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MODEL OF PHYSICAL PROCESSES IN PRIMARY AND SECONDARY CONVERTERS OF THE DETECTOR

The level of development and application of radiation technologies is largely determined by the state of nuclear instrumentation. 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), a 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 structural diagram of detector consists of two main parts: a primary converter of ionizing radiation (IR) energy into an electrical signal - a sensor; secondary converter of this electrical signal. The characteristics of 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 the process of recording an electrical signal.

The process of registering an IR consists in converting a non-electrical quantity characterizing it into an electrical signal. In other words, this converts one type of energy - the energy of IR - into another, more convenient for processing and accumulating information. A current or voltage pulse arises in the radiation sensor directly as a result of ionization of its active medium - a semiconductor; this pulse carries extensive information. First of all, it is correlated with the moment of time of the nuclear process. In addition, the pulse marks the fact that radiation is emitted within the solid angle at which the sensor is visible from the source. Pulse amplitude is often a measure of the energy loss of radiation in the sensor. The pulse shape is different for different types of radiation, as well as for different areas and angles of radiation hitting the sensor. In this 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 the sensor differs in time, which leads to a spread of signal pulses in duration and amplitude. In this regard, model shows the need to use a charge-sensitive preamplifier. The main advantage of the model is solution to problem of optimizing signal-to-noise ratio in detector.

Keywords: detector, primary and secondary converters, ionizing radiation energy, signal pulse spread

Introduction. At present, practically all branches of industry, many branches of science use sources of ionizing radiation (IR). Nuclear power plants, gamma plants of various capacities, flaw detectors, counters and many other equipment are widely used in the defense complex, medicine, agriculture. However, the most important sector of the use IR in Ukraine after the elimination of nuclear combat potential is nuclear power [1]. The country has five nuclear power plants (NPP) with reactors of two types, which generate about 40% of the country's total electricity [2].

In this regard, the problems of dosimetry, which today have become an independent scientific and technical area of nuclear physics, are acquiring ever increasing importance. Dosimetry, in its essence, solves the problem of linking physical quantities with the expected radiation effects of the use of IR. The main task of dosimetry - identification of sources radiation, posing a threat to the environment and humans - today is solved using a variety of technical registration tools with varying degrees of efficiency. A comparative analysis of such means and methods of their application for registration and dosimetry is presented in this section [3]. In addition, the existing variety of terms and values in this industry requires some clarification in order to convey the reliability of the presented research results.

Formation of the problem. Turning on CdZnTe-detector in the mode of operation pulsed proportional ionization chamber makes it possible to significantly increase its sensitivity and expand the dynamic range of recorded values dose rate from background to emergency operating modes of the reactor facility. The use of pulsed mode makes it possible to practically realize other possibilities and, first of all, the compensation of energy dependence of sensitivity (EDS), so-called "stroke with stiffness".

Currently, dosimetric devices with silicon-based semiconductor detecting units are commercially available [1]. Advantages of CdZnTe over Si – higher sensitivity and lower energy equivalent of noise [1, 2]. However, a large effective atomic number also determines a larger (more than 10) value of the energy dependence of sensitivity.

Analysis of previous studies. 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 the works of A.B. Dmitriev, S.N. Perelman, V.G. Tchaikovsky, and V.G. Baranov, which are closer to us in time Golbek G.R., Nemirovsky B.V., Yakubovich A.L. and many others. The basis for the progress of nuclear instrumentation was the simultaneous development of two areas - 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 - a semiconductor detector. It combines a semiconductor primary converter of ionizing radiation (sensor), a 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, the development of nuclear power, the spread of nuclear technologies has put forward new requirements for the control and metrology of ionizing radiation. The current 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 existing automatic control of radiation safety (CRS).

Main part. From a formal point of view, any sensor with electrical information pickup can be considered as a current generator to an external recording circuit. As you know, a current generator is understood as a device, the internal resistance R_{BH} of which is much greater than the resistance of the load circuit $R_H : R_{BH} \succ\succ R_H$ (Fig. 1).

