New perspectives in X-ray detection of concealed illicit materials brought by CdTe/CdZnTe spectrometric detectors

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ABSTRACT

Most of present X-ray approaches for explosive detection in packages are based on density and atomic number characterization of materials through dual energy transmission imaging. Due to the poor resolution in energy of classical "sandwich detectors" (two detectors one over the other separated by a filtering material to favour high energy detection in the second detector) used on the dual energy systems, the identification of illicit materials remains tricky. A way to improve and to upgrade these systems has been proposed by using multi-energy X-ray generators. Nevertheless, the use of these systems has been limited in reason of a complicated technological implementation of multi-energy X-ray shots. Another way of improvement of material characterization has been investigated by combining X-ray transmission information with analysis of narrow angle scattering profile in energy. Such systems need detectors with high energy resolution and were based on the use of single pixel Germanium semi-conductors detectors. These systems remain slow and need a cumbersome nitrogen cooling systems, which limits their use.
Semi-conductor material, and more specifically CdTe or CdZnTe, enables to build spectrometric detectors operating at room temperature with a high energy resolution. Moreover, these detectors can be pixelated and assembled in order to provide either 1D linear spectrometric detectors or 2D spectrometric imagers with high count rate. These characteristics associated to dedicated spectrometric information processing (multi-energy image processing, spectral information of narrow angle scattering) open the gate to new improved systems for an effective explosive detection and identification, overcoming the drawbacks encountered by the present systems. As CdTe/CdZnTe detectors count the number of photons collected in several energy channels, a multi-energy analysis with a single shot X-ray generator can be implemented. Compared to a classical dual energy approach, such multi-energy approach refines the characterization of observed materials in terms of transmission properties. Moreover, as CdTe/CdZnTe enables to design linear or matrix spectrometric detectors, parallelized detections of narrow angle scattering profiles can be carried out, enabling a fast characterization of observed materials through their narrow angle scattering signature in energy.
CdTe/CdZnTe based room temperature spectrometric detectors presenting a high energy resolution are well adapted for the development of fast, new portable explosive detection systems with high performances of explosive detection and identification.

1.0 INTRODUCTION

Most of present explosive detection approaches by X-Ray are based on the acquisition of a radiographic image representative at each pixel of the absorbed energy of the X-ray flux inside the observed object. A standard acquisition with such a system provides information on shapes and X-ray attenuation of components present in the parcel. However, as X-ray attenuation is correlated to material thickness as well as to material composition, it is very tricky to identify from a single radiograph the nature of materials present in the parcel: for example, an important attenuation might be due either to a high thickness/moderate density of material or to moderate thickness/high density. In order to discriminate between organic and inorganic materials, detection systems carry out two radiographic acquisitions at two different energies of the X-ray flux. Based on the same principle of enriching information by adding acquisitions at different energies of X-ray flux, we propose a way to use a large number of images corresponding to different X-ray flux energies in order to improve characterization of detected materials and to provide a more precise classification than organic/inorganic. One way to get acquisitions at different X-ray flux energies is to carry out acquisitions at different working points (voltage, current, filtering) of the X-ray generator. This approach is demanding in term of X-ray generator technology and is requiring time to carry out several acquisitions of a same object. We propose an alternative approach by using a spectrometric X-ray detector; this type of detector counts the detected photons and classifies them in energy channel. The main advantage of such an approach is to provide information on X-ray attenuation at a wide range of energy channels from a single X-ray shot.

In a first part we will describe a technology of spectrometric detector based on the use of CdTe or CdZnTe semi-conductor material and present an overview of its main characteristics. In a second part we will show how spectrometric detectors can be used in order to improve detection and identification of illicit material concealed in parcels and point out main advantages of CdTe/CdZnTe detection technologies for this objective.

