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MODEL OF PHYSICAL PROCESSES IN THE PRIMARY AND SECONDARY CONVERTERS OF THE DETECTOR FOR RADIATION MONITORING SYSTEMS

Annotation. The level of development and application radiations technologies is largely determined by the state of nuclear instrumentation. The advent of modern semiconductor sensors for the first time connected nuclear instrumentation and electronics into a single complex - semiconductor detector. It combines a semiconductor primary converter of ionizing radiation (sensor), secondary converter of information from the sensor (electronics) and software for processing this information, interconnected in terms of problem being solved and parameters.

The block diagram of the detector consists of two main parts: the primary converter of ionizing radiation (IR) energy into an electrical signal - sensor; secondary converter of this electrical signal.

The characteristics of the detector are determined mainly by the physical properties of the semiconductor crystal as the sensitive element of the primary transducer, as well as by the features of process recording the electrical signal.

The process of registering IR consists of converting a non-electrical quantity that characterizes it into an electrical signal. In other words, one type of energy is converted - IR energy - into another, more convenient for processing and storing information. A current or voltage pulse occurs in a radiation sensor directly as a result ionization of its active medium - a semiconductor; this pulse carries extensive information. First of all, it is correlated with the time of the nuclear process. In addition, the pulse marks fact that radiation is emitted within the solid angle at which sensor is visible from the source. Pulse amplitude often serves as a measure of the energy loss of radiation in the sensor. The pulse shape differs for different types of radiation, as well as for different areas and angles of radiation entering the sensor.

In this work, model of gamma radiation detector is created as a single system of primary and secondary converters. It contains a physical analysis and analytical representation of the processes occurring in CdZnTe-sensor and electronic preamplifier. It is shown that the collection of charges in sensor varies over time, which leads to a scatter of signal pulses in duration and amplitude. In this regard, the model shows need to use a charge-sensitive pre-amplifier.

The main advantage of the model is the solution to problem of optimizing signal-to-noise ratio in the detector.

Key words: detector, primary and secondary converters, ionizing radiation energy, signal pulse spread, radiation monitoring systems

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Most of the information transmitted by pulses is characterized by a continuous spectrum: a pulse can appear at any time with different amplitudes. In addition, electrical signals from the detector generally arrive against a background of interference, which significantly reduces the reliability of the transmitted information. Interference can be caused by parasitic electrical signals (noise of circuit elements, external interference) or extraneous sources of IR. The reliability of measurements increases if the signals have qualities other than interference.

Main part. Analysis of initial parameters of the crystal.

A semiconductor material for use in ionizing radiation sensors must satisfy the previously stated conditions and be characterized by a set of the following functional qualities [1, 2, 3].

When interacting with photons, it should generate as many free charge carriers as possible. Their number is linearly proportional to the energy of the absorbed quantum, therefore, the lower the energy of formation of an electron-hole pair (the band gap of the crystal), the easier it is to register quanta of relatively low energy. In addition, and this is the main thing, with an increase in the number of generated charge carriers, its relative fluctuation decreases. This increases the accuracy of determining the energy of absorbed quanta of ionizing radiation.

To receive a signal in the external electrical circuit in which the sensor is connected, charge carriers must move quickly enough in the electric field of the crystal, and in order to obtain a signal linear in energy, energy losses on the way to the electrodes must be minimal (absent). In general, this means that it is necessary to ensure the highest mobility of both types of charge carriers (if they are collected unipolarly – mobility of electrons) and the minimum concentration of traps that capture carriers as they drift to the electrodes.

To register small signals, it is necessary to have minimal loss currents at sufficiently high voltages applied to the sensor. This means that the semiconductor material must be highly resistant. It must effectively absorb X-ray or gamma radiation quanta in a fairly small volume. Therefore, greater the density of the material and its atomic number Z, greater the absorption cross section on an individual atom and the ability of material to inhibit ionizing radiation as a whole. This quality is fundamental to ensure significant sensitivity of the sensor with a sufficiently small size. This quality plays a particularly important role in the case of high-energy gamma-ray spectrometry, since the efficiency of recording high-energy gamma quanta strongly depends on the thickness of the sensor and the properties of the active medium (the photoelectric cross section is proportional to Z^5).

