OPTIMIZATION OF TECHNOLOGY FOR FABRICATION OF SECTIONAL NUCLEAR RADIATION DETECTORS BASED ON HIGH-RESISTANCE SILICON

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On the basis of experimental studies the surface-barrier technology for fabrication of sectional nuclear radiation detectors with using of the high-resistance *n*-Si plates of large diameter (~ 100 mm) was optimized. The 9-sectional detector matrixes were manufactured. In such matrix each section is a separate detector with the thickness of sensitive area $W \leq 350$ μm, the working area $S = 4$ cm^2, and the energy resolution $R = 50…75$ keV under irradiation by three-component α-source. The electrophysical and spectrometric characteristics of the sectional silicon detectors were determined. The manufactured detectors can be used in the nuclear experiments involving heavy ions at the low yields of reaction products.

PACS: 29.00.00; 29.40.Wk

INTRODUCTION

In the experiments concerning investigation of the nuclear structure and the nuclear reaction mechanisms are almost always necessary not only to measure the energy of particles, but also to identify them. The numbers of reaction channels, which are opened, and respectively the set of nuclei that are formed, are increased with growth of the energy and mass of bombarding particles. The nuclear radiation detectors were used for reliable identification of the reaction products. At present there are a large variety of detectors depending on the type of particles, energy range, destination, structure, and operation principle.

Semiconductor detectors are widely used in many important experiments: for α-spectroscopy [1], γ- and X-ray spectroscopy [2, 3], for registration of monoenergetic electrons [4, 5], heavy ions [6], and for study of nuclear fission [7, 8]. Thus, the process of nuclear fission is of great practical importance, but most of its features are still not found an explanation. This applies, for example, to the mechanism of asymmetric fission [9].

With the exception of the radiochemical methods, the devices such as dual ionization chambers or system of flight time with the scintillation detectors were used for study of the fission fragments. It is impossible to use only the scintillation detector, because poor energy resolution and saturation effect that takes place at very high density of ionization from the fission fragments, are inherent in it. The methods of flight time are characterized by the high energy resolution at the small solid angle. Semiconductor detectors allow obtaining a very high energy resolution at the large solid angle [10, 11]. They can be successfully used to study the processes of fission, since the used sources and targets must be very thin. When using semiconductor detectors, the problem of placement of the thin active source between two ionization chambers was removed, since the fissionable material can be deposited on a working surface of one from two mutually facing detectors. The surface-barrier and diffusion detectors with small depth of the diffusion layer have very thin "window" and therefore are suitable for detection of the short-range fission fragments. The operating speed of detectors with *p-n*-junction is also an advantage when measuring the coincidence of the simultaneously flying out pairs fragments. Long-continued measurements can be carried out owing to the stability of silicon detectors with *p-n*-junction.

In the track with high density of ionization, which creates by means of fission fragment, the loss of charge carriers is occurred. Therefore, the dependence of amplitude of pulses for silicon detectors with *p-n*-junction on the energy of fission fragment is not linear. When comparing the pulse amplitude from the fission fragment with the value obtained by extrapolation of the amplitude of pulses from the particles that create a smaller ionization density (for example, α-particles), the difference, called "the ionization defect", is determined. In this comparison the values of the average energies for groups of light and heavy fragments are determined using data obtained by the method of flight time. The difference of amplitudes corresponds to the energy, which is equal to about 10 MeV. It was determined that this difference for group of the heavier fragments is more on ~ 2.5 MeV than for light fragments, and does not depend on the type of conductivity and resistivity of silicon.

With an increase of the average electric field in the detector from $2 \cdot 10^3$ to $2 \cdot 10^4$ V·cm^{-1} the ionization defect decreases by 2 times, since it is due to recombination of carriers till to their collection. In large fields the reverse effect was found. This effect is responsible for reduction of the effective energy for formation of one electron-hole pair in some parts of detector. This effect is due to the process of reproduction, which can occur in fields close to critical (such field is equal approximately $6 \cdot 10^4$ V·cm^{-1} for silicon).

The semiconductor material for production of detectors must correspond to certain conditions [12]. So, the choice of the silicon resistivity for detectors is caused by several of the following factors:

1) resistivity should not be too low (must be exceed of 25 Ohm·cm), since in otherwise the electric field,

which is necessary to obtain the depleted layer with the thickness, that is equal to the fission-fragment path, may exceed the field at which breakdown occurs;

2) if the area of the detector is large, in order to improve the signal to noise ratio we should reduce the capacity of detector; for this purpose the material with higher resistivity must be used;

3) the electric field may be insufficient for full charge collection at too high resistivity; the required value of the field is about 10^4 V·cm^{-1};

4) in the material with high resistivity the depleted layer is too thick, which leads to the excessive noises, high sensitivity to γ-rays, and also to the background caused by fast neutrons.