2.0 CdTe/CdZnTe SPECTROMETRIC DETECTORS

Most of the nowadays digital detectors used are based on an indirect conversion of X-ray: X-ray conversion occurs in a scintillator and the light produced is converted to an electrical signal in a Thin Film Transistor (TFT) array or Charged Coupled Device (CCD) [1]. For now more than 10 years, a new technology of detection based on the use of semi-conductor detectors has been studied. It is based on a direct conversion of X-ray photons in an electrical signal in a single material [2]. One of the main advantage of this technology is to provide the possibility to process electrical signal of each detected photon and therefore to count the number of detected photons and to characterize each photon in term of energy. Different semi-conductor materials can be considered, CdTe/CdZnTe is one of the most promised candidate which presents properties adapted for X-ray detection [3]. This material has been more precisely studied and used at CEA-LETI for the development of gamma-ray and X-ray detectors.

As shown on Figure 1, the principle of a direct semi-conductor detector is at first the conversion in the semi-conductor material of an incoming X-ray photon in an electron and the generation of electron-hole pairs. An electric field is applied across the detector thickness which enables collection of the electrons and the holes by the electrodes. This collection provides an electrical signal representative of the energy of the X-ray photon. Then an electronic chain acquires, forms, and processes this signal in order to count the photon and to determine its energy.

One of the main advantages of CdTe/CdZnTe semi-conductor detectors is that they work at room temperature and do not need any mean of cooling while providing a good energy resolution of the detected spectra. Figure 2 compares the resolution of the spectrum for different technologies of spectrometric detectors. One can observe that the best resolution is obtained with a Germanium detector, but such a detector needs cumbersome nitrogen cooling. An indirect spectrometric detector based on an association of a scintillator (NaI) and a photomultiplier (PM) works at room temperature but leads to a poor spectrum resolution.

A second important advantage of CdTe/CdZnTe is the possibility to develop structured matrix of pixels and therefore to carry out dedicated X-ray and gamma-ray imagers.

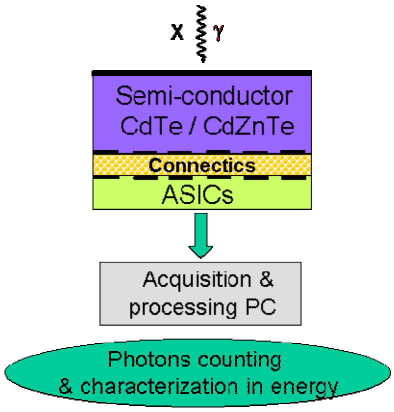


Figure 1: Principle of detection and processing in a semi-conductor CdTe/CdZnTe detector

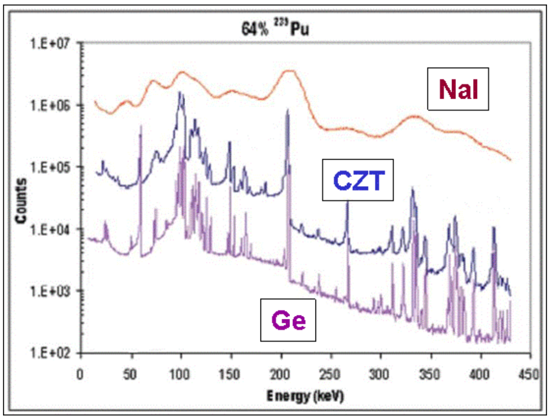


Figure 2: Comparison of an acquired spectrum for different types of spectrometric detectors

As described on Figure 3, the development of such detectors relies on the association of different complementary skills. A first step is to design the geometry and to choose adapted properties of the material for the application. These choices and design are based on the use of a laboratory simulation tool [4, 5] which models the different phenomena of signal formation in CdTe/CdZnTe material. A second step consists in connecting the material to the electronic and then to develop an acquisition and a processing electronics in order to provide the acquired signal. Then this signal is processed in order to provide the energy of the detected photon and to build up the spectrum [6]. CEA-LETI presents all these competences enabling to develop detectors dedicated to specific applications.