The listed requirements apply both to the quality of sensor material and its design. In what follows, as a main example, we will consider a sensor based on single crystals of the CdZnTe solid solution.

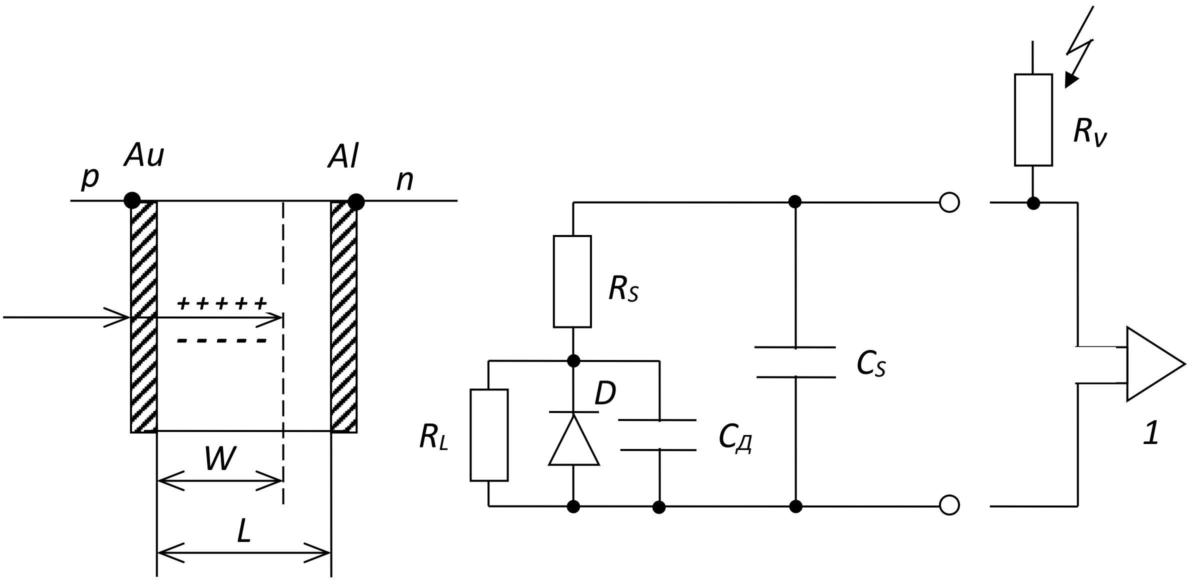
Model of physical processes in the primary and secondary detector converters.

From a formal point of view, any sensor with electrical information collection can be considered as a current generator into an external recording circuit.

Block diagram of a semiconductor sensor and circuit diagram for connecting the preamplifier of the secondary converter, i.e. the entire detector are presented in figure 1.

Let us consider the processes occurring in the primary and secondary blocks of such a detector. When the energy of ionizing radiation is absorbed in W zone of the intrinsic semiconductor, electron-hole pairs are formed, which drift under the influence of an electric field between p- and n- contacts, inducing a charge pulse at the sensor electrodes (fig. 1 a). The zone width W is determined by the material thickness L and the applied voltage U_b. For CdZnTe, the charge carrier-free zone is determined by the properties of the material (table 1).

To ensure directional movement (drift) of charge carriers created by IR, a direct bias voltage is applied to the contacts of sensor D through load resistance R_V (fig. 1 b). The resulting pulsed voltage drop $U = \frac{Q}{C}$ in most cases is not proportional to the energy lost by γ-quantum. The difference in the time of collection of charges leads to a scatter in the duration, and therefore in the amplitude of the pulses. In addition, the capacitance of the sensor itself does not remain constant. Therefore, in the detector circuit it is necessary to use a charge-sensitive pre-amplifier 1 (fig. 1 b).



a b

Figure 1 – Sensor structure (a) and equivalent circuit (b) for connecting a semiconductor detector: symbols are in the text

The equivalent circuit of a semiconductor sensor contains, in addition to the diode D itself, a depletion zone capacitance $C_Д$, a parasitic capacitance C_S, a leakage resistance R_L and a “path” resistance R_S. The latter is a combination of output electrode resistances. The diode capacity also depends on the voltage and quality of the crystal. This dependence can be approximately represented in the form [4, 5]:

$$C_Д = 21 \cdot 10^3 A(\rho U_b)^{-\frac{1}{2}}, \text{ pF}, \tag{1}$$

where A – is the sensor area, см^2; ρ – resistivity of semiconductor material; U_b – blocking voltage.

