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# Performance enhancements of compound semiconductor radiation detectors using digital pulse processing techniques

L. Abbene *, G. Gerardi

*Dipartimento di Fisica, Università di Palermo, Viale delle Scienze, Edificio 18, Palermo 90128, Italy*

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ABSTRACT

The potential benefits of using compound semiconductors for X-ray and gamma ray spectroscopy are already well known. Radiation detectors based on high atomic number and wide band gap compound semiconductors show high detection efficiency and good spectroscopic performance even at room temperature. Despite these appealing properties, incomplete charge collection is a critical issue. Generally, incomplete charge collection, mainly due to the poor transport properties of the holes, produces energy resolution worsening and the well known hole tailing in the measured spectra. In this work, we present a digital pulse processing (DPP) system for high resolution spectroscopy with compound semiconductor radiation detectors. The DPP method, implemented on a PC platform, performs a height and shape analysis of the detector pulses (preamplifier output pulses), digitized by a 14-bit, 100 MHz ADC. Fast and slow shaping, automatic pole-zero adjustment, baseline restoration and pile-up rejection allow precise pulse height measurements both at low and high counting rate environments. Pulse shape analysis techniques (pulse shape discrimination, linear and nonlinear pulse shape corrections) to compensate for incomplete charge collection were also implemented. The results of spectroscopic measurements on a planar CdTe detector show the high potentialities of the system, obtaining low tailing in the measured spectra and energy resolution quite close to the theoretical limit. High-rate measurements (up to 820 kcps) exhibit the excellent performance of the pulse height analysis and the benefits of pulse shape techniques for peak pile-up reduction in the measured spectra. This work was carried out in the framework of the development of portable X-ray spectrometers for both laboratory research and medical applications.



## 1. Introduction

It is now widely recognized the great advantage of using compound semiconductors for radiation detectors [1–3]. Among the compound semiconductors, cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe ) have become commercially available and are very attractive for X-ray and gamma ray spectroscopy [4,5]. Due to their physical properties, i.e. the high atomic number ($Z_{max}=52$), the high density (CdTe: $\rho=6.20$ g/cm$^3$; CdZnTe: $\rho=5.78$ g/cm$^3$) and the wide band gap (CdTe: $E_G\sim1.44$ eV; CdZnTe: $E_G\sim1.57$ eV), CdTe and CdZnTe detectors ensure high detection efficiency, good room temperature performance and are well suited for the development of portable detection systems [6–8].

Despite these appealing properties, charge trapping and recombination, typical phenomena in compound semiconductors, may prevent the full charge collection and worsen the performance of the detectors. In CdZnTe and CdTe, the poor transport properties of the charge carriers, expressed by the low values of the mobility-lifetime product ($\mu_h\tau_h\sim10^{-5}$–$10^{-4}$ cm$^2$/V; $\mu_e\tau_e\sim10^{-3}$–$10^{-2}$ cm$^2$/V) if compared with Si and Ge ones ($\mu_h\tau_h\sim\mu_e\tau_e\sim1$ cm$^2$/V), give rise to a significant reduction of the charge collection efficiency; moreover, the wide disparity between the transport properties of the holes and the electrons produces peak asymmetry and long tailing in the measured spectra. The charge trapping effects, well described in planar detectors by the Hecht equation [2–5], depends on the mean drift lengths $\lambda$ of charge carriers and in particular on the $\lambda/L$ ratio, wherein $L$ is the detector thickness. Small $\lambda/L$ ratios reduce the charge collection and increase the dependence by the photon interaction point [2–5]. So, the random distribution of the interaction point increases the fluctuations on the induced charge and thus produces peak broadening in the energy spectra. Poor mobility-lifetime products, especially for holes, result in short $\lambda$ and therefore small $\lambda/L$ ratios, which limit the maximum thickness of the detectors with significant reduction of the useful energy range.

Thin CdTe and CdZnTe detectors (1–2 mm thick) are very appealing for X-ray spectroscopy in low energy range (1–40 keV), showing good energy resolution and low hole trapping effects in the measured spectra. These detectors are widely used for the development of portable detection systems for X-ray spectra measurements in mammography [5–7,9–11].

* Corresponding author. Tel.: +39 091 23899151; fax: +39 091 23860815.
*E-mail address:* abbene@difter.unipa.it (L. Abbene).

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On the contrary, hole trapping effects are severe for thick detectors, needed for measurements in a higher energy range. From the medical point of view, thick CdTe and CdZnTe detectors would be also attractive for the development of portable systems for X-ray spectra measurements in computed tomography (20–140 keV).

To reduce the effects of the poor transport properties of the holes, single charge carrier sensing detectors, basically based on the collection of the electrons, have been developed. Single charge carrier sensing techniques are widely employed in compound semiconductor detectors by developing careful electrode designs (Frisch-grid [12,13], pixels [14–17] coplanar grids [18], strips [19,20] and multiple electrodes [8,21]) and by using electronic methods (pulse shape analysis [22–28]).

