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A test device for isotopic γ-ray imaging with CdZnTe detector

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Abstract A test device for isotopic γ-ray imaging, which consists of an isotope γ-ray source, a CdZnTe γ-ray spectrometer and other auxiliary equipment, is studied here. Compared with the conventional X-ray, the isotope γ-ray, which is utilized in this project, has its own advantages in imaging. Furthermore, with a room-temperature high-energy-resolution CdZnTe detector and a modern imaging processing technique, this device is capable of effectively suppressing the background and gaining more information, thus it can obtain a better image than conventional X-ray devices. In the experiment of PCB imaging, all soldered points and chip components are sharply demonstrated.

Keywords Imaging, Isotopic γ-ray, CdZnTe detector

CLC number TL8

1 Introduction

Radiography, which is an important approach for industrial and medical detection, has been evolving fast as the development of information technology and detectors[1]. Compared to radiography using X-ray source, which has been widely used, an isotope-γ source has a discrete energy spectrum. Suppose a γ-beam of mono-energy passes through a sample of x thickness, which has a fixed mass attenuation coefficient, μ, and if a detector responding to γ energies accepts the beam behind the sample, and the counts in a given energy window are read out from the detector, the simple exponential law of the narrow beam of mono-energy is strictly followed. It is expected that there are some well-known advantages in the test system with isotope-γ source plus energy discrimination (simplified as γ system), compared with the one with continuous-energy X-ray source plus counter (simplified as X-system). For one example, γ system is able to suppress the scattering background; for another example, mass attenuation coefficients for γ-rays of different energy could be gained at the same time, if the isotope-γ source radiates a mixture of several mono-energy rays. To explore the potentials of the γ system, a test desk combining the γ-ray source of ^{241}Am with CdZnTe spectrometer has been built. The following paragraphs are arranged to demonstrate the performance of the γ system in this test desk.

2 The test desk

The test desk consists of a collimated γ-beam of 59.5keV from the ^{241}Am source, the sample table, which is capable of 3D programmable movement (horizontal, vertical, and rotatory), and the CdZnTe spectrometer. The whole system diagram is shown in Fig.1. The spectrometer consists of a CdZnTe detector, an amplifier, and a Multi-Channel Analyzer (MCA) card plugged into the online PC. The detector, which is produced by eV Products, is equipped with a 10 mm × 10 mm × 4 mm CdZnTe crystal. The energy spectra of γ-rays from ^{241}Am are displayed in Fig.2. The photo-electric peak of 59.5 keV reaches 5% energy resolution, X-ray escape peaks of Te and Cd elements, and Np-X-ray peaks are also clearly shown.

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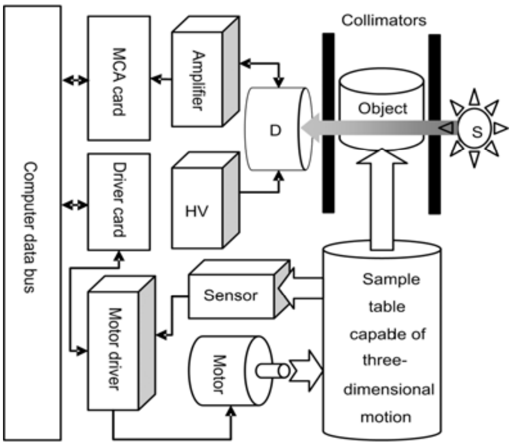

Fig.1 System diagram.
D: CdZnTe detector; S: ^{241}Am source. Line: electronic connection; Hollow arrow: mechanic connection; Solid arrow: beam of rays.

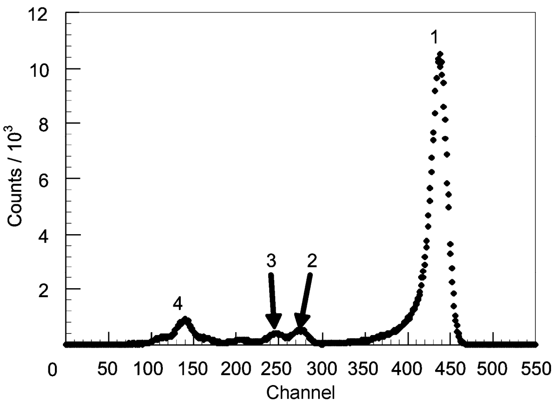

Fig.2 ^{241}Am γ-ray spectra.
Peak 1: 59.5keV photo-electric peak (resolution: 5.0%); Peaks 2,3: X-ray escape peaks in CdZnTe detector; Peak 4: Np *L*X-rays (13.9keV and 17.8keV).

