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Small-grained detector of ionizing radiation based on ZnSe(Te)

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Abstract. A highly efficient ZnSe(Te) scintillation detector combined with Si-photodiode has been developed. A conglomerate made up of ZnSe(Te) grains is used as a scintillator. Optimal shape of the grains, reflecting cover and disperse environment type are selected to improve light collection within the detector using numerical simulation. Various shapes of light guides have been considered to maximize light output of the detector.

Keywords: small-grained scintillator, γ-, β-radiation, light transducer.

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1. Introduction

Scintillators based on ZnSe(Te) in combination with silicon photodiode are distinguished by their high scintillation efficiency η (18%) [1] and good spectral matching coefficient $F = 91\%$. This makes them very promising for detection of beta- and low energy gamma-radiation. Single crystalline plates ZnSe(Te) in combination with photomultiplier PMT-110 have energy resolution of $\cong 9\%$ for conversion electrons ^{137}Cs [2]. In addition, crystals ZnSe(Te) are non-hygroscopic and have high radiation stability (up to 10^8 rad). Electron back scattering coefficient k in ZnSe(Te) is 40-50%.

Present-day preparation techniques of scintillation crystals ZnSe(Te) do not allow to obtain plates larger than 4 cm in diameter. An improvement of detector sensitivity can be achieved not only by increasing its area, but also by creation of optimum conditions of light collection in the scintillator.

One of the possible ways to increase the detector area is to make a detector in the form of a conglomerate of small grains of ZnSe(Te) combined into a single "small-grained" ("small-crystalline") scintillator. The area of such scintillator is practically unlimited from the point of view of its preparation technology. In this case the problem of optimum light collection conditions becomes vital. Ways of its solution involve optimization of the grain size, the use of additional reflective coatings and transparent disperse medium in which the grains are installed.

In this paper we report a small-grained scintillator based on ZnSe(Te). Its thickness is 0.15-0.2 cm, which corresponds to 90% absorption of 50 keV γ-ray radiation or 2.4 MeV beta-radiation [3]. The grain size was chosen to correspond to the scintillator thickness (single-layer packing). Multilayer structures with particle size smaller than the scintillator thickness have low output efficiency of intrinsic radiation due to light losses on the grain boundaries.

2. Calculation of optimum light collection conditions in a ZnSe grain

Using the Monte-Carlo (MC) method, calculations of optimum light collection conditions in the small-grained ZnSe(Te) scintillator were carried out. The MC procedures for calculation of light collection in scintillation detectors have been described in detail [4]. For the calculations, we assumed that grain sides were mirror-smooth (cleavage surfaces). Two limiting cases were considered of the location of scintillation flashed inside the grain: a) high penetrating ability of the detected radiation – the flashes are uniformly distributed inside the crystal; b) low penetrating ability of the detected radiation, which is completely absorbed by the thin layer adjacent to the crystal surface (the layer thickness is small as compared with characteristic dimensions of the crystal). For intermediate values of penetrating ability, the light collection coefficient τ is between these limiting cases.

Several shapes of ZnSe(Te) grains, which are easily obtainable practically, have been considered: parallelogram, parallelogram with rounded upper side, tetrahedral pyramid, trihedral and hexahedral prisms, and a hemisphere. In Table 1 calculated values τ are presented for grains of these shapes, both without additional reflective coating and for two cases of reflective coatings. These cases were: a) diffusely scattering coating without optical contact with crystal surface and reflection coefficient $R = 0.9$, which is realized with Teflon reflectors (reflector 1); b) reflective coating in optical contact with the crystal surface, $R = 0.9$ (reflector 2), which corresponds to covering of the crystal surface with MgO powder.

Calculation results accounting for effects of the adhesive composition with $n = 1.5$ and absorption coefficient $\alpha = 0.05$ cm^{-1} upon light transmission from the output window to the light sensitive surface of the silicon photodiode with $n = 4$ showed that 68% of the total light passed through the output window of the scintillator are reflected from the boundary “crystal-adhesive”; 6.7% are reflected from the boundary “adhesive – photodiode surface”; 0.3% are absorbed in the bulk of adhesive, and only 25% interact with the light-sensitive surface of the photodiode. For adhesives with $n = 1.6$ this value increases up to 30%, and with $n = 1.8$ – even 40%. Filling with adhesive of the space above the output window leads to a decrease in τ with higher filling levels.

It can be concluded from these results:

- maximum τ value for a single crystalline grain of ZnSe(Te) is reached when it is pyramid-shaped with side inclination angle to the base 60°;
- light collection for all the considered crystal shapes is improved in the presence of light-reflecting coating, degree of this improvement is substantially different with different shapes;
- filling the space between grains with an optical adhesive leads to a decrease in the light output;
- the fraction of intrinsic radiation that interacts with the sensitive surface of the photodiode substantially increases with higher n of the adhesive ensuring the optical contact between the detector output window and the photodiode;
- application of the reflective coating onto the grain surface favors rise in integral light output of the small-grained scintillator.

