Readout System for Arrays of Frisch-Ring CdZnTe Detectors

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***Abstract*—Frisch-ring CdZnTe detectors have demonstrated good energy resolution for identifying isotopes, <1% FWHM at 662 keV, and good efficiency for detecting gamma rays. To facilitate the application of this detector in radiation detection, we are designing a portable device that can incorporate with an 8 × 8 Frisch-ring detector array. A prototype system has been designed, which includes detector modules, front-end electronics, signal processing circuit, USB interface and high-voltage power supply. This paper describes the design and assembly of the detector modules and the structure of the prototype system. Some test results are also reported.**

***Index Terms*—CdZnTe, data acquisition system, Frisch-ring detector.**

I. Introduction

CdZnTe (CZT) is very attractive material for room-temperature semiconductor detectors due to its wide bandgap and high atomic number [1]. However, CZT detectors are typically single-charge-carrier devices because holes have poor mobility. Thus, to achieve high-energy resolution, techniques for designing special detectors are required, such as pixilated, co-planar grid, and virtual Frisch-grid devices [2]. Since the introduction of the first Frisch-ring CZT detector [3], a variety of similar devices were designed and tested. Our group in Brookhaven National Laboratory has expended efforts in improving the performance of the Frisch-ring CZT detectors; our most recent work focused on the non-contacting Frisch-ring detector [5]–[7]. The unique features of this configuration are its simplicity, yet outstanding spectral performance [5]. Its form allows us to build an inexpensive large-volume detector array, which has high energy resolution and a large effective area.

In addition, compact efficient radiation spectrometers are needed in nondestructive detection, radiation imaging, and homeland security (for example, nonproliferation safeguards, custom inspection, and radiation field survey). Most of these applications desire an instrument with compact size, room-temperature operation, high gamma-ray energy resolution and absorption efficiency, and low cost. The devices presently used for portable gamma ray spectroscopy include NaI(Tl)-based detectors and portable high-purity germanium (HPGe) detectors, yet neither of them fulfill the aforementioned requirements. Gamma-ray spectrometers based on CZT detectors have been developed in the past; they are either very expensive or have low gamma-ray absorption efficiency. Our improvements on the Frisch-ring technique makes it possible to assemble a detector array that meets the above requirements.

Recently, our group at Brookhaven National Laboratory is designing a 64-channel portable gamma-ray spectrometer utilizing the non-contacting Frisch-ring detectors. Our goal is to demonstrate the feasibility of employing such detectors in hand-held or portable systems. Design of a detector module for Frisch-ring detector array has been completed. One module has been partially populated with four Frisch-Ring detectors. The front-end preamplifier board has been designed and fabricated. By using the Multiple Input/Output System (MIOS) developed by BNL's Instrumentation Division, a prototype system has been built. In this paper, we describe the system design and detail the assembly of the detector module. Test results from test pulses and real detectors are also analyzed in this paper. These analyses help us to characterize the system performance and determine the structure of our final spectrometer system.

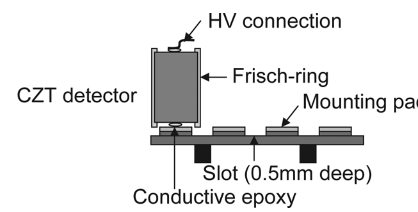

Fig. 1. Detector module assembly.

II. Detector Module

To make the system installation easy, we divided 64 CZT crystals into a series of detector modules, each consisting of a 4 × 4 array.

