SILICON DIODE ARRAYS AS COORDINATE-SENSING DETECTORS FOR NUCLEAR PHYSICS*

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Abstract. The matrixes of silicon diodes integrated on one plate of silicon, can be utilized as coordinate-sensing detectors in researches in the field of nuclear physics. In the given activity are analyzed of their advantage in front of strip-detectors at the large fissile areas and rather small amount of cells. In particularize outcomes of development of matrixes from 6x6 cells having the area of a cell 0,5 cm^2, feature of their design and production process. In particular, the new designs of guard rings utilized, due to which one the increase of an electrical field near to perimeter p^+-п of transition can be completely removed, and also influencing surface drift of ions on detector characteristics is eliminated. The possibilities using of similar designs in gaps between bands of silicon strip-detectors are discussed.

The stability of silicon matrixes to γ-radiation ^{60}Co was investigated. The changes of leakage currents of cells, electric noises, of the C-V characteristics and losses of charges were measured. Last were determined from relations of amplitudes of signals of on α-particles to voltage on the detector and heating-up period of a signal impulse.

The spatial resolving power of a matrix can be considerably improved if use a system " a silicon matrix - scintillator CsJ (Tl) ". The position coordinates of absorption of a fragment or photon in a scintillator are determined from ratio of photoelectric signals on adjacent cells. The experimental findings of investigation of such system is resulted.

Introduction

As coordinate - sensing detectors of charged particles will use silicon strip-detectors [1] more often. However when the number of cells of decomposing is insignificant, it is more expedient to use silicon matrixes [2]. If the detector consists from **n**x**n** of cells, number of output and, accordingly, the number of processing channels of signals for strip-detectors makes 2**n**, and for matrixes - $\mathbf{n}^2$. At **n** > 2 matrixes demand the greater number of channels of amplification. On the other hand, the strip's area considerably exceeds the area of one cell of the conforming matrix. For example, for the coordinate-sensing detector of the format 6x6 cells at the area of one cell 1 cm^2 the area strip of the equivalent strip-detector is peer 6 cm^2. The energy resolution of detectors on α-particles will be approximately 15 keV for a matrix and about 40 keV for strip-detector. Besides for strip-detector the requirements to charge sensitive preamplifier are increased, as the capacitances of full leaning of a cell of the matrix and strip will be accordingly 30 pF and 180 pF at depth of a plate of silicon 300 microns. Thus, at usage of the strip-detector there can be difficulties, bound noisy of detector and preamplifier. For example, in case of registration mip-particles, specially at temperature rise or availability of a degradation conditioned producing dose. One more argument for the benefit of matrixes can be more stand a processing logic of signals. Apparently, at number of cells less than 7x7 in a number of cases it is more expedient to use silicon matrixes.

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1. Properties of silicon matrixes

We design a silicon matrix of the format 6x6 cells with the area of a cell 0,5 cm^2 and there is in mining a matrix 6x6 with the area of a cell 1 cm^2. Its designs are shown in a fig. 1. Matrix by depth 300-350 microns and specific resistance about 4 kΩ*cm are produced on plate of n-type silicon.