CEA-LETI has developed such detectors for a wide range of applications. Figure 4(a) presents a portable probe developed at CEA-LETI for detection and automatic identification of radio-isotopes. Figures 4(b) and 4(c) show examples of spectra obtained with CdZnTe semi-conductor probes.

Developments carried out to associate a pixelated monolithic detector of CdTe/CdZnTe semi-conductor to an integrated pre-amplifier electronic and with suitable signal processing have led to new 2D spectrometric imagers. Figure 5(a) shows the new CdZnTe pixelated module, and figure 5(b) its associated readout electronic. Figure 5(c) shows an example of spectrum obtained at a pixel for this new gamma-ray imager.

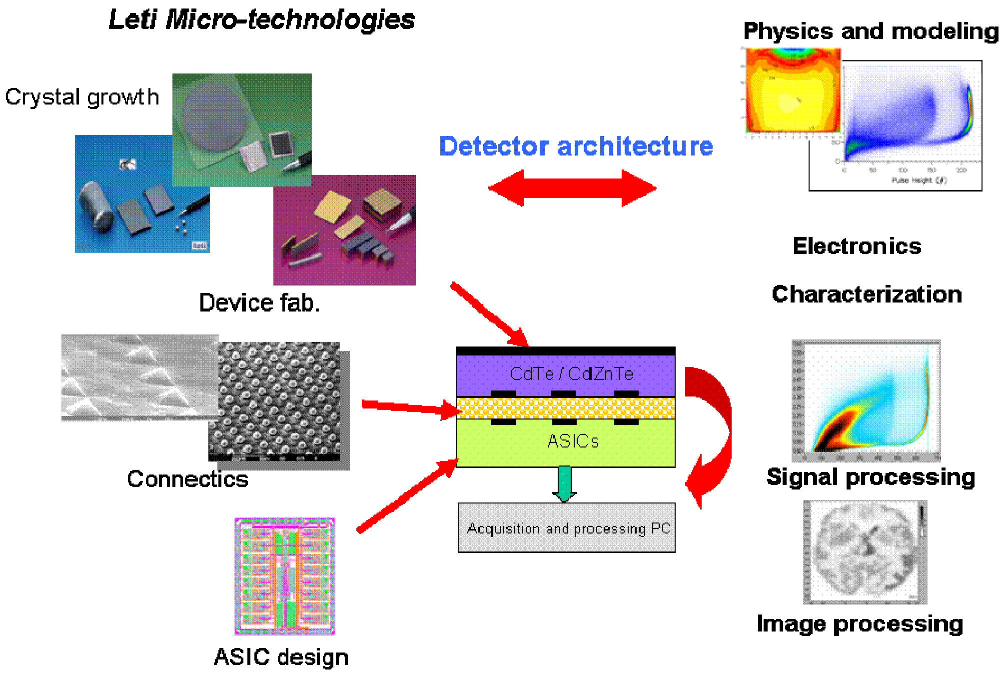
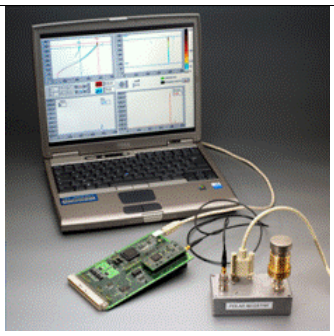
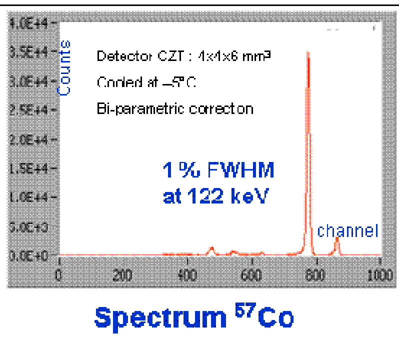
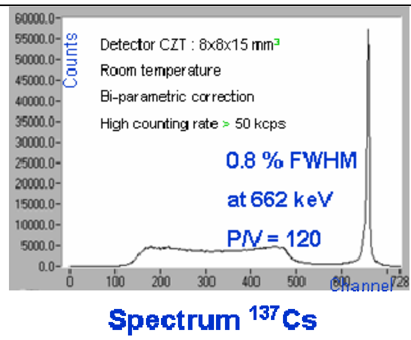


