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POLARIZATION EFFECTS IN Si-n-p RADIATION RECEIVERS

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This paper presents a comprehensive analysis of n-p junction currents and polarization effects in diffusion Si detectors (receivers) for radiation. The mechanisms of polarization induced by charge-carrier capture at localized centers and the formation of space charge in the detector's sensitive region are investigated. The relationship between the presence of "large-scale" traps, which are local clusters of impurity atoms, and the appearance of anomalous spectral characteristics in the form of doublets has been established. It has been experimentally shown that ultrasonic treatment of Si-n-p detectors leads to a significant reduction in polarization effects due to the redistribution of impurity atoms and smoothing of the potential relief in the semiconductor structure. A physical model is proposed to explain the mechanism by which ultrasonic influence affects the electrophysical and spectrometric characteristics of silicon detectors. The results obtained have practical significance for optimizing production technology and improving the operational parameters of Si-n-p radiation detectors.
Keywords: *Silicon detectors; n-p junctions; Polarization effects; Capture centers; Ultrasonic treatment; Spectrometric characteristics; Space charge; Potential relief; Diffusion detectors; Local impurity clusters*
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INTRODUCTION

The study of polarization effects in silicon n-p radiation detectors is one of the key areas of modern semiconductor electronics and detector technology. This issue is particularly relevant in the context of the ever-increasing demands on the accuracy, stability, and reliability of semiconductor detectors used in various fields of science and technology - from fundamental research in nuclear physics to applied problems in medical diagnostics, space technology, and radiation monitoring systems. Polarization effects that occur during the operation of Si-n-p detectors significantly limit their functionality, reduce temporal stability, and distort spectrometric characteristics, which makes the study of the nature of these phenomena and the development of methods for their minimization a critically important task [1].

The physical nature of polarization effects in silicon detectors is complex and is associated with charge-carrier capture and accumulation at localized centers within the semiconductor volume. The formation of a volume charge in the sensitive region of the receiver distorts the internal electric field, which in turn causes a change in the efficiency of collecting charge carriers generated by radiation and, as a consequence, degradation of the spectrometric characteristics of the detector [2]. The so-called "large-scale" traps play a special role in these processes: local clusters of impurity atoms that form inhomogeneities, the potential relief in the semiconductor structure, and contribute to the appearance of anomalous spectral characteristics, in particular, doublet peaks [3,4].

Traditional approaches to solving the polarization problem, based on increasing the purity of the source material and improving detector manufacturing technology, demonstrate some efficiency but do not fully eliminate undesirable effects. In recent years, alternative methods for modifying the properties of semiconductor structures, in particular, ultrasonic treatment, have attracted considerable interest from researchers. Experimental data indicate that the effect of ultrasound on Si-n-p-receivers can lead to a significant reduction in polarization effects due to the redistribution of impurity atoms and smoothing of the potential relief in the semiconductor structure [5,6].

In this paper, we present the results of a comprehensive study of n-p junction currents and polarization effects in diffuse Si radiation detectors. Particular attention is paid to the analysis of the mechanisms of polarization occurrence caused by the processes of charge carrier capture at localized centers and to the study of the effect of ultrasonic treatment on the electrophysical and spectrometric characteristics of silicon detectors. A physical model is proposed that explains the mechanism of ultrasound action on the semiconductor structure and allows one to predict changes in the parameters of Si-n-p detectors resulting from such treatment.

MATERIALS AND METHODS

For the fabrication of Si-SDD (semiconductor diffusion detectors) detectors, we used p-type monocrystalline silicon ingots with a resistivity of $\rho = (10\div14)\cdot10^3\Omega\cdot$cm and a minority carrier lifetime of $\tau = 450\div650\mu$s, as well as lower-resistance p-Si ingots with $\rho \leq (2\div5)\cdot10^3\Omega\cdot$cm and τ=800÷1000μs. The oxygen concentration N_{O_2} was no more than 10^{16}cm^{-3} and the dislocation density $N_D\sim10^4$cm^{-2}. The cylindrical ingots were cut into plates up to 0.5 mm thick. The plates had an area S from 0.25 cm^2 to 2.0 cm^2. The Si plates were ground on both sides with M15 abrasive powder. After appropriate chemical treatment, aluminum (Al) with a thickness of l≈0,45μm ÷ 0,5μm was sprayed onto one side of the