The test sample is located on the table crossing the well-collimated γ beam (width of the beam depending on the collimators) between the source and the detector. The steps and timing of both x and y movements are programmed according to the test requirement. Counts in the total areas of the photo-electric peak and escape peak with samples out of the γ-beam are measured as the initial intensity of the γ-beam I_0. The counts in the total area of the same peaks when the sample is in a given position (x,y) are measured as the intensity of $I(x,y)$. The spectrum on each position (x,y) is formed in the MCA card and then moved to the PC buffer to abstract peak information. $I(x,y)/I_0$ is expressed as the color at point (x,y) in the original image according to an adjustable count-color mapping and the final image is enlarged by bi-cubic or spline interpolation.

3 Property of 59.5keV γ-ray related to imaging

First, for a beam of a given energy, there is an optimal thickness, which refers to the thickness of a homogeneous sample being measured with the smallest relative error in the same measuring time. This could be proved as follows. After the rays of single energy pass through an object of thickness x and a uniform density ρ, the intensity of the ray would drop from I_0 to I, then

$$I = I_0 \mathrm{e}^{-x\mu\rho} \tag{1}$$

On the basis of Eq. (1), the thickness of the sample can be calculated using the following expression:

$$x = \frac{1}{\mu\rho}\ln\left(\frac{I_0}{I}\right) \tag{2}$$

Provided the counting rate of the source is n_0, the detected counting rate is n, and counting time is t, the relative error of x is expressed by

$$\frac{\Delta x}{x} = \frac{1}{\mu\rho x\sqrt{nt}} = \frac{1}{\mu\rho x\sqrt{n_0 t \mathrm{e}^{-\mu\rho x}}} \tag{3}$$

When the derivative of the above expression is 0, that is,

$$x = x_{\mathrm{Best}} = 2/\mu\rho \tag{4}$$

Eq (3) can be reduced to

$$\frac{\Delta x_{\mathrm{Best}}}{x_{\mathrm{Best}}} = \frac{\mathrm{e}}{2\sqrt{n_0 t}} \tag{5}$$

Meanwhile, $n_0/n=\mathrm{e}^2 \approx 7.4$. It is x_{Best} that the optimal thickness is. On the basis of the conclusion of Eq. (4), x_{Best} of various materials could be calculated in Table 1. It would be best that the sample's thickness varies around the optimal thickness to get a clear image.

Secondly, the proportion between mass attenuation coefficients of different materials is distinctive. As to ^{241}Am γ-rays, mass attenuation coefficient[2] varies discontinuously with the chemical elements (Fig.3). As the atomic number (Z) changes from 20 to 68 or 70 to 100, the mass attenuation coefficient grows considerably. However, it dramatically drops more than four times when Z is between 68 and 70 (because 60keV is just between the absorption edge of the sixty-eighth element and that of the seventieth one). Thus, using γ-rays of ^{241}Am, a small quantity of heavy metal such as Fe, Cu, or Sn can be distinguished easily from a massive organism or light metal such as Al, because their attenuation coefficient might differ by one or two orders of magnitude. Furthermore, it is also possible that elements of 50< Z<68 could be identified from those of 80>Z>70, if they had similar mass thickness.

Table 1 Optimal thicknesses of various materials for 60 keV γ-rays

Materials in common solid state	Z	μ /cm^2•g^{-1}	ρ /g•cm^{-3}	x_{Best} /cm
Al	13	0.3	2.70	2.6
Fe	26	1.200	7.87	0.212
Cu	29	1.580	8.96	0.141
Sn	50	6.550	7.29	0.042
W	74	3.670	19.3	0.028
Pb	82	4.940	11.34	0.036
Water	---	0.21	1.00	9.751
Glass* (ex. SiO_2)	---	0.250	~2.5	~3
Organism * (ex. C_2H_4O)	---	0.194	~2	~5

* Because the component of glass and organism varies, the optimal thicknesses can only be estimated.

