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DUAL-ENERGY SEMICONDUCTOR DETECTOR OF X-RAYS AND GAMMA RADIATION

The major types of ionizing radiation detectors, their advantages and disadvantages have been analyzed. The application of ZnSe-based semiconductor detector in high temperature environment has been substantiated. Original ZnSe-based detectors and a double-chip design for registration of X- and gamma rays have been used in a broad energy range. Based on the manufactured simulator, the feasibility of gamma quanta recording by a high-resistance ZnSe-based detector operating in perpulse mode has been proved.

Key words: X-radiation, gamma radiation, semiconductor detector, ZnSe single crystal, and charge sensitive amplifier.

1. MAJOR TYPES OF DETECTORS, THEIR ADVANTAGES AND DISADVANTAGES

It is a well-known fact that in the present-day dosimetry and radiometry for quick determination of intensity (density of current energy) or exposure dose of ionizing radiation, generally, there are used three types of detectors: *the scintillation, the semiconductor*, and *the gas* ones. The principally new methods for recording of ionizing rays: *the chemical* (including, photographic), *the thermo-luminescent* (thermally stimulated luminescence (TSL dosimetry)), and *the calorimeter* (in bolometers) are applied to measurement of the dose of ionizing radiation flux (absorbed or equivalent) and based on the effect of longstanding accumulation of radiation.

The basic physical principle of the first three types of detectors is the formation of numerous free charge carriers in a small local region under absorption of radiation quantum. In these techniques, there are recorded either quantitative results generated by motion of charge carriers in electric field (the discharge and semiconductor detectors) or their recombination (the scintillation detectors). Below, there are showed the known physical mechanisms that can be used to record ionizing radiation:

$$h\nu \rightarrow \begin{cases} X\text{-absorption} \\ \gamma\text{-compton} \end{cases} \rightarrow \begin{cases} e^- - h^+ \left(N_0 = \dfrac{h\nu}{3E_g} \right) \rightarrow \begin{cases} e^- \text{в}\, \overrightarrow{E_0} \rightarrow \text{semiconductor} \\ \text{recombination} \rightarrow \text{scintillators} \\ \text{localization} \rightarrow \text{TSL} \end{cases} \\ \text{phonons} \left(\dfrac{2}{3} h\nu \right) \rightarrow \begin{cases} \text{heat} \rightarrow \text{bolometers} \\ \text{acoustics} \rightarrow \text{acoustic} \end{cases} \end{cases}$$

The main disadvantage of scintillation detectors is two-phase energy transformation of gamma quanta, namely: the recombination of electron excitations in a dielectric scintillation crystal generates an optical scintillation which subsequently converts into an electrical pulse with the help of photo-electronic multiplier (PEM) or photodiode (PD) [1].

Also, it should be noted that the PEM and PD lose their ability to operate at super-ambient temperature, insofar as this greatly increases the dark current of photo converter and the noises against the background of which the scintillation pulse is

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recorded. In addition, in this case, the effect of temperature fading of luminescence plays a significant adverse role. In addition to the above factors it imposes severe restrictions on the use of scintillation detectors at super-ambient temperature. When using the insulators ($E_g \geq 5$ eV) as scintillation materials, on the one hand, the probability of recombination of electron-hole pairs on recombination centers increases (due to a low mobility of free charge carriers), but on the other hand, the number of generated electron-hole pairs caused by the gamma-quantum absorption decreases significantly. However, there are some dielectric materials with high-performance absorption of ionizing radiation.

An important advantage of semiconductor detectors is direct transformation of gamma-quantum energy into electrical impulses and, consequently, better spectral resolution and accuracy of measurement of energy radiation quanta. The high-quality silicon *p-i-n*-detectors are the most widely used devices, however they have low-performance absorption of X-ray and gamma radiation, and, in addition, there is a limit on the depth of detector's p-n transition. The CdTe and ZnCdTe crystals have a much better absorption of radiation flux, but a low structural perfection of these materials (the presence of various defects) causes other problems. The main disadvantage of these detectors is a small forbidden bandwidth and, consequently, a large intrinsic conductivity of these materials at ambient temperature. This entails a gain in detector noises. In case of high temperature of working environment the spectrometer detectors are cooled forcedly. The semiconductor and scintillation detectors cannot be used at a high temperature, therefore the gas detectors despite their low sensitivity are still reluctantly employed as critical detectors in cooling systems of nuclear power plants and thickness gauges of hot rolled steel plants.

