DETECTORS AND NUCLEAR RADIATION DETECTION

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SPECTROMETRIC STAND FOR MEASURING THE ENERGY RESOLUTION OF UNPACKAGED ELEMENTS OF SILICON PLANAR DETECTORS

O.A. Kapliy, S.K. Kiprich, N.I. Maslov, V.D. Ovchinnik, S.M. Potin, I.N. Shliakhov, M.Yu. Shulika, G.P. Vasiliev, V.I. Yalovenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine

A spectrometric stand for measuring the energy resolution of unpackaged single-channel silicon planar detectors has been developed and manufactured. The developed spectrometric stand makes it possible to reject detectors with unsatisfactory spectrometric characteristics at an early stage of manufacturing the detecting modules. Also, a technique has been developed for studying the spectrometric characteristics of unpackaged silicon detectors intended for the manufacture of detecting modules for ionizing radiation for various purposes.

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INTRODUCTION

Manufacturing of detecting modules based on uncooled silicon planar detectors provides preliminary studies of static characteristics, which makes it possible to carry out the first stage of rejection of detectors with unsatisfactory characteristics during manufacturing. The designs of planar silicon uncooled detectors based on high-resistance n-type silicon, developed at NSC KIPT, are described in detail in [1 - 4]. They are made from high-resistance n-type silicon and usually contain a p-n junction of the active region surrounded by a protective p+ ring for increased energy resolution.

Static characteristics, such as current-voltage characteristics (I-V characteristics) of the active region and the protective ring of the detector, as well as the capacitance-voltage characteristic of the detector, are determined on light-isolated probe stations with manual movement of probes or on automatic probe stations [2, 5]. Probe stations provide accurate positioning of the probes along the coordinate, reliable electrical contact of the probes with the pads with minimal damage of the pads aluminum surface, the dimensions of which are usually about 100×100 μm. The detectors are connected to the measuring circuits of the equipment using precision micro-position measuring probes using a microscope. However, these probes have significant physical dimensions (150×30×50 mm), what leads to an unjustified increase in the length of the input circuits which are interference sensitive. Accordingly, that leads to an increase of noise in the measuring circuits. In addition, such probes require the use of a large-sized light-isolating chamber.

The determination of the spectrometric characteristics of a silicon detector is usually performed after its installation in the detector module case, which requires providing assembly operations (gluing, bonding, heat treatment, sealing, etc.) without a guarantee that a detector with the required characteristics arrives at the assembly operation, since rejection is performed after assembly [4].

1. ELECTRONICS OF THE SPECTROMETRIC STAND

In order to eliminate unjustified costs for assembling modules with detectors that have not passed testing, a special stand has been designed and manufactured for studying the spectrometric characteristics of unpackaged single-channel silicon planar detectors. The spectrometric stand consists of a small-sized light-insulating shielded box and a spectrometer, the preliminary charge-sensitive amplifier (CSA) of which are located inside the box.

Fig. 1 shows a block diagram of the developed spectrometric stand.

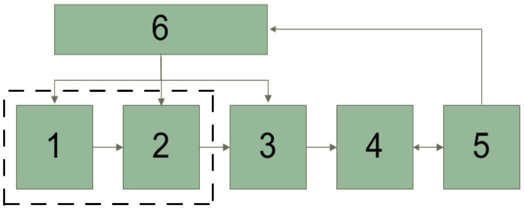


Fig. 1. Block diagram of the spectrometric stand: 1 – detecting element; 2 – charge sensitive amplifier; 3 – spectrometric amplifier; 4 – spectrometric analog-to-digital converter (ADC); 5 – computer; 6 – DC/DC-converter

A simplified diagram of a CSA is shown in Fig. 2.