The given dependence can be used in a comparative assessment of the sensor activation modes.

One of the important characteristics of the sensor is the level of parasitic signal components - noise that is not associated with the physical processes of interaction between the crystal and the IR. The noise level determines the minimum threshold for recording IR energy.

The conversion of the energy lost by the particle in the sensor into an electrical signal of the appropriate amplitude occurs with an accuracy characterized by the resolution of the system. The latter depends on many reasons, in particular on the properties of the amplifier. Indeed, since the amplitude of the signal generated by the semiconductor sensor is small, the distortion of the amplitude spectrum is caused, first of all, by modulation by noise pulses arising in it and in the resistances. Chaotically combining with useful signals, noise “blurs” the original amplitude spectrum. Noise amplitude distribution is Gaussian:

$$p(U) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(U_i - \overline{U})^2}{2\sigma^2}}, \tag{2}$$

where σ^2 – is the dispersion or mean square deviation of the amplitude U_i from the average value $\overline{U}$.

Let us assume that all other reasons distorting the signal amplitude spectrum, compared to the influence of noise, are negligible and register monochromatic charged particles that leave all the energy in the sensor. In this case, the measured signal amplitude spectrum is also determined by expression (2). However, now $\overline{U}$ – is the average amplitude of the signal, and σ is determined by noise, and σ is equal to the root-mean-square noise $\sqrt{\overline{U_{ш}^{2}}}=U_{ш}$ voltage. The width at half maximum of the curve is called resolution $\frac{1}{2}\Delta$ (FWHM). Substituting the value into equation (2) $p(U)=\frac{1}{2}p(\overline{U})$, it is easy to obtain $\frac{1}{2}\Delta=2.36\sigma$. By measuring the resolution in energy units (in electron volts), it is possible to determine which part of the energy corresponds to the noise level converted to the input of a given amplifier [6, 7].

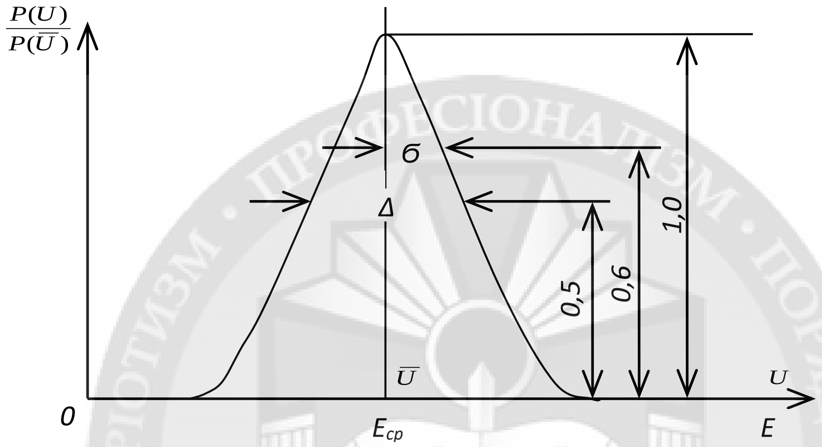


Figure 2 – Expansion of the energy line due to noise

The absolute value of $C_Д$ capacitance, as well as the parasitic capacitance C_S, largely determines the noise level, and with it the energy resolution of the charge-sensitive preamplifier. The current flowing through the leakage resistance R_L is another source of noise, which also degrades the energy resolution.

In order for subsequent detector devices to work – amplitude analyzer, discriminator, coincidence circuit – an amplifier with a high gain is required. Typically, an amplifier consists of two separate units: a preamplifier and a main amplifier. This separation is due to the desire to minimize the input capacitance *C*, which affects the resolution, while the preamplifier is located next to the sensor. The signal, amplified by first block to a level at which the noise of the subsequent amplifier has virtually no effect, is transmitted to the second block via a matched cable. Particular attention should be paid to obtaining a minimum of noise in the preamplifier [8, 9].

