TEMPERATURE DEPENDENCE OF THE ENERGY RESOLUTION AND LEAKAGE CURRENT OF THE PLANAR SILICONE DETECTORS

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The method of measurement and automated test probe station for the study of the temperature dependence of the leakage current and energy resolution of single-channel planar silicon detectors (PSD) was created. Energy resolution and leakage current of PSD with different initial (at room temperature) energy resolution in the temperature range from $-30^{\circ}C$ to $60^{\circ}C$ was measured. Method allows to make the PSD selection for the detector systems with the possibility of use at elevated temperatures.

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1. INTRODUCTION

Detecting systems based on planar silicon detectors (PSD) are now widely used in spectrometric systems of high energy physics, nuclear physics studies and for various applications [1, 2]. In order to use the PSD in a wide temperature range this is necessary to know the temperature dependence of the static and dynamic characteristics, and above all, the current-voltage characteristics and the energy resolution [3, 4].

Temperature may significantly affect on the leakage current of the detector, because the temperature of detector material changes the probability of generation-recombination processes in the bulk semiconductor detector material and in the detector surface layers. Leakage current for the planar silicon detector is

$$I = \frac{qn_i WA}{2\tau} \quad (1)$$

where q - electron charge, W - the thickness of detector depleted layer, A - the active area of the detector, n_i -intrinsic concentration of charge carriers in a semiconductor detector material, τ - the effective lifetime of nonequilibrium charge carriers [5].

The energy resolution of PSD is largely determined by a detector leakage current. Full energy resolution spectrometer developed on the basis of planar silicon detectors is defined as the processes occurring in the detector and electronics noise.

The goal of this study is to investigate the temperature dependence of detector leakage current and the energy resolution of the PSD with different initial (at room temperature) energy resolutions. A preamplifier with resistive feedback was used for measuring the energy resolution.

Custom probe stations and methods of measurement were developed for the investigations of the temperature dependence of the silicon single-channel detectors static and the spectral characteristics. A number of measurements of the energy resolution and leakage current for the detectors with different values of these characteristics were carried under room temperature.

2. PROBE STATION FOR INVESTIGATION OF THE TEMPERATURE DEPENDENCE OF THE PSD ENERGY RESOLUTION AND LEAKAGE CURRENT

An automated multi-channel probe station provides a measurement of static and spectral characteristics of the PSD and the single-channel probe station for investigating the temperature dependence of leakage current of the PSD less than 1 nA. Probe stations allow measurements of the spectra radiation and leakage current PSD at a controlled temperature in the range from -30 $^{\circ}C$ to +60 $^{\circ}C$.

2.1. Measurement of the dependence PSD leakage current on the temperature

Multi-channel probe station uses for measuring leakage current of the active area and protection ring with PSD leakage current larger than 1 nA. The probe station allows to make control of 4 measurement channels. Thus two single-channel detector may be investigated simultaneously. When two detectors are connected, two channels are used for

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measuring the leakage current of the active area of detectors and two channels for measuring the leakage current of detectors protective rings. A block diagram of the probe station for the investigation of the temperature dependence and the spectral characteristics PSD is shown in Fig. 1.

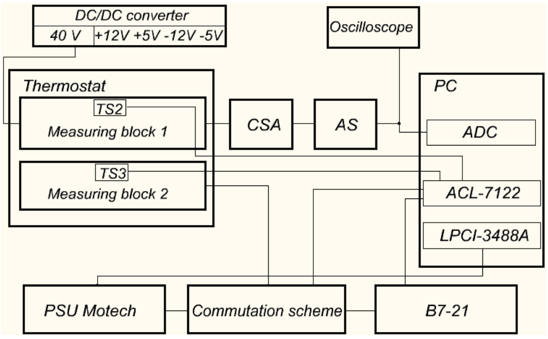

Fig.1. *A block diagram of the probe station for the investigation of the temperature dependence and PSD spectral characteristic*

The probe station for the measurement of leakage current consists of the following devices: power supply unit (PSU), current meter (B7-21), commutation unit, temperature sensors (TS), a computer with a digital adapter ACL-7122 and interface card (IC). Current meter, commutation unit and temperature sensors are connected to a computer and controlled via built-in digital adapter ACL-7122, power supply control by a computer via an interface card.

