# Growth of Clusters of Thermodonors in p-Silicon Under Gamma Irradiation

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**Abstract:** *It is confirmed that quasi-point clusters of donor–type defects occur in p-Si grown by the Chokhralsky method at temperatures (600 ° C and 900 ° C), the content of 3 to 10 defects in each. No such accumulations were found in pSi that were not subjected to heat treatment.*

*It has been experimentally established that as a result of gamma irradiation, clusters of donors in pSi grow (the number of donors included in them increases) if there are nuclei of clusters in the non-irradiated material.*

***Keywords****: NA acceptors and ND donors, proper-point defects, quasi-point defects, effective cross-section, diffusion, drift path, electrically active centers, thermodonor, embryos.*

**Introduction.** The study of structural defects in crystals is of great importance both for the development of solid state theory and for solving practical problems, since the occurrence of defects can have a decisive influence on various properties of crystals and devices based on them.

This work is devoted to the study of the distribution of donor-type centers in p-silicon grown by the Chokhralsky method and subjected to heat treatment, as well as to the study of changes in this distribution under gamma irradiation. P-type silicon with boron concentration $1{,}5 - 2{,}0\cdot10^{15}$ cm-$^{3}$, oxygen $8{,}7\cdot10^{17}$ cm$^{-3}$ and carbon $1\cdot10^{17}$ cm$^{-3}$ were subjected to heat treatment at 600 ° C and 900 ° C. At the same time, the divergent concentration of acceptors and donors decreased slightly (within 10%). The parameters of the material before irradiation, before heat treatment and after heat treatment (samples 1-3) and the control material p–Si <p> (sample 4) are presented in Table 1.

**Experimental data.**

The temperature dependence, as well as the concentration and mobility of charge carriers, was experimentally obtained.

The same p-silicon was irradiated on a $^{60}$Co gamma installation at room temperature. The concentration and mobility of charge carriers as a result of irradiation changed slightly (see data in Tables 1 and 2).

To detect clusters of donor centers and to find the distribution function of donor clusters, i.e., the dependence of the concentration of clusters of $N_Z$ on the number Z of thermodonors included in them before and after irradiation, photovoltaic measurements were used according to the method described in [1]. The dependences of φ2(t) on the observation time, η(t) of the current charge n on the observation time (t) and the dependence f(t) for the volume of the space charge area occupied by f clusters on the observation time t after the light was turned off for different p-Si samples before and after gamma were found from experimental data- irradiation. By comparing the values of η(t) and f(t) at the same time, the dependence of *f*(η) (before and after irradiation) was found and this dependence is shown in Figure 1.

