arXiv:physics/0207089 v1 23 Jul 2002

Scintillator-photodiode type detectors for multi-energy scanning introscopy

V.D. Ryzhikov, S.V. Naydenov, D.N. Kozin,
E.K. Lisetskaya, A.D. Opolonin, V.M. Svishch, T.V. Kulik

Concern "Institute for Single Crystals" of the National Academy of Sciences of Ukraine

Results of experimental studies of detector arrays S-PD (scintillator-photodiode) and PRD (scintillator-photoreceiving device) used for X-ray digital radiography have shown that there exist further possibilities to increase spatial resolution of this system up to 2-3 line pairs per mm. Theoretical analysis and experimental studies show that the two-energy detection method not only allows one to detect organics on the background of metal, but also substantially increases (by 3-5 times) the detection ability of the system as a whole, especially if parameters of the S-PD pair are optimized, in particular, when ZnSe(Te) is used in the low-energy circuit. A possibility to distinguish, in principle, between substances with insignificant differences in atomic number has been theoretically proven – by transition to multi-energy radiography. 3D-imaging has been realized using S-PD detector arrays.

1 Introduction

X-ray digital radiography is a rapidly expanding and one of the most important methods of modern non-destructive testing [1]. In this method, alongside with the use of luminescent screens with subsequent transformation of the image onto SCS-matrices (spatial charged systems), one of the main technical solutions is conversion of the penetrating X-ray radiation by the detector array of "scintillator-photodiode" (S-PD) type with its subsequent amplification and digitalization of the signal.

Advantages of SCS-devices are instant imaging of all the object and high spatial resolution (3-5 line pairs per mm). Their disadvantage is a limited energy range, consequently, limited steel thickness of the inspected object, as well as higher costs, as compared with S-PD arrays.

In non-destructive testing systems using S-PD arrays it is possible to use scintillators of different atomic number, density and element length, which allows working in the energy range from 20 keV to 16 MeV, i.e., steel equivalent thickness is from 100 μm to 300 mm. The use of two-energy detection systems solves the problem of distinguishing between substances of similar density, but different effective atomic numbers. Both these qualities are not attainable for SCS-matrices.

Our task in developing this method consisted in the maximum use of its advantages. Specifically, we aimed at increased sensitivity and detecting ability due to optimization of parameters of the S-PD pair and an extensive use of the features of two-energy radiography. Transition to multi-energy radiography was envisaged for detection of substances with close values of the effective atomic number. The resolution was to be increased due to modernization of the design and making smaller the detector aperture. And, finally, passing from two- to three-dimensional imaging was also essential.

The above-listed directions in the system improvement were the aims of our studies in this work.

2 Experimental procedures

Measurements of the detector sensitivity and light output of the crystals were carried out on a testing board using X-ray sources IRI ($U_a = 40 - 200kV$, $I_a = 0.4 - 1.0mA$, W-anode) and REIS ($U_a = 5 - 45kV$, $I_a = 5 - 50\mu A$, Ag-anode) and an optical power meter "Kvarts-01". Time characteristics were measured using a testing board designed for afterglow measurements [2].

To obtain shadow X-ray images, we used testing boards "Poliscan" (a 128-channel array of photodiode-based detectors) and "Photocell" (for 32-, 64-, 128- and 1024-channel detectors based on PRD). Using the Photocell board, sixty 2D-images of a small object were obtained at different angles (with step 6), from which a 3D image was reconstructed.

For detection of X-ray radiation, we used detector arrays of types S-PD and PRD. Detectors of PRD type includes an array of photodiodes (32, 64, 128 and 1024 channels), amplifier and commutator mounted on one silicon crystal.

We used standard scintillation crystals CsI(Tl), $CdWO_4$ and an original scintillator ZnSe(Te) developed by STC "Institute for Single Crystals" [2].

Parameter	ZnSe(Te)	CsI(Tl)	$CdWO_4$
Conversion efficiency	19,4	15	3,5
Decay time τ, μs	5-7	1	5-7
Density, g/cm^3	5,4	4,5	7,9
Effective atomic number, Z_{eff}	33	52	66
Luminescence maximum λ_m at 300 K, nm	610	570	490
Afterglow, % (after 10 μs)	0,05	1-8	0,05
Absorption coefficient at λ_m, cm^{-1}	0,1-0,3	0,05	0,02-0,05
Refraction coeff. at λ_m	2,4	1,79	2,25
Total internal reflection angle γ for n_1=1,4 n_2=1,5	37° 40°	$57{,}17^\circ$ $63{,}25^\circ$	$42{,}75^\circ$ $16{,}45^\circ$
Spectral matching coefficient with Si-PD, K_{SC}	0,49	0,34	0,27
Radiation stability limit, rad	10^8	10^4	10^7
Energy of K-jumps, keV	9,7 12,6	33,2 35,9	26,1 69,5

Table 1: Characteristics of scintillators used in "scintillator-photodiode" system.