In this case, the generator output current does not depend on the load resistance of the external circuit R_H. The role R_H is played by the secondary converter - electronic unit of the detector. This statement is practically true for all types of sensors, since the current pulse $i_{Д}$, as well as its duration are determined by internal processes and do not depend on R_H in a wide range of values used in practice [5, 6].

Therefore, for a formal analysis of the formation and transmission of the output signal, the sensor can be represented as an equivalent circuit of a current generator $i_{\text{Д}}$ (Fig. 1). The detector current iД, through the key K, closed for the duration of the current pulse ti, enters the external load circuit R_H of the sensor, consisting of the load resistance and load capacitance C_H connected in parallel R_H, where $C_H = C_{\text{Д}} + C_{\text{ВХ}} + C_{\text{М}}$, $C_{\text{Д}}$ – is the capacitance of sensor; $C_{\text{ВХ}}$ – input capacity of the electronic device connected to sensor; C_M is the mounting capacity, including the capacity C_H of the connecting wires between the sensor and the electronic device. Thus, C_H is the total capacitance of the output circuit ("output" in Fig. 1) relative to ground. The resistance and capacitance of the load form an integrating RC-circuit at the sensor output, the time constant $\tau_{\text{н}} = R_{\text{н}} C_H$ of which significantly depends on the accuracy of measuring the particle energy and moment of registration.

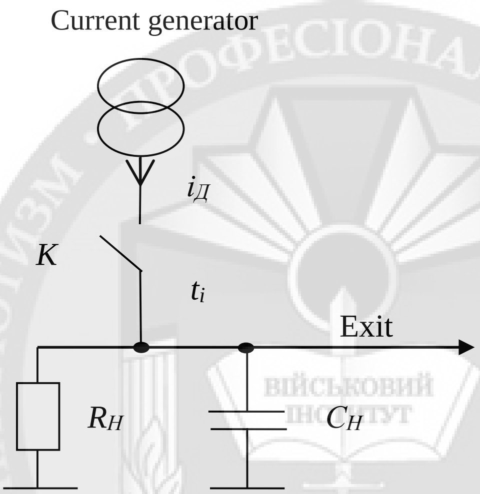
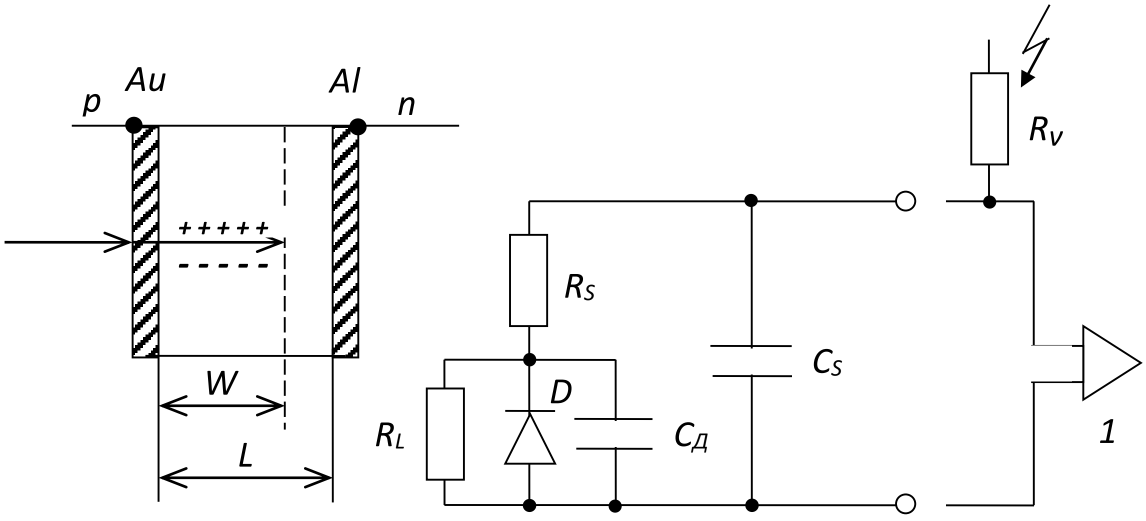


Figura 1 – Equivalent circuit for switching on the sensor

Block diagram of a semiconductor sensor and a circuit for switching on the preamplifier of secondary converter, i.e. of entire detector are shown in Fig. 2.

