UDC 621.039.564

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DOI: https://doi.org/10.17721/2519-481X/2020/68-01

DETECTOR SIMULATION FOR RADIATION MONITORING SYSTEMS

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

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 resistive.

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

The creation of a model gamma-radiation detector as a single system of primary and secondary converters is considered. It contains physical analysis and analytical presentation of processes occurring in CdZnTe-sensor and electronic preamplifier. It is shown that the charge collection in the sensor differs in time, which leads to a spread of signal pulses in duration and amplitude. In this regard, the model shows need to use a charge-sensitive preamplifier.

Keywords: model of primary converter, gamma radiation sensor, detector, maximum quantum efficiency, single crystals of solid solutions

Introduction and problem statement. The level of development and application of radiation technologies is largely determined by the state of nuclear instrumentation. In a relatively short period of time, this industry went through several stages of development, and each of them was marked by the emergence of various devices that register and measure the parameters of ionizing radiation: gas-discharge counters, scintillators, semiconductor detectors, and others. Their appearance and further widespread use was provided in the past by works from Crookes, Rutherford, Geiger and Müller to more close to us in time works by Dmitriev A.B., Perelman S.N., Tchaikovsky V.G., as well as Baranov V.I., Golbek G.R., Nemirovsky B.V., Yakubovich A.L. and many others. The basis of the progress nuclear instrumentation was the simultaneous development of two directions - nuclear physics research and electronics. However, both directions at that time developed independently, without proper mutual connection. The advent of modern semiconductor sensors for the first time linked nuclear instrumentation and electronics into a single complex - semiconductor detector. It combines 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 the problem being solved and parameters. The possibility of the appearance of such a complex is provided in materials science by the works of V.S. Vavilov, P.I. Baransky, in applied nuclear physics research - M.V. Maksimov, O.V. Maslov and others. In these works, a technique was shown for the selection of semiconductor materials and a design of sensors was proposed, directions for the creation of electronics and computer programs for detectors were determined. This ensured the creation and effective use of semiconductor detectors in dosimetry, radiation control of materials and technological processes of nuclear power plants.

However, development of atomic energy, the spread of nuclear technologies have put forward new requirements for the control and metrology of ionizing radiation. The modern level of nuclear instrumentation cannot fully satisfy them. The solution to this problem can be provided by the development of: methods for choosing the optimal type of semiconductor materials and controlling their properties to create uncooled detectors; sensors with higher resolution; electronics with less noise; computer methods and information processing programs with lower estimated costs; control systems for nuclear materials and the state of NES protective barriers that meet the requirements of the existing automatic control of radiation safety (ACR).

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

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

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

The equivalent circuit of the semiconductor sensor contains, in addition to the diode D itself, depletion zone capacitance C_D, parasitic capacitance C_S, leakage resistance R_L and "trajectory" resistance R_S. The latter is a combination of resistances of output electrodes. The capacitance of a diode also depends on the voltage and quality of crystal. This dependence can be approximately represented in form [1, 2]:

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

where A – is sensor area, sm^2; ρ – resistivity of semiconductor material; U_b – locking voltage.

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

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

The conversion of the energy lost by particle in sensor into an electrical signal of the corresponding amplitude occurs with an accuracy characterized by the resolution of system. The latter depends on many reasons, in particular, on properties of amplifier. Indeed, since the amplitude of signal generated by semiconductor sensor is small, distortion of amplitude spectrum is caused, first of all, by modulation by noise pulses arising in it and in the resistances. Adding chaotically to the useful signals, the noises "blur" original amplitude spectrum. Distribution of noise in amplitude – 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 variance or mean square of deviation amplitude U_i from mean $\overline{U}$.

Let us assume that all other reasons that distort the spectrum of the signal amplitude, compared to influence of noise, are negligible and register monochromatic charged particles, leaving all the energy in the sensor. In this case, the measured spectrum of signal amplitudes (Fig. 1) is also determined by expression (2). However, now $\overline{U}$ – is average signal amplitude and σ is determined by the noise, with equal to the rms noise voltage $\sqrt{\overline{U_ш^2}} = U_ш$. The width of curve at half maximum is called resolution $\frac{1}{2}\Delta$. Substituting the value $\boldsymbol{p(U) = \frac{1}{2} p(\overline{U})}$ in equation (2), it is easy to obtain

$\frac{1}{2}\Delta = 2.36\sigma$. By measuring the resolution in units of energy (in electron volts), it is possible to determine what part of energy corresponds to noise level, recalculated to the input of this amplifier [3, 4].