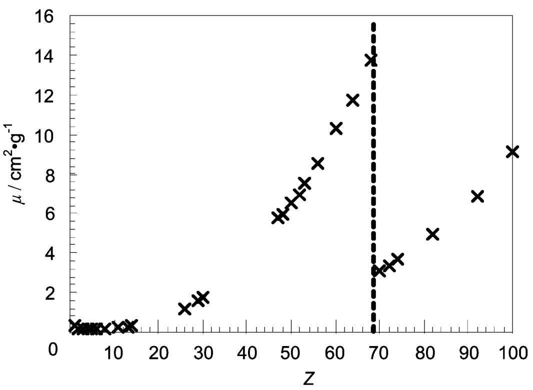

Fig.3 Mass attenuation coefficient of 60keV γ-rays for some of the chemical elements.

4 Spatial resolution

To obtain spatial resolution of this system, firstly, Edge Response Function (ERF), which stands for the response of the system to a sharp edge sample, is measured (Fig.4 (a)). Data point is obtained by imaging the edge region of a completely absorptive iron plate. Horizontal axis of Fig.4 (a) is the displacement perpendicular to the edge of the iron plate, and vertical axis is the counts in the area of the photo-electric peak in 20 seconds. Then Point Spread Function (PSF), which means the response of the system to a delta function, is obtained by calculating the derivative of ERF (after a fit and smooth process) and normalizing the peak value. FWHM of PSF, which is the space resolution of this system, is 0.74 mm as shown in Fig.4 (b). If the diameter of the collimator is enlarged from the original 1 mm to 2 mm, FWHM of PSF changes to 1.34 mm, which is approximately doubled too. Thus, the spatial resolution is controlled mainly by the diameter of the collimator, which also suggests that the background of this system is low.

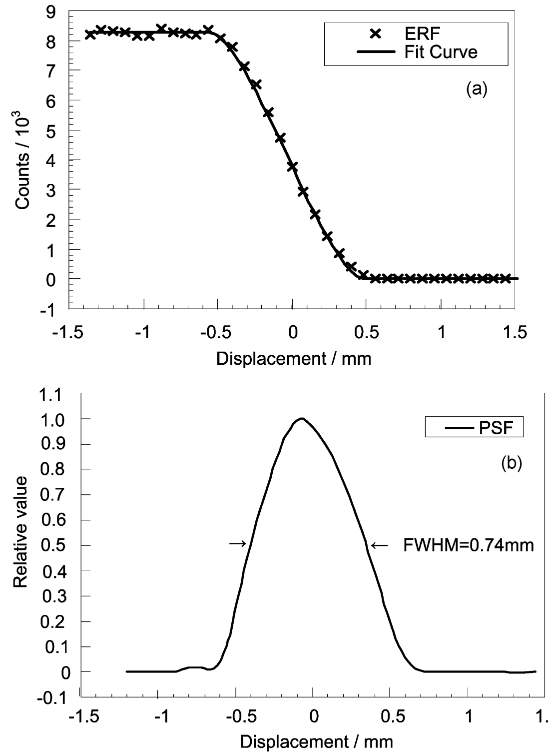

Fig.4 (a) Edge Response Function (ERF) and (b) Point Spread Function (PSF) of this system.

5 Demonstration of imaging capability

As an instance of application, a printed circuit board (PCB) for PM R7400U is scanned. On the basis of the information in Fig.3 and Table 1, Sn is among the elements with the highest absorbency of ^{241}Am γ-rays; because even a 1 mm block tin would reduce the intensity of the rays by two orders of magnitude. Thus it can be expected that this device will check soldered points on PCBs. With rays perpendicular to the PCB, as in Fig.5 (a) and (b), using different count-color mapping, two images can be obtained as

(c) and (d). In (c), only soldered points, whose attenuation coefficients are much higher than others are expressed, whereas in (d), all soldered points, socket of PM, chip resistor, and chip capacitor can be identified. A part of the wires is also visible in (d). However, the PCB board, which is composed of light elements, has too little absorption to the 59.5 keV γ-ray. Thus it cannot be seen on (c) or (d). But, the X-Ray of ^{241}Am is sensitive to the PCB board. Thus a second image, Fig.5 (e), can be formed on the spectrum by utilizing the X-ray peak (Peak 4 in Fig.2). Even a small hole on this board can be seen on the final image. With 1 mm detector collimator and 40 second per pixel, the original image reaches a size of 43 × 20 pixels (34.4 mm × 16.0 mm), that is, 0.8 mm × 0.8 mm per pixel. Maximum count of γ photons per pixel is 5440, whereas minimum count is 8.(c)-(e) are enlarged by bicubic interpolation.

