

Multichannel CdZnTe Gamma Ray Spectrometer

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JUL 03 2000
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Abstract

A 3 cm³ multichannel gamma spectrometer for DOE applications is under development by Digirad Corporation. The device is based on a position sensitive detector packaged in a compact multi-chip module (MCM) with integrated readout circuitry. The modular, multichannel design will enable identification and quantitative analysis of radionuclides in extended sources, or sources containing low levels of activity. The MCM approach has the advantages that the modules are designed for imaging applications, and the sensitivity can be arbitrarily increased by increasing the number of pixels, i.e. adding modules to the instrument. For a high sensitivity probe, the outputs for each pixel can be corrected for gain and offset variations, and summed digitally. Single pixel results obtained with discrete low noise readout indicate energy resolution of 3 keV can be approached with currently available CdZnTe. The energy resolution demonstrated to date with MCMs for 511 keV gamma rays is 10 keV.

Introduction

Nondestructive analysis of containerized mixed low-level waste (MLLW) and mixed transuranic (MTRU) waste is an important need for DOE. MLLW is defined as waste that contains both hazardous chemical constituents, and radioactive constituents with concentrations below 100 nCi / gram. The characteristics of all mixed waste streams must be adequately documented to satisfy regulatory requirements, and to verify they meet the waste acceptance criteria for specific treatment and disposal facilities. Traditional approaches to characterizing waste streams can be loosely divided into (1) process knowledge, (2) waste sampling and subsequent measurement in analytical laboratories, and (3) non-invasive assay.

Knowledge of the materials and processes that generated a mixed waste can be sufficient for characterization if appropriate records are available, but DOE has insufficient process knowledge to adequately judge the contents of waste containers for 40% of the 130,000 m³ of LLMW currently in storage[1]. Traditional waste sampling and laboratory analysis can also be used to effectively characterize waste, but the value of obtaining additional analytical data must be carefully evaluated versus exposing workers to measurable radiological dose and chemical hazards during sample collection and subsequent handling. High costs are incurred with mixed waste analysis, because of the need to provide protection and controls that keep radiological exposures as low as reasonable achievable (ALARA). Therefore a critical need exists for a field compatible, high sensitivity detector capable of *in-situ* analysis of radioisotopes in containerized MMLW and MTRU.

Approach

Field compatibility implies low power, portable and non-cryogenic. Energy resolution is also required, to identify specific radionuclides and infer their concentrations. These requirements rule out available detectors such as HPGe, which require cooling, and scintillator-based systems, which have poor energy resolution. One approach is to develop new detectors based on a wide bandgap semiconductor material, such as CdZnTe. The sensitive areas and volumes of CdZnTe and other room-temperature semiconductors are currently limited by material properties^{2,3,4,5,6}. The reduced trapping-lengths compared to cooled silicon and germanium devices limit the useful thickness of CZT detectors, while leakage current and capacitance determine the energy resolution of a single-channel large area device. These factors can be mitigated by electron sensitive, multi-anode detectors read out with multiple electronic channels^{7,8}.

Results from detectors based on the semiconductor CdZnTe (CZT) are reported in this work. CZT detectors, which operate at room-temperature and exhibit improved energy resolution compared to scintillators, are under development by Digirad primarily for medical applications^{9,10,11,12}. The approach described here uses 64 element CZT arrays with, with element size 3mm x 3mm x 5mm, read out with an

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application specific integrated circuit (ASIC) with separate charge amplification per channel. The ASIC used in this study was designed for imaging rather than spectroscopy, and non-optimal results were obtained. Likewise, the CZT arrays were not selected for spectroscopic resolution or uniformity, and should be perceived as neither representative nor exceptional examples of Digirad's detectors. Rather, the aim of this work is to demonstrate the usefulness of the approach using readily available materials and apparatus.

Spectroscopy with electron sensitive detectors

The detectors employed in Digirad's imaging array modules are of a patented electron-sensitive design which has been described elsewhere^{13,14,8}. Electron sensing detectors reduce the dependence of pulse height on the position of photoelectric absorption in the semiconductor (charge-deficit tailing), because electron trapping lengths are usually much greater than hole trapping lengths in current commercially available material. For example, typical electron $\mu\tau$ products are on the order of $10^{-3} \text{ cm}^2 \text{ v}^{-1}$, which correspond to trapping lengths on the order of 1 cm under practical applied fields. Hole $\mu\tau$ products are typically on the order of $10^{-5} \text{ cm}^2 \text{ V}^{-1}$ or less, with correspondingly reduced trapping lengths. In simple slab geometry detectors of practical dimensions trapped holes result in a reduction in signal, even though electron collection is nearly complete. Therefore, electron sensitive detector designs enable both increased drift length and improved energy resolution.