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Si plates; during this technological procedure, the edges of the Si plates were protected with a mask. After that, a solution of phosphorus pentoxide P_2O_5 was applied to the other side of the Si plate, and this coating was dried. The next technological step was the phosphorus diffusion into the Si plates. The samples, located in quartz cassettes, were placed in a diffusion furnace. Phosphorus diffusion was carried out at a temperature of T = 1073K in a stream of inert gas for a time of t = 60 minutes. Then the temperature was slowly lowered to room temperature. Aluminum deposited on the Si wafer is alloyed with it at T≈820K and then, diffusing from the melt into the Si wafer, forms a heavily doped p^+-layer of silicon. After cooling, the Si wafer undergoes a series of chemical-technological operations to clean and remove the phosphosilicate glass on the n^+-layer obtained by phosphorus diffusion. Gold with a density of about 30÷50 $\mu g/cm^2$ was sputtered onto the input window of the Si-n-p structure. Electrical contacts to the n- and p-layers were made in the form of pressure or by attaching thin metal wires using conductive silver pastes. The structure was then mounted in a case. Large-area Si-n-p structures can be cut into smaller plates and also used to make SDD detectors for specific purposes. It is also envisaged to protect and seal the semiconductor detector edges with specialized protective coatings [7,8].

The theoretical analysis and experimental studies presented in this work aim to deepen the understanding of the physical processes underlying polarization effects in silicon detectors and to develop effective methods to minimize them. The results obtained are not only fundamentally important for semiconductor physics but also practically valuable for optimizing production processes and enhancing the operational performance of Si-n-p radiation detectors, opening new opportunities for their use in various scientific and technological fields.

It was found that local clusters of impurity atoms with an effective size l>6µm÷30µm are present in Si-n-p radiation detectors, determining the behavior of the signal amplitude in different intervals of electric and temperature fields. It was found that at E>1500 V/cm and T>168 K, the efficiency of collecting nonequilibrium charge carriers increases significantly and the doublets of spectral α-lines and "humps" in the temperature dependences of the signal amplitude disappear. The main physical processes and mechanisms determining the occurrence of the phenomenon of "polarization" of Si-n-p detectors were investigated. This phenomenon is due to the existence of local gold atoms that arise during the technology of manufacturing Si-n-p detectors and act as effective capture centers.

Previously, similar studies were carried out in detail for Si(Li)-p-i-n-detectors [9], where it was shown that the energy resolution is significantly affected by the inhomogeneities of the specific resistance of silicon. Since the process of compensation of inhomogeneity in the manufacture of SDD (semiconductor diffusion detector) - Si-n-p-detectors does not exist, then the effect of self-regulation of the system (sensitive region) does not occur here, as in the case of lithium-ion drift. Therefore, the potential relief of the concentration of the main dopant is preserved. This leads to fluctuations in the carrier lifetime and, in the case of the formation of local clusters of impurity atoms, leads to a strong inhomogeneity of the electric field in a given microvolume of the sensitive region of the radiation receiver [10].

The experiments conducted allowed us to establish critical parameters at which the influence of these inhomogeneities is significantly reduced: at an electric field strength exceeding 1500 V/cm and a temperature above 168 K, a significant increase in the efficiency of collecting nonequilibrium charge carriers is observed. Under these conditions, the characteristic anomalies in the spectral characteristics of the detectors, such as the doublet peaks of gamma lines and specific "humps" in the temperature dependence of the signal amplitude, practically disappear.

The physical interpretation of this effect is that the increased field strength provides sufficient energy for charge carriers to overcome potential barriers created by impurity clusters, while the increased temperature promotes thermal activation of carriers captured at localized centers. In the course of the study, the main physical processes and mechanisms underlying the well-known but poorly understood phenomenon of "polarization" of Si-n-p detectors were thoroughly studied. Our experiments convincingly showed that this phenomenon is directly related to the presence of local clusters of gold atoms in the semiconductor structure, which form during the manufacturing process of Si-n-p detectors.

Gold atoms, when they penetrate the silicon crystal lattice, form deep energy levels in the semiconductor's forbidden zone and act as effective centers for capturing charge carriers. The process of carrier capture and subsequent release at these centers has characteristic time constants that determine the dynamics of polarization effects. Charge accumulation at localized centers distorts the detector's internal electric field, which in turn alters the efficiency of charge collection and, consequently, degrades the spectrometric characteristics of the receiver. These effects are especially pronounced at low temperatures and low field strengths, when the probability of thermal release of captured carriers is minimal, and the drift velocity is insufficient to overcome potential barriers effectively.