The photodiodes used were obtained from producers CCB Ritm, SPO Bit, Ukraine, and Hamamatsu, as well as PRD from SPO Bit.

Main parameters of scintillation materials for S-PD and S-PRD detectors are presented in Table 1.

3 Theoretic analyze of multi-energy radiography

In the recent years, an important role in the modern digital radiography has been taken by the so-called multi-energy method [1-3]. Its application in X-ray introscopy systems [4-5] is promoted by new inspection possibilities that are provided by this method as compared with conventional radiogra-

phy means. Thus, two- and three-energy introscopy systems can not only distinguish between organics and inorganics, but also discern one organic compound from another.

A physical model of the multi-energy radiography is based on the property of exponential attenuation of hard ionizing radiation in the inspected object. An important element of multi-energy systems is digital processing of data arrays that are coming simultaneously from detectors of different types. The computer does also allow presentation of the output signal in the most convenient form (logarithmic and normalized). Theoretically, multi-energy radiography is described by a system of linear equations [3]

$$R_\gamma = \sum_{\delta=1}^{M} M_{\gamma\delta} X_\delta; \quad M_{\gamma\delta} = \hat{M}\left(E_\gamma;\, E_\delta\right) \tag{1}$$

where $R_\gamma = R\left(E_\gamma\right) = \ln\left[F_0\left(E_\gamma\right)/F\left(E_\gamma\right)\right]$ is the system reflex; F_0 and F – output signals from the background (in the absence of an object) and from the object E_γ one of the selected radiation energies; M – the order of multi-energeticity. For two-energy radiography, $\gamma = 1, 2$; $\delta = 1, 2$ and $E_\gamma = \{E_1; E_2\}$. The unknown X correspond to physical parameters under control. The monitoring matrix $\hat{M}$ does not depend upon properties of the studied object. Its components are determined after calibration measurements on samples of the known composition (effective atomic number Z_δ and density ρ_δ) and thickness L_δ: $C_{\gamma\delta} = R\left(E_\gamma;\, Z_\delta, \rho_\delta, L_\delta\right)$.

In the two-energy radiography, the effective atomic number of an unknown material can be reconstructed using the formula obtained from the general equations system (1)

$$Z_{eff} = Z\left(Y\right) = Z_1\left[\frac{Y-\Delta_1}{Y-\Delta_2}\right]^{1/3}; \quad Y = \frac{C_{12}R_2 - C_{22}R_1}{C_{11}R_2 - C_{21}R_1} \tag{2}$$

Here auxiliary values are introduced: $\Delta_1 = \left(Z_2/Z_1\right)^3\left(\rho_2 L_2/\rho_1 L_1\right)$; $\Delta_2 = \Delta_1\left(Z_1/Z_2\right)^2$; Y is the reduced (relative) output signal. The expressions obtained depend only on radiographic measurement data $R_{1,2} = R\left(E_{1,2}\right)$ from the detector pair and the calibration (reference) data $C_{11}, C_{12}, C_{21}, C_{22}$ and Δ_1, Δ_2. It should be stressed that this is a direct method for determination of the effective atomic number.

We have to note that all the existing developments in the field of two- and even three-energy radiography involve only qualitative methods of effective atomic number determination. Their accuracy does not exceed 50% for

compounds with large Z_{eff}. Within these limits, it is possible only to distinguish between organics and inorganics, or heavy alloys (of iron, $Z_{eff} \approx 26$) from light alloys (of aluminum, $Z_{eff} \approx 13$). However, possibilities of the two-energy radiography have not yet been fully studied and used.

Our analysis have shown that the effective atomic number of the material can be reconstructed with the accuracy of 5-10% using the formula (3) (see Fig.1a). This is by an order of magnitude better than the highest level obtained by now. Obviously, such an improvement in diagnostics will allow one to identify inorganic and inorganic materials with much higher probability (up to 80-90%). This increase in sensitivity of effective atomic number determination is sufficient to allow detection of, say, explosives on the background of organic substances (and not just inorganics). Among practical application of this method is detection of plastic explosives inside postal parcels and letters, transported goods and merchandise, etc.

