FİZİKA 1996 CİLD II № 3

CALCULATION OF SPECTRAL DISTRIBUTIONS OF SENSITIVITY OF A NON-LINEAR γ-RAY DETECTOR

I.V. ALEXEYEV
Joint Institute for Nuclear Research, 147980, Dubna, Moscow Region, Russia

The spectral distribution of the sensitivity of the $TlInSe_2$ γ-ray detector is calculated using the Monte-Carlo method. The non-linearity of the ampere-watt characteristic (AWC) of the detector and the inhomogeneity of radiation absorption in the crystal are corrected by means of the coefficient $s \le 1$, which depends on γ-quantum energy, crystal thickness and the AWC shape. Comparison of the calculated and experimental data is carried out in the 0.02-1.25 MeV range.

The spectral distributions of efficiency $f(E)$ and sensitivity $I(E)$ are important characteristics of detectors and detector materials. The first is calculated with programs based on the Monte-Carlo method, which, as is well-known, makes it possible to solve radiation absorption problems for samples with limited dimensions. Such calculations for solid state detectors have been made by a number of authors (see, for example, [1-3]).

To calculate the sensitivity spectrum $I(E)$ for linear case is not difficult either, since, exclusive of the region of very small energies E, it is identical to the efficiency spectrum, $f(E)$. As a rule though, semiconductors with high radiation sensitivity, such as CdSe, CdTe, $TlInSe_2$, have a "sub-linear" ampere-watt characteristic. For this non-linear case, the above-mentioned identity does not hold. The form of $I(E)$ is determined not only by the process of generating free charges (for both $f(E)$ and $I(E)$ in the linear case) but also by the exchange process between the zone of allowed states and local centers of the forbidden zone. Also, in the linear case, non-uniformity of radiation absorption in the depth of the sample significantly influences $I(E)$.

As is shown in the present paper, under certain conditions in the linear case, $I(E)$ is easy to calculate using the data on $f(E)$ and introducing a certain parameter, $s \le 1$, which is obtained analytically and contains information on the AWC type of detector. The ELSS program [4] simulating electromagnetic showers (adapted for IBM PC) was used to calculate $f(E)$. The efficiency, meaning the relative part of the photon energy converted to the kinetic energy of free charges in the sample volume, is defined in ELSS as $E-W/E$, where E is the energy of a γ-quantum incident on the sample and W is the total energy of γ-quanta and free charges leaving the sample.

As already mentioned, $TlInSe_2$ crystals have a "sub-linear" AWC. This can be represented as an exponential function $I \approx G^{\alpha}$, where I is the detector response and G is the energy of radiation absorbed by the sample. The exponent $\alpha \le 1$ and is determined experimentally [5]. Thus for the case of uniform (weak) absorption, the $I(E)$ spectrum can be described by the following relationship:

$$I(E) = I(E')\left(\frac{G(E)}{G(E')}\right)^{\alpha} \qquad (1)$$

where E' is any fixed energy value from the interval being considered.

For the $I_F(E)$ spectrum reduced to an equal flux density of radiation energy F, G can be replaced in (1) by f:

$$I_F(E) = I(E')\left(\frac{f(E)}{f(E')}\right)^{\alpha} \qquad (2)$$

In the general case, relationships (1) and (2) need to be corrected to take into account non-linear effects under conditions of non-uniform radiation absorption in the depth of the sample. For this purpose, let us consider the relationship:

$$s(E) = \frac{I(E)}{\overline{I}(E)} \qquad (3)$$

where $I(E)$ and $\overline{I}(E)$ are the sample responses for two limiting cases: when the diffusion equalization does not take place and *vice versa*, in the case of the "instantaneous" diffusion equalization of the concentration of free charges generated by the radiation in the depth of the sample.