For a more detailed study of the causes of polarization effects and low values of the functional characteristics of the radiation receivers, Si- SDD were selected. Then, Si- SDD were divided, in accordance with the selection, into 3 groups (recall that the polarization effect consists in the fact that, being in the operating mode, the radiation receiver gradually worsens its functional characteristics due to the strong capture of charge carriers by traps [6]. After heating to room temperatures, the radiation receiver restores its characteristics).

a) Group 1. In this group, Si- SDD had high functional characteristics and insignificant capture effects were observed in them, the linearity of the $\lambda(1/E)$ dependence was preserved in a wide range of electric field strengths E;

b) Group 2. Capture effects were observed in the Si- SDD of this group (the field dependences $\lambda(1/E)$ had a nonlinear form in the region of low values E≤1000 V/cm), which is associated with shallow capture centers. The detectors of this group had average spectrometric characteristics. In this case, the spectral lines had a long decline on the low-energy side, which is due to the presence of a certain number of local clusters of impurity atoms in the sensitive layer.

c) Group 3. The polarization effects of Si- SDD of this group manifested themselves most clearly and quickly for radiation registration times t_p<2 hours. The spectral lines of this Si-SDD group showed doublets (Fig. 1, spectra 1 and 2). As shown above, these Si- SDD have significant sizes of local clusters of impurity atoms, determined by us using the phase-frequency method [7].

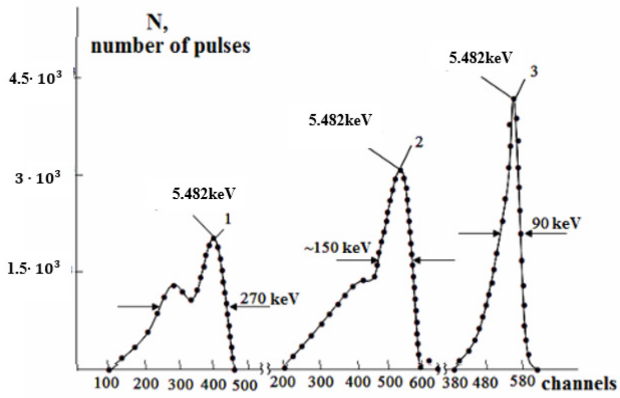

Figure 1. Spectral α-lines of the isotope ^{241}Am from Si-n-p-detector No. 12 d=130 μm, T=300 K. a) spectra 1 and 2 were obtained at E=400 V/cm and E=550 V/cm before irradiating the detector with ultrasound. b) spectra 3 were obtained at E=550 V/cm and T=300 K after irradiating the detector with ultrasound with I*=0.4 W/cm^2, f=15 MHz for 43 min.

It seems interesting to us to analyze the observed phenomena for Si- SDD of the second and third groups, using for this purpose not only the study of the shapes of the spectral lines, the dependences λ(1/E), λ(T), but also using such an important tool as the analysis of the electrophysical characteristics of these groups of radiation receivers.

RESULTS AND DISCUSSION

We conducted an independent study of the causes of the observed phenomena by analyzing the additional behavior of the dependence of the current density on the reverse bias voltage at temperatures T = 300 K based on the Fowler-Nordheim field emission model [11].

This model describes the behavior of this dependence quite well in the presence of inhomogeneities in the region of p-n-junctions [12,13].

The studies were carried out for 15 most prominent representatives of each group. Typical results for two of them are given below. For simplicity and convenience, we introduce the following designations: Si-receivers with a strong capture effect Si- SDD -R and with a weak one - Si- SDD -W, respectively. Figure 2 shows the measured dependences of the current on the reverse bias voltage V_b at a temperature of T = 300 K for two Si-n-p radiation detectors Si- SDD -R and Si- SDD -W, containing, respectively, large-scale and small-scale local accumulations of impurity atoms. It is evident from the graph that a sharp increase in the current (deterioration of the characteristics) of Si- SDD-R and Si- SDD -W begins at a voltage of V_b ≈ 1,5 V (curve 4 in Fig. 2) and V_b ≈ 3.0 V, (curve 1 in Fig. 2), respectively. In addition, it was found that the reverse current of Si- SDD -R is almost independent of temperature in the temperature range T = 77 ÷ 300 K, but at the same time a noticeable temperature dependence of the reverse current was observed in Si- SDD -W.

