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Multi-element germanium detectors with integrated readouts

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Abstract

We have developed a series of monolithic multi-element germanium detectors coupled with custom developed CMOS application specific integrated circuit (ASIC) for readout. Several strip detectors with element counts ranging from 64 to 384 were developed and are currently used at the National Synchrotron Light Source II in Brookhaven National Laboratory and the Advanced Photon Source in Argonne National Laboratory. The detectors are photon counting and are used at high-energy diffraction and energy dispersive diffraction beamlines.

Introduction

Germanium has been the material of choice in detectors of high-energy x-rays and gamma rays for many years, largely because it is relatively easy to obtain high quality material in large quantities. Consequently, efficient detectors with reasonable depletion voltages with excellent charge collection efficiency can be built. There are, however, several challenges in developing germanium wafer process, due to the low stability of its native oxide. Unlike silicon oxide, the oxides of germanium are water soluble and thermally unstable rendering pixilation difficult. A novel technique for fabricating monolithic Ge-detectors using trenching was developed by D. Protic and T. Krings [1, 2]. Detectors made using this technique show low leakage (~1.3 pA per strip) and high inter-segment isolation (~1000GOhm). We have built segmented Ge detectors using trench isolation and coupled them with the low-noise integrated circuits developed at Brookhaven National Laboratory. We have listed some of the detector system built and the application of such systems below.

64-Strip Detector

The first detector system was a 64-strip sensor with a very simple read-out electronics. The sensors had a pitch of 0.5 mm with about 30 μm trenches separating them. The sensor were mounted to a liquid nitrogen cryostat and the operating tempearure was close to 100 K. The readout system was based on the HERMES application specific integrated circuit (ASIC) [3]. The ASIC was a designed for low-noise photon

counting application. The analog signals could be be read by an external multi-channel analyzer (MCA) one channel at a time [4]. Figure 1 shows the detector system and the spectrum of Am^{241} as recorded by one of the 64 detector strips. The energy resolution was measured to be at 450 eV at 60 KeV.

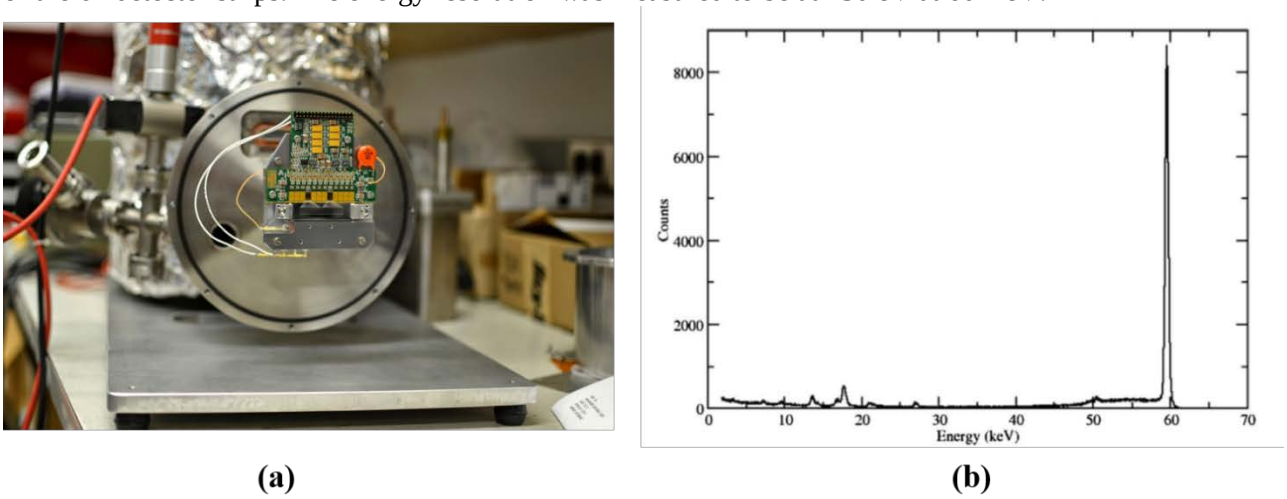


Figure 1: (a) Photograph of the finished detector system mounted on liquid N_2 dewar. (b) Spectrum of the Am^{241}.

