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NAS RK is pleased to announce that Bulletin of NAS RK scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of Bulletin of NAS RK in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential multidiscipline content to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабаршысы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Web of Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабаршысының Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді мультидисциплинарлы контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Вестник НАН РК» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Вестника НАН РК в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному мультидисциплинарному контенту для нашего сообщества.

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HIGH-SENSING DETECTING SYSTEMS FOR X-ray FLUORESCENCE SPECTROMETER

Abstract. In this paper, the characteristics of the signal produced by the action of X-ray radiation on silicon detectors are considered. The electronic scheme of a detection system based on a silicon-lithium p-i-n detector for an X-ray fluorescence spectrometer is proposed. To extract the signal from the detector, a charge sensitive preamplifier was designed on the basis of an operational amplifier. The charge sensitive preamplifier is fully compatible with the Si (Li) strip detector operating in the signal frequency range close to 12.5 MHz. Also, the calculation of the signal frequencies of the detector is proposed, taking into account the size of the detector and stripe contacts. The resulted electronics and calculations are useful for manufacturing of an industrial detecting system based on Si (Li) detectors.

Keywords: detector electronics; filters, signal generation in silicon detectors.

Introduction. Nowadays, the mining and metallurgical complex is one of the basic parts of industries. In the modern world, analyzers that determine the chemical composition of a substance are widely used in mining and metallurgical industries. X-ray fluorescent system has a number of advantages among the analyzers of elemental composition. These include simplicity of analysis and sample preparation, the possibility of conducting both qualitative and quantitative analysis, a short analysis time, the definition of a wide range of elements and ranges of their concentrations. Special mention should be made of the advantage of the X-ray fluorescent method of analysis, such as the rapid analysis of petrogenic elements (Si, Al, Ca, Mg, S etc.). Therefore, improving the sensitivity of devices receiving data on useful minerals is one of the main priorities of instrumentation. An important part of the spectrometer is the sensitivity of the detector and the high stability of the output signals in spectrometers. Such systems based on semiconductor detectors are widely used by X-ray fluorescence spectrometers to determine the real composition of geological samples [1, 2]. Compared to other similar detectors, silicon-lithium detectors have the following advantages: high energy resolution; linearity of signals over a wide range of energies for particles of different types; lack of sensitivity to magnetic fields; stability and small overall dimensions [3-12]. Despite the fact that such systems were invented and put into operation for a long time, the versatility of using different types of silicon detectors makes them relevant for development and research to date.

For the successful operation of detection systems, it is very important to construct suitable electronics, since detection of signals using silicon band detectors is complex. This is due to the following characteristics of the detectors: small multichannel signals, pending intelligent electronics for signal detection (high gain and noise suppression), leakage current (DC)

In [13-15], electronic parts of multichannel silicon detectors were considered. As the analysis of the results of these studies shows, one of the important parts of the system is a filter for extracting signals from the detector.

In this paper, it is proposed to calculate the charge amount, and to develop an electronic signal filter for these detectors. The work is devoted to signal modeling and designing a charge sensitive preamplifier-circuit based on an operational amplifier for X-ray fluorescence analyzer systems. As detector of the system it was used Si (Li) detector.

Methods and experiment. Development of Si (Li) p-i-n structures with a diameter of the sensitive region of ~ 50-50 mm and a thickness of >1.5 mm is a technological challenge. In particular, it is necessary to create a sufficiently extended, uniformly lithium compensated sensitive region. To obtain these characteristics of a large-size silicon detectors, parameters such as temperature, diffusion annealing time, voltage values, and drift conductivity are important. Detectors which obtained with this method with an operating voltage U_{rev} = 100-500 V, at room temperature has a value of I = 0.5-1 μA, the value of the dark current, and has an R = 5 kΩ resistivity. The working area of the detector has metal contacts Au (200 Å).

To successfully reading of the detector signals, it is needed to create a suitable charge sensitive preamplifier. For this purpose, a charge sensitive preamplifier was designed on the operational amplifier which is shown in figure 1.

