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DETECTOR MODELING USING CA-ZN-TE SOLID SOLUTION FOR RADIATION MONITORING SYSTEMS

Abstract

The article created a model of the primary converter - a gamma radiation sensor. 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 a significant sensitivity of sensor with the minimum size of crystal. The inconsistency of such a combination must be eliminated both in the process of manufacturing a crystal (for example, a high-resistance crystal can be obtained by the simultaneous use of cleaning, components, and compensating 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 Cdx-Zn1-xTe solid solutions have the optimal combination of the above properties and possibilities of their preparation.

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 problem being solved and parameters. However, the development of nuclear energy and the spread of nuclear technologies have 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 lower noise level; computer methods and information processing programs with lower estimated costs; control systems for nuclear materials and the state of AES protective barriers that meet the requirements of the existing automatic control of radiation safety (ARS).

This article is devoted to the solution of such problems, which ensures the relevance of its topic. The main principle of solving the named scientific problem was results of nuclear-physical studies of the interaction of ionizing radiation with semiconductors, the development and experimental verification of physical-mathematical models of technological processes dosimetry and control of nuclear materials.

Introduction

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

In this regard, the problems of dosimetry, which today has become an independent scientific and technical area of nuclear physics, are becoming increasingly important. Dosimetry inherently solves the problem of relating physical quantities to the expected radiation effects of IR application. The main task of dosimetry is to identify sources of IR that pose a danger to the environment and humans. Today, it is solved using a variety of technical means of registration with varying degrees of efficiency. 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.

Materials and methods

The use of digital signal processing in gamma-ray spectrometers makes it possible to provide higher resolution, stability, and load capacity (input load) compared to analog methods [4, 5]. The modern elemental base of electronics makes it possible to convert the signal immediately after the preamplifier. Therefore, methods of direct processing sequence of input pulses are interest, in contrast to the methods of analog-to-digital conversion, which are typical for analog equipment [6]. The construction of the energy spectrum in a gamma spectrometer involves the selection in the input sequence of pulses with a leading edge duration within specified limits (about 20 ns for high-temperature semiconductor detectors [7, 8]), determining their amplitude and constructing a histogram that will show how many pulses and with what amplitude received at the input for a given time. The most crucial moment of this procedure is the determination of the amplitude of the input pulses.

The purpose of the spectrometric amplifier is undistorted transmission and amplification of the amplitude of the input signal, and not its shape or rising edge. Therefore, appropriate circuits need to select such a form of the frequency response of amplifier, in which the main frequency spectrum of the signal passes, but the noise spectrum is limited as much as possible. These requirements are contradictory, since the maximum signal gain requires a wide bandwidth, while for noise suppression, the bandwidth must be narrow. You can find the best forming circuits if you use some of the conclusions of the theory optimal radio reception methods developed by V. A. Kotelnikov et al. [9, 10, 11].

It is theoretically shown that the maximum signal/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:

$$\tau_0 = C\sqrt{R_S R_P}\,. \tag{1}$$

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

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

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

The conversion of the energy lost by the particle in sensor into an electrical signal of the appropriate amplitude occurs with an accuracy characterized by the resolution of system. The latter depends on many reasons, in particular, on the properties of amplifier. Indeed, since the amplitude of signal generated by a semiconductor sensor is small, the distortion of amplitude spectrum is due, first of all, to the modulation of noise pulses that occur in it and in the resistances. Randomly adding up with useful signals, the noise "blurs" the original amplitude spectrum. The amplitude distribution of noise is Gaussian:

$$p(U)=\frac{1}{\sigma\sqrt{2\pi}}\cdot e^{-\frac{(U_i-\overline{U})^2}{2\sigma^2}}, \tag{3}$$

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

Let us assume that all other factors distorting the signal amplitude spectrum are negligible compared to the effect of noise and register monochromatic charged particles that leave all the energy in the sensor. In this case, the measured spectrum of signal amplitudes is also determined by expression (3). However, now $\overline{U}$ – is the average amplitude of the signal, and σ is determined by the noise, with σ equal to $\sqrt{\overline{U_n^2}}=U_n$ voltage of the noise. The width of the curve at half maximum is called the resolution $\frac{1}{2}\Delta$. By substituting the value $p(U)=\frac{1}{2}p(\overline{U})$ into equation (3), it is easy to obtain $\frac{1}{2}\Delta=2.36\sigma$. By measuring the resolution in units of energy (in electronvolts), one can determine which part of the energy corresponds to the noise level recalculated to the input of a given amplifier [12, 13, 14].

The absolute value of capacitance C_d, as well as 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.