Thus, remaining within the limits of two-energy radiography, one can carry out quantitative diagnostics of the effective atomic number and density of materials with accuracy of 5-10% . There will be two controlling parameters, not one, which also contributes to the inspection efficiency. Moreover, transition from two- to three-energy radiography ensures better control not only of the effective atomic number, but also of atomic (molar) concentrations of a complex chemical compound. The number of reconstructed parameters corresponds to the order of multi-energeticity. In the case of organic compounds, it is possible to determine the relative content of two or three "heaviest" simple elements – carbon ($Z = 6$), nitrogen ($Z = 7$) and oxygen ($Z = 8$). As a result, there is a high probability to clearly distinguish between an explosive (with higher content of the latter two elements [7]) and other organic compounds. Combination of diagnostics involving atomic numbers and that involving concentrations of predominant atomic components seems to be a key factor in the solution of this important problem. It is essential that practical realization of the outlined approach is based upon the use of mobile multi-energy X-ray inspection systems for non-destructive testing, and not of large-sized and expensive installations of neutron technologies.

In X-ray customs inspection systems, distinction between organic and inorganic substances is made by the two-energy method, which consists in the following. The X-ray tube has a continuous spectrum (Fig.1b). Passing through the inspected object, the initial flux of X-ray radiation is partially absorbed, and in the luminescence spectrum the ratio of low-energy and high-energy contributions is changed. The higher is the effective atomic number

Z_{eff} of a substance, the smaller is fraction of the low-energy radiation. To determine the ratio between high- and low-energy parts of the spectrum, a "two-energy" detecting array is used, which consists of two detector arrays of S-PD type placed one after another. The array that is closer to the X-ray source is optimized for detection of low-energy (30-50 keV) radiation, and the second array, which is placed behind the first, is optimized for detection of high-energy (80-120 keV) radiation. The total signal from the low- and high-energy detectors is characterized by the product $\rho\, l$, where ρ is density of the inspected object, l is its radiation length. The ratio of these detector signals depends upon Z_{eff}.

We have carried out theoretical calculations for the following model of the two-energy system. As initial radiation spectrum, we took the spectrum of an X-ray tube at constant anode voltage (150 kV); the anode material is tungsten (Fig.1b). As inspected object, we selected sugar ($C_{17}H_{22}O_{11}$ – organics) and iron (Fe – inorganics). Two-energy detector arrays include two types of scintillators: the first one (closer to the radiation source) – ZnSe(Te) of thickness 0.5 mm, and the second one (behind the first) – CsI(Tl) of thickness 4 mm. Fluxes of optical quanta emerging in the scintillators under X-ray irradiation are considered as output signals. The calculated signal was normalized and conditionally transformed by a 12-digit analog-to-digit converter. Confidence intervals related to the quantum noises were calculated. The results are presented in Fig.1c.

4 Spatial resolution and detector sensitivity

Transition from the film radiography to the digital radiography has already resulted in important improvements in many fields as for productivity and quality of X-ray non-destructive testing. However, medical and non-destructive testing applications requiring detection of non-homogeneities of less than 0.5 mm size are related to the need to improve spatial resolution at least to 5-8 line pairs per mm .

Among principal ways to solve this problem, one could note – 1) development of multi-channel detector arrays with small step and low aperture; 2) using principles of geometrical optics to obtain expanded shadow images of the inspected object; 3) the use of various methods of mathematical processing for image analysis.

The first method is the most preferable, as it allows one to obtain a

shadow image of the object with the least possible geometrical distortions. However, this way to improve the resolution encounters significant technological and technical difficulties. Our experience in developing S-PD and S-PRD detectors, as well as detector arrays based thereon, have shown that development and production of multi-channel diode arrays with step $\sim 25\mu$ (up to one thousand channels on one silicon crystal) does not evoke major technological problems. However, compact placement of a large number of pre-amplifiers close to the diode array (a separate amplifier is required for each photodiode) becomes problematic already at the detector step of 0.8-0.4 mm . A solution to this problem could be found by placing PD, pre-amplifiers and the commutator upon one silicon crystal. On the basis of such photoreceiving devices (PRD), we have developed multi-channel detecting modules. A multi-channel detection module is a multi-channel (16,32, 64, 1024 channels) photoreceiver (PD or PRD), upon the photosensitive area of which a scintillator plate is attached by means of an optical adhesive [6].

Scintillator plates of the following types were tested:

- Plates of discrete scintillation elements (DSE) – one element per channel.
- Continuous solid plates of a single crystal (SCP) – by the size of the photosensitive area of a multi-channel photoreceiver.
- Plates of dispersed scintillator (DSP) – made of tiny calibrated particles of ZnSe(Te) crystals arranged into a monolayer and optical epoxy adhesive UP4-20-3M [3].

Fabrication of plates composed of DSE at the step of photosensitive elements in the array less than 0.8-0.5 mm is limited by technological difficulties. Therefore, with the aim of looking for alternative ways to improve the resolution, we studied properties of SCP and DSP. The plates were compared by two main parameters – light output and interference of the neighboring channels.