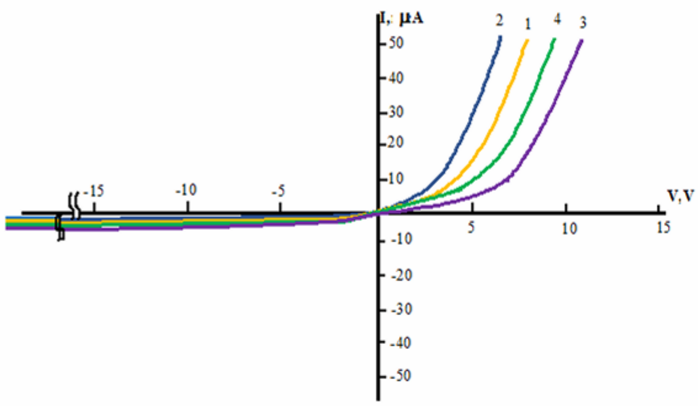

Figure 2. Current dependences on reverse voltage for Si- SDD -W and Si- SDD -R radiation receivers, T=300K
a) Si-PI-W-curve 1 before ultrasound irradiation, curve 2- after irradiation; b) Si- SDD -R-curve 3 before ultrasound irradiation, curve 4- after irradiation. Parameters of ultrasound I*=0.4 W/cm^2, f=15 MHz, t=45 min, T=300K.

The use of the Fowler-Nordheim model allows one to calculate the dependence of the reverse current density on the reverse bias voltage $I(V_b)$ based on an equation of the following form [11]:

$$I(T,E) = \int_{-\infty}^{-\infty} A(T,E^1)D(E,E^1)dE^1 \tag{1}$$

where $A(T,E^1)$ is a function describing the process of charge carrier transfer to the barrier surrounding the local cluster of impurity atoms, $D(E,E^1)$ is the transmission coefficient describing the probability of charge carrier tunneling through the barrier. This is true, since the barrier becomes repulsive after the carriers are captured by the local cluster of impurity atoms, or the barrier is initially repulsive due to the nature of the atoms forming the cluster. Then, as calculations and computations show [11], the functions $A(T,E^1)$ and $D(E,E^1)$ can be written as follows:

$$A(T,E^1) = (4\pi m^* \cdot kT/h^3)\ln[1+\exp(-E^1/kT) \tag{2}$$

$$D(E,E^1) = \exp(-4(2m^*)^{1/2}(q\Phi_B-E^1)^{3/2}\cdot V(y))/2h^*qE, \tag{3}$$

$$\text{where } y = (q^3\cdot E)^{1/3}/q\Phi_B \tag{4}$$

The following notations are used in the equations: m* - is the effective mass of charge carriers; k is the Boltzmann constant; T is the absolute temperature; h* - is the Planck constant; q is the electron charge; Φ_B- is the barrier height; E - is the electric field strength; E^1 -is the carrier energy (electrons or holes); V(y) -is the Fowler-Nordheim function. In the calculations, it is assumed that V(y) = 1. For $T \to 0$, equation (1) will have the following form:

$$I(0,E) = q^3E^2\exp(-4(2m^*)^{1/2}(q\Phi_B)^{3/2}/3h^*qE)/16\pi^2h^{*2}q\Phi_B \tag{5}$$

It is natural to assume that near a local cluster of impurity atoms, the electric field is amplified by β times, since the presence of the cluster causes the emergence of a local p-n junction, the electric field of which determines the processes of carrier drift in a given place of the active element (sensitive region) of the radiation receiver [12]. That is, the expression for the electric field in this case will have the following form:

$$E = \beta(2qN_D/\varepsilon_s)^{1/2}(V_i+V_b)^{1/2}. \tag{6}$$

Where N_D is the donor concentration, ε_s - is the semiconductor permittivity, V_i - is the built-in voltage, and V_b - is the reverse bias voltage. The calculation is based on a model of an abrupt p-n junction, assuming that local clusters of impurity atoms are located near the region of the maximum field of the p-n junction of the Si radiation receiver. Given the above, the electric field gain can be calculated as follows.