A spectrum recently obtained with a discrete Digirad SpectrumPlus™ 3mm x 3mm x 5mm production detector element is shown in Figure 1. The resolution of the 511 keV photopeak gamma rays detected from ²²Na is >3keV. This result was obtained without cooling any part of the system, using an Oxford/Tenelec TC170 preamplifier, Ortec 672 amplifier/shaper, Oxford PCA3 MCA and Oxford Quantum MCA software. The performance achievable with CZT arrays can approach that of a single discrete element. In principle, the data from multiple calibrated channels with this performance can be digitized, adjusted for response variations and summed, to obtain similar energy resolution with much higher sensitivity.

Spectroscopy with arrays

To date, increased sensitivity has been demonstrated only for CdZnTe arrays with ASIC readouts designed for imaging rather than spectroscopy. Calibration requires accurate determination of the gain for each detector/readout channel. This is easily accomplished by exposing arrays to a flood source, to obtain a large number of counts in each pixel. Results of such an experiment are histogrammed in figures 2 and 3. A 64 element, 25mm x 25mm x 5mm array, read out with a proprietary Digirad ASIC, was irradiated with a 17 μCi ^{57}Co point source located a distance of 5 cm from the center. Data were recorded until the highest channel reached about 10^6 counts, approximately 20 hours.

Figure 2 is a histogram of the total counts per working pixel. The mean number of total counts in the spectra was 1.23×10^7 , and the observed standard deviation was 3.55%. The estimated deviation from the detector-source geometry is less than 0.5%, and the statistical deviation between channels with this number of counts should be approximately 0.03%. The remaining variation is mainly attributable to the CdZnTe detector and material properties. Therefore the estimated relative counting efficiency is uniform within about +/- 3% for this particular array.

Figure 3 is a histogram of peak channel numbers for this experiment. The gaps in the histogram indicate a slight differential nonlinearity in the ADC used for this experiment. The approximately gaussian distribution of gains is centered on MCA channel 147, with a standard deviation of 3.4 channels or 2.3%. Thus a slight correction for gain differences is necessary to minimize the peak widths, when summing the data to record a composite spectrum.

The best performance obtained to date using this method is demonstrated in figure 4. The spectrum is a summed composite of gain-corrected spectra from all 64 pixels in a MCM acquired with the isotope ^{22}Na . Note that Digirad's current readout ASIC is designed for low energy applications, thus the gamma ray at 1.27 MeV is not recorded in this demonstration. The energy resolution seen here for the 511 keV line is 10.1 keV. This is only slightly greater than the resolutions expected of the individual channels for this device, and shows that the gain calibration method was successful.

Sources of response variation

The energy resolution achievable with the multichannel approach is determined by the resolution of the individual channels. By calibrating the pulse height data from each channel, the variations indicated in the histogram in figure 3 can be corrected, minimizing the peak widths for composite spectra. The nonuniform response of the individual channels is due to effects in the semiconductor as well as the electronic channels. Therefore this approach somewhat relaxes requirements for semiconductor homogeneity. That is, the material properties must only be uniform on the scale of the pixellation, rather than the entire device, to obtain narrow composite pulse height distributions.

Component tolerances affect the gain distributions by introducing systematic error in each electronic channel. The most important sources of these gain variations in the ASIC are capacitor tolerances and MOSFET bias sensitivity. These effects, and variations in stray capacitance are mainly responsible for the observed 2.3% deviation of the relative gains.

Materials factors can also affect gains, through variations in the CdZnTe alloy composition, trap densities, etc. The compositional variation, which is necessarily present due to segregation in melt-grown crystals, results in variation of the bandgap, and hence the ionization energy of the material. The magnitude of this effect actually depends on the length of the ingot and the position from which a detector is drawn. For 10 kg ingots routinely produced by Digirad the bandgap changes less than 1% per cm over most of the ingot, therefore gain and counting rate variations due to this effect are negligible for individual detectors and monolithic arrays. It is possible, however, for two detectors drawn from different locations to have significant differences in the bandgap. More important materials factors include electron $\mu\tau$ product variations, gross defects and boundary effects. These introduce random error in the pulse heights recorded within individual channels, broadening the pulse height distributions.