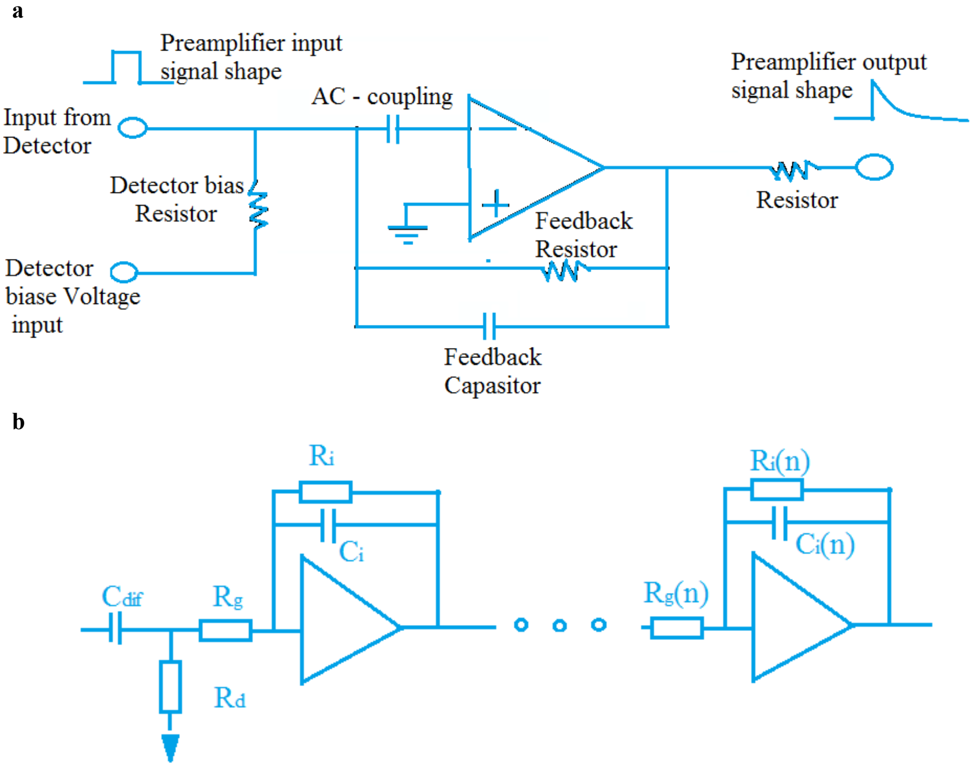

Figure 1 –
a – schematic diagram of the charge sensitive preamplifier based on the operational amplifier;
b – block diagram of the shaper with a single differentiation and n-fold integration.

The first stage of the circuit for the silicon detectors is a preamplifier designed to integrate the electric charge received from the sensor and to amplify the voltage. This is the most important unit, because it determines the overall sensitivity of the system. The preamplifier consists of an operational amplifier configured as a charge sensitive amplifier. The charge sensitive amplifier uses a negative feedback network with a capacitor and a resistor.

A high impedance for the preamplifier is used to bias the detector signal. The sensor is connected to the input of the preamplifier via a coupling capacitor. This capacitor isolates the preamplifier input from any DC bias that can lead to saturation, as well as from the leakage current of the sensor. Thus, a signal is generated.

The charge sensitive amplifier and shaper, which includes the signal transmission lines between the channel blocks, is exposed to various noise and interference. The total fluctuations of the signal in the channel are made up of two components:

– fluctuations of the signal proper, arising during its formation,

– electrical noise of the channel circuit elements, independent of the signal.

Fluctuations of the signal itself due to the probabilistic nature of the formation and collection of electron-hole pairs in the silicon detector have a distribution close to the Poisson distribution, and its width N_{eh} is half the maximum value with sufficient accuracy:

$$\mathrm{N_{eh}} = 2.35 * \sqrt{E * \varepsilon * F} \tag{1}$$

where E is the energy loss in the detector, ε is the average energy of formation of one electron-hole pair in silicon, F is the Fano factor equal to 0.12 for silicon.