First, by numerical integration of equation (1), the dependences $I(V_b)$ are calculated for different values of the effective barrier height $\Phi=(m^*/m_0)^{1/3}\Phi_B$ at temperatures T = 77 K and T = 300 K. These dependences for the values qΦ = 0,31; 0,52 and 0.72 eV at $N_D=1{,}2\cdot10^{15}cm^{-3}$ and $V_i=0$ were calculated, measured and presented as an example for the value qΦ = 0.31 eV in Figure 3. Then, a comparison of the experimental dependences $I(V_b)$ with the calculated dependences $I(V_b)$ was carried out until they completely coincided and the coefficient β was determined from a simple relationship (7):

$$\beta = [\, V_b \text{ (theoretical value)}/ V_b \text{ (experimental value)} \,]^{1/2} \tag{7}$$

It is easy to see that the values of the coefficients β for the Si- SDD -R and Si- SDD -W radiation receivers are $\beta_1 \approx 128$ and $\beta_2 \approx 13$, respectively. The effective barrier height Φ is also determined using the matching procedure described in [11]. It was found that the value of Φ for Si- SDD -R and Si- SDD -W is $\Phi_R \approx 0{,}62$ V and $\Phi w \approx 0.67$ V, respectively.

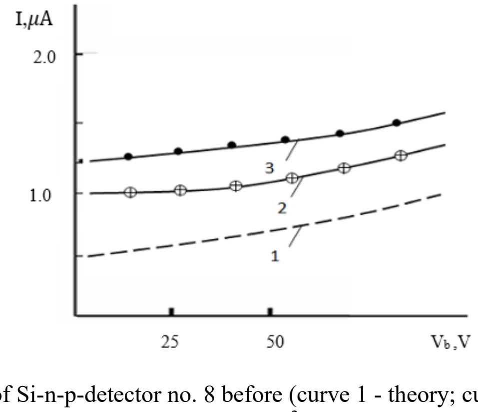

Figure 3. Volt-ampere characteristic of Si-n-p-detector no. 8 before (curve 1 - theory; curve 2 - experiment) and after (curve 3 - experiment) ultrasonic treatment at I* = 0.4 W/cm², f = 15 MHz, t = 125 min at T = 300 K.

The peculiarity of the presented model of the current transfer mechanism is that the temperature dependences of the reverse currents of the Si radiation receivers are calculated without introducing any special approximations. For this, as noted earlier, numerical integration of equation (1) is carried out for different values of β, Φ_B and reverse bias voltage V_b.

It was noted above that for Si- SDD -R the reverse current density depends weakly on temperature. This is explained by the fact that the temperature-independent coefficient D in equation (1) significantly exceeds the temperature-dependent function $A(T,E^1)$ due to the very small barrier width. The decrease in the barrier width is caused by a significant increase in the local field near the local cluster of impurity atoms. In the Si- SDD -W radiation receiver, the reverse current density strongly depends on temperature due to the low value of the parameter $\beta_2 \approx 13$, which is associated with smaller values of local clusters of impurity atoms in this type of Si- SDD -W compared to the values of the local cluster of impurity atoms existing in Si- SDD -R radiation receivers. From the analysis of the obtained data, it is possible to determine the values of the intensity of localized (internal) electric fields near local clusters of impurity atoms, the values of which are $E \approx 10^6$-10^7 V/cm, which is approximately two orders of magnitude greater than the maximum electric field in the p-n junction of Si radiation receivers. For example, if we take Si- SDD -R with a p-n junction width of W = 20 μm, at a voltage of V_b = 10 V, the value of $E^{max}_{p\text{-}n}$ = 5000 V/cm, and for a receiver of the Si- SDD -W type, the value of $E^{max}_{p\text{-}n} = 2{,}5{\cdot}10^4$ V/cm.

The figures (2, 3) show changes in the current characteristics after ultrasonic waves with a frequency f = 15 MHz and an intensity I* = 0.4 W/cm^2 pass through Si receivers.

It is clearly seen that the curves of the dependence of the reverse current on the bias voltage V_b shift toward lower current values (Fig. 2, curves 2 and 4; Fig. 3, curve 3). We believe that after the ultrasonic treatment of Si-receivers, a decrease in the value of qΦ occurred, that is, a decrease in the height of the potential barrier of the p-n-junctions formed by the presence of local clusters of impurity atoms occurred, which is reflected in Table 1.