The prototype detector was used to highlight the advantages of energy dispersive diffraction (EDX). Unlike regular x-ray diffraction which uses a monochromatic beam, EDX utilizes a white beam typically containing energies between 20 keV and 150 keV [5]. The collimated beam is directed to the sample which selects a laterally constrained volume of sample for diffraction. Each point of the sample along the incident beam caused diffraction and since a white beam is used, the Bragg planes in the sample select appropriate wavelengths and scatter them through a beam slit as shown in figure 2a. An energy resolving strip detector would then map the whole gauge volume of the sample. Figure 2b shows the diffraction data from three different compounds performed as a proof of principle.

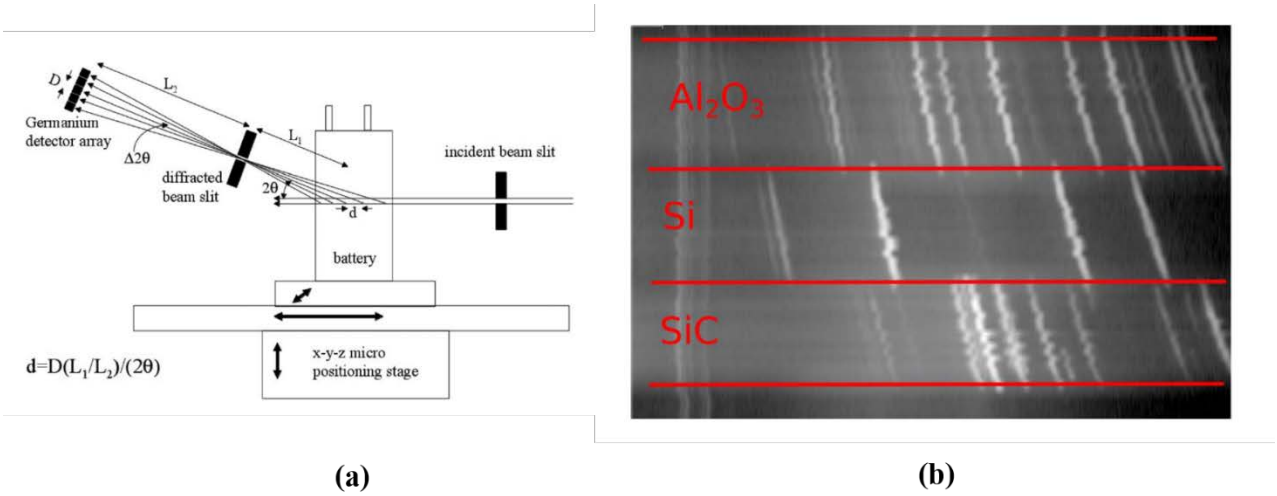


Figure 2: (a) Energy dispersive diffraction set up with a position sensitive detector. (b) Diffraction data from three different test samples.

Following the success of the prototype detector system we developed a program to fully exploit the capabilities of the sensor. The initial readout scheme was simple and had to be multiplexed to read one

channel at a time. We developed a new system based on the new MARS (multi-element amplifier and readout system) ASIC for subsequent Ge detector development. The ASIC has 32 channels each consisting of charge sensitive preamplifiers (with four programmable gains which would make the range from 12.5 keV to 75 keV) and a shaping amplifier (with shaping times from 0.25 μs to 2 μs). Furthermore, each channel has a peak detector and time-to-analog converter. The timing system of the ASIC could be used in two different ways: to measure the time over threshold or the time of arrival of photons [6]. For the Ge sensor, the time of arrival could be used for detecting charge-shared events. Since all the data from one ASIC is multiplexed through one differential analog port, photon events are retrieved sequentially by the data acquisition (DAQ) module. The analog timing system records the interval between the photon peak-detect signal and the actual readout of the value. Simultaneously with reading out the peak value, the DAQ system records the value of a system clock. Together, the system clock and analog time values can be used to reconstruct the real time of arrival. The data stream can then be examined for time-coincident events in neighboring strips, which is a signature of a charge-shared event.