Consider 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 action of an electric field between p- and n-contacts, inducing a charge pulse on the sensor electrodes (fig.2a). The width of the zone W is determined by the thickness of material L and applied stress U_b. For CdZnTe, carrier-free zone is determined by the properties of the material.

To ensure directional movement (drift) of charge carriers created by IR, a forward bias voltage $U = \frac{Q}{C}$ is applied to the contacts of the sensor D through load resistance R_V (fig.2b). The resulting impulse voltage drop in most cases is not proportional to the energy lost by the γ-quantum. The difference in the collection time of charges leads to a spread in the duration, and therefore in the amplitude of pulses. In addition, capacitance of the sensor itself does not remain constant. Therefore, in the detector circuit, it is necessary to use a charge-sensitive preamplifier 1 (fig. 2b).



a

b

Figura 2 – Sensor structure (a) and equivalent circuit (b) for switching on a semiconductor detector: designations - in the text

The equivalent circuit of semiconductor sensor contains, in addition to the diode *D* itself, the depletion zone capacitance $C_Д$, parasitic capacitance C_S, leakage resistance R_L and the "trajectory" resistance RS. The latter is a combination of the resistances of the output electrodes. The capacitance of a diode also depends on the voltage and quality of crystal. This dependence can be approximated as [7-9]:

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

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

The given dependence can be used for a comparative assessment of the modes switching on the sensor. One of the important characteristics of the sensor is the 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 the energy of IR.

The conversion of the energy lost by the particle in the sensor into an electrical signal of corresponding amplitude occurs with an accuracy characterized by resolution of system. The latter depends on many reasons, in particular, on the properties of amplifier. Indeed, since amplitude of the signal generated by semiconductor sensor is small, distortion of amplitude spectrum is primarily due to modulation by noise pulses that arise in it and in the resistances. Adding chaotically to the useful signals, noises "blur" original amplitude spectrum. Distribution of noise in amplitude - Gaussian:

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

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

Let us assume that all other reasons that distort spectrum of signal amplitude, in comparison with the effect 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. 3) is also determined by expression (2). However, now $\overline{U}$ – is the average signal amplitude, and σ is determined by the noise, with σ equal to the rms voltage of the noise $\sqrt{\overline{U_{ш}^{2}}}=U_{ш}$. The width of the curve at half maximum is called the resolution $\frac{1}{2}\Delta$. Substituting value in equation (2), it is $\frac{1}{2}\Delta = 2.36\sigma$ easy to obtain $p(U)=\frac{1}{2}p(\overline{U})$. By measuring the resolution in energy units (in electron volts), it is possible to determine what part of the energy corresponds to noise level, recalculated to the input of this amplifier [10, 11].