Table 1. The effect of ultrasonic treatment on the value of qΦ

qΦ, eV, before ultrasonic treatment	qΦ, eV, after ultrasonic treatment
0.31	0.25
0.52	0.45
0.72	0.66

Thus, the decrease in the reverse currents of Si-n-p-receivers after the passage of ultrasonic waves through them is most likely associated with the decay of local clusters in ultrasonic fields.

The spectral lines of Si-receivers measured after ultrasonic processing also underwent significant changes, namely:

a) the energy resolution and shape of the spectral lines improved (the low-energy "tail" decreased, the "humps" smoothed out (Fig. 1, spectrum 3);

b) the amplitude of the signal "A" increased, which is determined by the position of the peak of the spectral line on the analyzer screen. "A" was measured in the channels (Fig. 4). In addition, after ultrasonic processing of Si-receivers, the charge pulses began to have a sharp leading edge and the signal rise time τ decreased by an average of 10÷15%.

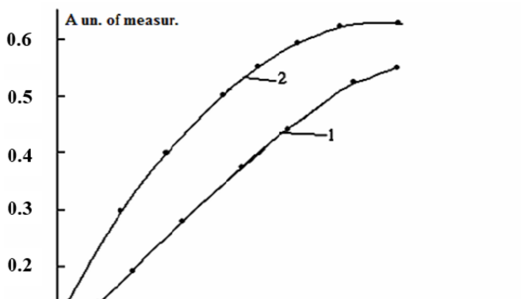

Figure 4. The amplitude of the signal of Si-n-p-detector no. 12 depending on the magnitude of the electric field strength. T = 300 K. Curve 1 - before irradiation with ultrasonic waves. Curve 2 - after irradiation with ultrasonic waves I* = 0.4 W/cm^2, f = 15 MHz, irradiation time t = 40 min

All these experimental data directly indicate that the potential relief in the active region of Si detectors became smoother after ultrasonic wave treatment, i.e. local clusters of impurity atoms began to exert less influence on the processes of carrier capture drift. Polarization effects in Si- SDD-W type detectors disappeared completely, and in Si-SDD -R detectors they significantly decreased. Figure 5 shows the temperature dependences of the signal amplitude for a Si-n-p detector containing local clusters containing Au atoms in the sensitive region, before and after ultrasonic waves passed through it (curves 1 and 2, respectively).

The appearance of a "hump" in the temperature range T = 148 K–168 K is clearly visible, which indicates the presence of a "large-scale" trap. Such "humps" were absent in gold-free silicon detectors. In the same temperature range, the spectral line is a doublet (see Fig. 5, spectrum 1). Therefore, it can be stated that gold, being a rapidly diffusing impurity in silicon and in the presence of dislocations and stacking faults in it, can be deposited on them, forming Au clusters. At elevated Au concentrations in such microvolumes of the sensitive region of the Si receiver, strong capture of charge carriers begins to occur, reducing the mobility and lifetime of the latter [14]. This leads to a sharp increase in charge losses (a drop in the signal amplitude) and the appearance of a polarization effect. Around the formed clusters of such impurity atoms, there is a zone of mechanical stresses in which strong absorption of ultrasound occurs, leading to the disintegration of clusters and a noticeable improvement in the characteristics of the Si-n-p receiver (Fig. 5, spectrum 2 demonstrates the disappearance of the doublet). Curve 2 shows the disappearance of local clusters after the action of ultrasonic waves on the receiver.

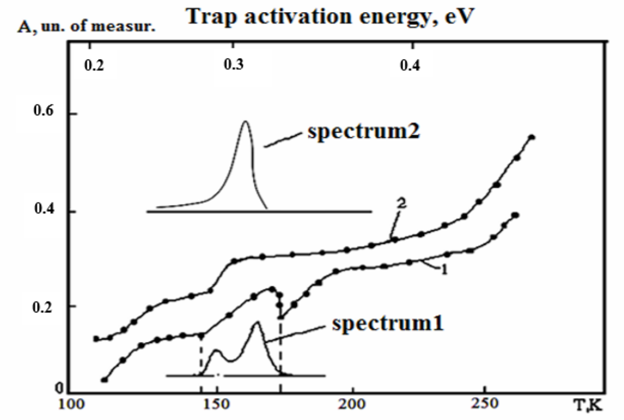

Figure 5. Temperature dependence of the amplitude of the α-spectrum signal from the ^{241}Am isotope of the Si-n-p-detector before (curve 1 and spectrum 1) and after irradiation with ultrasonic waves (curve 2 and spectrum 2) at T=300 K, I* =0.4 W/cm^2, f =15 MHz, t=40 min.