Results

The presented model of the primary converter makes it possible, taking into account the real properties of the crystal, to calculate the dependences of the energy equivalent noise on the time constant of the input stage of the preamplifier (Fig. 1).

The use of digital signal processing in gamma-ray spectrometers makes it possible to provide higher resolution, stability, and load capacity (input load) compared to analog methods [12, 13]. Figure 4 shows an off-scale image of a typical segment of the preamplifier output signal containing two pulses [11]. The duration of the leading edge of a single pulse is – $\Delta t=20$ ns, the decay constant of the trailing edge is – $\alpha=20$ mks. The amplitude is expressed in ADC increments. The simplest first way to determine the impulse amplitude in such an input sequence is to find the difference between the local minimum and the subsequent local maximum. Let's introduce the following designations of the input signal: $f_1(t)$ – function describing the fall of the first impulse; $f_2(t)$ – function describing the decay of the second impulse.

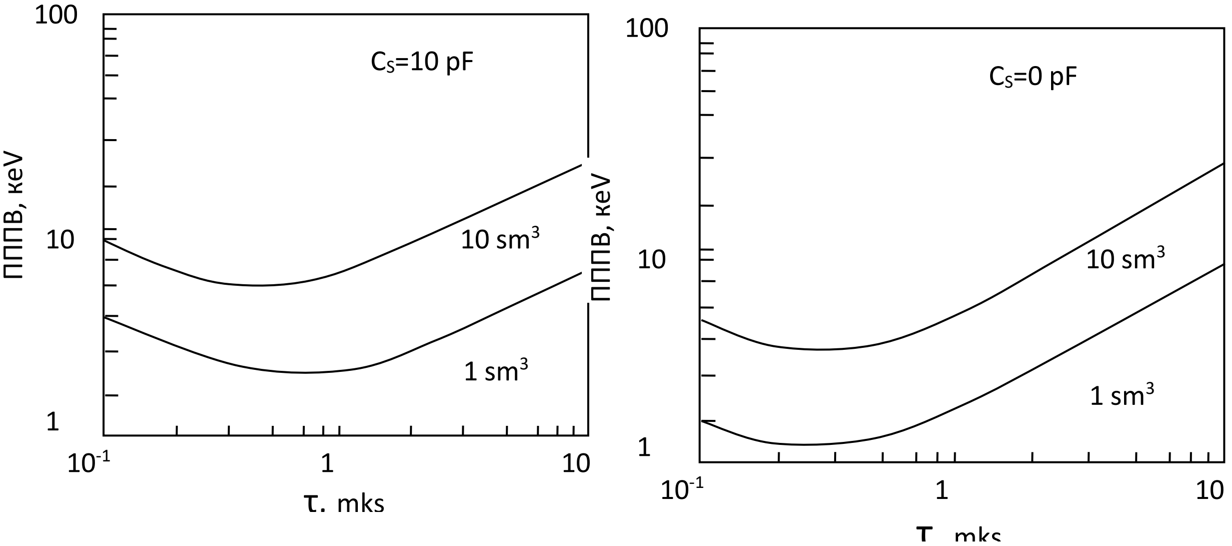

Fig. 1 Dependence of noise $\left({}^{1}\!/_{2}\Delta_E\right)$ on the charge formation time for the spectrometric path with CdZnTe sensors with a volume of 1 and 10^3 sm

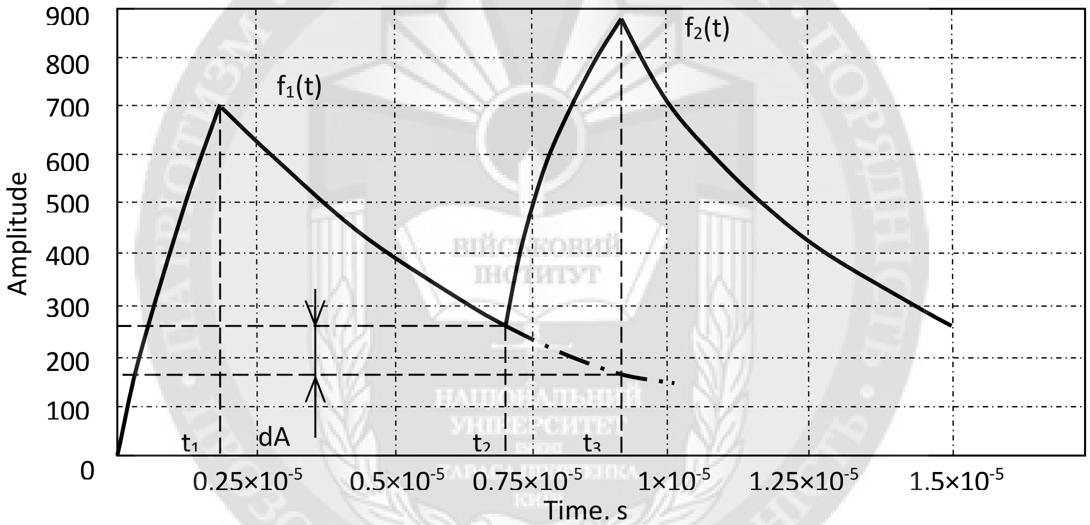

Fig.2 Analysis of the structure of a typical fragment of the input pulses of the preamplifier

