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CZT Virtual Frisch-grid Detector: Principles and Applications

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Abstract— Cadmium Zinc Telluride (CdZnTe or CZT) is a very attractive material for using as room-temperature semiconductor detectors, because it has a wide bandgap and a high atomic number. However, due to the material's poor hole mobility, several special techniques were developed to ensure its suitability for radiation detection. Among them, the virtual Frisch-grid CZT detector is an attractive option, having a simple configuration, yet delivering an outstanding spectral performance. The goal of our group in Brookhaven National Laboratory (BNL) is to improve the performance of Frisch-ring CZT detectors; most recently, that effort focused on the non-contacting Frisch-ring detector, allowing us to build an inexpensive, large-volume detector array with high energy-resolution and a large effective area. In this paper, the principles of virtual Frisch-grid detectors are described, especially BNL's innovative improvements. The potential applications of virtual Frisch-grid detectors are discussed, and as an example, a hand-held gamma-ray spectrometer using a CZT virtual Frisch-grid detector array is introduced, which is a self-contained device with a radiation detector, readout circuit, communication circuit, and high-voltage supply. It has good energy resolution of 1.4% (FWHM of 662-keV peak) with a total detection volume of $\sim 20 \text{ cm}^3$. Such a portable inexpensive device can be used widely in nonproliferation applications, non-destructive detection, radiation imaging, and for homeland security. Extended systems based on the same technology have potential applications in industrial- and nuclear-medical-imaging.

Index Terms—Cadmium Zinc Telluride (CdZnTe or CZT), gamma-ray detection, spectrometer

Introduction

Highly efficient, compact radiation spectrometers are in high demand for nonproliferation applications, non-destructive detection, radiation imaging, and homeland security (for example, monitoring vehicles and containers, custom inspections, and radiation-field surveys). Most of these applications require an inexpensive, compact instrument incorporating room-temperature operation, high gamma-ray energy resolution, and absorption efficiency. Previously, scintillators, NaI(Tl) or CsI(Tl), and high-purity germanium, HPGe-based detectors have been employed. However, scintillator detectors exhibit low energy resolution, and HPGe needs a bulky cooling system. None of them satisfies all the above requirements.

Cadmium Zinc Telluride (CdZnTe or CZT) is a very attractive material for using as room-temperature semiconductor detectors, because it has a wide bandgap and a high atomic number [1]. However, because of the material's poor hole mobility, special techniques were developed to ensure its suitability for radiation detection. Two major techniques explored were 3-D pixilated detectors and Frisch-ring detectors [2][3].

The Frisch-ring CZT detector, with its simple configuration and outstanding spectral performance, is a particularly attractive option. The goal of our group in Brookhaven National Laboratory (BNL) is to improve the performance of Frisch-ring CZT detectors; most recently, the effort focused on the non-contacting Frisch-ring detector, allowing us to build an inexpensive large-volume detector array with high energy-resolution and a large effective area [4]-[6].

To facilitate the applications of CZT Frisch-ring detectors, BNL developed a novel hand-held gamma-ray spectrometer. This device incorporates an 8x8 detector array, and reaches a total detection volume of $\sim 20 \text{ cm}^3$, thereby significantly improving the efficiency of gamma-ray

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detection.

In this paper, the principle of CZT Frisch-ring detectors is introduced, followed by the detailing of the design of our hand-held spectrometer.

Virtual Frisch-grid CZT detector

Fig. 1 is a schematic drawing of a virtual Frisch-grid CZT detector. The geometry of its electrodes [7] includes the features of two designs previously proposed for parallelepiped-shaped CZT detectors: the CAPture device [8][9], and the Frisch-ring (or capacitive Frisch-grid) detector [6][11]. The configuration of the cathode's electrode cap is similar to that in the CAPture device, but extends only 2 mm on the side surface. The shielding electrode (Frisch-ring), separated from the cathode by a layer of insulator and grounded in the final assembly, overlaps the cathode and extends up to the far end near the anode. This shielding, together with the cathode cap, ensures that the side surfaces of the crystals are shielded properly. When the cathode is biased negatively, this configuration (cathode, anode, and shielding) forms a focusing electrical field in the crystal's bulk [2].