2. COMPARATIVE ANALYSIS OF SEMICONDUCTOR DETECTORS

In order to identify the semiconductor materials which minimize these disadvantages, a comparative analysis of detectors has been made on the basis of the following criteria:

- Efficiency of absorption of ionizing radiation;
- Efficiency of generation of electron-hole pairs under absorption of radiation quantum;
- Mobility of free electrons and holes under the action of electric field;
- Temperature dependence of dark and X-conductivity;
- Uniformity of crystal structure and process capability of growing large high-quality single crystals;
- Radiation resistance of material; and
- Electrical noises of semiconductor detector.

Two methods of recording: *the integral* and *the impulse* ones, has been considered. The conclusion is as follows: at the super-ambient temperature, the wide-gap semiconductor ($E_g > 2.5$ eV) of very high purity, with low concentration of intrinsic structural defects should be used as material for semiconductor detector.

According to the estimates, as of today, the most structurally perfect materials among wide-gap semiconductors are the zinc selenide (ZnSe) crystals. However, the single Si crystals have better parameters than the ZnSe ones, inasmuch as the researchers spent a lot of time, efforts, and money to get silicon of extremely high quality. However, if the quality of ZnSe single crystals is close to that of silicon, the ionizing wave analyzer on the ZnSe detectors will have better specifications than that on the silicon detectors. This assumption is based on the fact that even at a temperature of 150 °C the dark current of high-resistant ZnSe detector does not exceed that of silicon *p-i-n*-photodiodes of the same geometry at a temperature of 25 °C.

Excellent dielectric properties of high-resistant ZnSe crystals make it possible to create the electric field having an intensity of up to 9000 V/cm in semiconductor detectors [2, 3]. This ensures a sufficiently high drift velocity and, consequently, charge carriers effectively gathering at the electrodes detectors. Thus, as compared with the scintillators, no reduction in signal has been reported as a result of conversion factor and loss of light flux occurring when the crystal scintillator is connected with photodetectors.

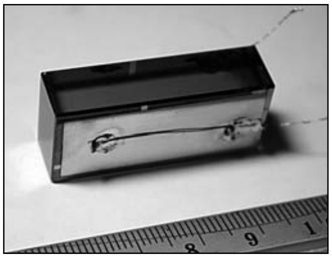
3. PRINCIPAL ADVANTAGES OF ZnSe DETECTORS

1. Large forbidden bandwidth ($E_g = 2.68$ eV at $T = 300$ K). This means that the concentration of free electrons at a temperature of up to 450 K is less than $n < 1$ cm^{-3} and only at a temperature of 600 K the conductivity of pure single ZnSe crystal can be observed. Of course, these pure crystals have not existed yet, but currently there are samples in which concentration of free electrons (due to donor levels at a depth of ~1 eV) is less than 1000 carriers per cm^3. This concentration of free charge carriers is smaller by many orders of magnitude than that in Si or CdTe. In this case, the dark conductivity in ZnSe is even difficult to record: the supplied voltage should be of kV order, while the measured current is of picoampere order. The direct current does not make a significant contribution to the noises of recording system. This allows the researchers to use both integral and impulse methods for detecting X-ray and gamma radiation.

2. The experimental curves of temperature dependence of zinc selenide X-ray conductivity show that the ZnSe sensitivity does not change significantly at a temperature within the range from 295 to 450 K [4]. The current of X-ray conductivity is larger than the current of dark conductivity.

3. The CVC of zinc selenide X-conductivity has been experimentally verified to be almost linear in electric field of up to ~5000 V/cm [4, 5]. Therefore, a smaller value of mobility of free electrons and holes in ZnSe, as compared with Si and CdTe, can be fully compensated by generating a strong electric field. In addition, the ZnSe crystals have a set of following attractive properties:

- Currently, quite large ZnSe crystals (diameter $d = 50$ mm, $h = 60$ mm) have been already available;
- Zinc selenide is a chemically non-toxic material whose production is environment friendly at all the stages;