To acquire data from this front end, we have developed the Ge Readout Module (GeRM). Briefly, the interface module takes the signal from 12 ASICs, digitizes them and transfers via high speed Ethernet to a computer storage system. The module has a powerful field programmable gate array (FPGA) with an embedded dual core ARM processor plus components necessary for memory, storage and networking etc [7]. The primary method for communicating from the outside world with the detector is via ethernet using the Zero-MQ protocol. A server program is provided which provides two primary functions. First it handles read/write requests to/from the FPGA registers to control the various aspects of the electronics and readout (Request/Reply). Second, it transmits out all x-ray data from the detector (by reading registers on the FPGA) and sends them out using ZeroMQ's Publish/Subscribe method.

384-strip detector

The 384-strip detector was built for monochromatic diffraction at the x-ray powder diffraction beamline (XPD) at NSLS II. The sensor is a 384 strip, each 125 μm x 8mm. The readout board has 12 MARS ASICs as shown in figure 3. The detector was cryogenically cooled by a commercial air cooled closed cycle refrigerator system. After initial set up, the detector system vacuum could be completely maintained by a small ion pump. Figure 4 shows the detector system mounted to the large 2-circle diffractometer at the XPD beamline. Figure 5 shows the diffraction pattern of a Barium Titanate sample collected at 53 keV photon energy over a 2θ of 30^{o}. The data is shown in logarithmic scale to show the weak high angle data. The energy resolving capability of this detector is particularly useful to suppress strong fluorescence or Compton emission which tends to degrade the data.