CONCLUSIONS

As a result of the conducted research, the features of diffusion Si-n-p-receivers, their electrophysical and spectrometric characteristics, as well as the influence of various types of trapping centers on them were identified and studied in detail. The obtained results are of significant importance both for the fundamental understanding of physical processes in semiconductor structures and for practical application in the development and optimization of silicon receivers.

It was established that diffusion Si-n-p-receivers are characterized by the presence of two types of defects: single trapping centers and so-called "large-scale" traps of charge carriers. It is the presence of "large-scale" traps that has a decisive effect on the functional characteristics of the studied receivers. These traps are local clusters of impurity atoms that form inhomogeneities in the semiconductor structure and significantly change its electrophysical properties.

The most striking manifestation of the influence of "large-scale" traps is the appearance of anomalous spectral lines in the form of doublets. This effect is observed precisely in those Si-n-p-receivers that contain local clusters of impurity atoms. In addition, pronounced polarization effects are observed in such receivers, indicating a violation of the electric-field homogeneity in the device's sensitive region.

A detailed analysis of the experimental data allowed us to establish the physical mechanism underlying the observed anomalies. The appearance of doublets in the spectral lines and characteristic "humps" on the temperature dependences of the signal amplitude is due to the formation of a space charge in the sensitive region of the receiver. The electric field of this space charge creates a counteraction to the normal drift of charge carriers to the contacts of the receiver, which leads to distortion of the recorded signal and the appearance of the above anomalies.

The conducted studies showed that local impurity accumulations within the Si-n-p receiver's structure actually form built-in n-p microjunctions in its sensitive region. These microjunctions create a complex potential relief, which significantly affects charge-transfer processes and, consequently, the device's spectrometric characteristics. The heterogeneity of the potential relief leads to charge carriers generated in different areas of the receiver moving at various speeds and along different trajectories, resulting in doublets in the spectral lines.

An important practical result of the study was the discovery of an effective method for eliminating the identified anomalies. It was experimentally established that ultrasonic treatment of Si-receivers with pronounced potential relief and polarization effects completely eliminates these undesirable phenomena. Ultrasonic action promotes the redistribution of impurity atoms and a decrease in the concentration of local impurity clusters, which leads to smoothing of the potential relief and normalization of the electrophysical characteristics of the receiver.

The conducted study of polarization effects in Si-n-p radiation detectors allowed to significantly expand the understanding of the physical processes underlying this phenomenon and to develop effective methods for minimizing the negative impact of polarization effects on the characteristics of semiconductor detectors. In the course of the work, the mechanisms of polarization occurrence associated with the capture and accumulation of charge carriers at localized centers in the volume of the semiconductor were studied in detail, which leads to a distortion of the internal electric field and, as a consequence, to the degradation of the spectrometric characteristics of the detectors. Particular attention was paid to the study of the role of "large-scale" traps - local clusters of impurity atoms that form inhomogeneities of the potential relief in the silicon structure and contribute to the appearance of anomalous spectral characteristics.

Experimental studies of the current characteristics of Si-n-p receivers in various operating modes allowed us to establish a correlation between the parameters of reverse currents and the degree of polarization effect manifestation. It was shown that the temperature dependence of reverse currents is complex and determined by a set of mechanisms for charge-carrier generation, including thermal generation in the space-charge region, tunneling through potential barriers, and generation on surface states. Analysis of the current-voltage characteristics of receivers before and after exposure to ionizing radiation revealed significant changes in the current structure, driven by charge redistribution at localized centers and the formation of additional conductivity channels.

An important result of the work was the discovery and detailed study of the effect of a peak doublet in the energy spectra of Si-n-p-receivers, which manifests itself when registering monoenergetic radiation. It was found that this effect is associated with the inhomogeneity of the electric field within the detector's sensitive volume, caused by the localization of charge on impurity centers. A physical model is proposed that explains the mechanism of doublet peak formation and allows predicting their parameters based on the operating conditions of the receivers. It is experimentally confirmed that the degree of manifestation of the doublet effect depends significantly on the irradiation intensity, temperature and applied bias voltage, which is consistent with theoretical ideas about the nature of this phenomenon.