This focusing electrical field defines an active region in which the device's response changes only a little (i.e., <5%) from its maximum. The boundary of this region is defined as the virtual Frisch-grid. Fig. 2 (a) shows the location of virtual Frisch-grid for a $5 \times 5 \times 12 \text{ cm}^3$ detector. Our calculations show that this location depends strongly on devices' width, not its length [2]. This distance of this location to the anode roughly is equal to the width of the device [2]. Thus, the volume of the active regions increases proportionally to the device's thickness, so that longer crystals will exhibit better spectral responses.

Since the cathode is isolated from the shielding on the side surfaces, the signal readout from cathode also can serve as a depth-sensing technique to correct the charge-loss caused by electron trapping, and further improve the spectral response.

Fabricating the virtual Frisch-ring detector is a simple process, as described in detail in [2]. Fig. 3 shows a single virtual Frisch-grid detector and a fully populated 4×4 detector array.

Fig. 1. Scheme of virtual Frisch-grid CZT detector. (a) cross-sectional view; (b) 3-D view; and, (c) focusing electrical field in the virtual Frisch-grid detector.

Fig. 2. Location of virtual Frisch-grid in a bar-shaped CZT detector.

(a)

(b)

Fig. 3. Photos of a virtual Frisch-grid detector. (a) A finished CZT detector; and, (b) a detector module with a 4×4 detector array.

Advantages of virtual Frisch-grid detector and its applications

Compared with other single-carrier CZT detector configurations, the virtual Frisch-ring detector is inexpensive, easy to fabricate, and readily integrated into large-area array.

Ease of fabrication

As the discussion in section II shows, a virtual Frisch-grid detector is simple to fabricate, from developing the contacts, wrapping the shield, and mounting the detector on the substrate. In contrast, making a 3-D pixilated detector entails developing a specific contact-pattern on the anode side, and precisely mounting detector on the substrate. Further, failure on any one pixel will necessitate re-working the whole detector. For a virtual Frisch-grid detector array, the failure of any detector bar merely involves replacing it.

Low cost

Virtual Frisch-grid CZT detectors employ small CZT crystals, i.e., $5 \times 5 \times 15 \text{ mm}^3$. Compared with the typical size of crystals for 3-D CZT detectors ($20 \times 20 \times 15 \text{ mm}^3$), this allows us to fabricate such devices from relatively thin, $< 7 \text{ mm}$, CZT wafers that offer large flexibility for cutting, and the screening of crystal defects [2]. Therefore, using ingots with the same density of defects, more Frisch-grid detector bars can be cut. This high yield is the main factor accounting for the low cost of the fabricated detectors.

Ease of integration

When integrated with front-end readout electronics, an array of virtual Frisch-grid detectors has a lower channel density than 3-D detectors. For example, an array with a $12 \times 12 \text{ cm}^2$ total area would require 400 $6 \times 6 \text{ mm}^2$ bar-shaped detectors and the same number of readout channels (this value must be doubled when employing a cathode signal to correct charge trapping). To make the same array of pixel detectors with the largest reported size for 3-D detectors of $20 \times 20 \times 15 \text{ mm}^3$, 121 readout channels, and the $\sim 2 \text{ mW}$ power consumption per channel [3] would necessitate having 36 detectors with 4356 readout channels and $\sim 9 \text{ W}$ to power such a device. Such a high dissipation of power requires active cooling that, in turn, increases the total power consumption. In contrast, an array of $6 \times 6 \text{ cm}^2$ Frisch-ring detectors requires ~ 10 times less power, which translates into a longer battery life and a smaller battery volume, and hence, a low-profile easily portable device.

High energy resolution

As demonstrated in [2], virtual Frisch-grid detectors offer an energy resolution of $< 1.5\%$ at 662 keV. So far, over 80 bar-shaped CZT crystals with areas ranging from 3×3 - to $10 \times 10\text{-mm}^2$ and thickness from 5- to 20-mm were tested at BNL. About 50% of these crystals gave a resolution less than 2%. Among them, 35 detectors exhibited $< 1.5\%$ resolution with the typical electronics noise of 3 keV. A 10-mm-thick detector gave the best resolution, 0.8% FWHM at 662 keV [2]. All these results were simply obtained by reading out the signals from the anodes. As demonstrated in [11], by reading out both the cathode- and anode-signals, and applying a bi-parametric correction (a technique similar to that used in 3-D detectors), most of the above detectors can achieve $< 1\%$ energy resolution.