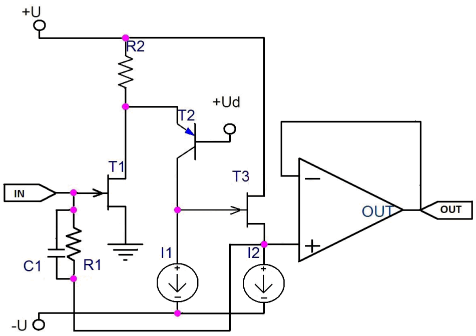


Fig. 2. A simplified diagram of CSA

The input stage of the frequency amplifier determines the noise properties of the entire preamplifier. A low-noise field-effect transistor T1 JFET with a high slope and low leakage current is used at the input of the CSA of the first stage. The operating mode of the field-effect transistor is selected in such a way as to optimize its noise parameters. The second stage has a low input and high output impedance, namely, it is a current amplifier.

Low input impedance, which is the load of the field-effect transistor, is necessary in order to reduce the influence of the through-capacity of the transistor. The stage on the T3 transistor provides matching of the high-resistance load of the current amplifier and the load of the following stages.

The feedback circuit consists of a high resistance resistor R1 and a small capacitor C1. When choosing the type of resistor, its noise characteristics were taken into account, since a high-resistance feedback resistor can have increased intrinsic noise.

The CSA output is additionally buffered by an operational amplifier, which is used for scaling.

For amplitude analysis, it is necessary to provide a good signal-to-noise ratio, since it determines the amplitude resolution and energy resolution of the spectrometer. Since the noise sources in the detector and the first amplifier stages have a wider frequency bandwidth than the useful signal bandwidth, the signal-to-noise ratio can be improved by appropriate filtering. To achieve the maximum signal-to-noise ratio, the signal with the CSA must be optimally filtered, selecting only the frequency band in which the useful signal has the highest energy and suppressing those frequencies where the noise dominates. The optimal filter for semiconductor detectors is a quasi-Gaussian signal shaper implemented as a CR-(RC)^n filter.

A quasi-Gaussian waveform can be obtained by single differentiation and multiple integration CR-(RC)^n. With an increase in the number of integrations, the signal acquires an increasingly symmetrical bell-shaped shape, close to the Gaussian curve. Presented spectrometer uses active filters based on operational amplifiers instead of simple CR-RC circuits.

The use of active filters allows to reduce the number of integration sections. The spectrometric amplifier is implemented according to the scheme of four integrating filters CR-(RC)^4, which makes it possible to obtain the excess noise ratio Ke.n. = 1.16. The formation time was chosen to be 2 µs to increase the signal-to-noise ratio when using the detecting module at room temperatures. In Fig. 3 shows a simplified schematic diagram of the shaping amplifier for the case of four integrating filters CR-(RC)^4.

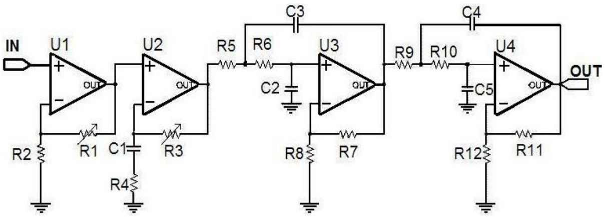


Fig. 3. Simplified schematic diagram of the spectrometric amplifier CR-(RC)^4

The spectromeric amplifier input stage of the operational amplifier U1 serves as a buffer, which provides a high input impedance at the input and pre-amplification of a weak signal from the CSA to the required value. The U2 circuit allows zero-pole compensation in an exponentially decaying signal with the CSA, which is necessary to stabilize the baseline at high numbers of pulses per second from the detector. The signal is integrated in sections U3 and U4, which are designed as low-pass filters [6].

The response of the spectrometric amplifier to the input pulse is analyzed using software simulation. The input pulse simulating the signal from the CSA has the following parameters: the leading edge duration is 10 ns, the flat top duration is 100 ns, the trailing edge duration is 5 µs, and the repetition period is 20 µs. The results of modeling the amplitude-frequency (AFC) and phase-frequency (PFC) characteristics of the spectrometric amplifier in the frequency range 100 kHz…10 MHz are shown in Fig. 4. The upper graph illustrates the behavior of the frequency response, and the lower phase response of the amplifier.