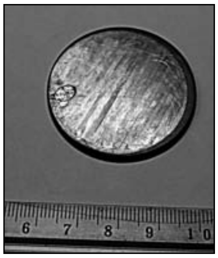


Fig. 1. ZnSe single crystal for measurement of gamma radiation

Fig. 2. ZnSe single crystal for soft X-ray radiation

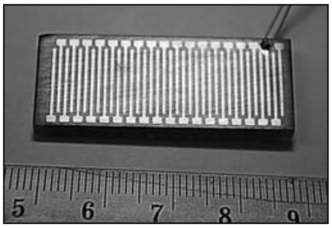


Fig. 3. ZnSe single crystal for measurement X-ray (soft and hard) and gamma radiation

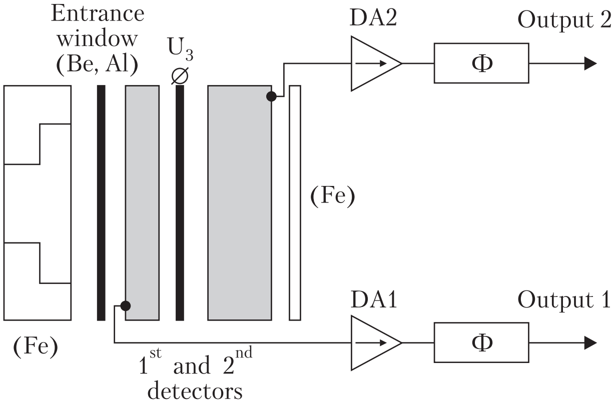


Fig. 4. Schematic representation of double-chip detector design

- The material has the highest radiation resistance (equal to 108 rad) among the known scintillators;
- The crystal is easily workable and polished mechanically;
- A technique for making ohmic electrical contacts has been developed.

The above research results for ZnSe crystals show that on their basis one can create semiconductor detectors for registration of low-energy X-ray and gamma radiation. However, depending

Fig. 5. External view of input block of ionizing radiation detector with entrance protective window

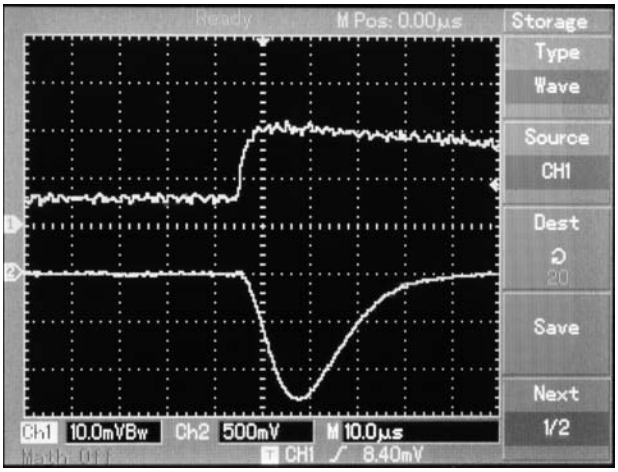


Fig. 6. Oscillograph traces of signal from Ra226 radionuclide source at the ZA234 CSA outputs

on the task either the integral or the impulse methods can be used to record ionizing radiation. In case of the integral method the present-day microelectronics allow the users to reliably measure direct current with a minimum sensitivity of 0.1 pA. The impulse method is implemented using the charge-sensitive amplifiers, such as ZA234 designed by the authors and industrial CPS10 detector with a sensitivity of a few hundred electrons (~1400 mV/rC).

4. SIZE OF DETECTORS AND GEOMETRY OF CONTACTS

Various detectors of different shape and configuration of electrical contacts can be made if the ZnSe single crystals have an adequate size. The measurements have been carried out on the following samples:

1) For powerful gamma-rays (Cs^{137}, Co^{60}) with energies $h\nu_X > 0.3$ MeV: box-shaped, dimensions 10 × 15 × 40 mm, volume $V = 6$ cm^3 (Fig. 1);

2) for X-rays: a) within the range of energy 2 keV < $h\nu_X$ < 80 keV: disc-shaped, diameter = 40 mm, thickness $d = 2$ mm; b) for energy $h\nu_X > 80$ keV: disc-shaped diameter = 40 mm, thickness $d = 3.5$ mm, area $S = 10.7$ cm^2; c) for «soft» X-rays with energy $h\nu_X < 40$ keV: disc-shaped, diameter = 40 mm, thickness $d \leq 2$ mm, with electrical contacts on one of crystal surfaces to reduce the detector capacitance (Fig. 2); d) a ruler for X- and gamma-rays: size 2 × 16 × 40 mm with a period between contacts of 1 mm (Fig. 3). This ruler can be used for registration of «soft» X-rays if the upper and the lower contacts are interconnected.