The reaction cross-sections and angular distributions of the fragments in the fission reactions caused by charged particles are measured by means of silicon detectors with *p-n*-junction. The observed cross-sections, as a rule, are small, so a large solid angle is an important advantage of the detectors with *p-n*-junction. Three detectors with *p-n*-junction, situated around the target, are used for convenience to observe the triple fission, induced by the neutrons. Meanwhile the α-particle is emitted, besides the two large fragments.

Thanks to the operating speed of detectors with *p-n*-junction and the ability to easily separate the impulses from alpha-particles, such detectors can be successfully used to measure the dependence of the fission yield on the neutron energy by the method of flight time.

The surface-barrier detectors of total absorption energy of charged particles (*E*-detectors) with a wide range of the thicknesses of sensitive area and the detectors of the specific energy losses (*dE*/*dx*-detectors) are used for nuclear radiation spectrometry.

Modern detectors, for the most part, are not used alone, but as constituent parts of the large detecting systems [ATLAS, CMS, LHCb, ALICE detectors at the LHC collider (CERN, Switzerland); at the Tevatron collider, at the electron-positron colliders] [13–15].

In view of the above, the aim of this work was to optimize the surface-barrier technology of the manufacturing of sectional detector matrixes based on the carried out comprehensive studies of the electrical characteristics of the initial n type conductivity silicon plates of large diameter and the definition of features of physical processes in the surface-barrier structures.

1. METHODS OF MANUFACTURING OF SILICON DETECTORS IN HISTORICAL RETROSPECTIVE

There are a number of methods for obtaining the detectors on the basis of silicon *n*- and *p*-type conductivity. In Refs. [16, 17] the diffusive technology was used to obtain detectors of the specific energy losses of charged particles (about 50 μm). The initial material was *p*-Si with a resistivity ρ = 5 kOhm·cm. The phosphorus diffuses into *p*-Si. The gold, sputtered on the planished surface of the crystal, served as contact to the back side.

The planar *p-n*-junction of controlled depth can be obtained by diffusion method; meanwhile the thickness of the input "window" of finished detector will be half of the diffusion depth [18]. The main disadvantage of this method is the significant reduction in the minority carrier lifetime in silicon during heating in the process of high temperature diffusion of phosphorus and hereupon increasing of the reverse current of *p-n*-junction.

The surface-barrier technology for manufacturing of semiconductor detectors, proposed in Ref. [19], received the wide spread occurrence.

Detectors of the specific energy losses with thickness of 50 μm were produced by authors [20] on the basis of combining the surface-barrier technology with the diffusive technology at using passivation by oxide. In this paper the principle of uniform etching in the slow etchant was proposed. The sample is carefully plane-parallel planished with the accuracy of 0.75 μm, since this thickness spread determines the limiting spread after etching of the sample. Cup with the etchant rotated with a rate of 12 revolutions per minute and was inclined at the angle of ~ 45°. The sample was mounted on the teflon disk with the rotation axis of disk, which is perpendicular to the rotation axis of cup. The etchant 1 HF:20 HNO_3 with volume about 250 cm^3 was used. In this system each part of the central surface of sample moves relative to the etchant with the same average rate. The etching rate was 1.2 μm/min. In order to remove the structural imperfections after grinding, the etching time was chosen on the basis of removal of 75 μm from each side of the crystal. The fluctuation of crystal thickness in typical samples was 0.75 μm. The area of constant thickness is located in a central part of the crystal and was equal approximately 2 cm^2. The sample had the profile view as I-beam. This fact added to it the mechanical strength [*Note*. I-beam or H-shaped is the profile (cross-section in the form of two letters T); I-beam provides a high resistance to loads for the whole construction under the significant mechanical effects].

In this paper the problem of particle channeling in the thin detector was first discussed. Anomalous energy losses of the charged particles along the directions of the crystallographic axes and planes degrade the energy resolution of detectors and the separation on the masses with help of telescopes.

In Ref. [21] the energy losses of charged particles in silicon depending on the track orientation were investigated, and the special cutting of crystals for detectors with a deviation of about 8° from the (111) plane in order to avoid the phenomenon of channeling was proposed.

Authors of Ref. [22] have successfully used the surface-barrier technology for obtaining detectors of the specific energy losses with thin "windows". The initial material was the high-resistance Si, the thickness of detectors was 70 μm.

Concept of the drift of lithium ions in the electric field of reverse bias junction showed the ability of substantial increase in sensitive area of the detector at the low resistivity of the initial *p*-Si. In Refs. [23, 24] *dE*/*dx*-detectors, fabricated on the basis of silicon, compensated by lithium, were described. Such method is allowed to receive detectors with the thin "windows" and the width of the sensitive area from hundreds of microns to several millimeters at low operating voltages.

From the literature data it can be concluded that the n-type silicon is suitable as the initial material for manufacturing of the detectors of specific losses with the small thicknesses (less than 100 μm), and the p-type silicon, compensated with lithium by means of the method of the ion drift, is suitable for detectors of medium and large thicknesses (above 100 μm). Meanwhile the surface-barrier technology of fabrication of detectors in order to create a working p-n-junction and provide the thin "windows" on both sides of the detector is most promising.