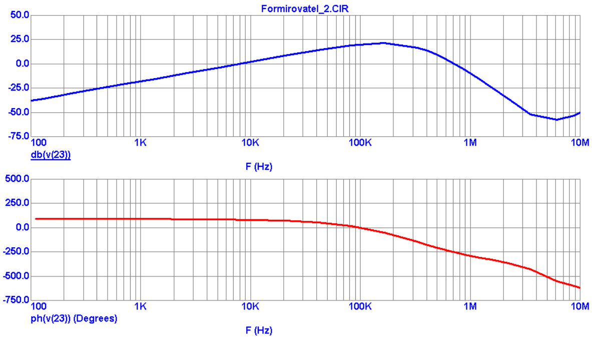


Fig. 4. Frequency response and phase response of the spectrometric amplifier

The response of the spectrometric amplifier to a pulse signal is shown in Fig. 5. The input signal is highlighted in red, the output signal is in blue.

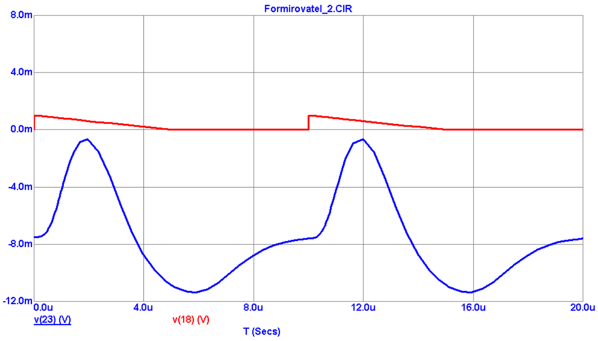


Fig. 5. Reactions of the spectrometric amplifier to input signal

Simulation confirmed the calculated characteristics of the developed spectrometric amplifier circuit [7].

To realize all the necessary supply voltages used in the spectrometer, a DC/DC converter was used (Fig. 6). Computer USB interface voltage (+5 V) is used as primary power supply for ease of use. The USB interface enables power consumption up to 3.5 W.

The level of high frequency ripple at the output of a DC/DC converter is critical for powering analog circuits. Therefore, in the manufactured DC/DC converter, for additional suppression of high-frequency ripples, additional filters are used, consisting of an input filter with smoothing elements C1, C2 and output filtering stages. All capacitors are used with low series equivalent resistance (ESR) to achieve low output ripple and high efficiency.

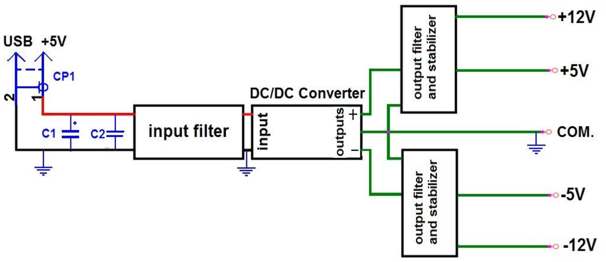


Fig. 6. Block diagram of DC/DC-converter

2. BOX FOR STUDYING

In order to ensure light and noise immunity, the box for placing unpackaged silicon planar detectors in the study of spectrometric characteristics is made of metal (aluminum). The box contains a holder for an unpackaged detector, an adapter commutation board, a preamplifier and connectors for connecting the subsequent stages of the electronic circuitry of the spectrometer (Fig. 7). The box also contains a metal opaque cover (not shown in the Fig. 7), which makes it possible to create the required conditions for measuring the spectrometric characteristics of an unpackaged detector.

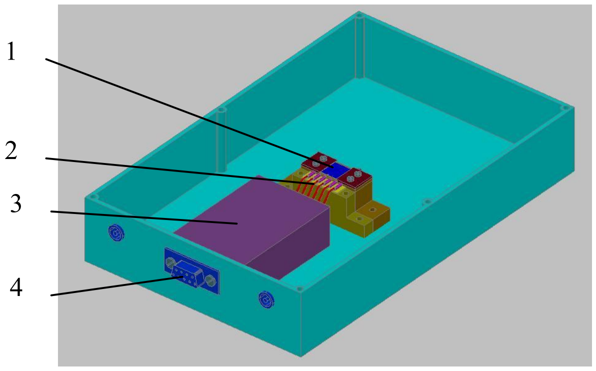


Fig. 7. Test box for placement of unpackaged detectors: 1 – silicon detector; 2 – adapter board; 3 – CSA; 4 – connector

The unpackaged silicon planar detector is mounted on a special holder and secured with side clamps made of a relatively soft dielectric material. To connect the open-frame silicon detector to the preamplifier, a dielectric adapter board with intermediate contacts preconnected to the preamplifier is used. The pads of the unpackaged silicon detector, installed and mechanically fixed on the holder in close proximity to the adapter board, are connected to the transition contacts of the board by jumpers made of aluminum wire with a diameter of 18 or 25 μm by ultrasonic (US) bonding.