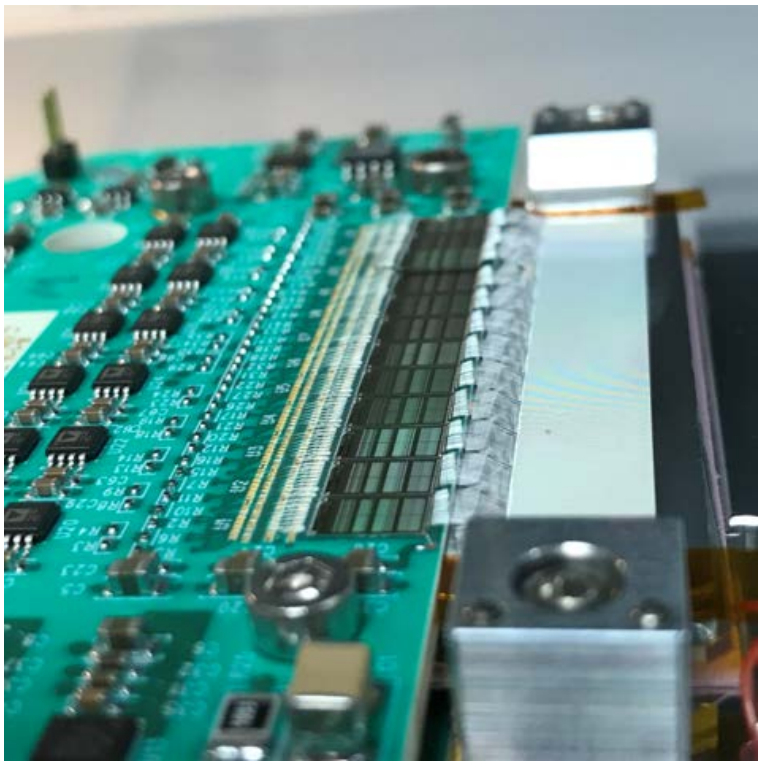


Figure 3: The 384-strip detector wire-bonded to 12 MARS ASIC

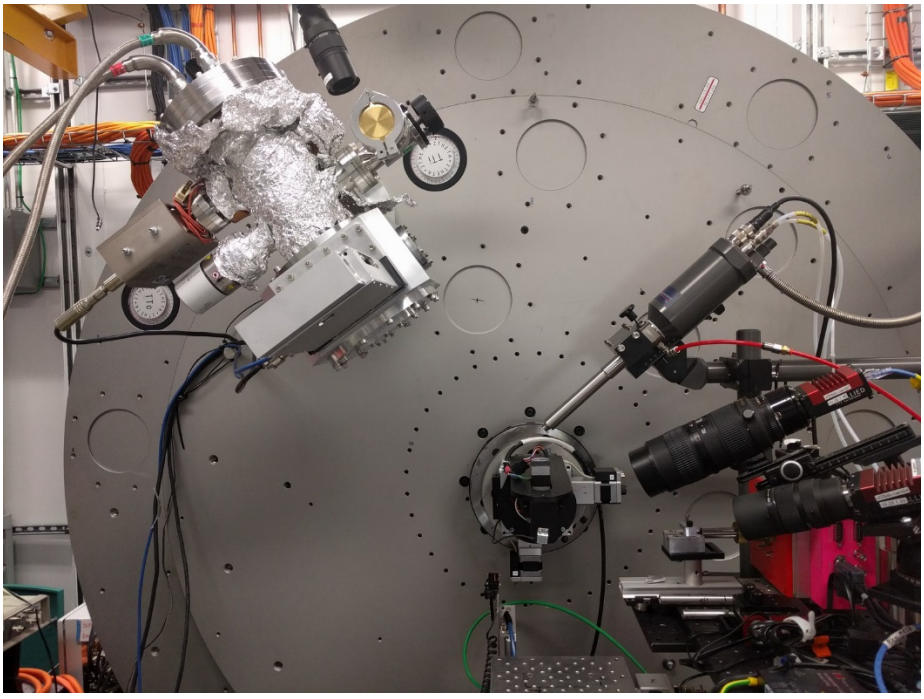


Figure 4: 384-germaium strip detector system in the XPD beamline

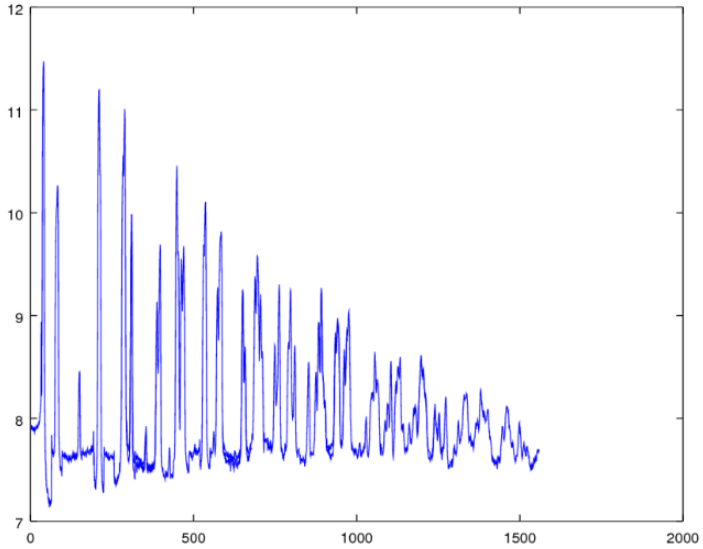


Figure 5: Powder diffraction pattern of $BaTiO_3$ collected at 53 keV

The small pitch of the sensor compared to the sensor thickness leads to a significant number of charge-shared events. The MARS time stamping capabilities enables us to identify simultaneous events in nearest neighbor strips. Such events can be recombined to obtain the full charge generated in a given pixel. Although the present analysis was done offline, it could be implemented in real time in the FPGA. Figure 6a shows the coincidence measurement performed between two adjacent strips. The output of the adjacent strips is plotted along the *x* and the *y* axis. The sum of the shared events forms a straight line between the peak energies as seen in figure 6a. If these partial charges are added together, they reconstruct the full energy of the incident photon. Figure 6b and 6c shows the spectra before and after reconstruction. The charge sharing phenomenon can in principle also be used to give spatial resolution better than the pixel size [8]. Reading out the data photon-by-photon provides a big advantage for time resolved measurements. Since we can time stamp the incoming photons with 40 ns timing resolution, the data can be re-binned offline in whatever time slices the user wants, using the same dataset.