The input "window" of the detector is determined by the thickness of the surface layer, which is traversed by the charged particle before it reaches the sensitive layer (space-charge region). In Ref. [25] the thickness of "window" was determined experimentally on the defect of pulse height, obtained at comparing of the pulse heights from the protons and γ-rays with the energy of 80 keV.

Fig. 1 presents the dependence of the input "window" thickness Δx on the reverse voltage for detectors, fabricated on the basis of n-Si with the different resistivity. As the experiment showed, Δx decreases linearly as a function of log V, and the slopes of the straight lines are dependent on the resistivity. When the voltage $V = V_0$, the thickness Δx is zero, where V_0 is a critical shift, which is decreased with resistivity ρ. Thus, the empirical relationship between the values has the following form: $\Delta x = A \cdot \log \dfrac{B\rho}{V}$, where A and B are the constants.

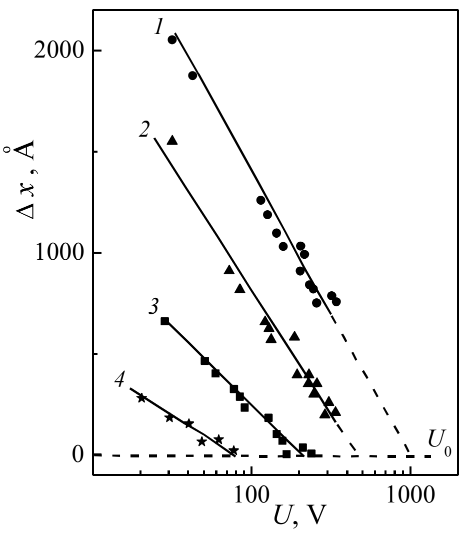

Fig. 1. For detectors made on the basis of n-Si, dependences of the thickness of input "window" Δx on the reverse voltage U at different resistivities ρ, kOhm·cm: 1 – 50; 2 – 10; 3 – 2; 4 – 1 [25]

The existence of the input "window" is entirely understandable, since there is p-n-junction beyond the contact. Therefore, the depletion region extends in p- and n-region, depending on the resistivity and applied voltage. The "window" is formed from oxide layer and the silicon layer disposed between the oxide and the boundary of the space-charge region. The electric field in this layer is very low and the high concentration of impurities increases the recombination. The surface-barrier diode structure can be formed due to the presence of two mechanisms: a) the diffusion of oxygen through the Au contact into the bulk of Si crystal, where it acts as an acceptor (in this case, the surface-barrier diode is similar to the diffused junction); b) the adsorption of oxygen on the surface, if the electron affinity of oxygen is higher than the work function of semiconductor (in this case, p-type layer is created on n-type material).

For the first case the thickness of "window" is defined as

$$\Delta x = \frac{1}{2}\ \ln\left[\frac{e^2 N_0^2 L^2 \mu_n \rho}{2\xi\xi_0 V}\right], \qquad (1)$$

and the value of critical displacement (at $\Delta x = 0$):

$$V_0 = \frac{e^2 N_0^2 L^2}{2\xi\xi_0}\mu_n \rho\,, \qquad (2)$$

where N_0 is the surface carrier concentration; L – the diffusion length; ξ and ξ_0 are the dielectric constants of silicon and vacuum, respectively. The depletion region reaches Au-contact at V_0.

In the second case:

$$V_0 = \frac{N_h^2 kT \mu_n \rho}{2}, \qquad (3)$$

$$\Delta x = \frac{kT}{e}\left(\frac{\xi\xi_0}{2}\cdot\frac{\mu_n \rho}{V}\right)^{1/2} \ln\left(\frac{N_h^2 kT \mu_n \rho}{2N}\right), \qquad (4)$$

where N_h is the hole concentration near the surface.

Authors of Ref. [25] obtain the best agreement of the experimental data with the first model, while they notice also the importance of the second model.

2. PHYSICAL BASE OF THE MANUFACTURING TECHNOLOGY OF DETECTOR MATRIXES ON THE SILICON PLATES OF LARGE DIAMETER

In order to select the silicon plates of the electron type conductivity of large diameter with parameters suitable for the manufacture of detectors, the comprehensive research of the electrophysical properties of initial semiconductor material was carried out, in particular, the resistivity spread along the diameter of ingots, distribution of the dislocation density, the lifetime of minority carriers were determined.

The important condition at the production of detectors of specific losses is the flatness of plates each of them, to provide the equal energy losses of charged particles that cross the detectors through the area of the input "windows". For the plane-parallel etching of crystals the special apparatus was developed. Such apparatus provides the equal access to all points of the crystal for etchant. This fact allows reaching the uniform rate of etching throughout the area of the plates and forming the high-quality surface-barrier structure.