Thus, a reliable connection of all electrical circuits of the detector to the measuring circuits is ensured with minimal damage to the contact pads. At the same time, in order to increase noise immunity, the requirement to minimize the length of the input circuits is fulfilled. It should be noted that after the installation and mounting of the unpackaged silicon detector on the holder, no procedures related to possible mechanical damage and contamination of the detector (soldering, gluing, etc.) are performed.

The geometrical dimensions of the test box, the height and location of the silicon detector holder inside the box take into account the permissible dimensions of the working space of the US bonder, which provides the bonding tool access to all the objects to be bonded with visual control of the objects.

To maintain a high insulation resistance between the intermediate contacts, the adapter board is made of glass ceramic CT50-1. The transition contacts are made of gold-plated nickel, which makes it possible to perform both soldering of copper conductors for connection to the CSA, and ultrasonic bonding of aluminum wires for connection to the pads of the detector.

US bonding of aluminum wire is performed on Delvotec 5330 using a microbonding tool with a minimum size of the working part, type FP45A-W-1515-L-CM VR Set "C" from SPT [8].

When performing ultrasonic bonding, it is required to rigidly fix the crystal of the silicon detector, for which the holder is provided with a vacuum mounting of the detector. To prevent the detector from displacing after turning off the vacuum when moving the box with the detector and when performing testing procedures, the holder is additionally provided with mechanical clamps that contact only the side faces of the silicon detector crystal.

Studies of spectrometric characteristics are carried out using an ionizing radiation source fixed on the box cover above the investigated detector.

After testing, the aluminum bridging wires are carefully removed with tweezers and the undamaged detector can be easily removed from the holder. The size of the bond spot of the aluminum wire on the detector's pads is slightly larger than the wire diameter, which leaves intact a significant area of the detector's pads and allows repeated bonds when the detector is installed in the module housing.

3. SOFTWARE OF THE SPECTROMETRIC STAND

The developed spectrometric system is used to measure spectra and determine the characteristics of the elements of single-channel detectors. The signals from the detector, after the CSA and spectrometric amplifier, are fed to the input of the spectrometric ADC. The ADC is to convert the amplitude of microsecond pulses entering the input into a digital code and accumulate the spectrum in the internal memory. ADC is designed as an external device connected to the USB port of a computer. This port is used to control, exchange information and power the ADC.

The ADC executes commands to start/stop signal conversion and spectrum accumulation, use and set the ADC threshold level, read and clear the spectrum accumulation memory. When measuring the spectrum, the ADC operates in autostart mode from incoming pulses. In this case, pulses that exceed the set response threshold are processed. This ADC can also operate in external clock mode via a separate input.

To programmatically connect the ADC to the system, a USB controller driver is used, there is also a library of I/O functions and functions for controlling the operation of the ADC.

The spectrometer software runs in a window interface. Commands for managing the spectrum set, express processing, calibration, storage and loading of files are available. The spectrum accumulated in the ADC memory is periodically read by the computer and displayed on the monitor screen. The corresponding windows display information about the spectrum acquisition time, the number of pulses in the entire spectrum and in the area of interest, and the loading of the measuring channel. The region of interest on the screen is highlighted with appropriate markers. The spectrum display is automatically scaled when the spectrum is displayed.

To determine the resolution of the spectrometer, an express processing program is used. During express processing, a background substrate is determined using the portion of the spectrum selected by markers and adjacent areas. The found background is subtracted from the spectrum, the maximum and deviation in the specified range are determined. Next, the parameters of the curve are determined that best describes the selected peak. The position of the center of the peak, its height and width of the peak at half height are determined. The obtained values are converted into energy units, taking into account the previously performed calibration (Fig. 8).