Preset voltage is supplied to the power supply on the investigated structure detectors (active areas, protective ring). Leakage current of the detector and the temperature are measured and recorded in the computer. The measured parameters are displayed on the computer monitor and written to the appropriate files. Displaying information is produced in tabular or graphical form. The procedure is repeated at the specified interval of time during a given period.

Programmable power supply MOTECH controlled by the computer used for the power supply of the detectors depletion voltage. the interface board LPCI-3488A firm ADLINK Technology Inc. uses for connecting MOTECH. It provides GPIB interface and it is fully compatible with IEEE488.2 standard instrumentation. Specialized driver used for transmission the information with interface card and software libraries GPIB-32.

Measurement of leakage detectors is performed us-ing current meter B7-21, connected to the computer through the block input-output register ACL-7122. The detectors are connected in course to the current meter through a special commutation scheme. Control for commutation scheme is also carried out through the block input-output register ACL-7122. Exchange of information between the computer and the power ACL-7122 is made using special driver and software libraries ACLS-DLL1.

Hot air used for heating of detector blocks. The air is heated to 60 $^{\circ}C$ by means of heating elements, which are controlled by an automated system. PSD was cooled below room temperature by nitrogen vapour. This is done by varying the voltage applied to the micro-heater placed in a vessel with nitrogen. Temperature control is made by means of three thermo sensors connected through the block ACL-7122 to the computer. Temperature sensor TD1 is placed outside of thermostat, TD2 - in the block for connection of the detector for the spectral characteristics measuring (measuring block 1), TD3 - in the block for connection of the detector for the static characteristics measuring (measuring block 2). Digital thermometer chip DS18S20 connected through the block input-output register ACL-7122 used as a temperature sensors.

Transmission of information with temperature sensors carried for single-channel lines through encoding timing and durations transmitted pulses. Special protocol used for data transmission and control, when these sensors work with a computer. The protocol allows create and receive pulses of short length.

Control of the temperature parameters, PSD voltage depletion, reading of the output thermal sensors and measurement characteristics of investigated detectors to the computer display are performed by a special program. Image of the program window with allocation of the used panel is shown in Fig. 2.

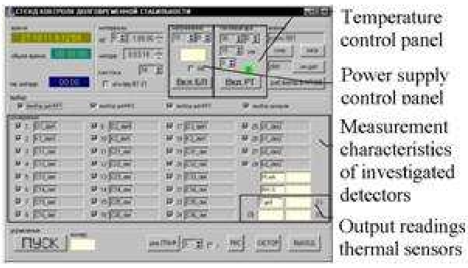

Fig.2. *The program window. Temperature control panel of the probe station*

The following parameters: temperature measurement interval of temperature measurement, temperature sensor number, used to control the temperature, offer on the temperature control panel. The connected measurement channels and their names can be specify in the program in the field of information output from the detectors. Selected channels are sampled with a given period. Leakage current, the temperature and time are displayed on the monitor in tabular or graphical form and stored in computer files. Multichannel probe station for investigating the temperature dependence of leakage current is limited by the minimum value of the measured current, constituting 1 nA. Limitation defined by the presence of leakage current of 0.1 nA in commutation unit, that is part of the probe station. An automated single-channel probe station created for the implementation the possibility of measuring leakage current less than 1 nA. Its block diagram is shown in Fig. 3.

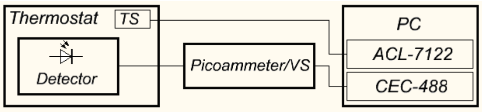

Fig.3. *A block diagram of an automated single-channel probe station for investigated the temperature dependence of the PSD leakage current, less than* $1\,nA$

The probe station contains thermostat with temperature sensor (TD), integrated picoammeter PSU KEITHLEY model 6487, computer with digital adapter ACL-7122 and interface card (IC).

Picoammeter used for measuring the current and voltage supply to the monitoring detector. Picoammeter connects to a computer through an interface card CEC-488. Changing the operating mode of picoammeter, set point voltage and current at the output device carried out through software. DS18S20 connected through the block input-output register ACL-7122 used as the temperature sensor.

Program that provides a sequence of measurements, control of picoammeter, the control characteristics of the detector, displaying the results on the screen in tabular and graphical form, saving the results in specified files used for operating of the probe station. Image of the program window with graphically displayed information is shown in Fig. 4.