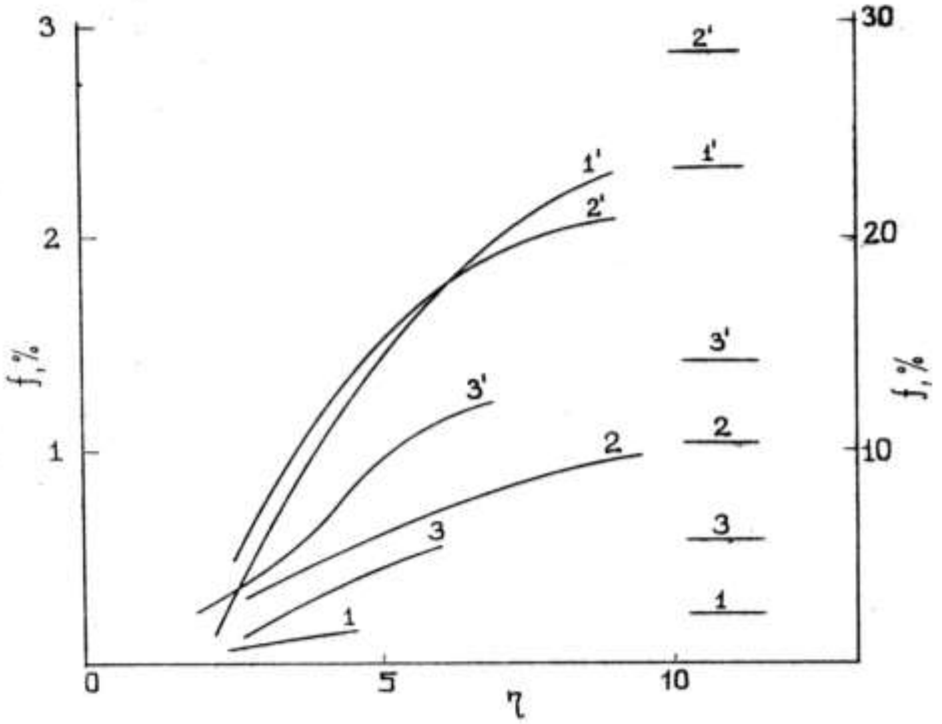


Fig. 1. Dependence for the volume of the occupied OPZ of the cluster f on the current charge η after switching off the light for different p-Si samples before and after irradiation:
1, 2, 3 – $F = 0$, $1^1$– $F = 7{,}30 \cdot 10^{18} cm^{-2}$,
$2^1$ – $F = 5{,}95 \cdot 10^{18} cm^{-2}$, $3^1$ – $F = 6{,}73 \cdot 10^{18} cm^{-2}$.
*The horizontal lines correspond to the dark f value. Curves 1, $1^1$: scale - left axis, curves 2, $2^1$ and 3, $3^1$: scale – right axis.*

The results of the analysis of this dependence, carried out using the formula according to the method [1], are presented in Fig.2.

In the control material not subjected to heat treatment, photoconductivity was not observed within the measurement accuracy $\left(\frac{\Delta\sigma}{\sigma_0} \leq 1{,}5\%\right)$ either before or after irradiation.

Therefore, how can it be argued that the concentration of clusters with $Z \geq 5$ does not exceed $N_Z^{\text{макс}} \approx 10^{11} \text{см}^{-3}$.

**Table 1**

| Sample Namber | $P_{300K}$, $cm^{-3}$ | Heat treatment temperature *) °C | Heat treatment time *) | $P_{300K}$, $cm^{-3}$ | Rσ, $cm^2$/B·c | | $N_A$ $cm^{-3}$ | $N_Д$ $cm^{-3}$ | K |
|---|---|---|---|---|---|---|---|---|---|
| | Before heat treatment | | | After heat treatment | 78 K | 300 K | | | |
| 1 | $1,77\cdot10^{15}$ *) | 600 | 6 | $1,35\cdot10^{15}$ | $8,71\cdot10^{3}$ | 404 | $1,52\cdot10^{15}$ | $1,71\cdot10^{14}$ | 0,11 |
| 2 | $1,78\cdot10^{15}$ *) | 600 | 8 | $1,26\cdot10^{15}$ | $8,91\cdot10^{3}$ | 454 | $1,41\cdot10^{15}$ | $1,54\cdot10^{14}$ | 0,11 |
| 3 | $1,75\cdot10^{15}$ *) | 900 | 24 | $1,51\cdot10^{15}$ | $7,77\cdot10^{3}$ | 390 | $1,65\cdot10^{15}$ | $2,34\cdot10^{14}$ | 0,14 |
| 4 | $2,3\cdot10^{15}$ | – | – | – | $1,03\cdot10^{4}$ | 470 | – | – | – |

** data by P.Gavarshevsky and K.Shmalyts*

**Table 2**

| Sample Namber | $F\cdot10^{-18}$, $cm^{-2}$ | $P\cdot10^{-15}$, $cm^{-3}$ 300K | Rσ, $cm^2$/B·c | |
|---|---|---|---|---|
| | | | 78K | 300K |
| 1 | 7,30 | 1,35 | | 364 |
| 2 | 5,95 | 1,23 | $3,5\cdot10^{3}$ | 364 |
| 3 | 6,73 | 1,10 | $6,17\cdot10^{3}$ | 329 |
| 4 | 6,51 | 2,24 | $9,86\cdot10^{3}$ | 461 |

Thus, it turned out that clusters of donor-type defects are formed precisely during heat treatment.

In view of the fact that the detected clusters are characterized by small Z values, and there is a risk of large errors in the determination of $N_Z$ associated with non-fulfillment of the condition $R_{ОПЗ} > L_{св.пр.}$

At our request, the staff of the A.F. Ioffe Institute of Physics and Technology N.T. Bagraev and L.S. Vlasenko conducted a study of the function of $N_Z(Z)$, i.e. the dependence of the concentration of clusters of $N_Z$ on the number of Z thermodonors included in them in the samples we studied p-Si methods of optical polarization of nuclei (OPN) [2]. The results of these studies indicate the presence of inhomogeneities in the distribution of thermodonors and that these inhomogeneities are characterized by two sharply different magnitude scales. It turned out that there are macro-heterogeneities with an average size of $\sim 2{,}5 + 5$ microns, their concentration is $\sim 10^9 см^{-3}$ and micro-heterogeneities, the content of several donors that are part of the macro-heterogeneities.