Then, according to the first method, the amplitude of the second pulse is found as:

$$A^{*}=f_2(t_3)-f_1(t_2), \tag{4}$$

where t_3 and t_2 – times indicated in figure 2.
True pulse amplitude:

$$A=f_2(t_3)-f_1(t_3). \tag{5}$$

Hence, the error in determining the amplitude is:

$$dA=A-A^{*}=f_1(t_2)-f_1(t_3). \tag{6}$$

Figure 4 shows a plot of the mathematical expectation of the error depending on the download frequency for A=700, $\Delta t = 20 \cdot 10^{-9}$ s, $\alpha = 20 \cdot 10^{-6}$ s. It can be seen from the graph that the error at a loading frequency of about 10^6 s^{-1} can reach 1-2%.

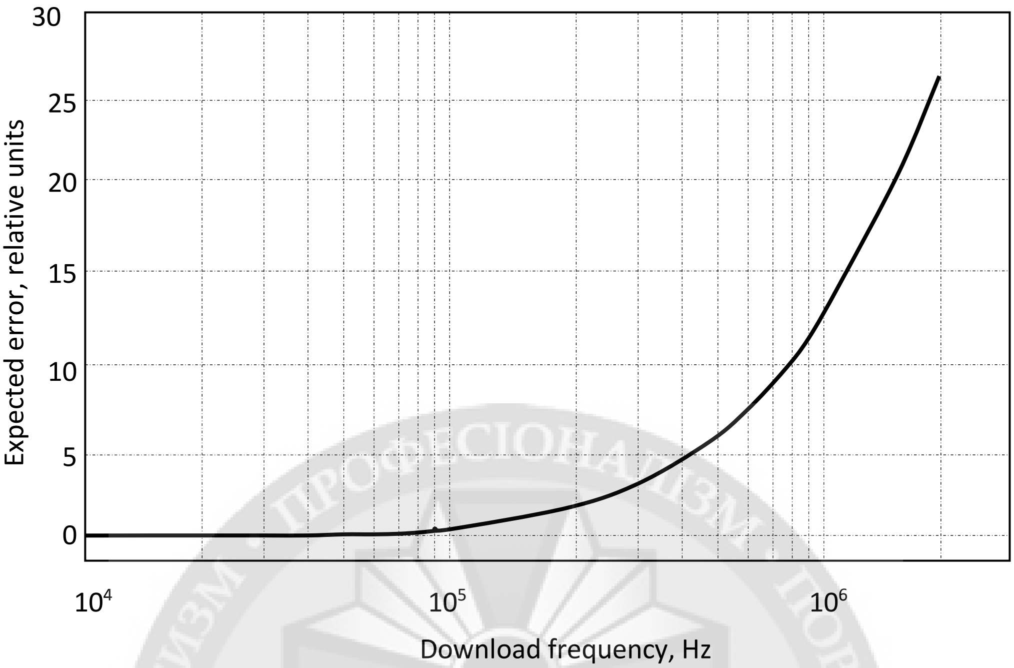

Fig. 3 Dependence of the expected error on the load frequency when determining the pulse amplitude by the method of its direct measurement between minima and maxima

This error can be avoided if we assume that the coefficient α depends on the sensor and preamplifier, i.e. is a constant value for a particular spectrometer and can be determined empirically. In particular, using the notation in fig. 3, we get:

$$\alpha = \frac{\ln(f_1(t_1)) - \ln(f_1(t_2))}{\delta t}. \tag{7}$$

Then the formula for the second method of determining the amplitude takes the following form:

$$A = f_2(t_3) - e^{-\alpha T} f_1(t_1). \tag{8}$$

The price to pay for the increase in accuracy in this method is an increase in the amount of computation. This must be taken into account when constructing spectrometers operating in real time. For a more complete comparison of the resolution methods described above, based on the model developed above, the process of measuring the pulse amplitude was simulated.

In this work, for the first time, an algorithm and a program for constructing the energy spectra of gamma radiation were created on the basis of above model. The spectra were constructed using the first (Fig. 3, 4) and second (Fig. 5, 6) methods.