Comparative measurements have shown (Fig.2) that serious competition to DSE plates can come only from DSP. Interference of neighboring channels was studied for DSP prepared from ZnSe(Te) grains of different size (Fig.3). It is obvious that with smaller grain size the interference of neighboring channels is reduced. However, the DSP light output is also dependent upon grain size and has maximum at the grain size $\sim 0.5mm$ (Fig.4). Thus, using

DSP, it is possible to make detector modules with step of the photosensitive elements $0.2 - 0.5mm$ for detection of X-ray radiation in the energy range $20 - 80keV$. Resolution of 1-2 line pairs per mm can be achieved.

The use of laws of geometrical optics, namely, placing the inspected object much closer to the source of sharp focus than to the detector array, allows one, using DSE with step 0.8 mm, to achieve detecting abilities of 10-15 μm (Fig.5, microchip). Mathematical processing of the digitalized signal using a modern software can substantially increase the informativity of the image (Fig.6, the same chip).

The image quality is also determined by the choice of a scintillator. Accounting for much higher, as compared with CsI(Tl), quantum yield of ZnSe(Te) (by 20-30%), it has clear advantages for low-energy detectors. With higher energies (Fig.7), CsI(Tl) becomes preferable because of its high transparence. However, if there are requirements for low afterglow level or high radiation stability, ZnSe(Te) can be used up to the energies of 150-200 keV. At energies above $1MeV$, superiority goes to $CdWO_4$.

5 Discussion

Results of our studies have shown that in S-PD detectors for digital radiography the most preferable scintillators for the high energy region are CWO (0.5-1.0 MeV), CsI(Tl) (0.08-0.5 MeV), while in the low-energy region (20-60 keV) ZnSe(Te) is unchallenged.

Accounting for a trend in the modern digital radiography (both in the inspection and medical instruments) to use two-energy detector arrays, the combination of ZnSe(Te) and CsI(Tl)/CWO results in a new quality.

Effective atomic number Z of ZnSe is the same as of copper, which is usually used as a filter of the high-energy array. Therefore, if a detector with ZnSe(Te) as filter is placed before the high-energy array, this simplifies the design and improves technical characteristics of the detecting circuit as a whole [9].

A unique combination of properties characterizing the original scintillator ZnSe(Te) – high light output, fast response, radiation stability, rather low effective atomic number together with sufficiently high density – makes this material the best among known scintillators for the low-energy detector. Combination of crystals ZnSe(Te)/CsI(Tl) in the two-energy detector array has substantially improved the sensitivity of equipment designed for

detection of organic inclusions.

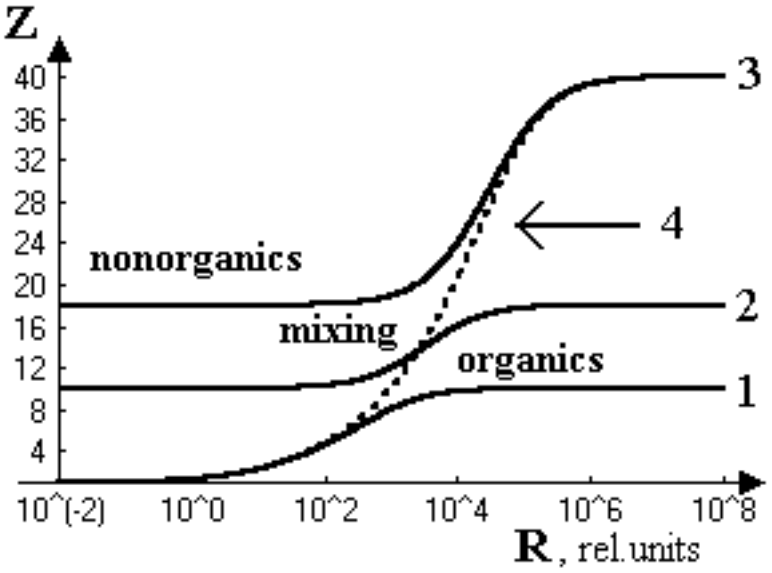
Theoretical estimates show that transition from the two-energy to multi-energy detection system will allow distinguishing between substances that differ in their effective atomic number insignificantly. In the applied aspect, this means a possibility to reliably (close to 100%) identify dangerous substances (explosives, drugs) on the background of metal or organics.