A small printed circuit board (PCB) served as the substrate of the detector module. The parasitic capacitance of the signal traces on this PCB board, which is proportional to the dielectric constant (ε) of the PCB material, increases the electronics

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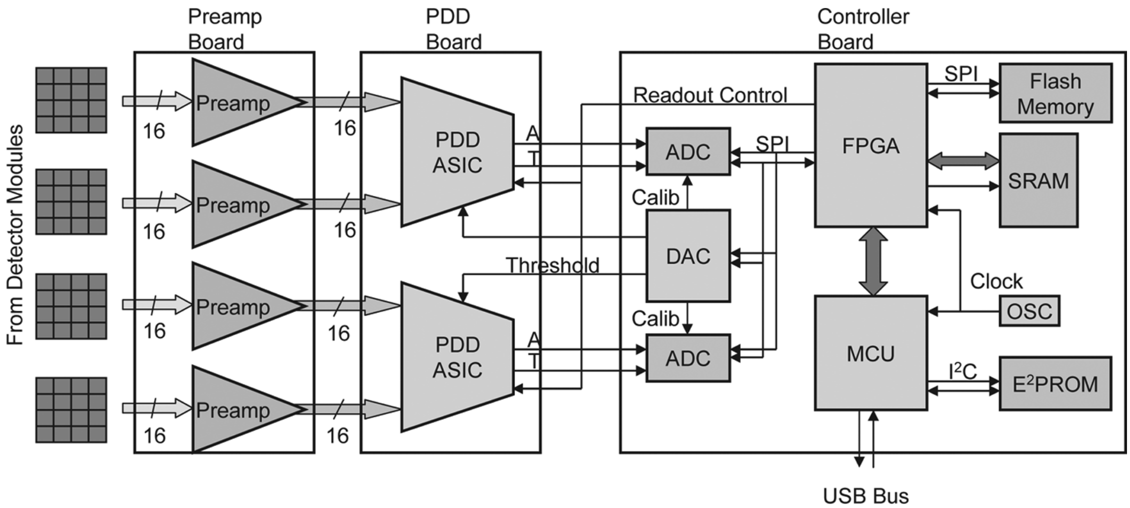

Fig. 2. The structure of the data-acquisition system for the Frisch-ring CZT detector array.

noise. To keep this capacitance small, we selected low ε material, Rogers 4003, to make the substrate.

On one side of the substrate, there is a 4 $\times$ 4 array of gold-plated square pads (3 mm $\times$ 3 mm) with a pitch between them of 5.5 mm. On the other side, there are two low profile connectors to the preamplifier board. CZT crystals are gold-coated on the top and bottom surfaces, and wrapped using conductive tape (Frisch-ring) forming the Frisch-ring detectors. Then, the detectors are glued onto the pad using conductive epoxy resin as shown in Fig. 1. To ensure a good connection between the crystal and the pad, the pad side of the substrate was grooved so there were slots, 1.5 mm wide and 0.7 mm deep, between pads as shown in Fig. 1. On the top of the crystal, high voltage is applied to the cathode through a small piece of conductive tape, which also is glued onto the crystal using epoxy. All the detector cathodes in the array share the same high voltage supply, and all the Frisch-rings are connected to the signal ground of the system.

With this approach, we assembled a detector module with four CZT crystals of different dimensions from different vendors. They were named as D1 ($4 \times 4 \times 12$ mm long), D2 ($5 \times 5 \times 14$ mm long), D3 ($6 \times 6 \times 14$ mm long), and D4 ($5 \times 5 \times 14$ mm long).

III. Data Acquisition System

To facilitate the portable radiation detection application of the Frisch-ring detector, the design of the data acquisition system (DAQ) used two Application Specific Integrated Circuits (ASICs) developed at BNL: a 16-channel low noise preamplifier ASIC for CZT detector readout [8] and a peak detector/derandomizer (PDD) ASIC [9]–[11]. The preamplifier ASIC has a continuous reset system, which keeps the output baseline stable with up to 150 nA leakage current from the CZT detectors, and a high-order shaping amplifier. Its input transistor and the shaping circuit are optimized for the CZT detector application so that the Equivalent Noise Charge (ENC) is only 93 e^- with 2 pF input capacitor, 1 nA leakage current, and 1 fC input charge. The PDD ASIC is a 32:1 multiplexer that uses analog techniques (precision peak detectors and