3. Efficiency of a small-grained ZnSe(Te) scintillator

Accounting for the results of computer calculations aimed at optimization of light collection conditions 4 samples of small-grained ZnSe(Te) scintillator were prepared, 3.5 cm in diameter and 0.15 cm thick:

Table 1. Light collection coefficients of ZnSe(Te) grains of different shapes and types of reflective coatings

Shape of grains	without reflector	reflector 1	reflector 2	without reflector	reflector 1	reflector 2
	the flashes uniformly distributed inside a grain			the flashes absorbed by the thin layer adjacent to the grain surface		
Tetrahedral pyramid	0,600	0,815	0,590	0,668	0,836	0,599
Hemisphere	0,437	0,508	0,536	0,627	0,656	0,548
Trihedral prism (pattern 1)*	0,357	0,447	0,484	0,378	0,461	0,470
Trihedral prisms (pattern 2)*	0,147	0,177	0,263	0,146	0,180	0,256
Hexahedral prism (pattern 1)*	0,202	0,258	0,190	0,221	0,264	0,193
Hexahedral prism (pattern 2)*	0,145	0,172	0,395	0,147	0,171	0,412
Parallelogram with rounded upper side **	0,339	0,410	0,297	0,371	0,432	0,296
Parallelogram	0,144	0,173	0,258	0,145	0,175	0,259

*pattern 1 corresponds to the case when one of the sides of the prism is the output window; pattern 2 – when the output window is the prism bottom.

**grain has a shape of parallelogram; the side opposing the output window is a part of cylindrical surface with $r = 0.17$ cm.

sample 1 – formed of several layers of grains of arbitrary size and shape, without reflective coating, in the matrix of an optically transparent polymer medium; it was located inside a metal container with output window of quartz glass;

sample 2 – formed of one layer of grains of the optimized sizes and shapes in the matrix of an optically transparent polymer medium; covered with a special housing, without reflective coating and quartz glass;

sample 3 – the same as the sample 2, but the grains are covered with light-reflective composition;

sample 4 – a single-crystalline ZnSe(Te) plate.

The efficiency of the detectors was determined by measurement of the output signal by the pulse method in the counting mode. Intrinsic radiation was detected with silicon *p-i-n* photodiodes S3590 Hamamatsu. ^{137}Cs was used as ionizing radiation source. This nuclide, alongside with 662 keV gamma-radiation, does also emit internal conversion electrons. We determined both total number of countings (I_{total}) and the number of counts corresponding to gamma-radiation only (I_γ). In the latter case, an aluminum disc was installed between the source and detector to cut off beta-radiation. The difference $I_\beta = I_{\text{total}} - I_\gamma$ characterizes beta-efficiency of the detector, and the value $k = I_\beta / I_{\text{total}}$ - its relative sensitivity to beta-radiation. X-ray sensitivity of the detector was determined by detection of the radiation with effective energy of quanta ~ 70 keV. As photoreceiver a PD-288 silicon photodiode was used. The light output of the sample 1 was taken to be equal to unity. Measurement results are presented in Table 2. The following conclusions could be made:

- the best sensitivity, both with ^{137}Cs and 70 keV X-ray sources, was observed for the sample 3;
- efficiency of the sample 2 as compared with sample 1 is practically the same for gamma-radiation. At the same time, the sample 2 is much more efficient for detection of beta-radiation;
- the use of reflective coating on grain surfaces (the sample 3) significantly improve the detector efficiency for gamma-radiation, sensitivity to beta-radiation remains practically unchanged;
- efficiency of the single crystalline plate of ZnSe(Te) is much lower for beta-radiation as compared with the samples 2 and 3. For gamma-radiation, this difference is not so significant.

4. Calculation of the optimum shape of light beam

To increase the output signal of the detector, the area of the substrate upon which scintillator grains are placed should be increased. The limit for such an increase is related to a small light sensitive area of Si-photodiodes. Thus, there is a need to use a light transducer to concentrate the scintillation light on the photodetector.

Transmission coefficients were calculated for different types of light transducers using the MC method. The reflection of light from the transducer surface, upon which scintillator grains were located, was considered as reflection from the boundary between media with refraction indexes of 1.5 and 2.57 respectively (light transducer – a ZnSe(Te) grain). If a light beam enters the grain, probability of its coming back to the transducer was taken as 0.6 (the value of light collection coefficient for the pyramid-shaped grain with the angle between the side and the base 60°). The direction of a light beam having entered the transducer was considered as evenly distributed in space (isotropic source).