To analyze the noise, let's take a closer look at the equivalent circuit of the preamplifier. Noise, like a signal, can be expressed numerically in units of voltage, charge, or energy. With energy losses *E*, electron-hole pairs $N=\frac{E}{W_p}$ are formed, giving a charge *Q* on the total input capacitance *C*. If $\tau_{вх}=RC$ it is large compared to the charge collection time, then the signal amplitude $U'=\frac{Q}{C}$. For further consideration, we will take into account the action of the forming chains. As a result of passing through the differentiating and integrating circuits with $\tau_{и}=\tau_{д}=\tau$ (this case is often used in practice), the signal will decrease by factor of *e* =2,72, i.e., it will be $U=\frac{Q}{C\cdot e}$. A similar reasoning can be carried out for noise, only starting with voltage $U_ш$, then moving to charge $Q_ш = U_ш C \cdot e$, the number of charge carriers $N_ш = \frac{Q_ш}{q}$ and, finally, to the equivalent noise energy [8, 10]:

$$E_ш = \frac{U_ш C \cdot e \overline{W_p}}{q}.$$

Often, when assessing the noise properties of amplifiers, ratio is usedsignal to noise $\eta = \frac{U}{U_ш}$. Knowing η and signal, it is not difficult to determine $U_ш$ and $\frac{1}{2}\Delta$.

The spectral density of the parallel noise current is equal to:

$$\frac{\bar{i}_p^{2}}{\Delta f} = 2qI + \left(\frac{4kT}{R_p}\right), \tag{3}$$

where I – is the sum (modulo) of all currents acting parallel to the sensor; R_p – resistance of all resistors connected in parallel with the sensor; Δf – fragment of the spectral characteristic; T – is absolute temperature.

This spectral density can be expressed by one equivalent noise resistance R_p, the value of which is determined by the relation:

$$\frac{1}{R_p} = \frac{qI}{2kT} + \frac{1}{R_S}. \tag{4}$$

Parallel noise is frequency independent, but the voltage it creates at the input capacitance C, as well as the input signal, depends inversely on frequency:

$$\frac{\bar{u}_p^{2}}{\Delta f} = 4kT \frac{1}{R_p} \frac{1}{(\omega C)^2}. \tag{5}$$

Another source of noise in the input stage is determined by the input amplifier device and the principle of its amplification. For a field-effect transistor, the series equivalent noise resistance is equal to $R_S \approx \frac{1}{S}$, where S – is slope of the transistor input characteristic. The intensity of the serial noise is also frequency independent and is:

$$\frac{\bar{u}_s^{2}}{\Delta f} = 4kTR_S. \tag{6}$$

In some cases, especially when recording X-ray radiation, the noise component of type transistors $\frac{1}{f}$ plays a significant role. This noise can be determined by the formula:

$$\frac{\bar{u}_s^{2}}{\Delta f} = \frac{A_f}{f^{\alpha}}, \tag{7}$$

where A_f – is a constant coefficient depending on the transistor manufacturing technology; $\alpha\approx 1$.

The total noise voltage of the noise sources at the amplifier input is equal to:

$$\overline{U_{ш}^2} = (4kT\frac{1}{R_p}\frac{1}{\omega^2 C^2} + 4kTR_s + \frac{A_f}{f})\Delta f = N(\omega)\Delta f, \tag{8}$$

where $N(\omega)$ – is the spectral density of input noise; Δf – narrow differential frequency bandwidth $f = \frac{\omega}{2\pi}$.