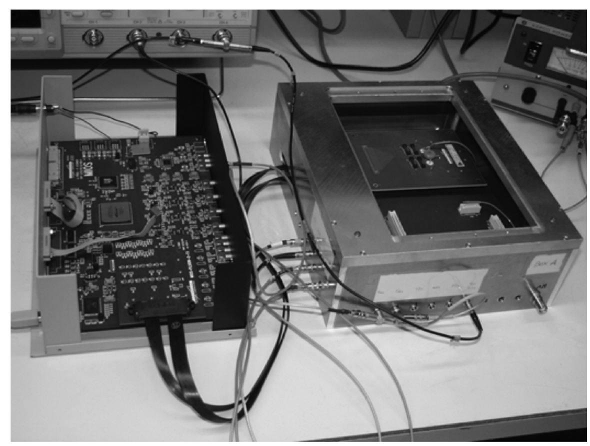

Fig. 3. The DAQ system for the CZT detector array.

time-to-amplitude converters) with arbitration logic to concentrate the data before digitization. For signals arriving at any of its 32 channel inputs, the ASIC provides amplitude and timing (occurrence time, rise time, or time-over-threshold) signals in analog format and the channel number in digital format. Fig. 2 shows our system's structure based on these two ASICs.

There are three PCB boards in this stacking system: preamplifier board, PDD board, and controller board. The detector modules reside on the top of the system.

Signals from each 16-channel detector module are amplified and shaped by a preamplifier ASIC that has a programmable gain (33 mV/fC to 200 mV/fC) and peaking time (0.6 μs to 4.0 μs). The output signals from two preamplifier ASICs are processed and buffered in a PDD ASIC. Then, the amplitude and timing are digitized by two 12-bit analog-to-digital converters (ADC) on the controller board. Thereafter, all the digitized information is collected by a FPGA and sent to a computer through a universal serial bus (USB) controlled by a microcontroller [12]. The computer has DAQ software to control the system and process the data stream.

Recently, we designed and fabricated the detector module and the preamplifier PCB board. To test these two boards, we

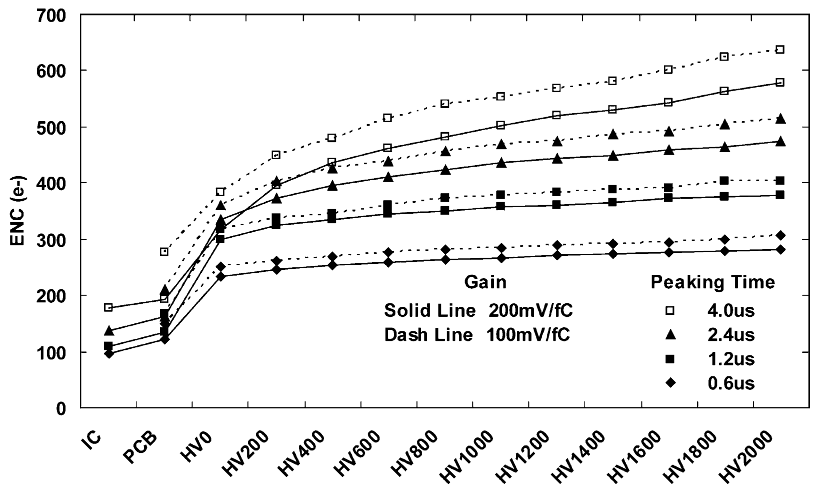

Fig. 4. Equivalent noise charge of the prototype system at different stages of system integration. IC: noise of ASIC itself when the input pin of the preamplifier ASIC is lifted up from the PCB board. PCB: noise of ASIC with parasitic capacitance of PCB traces when the input pin of the preamplifier ASIC is soldered onto the PCB board and no detector is plugged into the system. HV0 to HV2000: noise of the whole system when detector module is plugged into the system, and biased at certain high voltage, e.g. HV 2000 means 2000 V.