All these advantages support the virtual Frisch-grid technique as a practical approach to employing CZT materials for making large-area detector planes for imaging and spectroscopy of gamma radiation.

A hand-held gamma-ray spectrometer

To facilitate the application of virtual Frisch-grid detector, BNL developed a hand-held gamma-ray spectrometer, which integrated 64 virtual Frisch-grid bar-shaped detectors, populated in four detector modules. Each module has a 4×4 detector array. In this section, the detailed design of this device is discussed, and the test results with sealed radiation sources are reported.

System structure

Fig. 4 is a schematic of our hand-held device. Signals from each detector are amplified by a specific channel in front-end application-specific-integrated-circuit (ASIC). Each ASIC has 32 channels, and there are two ASICs in each device. Each channel of the ASIC has its own preamplifier and peak detection- (PD-) circuit. When the input signal's amplitude is higher than preset threshold and signal's peak is found, the amplitude information is latched in the analog buffer in the PD circuit. With the control of a sparsification readout circuit, only channels with a hit are read-out one by one, and digitized by a low power ADC. The on-device memory saves the digitized information, and a USB transfers it to a computer. To save space on the PCB board, all the digital circuits are implemented in an FPGA.

Fig. 4. Schematic of our hand-held gamma-ray spectrometer

To avoid crosstalk from the digital control circuit to the front-end circuit and to minimize the size of the spectrometer, the whole device was divided into two parts, front-end board and controller board, as shown in Fig. 5. Fig. 6 has photographs of the device from various angles.

By separating the front-end ASIC from the digital control circuit, the ASIC could be placed underneath the detector modules. This stacked structure allows easy extension the detector array by simply duplicating the front-end board and the detector modules. Therefore, this device demonstrates not only the spectroscopy capability of the virtual Frisch-grid detectors, but also its potential use in imaging.

Fig. 5. Stacked structure of device assembly

Fig. 6. Photos of the hand-held gamma-ray spectrometer

Test results with a sealed radiation source

Due to the low availability of suitable CZT crystals, so far only 32 virtual Frisch-grid detectors were fabricated and integrated into two detector modules (Fig. 6). The device was tested at room-temperature with the detector modules biased at -1700 V with the preamplifier settings as gain of 57 mV/fC, and shaping time of 2 μ s.

The device was exposed to three radiation sources, ^{137}Cs , ^{133}Ba , and ^{57}Co . First, the energy lines of the photopeaks from these sources were used to calibrate the system and correct the gain and baseline variations between channels. Thereafter, the combined spectra using the data from all 32 detectors were generated. Fig. 7 and Fig. 8, respectively, show the spectra of ^{137}Cs and ^{133}Ba . For the photopeak of ^{137}Cs , the energy resolution was about 1.4% (full-width-half-maxima, FWHM).

Fig. 7 reveals that there is a high Compton platform; it can be lowered by recovering the Compton events between adjacent channels [12]. Unfortunately, the current ASIC does not record timing information for the input signals. However, a new ASIC to register both timing- and

amplitude-information is considered, which will use similar technologies as in [13][14].

Fig. 7. Combined ^{137}Cs spectrum obtained by a 4x8 detector array

Fig. 8. Combined ^{133}Ba spectrum obtained by a 4x8 detector array

Conclusion

The improved design of a virtual Frisch-grid CZT detector was innovated. CZT detectors fabricated with this method exhibits an energy resolution as high as a 3-D CZT detector, yet has the advantages of lost cost, easy fabrication, and easy integration. The hand-held gamma-ray spectrometer based on these detectors demonstrated the virtual Frisch-grid CZT detectors' capabilities in applications of spectroscopy and imaging in a custom-designed hand-held spectrometer.

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