Omitting elementary reasoning, let us write for I and $\overline{I}(E)$:

$$I(E) = a\int_0^d j(x)\,dx = a\,j(x=0)\left(\int_0^d \frac{g(x)}{g(x=0)}\right)^{\alpha} dx \qquad (4)$$

$$\overline{I}(E) = a d\, j(x=0)\left(\frac{\overline{g}}{g(x=0)}\right)^{\alpha} \qquad (5)$$

where we make use of relationship like (1) applied to the density of the current j flowing through a layer having a negligibly small thickness dx. In (4) and (5) $g(x=0)$ is the radiation energy absorbed by unit volume of this layer on the sample receiving surface, $j(x=0)$ is the current density in this layer, $g(x)$ and $j(x)$ denote the same at a depth of x, d is the area of the sample electrodes, and $\overline{g}$ is ratio of G to the sample volume, i.e.:

$$\overline{g} = \frac{1}{d}\int_0^d g(x)\,dx$$

Let us note that $j(x=0)$ is identical in (4) and (5) and $g(x)=F(0)\mu_n \exp(-\mu x)$, where μ_n and μ are linear coefficients of energy absorption and attenuation, respectively. Therefore, by simple manipulations, we get:

$$s(E)=\frac{(\mu d)^{a}(1-\exp(-\mu d a))}{\mu d a(1-\exp(-\mu d))^{a}} \tag{6}$$

In (6) we neglected the slight change in the qualitative composition of the radiation with depth.

Relationship (1) and (2), which describe the spectral distribution of sensitivity of non-linear detector in the case uniform (weak) absorption, are also true for $I(E)$ introduced for the case of "instantaneous" diffusion equalizing the concentration of generated free charges. Therefore

$$I(E)=\frac{\overline{I}(E')}{G^{a}(E')}G^{a}(E)\,s(E)$$

or, per unit density of energy flux,

$$I_F(E)=\frac{\overline{I}(E')}{f^{a}(E')}f^{a}(E)\,s(E) \tag{7}$$

Relationship (7) is used when the influence of diffusion on the distribution of the free charge concentration generated by radiation may be neglected. This situation takes sensitivity [6]. Among these semiconductors is $TlInSe_2$.

Reference to (6) shows that $s=1$ at a weak absorption ($\mu d \leq 1$) and decreases with and the enhancement to $s=\frac{(\mu d)^{a}}{\mu d a}$ at $\mu d \geq 1$. In this way, the discussed coefficient s corrects the effect which causes a relative fall in detector sensitivity in the long wavelength spectrum range that results from detector non-linearity under conditions of non-uniform radiation absorption. The more the absorption and the AWC depart from the linear case (i.e., the greater μd is and the less a is) the greater the effect is.

Our calculations were compared with the experiment for spectra reduced to an equal power of the exposure dose P, since in the case it is easier to monitor the beam. For a given spectrum, relationship (7) takes the form:

$$I_P(E)=const\,(F_0(E)\,f(E))^{a}\,s(E) \tag{7'}$$

where $F_0(E)$ is the density of the radiation energy flux responsible for a unit exposure dose and is numerically equal to the ratio of the Roentgen energy equivalent to the mass coefficient of energy absorption in air [7].

Unlike the calculations where radiation was assumed to be monochromatic, the continuous bremsstrahlung radiation (homogenized by means of copper filter) was used in the experiment. The measurements were made in the range from 0.02 to 0.13 MeV of effective X-ray radiation energies and were supplemented by point E=1.25 MeV. The experimental procedure is presented in [5].

The experimental curves of the $I_P(E)$ spectra for $TlInSe_2$ samples of different thicknesses are given in Fig. 1. The curves calculated with (7') for the same samples are shown in the lower part of the figure. The exponent a for the studied samples was 0.5.