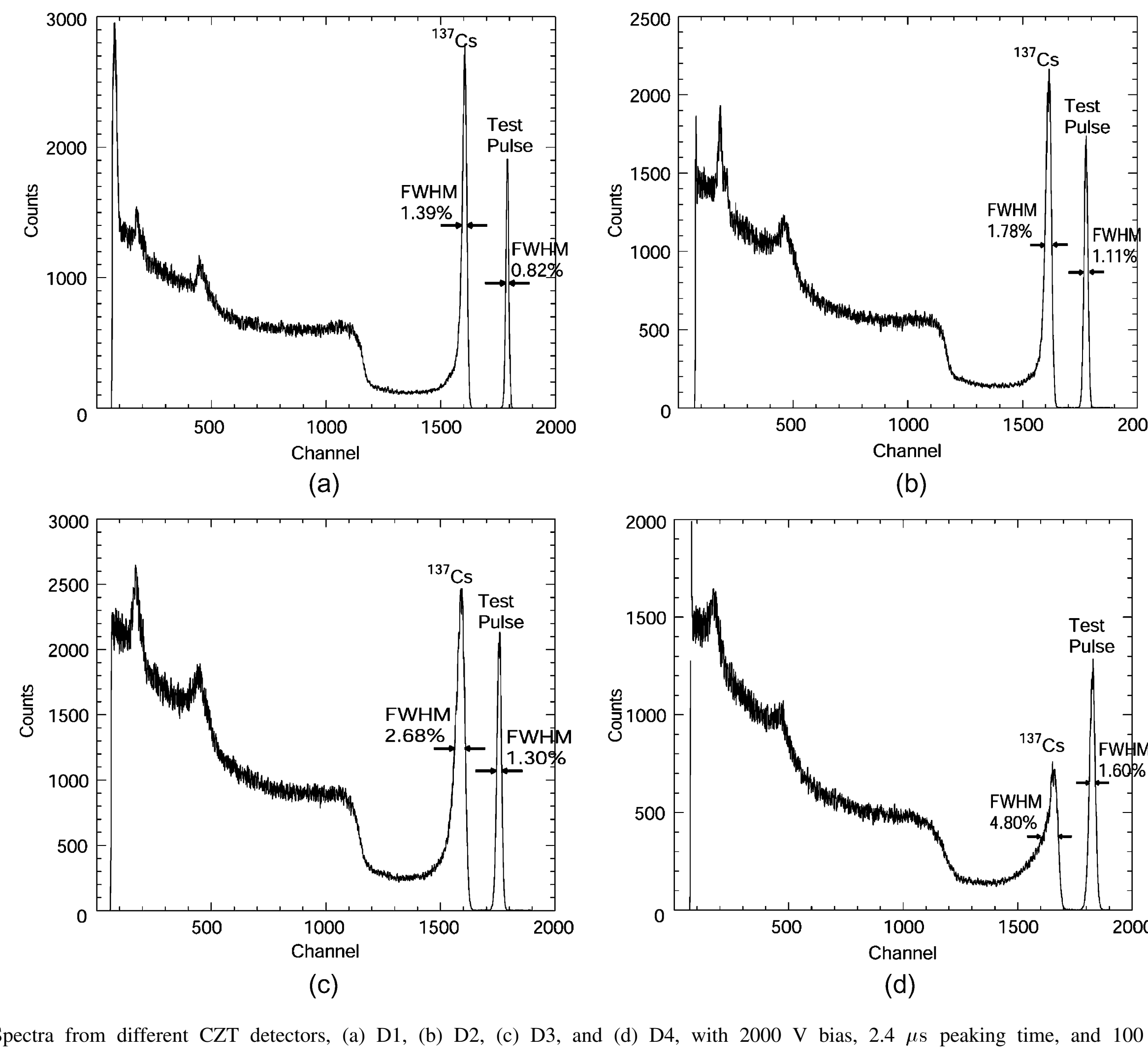

Fig. 5. Spectra from different CZT detectors, (a) D1, (b) D2, (c) D3, and (d) D4, with 2000 V bias, 2.4 μs peaking time, and 100 mV/fC gain.