Figure 3: Spectrometric detectors development at CEA-LETI : from material to imaging







(a) portable and compact gamma probe	(b) example of spectrum obtained with a low energy probe	(c) example of spectrum obtained with a high energy probe

Figure 4: Examples of developments of CdTe/CdZnTe probes for radioisotopes detection and identification

New radiographic detectors, based on the use of CdTe/CdZnTe semi-conductor material, are now being studied and developed [7,8]. Compared to standard radiographic detectors, they present spectrometric capabilities, i.e at each pixel of detection they provide an energy spectrum. The main difference with gamma-ray imager is the necessity to take into account higher flux rates corresponding to radiographic imaging. In next part we will present advantages brought by these new X-ray spectrometric detectors for detection and identification of illicit material concealed in parcels.

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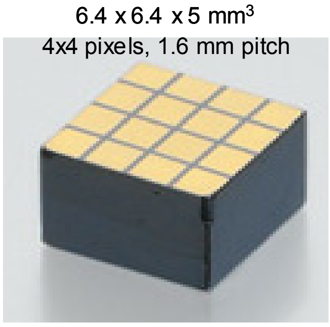
<td>
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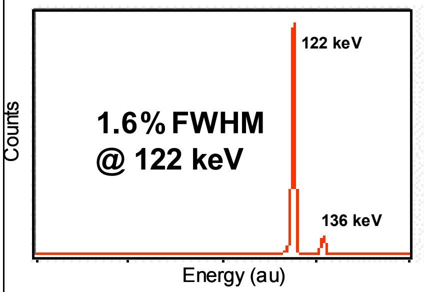
<td>
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<td>(a) New CdZnTe pixelated detector</td>
<td>(b) Associated electronic readout</td>
<td>(c) Spectrum obtained at one of the pixels of the imager</td>
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Figure 5: Main components of a CdZnTe spectrometric imager and example of spectrum

3.0 CdTe/CdZnTe SPECTROMETRIC DETECTORS FOR EXPLOSIVE DETECTION

3.1 X-ray detection of explosives

As mentioned previously and illustrated on Figure 6(a), a single radiograph of a parcel or a luggage only provides information on the shape and on the X-ray attenuation properties of the observed objects. This information remains too poor for an efficient detection and identification of illicit or dangerous material in the parcel. Illicit materials can be dissimulated by presenting benign shapes and the only attenuation information is insufficient to precisely decide of the potential risk of the observed materials. In order to refine information, some detection systems use a dual energy acquisition, based on the combination of two radiographs obtained at two different X-ray energies of irradiation. As shown on Figure 6(b) this imaging technique provides in addition to the shape of the objects discrimination between organic and inorganic materials. This information enriches significantly the examination; however it would be very useful to be able to distinguish dangerous organic materials from materials of common use.