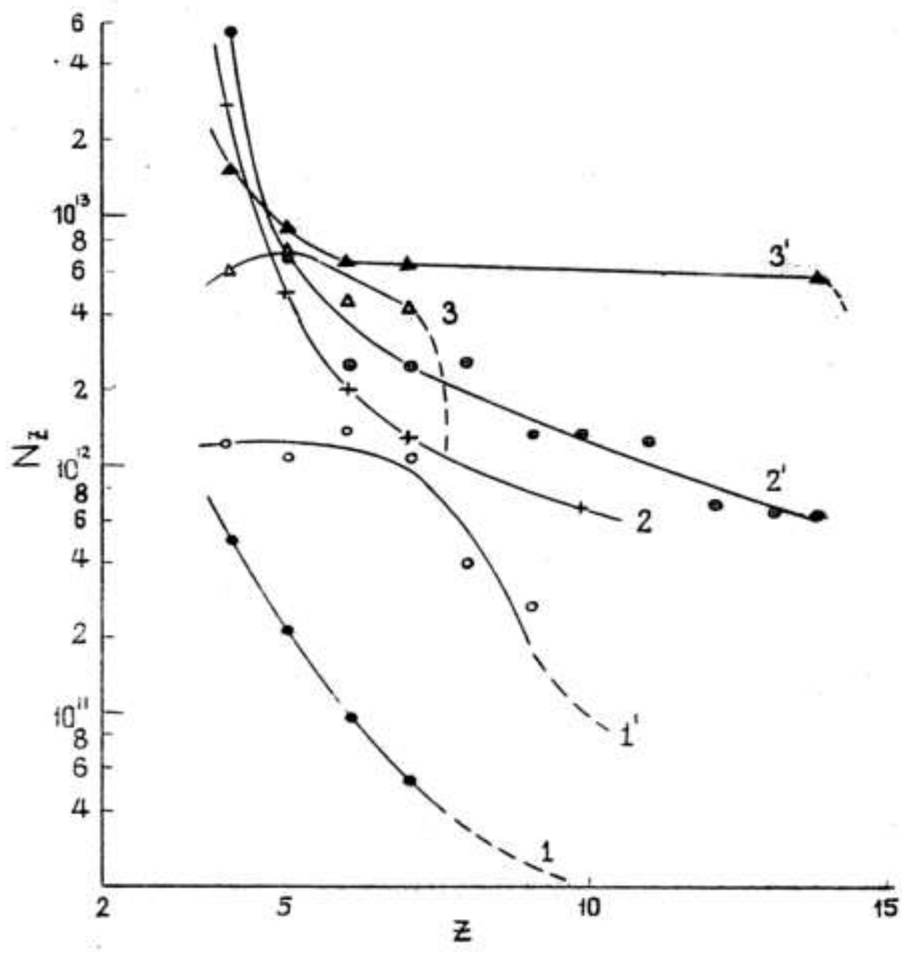


*Fig. 2. Dependences of the concentration of clusters on the number of thermodonors included in them in p-Si for different samples.*

*1, 2, 3 – F = 0; $1^1$ – F = 7,3 $10^{18} cm^{-2}$,*

*$2^1$ – F = 5,95 $10^{18} cm^{-2}$, $3^1$ – F = 6,73· $10^{18} cm^{-2}$.*

The magnitude of the nuclear relaxation time in the space between micro-inhomogeneities in silicon heat-treated at 900 ° C indicates the almost complete absence of thermodonors and other lattice defects between them. It is found that macro-heterogeneities include both single thermodonors and their clusters. With the help of the dependences of the relaxation time of the OPN on the magnetic field, it was possible to find the distribution of clusters by the number of their constituent paramagnetic centers. In Fig. 3 shows the distribution of $N_Z(Z)$ obtained by two methods: using the study of the photovoltaic properties of the material (curves I, 2) and using the OPM method (curves $1^1$, $2^1$). (curves $1^1$, $2^1$ of Fig.3 correspond to curves 2, 3 of Fig.2).