built a prototype system using an existing PDD test box [13] and the MIOS system developed by BNL's Instrumentation Division. Fig. 3 shows a photo of the whole system. Our preamplifier boards are plugged into the PDD test box directly (shown on the right in Fig. 3). The MIOS system (shown on the left in Fig. 3), which has a similar structure to our

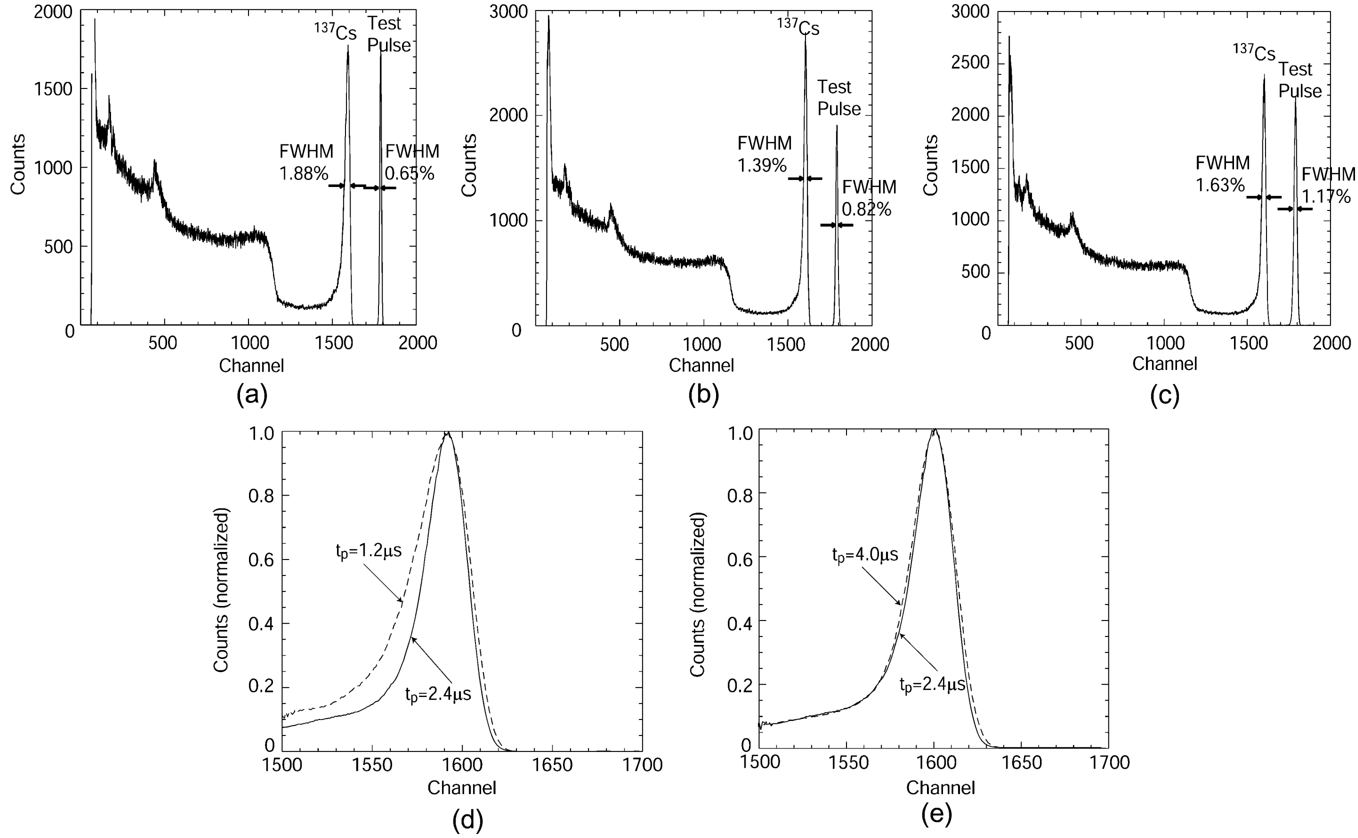

Fig. 6. Spectra with different peaking time. (a) 1.2 μs peaking time; (b) 2.4 μs peaking time; (c) 4.0 μs peaking time; (d) normalized peaks of 1.2 μs and 2.4 μs peaking times; and (e) normalized peaks of 2.4 μs and 4.0 μs peaking times. In (d) and (e), the solid lines are the spectra with 2.4 μs peaking time.

controller board, digitizes the signals from PDD ASICs and sends the data to computer.

IV. Test Results

We tested the system in the laboratory using both a pulse generator and a ^{137}Cs gamma ray source. In this section, we discuss some results from the four detectors that were mentioned in Section II.

A. Noise

To identify and understand the contributions of different sources to the total noise, we measured the ENC of the prototype system at different stages during system integration process: 1) with the preamplifier ASIC's input pins lifted up; 2) with the preamplifier ASIC input pins soldered onto the preamplifier board; 3) with the detector module plugged onto the preamplifier board; and, 4) with the detector biased at different high voltages. Fig. 4 shows the test results from D1 detector with two different gain settings, 100 mV/fC and 200 mV/fC.

It can be seen from Fig. 4 that the detector's noise dominates the total noise level. In particular, due to the detector's leakage current, the total noise increases as the bias voltage increases. From these values, we determined the intrinsic system noise. For example, with a 2000 V bias, 2.4 μs peaking time, and gain of 100 mV/fC, the ENC is about 500 e^-, equivalent to 0.8% FWHM resolution for energy of 662 keV.