Conclusions

An approach to making a field portable, high sensitivity gamma ray spectrometer has been demonstrated. Results were obtained from 25mm x 25mm x 5mm CdZnTe detector array, a sensitive volume of 3 cm³.

Energy resolution of 10 keV was achieved using non optimal detector material and readout ASIC. Results with a single discrete element and low-noise electronics showed energy resolution > 3 keV is achievable with currently available CdZnTe. To approach this level of performance with a multichannel device will require a new ASIC designed specifically for spectroscopy.

Figures

Figure 1 Spectrum from ^{22}Na obtained with a discrete CZT detector and readout. The resolution is $>3\text{keV}$ FWHM for the 511 keV annihilation peak.

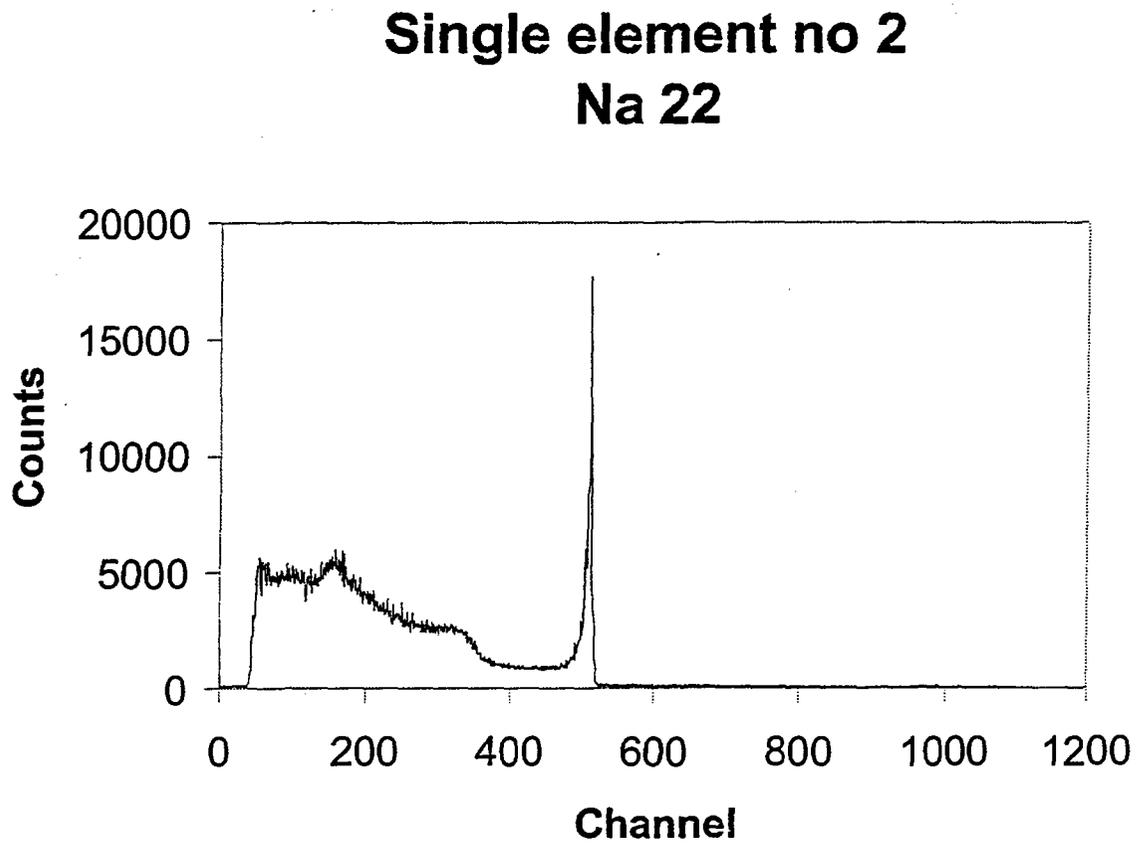


Figure 2 Histogram of ^{57}Co peak channel for a 64 element CZT array. The standard deviation of observed gains is 2.3 %, caused by component tolerances and CZT properties.