A logical way to better resolution in digital radiography is decreasing the aperture of a unit detector. Experimental data obtained in this work show that with the existing standard production technology of the arrays and the S-PD detector as a whole it would be very difficult to make them with step less than 0.8-1 mm. At the same time, if there is a discrete amplifier for each channel, requirements to the photodiode-preamplifier system become more complex. In this relationship, for detector arrays of step 0.05-0.8 mm that have been studied in the present work, it is desirable to pass over to a solid scintillation plate (single crystal or dispersed scintillator) and, in parallel, to replace the photodiode with a photoreceiving unit with an amplifier-commutator at the back side. This allows the use of just one amplifier channel after a photoline of 32-1024 channels of the photoreceiving device.

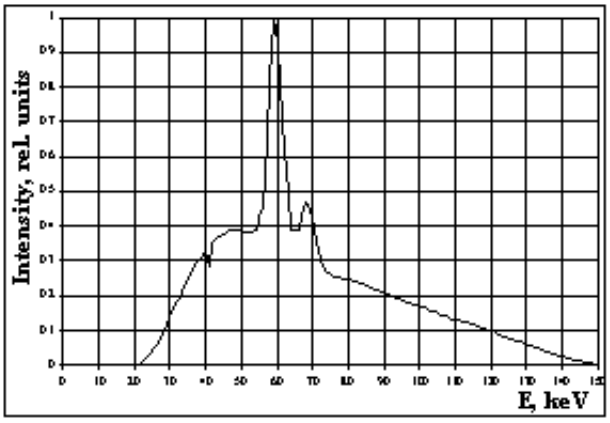
Limitations imposed upon detectors "scintillator plate – photoreceiving device" are, from the one side, the requirement for the plate to be thin as to decrease interference of the neighboring channels, which limits the energy range of the detector. From the other side, low radiation stability of modern PRD requires their shielding from radiation, i.e., their use at low dose loads, which is just the conditions used in inspection equipment and medicine. For systems of technical digital radiography and tomography, the preferable solution is discrete arrays S-PD, with ZnSe(Te) and CWO crystals of high radiation stability being the recommended scintillators, and photodiodes as p-n structures, desirably in the photogalvanic mode. Using such structures, after amplification under the laws of geometrical optics, we have obtained, in the tomographic mode with transition to 3D image, sufficiently high spatial resolution (Fig.8).

6 Reference

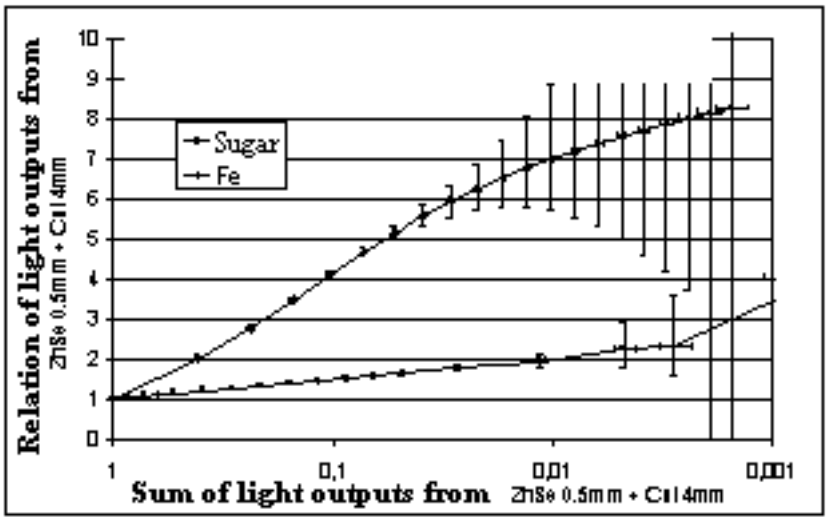
[1] R.M. Harrison, "Digital radiography – a review of detector design", *Nucl. Instr. and Meth.* **A310**, 24-34 (1991).
[2] V.D. Ryzhikov, N.G. Starzhinskiy, L.P. Gal'chinetskii, D.N. Kozin, V.P. Sokhin, A.D. Opolonin, V.M. Svishch, E.K. Lisetskaya, "Scintillator-photodiode detecting systems for two-level X-ray inspection systems", 15th World Conference on Non-Destructive Testing, Rome (Italy), 15-21 October, 2000, Abstracts Book, p. 466.
[3] S.V. Naydenov, V.D. Ryzhikov, "Determining Chemical Compositions by Method of Multi-Energy Radiography", *Technical Physics Letters* **28**, # 5, 357-360 (2002).
[4] Heimann, Prospects, 2002, **http://www.heimannsystems.com**.
[5] The X-Ray Introscopy System "Poliscan-4", Prospects, stcri@isc.kharkov.com.
[6] L.V. Atroshchenko, B.V. Grinev, V.D. Ryzhikov et al. (ed. by V.D. Ryzhikov), *Scintillator crystals and detectors of ionizing radiation on their base*, Kiev, Naukova Dumka, 1988 (in Russian).
[7] V.G. Volkov, B.V. Grinev, V.D. Ryzhikov et. al., "Small-crystalline detectors of ionizing radiation on the basis of ZnSe(Te)", *Pribory i Tekhnika Eksperimenta* (Moscow), No. 6, p. 37-42 (1999).
[8] Detection system for X-ray introscopy, Patent of Ukraine, No. 2001053401 from 21.05.2001.