B. Spectra From CZT Detectors

Fig. 5 shows the spectra from detector D1, D2, D3 and D4 with a ^{137}Cs source, 2000 V bias voltage, 2.4 μs peaking time, and 100 mV/fC gain. Detector D1 gives the best resolution of 1.39% (FWHM) at the ^{137}Cs 662 keV peak. Detector D2 and D3 also have good results with 1.78% and 2.68% (FWHM) respectively. However, detector D4 is noisy and has relatively broad peak. We note that the performance of CZT crystals varies greatly due to the growing process and other factors, although the same Frisch-ring fabrication process was used.

C. Energy Resolution vs. Peaking Time

To see how the peaking time affects the energy resolution, we took spectra using detector D1 with (a) 1.2 μs, (b) 2.4 μs, and, (c) 4.0 μs peaking time (Fig. 6). From the test pulse spectra, we see that the total noise worsens as the peaking time increases, a result in agreement with our test in Section IV-A. However, the ^{137}Cs spectrum has best energy resolution with 2.4 μs peaking time.

To find the reason for this, we compared the peak shapes at different peaking times by linearly normalizing the ^{137}Cs peaks with 1.2 μs and 2.4 μs peaking times, and comparing them in Fig. 6(d). Note that we aligned two centroid positions in Fig. 6(d) by moving peak of 2.4 μs from channel 1599 to channel 1590 where peak of 1.2 μs is located. We did the same for 2.4 μs and 4.0 μs peaking times in Fig. 6(e). As Fig. 6(d) shows, the marked difference between two peaks is in the left slope of the peak with 1.2 μs peaking time. This can be explained by the electronics ballistic deficit [2]. In Fig. 6(e), the two peaks have the same shape. The peak taken with 4.0 μs peaking time is just slightly wider than that with 2.4 μs peaking time, because the parallel noise (detector's leakage current) dominates the total noise level in the system.