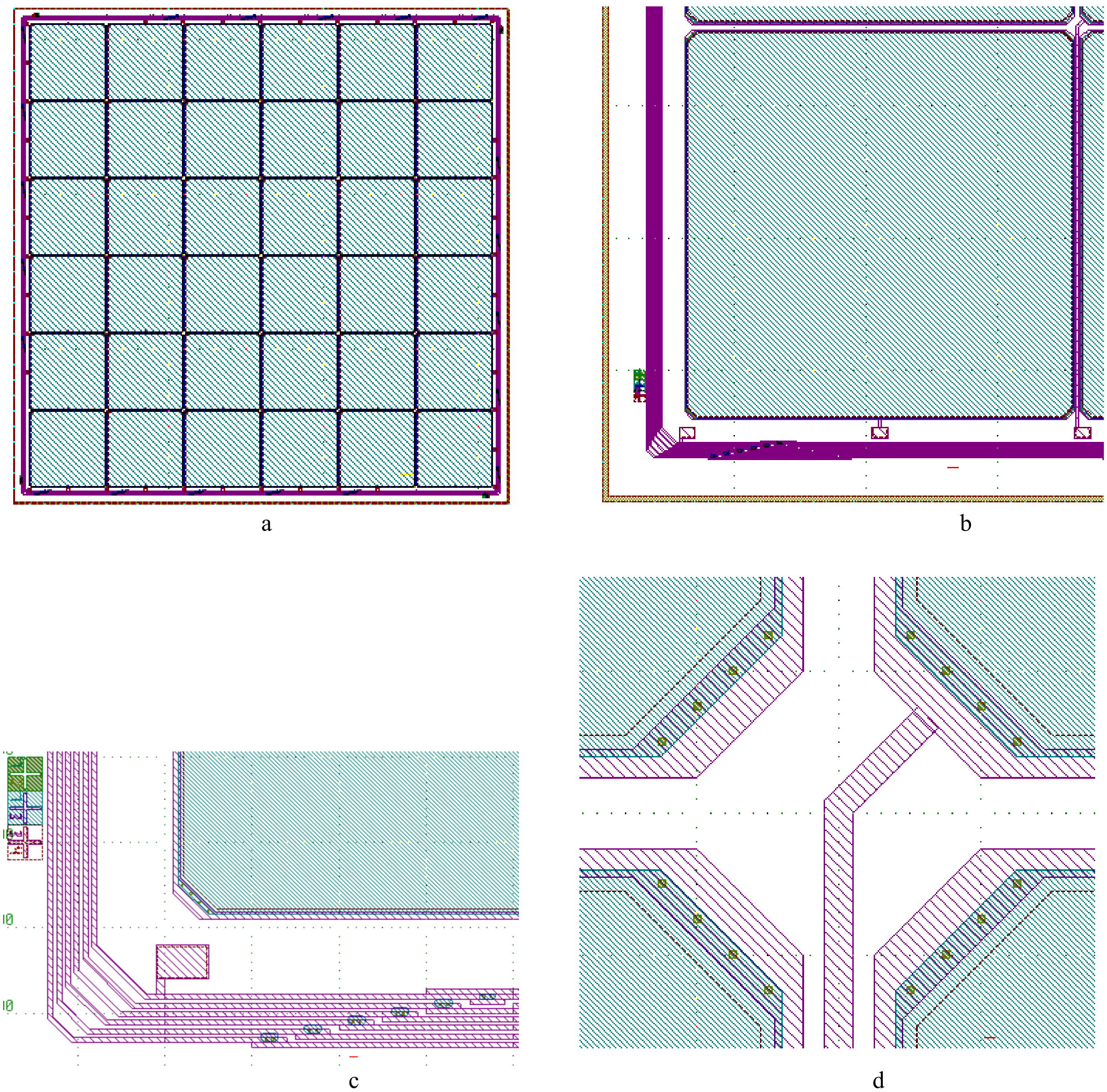

Fig.1. Topology of a silicon matrix, a - general view, b - corner structure, c - area of a corner of a matrix, d - corners of four adjacent units.

They are installed on fiberglass plate and can be made by the way ΔE of detectors. The matrixes can be assembled in metal case. At voltage on detector U=10 V depth of depletion in silicon makes 100 microns, full depletion is reached at U=80-100 V. Leakage current of a cell of the matrix 0,5 cm^2 at U=40 V about 15-20 nA. The electrical noise of a cell was measured as FWHM of a generating signal, is peer 4-6 keV. There is also other characteristic reflecting a detector noise. Its usage gives of large advantage, when the silicon detector is applied to registration of particles leaving in silicon small losses of energy. This characteristic is a spectrum of noise impulses. The similar spectrum for a cell of our matrix is shown in a fig. 2.

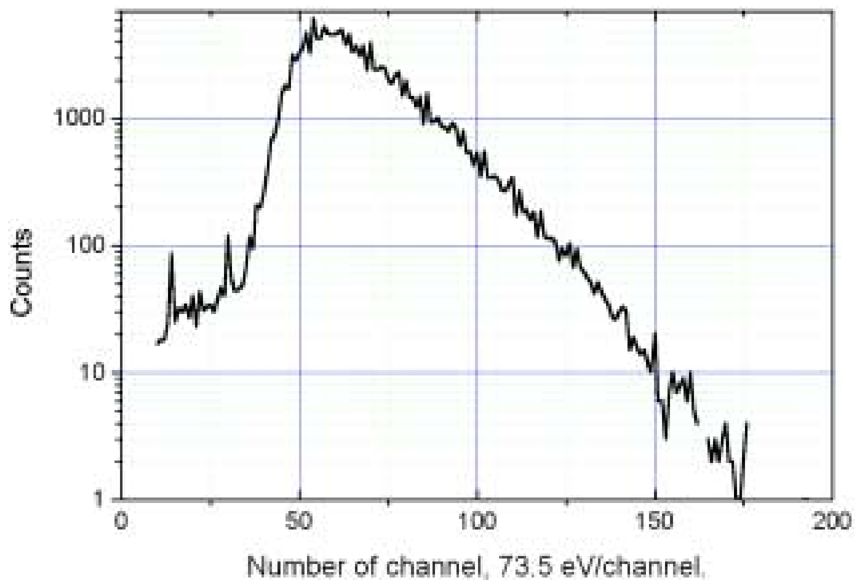

Fig. 2. Spectrum of a noise of a detector and preamplifire.

This spectrum enables precisely to calculate frequency of noise impulses, the energy exceeds which one a certain predetermined threshold, i.e. frequency of spurious noise impulses contribution into a counting channel at a task of a definite lower layer of the discriminator. It is possible to decide and inverse problem - definition of a threshold of the discriminator, at which one the frequency of noise impulses does not exceed given. Thus, however, it is necessary to allow, that the number of noise impulses with energy above by given needs to be received by integrating of quantity of readouts in a fig. 2 on channels of a spectrometer. For point of intersection of a noise spectrum from a horizontal straight line conforming 1 imp in a channel, the expression is fair

$$A = 1/\left(1-10^{-1/n}\right), \qquad (1)$$

where A - number of impulses in all channels to the right of point of intersection, n - number of channels in range, within the limits of which one the number of noise impulses changes on an order of magnitude. We suppose, that the shape of a noise spectrum is exponential. It is executed, if the energy of noise impulses is not so small. Energy in point of intersection we shall designate as E_1. A return problem, when the number of noise impulses is set and the energy of a threshold of the discriminator is determined, is decided with the help of following expression:

$$E_{threshold} = E_1 + n\cdot\delta E\cdot \lg A, \qquad (2)$$

Where δE - price of a channel. For a spectrum in a fig. 2 δE = 0.074 keV, A = 11.5, E_1 = 12.9 keV, $E_{threshold}$= 14.9 keV.