Z
40
36
32
28
24
20
16
12
8
4
nonorganics
mixing
organics
3
4
2
1
10^(-2)
10^0
10^2
10^4
10^6
10^8
R, rel.units

(a)


Intensity, rel. units
E, keV

(b)



(c)

Figure 1: Two-energy method for determination of effective atomic number Z_{eff}. (a) Theoretical plots of the effective atomic number $Z\,(R)$ as function of the ratio $R = R_1\,/R_2$ of two output signals in the two-energy radiography inspection of Z_{eff} in different ranges: 1 – $[Z_1;\ Z_2] = [10;\ 1]$; 2 – [18; 10]; 3 – [40; 18]; 4 – [40; 1]. (b) Spectrum of X-ray tube with W-anode at 150 kV. (c) Calculated dependence of $R = R_1\,/R_2$ ratio on thickness of the studied object (for sugar and Fe) accounting for quantum noises of the analog-to-digit converter.

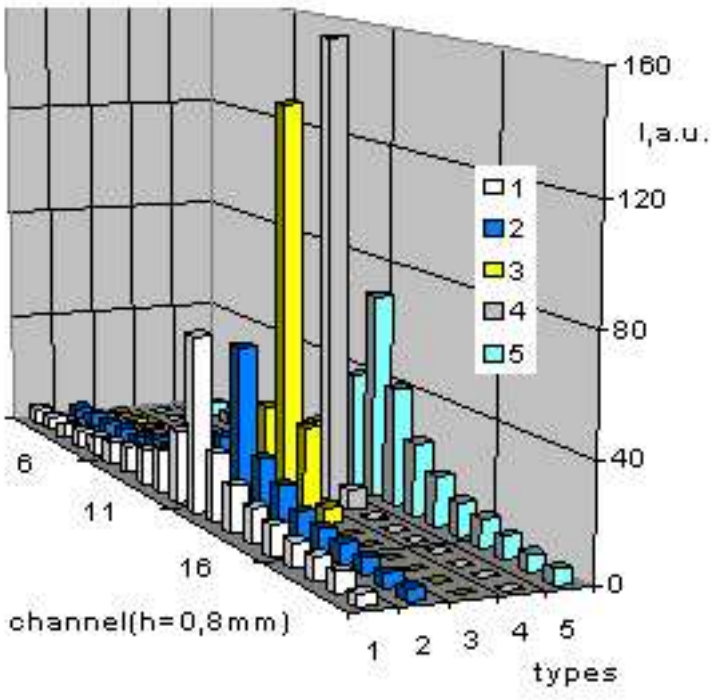


Figure 2: Mutual interference of neighboring channels for different scintillators and types of scintillation elements: 1 – single crystal plate ZnSe(Te) with $h = 0.8mm$; 2 – single crystal plate ZnSe(Te) with $h = 0.6mm$; 3 – composite small-crystalline plate ZnSe(Te) (grain size $0.4mm$); 4 – individual single elements for each channel; 5 – single crystal plate CsI(Tl) with $h = 0.8mm$.

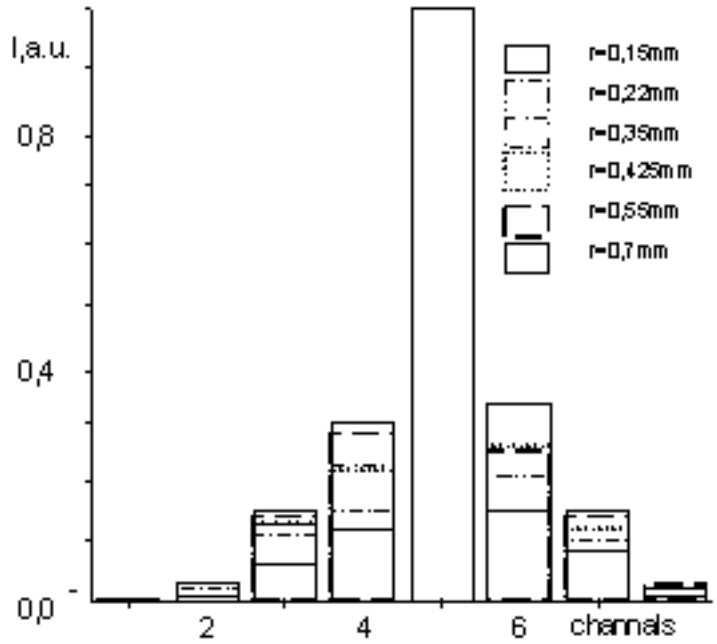


Figure 3: Interference of neighboring channels in 16-element detectors for a dispersed scintillation plate as function of ZnSe(Te) scintillator grain size.