The transducer efficiency can be characterized by the relationship

$$P = \tau S_2 / S_1 \qquad (1)$$

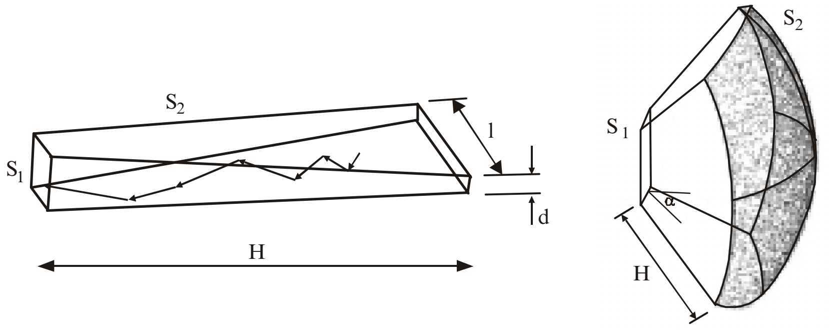
where S_2 is the area occupied by scintillator grains, S_1 is the area of the transducer output window connected to the photoreceiver.

It shows how many times the signal from small-grained scintillator with light transducer is stronger than that in the case when scintillator grains are applied directly upon the transducer. The optimum shape for light transducer is wedge-like (Fig.1a).

Scintillator grains are applied onto the surface of the wedge of large area. The back end of the wedge is light-sensitive (coupled with a photodiode). Optimization of the design consists in choosing wedge length H and its width at the far end (from the output window) l to ensure the highest efficiency P as defined by (1). Fig. 2 shows calculated two-dimensional dependence of efficiency P upon the said geometrical factors. It is important that value of S_1 is practically not limited and should be related only with conditions of specific detector application.

Table 2. Efficiency of ZnSe(Te) small-grained scintillators for detection of beta-, gamma-radiation of ^{137}Cs and X-ray radiation

Sample	Number of countings			X-ray sensitivity, arb. units	κ
	I_{total}	I_γ, E = 665 кеВ	I_b, E = 512 кеВ		
1	1900	1700	200	1,0	0,1
2	3500	1700	1800	1,31	0,5
3	4600	2700	1900	1,75	0,4
4	2700	2400	300	-	0,09



a) b)

Fig. 1. Concentrating light transducers. S_1 – area coupled with the photodetector; S_2 – area covered with scintillator grains; a – wedge-like transducer (counting mode); b - transducer with spherical input surface (spectrometry).

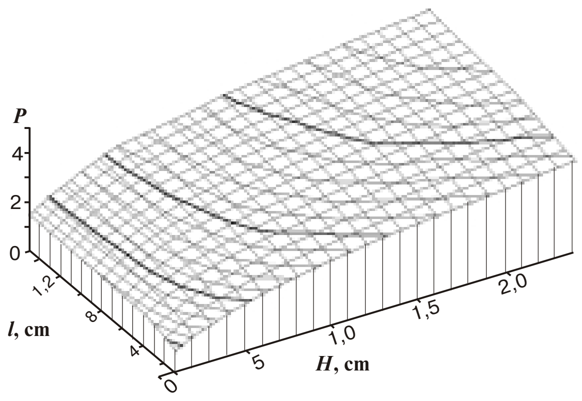


Fig. 2. Efficiency P of the wedge-shaped light transducer as a function of its dimensions – length H and width at the end opposite to the transducer l. Dimensions of the output window S_1 = 1×1 cm^2.

To use a small-grained detector for spectrometry, the light transducer design should ensure equality of τ in different points of S_1. Analysis of different transducer shapes from this point of view showed that the optimum design is concentric in shape with input window in the form of spherical surface element (Fig. 1b). Calculation of τ for such transducer (2 cm length, inclination angle of the sides to the output window 30°) results in a contribution of ~ 2% of non-uniformity τ to the energy resolution. Such detectors, as for their total light output ($P = 1.17$), are worse than detectors with wedge-shaped transducers ($P = 1.8$ for $S_2 = 10$ cm^2), but are promising for spectrometric applications.

Conclusions

1. Using light collection model, optimum grain shape was determined for ZnSe(Te) scintillator, and calculations have been made of the effects of reflective coatings and parameters of the transparent matrix of the small-grained scintillator upon its sensitivity.

2. Accounting for the results of modelling, small-grained scintillators were prepared, which were much more sensitive than detectors made of single crystalline plates of the same material.

3. Optimum design of the concentrating light transducer for efficient light collection from the small-grained scintillator of large area onto light sensitive area of the photodiode for operation both in the current mode (wedge-shaped transducer) and in the spectrometric mode (transducer with spherical surface) has been calculated.

4. The results obtained allow to produce highly efficient detectors of beta-, X-ray and soft gamma radiation based on these small-crystalline ZnSe(Te) scintillators.

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