It is possible to enter the norm by the way tolerance frequencies of spurious noise signals, which one, naturally, will depend generally on a field of application and requirements to instrumentation. For determinancy let's assume its equal 1 imp/min. Then on a level of a threshold of discrimination $E^*_{threshold}$ it is possible to judge quality and applicability of the given detector. If the time of measurement (T_m) of a noise spectrum is equal 1 min, the formulas (1) and (2) remain valid. If T_m > 1 min it is necessary to enter , $E_1' = E_1 - n \cdot \delta E \cdot T_m/10$, then

$$E^*_{threshold} = E_1' + n \cdot \delta E \cdot \lg A. \qquad (3)$$

For a spectrum in a fig. 2 $E^*_{threshold}$ = 8.4 keV. Allowing, that losses mip - particles in silicon on depth 300 microns make about 100 keV, it is possible to made a conclusion about a considerable reserve in sensitivity of the given matrix, which one can be realised at heightened temperatures or at degradation of the detector under operating of irradiation.

Of spectrum of α-particles is adduced in a fig. 3. The energy resolution in 21 keV is determined by the resolution of the detector 11 keV, preamplifier 5 keV and source of α-particles 17 keV.

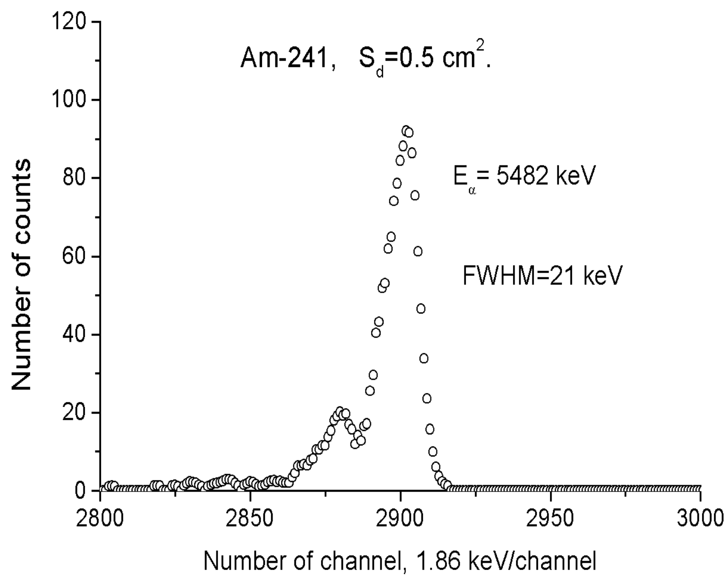

Fig.3. Spectra of a α-particles ^{241}Am.

In a fig. 4 the spectra of losses of β-particles from a source Sr + Y, removed are rotined at different displacement of the detector. The spike at U = 50 V and energy of losses E = 110 keV is connected to high-velocity electrons with energy above 800 keV. At small voltage the peak shows is more gentle because of a non-uniformity on the area of the detector of a diffusion length of vacant electron sites, that results in a dispersion of losses of electrons of high energies and bleed of a peak. Availability of a peak at U = 50 V and small energy of noise testify to the sure registration of mip-electrons.

One of advantages of silicon detectors is the high controllability by their characteristics. In parameters of detectors it is possible to vary over a wide range by voltage variation on the detector and shaping-time of a impulse τ_s . The bias regulates depth of leaning in silicon, and τ_s - time of a congregating charge of a signal. For example, for increase of response it is possible to reduce τ_s up to 100 ns and below, but thus it is usually necessary to augment U to supply a full enough collecting of charges from all depth of a plate. If the requirements to response are low-level, it is expedient to increase τ_s, for example, till 3-10 μs. In this case it is possible to lower U up to 10 - 40 V, that will lower the requirements to production process of the detector, will lower its cost and will improve reliability. It is possible to ensure the requirement of a full collecting of charges and in this case, as at considerable τ_s (from 1 up to 10 μs) the diffusion length of vacant electron sites in the detector makes 250 - 300 microns. It allows to achieve a full collecting of charges even at U = 10 V.

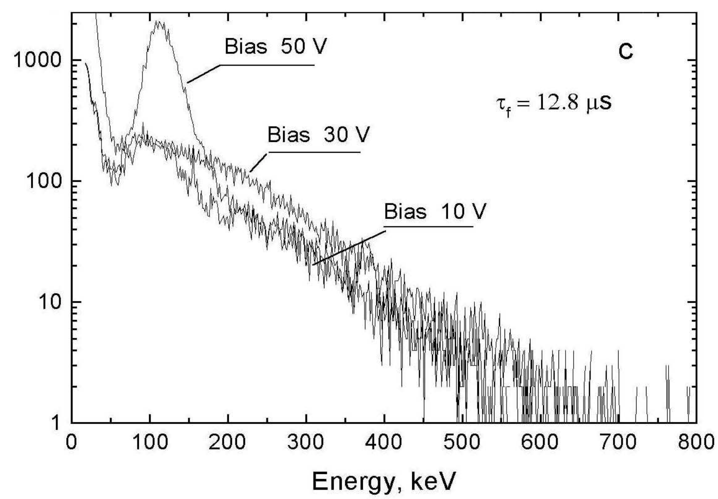

Fig. 4. Spectra of energy losses of electrons from a source Y+Sr.