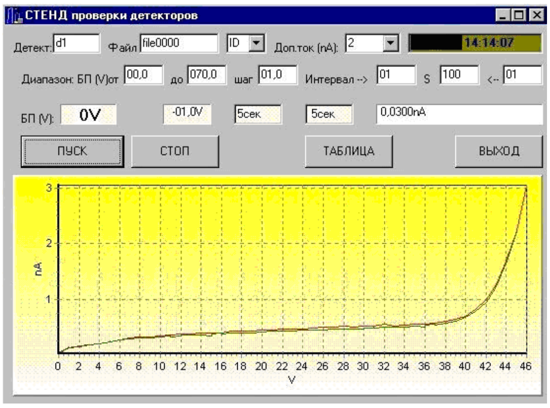

Fig.4. *Image of the program window when displaying information graphically*

The program has the ability to set the following parameters: the name of the test detector, file to record the results, the mode of measurement, permissible value of the current range and step changes tester voltage, timing measurements. The measuring current compares with specified valid value while the program operates.

2.2. Measurement of the dependence energy resolution of the temperature

The probe station shown in Fig. 1., also allows investigate the dependence of the energy resolution of single-channel silicon detectors on the temperature. To do this, the detector is connected to a special unit that is placed in a temperature-controlled thermostat. In this unit is also the head transistor of preamplifier. Signal, which is formed in the detector, goes to the charge-sensitive amplifier (CSA). Signal from CSA goes to the amplifier-shaper (AS) and further to the analog-to-digital converter, built-in computer. To supply the spectrometer electronics power supply, based on DC / DC converters, is used.

In the measurement of the spectral characteristics, the detector temperature and the head of the transistor CSA with resistive feedback is controlled. Feedback offset voltage $40\,V$ is supplied to the detector. A high-intensity source of ^{241}Am in a stainless steel used for measurements of the spectra (Fig. 5.). The isotope ^{241}Am source is placed above the detector in a lead container, open on the part detector. The high intensity of the $(10^7 Bq)$ allows you to register a sufficient number of X-rays in a relatively short time of exposure.

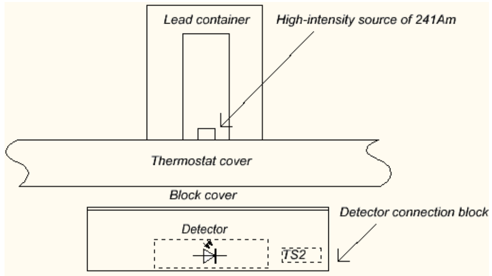

Fig.5. *Location scheme the detector and the gamma-ray source*

As the figure shows, the radiation from the source towards the detector goes through the cover of the connection of the detector and the thermostat. Thermostat cover is made of foam thickness is $2\,cm$. Cover for the detector is needed to shield the internal volume of the unit from external electromagnetic interference, and is made of aluminium foil with a thickness of $0.1\,mm$. Effect of materials and thickness covers the value of the energy resolution is minimal. Effect of the thickness of the foils and liners kind of measured spectra was shown in [6].

Special software used for a set, display, processing and recording of spectra. Fig. 6 shows the image of the program window for measuring spectra.

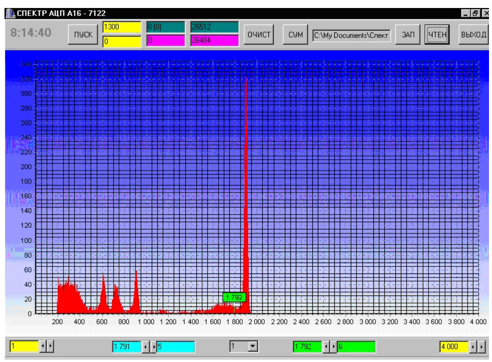

Fig.6. *Image of the program window for measuring the spectra of single-channel silicon detectors*

At a set of spectrum, program controls the operation of the ADC, displays time of spectrum, loading of the measuring channel and the number of pulses in the spectrum in special fields. It is possible to define a set spectrum time, stop the program to record the intermediate range and set of to continue after stopping the spectrum to the desired level of statistical measurements.

In the program there the ability to increase the selected area spectrum, to provide markers of the area of interest of the spectrum, for which automatically counts the number of pulses. Express processing to calculate the parameters of the selected peak is provided. The spectra obtained are stored in files on disk. It is possible to call the previously recorded spectra of the disk and process them.