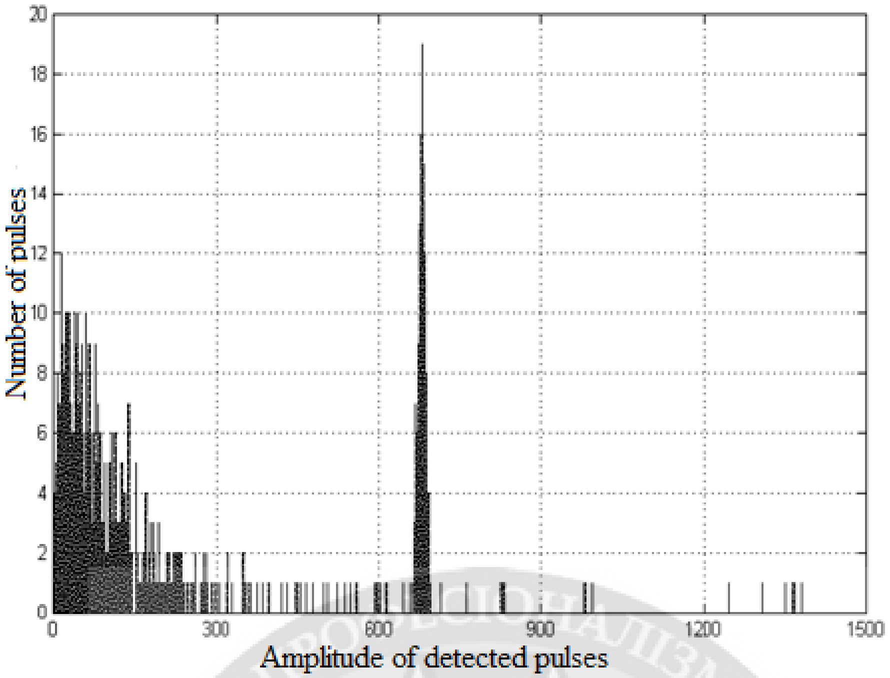

Fig. 3 Energy spectrum of pulses when using the first method for determining the amplitude

In the model, the input signal is an additive mixture of two independent Poisson pulse sequences and background noise:

– first sequence A_1=698, $\Delta t = 20 \cdot 10^{-9}$ s, $\alpha = 20 \cdot 10^{-6}$ s;

– second sequence A_2=700, $\Delta t = 20 \cdot 10^{-9}$ s, $\alpha = 20 \cdot 10^{-6}$ s.

The time intervals between pulses were random and had an exponential distribution density:

$$P(\tau) = \lambda \cdot e^{-\lambda\tau}, \ \tau \geq 0 \tag{9}$$

with flow $\lambda = 2 \cdot 10^5$ rate. The total download frequency, taking into account background, is 10^6 Hz. The simulated sampling rate in time is 10^8 Hz, the number of amplitude quantization levels is 1024, the simulated measurement time is 1 ms.

It can be seen from a comparison of figures 4 and 6 that the first method, unlike the second, does not allow resolution of spectral lines that are separated from each other by a value comparable to the calculated error.

At the same time, the use of the digital signal processing technique proposed in this work makes it possible to obtain an energy resolution not exceeding 40 keV by both methods. This is sufficient to create a dosimeter with compensation for the energy dependence of sensitivity (ESD). In addition, these results show that the second method is optimal for creating high-resolution spectrometers - less than 10 keV.