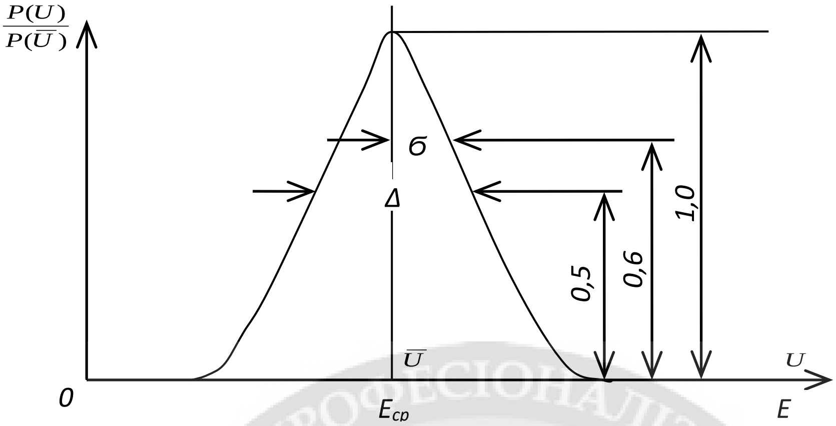

Figura 1 – Expansion of power line due to noise

The absolute value of the capacitance of the C_D, as well as of 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 leads to poor energy resolution.

For the subsequent devices of the detector to work - an amplitude analyzer, discriminator, coincidence circuit - an amplifier with a large gain is required. Usually the amplifier consists of two separate blocks: the preamplifier and the main amplifier. This separation is due to the desire to minimize input capacitance *C*, which affects the resolution, while preamplifier is located near sensor. The signal, amplified by first unit to a level at which the noise of subsequent amplifier practically does not affect, is transmitted to second unit via a matched cable. Particular attention should be paid to obtaining a minimum of noise in the preamplifier [5-7].

For noise analysis, let us consider in more detail the equivalent circuit of preamplifier. Noise, like a signal, can be expressed numerically in terms of voltage, charge, or energy. With energy losses *E*, electron-hole pairs are formed $N = \frac{E}{W_p}$, giving a charge *Q* at the total input capacitance *C*. If $\tau_{вх} = RC$ it is large compared to the time of charge collection, then 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 $\tau_{и} = \tau_{д} = \tau$ (this case is often used in practice), the signal will decrease by a factor of *e* = 2.72, i.e. number $U = \frac{Q}{C \cdot e}$ of charge carriers $Q_ш = U_ш C \cdot e$ and, finally $N_ш = \frac{Q_ш}{q}$, to the equivalent noise energy [8]:

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

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

The spectral density of the parallel noise current is:

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

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

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

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

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

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

Another source of noise in the input stage is determined by input amplifier, principle of its amplification. This noise does not depend on the input elements, so it is convenient to take it into account by the equivalent noise impedance R_S connected in series with the amplifier input. For a field effect transistor, the series equivalent noise impedance is $R_S \approx \frac{1}{S}$, where S – is the slope of the transistor's input characteristic. The sequential noise intensity is also frequency-independent and amounts to:

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

In some cases, especially when registering X-ray radiation, the noise component of transistors of the type $\frac{1}{f}$ 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 manufacturing technology of transistor; $\alpha \approx 1$.

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

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

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

In (8) $N(\omega)$ is the spectral density of the input noise Δf – narrow differential bandwidth of frequencies around the 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 amplifier output is determined by the integral expression:

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

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

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

The choice of the best frequency response of spectrometric channel in order to obtain the maximum signal-to-noise ratio is essence of optimal filtering [9, 10].

The purpose of spectrometric amplifier is undistorted transmission and amplification of the amplitude of input signal, and not of its shape or rising edge. Therefore, with the appropriate circuits, it is necessary to select such a form of frequency response amplifier, at which the main spectrum of signal frequencies passes, but the noise spectrum is limited as much as possible. These requirements are contradictory, since maximum signal amplification requires widening the bandwidth, while bandwidth must be narrow to suppress noise. It is possible to find the best shaping circuits if we use some conclusions of theory of optimal methods radio reception, developed by V.A. Kotelnikov et al. [1, 10].

According to this theory, the square of maximum possible signal-to-noise ratio is [11]:

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

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

It is 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:

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

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

$$\overline{U_{ш}^{2}} = \frac{1}{2\pi}\int_{0}^{\infty} N(\omega)\frac{\omega^{2}\tau^{2}}{(1+\omega^{2}\tau^{2})^{2}}d\omega = 4kT\frac{R_S}{8\tau} + \frac{4kT\tau}{8C^{2}R_P} + \frac{A_f}{2}. \tag{11}$$

As can be seen from (11), serial noise depends inversely, parallel one is proportional, and type noise $\frac{1}{f}$ does not depend at all on τ. Minimum noise value at $\tau = \tau_0$ equals $\overline{U_{ш.мин}^{2}} = \frac{kT}{C}\sqrt{\frac{R_S}{R_P}}$ (excluding $\frac{1}{f}$ type noise). Considering that with CR-RC shaping, the amplitude of the output signal does not depend on τ, the minimum noise corresponds to maximum signal-to-noise ratio:

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

This formula shows ratio of amplitude output voltage to the RMS voltage of output noise. The input signal to the spectrometric amplifier is charge *Q* or energy *E* released by the ionizing radiation in the sensor, therefore, in practice, it is customary to express the noise level also in terms of charge or energy. Having accepted $\eta_{макс}^{RC} = 1$, we find the equivalent rms noise charge for CR-RC formation:

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

where σ_q is minimum possible noise charge.