In (8) $N(\omega)$ represents the spectral density of the input noise Δf – narrow differential bandwidth around frequency $f = \frac{\omega}{2\pi}$. Narrowband amplifiers are only suitable for amplifying sinusoidal signals. The frequency response $K(\omega)$ of spectrometric amplifiers extends from low to high frequencies and the noise level $U_{ш}$ at the amplifier output is determined by the integral expression:

$$\overline{U}_{ш}^2 = \frac{1}{2\pi}\int_0^{+\infty}\left|N(\omega)\right|\left|K(\omega)\right|^2 d\omega. \tag{9}$$

The limiting effect of the amplifier bandwidth $K(\omega)$ also affects the signal shape. The dependence of the amplifier output signal on time can be determined using the inverse Fourier transform formula:

$$S_2(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} S(\omega)K(\omega)e^{j\omega t}d\omega.$$

Selecting the best frequency response of the spectrometric path in order to obtain the maximum signal-to-noise ratio is the essence of optimal filtering [11].

The purpose of a spectrometric amplifier is undistorted transmission and amplification of the amplitude of the input signal, and not its shape or rising edge. Consequently, with the appropriate circuits it is necessary to select such a form of the frequency response amplifiers, in which the main frequency spectrum of the signal passes through, but the noise spectrum is maximally limited.

According to this theory, the square of the maximum possible signal-to-noise ratio is [12]:

$$(\eta_{макс}^{\infty})^2 = \frac{2}{\pi}\int_0^{\infty}\frac{U^2(\omega)}{U_{ш}^2(\omega)},$$

where $U(\omega)$ and $U_{ш}(\omega)$ – are the spectrum of signal and noise at the amplifier input, respectively.

It has been shown theoretically that the maximum signal-to-noise ratio in this case is achieved at equal integration and differentiation time constants $\tau_{CR} = \tau_{RC} = \tau$. In this case, the noise level is minimal at some optimal time constant τ_0:

$$\tau_0 = C\sqrt{R_S R_P}\,. \tag{10}$$

Then the noise level at output of the amplifier is determined by the integral expression:

$$\overline{U_{\text{ш}}^2} = \frac{1}{2\pi}\int_0^\infty N(\omega)\frac{\omega^2\tau^2}{(1+\omega^2\tau^2)^2}d\omega = 4kT\frac{R_S}{8\tau}+\frac{4kT\tau}{8C^2R_P}+\frac{A_f}{2}. \tag{11}$$

As can be seen from (11), series noise depends inversely, parallel noise depends proportionally, and type noise $\frac{1}{f}$ does not depend at all on τ. The minimum value of noise at $\tau=\tau_0$ is equal to $\overline{U^2_{\text{ш.мин}}}=\frac{kT}{C}\sqrt{\frac{R_S}{R_P}}$ (ignoring type noise $\frac{1}{f}$). Considering that during CR-RC formation amplitude of the output signal does not depend on τ, the minimum noise corresponds to the maximum signal-to-noise ratio:

$$\eta^{RC}_{\text{макс}} = \frac{S_{2\text{макс}}}{U_{\text{ш.мин}}} = \left(\frac{2}{e}\right)\frac{Q}{\sqrt{4kTC}}\sqrt[4]{\frac{R_P}{R_S}} = \left(\frac{2}{e}\right)\eta_\infty. \tag{12}$$

This formula shows ratio of amplitude output voltage to rms voltage of the output noise. The input signal to the spectrometer amplifier represents charge *Q* or energy *E* deposited by the ionizing radiation in the sensor, so in practice it is common to express the noise level also in units of charge or energy. Taking $\eta^{RC}_{\text{макс}}=1$, we find the equivalent root-mean-square noise charge for CR-RC formation:

$$\sigma_q^{RC} = \left(\frac{e}{2}\right)\sqrt{4kTC}\sqrt[4]{\frac{R_S}{R_P}} = 1{,}36\sigma_q, \tag{13}$$

where σ_q is the minimum possible noise charge.

In foreign literature, the root-mean-square noise charge is designated ENC – Equipment Noise Charge [14, 15]. In formula (13), the coefficient $\frac{e}{2}=1{,}36$ was deliberately highlighted.