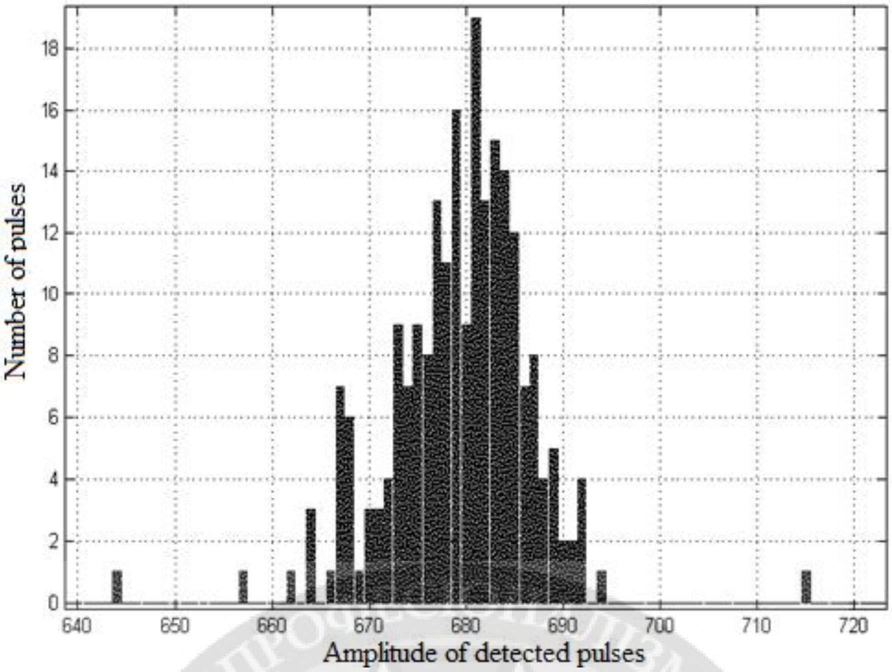

Fig. 4 A fragment of the spectrum shown in Figure 4, on an enlarged scale

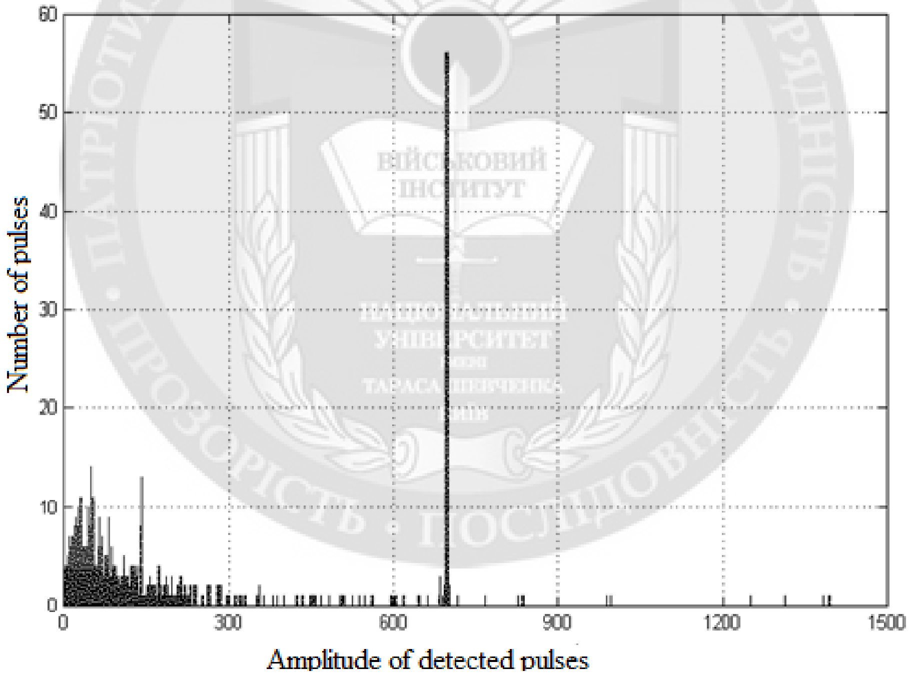

Fig. 5 Energy spectrum of pulses when using the second method for determining the amplitude

Thus, a comparison of two methods for determining the amplitude showed that at a low loading frequency ($<10^5$ s^{-1}), the first method is preferable: it is characterized by a smaller amount of calculations with the same accuracy characteristics. At high loading frequencies (of the order 10^6 s^{-1} and more), preference should be given to the second method, which retains its accuracy and resolution.

In addition to the method for determining the amplitude of the pulses, the resolution of a digital gamma spectrometer is significantly affected by the choice of sampling frequency.

At a sampling frequency of 10 MHz and higher, the shape of pulse peak in the sampling interval can be considered triangular (Fig. 7).