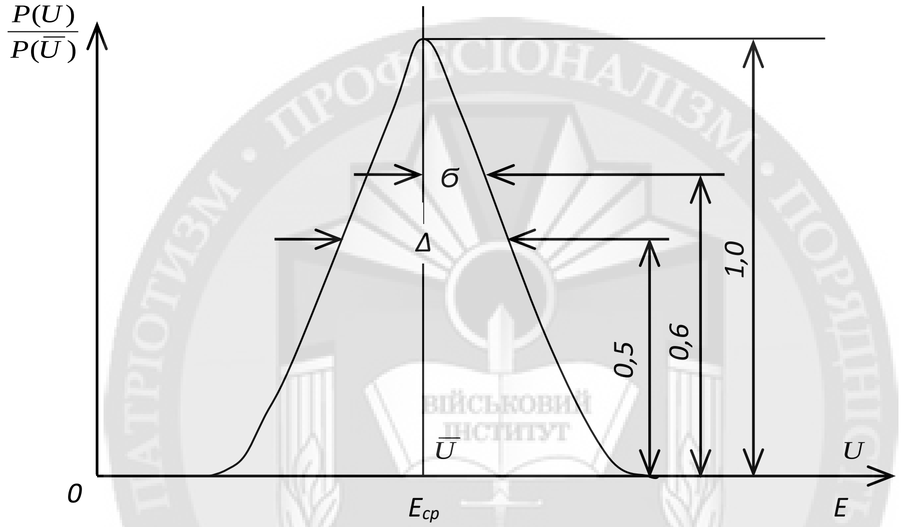


Figura 3 – Expansion of power line due to noise

The absolute value of $C_Д$ capacitance, as well as the parasitic capacitance C_S, largely determines the noise level, and with it 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 a deterioration in energy resolution.

For the subsequent devices of detector to work – an amplitude analyzer, discriminator, coincidence circuit – amplifier with a high gain is required. Usually 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 the sensor. The signal, amplified by the first unit to a level at which 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 [12,13].

For noise analysis, 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 $N=\frac{E}{\overline{\overline{W_p}}}$ are formed, 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 circuits. As a result of passing through the differentiating and integrating circuits $\tau_{и} = \tau_{д} = \tau$ with (this case is often used in practice), the signal will decrease by a factor of e = 2.72 times, i.e. $U = \frac{Q}{C \cdot e}$ number of charge $Q_{ш} = U_{ш} C \cdot e$ carriers $N_{ш} = \frac{Q_{ш}}{q}$ and, finally, to the equivalent noise energy [14]:

$$E_{ш} = \frac{U_{ш} C \cdot e \overline{W_p}}{q}.$$

Signal-to-noise ratio $\eta = \frac{U}{U_{ш}}$ is often used when evaluating the noise properties of amplifiers. Knowing signal η and, it is not difficult to determine $U_{ш}$ and $\frac{1}{2}\Delta$.

The simplest equivalent circuit of the preamplifier input circuit is shown in fig. 4 a. It includes a signal source – semiconductor sensor *D*, field – effect transistor and noise sources acting at the input of preamplifier. The total input capacitance *C* consists of the capacitance of the sensor $C_{Д}$, input capacitance of the field-effect transistor $C_{ПТ}$ and possible parasitic capacitances of $C_{П}$, i.e. $C = C_{Д} + C_{ПТ} + C_{П}$. The input capacitance *C* receives a charge *Q* generated as a result of interaction with ionizing radiation, so that the input signal of preamplifier is a step, a voltage drop with an amplitude $S = Q/C$.

The spectral composition of such a signal is inversely proportional to the frequency ω, i.e.,

$$S(\omega) = \frac{Q}{C} \cdot \frac{1}{j\omega},$$

where $j = \sqrt{-1}$.

The equivalent circuit takes into account two main sources of noise. The first is connected in parallel with the signal source and the input capacitance C and is therefore called parallel noise. It is caused by the reverse current of $i_{Д}$ sensor and input current of gate field-effect transistor $i_{ПТ}$, as well as the leakage resistances R_P in crystal and resistors connected in parallel with the input. 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 $\overline{u}_s^2(\omega)$ serial (a) and parallel $\overline{u}_p^2(\omega)$ (b).