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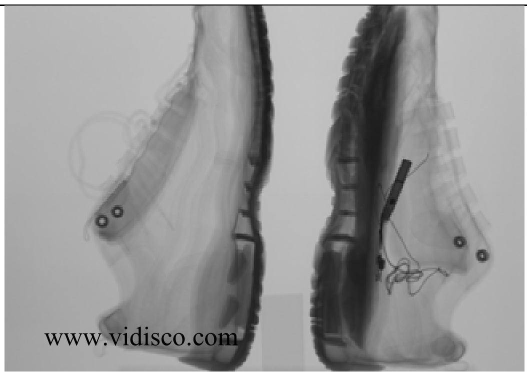
<td>
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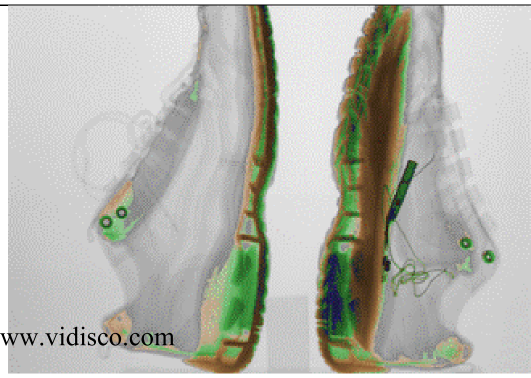
<td>
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<tr>
<td>(a) a single X-ray image : provides essentially information on the shape of examined object</td>
<td>(b) dual-energy radiography : the combination of two acquisition at different energies provide a discrimination between organic and inorganic materials.</td>
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Figure 6: Radiographic examination by X-ray imaging by using standard X-ray detection chains

3.2 Multi-energy X-ray imaging

Studies based on the use of more than two energies of X-ray irradiation [9, 10] have shown that the combination of information obtained from six energies of irradiation significantly increases capacities of discrimination between the nature of materials present in a parcel. One difficulty of such an approach is its technical implementation and its strong requirements in terms of X-ray generator capabilities. In order to get good performances of identification of materials, it is essential to reach a good separation between the different irradiation spectra. This requires switching the tube working point across a wide range of energies and for each irradiation to associate an adequate filtration.

The same kind of information can be obtained by irradiating an object with a large X-ray spectrum and to detect with a spectrometric detector: it provides attenuation information in each energy channel of the spectrometric detector, as would be obtained by acquisitions at each energy of the different channels. Combination of information between the different channels enables to significantly improve the characterization between the materials. Therefore the use of a spectrometric detector enables to get multi energy information on the observed object from a single radiographic irradiation. Compared to a multi-energy irradiation, it is easier to use and it enriches the provided information.

3.2 X-ray diffraction analysis

Studies [11] have shown that the spectrum of the small angle scattering represents a signature of the nature of an observed material. The principle of acquisition of small angles X-ray signature is presented on Figure 7. Figure 8 shows examples of signatures of different illicit and current materials. Acquisitions of such signatures require a high resolution in energy of the detector. They can be obtained by the use of a Germanium spectrometric detector but at the price of cumbersome nitrogen cooling system. Use of CdTe/CdZnTe spectrometric detectors enables to get a signature with an adequate energy resolution while working at room temperature. Moreover, as it is possible to develop linear or 2D CdTe/CdZnTe spectrometric detectors, acquisitions can be parallelized and significantly fastened (see Figure 9).

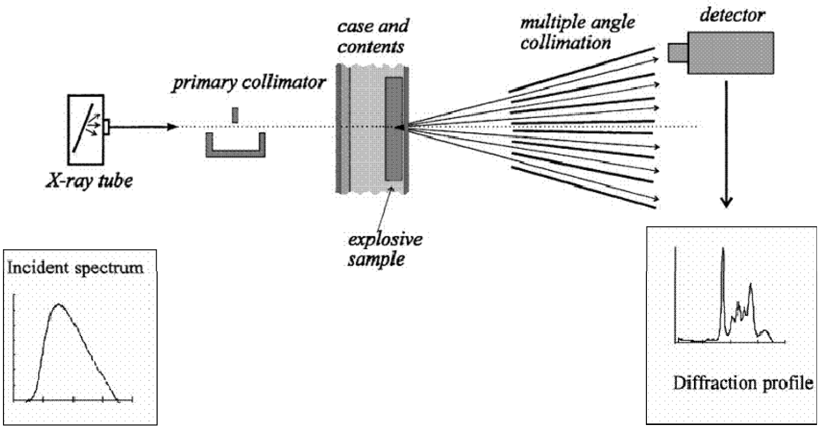

Figure 7: Principle of small angle scattering profiles acquisitions
(taken from *"A CdZnTe array for the detection of explosives in baggage by energy-dispersive X-ray diffraction signatures at multiple scatter angles"* C.H. Malden et al., NIMA, 2000)