Before etching the plate was plane-parallel planished (by means of powders with a gradual decrease in grain size from M20 to M7), and then thoroughly washed in the organic solvents and high-resistance water

(~ 3…5 MOhm). We used a number of etchants on the basis of concentrated especially pure acids [hydrofluoric (HF), nitric (HNO_3) and acetic (CH_3COOH)], combined in the different proportions: $3HF:5HNO_3:3CH_3COOH$ (the etchant number 1), $1HF:20HNO_3:1CH_3COOH$ (the etchant number 2) and $17HF:110HNO_3:7.3CH_3COOH$ (the etchant number 3). The measurement of plate flatness was carried out on the apparatus "Optimeter", which has an accuracy of 0.5 μm. The spread in thickness for the surfaces, etched by means of etchants number 1 and 3, exceeded of 15 μm. Therefore, these etchants were unsatisfactory from the viewpoint of flatness. When using etchant number 2 the flatness reaches about 0.5 μm that fully satisfied the requirements. For used etchants the following etching rates were obtained: for etchant number 1 – 2.2 μm/min; number 2 – 1.7 μm/min; number 3 – 3.3 μm/min, i. e. these etchants are slow.

The state of the semiconductor surface was controlled by techniques of measuring the field effect and contact potential difference when forming the surface-barrier structure. This allowed determining the value of band bending on the silicon surface under the different chemical treatments, as well as the kinetics of the surface potential φ_k and its homogeneity. In particular, for the slow etchants number 1–3 the value of the surface potential, measured immediately after the etching, showed that the inversion layer is already formed, and consequently, the effects of aging appear weakly less for such surfaces.

It has been experimentally proved that the distribution of the surface potential for crystal silicon, treated by quickly etchants (~ 20 μm/min), is nonuniform. The kinetics of change of the surface potential is quite slow. The surface potential of crystals, chemically polished by the slow etchants (~ 2…5 μm/min) in the made apparatus, is very uniform ($\Delta\varphi_k$ ~ 15 mV), in this case the equilibrium of value of the surface potential on the surface comes quickly. The magnitude of the band bending corresponds to the formation of surface-barrier *p-n*-junction.

The important information concerning electronic state of the real surface of *n*-type silicon, etched by the different etchants, was obtained from measurements of the field effect and the contact potential difference. This allowed formulating some preliminary conclusions concerning quality of the surface barrier of detector, as follows:

1) the *n*-type silicon surface immediately after the etching in the fast etchants based on the concentrated especially pure acids (nitric, hydrofluoric and acetic), combined in different proportions, has the electron conductivity (small enrichment by the main carriers);

2) at the end of the etching process the strongly depleted layer (the inversion layer on the concentration) in the surface region was created at slow etching (the composition of etchants was chosen another, but on the basis of the same acids), i. e. the near-surface *p-n*-junction appears;

3) the surfaces treated by the fast etchants gradually change the enriched layer on the inversion layer in the aging process in atmospheric conditions, i. e. the aging time of detectors produced then on such crystals would be very significant;

4) the concentration of the surface levels on the chemically polished silicon surfaces is quite large and, therefore, will lead to the screening of the external influences and to the more stable characteristics of the fabricated detectors of specific losses when the external conditions of the capture of carriers on the surface levels are changed.

The technological regime of formation (after chemical polishing of the crystals) the back noninjecting contact of detectors during the sequential thermal deposition of Ge and Al thin layers on the back side of the crystal through the 9-sector masks was developed on the basis of the conducted researches. In this case *p*-Ge with resistivity about 3 Ohm·cm was used. Germanium of *p*-type conductivity was sputtered at the vacuum 10^{-6} Torr with the evaporation rate of about 1 Å/s. It should be noted that at the lower vacuum and lower evaporation rate, the germanium layer is saturated by the oxygen atoms (up to about 1%), that resulting in undesirable change in conditions on the crystal surface. Development of the production technology for such noninjecting contact allowed manufacturing the detectors, capable of operating at the reverse biases, exceeding the voltage of the total depletion of detector.

Germanium and aluminium plates were kept in the air for two days after deposition in order to form the stable oxide film on the real silicon surface. Thereafter the thin layer of gold (~ 200 Å) was deposited on the work surface through the specially manufactured mask for forming the surface-barrier structure.

The possibility to accelerate the formation of surface-barrier junction by applying to the Au-Si contact the reverse voltage of the order of the potential barrier height was found. In this case the electric field in the metal-semiconductor contact, without substantial affecting on the equilibrium height of the barrier, will accelerate the drift of the oxygen ions through the gold film to the semiconductor surface, which results in a more rapid formation of surface-barrier junction.

The significant influence of the environment on the level of reverse currents of the freshly manufactured surface-barrier structures was established as a result of the conducted researches. It was found that if immediately after the deposition of gold on the silicon surface the environment of dry oxygen is created, then the barrier is not formed and the detector has a high reverse current, while in the atmosphere of moist oxygen the stable surface-barrier *p-n*-junctions are formed most efficiently.