To determine the energy equivalent of input noise δ_E, it is sufficient to multiply the equivalent noise charge δ_q by energy of formation an electron-hole pair ε:

$$\sigma_E(эB) = \sigma_q(eiectron)\varepsilon({}^{eV}\!/_{pair}).$$

In spectrometric practice, to estimate the noise of amplifiers, it is more often not standard σ_E deviation that is used, but the distribution width at level of 0.5 of the maximum value. This value in the domestic literature is called the energy resolution:

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

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

$$\Delta_E = \sqrt{\varepsilon^2 (C^2_{П.Т.} \frac{R_S}{\tau}) + \varepsilon^2 \frac{R_S}{\tau} C^2_Д} \approx (\Delta_E)_0 + \varepsilon \sqrt{\frac{R_S}{\tau}} C_Д . \qquad (15)$$

The first term $(\Delta_E)_0$ does not depend on the external capacitance and represents initial noise contribution of amplifier at zero capacitance of the sensor, it is determined by parallel noise and partially serial. The second term grows with an increase in the sensor capacitance. The multiplier here represents the slope of the dependence noise characteristic on external capacitance.

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

$$|\Phi_1(\omega)|^2 = \frac{1}{U^2_ш(\omega)} = \frac{\omega^2 C^2}{4kTR_S \omega^2 C^2 + 2qI_c + C_Д} . \qquad (16)$$

Thus, modified signal and white noise will enter the input of the second filter. As a result, i.e. the frequency response of filter repeats (in modulus) the spectrum of signal supplied to it. The multiplier means that the filter is delayed by a time equal to duration of input pulse. At the moment, amplitude is measured, since it is at this moment that the output signal reaches its maximum. In this case, pulse is infinite and is determined by the maximum allowable delay in the moment of amplitude measurement.

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

The frequency response and uniquely determine the transient response of the filters, and therefore the overall amplifier. The transient response of the first filter matches the waveform at the input of the other filter. The transient response of the second filter, where $h_2(t)$ – is the impulse response to a unit δ-function equal to the mirror image of the signal.

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

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

It is known that $\eta^t_{макс} = 0{,}74 \eta^\infty_{макс}$. Consequently, 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 dependences of energy equivalent noise on the time constant of the input stage preamplifier.

Conclusions. In the work, a model of primary transducer - gamma radiation sensor has been created. The model allows calculating the dependence of energy equivalent of noise on the properties preamplifier input stage, taking into account the real properties of crystal. It is shown that:

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

- results of the analysis applied to CdZnTe crystals used in this work indicate the possibility of the sensor operation without cooling.

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

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

- energy resolution of a charge-sensitive preamplifier is determined by the level of noise, which depends on capacitance of sensor, and therefore on the bias voltage and crystal quality;
- in order to obtain the maximum signal-to-noise ratio, it is necessary to select the frequency response of spectrometric path according to the theory of optimal filtering by V.A. Kotelnikov; for this, filters of both low and high frequencies must be included in the path; thus, simplest driver of a spectrometric amplifier should consist of a CR-RC filter; optimal shaping gives a 26% signal-to-noise ratio gain over simple shaping.

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МОДЕЛЮВАННЯ ДЕТЕКТОРА ДЛЯ СИСТЕМ РАДІАЦІЙНОГО КОНТРОЛЮ

У роботі створена модель первинного перетворювача - датчика гамма-випромінювання. Вона заснована на наступних властивостях кристала напівпровідника: максимальна квантова ефективність; максимальна рухливість; мінімальна щільність дефектів структури; максимальні значення питомої опору і щільності. Поєднання перерахованих властивостей забезпечує значну чутливість датчика при мінімальних розмірах кристала. Суперечливість такого поєднання необхідно усувати як в процесі виготовлення кристала (наприклад, високоомний кристал отримувати одночасним застосуванням очищення, компонентів і компенсуючого легування), так і подальшою обробкою запропонованими в даній роботі методами (термополевий метод, іонізаційний отжиг).

Для реєстрації малих по величині сигналів необхідно мати мінімальні струми втрат при досить великих напругах, доданих до датчика. Це означає, що напівпровідниковий матеріал повинен бути високоомним.

Серед відомих матеріалів для датчиків гамма-випромінювання оптимальним поєднанням перерахованих вище властивостей і можливостями їх отримання мають монокристали твердих розчинів $Cd_xZn_{1-x}Te$.

Розглядається створення моделі детектора гамма-випромінювання як єдиної системи первинного та вторинного перетворювачів. Вона містить фізичний аналіз і аналітичне уявлення процесів, що відбуваються в CdZnTe-датчику і електронному зовнішньому підсилювачу. Показано, що в датчику збір зарядів різниться в часі, що призводить до розкиду імпульсів сигналу по тривалості і амплітуді. У зв'язку з цим в моделі показана необхідність використання зарядово-чутливого попереднього підсилювача.

Ключові слова: модель первинного перетворювача, датчик гамма-випромінювання, детектор, максимальна квантова ефективність, монокристали твердих розчинів.