5. DETECTOR DESIGN

There are two options for the design of detector: the single-chip detector (traditional) and the double-chip detector (showed schematically in Fig. 4) where the first chip detector records the X-ray radiation and is a filter for the second chip detector used for the gamma radiation. The single-chip detector has two electrical contacts: the first one is for supply of voltage U_0, while the second one is connected to the input of amplifier (DCA or charge sensitive amplifier CSA). The double-chip detector can measure the intensity of both X-ray and gamma radiation.

It should be noted that the ZnSe crystals are extremely sensitive to UV radiation and therefore, to record the X-rays it is necessary to use an entrance protective window (Fig. 5). To record the intense polychromatic radiation the laboratory has developed a double-channel DCA with a sensitivity of 0.1 pA, which allows the user to measure the current from each detector and their difference (i.e., to separate the X-ray and the gamma-ray components of intensity). The same system makes it possible to measure the intensity of pure X-rays more accurately, if the second detector is used to compensate the dark current of the first detector.

To record impulses the ZA234 charge-sensitive amplifier developed by authors and AFS2d impulse generator were used. The former makes it possible to compensate dependence of CSA transfer coefficient on detector capacitance, which greatly improves the spectrometric performance of instrumentation. The ZA234 unit provides a very high-speed performance: time of signal buildup at the CSA output is less than 1 ns at a detector capacitance of 50 pF and less than 10 ns at a capacitance of 500 pF.

When using the Ra-226 radionuclide as a source of ionizing radiation, at the outputs of both detectors the clear Gauss pulses are recorded after passing through AFS2d signal generator (lower curve in Fig. 6). It should be noted that the noise level of ZnSe detectors is extremely low: when the voltage on detector (U_0) varies from 0 to 600 V the noise level remains practically constant (<1 mV).

6. PROSPECTS FOR THE CREATION OF A PORTABLE DOSIMETER

There are several options for design of portable dosimeter depending on its use. For example, for effective record on the landfills of extremely dangerous Am-241 radionuclide the most appropriate design is a double-chip detector with impulse system of record. According to the preliminary estimates, the size of portable detector with a working surface of about 10 cm^2 should not exceed 80 × 80 × 170 mm; its weight is 800 g.

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ДВУХЭНЕРГЕТИЧЕСКИЙ ПОЛУПРОВОДНИКОВЫЙ ДЕТЕКТОР РЕНТГЕНОВСКОГО И ГАММА-ИЗЛУЧЕНИЯ

Проведен краткий анализ главных типов детекторов ионизирующего излучения, их преимуществ и недостатков. Обосновано применение полупроводникового детектора на базе ZnSe при повышенных температурах. Использованы разные формы образцов детекторов, изготовленных из селенида цинка, и двокристальная схема для регистрации рентгеновского или гамма-излучения в широком энергетическом диапазоне. С помощью изготовленного макета прибора продемонстрирована возможность регистрации гамма-квантов высокоомным детектором из ZnSe в режиме отдельных импульсов.

Ключевые слова: рентгеновское и гамма-излучение, полупроводниковый детектор, монокристалл селенида цинка, зарядочувствительный усилитель.

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ДВОЕНЕРГЕТИЧНИЙ НАПІВПРОВІДНИКОВИЙ ДЕТЕКТОР РЕНТГЕНІВСЬКОГО ТА ГАММА-ВИПРОМІНЮВАННЯ

Проведено короткий аналіз основних типів детекторів іонізуючого випромінювання, їхніх переваг та недоліків. Обґрунтовано вибір та застосування напівпровідникового детектора на основі ZnSe при підвищених температурах. Використані оригінальні форми зразків детекторів із селеніду цинку та двокристальна схема для реєстрації рентгенівського та гамма-випромінювання в широкому діапазоні енергій. На виготовленому макеті приладу продемонстрована можливість реєстрації гамма-квантів за допомогою високоомного детектора із ZnSe в режимі окремих імпульсів.

Ключові слова: рентгенівське і гамма-випромінювання, напівпровідниковий детектор, монокристал селеніду цинку, зарядочутливий підсилювач.

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