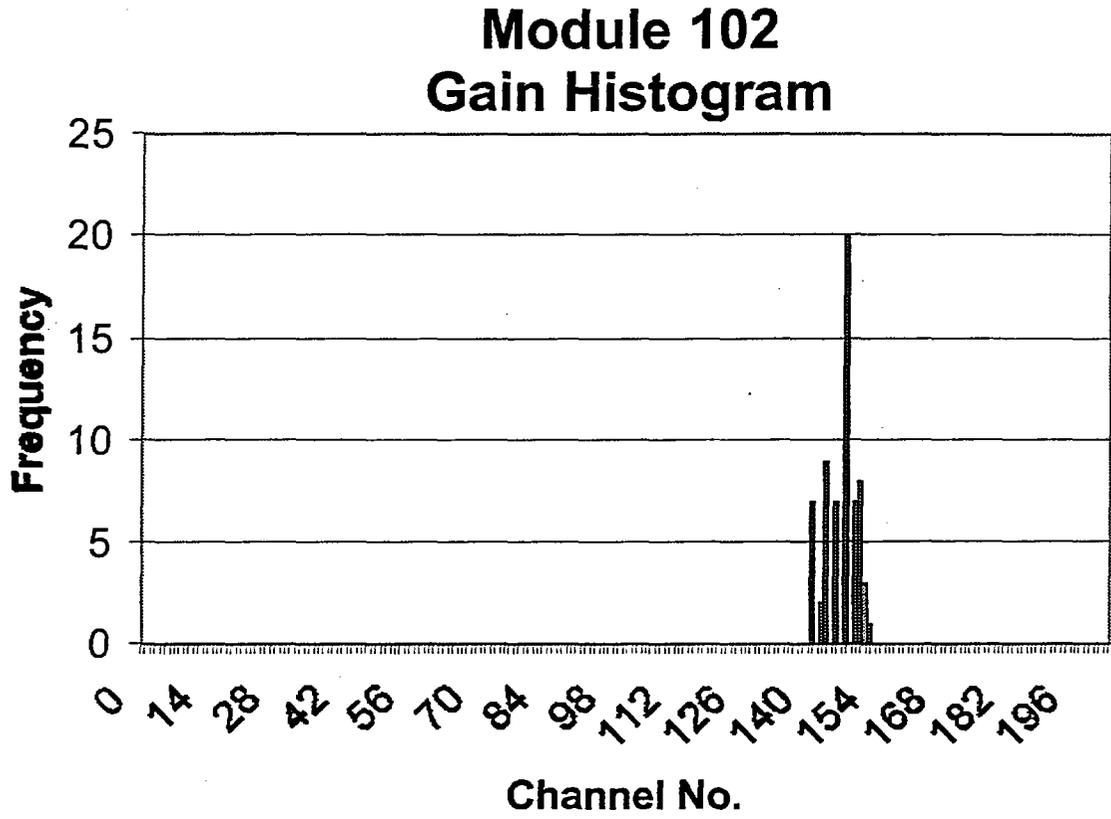


Figure 3 Count rate histogram for the same CZT module as Figure 2. Observed standard deviation of 3.55

% is largely attributable to nonuniform properties of the CZT.