Let us return to Fig. 1 and consider the operation of the channel from the bandpass filter. A short current pulse produced by an ionized particle charges the capacitance of the detector Cd and the feedback capacitance $C_f = C_{fb}$. This leads to a voltage jump at the output of the amplifier:

$$\Delta U = \frac{Q}{C_{fb}+\frac{C_d}{k}} \tag{2}$$

where k is the loop gain of the preamplifier, Q is the charge in the detector. The rising edge ΔU is determined by the time of charge collection, the speed of the preamplifier and its load, and the decay is the type of the discharge circuit. In the discharge circuit of the feedback capacitance, a high-resistance resistor is most often used (figure 1), less often a digit key [16]. The minimum possible preamplifier front is determined by the acquisition time of the carriers. The mobility of electrons in silicon is $\mu_e = 1250$ cm^2/(V·s), for holes $\mu_p = 450$ cm^2/(V·c). The carrier velocity is $v = \mu \cdot E_f$, where E_f is the electric field strength. Obviously, the collection time depends on the thickness of the detector and is 10-20 nanoseconds for the most common detectors with a detector thickness of 300-400 microns and an operating voltage of -100V. The second factor is the input time constant of the charge sensitive amplifier [17] $\tau_{in} = C_d \cdot R_{in}$ where the input resistance is:

$$R_{in} = \frac{\mathrm{C_{in}}}{\mathrm{g_m * C_{fd}}} \tag{3}$$

where g_m is the steepness of the input stage, C_{in} is the input capacitance of the preamplifier. The input resistance of the preamplifier is purely resistive and low impedance, so τ_{in} is usually comparable with the time of collection of carriers. The main factor of speed, as experience shows, is the frequency band of the preamplifier, determined from its first pole. Further shaping of the signal and its filtering from noise is performed by the shaper.

The signal conditioning in time and noise filtering is performed by the shaper with the transfer function K (S).

Let us consider in detail the types of shapers most often used for silicon detectors. Since the use of silicon detectors in high-energy physics implies, as a rule, multichannel reading electronics and, as a result, minimization of its size and consumption, the use of very complex shaping chains is not advisable. Let us consider the most frequently used schemes of shapers. The most common type of shaper is the so-called CR- (RC) ^{n} shaper. Its transfer function k (s) without taking into account the signal inverting by the links of the shaper has the form:

$$k(s) \frac{s*\tau_d}{1+s\tau_d} * \left(\frac{k}{1+s*\tau_i}\right)^n \tag{4}$$

where τ_d is the time constant of differentiation, τ_i is the integration time constant, k is the amplification factor compensating for the amplitude loss. Usually the shaper is implemented according to the scheme shown in figure 1-b.

Results and discussion. Taking into account the above parameters, it is possible to estimate the total capacitance of a detector with a reverse bias of Cr and an interband capacitance Cs and a volume capacitance Cb [16]. The meaning of the experimental data of Cb is Cb = 300 pF [10]. Cs can be found from this expression:

$$C_s = 2 * (w + L)\left(0.03 + 1.62\frac{w+20}{p}\right)\left[\frac{pF}{cm}\right] \tag{5}$$

where L is the length, and w is the width of the bands, and p is the step. The total capacitance Cr = Cb + Cs = 330 pF. The resistance of the metal electrodes is R = ρ L/w·t, where ρ = 2.44 μΩ·cm is the resistivity, t is the thickness, for this p-i-n detector R = 0.1 Ω.

From these calculations it can be said that radiation conditions and detector geometry play a key role for the output signal of the detector, and the total working area of the detector determines the frequency of the detector signals. For example, the current density in the bright detector field can be 0.1 nA/cm^2, it gives 160 ns between the events of electrons per cm^2 of the working region [18]. In our case, the active working area is 40 mm x 5 mm = 2 cm^2, so the electrons will affect on detection contact every 160/2 = 80 ns. From the above calculations, we can say that the electronics of the proposed detector operates at a frequency f ≥1/80 ns or 12.5 MHz.