The final stage of the process is the production of frames for mounting of the detector matrixes and, finally, the mounting of sectional detectors. Thereafter the testing of the electrophysical and spectrometric parameters of the experimental samples was carried out. The measurements of the voltage-current and capacity-voltage characteristics allow evaluating a range of working bias of detectors, the value of the breakdown voltage, and the level of reverse currents, which contribute to the noise detectors.

The results of the conducted researches of bulk and surface properties of the initial semiconductor material became the basis for the development of manufacturing technology of sectional detectors based on the silicon plates of large diameter (~ 100 mm). It was necessary to create the 9-sectional detector matrixes, wherein each section is a separate detector and they all must have the same characteristics at the single reverse voltage.

The 9-sectional detectors with the thickness of sensitive area $W \leq 350$ μm, in which each of nine sections has the area of working surface of $S = 4$ cm^2, were manufactured based on the selected initial silicon plates with resistivity $\rho = 1.5\ldots2$ kOhm·cm and lifetime of the minority carriers $\tau = 1000$ μs.

Fig. 2 shows the general view of the obtained 9-sectional detectors from the side of input and output "windows" of sensitive area.

Fig. 3 shows the voltage-current characteristics of the each of detectors of the typical 9-sectional matrix.

Fig. 4 shows the dependences $1/C^2 = f(V)$ for the typical 9-sectional detector on the basis of n-Si from the side of output "window" (the aluminum back contact).

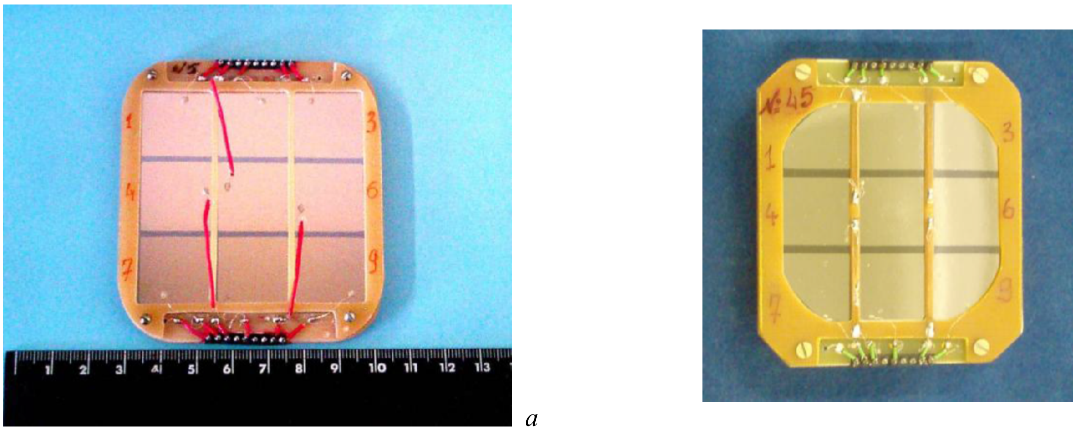

Fig. 2. General view of the 9-sectional detector:
a – from the side of input "window" of sensitive area; b – from the side of output "window"

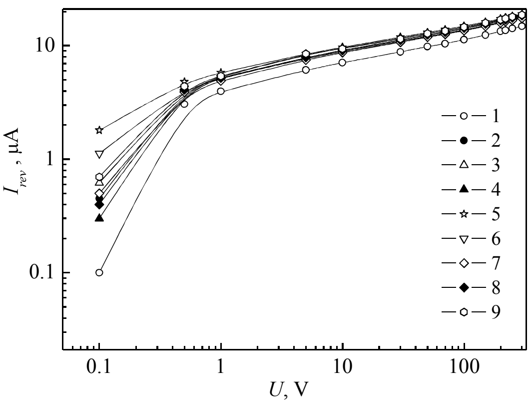

Fig. 3. The reverse current-voltage characteristics of the typical 9-sectional detector on the basis of n-Si

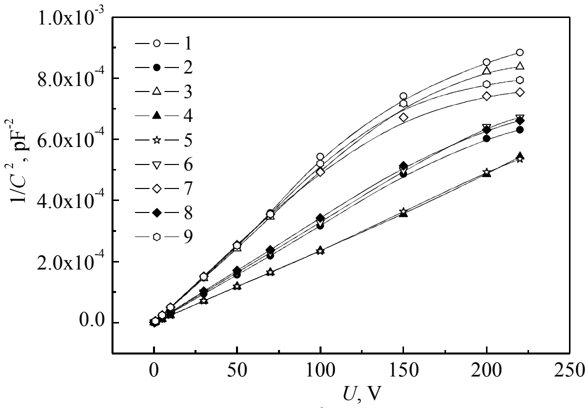

Fig. 4. Dependences $1/C^2 = f(V)$ of the typical 9-sectional detector at the basis of n-Si

Capacity-voltage characteristics show that the full depletion of the detector occurs at reverse voltage about 200 V. Current-voltage characteristics indicate that the detector can work under the maximal reverse voltage of about 300 V, while the electric field strength in the detector is $2 \cdot 10^4$ V/cm. At such electric field strength the spectrometry of heavy charged particles is feasible. The heavy charged particles cause under absorption the high density of the electron-hole pairs.