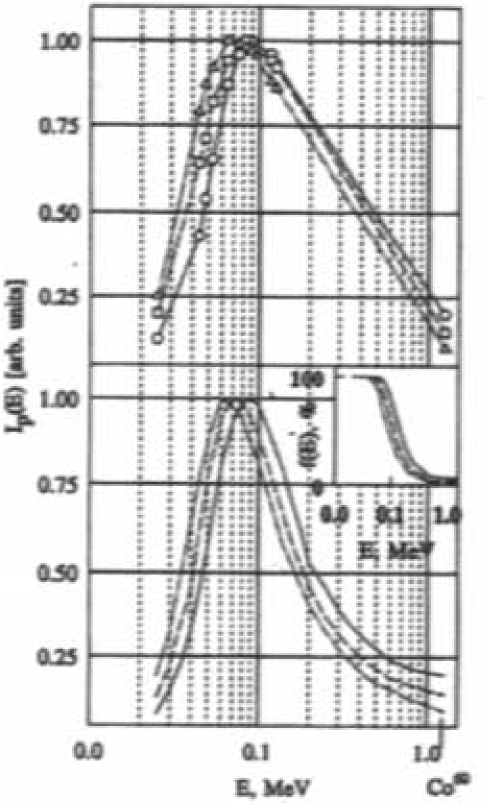

Fig. 1. Experimental (upper part of the figure) and calculated (lower part of the figure) curves of the spectral distribution of the sensitivity of $TlInSe_2$ samples d= 0.21 cm (solid line), 0.104 cm (dash line) and 0.05 cm (dash and dotted line) thick. Efficiency curves $f(E)$ of the corresponding samples are in the corner of the lower part of the figure.

In the calculated spectra, as well as in the experimental ones, we can observe a wide maximum that shifts as the sample thickness changes, a steep fall in the long wavelength spectrum range, and a gentle slope in the short wavelength spectrum range

A systematic deviation (up to 10-15%) of the experimental data from the calculated data is seen at the 25 keV point, as well as over the 90-130 keV interval. In the former case, the deviation is due to the fact that (in accordance with accepted procedure) the radiation with E_{eff}< 30-40 keV is formed by aluminum filters. This impairs radiation homogeneity by making the radiation harder. In the latter case, the fact that the experimental data exceeds the calculated data results from certain features of the ELSS program, where there is no way to take into account the considerable jump in absorption in $TlInSe_2$ at E=85.5 keV (K-jump of Tl).

The legitimacy of the described calculation procedure is supported not only by its resemblance to the general view of the calculated and experimental spectra, but also by such quantitative spectrum characteristics as the ratio of the response in the spectrum maximum to the response at the point E=1.25 MeV. For the samples where d=0.05 cm, 0.104 cm and 0.21 cm thick, the calculation gives the values 10.75, 7.04 and 5.05, respectively, and in the measurement for the studied group of samples, the mean results were 10, 7 and 5.

Conclusions

Calculation of spectral distribution of sensitivity of a semiconductor detector with non-linear characteristics can be done using the data on efficiency obtained by the Monte-Carlo method. The non-linearity of the characteristics and non-uniformity of radiation absorption in the sensitive element volume are taken into account with the aid of the corrective coefficient $s\leq 1$. The given calculation method does not require data on recombination or other capture processes in semiconductors. This method can be used when the influence of diffusion on the distribution of the concentration of free charges generated by radiation can be neglected.

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İ.V. Alekseyev

QEYRİ-XƏTTİ RADİASİYA DETEKTORUNUN HƏSSASLIĞININ SPEKTRAL PAYLANMASININ HESABLANMASI

Monte-Karlo metodunun köməyi ilə $TlInSe_2$ radiasiya detektorunun həssaslığının spektral paylanması hesablanmışdır. Detektorun amper-vatt xarakteristikasının qeyri-xəttiliyi və kristalda radiasion udulmanın qeyri-bircinsliyi, γ-kvantın enerjisindən, kristalın qalınlığından və detektorun amper-vatt xarakteristikası haqqında mə`lumat daşıyan $s\leq 1$ əmsalı ilə nəzərə alınır. Hesablanmış və təcrübi nəticələrin müqayisəsi 0.02-1.25 MeV enerji oblastında aparılmışdır.

И.В. Алексеев

ВЫЧИСЛЕНИЕ СПЕКТРАЛЬНОГО РАСПРЕДЕЛЕНИЯ ЧУВСТВИТЕЛЬНОСТИ НЕЛИНЕЙНОГО γ-ДЕТЕКТОРА

Методом Монте-Карло получено спектральное распределение чувствительности γ-детектора на основе $TlInSe_2$. Нелинейность ампер-ваттных характеристик (АВХ) детектора и неоднородность радиационного поглощения в кристалле учитывается коэффициентом $s\leq 1$, который зависит от энергии γ-квантов, толщины кристалла и содержит сведения о форме (АВХ) детектора. Сравнение вычисленных и экспериментальных результатов приведено для энергий 0.02-1.25 MeV.

Дата поступления: 01.07.96

Редактор: Т.Р. Мехтиев