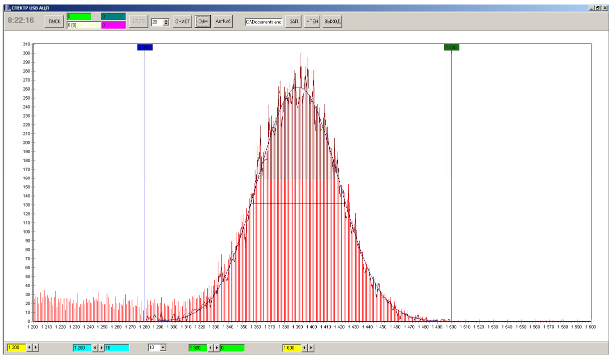
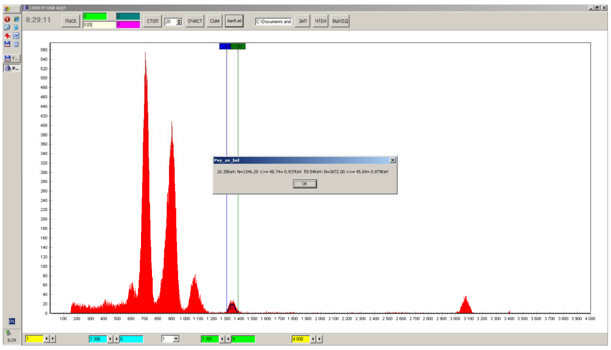


Fig. 8. Screen view of the program when performing express processing of the selected spectrum peak

The calibration procedure is carried out by the program according to the spectrum peaks from the calibration radiation source (Fig. 9). The program finds the specified peaks in the measured spectrum and determines their characteristics. Calibration results are saved in the configuration file of the program, and are loaded by the program at initial startup.


Pxy_av_bel

26.35KeV: N=1346.20 <>= 48.74= 0.937KeV 59.54KeV: N=3072.00 <>= 45.69= 0.879KeV

Fig. 9. Screen view of the program during calibration

Thus, the spectrometer program makes it possible to accumulate and process spectrometric information for the investigated planar silicon detectors.

4. RESEARCH OF THE CHARACTERISTICS OF UNPACKAGED DETECTORS

A method for studying the characteristics of unpackaged silicon planar detectors has been developed, which provides for the determination of static and spectrometric characteristics before performing the assembly operations of the detecting modules. The static and spectrometric characteristics of an unpackaged silicon detector developed by NSC KIPT with a size of 2×2 mm were determined using the developed stand in two variants of connecting depletion circuits (Figs. 10 - 12):

- 1st option – connection to a solid aluminum layer on the n+ side of the detector (the back side in relation to the front p+ side);
- 2nd option – connection to the n+ ring on the p+ side of the detector.

Fig. 10. Spectrometric stand:
1 – test box; 2 – ADC; 3 – amplifier-shaper and DC/DC-converter; 4 – computer

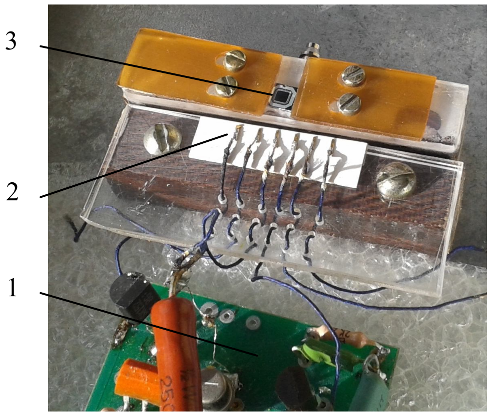


Fig. 11. The investigated detector in the test box:
1 – CSA; 2 – adapter board; 3 – unpackaged detector