Fig. 5 shows the typical spectrometric characteristics received under irradiation by the certified three-component source of α-particles ($E_{\alpha1} = 4.821$ MeV; $E_{\alpha2} = 5.156$ MeV; $E_{\alpha3} = 5.467$ MeV) by means of 9-sectional surface-barrier detector, which demonstrate the identity of the results obtained. The energy resolution of the sectional detectors is equal $R \approx 50\ldots75$ keV under irradiation by the α-source.

Thus, our study of bulk and surface properties of specially selected initial material and optimizing the surface treatment method of silicon allowed manufacturing the qualitative detectors with stable parameters and the high energy resolution.

Measurements of the front duration of pulse rise, received from the experimental detector samples showed that the front duration is less than 5 ns, that was an order of magnitude lower than the similar value for detectors fabricated on the basis of silicon, compensated by lithium. This allows to use the obtained detectors for the schemes with the temporary binding, where it is necessary not only the high energy resolution, but the high temporal resolution.

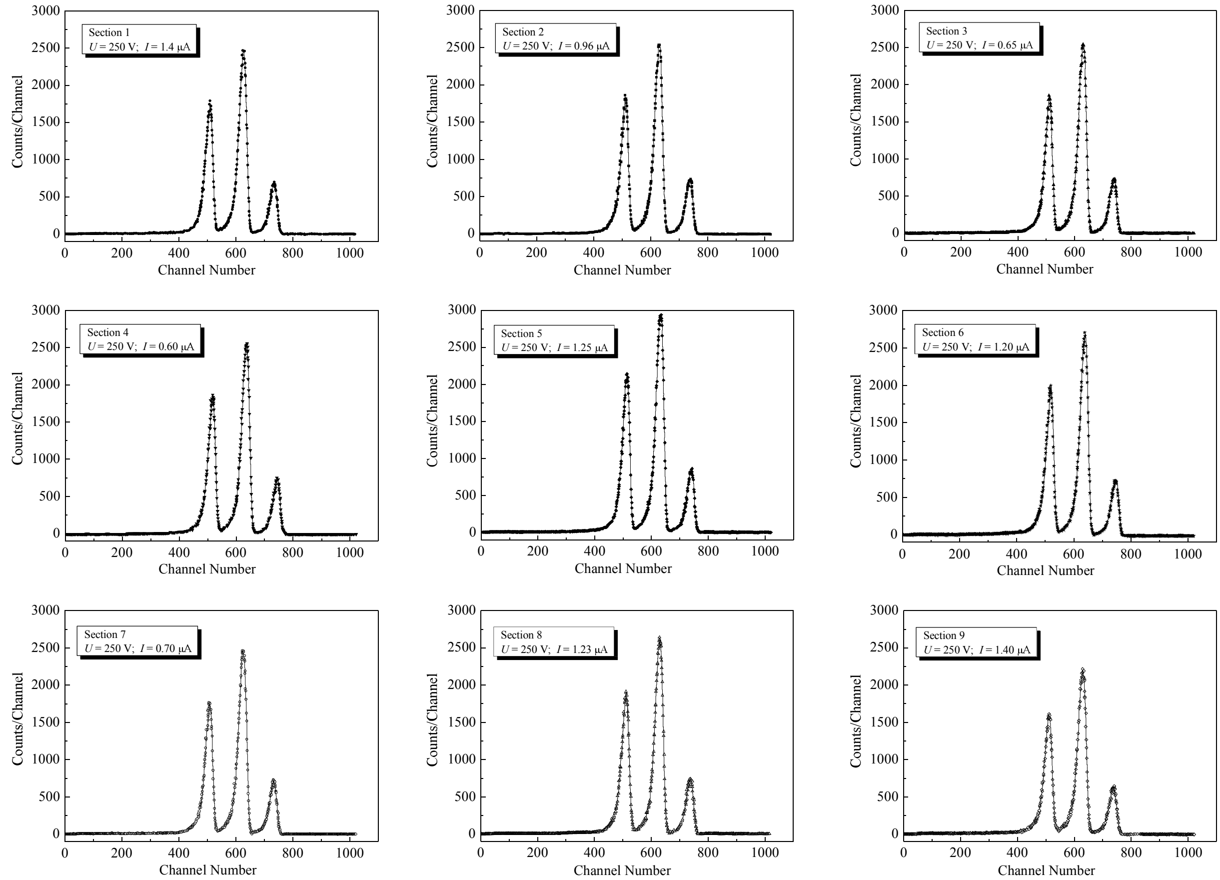

Fig. 5. The α-particle spectra of the three-component source (^{233}U, ^{237}Pu, ^{241}Am), obtained by means of the typical 9-sectional surface-barrier detector

CONCLUSIONS

1. The methods of chemical treatment of silicon were developed to produce the great working planes of detectors with homogeneous characteristics and the formation of qualitative surface-barrier structures.