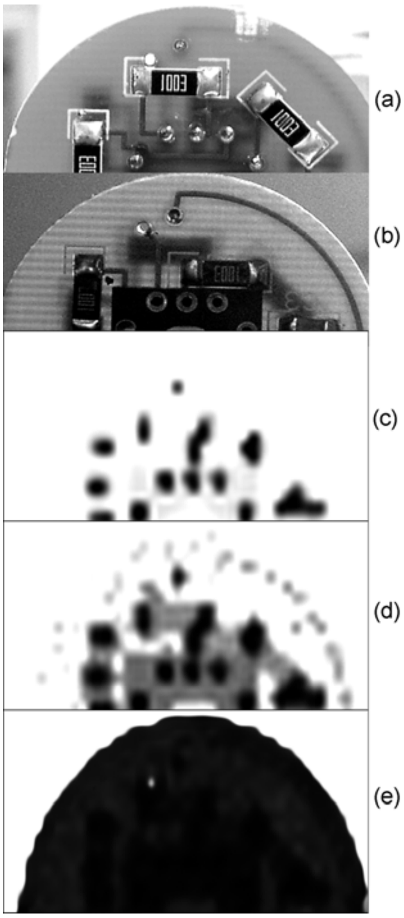

Fig.5 Three different images for a PCB in one scan.
(a) Photo of horizontal mirror image of back view; (b) Photo of front view; (c) Soldered points image; (d) Image for soldered points, socket of PM, chip electric components and part of wires; (e) Detailed edge of PCB board. In one scan, (c), (d) is based on peak area of 59.5 keV γ-ray, whereas (e) is based on peak area of X-Ray (Peak 4 of Fig.2).

It is true that Sn is easy to detect, however, organisms whose thickness is only several-centimeters, can also be imaged expediently. A package of cigarette, which is just thick enough for detection, is scanned (Fig.6 (a)). Compared to (b), the profile of every cigarette is obvious in (c). However, the skin of the cigarette cannot be seen here. With 1 mm detector collimator and 50 second per pixel, the original image reaches a size of 30 × 20 pixels (15.0 mm × 10.0 mm), that is, 0.5 mm × 0.5 mm per pixel. Maximum count per pixel is 6635, whereas minimum count is 3731.

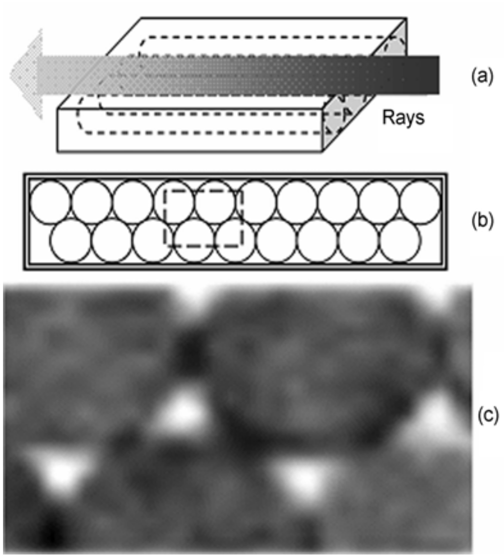

Fig.6 γ-ray image for unpacked cigarette.
(a) Diagram, (b) Viewing parallel to rays, dashed square frame is the scanning area, (c) Image enlarged by bicubic interpolation.

6 Conclusions

Despite the low counting rate, this prototype can be improved by using stronger source or detector arrays. From the discussion and experiment mentioned above, a conclusion can be reached that the imaging system of isotopic γ-ray plus the ZnCdTe spectrometer have their own advantages: efficiency in utilizing information brought by rays and anti-background. Successful experiments on PCB and cigarettes also indicate that this device has potential value for industry and customs inspection.

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