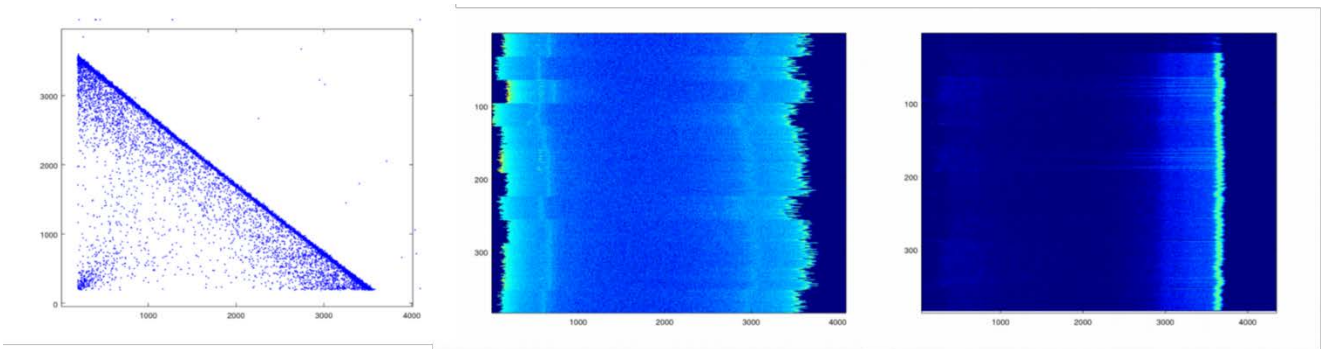


Figure 6. (a) A parametric plot of the energy detected in one strip vs the energy detected simultaneously in its neighboring strip. (b) A plot of energy (x-axis) vs strip number (y-axis). The color represents the log of the intensity. (c) the same data after energy normalization and charge-sharing reconstitution

64 and 192-strip detector at the APS

A 64-strip germanium detector with the MARS readout was built for the beamline 6BM at the Advanced Photon Source (APS) to explore its use for the EDX technique. One of the fist experiment with the detector was tomography with energy dispersive diffraction [8]. The energy sensitivity is key factor for this experiment. The details of the experiment and the sample used can be found elsewhere [8]. Briefly, EDX technique enables us to probe a gauge volume by projecting the scattered beam through a slits to a linear detector. If we are to raster the beam in the transverse direction we would be able to obtain a tomographic slice of the sample. Sample rotation or image reconstruction which are critical for conventional tomography experiments are not require for this technique. This experiment has tremendous potential as a single scan can map structure and possibly strain in two dimensions. For the experiment a cross section energy dispersive diffraction (EDD) tomography slices of an elliptical hydroxyapatite (hAp) phantom and of the carbonated apatite (cAp) mineral distribution in an archeological human second metacarpal bone (Mc2) shown in figure 7 and 8.