In order to the charge sensitive amplifier to act as a current integrator, the values of the feedback resistor and the capacitor of the charge sensitive amplifier should be chosen so that the time constant should be high. At the same time, the total input capacitance must be low to minimize noise, so the feedback capacity should be small. However, this value is set according to the capacitance of the sensor, and therefore, must be large enough to minimize the cross-linking between contacts. On the other hand, to minimize thermal noise, a high feedback resistance is required.

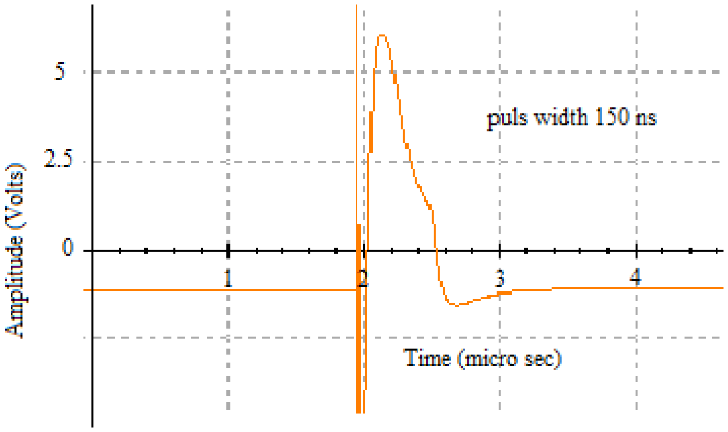

Figure 2 – Voltage at the output from the shaper when the preamplifier pole is compensated for the input pulse from the preamplifier with the resistor in the discharge circuit and withk=1, n=1, T=t/ τ, $\tau = \tau_d = \tau_i$

Voltage from the output of the shaper defines by expression:

$$U_{out}(s) = \frac{\tau_{fb}}{1+s*\tau_{fb}} \tag{6}$$

with κ=1, n=1.

It is seen from figure 2 that the recovery time of the baseline sharply increases, in comparison with the recovery of the shaper after the action of a single voltage pulse.

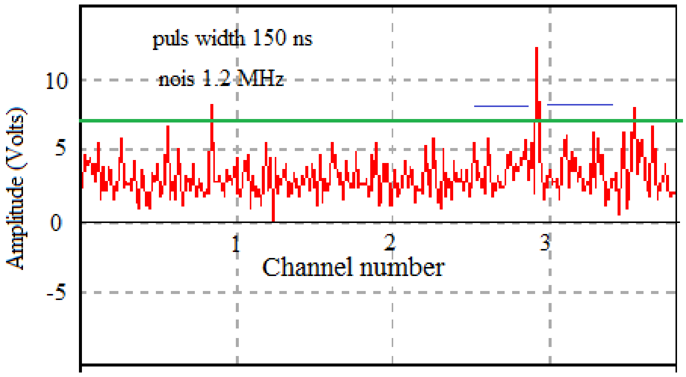

Figure 3 – Spectrum of preamplifier output signal

Figure 3 shows the output signal spectrum of the preamplifier. A bandwidth preamplifier passes a certain frequency range by cutting off a lower frequency and cuts a higher frequency. It is clearly seen from figure 3 that the preamplifier passes the peak frequency of 12.5 MHz with a capture width of $4 \cdot 10^{-7}$ sec.

Next, an electronic circuit can be described which, together with the Si detector, must provide a narrow digital pulse each time the electron acts close to the corresponding band. Fig.4. shows the functional blocks of a typical front circuit used with semiconductor detectors, where the detector converts the energy of the incident radiation into electrical pulses, which are amplified by the preamplifier and generated by the signal processing unit, also called the shaper.