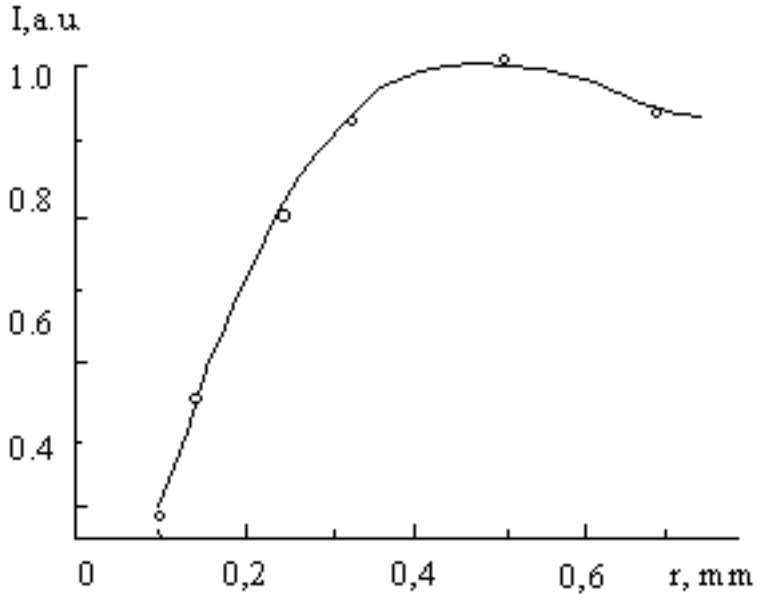


Figure 4: Light output dependence upon grain size.

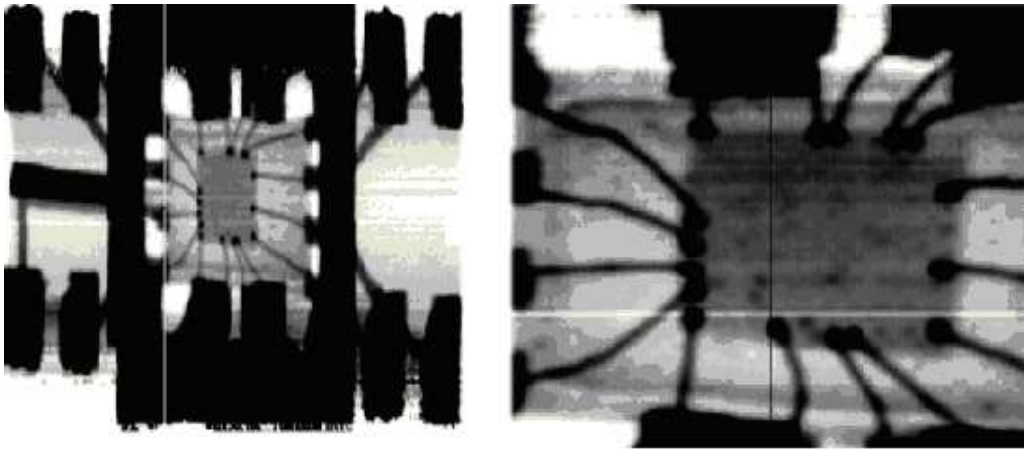


Figure 5: Internal connection wire pattern from the semiconductor crystal in a microchip.

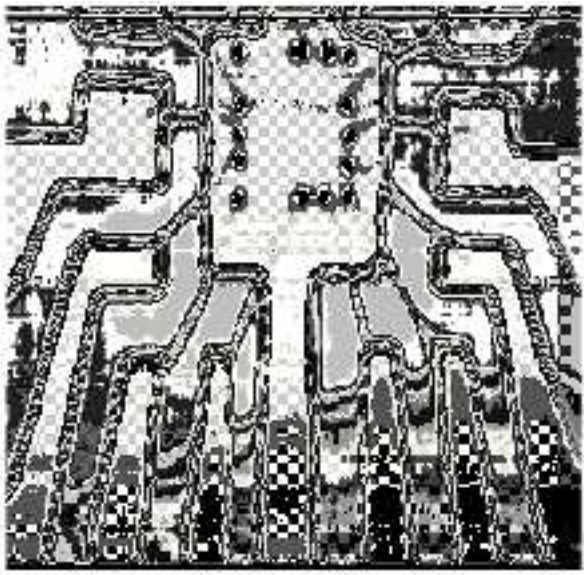


Figure 6: Microchip in plastic tank.