2. It was proved experimentally that at the low etching rate and the ensuring of the conditions of equal access of etchant to the entire surface of the crystal, the homogeneous surface with high uniformity of the surface potential ($\Delta\varphi_k \sim 15$ mV) can be obtained that allows to produce the high-quality detectors.

3. On the basis of the optimized surface-barrier technology with use the high-resistance *n*-type silicon plates of large diameter (~ 100 mm) the sectional silicon semiconductor detectors with the thickness of sensitive area $W \leq 350$ μm, the working area $S = 4$ cm^2, and with the energy resolution R from 50 to 75 keV under irradiation by means of the certified three-component α-source were developed. The manufactured detectors can be used in the nuclear experiments involving heavy ions at the low yields of reaction products.

4. The main electrophysical parameters and spectrometric characteristics of the surface-barrier silicon detectors of nuclear radiation, which enter into the composition of the 9-sectional detector matrixes, were determined. Detectors have identical parameters and low reverse current at voltages of about 300 V. Meanwhile the voltage of full depletion of the sensitive volume of detectors was about 200 V.

5. The measurements of capacity-voltage dependencies of all nine working sections of the detector matrix shown that its constituent elements (detectors) have abrupt working *p-n*-junction. At the same time the electric field strength in detectors was about 10^4 V/cm, which is enough for the efficient collection of charge carriers during the spectrometry of fission fragments of heavy atomic nuclei with high energy resolution.

REFERENCES

1. M. Cywiak, J.L. Iturbe, R. Gallardo, S. Bulbulian. Surface barrier detector device and its application to alpha spectroscopy // *J. of Radioanalytical and Nuclear Chemistry*. 1988, v. 126, N 2, p. 145-151.

2. A.H.F. Muggleton. Semiconductor devices for gamma-ray, X-ray and nuclear radiation detection (Review article) // *J. Phys. E: Sci. Instrum*. 1972, v. 5, N 5, p. 390-404.

3. F.J. Walter. The Impact of Semiconductor Detectors on X-Ray Spectroscopy // *IEEE Transactions on Nuclear Science*. 1970, v. 17, N 3, p. 196-214.

4. R.-D. Von Dincklage, J. Gerl. The response function of a Si(Li) detector for monoenergetic electrons // *Nucl. Instr. Meth. Phys. Res. Sect. A*. 1985, v. 235, N 1, p. 198-199.

5. A. Damkjaer. The response of a silicon surface barrier detector to monoenergetic electrons in the range 100–600 keV // *Nucl. Instr. Meth. Phys. Res*. 1982, v. 200, N 2-3, p. 377-381.

6. Y. Zhang, H.J. Whitlow. Response of Si *p-i-n*-diode and Au/*n*-Si surface barrier detector to heavy ions // *Nucl. Instr. Meth. Phys. Res. Sect. B*. 2002, v. 190, N 1-4, p. 383-386.

7. Yu.K. Akimov, O.V. Ignat'yev, A.I. Kalinin, V.F. Kushniruk. *Semiconductor detectors in experimental physics*. M.: "Energoatomizdat", 1989, 344 p.

8. Yu.K. Akimov, A.I. Kalinin, V.F. Kushniruk, Kh. Yungklaussen. *Semiconductor detectors of nuclear particles and their application*. M.: "Atomizdat", 1967, 256 p.

9. M.G. Itkis, V.N. Okolovich, A.Ya. Rusanov, G.N. Smirenkin. Symmetric and asymmetric nuclei fission, which easier in comparison with thorium // *Fizika elementarnykh chastits i atomnogo yadra.* 1988, v. 19, N 4, p. 701-784 (in Russian).

10. R.P. Sharma. Development of high resolution silicon surface barrier detectors // *Pramana – J. Phys*. 1988, v. 31, N 3, p. 185-195.

11. E.D. Klema, J.X. Saladin, J.G. Alessi, H.W. Schmitt. Energy resolution of silicon surface-barrier detectors for alpha particles, oxygen ions, and fission fragments // *Nucl. Instr. and Meth*. 1980, v. 178, N 2-3, p. 383-393.

12. J.C. Fontaine, S. Barthe, J.P. Ponpon, J.P. Schunck, P. Siffert. Material characterization during the fabrication of silicon nuclear detectors // *First European Conference on Radiation and its Effects on Devices and Systems*. RADECS 91. 1991, p. 84-88.

13. L.N. Smirnova. The *ATLAS detector of the Large Hadron Collider: a tutorial*. M.: "Universitetskaya kniga", 2010, 216 p. (in Russian).