3. TEMPERATURE DEPENDENCE OF LEAKAGE CURRENT AND ENERGY RESOLUTION OF PSD

Energy resolution by increasing the temperature of the detector in the range studied is incremented significantly less than the PSD leakage current. The reason is that, the leakage current is in relation to the noise detector and pre-amplifier is:

$$Q_n^2 = \left(\frac{e^2}{8}\right)\left[\left(2q_eI_d + \frac{4kT}{R_p} + i_{na}^2\right)\tau + \left(4kTR_s + e_{na}^2\right)\frac{c^2}{\tau} + 4A_fC^2\right] \quad (2)$$

where: e - the base of natural logarithm; q_e - electron charge; I_d - leakage detector; k - Boltzmann constant; T - absolute temperature; R_p - equivalent parallel resistance input; i_{na} - noise spectral density of the input current preamplifier; τ - signal time; R_s - equivalent series resistance of the input; e_{na} - noise spectral density of the input voltage preamplifier; C - total input capacitance; A_f - noise spectral density of the form $1/f$ [7].

The presence of leakage current due to the thermal generation of electron-hole pairs in the bulk of semi-conductor detectors, and leakage current on the surface of the detector degrades its limiting parameters, since the statistical fluctuations of the charge created by these currents in the integrating circuit, formed by the statistical fluctuations of the charge created particle. The leakage current depends on the type of detector, design, the operating temperature and other characteristics and other things being equal increases linearly with increasing area of the detector.

3.1 Temperature dependence of the leakage current of the PSD

Earlier [3], the results of the effect of temperature on the characteristics of PSD in the temperature range above $0°\,C$ was presented. In this work measurements the temperature dependence of leakage current and energy resolution of the single-channel silicon detectors in the temperature range from $-30°\,C$ to $60°\,C$ were performed.

The test detectors had the same type of constructions and different initial characteristics at room temperature. Figs. 7-9 are shown the dependencies of detectors leakage current on temperature.

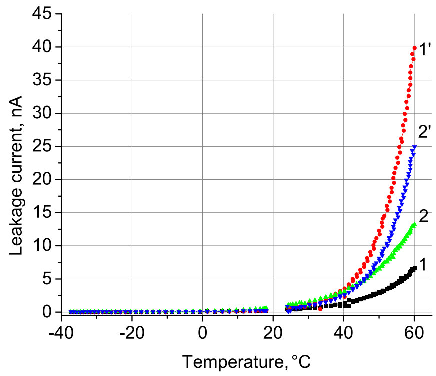

Fig. 7. *Detectors H28 and X31 temperature dependence of the leakage current of active areas and protective rings*

Curve 1 (see Fig. 7) corresponds to the leakage current of the active area of the detector X31, curve 2 - leakage current of the active area of the detector H28, curve 1 '- current of detector X31 protective ring, curve 2' - current of detector H28 protective ring.

Fig. 8 shows the results of the measurements of leakage current of the active area (1, 1') and a protective ring (2, 2') on the temperature of the detector $X28$. Measurements are satisfied semi-automatically to in-crease the accuracy of measurements at temperatures below zero, when the leakage current values attain picoampere.

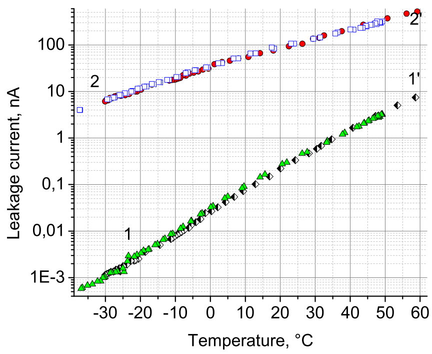

Fig. 8. *Detector X28 dependence of the leakage current of the active area and the protective ring on the temperatures*

Two temperature modes were applied: "slow" - passing area temperature range for the time of about 3 hours (in the figure corresponds to curves 1' and 2'), and "fast" - the passage temperature range, a time of about 1 hour (curves 1, 2). The coincidence of the curves indicates a good accuracy of the experimental measurements. Fig. 9 shows the dependence of the leakage current of the active area PSD H28 on temperature in the range of temperatures below $0°\,C$. The value of leakage current gradually decreases with decreasing temperature and when it reaches -30 $°C$ reaches pikoamps values. Curve 1 corresponds to the measurements made in a "fast" mode, curve 2 - in the "slow".