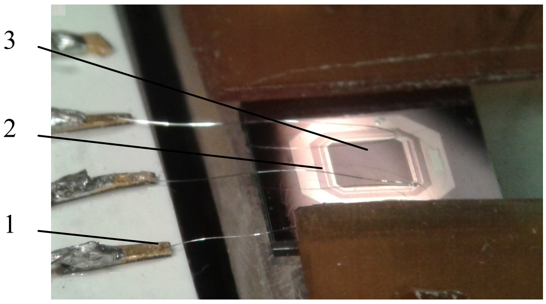


Fig. 12. Enlarged image of unpackaged detector with attached wire jumpers: 1 – intermediate contact; 2 – wire jumper; 3 – unpackaged detector

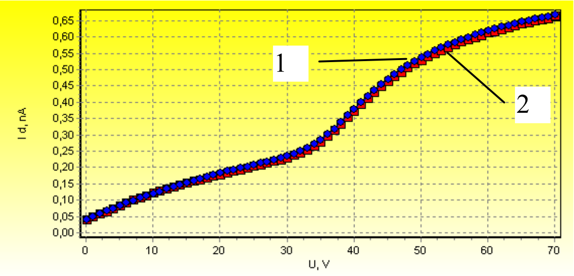


Fig. 13. VAC of the active region of the detector: 1 – connection the depletion circuit according to the first option; 2 – connection the depletion circuit according to the second option

Measurements of the voltage-current characteristics (VAC) of the detector did not reveal significant differences in the leakage currents of the active region and the protective ring (Fig. 13). The leakage current of the active region at a voltage of 70 V in the first version is 0.66647 nA, and in the second version - 0.66068 nA.

After studying the static characteristics, the spectrometric characteristics were studied using a ^{241}Am radiation source. The radiation spectra recorded by the detector using the developed stand are shown in Fig. 14.

The energy resolution of the detector at a depletion voltage of 36 V when connected according to the first variant is 1.27 keV, according to the second variant it is 1.26 keV.

The absence of significant differences in the results of measurements of the energy resolution allows us to conclude that the connection of the depletion circuit from both the n+ side and to the n+ ring on the p+ side is equivalent. This makes it possible to exclude the operations associated with bonding wires to the rear side of the detector, and, thus, to leave bonding only on the front side of the detector, which greatly simplifies the procedure for creating bonded joints when assembling the detector module.

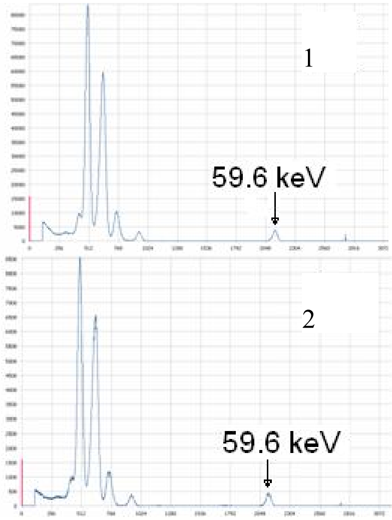


Fig. 14. Spectra of ^{241}Am recorded by the same detector: 1 – connection according to the first option; 2 – connection according to the second option

After investigating the static and spectrometric characteristics of the unpackaged detector, the assembly of the detecting module with the same detector and with the same two options for connecting the depletion circuit was performed. The results of measurements carried out on the stand showed a slight improvement in the energy resolution of the detector as part of the assembled module as compared to the results when the detector was unpackaged. The energy resolution when connected both according to the first and second options was 1.2 keV (Fig. 15).

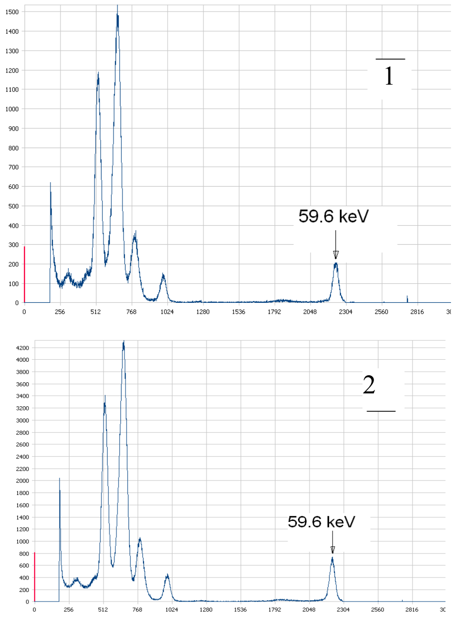


Fig. 15. Spectra ^{241}Am recorded by the same detector placed in the housing: 1 – connection according to the first option; 2 – connection according to the second option