14. N.V. Krasnikov, V.A. Matveev. The search of new physics at the Large Hadron Collider // *Uspekhi fizicheskikh nauk*. 2004, v. 174, N 7, p. 697-725 (in Russian).

15. R. Santoro. Status of the ALICE silicon pixel detector // *Nucl. Instr. Meth. Phys. Res. Sect. A*. 2007, v. 581, N 1-2, p. 330-334.

16. H.E. Wegner. *dE/dx*- and *E*-Semiconductor Detector Systems for 25 MeV He^3 and alpha-particles // *I.R.E. Trans. Nucl. Sci*. 1961, v. 8, N 1, p. 103-111.

17. C.N. Inskeep, W.W. Eidson, R.A. La Salle. Considerations in the Development and Use of Very Thin Junction Counters Suitable for ΔE/ΔX Detection // *I.R.E. Trans. Nucl. Sci*. 1962, v. 9, N 3, p. 167.

18. I. Brouday, Dzh. Merey. *Physical basis of microtechnology* / Per. s angl. M.: "Mir", 1985, 496 p. (in Russian).

19. G. Dearnaley, A.B. Whitehead. The Semiconductor Surface Barrier for Nuclear Particle Detection // *Nucl. Instr. Meth*. 1961, v. 12, p. 205-226.

20. T.C. Madden, W.M. Gibson. Uniform and Stable *dE/dx p-n*-junction Particle Detectors // *IEEE Trans. Nucl. Sci*. 1964, v. 11, N 3, p. 254-261.

21. G. Fabri, G. Redaelli. Totally depleted surface silicon detectors: Construction and properties // *Nucl. Instr. Meth*. 1965, v. 35, N 1, p. 130-132.

22. L.I. Barabash, V.G. Gonchar. Semiconductor spectrometers with wide sensitive area // *Radiation Physics of Non-metallic crystals. Proceedings of the meeting*. September 8–15, 1967. Kiev: "Naukova dumka", 1967, p. 416-419.

23. R.A. Muminov, S.A. Radzhapov, A.K. Saymbetov. Development of Si(Li) detectors of nuclear radiation by the method of pulsed electric field // *Pis'ma v Zhurnal tekhnicheskoy fiziki*. 2009, v. 35, N 16, p. 59-63 (in Russian).

24. S.A. Radzhapov. A. Versatile. Spectrometer Based on a Large-Volume Si(Li) *p-i-n*-structure // *Instruments and Experimental Techniques*. 2007, v. 50, N 4, p. 452-454.

25. G. Forcinal, P. Siffert, A. Coche. Window Thickness and Rectifying Process in Surface Barrier Detectors // *IEEE Trans. Nucl. Sci*. 1968, v. 15, N 3, p. 275-280.

Article received 07.11.2016

ОПТИМИЗАЦИЯ ТЕХНОЛОГИИ ИЗГОТОВЛЕНИЯ СЕКЦИОННЫХ ДЕТЕКТОРОВ ЯДЕРНЫХ ИЗЛУЧЕНИЙ НА ОСНОВЕ ВЫСОКООМНОГО КРЕМНИЯ

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На основе проведенных экспериментальных исследований оптимизирована поверхностно-барьерная технология изготовления секционных детекторов ядерных излучений с использованием пластин высокоомного *n*-Si большого диаметра (~ 100 мм). Изготовлены 9-секционные детекторные матрицы, где каждая секция является отдельным детектором с толщиной чувствительной области $W \leq 350$ мкм, рабочей площадью $S = 4$ см^2 и энергетическим разрешением $R = 50…75$ кэВ при облучении трехкомпонентным α-источником. Определены электрофизические и спектрометрические характеристики секционных кремниевых детекторов. Изготовленные детекторы могут быть использованы в ядерных экспериментах с участием тяжелых ионов при низких выходах продуктов реакций.

ОПТИМІЗАЦІЯ ТЕХНОЛОГІЇ ВИГОТОВЛЕННЯ СЕКЦІЙНИХ ДЕТЕКТОРІВ ЯДЕРНИХ ВИПРОМІНЮВАНЬ НА ОСНОВІ ВИСОКООМНОГО КРЕМНІЮ

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На основі проведених експериментальних досліджень оптимізовано поверхнево-бар'єрну технологію виготовлення секційних детекторів ядерних випромінювань з використанням пластин високоомного n-Si великого діаметра (~ 100 мм). Виготовлено 9-секційні детекторні матриці, де кожна секція є окремим детектором з товщиною чутливої області $W \leq 350$ мкм, робочою площею $S = 4$ см^2 та енергетичною роздільною здатністю $R = 50\ldots75$ кеВ при опроміненні трикомпонентним α-джерелом. Визначено електрофізичні та спектрометричні характеристики секційних кремнієвих детекторів. Виготовлені детектори можуть бути використані в ядерних експериментах за участю важких іонів при низьких виходах продуктів реакцій.