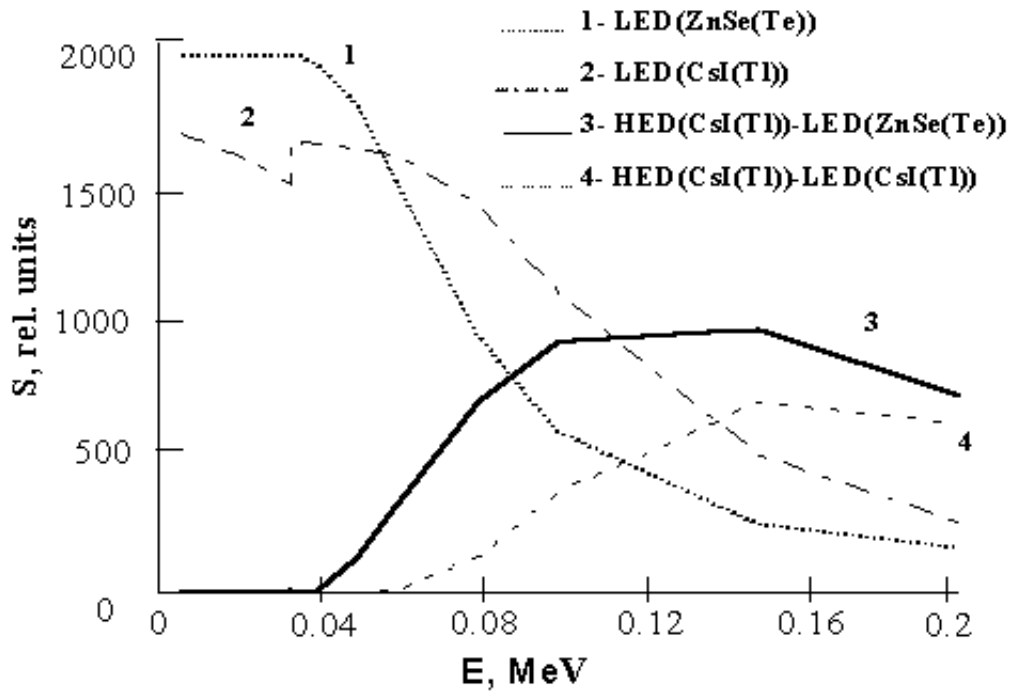


Figure 7: Sensitivity of detectors using CsI(Tl) and ZnSe(Te) as function of the radiation energy.

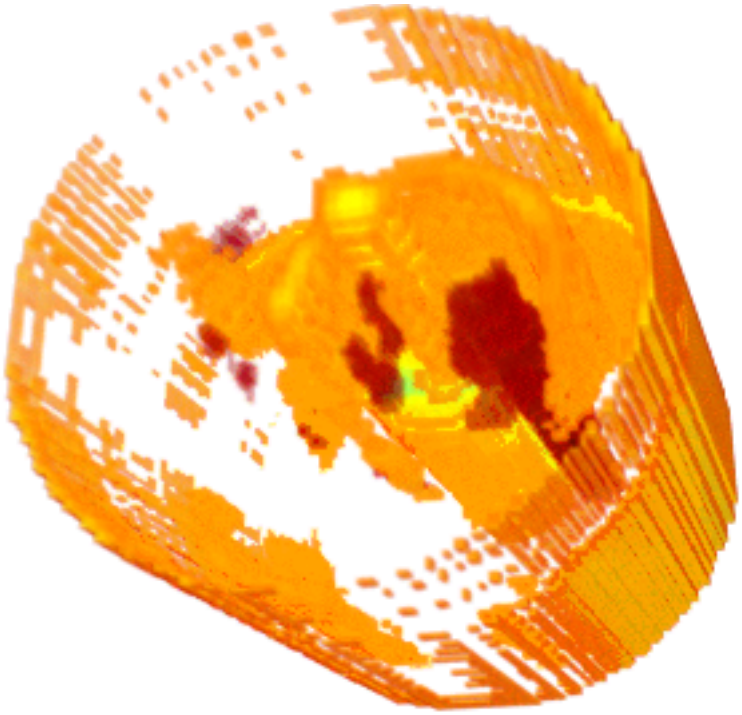


Figure 8: Tomographic image of the lighter friction head.