One of the key achievements of the study was the development and experimental testing of the method of ultrasonic processing of Si-n-p-receivers aimed at minimizing polarization effects. It was shown that the effect of ultrasound of a certain frequency and intensity leads to the redistribution of impurity atoms in the semiconductor structure, smoothing of the potential relief and, as a result, to a significant reduction in polarization effects. The parameters of ultrasonic processing were optimized, providing maximum improvement in the characteristics of the receivers with a minimum risk of mechanical damage to the structure. Long-term tests of ultrasonic-treated detectors confirmed the stability of the achieved improvements and the absence of degradation of the parameters during operation.

A comprehensive study of the influence of various factors on the manifestation of polarization effects allowed us to develop recommendations for optimizing the operating modes of Si-n-p radiation detectors. It was found that increasing the operating temperature of detectors in a certain range helps to reduce the lifetime of charge carriers at localized centers and, accordingly, to reduce the degree of polarization. Optimum values of bias voltage were determined, providing a compromise between the efficiency of charge collection and minimization of polarization effects. Algorithms for compensating for the effect of polarization on the results of spectrometric measurements by introducing appropriate corrections when processing experimental data were proposed.

Theoretical analysis of the experimental results allowed us to develop a refined physical model of polarization effects in Si-n-p detectors, taking into account the spatial distribution of impurity centers, their energy spectrum and the kinetics of the processes of capture and release of charge carriers. The model successfully describes the observed experimental patterns and allows us to predict the behavior of detectors under various operating conditions. Based on this model, a software package for numerical simulation of processes in Si-n-p detectors was developed, which can be used to optimize the design and manufacturing technology of semiconductor detectors.

The successful implementation of the developed methods and recommendations in the production of Si-n-p radiation detectors confirms the practical significance of the obtained results. Detectors manufactured with the proposed modifications to the technological process and subjected to ultrasonic treatment demonstrate significantly improved characteristics: increased temporal stability, improved energy resolution, and reduced sensitivity to changes in operating conditions. This opens new opportunities for the application of Si-n-p receivers across various fields of science and technology, including nuclear physics, space research, medical diagnostics, and radiation monitoring systems.

Thus, the conducted research makes a significant contribution to the development of the physics of semiconductor detectors and the technology of their production. The obtained results not only expand fundamental understanding of processes in semiconductor structures but also have direct practical significance for improving the characteristics of Si-n-p radiation detectors. Further research in this direction can focus on a more detailed study of the microscopic mechanisms underlying ultrasound's effect on semiconductor structure, the development of new methods to modify the properties of silicon detectors, and the expansion of their application scope.

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ЕФЕКТИ ПОЛЯРИЗАЦІЇ В ПРИЙМАЧАХ Si-n-p ВИПРОМІНЮВАННЯ

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У цій статті представлено комплексний аналіз струмів n-p переходу та ефектів поляризації в дифузійних Si-детекторах (приймачах) випромінювання. Досліджено механізми поляризації, індукованої захопленням носіїв заряду в локалізованих центрах та формуванням об'ємного заряду в чутливій області детектора. Встановлено зв'язок між наявністю "великомасштабних" пасток, які є локальними кластерами домішкових атомів, та появою аномальних спектральних характеристик у вигляді дублетів. Експериментально показано, що ультразвукова обробка Si-n-p детекторів призводить до значного зменшення ефектів поляризації завдяки перерозподілу домішкових атомів та згладженню потенційного рельєфу в напівпровідниковій структурі. Запропоновано фізичну модель для пояснення механізму, за допомогою якого ультразвуковий вплив впливає на електрофізичні та спектрометричні характеристики кремнієвих детекторів. Отримані результати мають практичне значення для оптимізації технології виробництва та покращення робочих параметрів Si n-p детекторів випромінювання.

Ключові слова: *кремнієві детектори; n-p переходи; ефекти поляризації; центри захоплення; ультразвукова обробка; спектрометричні характеристики; просторовий заряд; потенціальний рельєф; дифузійні детектори; локальні домішкові кластери*