The improvement in the energy resolution after assembly of the module can be explained by the additional heat treatment of the unpackaged detector before sealing, as well as by filling the case of the module with gaseous nitrogen, i.e. excluding the negative influence of atmospheric moisture vapors, which were present during measurements on the spectrometric stand.

Thus, it has been shown that the use of the developed spectrometric stand makes it possible to determine the spectrometric characteristics of the detectors immediately after cutting the detectors from the wafer and reject detectors with unsatisfactory characteristics before the stage of assembling the detecting modules.

In addition, the ability to connect depletion circuits to the front side of the silicon detector makes it possible to simplify the assembly procedure, and in the future, to develop the design of silicon detectors, taking into account the elimination of the need to connect electrical circuits to the rear side of the detector.

CONCLUSIONS

A special stand was developed and manufactured to determine the spectrometric characteristics of unpackaged silicon planar detectors.

A technique was developed and studies of the spectrometric characteristics of unpackaged detectors were carried out, which showed the coincidence of the measurement results for various options for connecting the detector and the preservation of the characteristics of the detector at all stages of the detecting modules assembly.

The conducted research allows to exclude the operations associated with bonding wires to the rear side of the detector, and, thus, to carry out bonding only on the front side of the detector. This greatly simplifies the assembly procedure for detecting modules for various purposes based on single-channel silicon planar detectors.

The developed spectrometric stand and research methodology allow to reduce material costs for manufacturing the detecting modules, due to the rejection of substandard detectors at the initial stage of the assembly of detecting modules, which reduces the cost of the finished product.

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СПЕКТРОМЕТРИЧЕСКИЙ СТЕНД ДЛЯ ИЗМЕРЕНИЯ ЭНЕРГЕТИЧЕСКОГО РАЗРЕШЕНИЯ БЕСКОРПУСНЫХ КРЕМНИЕВЫХ ПЛАНАРНЫХ ДЕТЕКТОРОВ

А.А. Каплий, С.К. Киприч, Н.И. Маслов, В.Д. Овчинник, С.М. Потин, И.Н. Шляхов, М.Ю. Шулика, Г.П. Васильев, В.И. Яловенко

Разработан и изготовлен спектрометрический стенд для измерения энергетического разрешения бескорпусных одноканальных кремниевых планарных детекторов. Разработанный спектрометрический стенд позволяет на ранней стадии изготовления детектирующих модулей отбраковывать детекторы с неудовлетворительными спектрометрическими характеристиками. Также разработана методика исследования спектрометрических характеристик бескорпусных кремниевых детекторов, предназначенных для изготовления детектирующих модулей ионизирующего излучения различного назначения.

СПЕКТРОМЕТРИЧНИЙ СТЕНД ДЛЯ ВИМІРЮВАННЯ ЕНЕРГЕТИЧНОЇ РОЗДІЛЬНОЇ ЗДАТНОСТІ БЕЗКОРПУСНИХ КРЕМНІЄВИХ ПЛАНАРНИХ ДЕТЕКТОРІВ

О.А. Каплій, С.К. Кіпріч, М.І. Маслов, В.Д. Овчинник, С.М. Потін, І.М. Шляхов, М.Ю. Шуліка, Г.П. Васильєв, В.І. Яловенко

Розроблено та виготовлено спектрометричний стенд для вимірювання енергетичної роздільної здатності безкорпусних одноканальних кремнієвих планарних детекторів. Розроблений спектрометричний стенд дозволяє на ранній стадії виготовлення детектуючих модулів бракувати детектори з незадовільними спектрометричними характеристиками. Також розроблена методика дослідження спектрометричних характеристик безкорпусних кремнієвих детекторів, призначених для виготовлення детектуючих модулів іонізуючого випромінювання різного призначення.