The low efficiency of detecting of γ-quanta by silicon detectors is known, that quite often it is very important at registration of charged particles. The low efficiency is obliged not only small cross-sections of a Compton scattering, but also inexact losses Compton and photoelectrons due to small depth of a plate of silicon. The sensitivity of silicon detectors to γ-quanta also can be controlled change U and τ_s. The decreasing U and τ_s can on orders of magnitude lower frequency of signals of a γ-background. These relations are rotined in a fig. 5.

The creation of a multichannel device of an analogue signal processing of a matrix (preamplifiers + shapers) is not a simple problem, as the high enough requirements on a noise and are mated (if it is necessary) on response with the requirements shaped by large number of channels - small powerful and overall dimensions. We design the multichannels plate of preamplifiers - shapers keeping till 8 channels. The sizes of plate is 133x136 mm^2, noise of a channel - 1 4 keV at capacitance on an input C_{In} = 0 and 5 keV at C_{In} = 25 pF (equivalent capacitance of a cell of the matrix with the area 0,5m^2 at U = 40 V). The time constants of formation can be $\tau_s \geq 1$ μs. Energy consumption of the one channel about 150 mW. For transition in area smaller τ_s it is necessary to exchange amplifying microcircuits of the preamplifier and conditioner.

2. The multisection detector on a silicon matrix

In a number of cases the very large areas of detectors in tens and hundreds cm^2 are demanded. However increase of the fissile area of detectors is connected to considerable difficulties. These difficulties concern all type of detectors, but in relation of silicon detectors they show specially clear. At increase of the area of a silicon detector the leakage current of the detector and bound with it a noise grows. Besides the capacitance of the detector and bound with her a noise of the charge sensitive preamplifier grows. The increase of a noise results in deterioration of the energy resolution and increase of the minimum detectable energy of the particles. We have offered idea of multisection detectors, which one allows bypass the indicated relation. This idea is encompass by following [3-5]. The detector is partitioned on **n** of independent parts (sections) with the area of each section **s**. Each section has the channel of amplification. The signals from all channels move on the special analog summator, in which one they are injected into one trunk and further move on the meter or kick-sorter. The analog

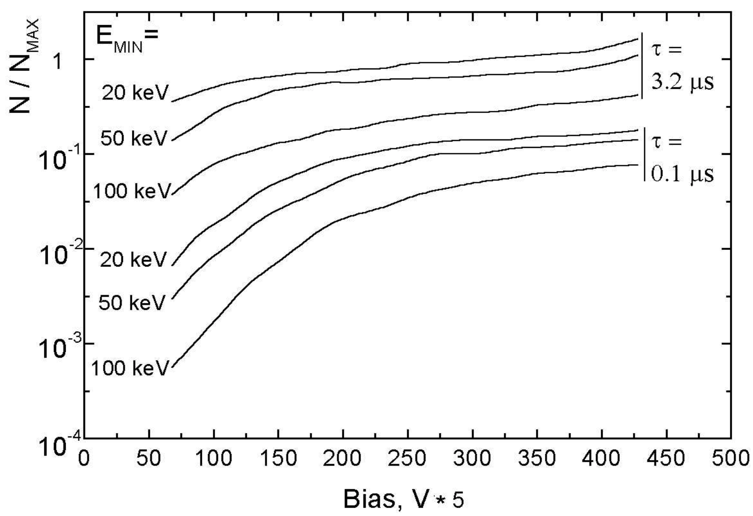

Fig. 5. Reduced number of signals, which energy exceeds selected values E_{min} =20, 50, 100 keV, depending on U and τ_s. Time of measurement 30 min.

summator is constructed in such a manner that skips a noise only of that channel, in which one in the given moment passes a signal. Thus, we receive the detector with the area **n*s**, thus a detector noise and preamplifier there correspond the areas **s**. The block scheem of the multisection unit of detecting is showed in a fig. 6.