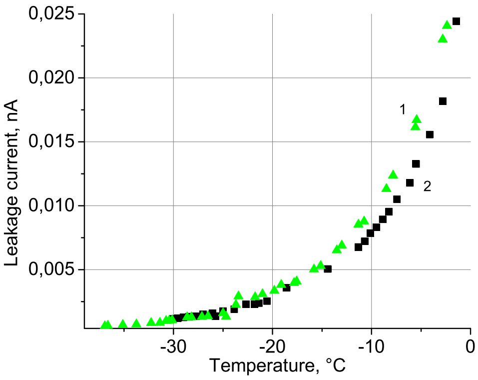

Fig.9. *Detector X28 temperature dependence of the leakage current of active area*

As seen from the chart, in the range from $-30°\,C$ to $60°\,C$ value of the leakage current varies approximately in factor of 10^4. The leakage current value increases smoothly with increasing temperature over the entire range. The dependence of the leakage current on temperature has exponential form.

3.2. Temperature dependence of the energy resolution of the PSD

Dependence of the energy resolution of temperature was measured for PSD in the temperature range from $-30°\,C$ to $60°\,C$. The energy resolution was measured through ^{241}Am with energy $59.54\,keV$, For the investigated detectors was measured few tens of spectra at different temperatures. From the measured spectra at different temperatures investigated detectors were calculated their energy resolution.

In Figs. 10-12 are shown the spectra of gamma radiation ^{241}Am for three different temperatures. The spectra are measured at the same time. With an increase in temperature, the width of the peaks in the spectrum of the radiation increases, and their height is reduced. Changes in the spectral characteristics of the influence of temperature related with planar silicon detectors in its resolution. When a detector temperature $T = -29.7°C$ energy resolution is $0.925\,keV$ (see Fig. 10), at a temperature $T = 19.8°\,C$ is $1.063\,keV$ (see Fig. 11), at $T = 58.95°\,C$ is $2.548\,keV$ (see Fig. 12).

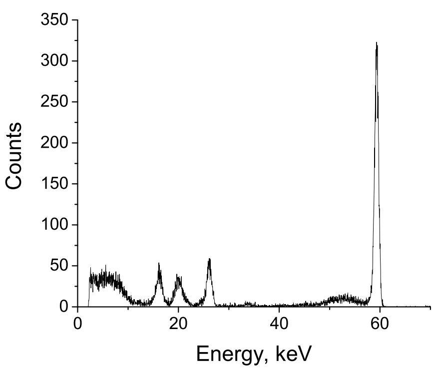

Fig.10. *The spectrum of gamma radiation* ^{241}Am *at temperatures* $T = -29.7°\,C$ *of the detector X31*

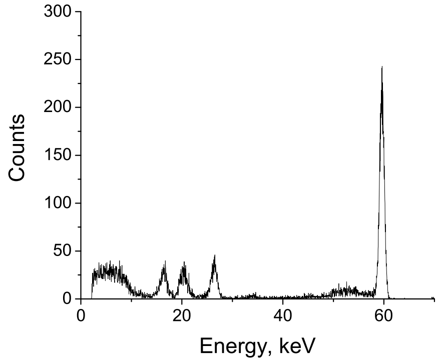

Fig.11. *The spectrum of gamma radiation* ^{241}Am *at temperatures* $T = 19.8°\,C$ *of the detector X31*

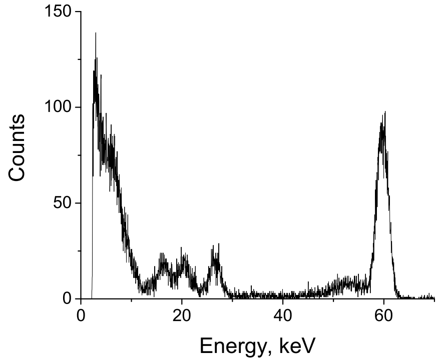

Fig.12. *The spectrum of gamma radiation* ^{241}Am *at temperatures* $T = 58.95\ °C$ *of the detector X31*

Spectra are shown detector with relatively low leakage current and high energy resolution. In the temperature range from $-30°\,C$ to $60°\,C$ energy resolution of detector system changes by more than half.