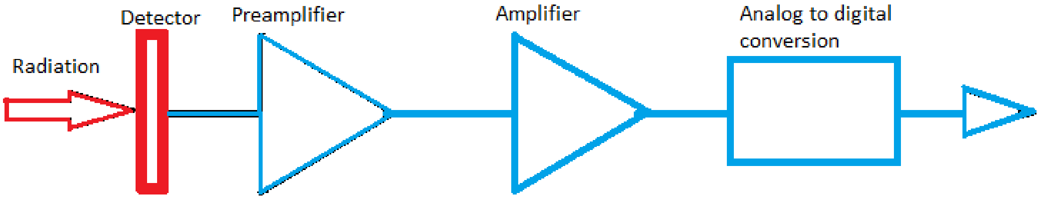

Figure 4 – Operational electronic block of X- ray detecting system

The amplification circuit has the task of increasing the signal-to-noise ratio (SNR), which is achieved by limiting the bandwidth and which, in turn, changes the time characteristic (shape) of the pulse[19, 20]. Therefore, there is a tradeoff between the SNR and the speed of the system. The final block in figure 4 is used to digitize the analog pulse for further processing and/or data transfer.

Conclusion. In the work it was determined that the output of the silicon p-i-n detector is in the region of 12.5 MHz with a capture width of $4{\cdot}10^{-7}$ sec. Also, considering the foregoing considerations, it can be said that the bias voltage sources of the detectors should have a low level of noise and interference, especially in the low-frequency region, since the charge sensitive amplifier for this type of noise is a low-pass filter. Contacts of detectors should have low impedance, much lower than the noise resistance of the input stage, determined by the steepness of its first transistor. The parallel noise of the discharge resistance of the charge sensitive amplifier has a maximum if the feedback time constant is equal to the formation time of the shaper.

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РЕНТГЕНДІК ФЛУОРЕСЦЕНТТІК СПЕКТРОМЕТРЛЕРГЕ АРНАЛҒАН АСА СЕЗГІШ ДЕТЕКТОРЛЫҚ ЖҮЙЕЛЕР

Аннотация. Жұмыста кремнийлік детекторлердегі рентгендік сәулелену арқылы алынатын сигналдардың сипаттамасы қарастырылған. Рентгендік флуоресценттік спектрометрге арналған кремний-литийлік p-i-n детоктор негізіндегі детекторлік жүйенің электронды сұлбасы ұсынылады. Сигналды детектордан алу үшін операциялық күшейткіш негізіндегі екінші ретті жолақты фильтір жобаланды. Фильтр, сигналдың 12.5 МГц-ке жақын жиілік диапазонында жұмыс жасайтын стриптік Si(Li) детектормен толығымен сәйкес келеді. Сонымен қатар, жұмыста детектор мен стриптік контактілердің өлшемін ескере отырып, детектор сигналының жиілігінің есептеуі келтірілген. Келтірілген электроника мен есептеулер стриптік детекторлер негізіндегі өндірістік детекторлік жүйелерді жасауда пайдалы болып табылады.

Түйін сөздер: детектор электроникасы; фильтрлер, детекторде сигналды генерациялау.

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ВЫСОКОЧУВСТВИТЕЛЬНЫЕ ДЕТЕКТИРУЮЩИЕ СИСТЕМЫ ДЛЯ РЕНТГЕНОФЛУОРЕСЦЕНТНОГО СПЕКТРОМЕТРА

Аннотация. В работе рассмотрен характеристики сигнала, создаваемого воздействием рентгеновского излучения в кремниевых детекторах. Предлогается электронная схема детектирующей системы, на базе кремний-литиевого p-i-n детектора для рентгенофлуоресцентного спектрометра. Для извлечения сигнала от детектора был спроектирован полосковый фильтр второго порядка на основе операционного усилителя. Фильтр полностью совместим с Si(Li) стриповым детектором, работающем в диапазоне частот сигнала близко к 12.5 МГц. Также, в работе предложен расчет частот сигнала детектора, учитывая размер детектора и стриповых контактов. Приведенная электроника и расчеты полезны для изготовления промышленной детектирующей системы на основ Si (Li) стриповых детекторах.

Ключевые слова: электроника детектора; фильтры, генерация сигналов в детекторе.

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