In spectrometric practice, to evaluate amplifier noise, they often use not the standard deviation σ_E, but the distribution width at the level of 0.5 of the maximum value. This value in the domestic literature is called energy resolution:

$$\frac{1}{2}\Delta_E = 2{,}35\sigma_E. \tag{14}$$

In practice, another way of expressing the noise properties of spectrometric amplifiers is widely used – in the form of the dependence of the energy resolution (or equivalent noise charge) on the external capacitance at the amplifier input *C*. Indeed, the total noise contribution to the energy resolution can be approximately represented in the form of two terms:

$$\Delta_E = \sqrt{\varepsilon^2\left(C^2_{\text{П.Т.}}\frac{R_S}{\tau}\right)+\varepsilon^2\frac{R_S}{\tau}C^2_{\text{Д}}} \approx (\Delta_E)_0 + \varepsilon\sqrt{\frac{R_S}{\tau}}C_{\text{Д}}. \tag{15}$$

The first term $(\Delta_E)_0$ does not depend on the external capacitance and represents the initial noise contribution of the amplifier at zero sensor capacitance; it is determined by parallel and partially series noise. The second term increases as the sensor capacitance increases. Its multiplier represents the slope of the dependence of the noise characteristic on the external capacitance. This term is determined only by the series noise of the amplifier. This visual (albeit somewhat simplified) representation of the noise properties of amplifiers is valid not only for the considered CR-RC

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formation, but also for any shaper. In this case, the nature of the dependences of the initial noise and the slope of the noise characteristic on R_S, R_P and τ (pulse duration) is preserved. However, quantitatively these parameters will be included in the general formula (8) with other coefficients.

Let's consider the shape of the output signal with optimal shaping. It is known that the frequency response of an amplifier with optimal shaping can be represented as the result of the action of two linear filters $\Phi_1(\omega)$ and $\Phi_2(\omega)$. In this case, linear filter converts the noise so that at filter $\Phi_1(\omega)$ output it becomes white, i.e. with a uniform spectrum:

$$\left|\Phi_1(\omega)\right|^2 = \frac{1}{U_{\text{ш}}^2(\omega)} = \frac{\omega^2 C^2}{4kTR_S\omega^2 C^2 + 2qI_c + C_{\text{Д}}}. \tag{16}$$

This expression is identical to the frequency response differentiating with the time constant $\tau = C\sqrt{\frac{4kTR_s}{2qI_c + C_{\text{Д}}}}$, i.e. equal to the optimal time constant $\tau_{\text{опт}}$ for simple shaping. The signal after passing through $\Phi_1(\omega)$ will take the form:

$$U'(t) = \frac{Q}{C}\cdot e^{-\frac{t}{\tau_{\text{опт}}}}. \tag{17}$$

Thus, the input of the second filter $\Phi_2(\omega)$ will receive a modified signal $U'(t)$ and white noise. As a result $\Phi_2(\omega) = U'(\omega)e^{-j\omega t_{\text{м}}}$, i.e. amplitude-frequency response of the filter repeats (in absolute value) the spectrum of the signal $U'(\omega)$ supplied to it. The multiplier $e^{-\frac{t}{\tau_{\text{опт}}}}$ means that there is a delay in the filter for a time $t_{\text{м}}$ equal to the duration of the input pulse. At this moment, the amplitude measurement occurs, since it is at this moment that the output signal reaches its maximum. In this case, the pulse is infinite and $t_{\text{м}}$ is determined by the maximum permissible delay of the moment of amplitude measurement.

The frequency characteristics uniquely determine the transient characteristics of the filters $\Phi_1(\omega)$ and $\Phi_2(\omega)$, consequently, the entire amplifier. The transient response of the first filter coincides with the waveform $U'(t)$ at the input of the other filter. Transition response of the second filter $H_2(t) = \int_0^\infty h_2(t)\,dt$, where $h_2(t)$ – is the impulse response to a unit δ-function, equal to the mirror image of the signal $U'(t)$.

In the case of simple *RC-RC* shaping, the maximum voltage $t_{\text{м}} = \tau_{\text{опт}}$ corresponds to , so it is interesting to know what the optimal shaping gives for the same $t_{\text{м}}$:

$$\eta^t_{\text{макс}} = \sqrt{1 - e^{-2}}\,\eta^\infty_{\text{макс}} = 0{,}93\eta^\infty_{\text{макс}}. \tag{18}$$

It is known that $\eta^t_{\text{макс}} = 0{,}74\eta^\infty_{\text{макс}}$. Therefore, the gain, compared to simple formation is 26%.

