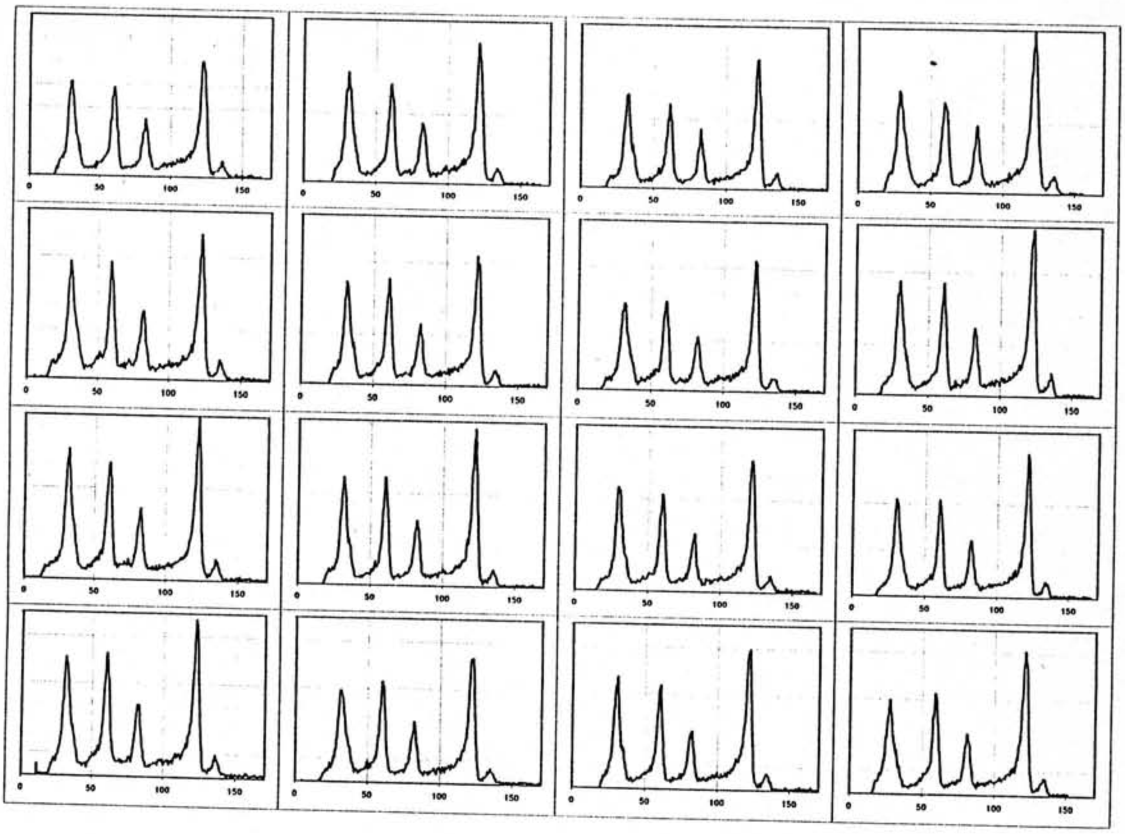
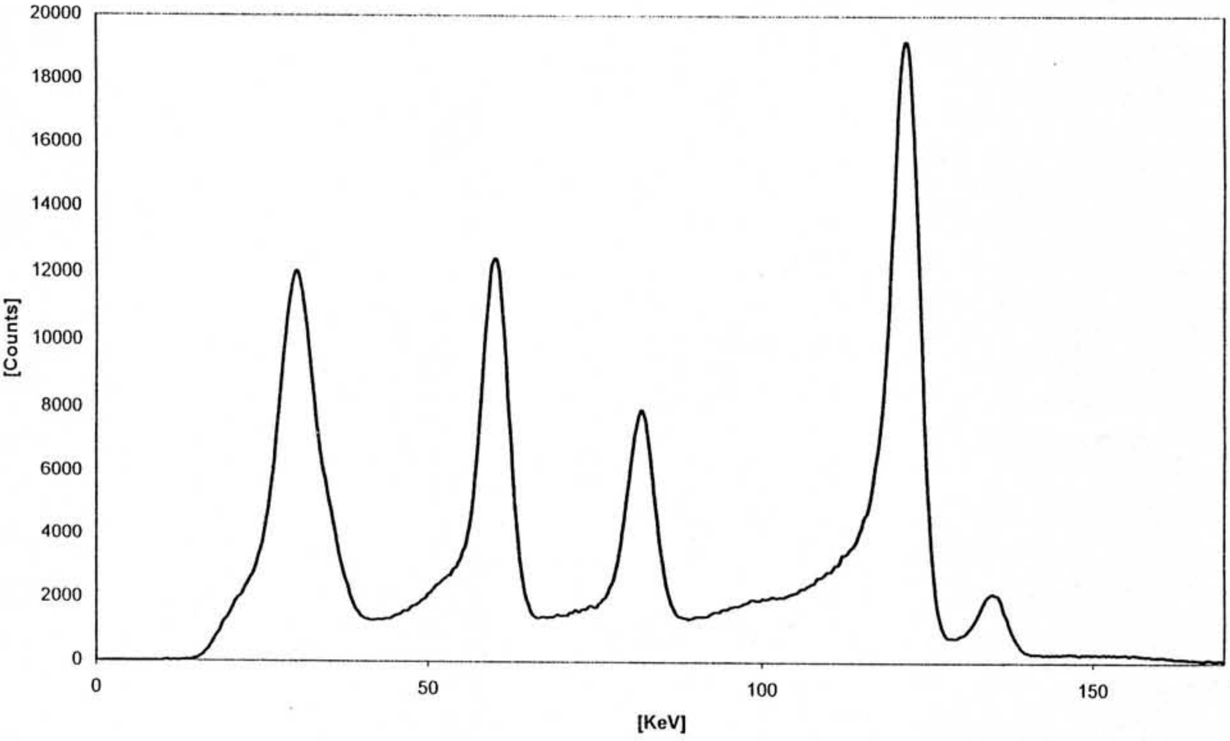


Fig. 6 (a) Spectra of 16 pixels (a quarter of a 8 x 8 pixel array). Each pixel is 2.4 mm x 2.4 mm on a 5 mm thick array. The source is made of ^{57}Co (122 keV and 136 keV), ^{133}Ba (30 keV and 80 keV) and ^{241}Am (59.5 keV) and is not collimated. The bias voltage is -600 V.



6 (b) Combined Spectra of all 64 pixels of the pixel-array described in (a).