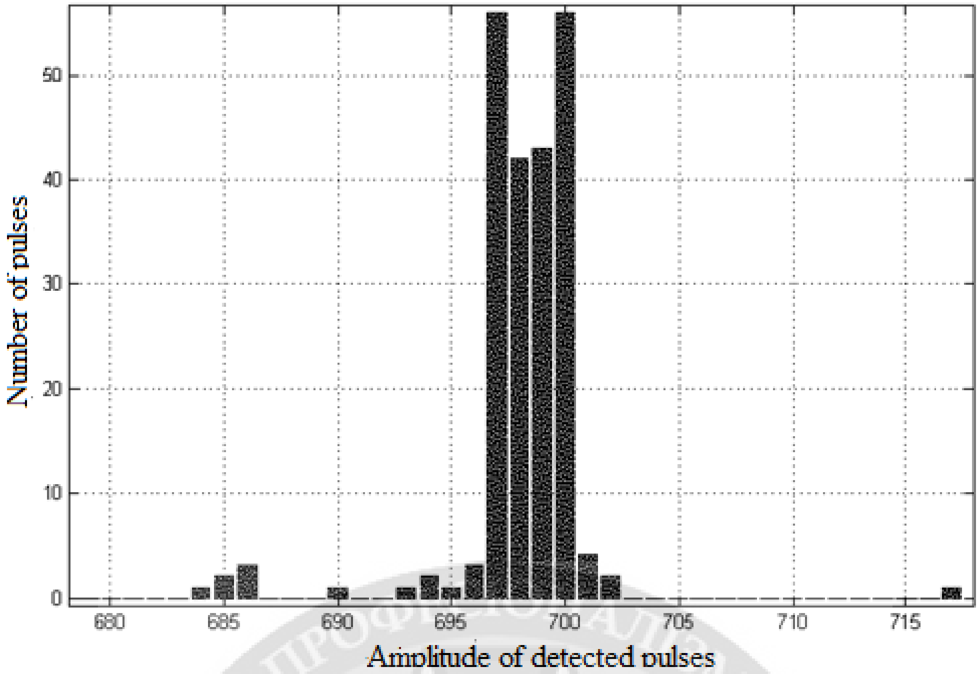

Fig. 6 Fragment of the spectrum shown in Figure 6, on an enlarged scale

The dependence of the amplitude of the maximum sample on the sampling frequency is shown in figure 7, where, for definiteness, the true amplitude of the input pulses is taken equal to 700 ADC quantization levels.

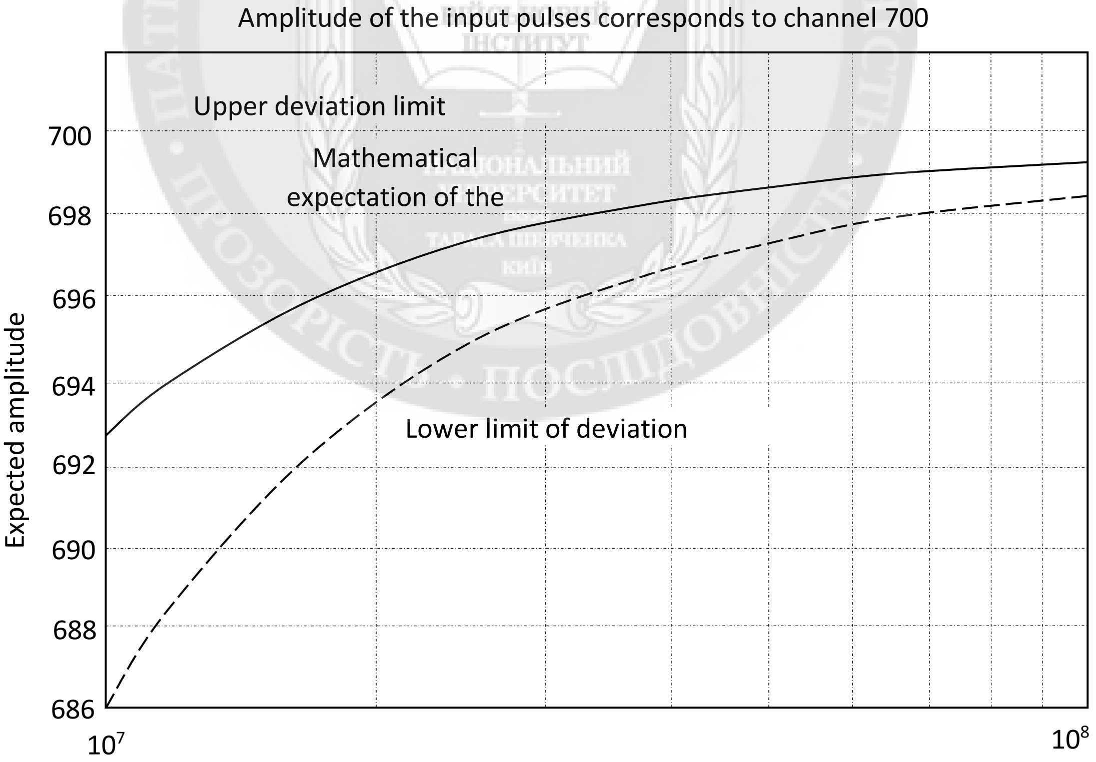

Fig. 7 Dependence of sampling error on its frequency

The plot of the expected amplitude of the maximum sample shows the location of the peak on the energy spectrum. As the sample rate increases from 10 to 100 MHz, the amount of peak reduction from true (700) decreases from 1% to 0,1%. The deviation boundaries characterize the peak width in the spectrum, which affects the resolving properties of the spectrometer.