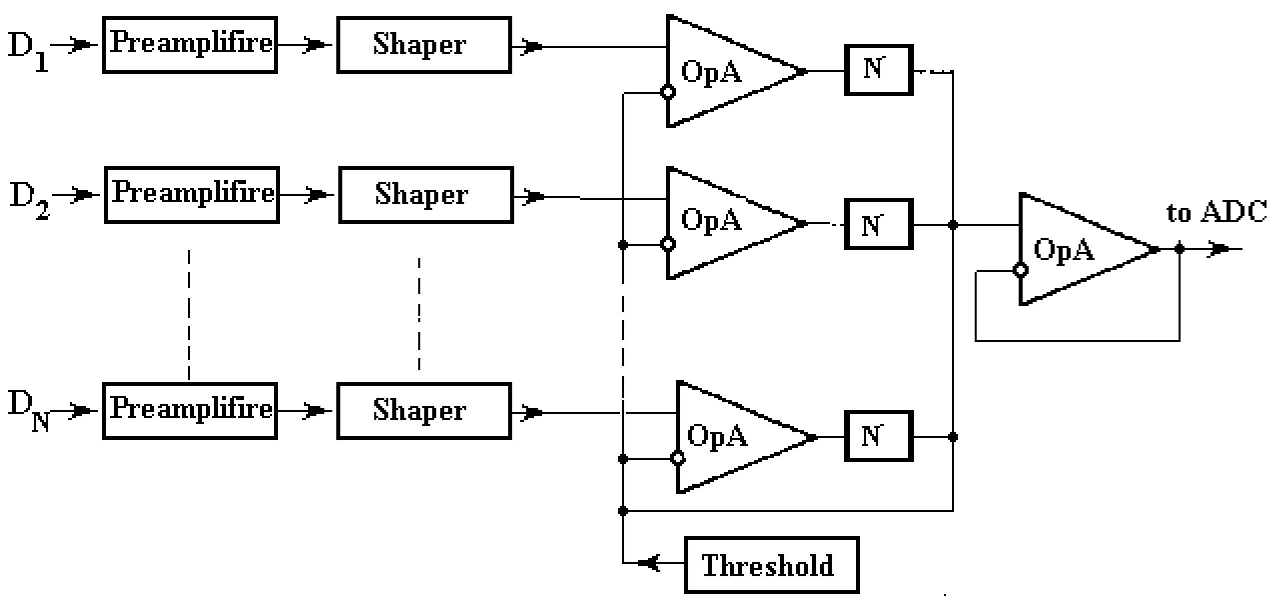

Fig. 6. Block scheem of summator. N – nonlinear element.

As the multisection detector the silicon matrixes described above can be utilised. In a fig. 7 the noise spectrums, measured are adduced at actuation of the same detector with the area 32 cm^2 in 4 modes: one-channel (when all cells are included on one channel of amplification), 2-channel (2 channels on 16 cm^2), 4-channel (4 channels on 8 cm^2) and 8-channel (8 channels on 4 cm^2).

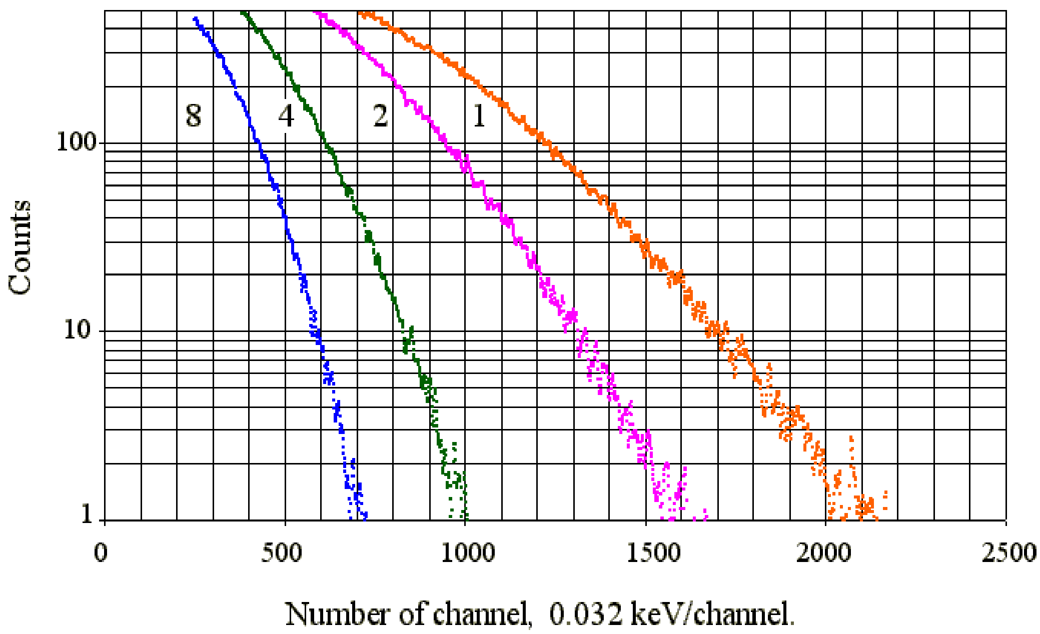

Fig. 7. The noise of matrix 32 cm^2 for 1, 2, 4 and 8 channel of the summator.

The outcomes of calculations of threshold energy of a noise from the data of spectra are tabulated 1.

First of all we shall mark, that $E^*_{threshold}$ conforming 1 imps / min, for the one-channel (customary) detector are too close to frequency of noise impulses to energy of losses of mip-particles

Table 1. Noise for different versions of the multisection detector.

Number of channels	E_1, keV	$E^*_{threshold}$, keV	Relation $E^*_{threshold,\, 1ch}$, 1к/ $E^*_{threshold,\, nch}$.	
			Theory	Experiment
1	67,6	90,6	1	1
2	51,5	62,2	1,4 ÷ 2	1,46
4	32,2	35,0	2 ÷ 4	2,6
8	22,5	25,3	2,8 ÷ 8	3,6

(100 keV at d_{Si} = 300 microns). Therefore, at the given standard on a tolerance frequency of a noise the similar detector can not be utilised for registration of mip-particles. At increase of number of channels

$E^*_{threshold}$ sharply decreases and in the 8-channel detector makes about 25 keV, that allows confidently to log mip-particles in a broad temperature band and to conduct measurement of spectra of fragments with the high enough energy resolution.

The decreasing $E^*_{threshold}$ in the multisection detector descends in $\sqrt{n}$ of time for a detector noise and in n of time for a noise of the preamplifier. As both components of a noise substantially act, the experimental outcomes should give intermediate values, as is watched (see table 1).