Module 102 Count rate histogram

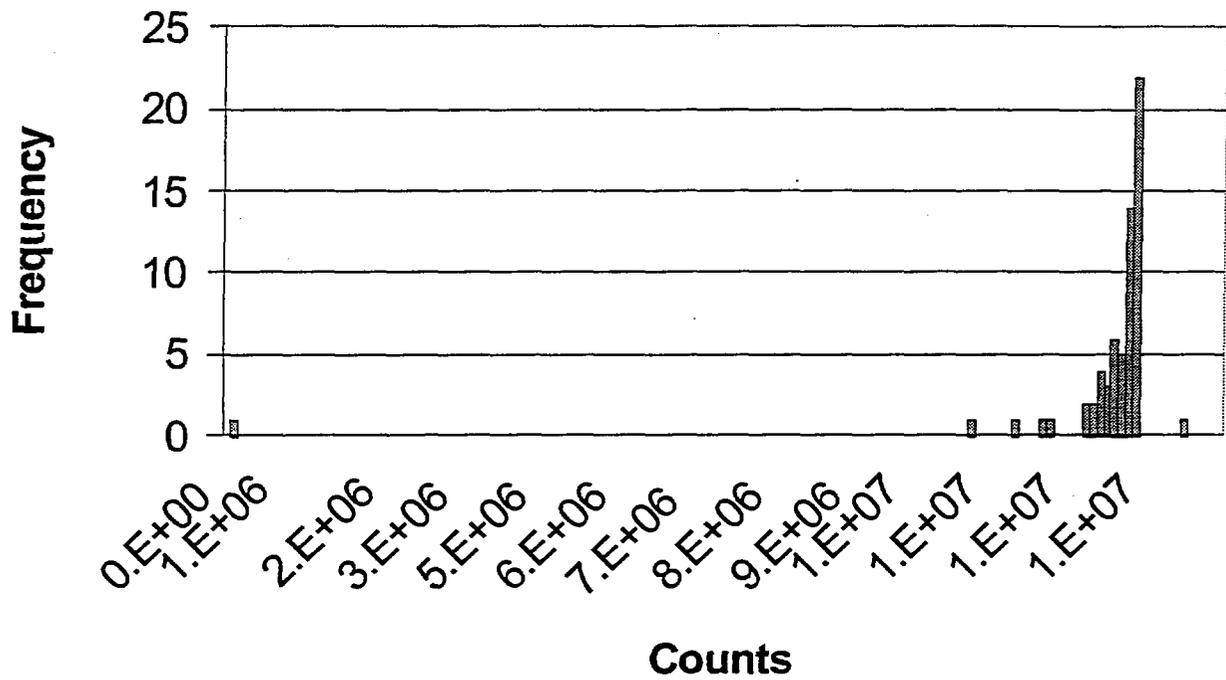
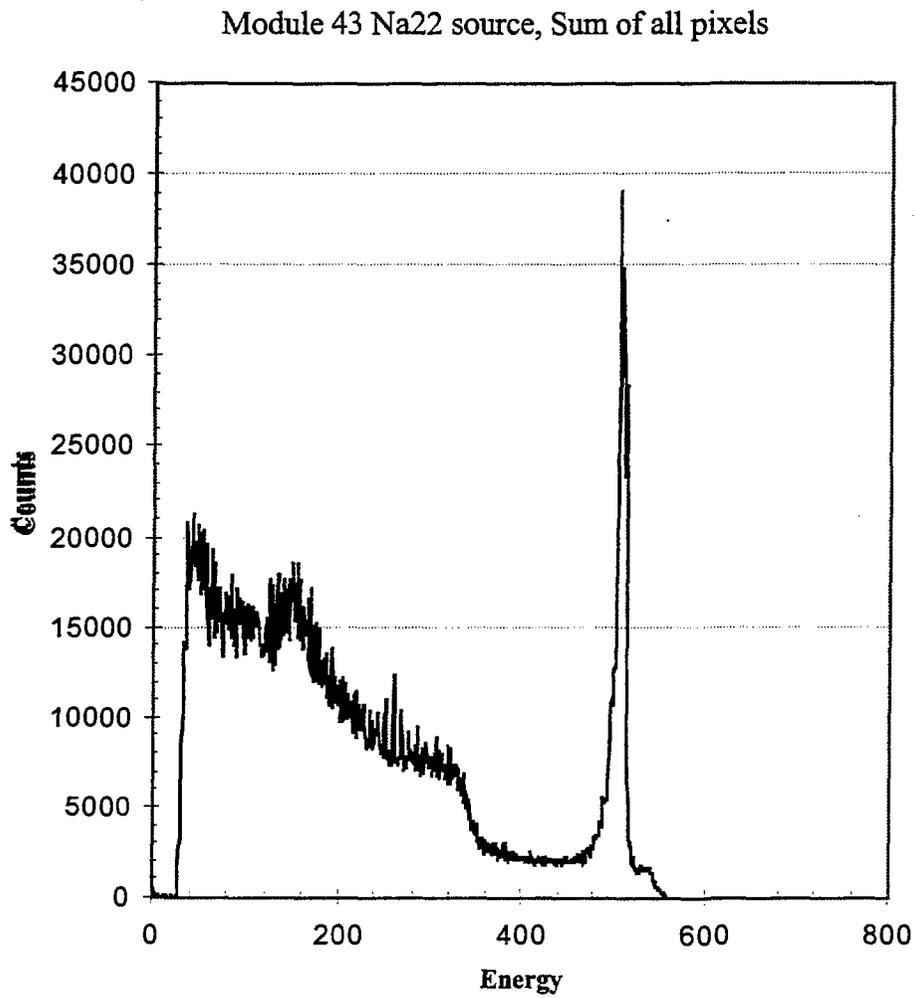


Figure 4 Composite spectrum from ^{22}Na obtained with a 64 element CZT array with ASIC readout. The resolution is 10.1 keV FWHM for the 511 keV annihilation peak. Sensitive volume is 25 mm x 25 mm x 5 mm.



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