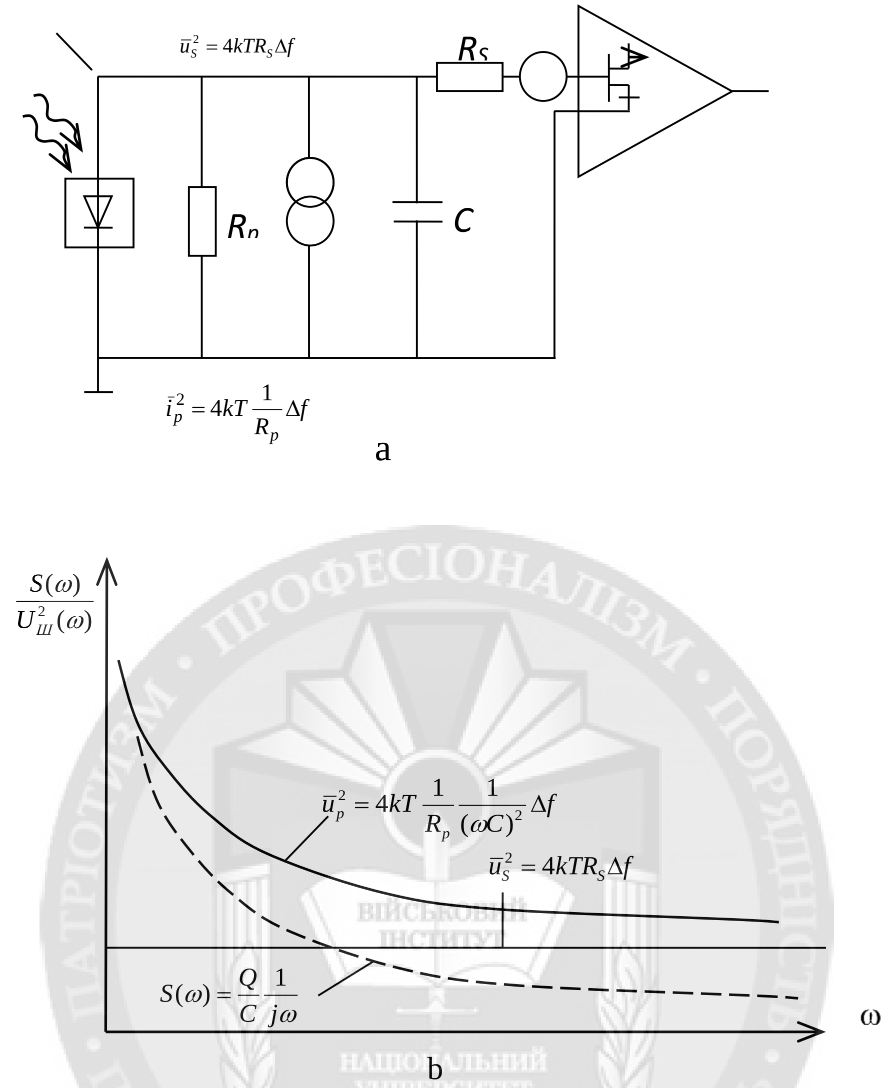


Figura 4 – Equivalent circuit of the input circuit of the preamplifier and its noise sources (a), the frequency spectrum of the input signal $S(\omega)$ and the main components of the input noise: serial $\bar{u}_s^2(\omega)$ and parallel $\bar{u}_p^2(\omega)$ (b)

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

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

Parallel noise is frequency independent, but voltage it creates at the 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 the input amplifier, the principle of its amplification. This noise does not depend on the input elements, so it is convenient to take it into account by equivalent noise impedance R_S connected in series with the amplifier input (fig. 4). For a field effect transistor, series equivalent noise impedance is $R_S \approx \frac{1}{S}$, where S – is the slope of input characteristic of transistor. The sequential noise intensity is also frequency-independent and amounts to:

$$\frac{\bar{u}_s^2}{\Delta f} = 4kTR_S \cdot \qquad (6)$$

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

$$\frac{\bar{u}_s^2}{\Delta f} = \frac{A_f}{f^a}, \qquad (7)$$

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 amplifier input is:

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

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

In (8) is spectral density of the input noise - a narrow differential bandwidth of frequencies around the frequency.