The similar effect at application of the multisection detector is watched and concerning the energy resolution. In a fig. 8 the spectra of α-particles ^{241}Am for detectors of one area, but with different number of sections are adduced. The values of the energy resolution for different versions are given in the table 2.

Table 2. The power sanction for single-element and multi-element detectors.

The active area of the matrix	Versions of detectors	Energy resolution, keV
16 см^2	1 ch × 16 см^2	104
	8 ch × 2 см^2	32
32 см^2	1 ch × 32 см^2	175
	8 ch × 4 см^2	52

The cardinal improvement of the energy resolution due to the multisection detector is visible.

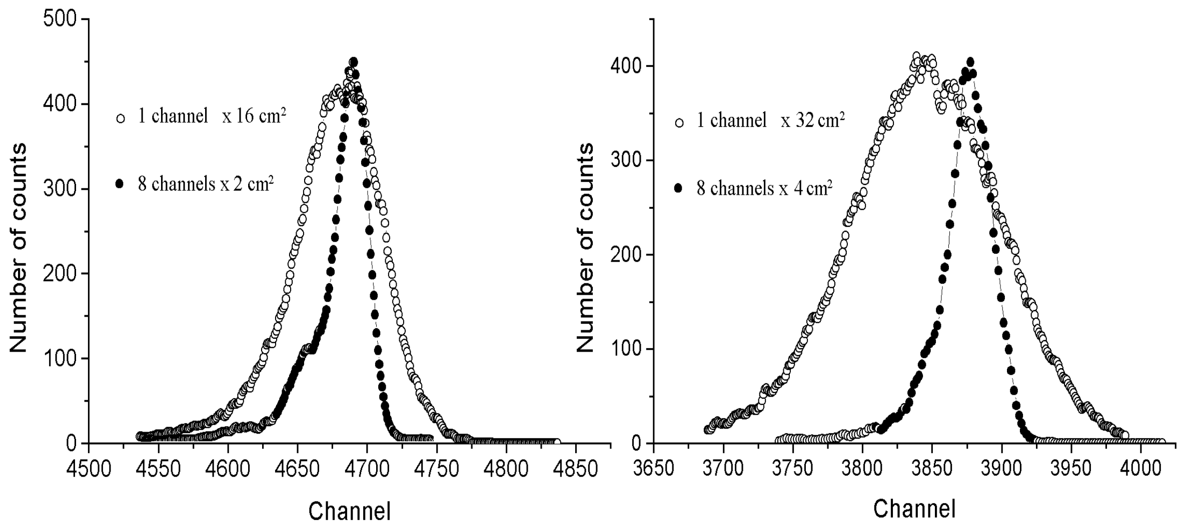

Fig. 8. Energy spectra of the α-particles ^{241}Am (E_α=5482 keV) for detectors of one area, but with different number of sections. Full area of matrix is 16 cm^2 (left) and 32 cm^2 (right).

Thus, the principle of multisection detecting allows considerably to augment the fissile area of the detector practically without increase of an electrical noise. Some lack of these detectors is the necessity for multichannel devices of amplification and pulse-shaping. However it is necessary to take into account, that the multi-channel preamplifiers are counted for smaller capacitance of the detector, therefore to them less rigid requirements, in particular, on response are presented. We design 8-channel plates of preamplifiers - shapers (see previous section).

3. The coordinate-sensing detector on a matrix with a scintillator

The receiver of the maps X, γ and charged particles can be made on the device " a matrix + scintillator ". If the scintillator introduces a solid chip covering all fissile area of a matrix, the spatial resolution considerably best than step of a matrix can be obtained. This principle is not new and will widely be used in an one-photon emission computed tomography (OPECT) [6]. In the conforming devices (gammas - chambers) as photoconverters are usually applied a photomultiplier. The coordinates of dip of particles or quanta are calculated from ratio of signals for several adjacent photomultipliers. Usage as the photoconverter of a silicon matrix gives an outlook of considerable improvement of the spatial resolution.