Thus, the model obtained makes it possible to estimate the influence of the sampling rate on the shift of the energy spectrum peaks and the resolving properties of the spectrometer when choosing the parameters of its hardware implementation.

When using direct digital processing, high resolution is achieved through efficient use of ADC bit depth.

The leading edge of the pulses is determined by the current generated movement of electrons and holes in the sensor, the trailing edge is determined by the constant discharge of the RC circuit in the preamplifier, and the constant component is determined by the large decay of the trailing edge of the pulse (about 20 μs) compared to the average pulse repetition limit.

Therefore, in order to effectively use ADC bit capacity, DC component must be subtracted from its input signal. The dynamic range of the signal change must be consistent with the diagnostic range of ADC. To solve this problem, an appropriate scheme of a digital spectrometer is proposed.

In this circuit, the processor, based on the analysis of signals from ADC, sets the necessary gains for the first buffer amplifier and the bias for the adder.

The maximum gain in KU1 is chosen so that when measuring the minimum background, the signal at ADC input corresponds to its dynamic range. The minimum value of the gain must match the input signal with the dynamic range of ADC at the maximum frequency of loading with pulses of the maximum possible amplitude and zero offset.

Therefore, the spectrometer circuit must take into account the features of the output signal of the preamplifier, a typical view of which is shown in figure 8.

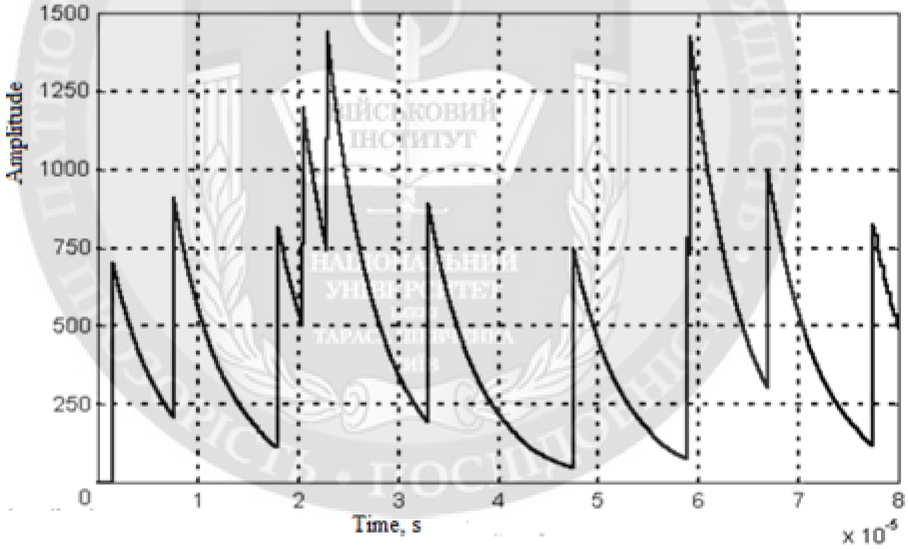

Fig. 8 Typical preamp output

It shows that when the loading frequency changes, the signal amplitude at preamplifier output increases by an order of magnitude. Based on this graph, the amount of offset should be able to change from zero to the amount of expected amplitude at a given load frequency. Similarly, the minimum gain should ensure that the signal is quantized with the maximum amplitude expected, with no clipping effects in the ADC and zero bias for the adders. In particular, if we proceed from the maximum amplitude of single pulses A = 700, the maximum loading frequency of 10^6 s^{-1} 100 times (here, it is additionally taken into account that the average value of the amplitude of a series of pulses is an order of magnitude less than the maximum amplitude of single pulses).

Conclusions

1. The model of the primary converter (sensor) makes it possible to calculate the dependence of the energy equivalent of noise δ_E on the properties of the input stage of preamplifier, taking into account the real properties of the crystal. This shows that:

– increase in 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 the sensor operation without cooling.

2. A model of a gamma radiation detector as a single system of primary and secondary converters has been created in this work. It contains a physical analysis and an analytical representation of the processes occurring in CdZnTe-sensor and electronic preamplifier. It is shown that the collection of charges in the 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 the solution of the problem of optimizing the signal/noise ratio in the detector. This shows that:

– energy resolution of the charge-sensitive pre-amplifier is determined by the level of noise, which depends on the capacitance of the sensor, and hence on the bias voltage and the quality of the crystal;

– in order to obtain the maximum signal-to-noise ratio, it is necessary to choose the frequency response of the spectrometric path according to the theory of optimal filtering by V.A. Kotelnikovs; for this, filters of both low and high frequencies are necessarily included in the path; thus, the simplest shaper of a spectrometric amplifier should consist of a CR-RC filter; optimal shaping gives a signal/noise ratio gain of 26% compared to simple shaping.