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

$$\frac{1}{2}\Delta_E = 2{,}35\boldsymbol{\sigma}_E \cdot \qquad (9)$$

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

$$\Delta_E = \sqrt{\varepsilon^2(C_{П.Т.}^2\frac{R_S}{\tau}) + \varepsilon^2\frac{R_S}{\tau}C_{Д}^2} \approx (\Delta_E)_0 + \varepsilon\sqrt{\frac{R_S}{\tau}}C_{Д} . \qquad (10)$$

The first term $(\Delta_E)_0$ does not depend on the external capacitance and is initial noise contribution of amplifier at zero capacitance of sensor, it is determined by parallel noise and partially serial. The second term grows with an increase in capacitance of sensor. The multiplier here represents the slope of the dependence of the noise characteristic on the external capacitance. This term is determined only by serial noise of amplifier. Such a visual (albeit somewhat simplified) representation of the noise properties of amplifiers is true not only for the considered CR-RC shaping, but also for any shaper. In this case, character of dependences 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 enter the general formula (8) with other coefficients.

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 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 turns white at the filter output, i.e. with a uniform spectrum:

$$\left|\Phi_1(\omega)\right|^2 = \frac{1}{U_ш^2(\omega)} = \frac{\omega^2 C^2}{4kTR_S\omega^2 C^2 + 2qI_c + C_Д}\ . \tag{11}$$

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

$$U^{'}(t) = \frac{Q}{C}\cdot e^{-\frac{t}{\tau_{опт}}}\ . \tag{12}$$

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

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

The model of the primary converter (sensor) allows calculating dependence of energy equivalent of noise on properties of preamplifier input stage, taking into account real properties of the crystal. It is shown that:

– increase in the crystal volume, bias voltage and sensor capacitance increases the noise leve δ_E l;

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

Conclusions. In this work, a model of gamma radiation detector has been created as a unified system of primary and secondary converters. It contains physical analysis and analytical presentation of the processes occurring in 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 the need to use a charge-sensitive preamplifier.

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

– energy resolution of the charge-sensitive preamplifier is determined by the noise level, 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, the simplest shaper of a spectrometric amplifier should consist of a CR-RC filter; optimal shaping gives a 26% signal-to-noise ratio gain compared to simple shaping.

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МОДЕЛЬ ФІЗИЧНИХ ПРОЦЕСІВ В ПЕРВИННОМУ І ВТОРИННОМУ ПЕРЕТВОРЮВАЧАХ ДЕТЕКТОРА

Рівень розвитку і застосування радіаційних технологій в значній мірі визначається станом ядерного приладобудування. Поява сучасних напівпровідникових датчиків вперше зв'язало ядерне приладобудування і електроніку в єдиний комплекс - напівпровідниковий детектор. У ньому поєднуються взаємозалежні по розв'язуванню задачі і параметрам напівпровідниковий первинний перетворювач іонізуючого випромінювання (датчик), вторинний перетворювач інформації від датчика (електроніка) і програмне забезпечення для обробки цієї інформації.Структурна схема детектора складається з двох основних частин: первинного перетворювача енергії іонізуючого випромінювання (ІІ) 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 ІІ полягає в перетворенні неелектричної величини, що характеризує його, в електричний сигнал. Інакше кажучи, при цьому перетворюється один вид енергії - енергія ІІ - в інший, більш зручний для обробки і накопичення інформації. У датчику випромінювання виникає імпульс струму або напруги безпосередньо в результаті іонізації його активного середовища - напівпровідника, цей імпульс несе велику інформацію. Перш за все, він коррелирован з моментом часу ядерного процесу. Крім того, імпульс відзначає факт випромінювання радіації в межах тілесного кута, під яким датчик видно від джерела. Амплітуда імпульсу часто служить мірою енергетичних втрат випромінювання в датчику. Форма імпульсу відрізняється для різних видів випромінювання, а також для різних областей і кутів попадання випромінювання в датчик.

В роботі створена модель 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 зовнішнього підсилювача. 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. Основною перевагою моделі є вирішення проблеми оптимізації співвідношення сигнал/шум в детекторі.

Ключові слова: детектор, первинний і вторинний перетворювачі, енергія іонізуючого випромінювання, розкид імпульсів сигналу.