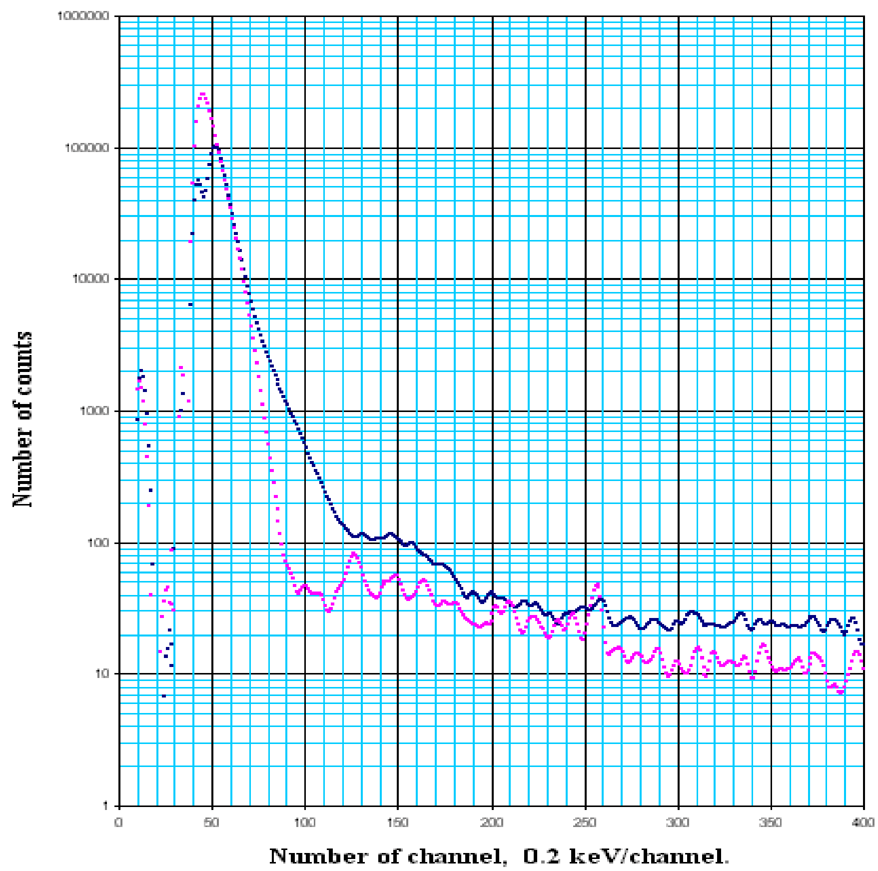

Fig. 9. Spectra a gamma of quanta ^{137}Cs of the lower matrix (black) and upper matrix (pink).

The experiments with a matrix 6x6 cells (area of a cell 0,5 cm^2) were conducted, on which one the scintillator CsJ(Tl) by an altitude of 7 mm is pasted. The spectra ^{137}Cs and ^{60}Co were removed at irradiation of a scintillator by a fascicle (diameter of 3 mm) quanta. Spectrum ^{137}Cs on one of cells, on which one the fascicle was directed, is adduced in a fig. 9, the spectrum ^{60}Co - in a fig. 10.

Spectrum of signals of the photodiode consists of three parts: an electrical noise, signals of a scintillator and signals at dissipation of quanta in silicon. It is possible to discharge a site of an electrical noise, measuring a spectrum of signals for want of irradiation. The part of a spectrum conditioned by losses of γ-quanta in silicon, is excreted first of all on nature of a spectrum - it has a small slope, as against a spectrum of a scintillator. Spectrum of losses in silicon it is possible also separately to meter, irradiating a silicon matrix arranged before a scintillator and which is not having

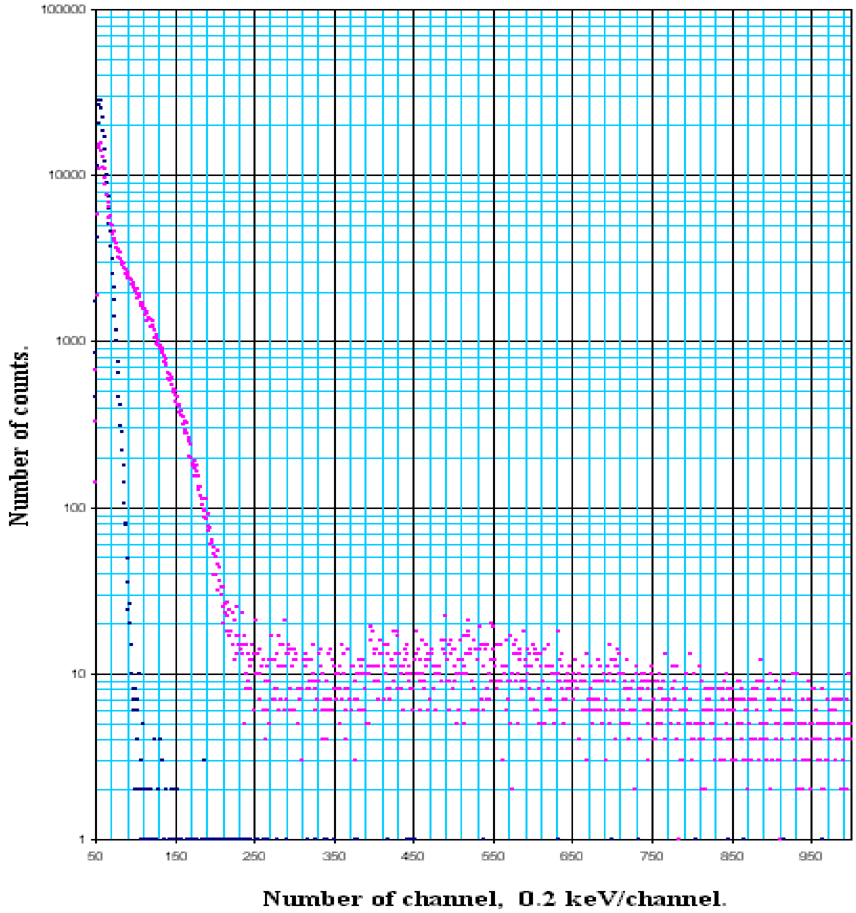

Fig. 10. Spectra a gamma of quanta ^{60}Co of the lower matrix (black) and upper matrix (pink).

with it of an optical contact. (Fig. 9). In a fig. 11 the spectrum of signals of a scintillator obtained from a full spectrum by deduction of a noise and spectrum of losses in silicon is shown.

The analysis of the reduced data allows to state following reasons.