The presented model of the primary converter allows, taking into account the real properties of the crystal, to calculate the dependence of the energy equivalent noise on the time constant of the input stage of the preamplifier.

Conclusions

1. In this work, a model of the primary transducer - gamma radiation sensor - has been created. It is based on the following properties of the semiconductor crystal: maximum quantum efficiency; maximum mobility of charge carriers; minimum density of structural defects; maximum resistivity and density values. The combination of these properties provides significant sensitivity of the sensor with minimal crystal dimensions. The inconsistency of such a combination must be eliminated both during the manufacturing process of the crystal (for example, a high-resistivity crystal can be obtained by simultaneous use of purification, components and compensatory doping) and subsequent processing by the methods proposed in this work (thermal field method, ionization annealing).

Among the known materials for gamma radiation sensors, single crystals of $Cd_xZn_{1-x}Te$ solid solutions have the optimal combination of the above properties and the possibilities for their production.

2. The model of the primary converter (sensor) allows you to calculate the dependence of the energy equivalent of noise δ_E on the properties of input stage preamplifiers, taking into account the real properties of the crystal. It is shown that:

– increasing the crystal volume, bias voltage and sensor capacitance increases the noise level;

– results of the analysis in relation to CdZnTe-crystals used in this work indicate the possibility of operating the sensor without cooling.

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МОДЕЛЬ ФІЗИЧНИХ ПРОЦЕСІВ У ПЕРВИННОМУ І ВТОРИННОМУ ПЕРЕТВОРЮВАЧАХ ДЕТЕКТОРА ДЛЯ СИСТЕМ РАДІАЦІЙНОГО КОНТРОЛЮ

Анотація. Рівень розвитку та застосування радіаційних технологій значною мірою визначається станом ядерного приладобудування. Поява сучасних напівпровідникових датчиків уперше пов'язала ядерне приладобудування та електроніку в єдиний комплекс – напівпровідниковий детектор. У ньому поєднуються взаємопов'язані за задачею, яка розв'язується та параметрами напівпровідникового первинного перетворювача іонізуючого випромінювання (датчик), вторинного перетворювача інформації від датчика (електроніка) та програмне забезпечення для обробки цієї інформації.

Структурна схема детектора і двох основних частин: первинного перетворювача енергії іонізуючого випромінювання (ІВ) в електричний сигнал – датчика; вторинного перетворювача цього електричного сигналу.

Характеристики детектора визначаються головним чином фізичними властивостями кристала напівпровідника як чутливого елемента первинного перетворювача, а також особливостями процесу реєстрації електричного сигналу.

Процес реєстрації ІВ полягає у перетворенні неелектричної величини, що характеризує його, в електричний сигнал. Інакше висловлюючись, у ньому перетворюється один вид енергії – енергія ІВ – в інший, зручніший для обробки та накопичення інформації. У датчику випромінювання виникає імпульс струму чи напруги у результаті іонізації його активного середовища – напівпровідника, цей імпульс несе велику інформацію. Насамперед, він корелюється з моментом часу ядерного процесу. Крім того, імпульс наголошує на факті випромінювання радіації в межах тілесного кута, під яким датчик видно від джерела. Амплітуда імпульсу часто є мірою енергетичних втрат випромінювання в датчику. Форма імпульсу відрізняється для різних видів випромінювання, а також для різних областей та кутів попадання випромінювання в датчик.

У роботі створено модель детектора гамма-випромінювання як єдиної системи первинного та вторинного перетворювачів. Вона містить фізичний аналіз та аналітичне представлення процесів, що відбуваються в CdZnTe-датчику та електронному підсилювачі. Показано, що в датчику збір зарядів різниться в часі, що призводить до розкиду імпульсів сигналу за тривалістю та амплітудою. У зв'язку з цим у моделі показано необхідність використання зарядово-чутливого попереднього підсилювача.

Основною перевагою моделі є вирішення проблеми оптимізації співвідношення сигнал/шум у детекторі.

Ключові слова: детектор, первинний та вторинний перетворювачі, енергія іонізуючого випромінювання, розкид імпульсів сигналу, системи радіаційного контролю