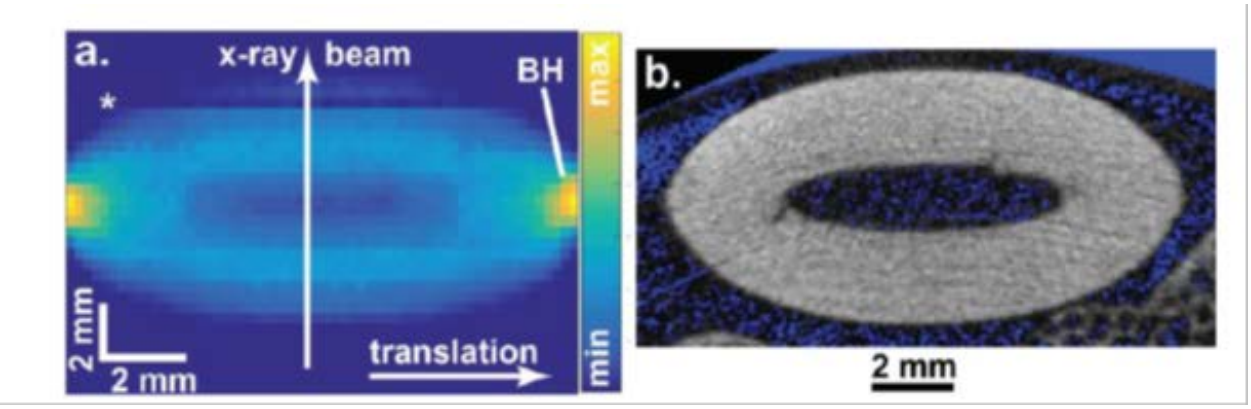


Figure 7: (a) Cross section of synthetic hAp phantom from EDD reconstruction with 2 1.1+ diffraction peak. (b) MicroCT slice. Figure obtained from Ref[8].

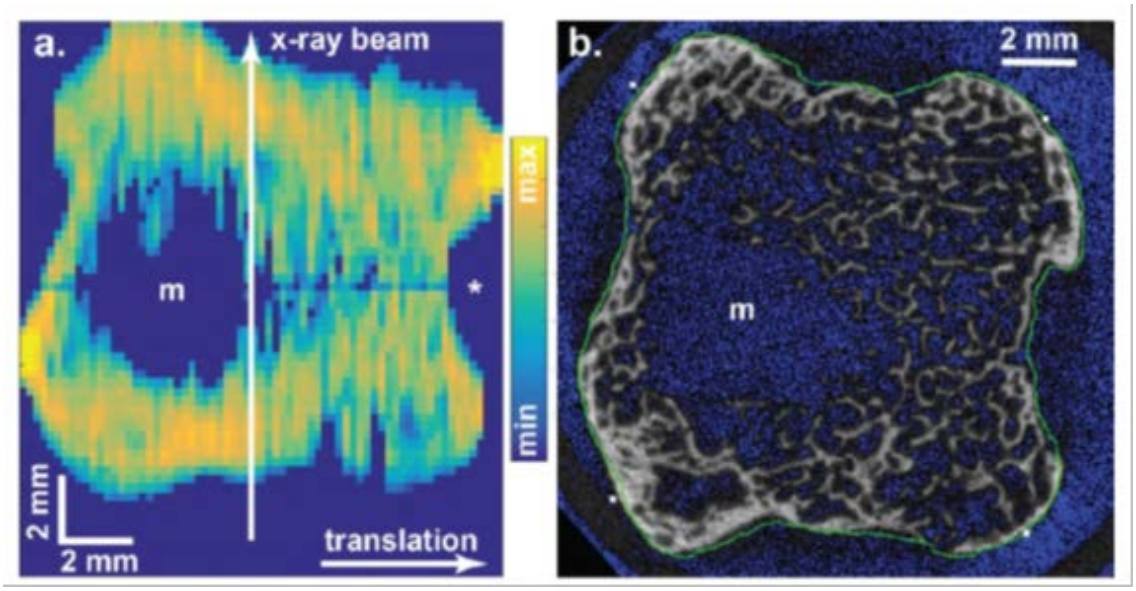


Figure 8: (a) Cross section of Mc2 ANC_241 from EDD reconstruction with 2 1. 1+ diffraction peak. (b) MicroCT slice. Figure obtained from Ref [8].