1. The amplitude of signals of a scintillator is lower in 2-3 times as contrasted to by signals of a customary scintillator, the area of a acceptance surface is approximately peer which one to the area of the photodiode. The underestimation is conditioned by drift of a part of a luminous flux in lateral directions.
2. The dispersion of signals of a scintillator exceeds a dispersion in case of customary ("closed" by lateral faces) scintillator. In outcome a maximum (photopeak) on a spectrum misses. This outcome can be connected with the same lateral drift of a luminous flux which is mentioned above. In the "open" scintillator there should be considerably large dispersion, than in "closed", conditioned by distribution of points of absorption of energy on the area and on depth of a scintillator.
3. The maximum signal amplitude for ^{137}Cs exceeds threshold energy of a noise in ~2 times, and for ^{60}Co - in ~ 7 times. However these ratio do not allow precisely to determine a primary deposit of a noise in error of a coordinates setting of a point of absorption. The padding experience, which one

leave for frameworks of the given activity, have allowed to establish, that the interference, bound with transit of noise impulses to a counting channel, miss. The dispersion of signals conditioned by a noise is more essential. She makes for maximum signals ^{60}Co 2-5 %.

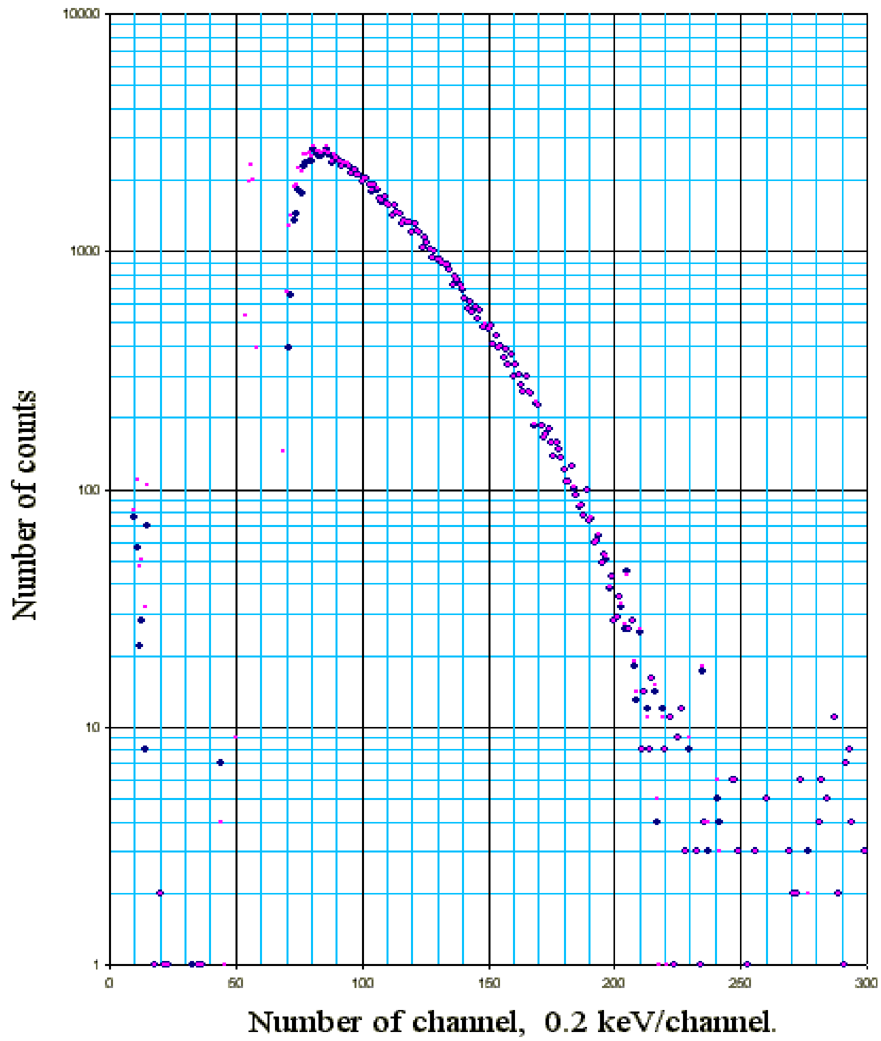

Fig. 11. The spectrum of signals of a scintillator obtained from a full spectrum by deduction of a noise and spectrum of losses in silicon

The registration of the maps of charged particles by a tendered method should be considerably more mild and precise, than in a case X and γ-quanta. Specially for fragments of one type and close on energy, since in this case main component of a dispersion of signals, bound with distribution of points of absorption of energy on depth considerably decreases.

Summary

The silicon diode arrays can be used for fulfilment of miscellaneous problems, bound with detecting of charged particles and γ-quanta. At usage as coordinate-sensing detectors they have of advantage encompassing by to a simplicity, low threshold amount of energy of registration, high energy resolution. At the large area and rather small number of members they are more preferential than strip-detectors.

If the large fissile area of a silicon detector is indispensable at low level of an electrical noise (registration of fragments low-loss, the spectrometry high resolution), that, apparently, without alternative judgement will be application of the multisection detector with usage of a silicon matrix.

The amplitudes of signals and noise in a system "a silicon matrix + scintillator" are investigated, which one is perspective for creation of the coordinate-sensing detector with large number of cells of decomposing (10^3 - 10^4). The experiments with irradiation of such frame by γ-quanta are conducted. At usage of a source ^{60}Co the signal-to-noise ratio allows to hope for enough split-hair accuracy of a coordinates setting of absorption. For coordinate-sensing registration of charged particles such principle, apparently, is even more perspective.

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