Pulse shape analysis, based on the measurement of the height and the peaking time of the detector pulses, is a powerful technique for spectral enhancements in compound semiconductor detectors. It is well known [22–30] that there is a strong correlation between the peaking time of the detector pulses and the hole contribution in the pulses: *pulses mostly influenced by hole contribution are characterized by longer peaking times than those influenced by electrons*. Pulse shape analysis, widely implemented in analog devices, generally consists of a simple selection of the peaking times of the detector pulses, rejecting the pulses with peaking times longer than a given time threshold. The lack of flexibility of analog devices is a critical issue to implement accurate pulse shape analysis techniques, which could be based on fine adjustments on the selecting operation and possible implementation of pulse height corrections. Moreover, analog devices, performing these techniques, need complex electronics with power consumptions, which are not acceptable for low-power portable instruments. In this contest, a digital pulse processing (DPP) approach is a powerful solution. Recently, the dramatic performance improvement of the analog-to-digital converters (ADCs) stimulated an intensive research and development on DPP systems. In a DPP chain, the preamplifier output signals are directly digitized by an ADC and so processed using digital algorithms. A DPP system leads to better results than the analog ones, mainly due to the stability and the flexibility of a digital system. It is possible to implement complex algorithms, which are not easily implementable through a traditional analog approach, for optimum filtering, accurate pulse shape analysis and better pile-up corrections, especially in a high counting rate environment.

In this paper, we report on a custom digital pulse processing (DPP) system for compound semiconductor radiation detectors based on height and shape analysis of the detector pulses (preamplifier output pulses), digitized by a 14-bit, 100 MHz ADC. This work was carried out in the sequence of previously developed DPP systems [11,28,31] with the goal of developing a digital spectrometer based on DPP techniques and characterized by high performance both at low and high photon counting rate environments. The digital method, combining fast and slow shaping, automatic pole-zero cancellation, baseline restoration, pile-up rejection and some pulse shape analysis techniques (pulse shape discrimination, linear and nonlinear corrections), allows precise pulse height measurements and compensation of incomplete charge collection even at high photon counting rates. Pulse shape analysis techniques were also used to reduce peak pile-up distortions in the measured spectra. Experimental test results on a planar CdTe detector, both at low and high photon counting rate (up to 820 kcps), were reported.

## 2. Materials and methods

### 2.1. Detector

The detector is based on a thin CdTe crystal ($2 \times 2 \times 1$ mm$^3$), wherein both the anode (indium) and the cathode (platinum) are planar electrodes covering the entire detector surface. The Schottky barrier at the In/CdTe interface ensures low leakage current even at high bias voltage operation (400 V), thus improving the charge collection efficiency. A Peltier cell cools both the CdTe crystal and the input FET of the charge sensitive preamplifier (A250, Amptek, USA) at a temperature of −20 °C. Cooling the detector reduces the leakage current, allowing the application of higher bias voltages to the electrodes; moreover, cooling the FET increases its transconductance and reduces the electronic noise. The detector, the FET and the Peltier cooler are mounted in a hermetic package equipped with a light-vacuum tight beryllium window (modified version of Amptek XR100T-CdTe, S/N 6012). To increase the maximum counting rate of the preamplifier, a feedback resistor of 1 GΩ and a feedback capacitor of 0.1 pF were used. The detector is equipped with a test input to evaluate the electronic noise.

### 2.2. Spectroscopic measurements

To investigate on the spectroscopic performance of the system, we used X-ray and gamma ray calibration sources ($^{109}$Cd: 22.1, 24.9 and 88.1 keV; $^{241}$Am: 59.5 and 26.3 keV and the Np L X-ray lines between 13 and 21 keV; $^{152}$Eu: 121.8 keV and the Sm K lines between 39 and 46 keV; $^{57}$Co: 122.1 and 136.5 keV and the *W* fluorescent lines, $K_{\alpha1}=59.3$ keV, $K_{\alpha2}=58.0$ keV, $K_{\beta1}=67.1$ keV, $K_{\beta3}=66.9$ keV, produced in the source backing). The 14 keV gamma line ($^{57}$Co) is shielded by the source holder itself. For high rate measurements, we also used another $^{241}$Am source, with the Np L X-ray lines shielded by the source holder. To obtain different rates (up to 820 kcps) of the photons incident on the detector (through the cathode surface), we changed the irradiated area of the detector using collimators (Pb and W) with different geometries.

To better investigate on the high-rate performance of the system, we also performed the measurement of Mo-target X-ray spectra at the "Livio Scarsi" Laboratory (LAX) [32] located at DIFI (Palermo). The facility is able to produce X-ray beams with an operational energy range of 0.1–60 keV (tube anodes: Ag, Co, Cr, Cu, Fe, Mo, W), collimated on a length of 10.5 m with a diameter at full aperture of 200 mm. We used a Mo-target X-ray tube (Seifert SN60) with 6° anode angle and 0.25 mm thick beryllium (Be) window. We measured the X-ray spectra at 32 kV with tube current values of 2 and 75 mA (photon counting rates up to 363 kcps). No collimators were used for these measurements.

To characterize the spectroscopic performance of the system, we evaluated, from the measured spectra, the *energy resolution* (*FWHM*) and the *FW.25 M to FWHM ratio*, defined in agreement with the IEEE standard [33]. We also evaluated the area of the energy peaks (photopeak area) through the *high side area* (*HSA*) [33], i.e. the area between the peak center line and the peak's high-energy toe; the photopeak area was calculated as twice the *HSA*. The measured spectra were analyzed using a custom function model, which takes into account both the symmetric and the asymmetric peak distortion effects [34]. Statistical errors on the spectroscopic parameters with a confidence level of 68% were associated.

### 2.3. Digital pulse processing system

The DPP system consists of a digitizer and a PC wherein the digital analysis of the detector pulses was implemented. The detector signals (preamplifier output signals) were directly digitized using a 14-bit, 100 MHz digitizer (NI5122, National Instruments). The digital data were acquired and recorded by a Labview program on the PC platform and then processed off-line by a custom digital pulse processing method (C++ coded software)