The measured spectra were analyzed, determined energy resolution detectors (FWHM). The resulting energy resolution depends on the temperature of the detectors are shown in Fig. 13.

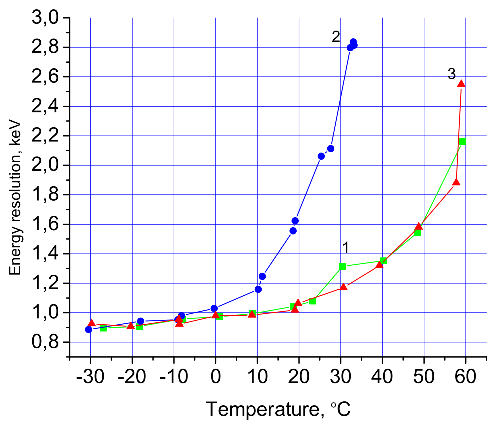

Fig.13. *Temperature dependence of the energy resolution of the detector H27 (1), H28 (2) and X31 (3)*

From Fig 13 shows, that an increase in temperature above ambient, detector with the worst of the initial energy resolution of the energy-parameter resolution increases faster than for detectors with the best initial energy resolution. When cooled to a temperature of about $-20^\circ\,C$, curves reach saturation energy resolution.

Dependence of the energy resolution on the temperature dependence is similar to detector leakage current (see Figs. 7, 9). However, the leakage current is continued to decrease with decreasing temperature detector and the temperature has been reached, at which the saturation curve of the energy resolution. From this fact, it can be concluded that the contribution of noise associated with leakage current becomes small compared to the total noise spectrometer system with sufficient cooling the detector. This means, that the limit value of FWHM detector due to the noise amplifier spectrometer path. PSD with nonhigh (FWHM $1.6\,keV$) and high (FWHM $1.1\,keV$) initial characteristics at the cooling shows the energy resolution $0.9\,keV$, the difference in the energy resolution is smoothed.

4. CONCLUSIONS

In the temperature range $-30^\circ\,C$ to $60^\circ\,C$ measured the energy resolution and leakage current of PSD with different initial energy resolution (at room temperature). The method allows for the selection of the PSD detection systems that operate at elevated temperatures.

Found that with increasing temperature above room temperature detectors with worse initial characteristics (starting with the worst energy resolution and leakage current) energy resolution and leakage current are deteriorated faster than for detectors with the better initial characteristics.

It is shown that when a certain of the temperature of the detector ($-20^\circ\,C$) contribution of noise associated with the leakage current of the detector, reaches to the relatively small to the general noise level spectrometer system and a further lowering of the temperature detector does not affect the energy resolution of the detector system as a whole.

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ТЕМПЕРАТУРНАЯ ЗАВИСИМОСТЬ ЭНЕРГЕТИЧЕСКОГО РАЗРЕШЕНИЯ И ТОКОВ УТЕЧКИ ПЛАНАРНЫХ Si ДЕТЕКТОРОВ

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Разработана методика измерений и созданы автоматизированные стенды для исследования температурной зависимости энергетического разрешения и токов утечки одноканальных планарных кремниевых детекторов (ПКД). В диапазоне температур $-30^\circ\,C$ до $+60^\circ\,C$ проведено измерение энергетического разрешения и токов утечки ПКД с различным начальным (при комнатной температуре) энергетическим разрешением. Методика позволяет производить отбор ПКД для детектирующих систем, работающих при повышенных температурах.

ТЕМПЕРАТУРНА ЗАЛЕЖНІСТЬ ЕНЕРГЕТИЧНОЇ РОЗДІЛЬНОЇ ЗДАТНОСТІ ТА СТРУМІВ ВИТОКУ ПЛАНАРНИХ Si ДЕТЕКТОРІВ

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Розроблена методика вимірювань і створені автоматизовані стенди для дослідження температурної залежності струмів витоку та енергетичної роздільної здатності одноканальних планарних кремнієвих детекторів (ПКД). В діапазоні температур $-30^\circ\,C$ до $+60^\circ\,C$ проведено вимірювання енергетичної роздільної здатності та струмів витоку ПКД з різними початковими (при кімнатній температурі) енергетичними роздільними здатностями. Методика дозволяє проводити відбір ПКД для детектуючих систем, працюючих при підвищених температурах.