3. Reducing the contribution of noise when using sensors with large crystals (more than 10x10x5 mm) in the detector, with a significant difference in the transport characteristics of charge carriers at high loads ($>10^6$ c^{-1}) is possible using digital signal processing methods.

The paper proposes a block diagram and creates a multichannel digital amplitude analyzer that provides selection of the input signal according to the pulse shape at high loads, which is inaccessible to existing devices today. The use of such an analyzer made it possible to increase the energy resolution, the stability of the detector operation with an even greater increase in the input load of the measuring path.

4. A model of a digital spectrum analyzer has been built, which makes it possible to determine the optimal method for measuring the pulse amplitude in order to create a gamma-spectrometer with maximum resolution. On the basis of the model, for the first time, an algorithm and a program for modeling the energy spectra of gamma-radiation were created.

The model compares two proposed methods for measuring the pulse amplitude:

– both methods make it possible to obtain an energy resolution of no more than 40 keV, which is sufficient to create a dosimeter with compensation for the energy dependence of sensitivity;

– the first method has an accuracy of 1 ... 2%, lower computational costs and is preferable at a low loading frequency ($<10^5$ c^{-1});

– the second method makes it possible to obtain a resolution of less than 10 keV and is preferable for the spectrometer operation at a loading of more than 10^6 c^{-1}.

The created model makes it possible to choose the optimal value and evaluate the influence of the sampling rate on magnitude of the shift energy spectrum peaks and resolution of gamma-spectrometer.

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МОДЕЛЮВАННЯ ДЕТЕКТОРА З ВИКОРИСТАННЯМ ТВЕРДОГО РОЗЧИНУ CA-ZN-TE ДЛЯ СИСТЕМ РАДІАЦІЙНОГО КОНТРОЛЮ

Анотація

У статті створено модель первинного перетворювача – датчика гамма-випромінювання. Вона ґрунтується на наступних властивостях кристала напівпровідника: максимальна квантова ефективність; максимальна рухливість носіїв заряду; мінімальна густина дефектів структури; максимальні значення питомого опору та щільності. Поєднання цих властивостей забезпечує значну чутливість датчика при мінімальних розмірах кристала. Суперечливість такого поєднання необхідно усувати як у процесі виготовлення кристала (наприклад, високоомний кристал отримувати одночасним застосуванням очищення, компонентів та легування, що компенсує), так і подальшою обробкою в цій роботі методами, що запропоновані (термопольовий метод, іонізаційний відпал).

Серед відомих матеріалів для датчиків гамма-випромінювання оптимальним поєднанням перерахованих вище властивостей і можливостями їх отримання мають монокристали твердих розчинів Cdx-Zn1-xTe.

Поява сучасних напівпровідникових датчиків уперше пов'язало ядерне приладобудування та електроніку в єдиний комплекс – напівпровідниковий детектор. У ньому поєднуються взаємопов'язані за задачею, що розв'язується та параметрами напівпровідникового первинного перетворювача іонізуючого випромінювання (датчик), вторинного перетворювача інформації від датчика (електроніка) та програмне забезпечення для обробки цієї інформації.

Однак розвиток атомної енергетики, поширення ядерних технологій висунули нові вимоги до контролю та метрології іонізуючих випромінювань. Сучасний рівень ядерного приладобудування неспроможна задовольнити їх у повною мірою. Вирішення цієї проблеми може бути забезпечене розробкою: методів вибору оптимального типу напівпровідникових матеріалів та управління їх властивостями для створення детекторів, що неохолоджуються; датчиків з більшою роздільною здатністю; електроніки з меншим рівнем шумів; комп'ютерних методів та програм обробки інформації з меншими розрахунковими витратами; систем контролю ядерних матеріалів та стану захисних бар'єрів АЕС, які відповідають вимогам існуючого автоматичного контролю радіаційної безпеки.

Вирішенню таких завдань присвячено цю статтю, що забезпечує актуальність її теми. Основним принципом вирішення названої наукової проблеми стали результати ядерно-фізичних досліджень взаємодії іонізуючих випромінювань з напівпровідниками, розробка та експериментальна перевірка фізико-математичних моделей технологічних процесів дозиметрії та контролю ядерних матеріалів.

Ключові слова: первинний перетворювач, датчик гама-випромінювання, напівпровідниковий детектор, радіаційна безпека, іонізуючі випромінювання.