Thus, the energy resolution is related to the peaking time. The selection of the peaking time is determined by the electron mobility in the CZT material, the high voltage bias applied to the detector, the detector's leakage current, and the detector's size.

V. Conclusions

We completed a prototype system for the compact spectroscopic device based on CZT Frisch-ring detectors. Test results show that the system's performance meets our requirement of 1.5% (FWHM at 622 keV) for the compact Frisch-ring CZT array spectrometer system. Our analysis of these findings helps us to determine the specifications of the final portable system design. Based on the work so far, we already started designing the portable system that will be published later.

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References

[1] T. E. Schlesinger and R. B. James, "Semiconductors and semimetals," in *Semiconductors for Room Temperature Nuclear Detector Applications*. San Diego, CA: Academic, 1995, vol. 43.

[2] G. F. Knoll, *Radiation Detection and Measurement*, 3rd ed. New York: Wiley, 2000.

[3] D. S. McGregor, Z. He, H. A. Seifert, D. K. Wehe, and R. A. Rojeski, "Single charge carrier type sensing with a parallel strip pseudo-Frisch-grid CdZnTe semiconductor radiation detector," *Appl. Phys. Lett.*, vol. 72, pp. 792–794, 1998.

[4] D. S. McGregor and R. A. Rojeski, "High-resolution ionization detector and array of such detectors," U.S. Patent 6 175 120, Jan. 6, 2001.

[5] A. E. Bolotnikov, G. C. Camarda, G. A. Carini, M. Fiederle, L. Li, D. S. McGregor, W. McNeil, G. W. Wright, and R. B. James, "Performance characteristics of Frisch-ring CdZnTe detectors," *IEEE Trans. Nucl. Sci.*, vol. 53, no. 2, pp. 607–614, Apr. 2006.

[6] W. J. McNeil, D. S. McGregor, A. E. Bolotnikov, G. W. Wright, and R. B. James, "Single-charge-carrier-type sensing with an insulated Frisch Ring CdZnTe semiconductor radiation detector," *Appl. Phys. Lett.*, vol. 84, pp. 1988–1990, 2004.

[7] A. E. Bolotnikov, G. S. Camarda, G. A. Carini, G. W. Wright, D. S. McGregor, W. McNeil, and R. B. James, "New results from performance studies of Frisch-grid CdZnTe detectors," in *Proc. SPIE*, 2004, vol. 5540, pp. 33–45.

[8] G. De Geronimo, P. O'Connor, and J. Grosholz, "A generation of CMOS readout ASICs for CZT detectors," *IEEE Trans. Nucl. Sci.*, vol. 47, no. 6, pp. 1857–1867, Dec. 2000.

[9] P. O'Connor, G. De Geronimo, and A. Kandasamy, "Amplitude and time measurement ASIC with analog deradomization: First results," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 4, pp. 892–897, Aug. 2003.

[10] G. De Geronimo, P. O'Connor, and A. Kandasamy, "Analog CMOS peak detect and hold circuits, part 1 and 2," *Nucl. Instrum. Methods Phys. Res. A*, vol. A484, pp. 533–556, May 2002.

[11] P. O'Connor, G. De Geronimo, J. Grosholz, A. Kandasamy, S. Junnarkar, and J. Fried, "Multichannel energy and timing measurements with the peak detector/derandomizer ASIC," in *Proc. Nuclear Science Symp. Conf. Rec.*, Rome, Italy, Oct. 16–22, 2004.

[12] Cypress, CY7C68013A/CY7C68014A/CY7C68015A/CY7C68016A EZ-USB FX2LP USB Microcontroller.

[13] A. Dragone, "The Peak Detector and Derandomizer ASIC: A High Rate Readout System for Multichannel Detectors," Ph.D. dissertation, Polytechnic Bari, Bari, Italy, Jul. 2006.