It must be mentioned that the MARS chip was designed for use with silicon drift detectors in a future enhanced MAIA detector system. The gain was optimized for relatively low photon energies and not for the large signals expected from high energy x-rays (greater than 75 KeV). Ge detectors on the other hand are suited for photon energies up to 200 keV. We have now designed a second version of MARS to address this issue. This chip is referred to as HE-MARS (high energy-MARS) and is identical to MARS except with a reduction in the gain settings. This makes the detector system optimized for energies ranging from 25 keV to 200 keV. The first detector system with HE-MARS was the 192-strip detector designed to be used at APS. The 192-strip detector has a pitch of 0.25mm which is a compromise between minimizing charge sharing and good spatial resolution.



Figure 9: Photograph of the completed 192-strip EDX detector. The gold pad are vacant ASIC positions, which would be filled for the 384-strip detector. The wirebonds now need to fan out to reach the strips.

The detector system was tested with a ^{57}Co source which has two prominent high energy gamma lines at 122 keV and 136 keV. The two lines were used for energy calibrations. Figure 10 shows the detector response for all 192 strips. A gaussian fit to the 122 keV line gave an energy resolution of about 710 eV.

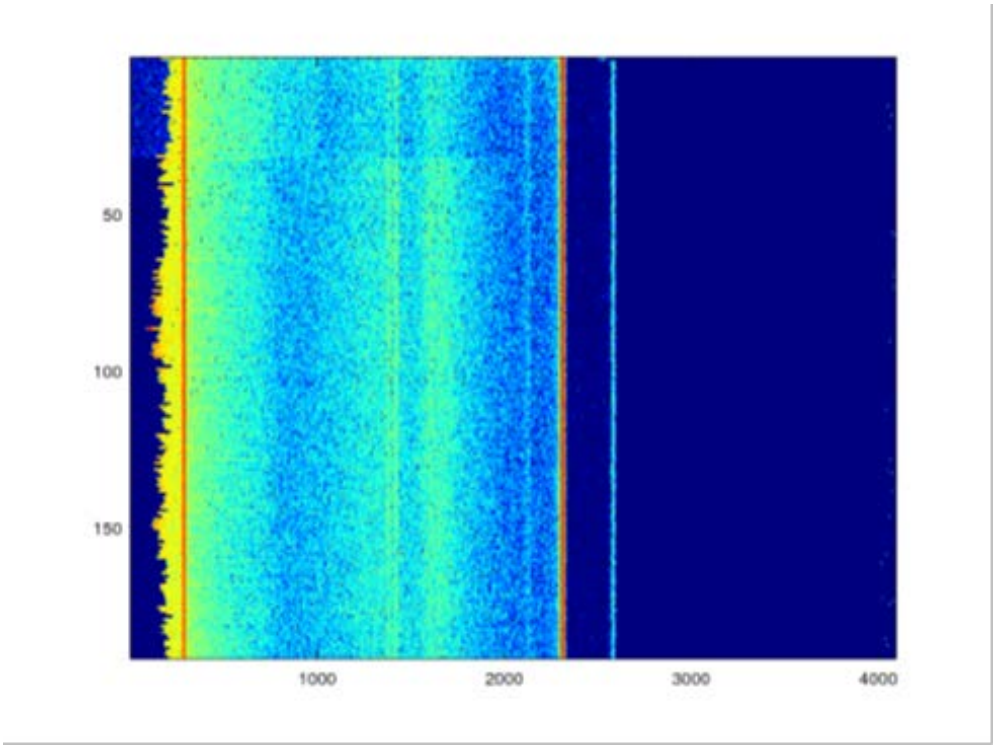


Figure 10: Detector response from ^{57}Co. The channel number is along the vertical axis and the energy on the horizontal.

There have been other efforts to integrate trenched Ge detectors with different readout schemes for synchrotron applications. Most notable is the multi-element monolithic detector developed at the Diamond Light Source, based on the CUBE preamplifier developed by the XGLab [9]. This 16 channel detector system was a demonstrator system for XAFS application.

Conclusion

In conclusion, we have developed a mature technology to fabricate multi-element germanium detectors for a variety of applications in synchrotron radiation research. The detector showed excellent energy resolution. The spectroscopic capabilities of high energy detectors will open possibilities for new synchrotron experiments, some of which were discussed in this paper.

Acknowledgements

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