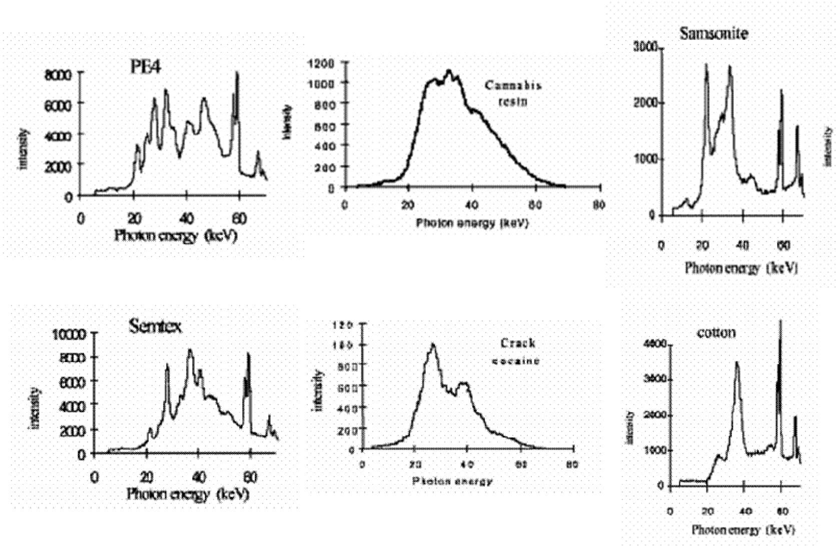

Figure 8: Examples of small angle scattering profiles for different material
(taken from *"Radiation-based security"*, R. Speller, Radiation Physics and Chemistry, 2001)

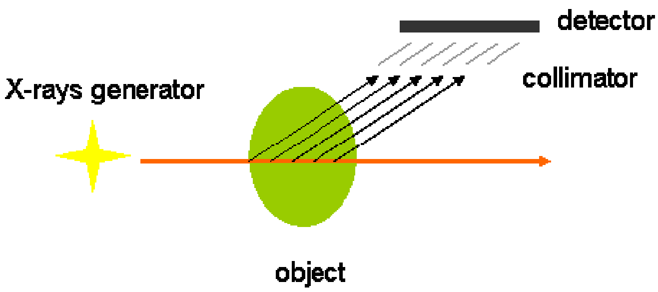

Figure 9: Possibility to design linear or 2D geometries of CdTe/CdZnTe detectors enables to parallelize small angle scattering acquisitions.

4.0 CONCLUSION

Presently X-ray remains one of the major mean to inspect the content of suspicious parcels. Single radiograph and dual energy X-ray approaches provide information on the shape and on the organic/inorganic nature of the content. The use of spectrometric X-ray detectors provides multi-energy information which enables to refine the characterisation of the nature of the content. Moreover addition of spectrometric information from the small angle scattering refines identification by providing information on the molecular structure of the observed materials.

CdTe/CdZnTe semi-conductor detectors provide spectrometric information with a good energy resolution, well adapted to multi-energy imaging and to small angle scattering profiles analysis. Compared to Germanium spectrometric detectors, which provide high energy resolution but need to be cooled, CdTe/CdZnTe spectrometric detectors work at room temperature. Therefore, they can be easily be used in the different systems (portable, check points, luggage control) of detection and identification of illicit materials in parcels. Moreover, they can be pixelated and therefore it is possible to develop linear or 2D detectors enabling a parallelization of the acquisitions which fastens significantly the acquisition process. As these detectors can also be designed for detection and identification of radioisotopes, it is possible, on the same technological basis, to develop portable probes or imaging systems for detection of nuclear material.

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