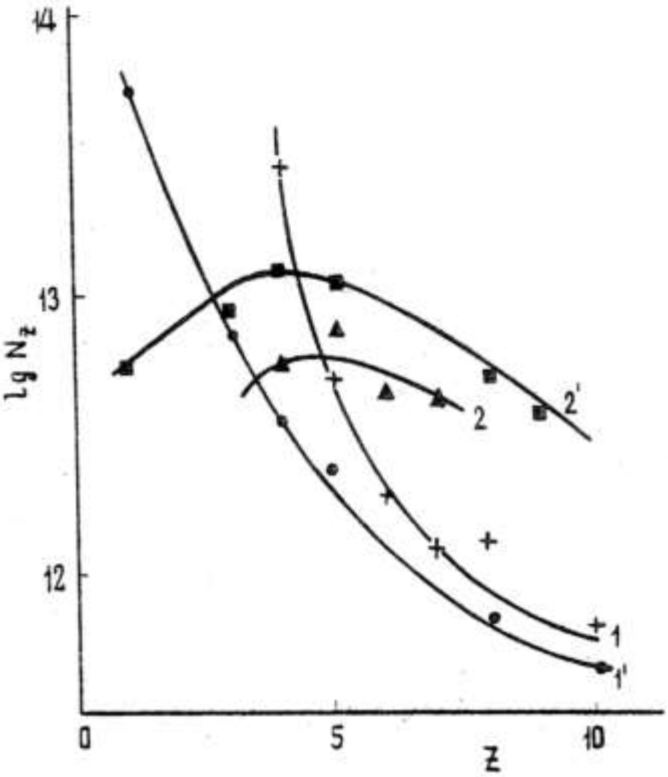


*Fig.3. Dependence of the concentration of clusters on the number of thermodonors included in them.*

*1, $1^1$ – after heat treatment at 600°C;*

*2, $2^1$ – by 900°C*

*1, 2 – photovoltaic research data;*

*$1^1$, $2^1$ – research data OPN.*

A satisfactory agreement is seen between the results obtained by these two methods for silicon heat-treated at both 600°C and 900 °C.

This consent gives grounds for the following conclusions:

1. The paramagnetic centers manifested in the experiments on OPN are electrically active.

2. The errors in the definition of $f$ associated with the violation of the condition $R_{\text{ОПЗ}} > L_{\text{св.пр.}}$, become unacceptably large only at $Z < 4$.

For large clusters, the method of photovoltaic registration of clusters of electrically active centers gives quite satisfactory results and can be used to find the distribution function of a $N_Z(Z)$.

**Discussion of the results and conclusion.**

1. Accumulations of thermodonors in p-silicon grown by the Chokhralsky method appear only as a result of additional heat treatment. In the control material, which was not subjected to heat treatment, no accumulations were detected either by the photoelectric method or by the OPM method.

2. The distribution functions of the number of clusters by the number of their constituent thermodonors turn out to be different in materials subjected to heat treatment at different temperatures.

The most significant difference is that in the material treated at 900 ° C, the concentration of single deep thermodonors is significantly less than in the material treated at 600 ° C. There is reason to believe that this is a consequence of the intensive decomposition of solid solutions of carbon and oxygen under heating conditions at 900 ° C.

At the same time, the process of accumulation formation is apparently determined by carbon precipitation. The higher the temperature of the heat treatment, the more intense the precipitation of carbon, the clusters of atoms of which are the centers of nucleation during the decomposition of a solid solution of oxygen. If, during heat treatment at 600 ° C, single or paired carbon centers still remain in the crystal, which, when interacting with oxygen atoms migrating during decay, form single point deep thermodonors, then at 900 ° C, there are practically no single carbon atoms left in the crystal, which leads to a sharp decrease in the concentration of single deep thermodonors (see curves 2 and $2^1$, Fig.3) [8].

At high temperatures, due to the decomposition of a solid solution of carbon, sufficiently large accumulations of deep-thermodonors can form, which, in turn, are the centers of the nucleation of the formation of other residual impurities during the decomposition of a solid solution.

The main deep ternodon, formed during the decomposition of solid solutions of carbon and oxygen, is a center with a donor level of $E_c$ – 0,48 [7]. During the formation of clusters, the ionization energy of the level fluctuates due to the interaction of defects with each other and the interaction of thermodonors with group III acceptors [3].

Small thermodonors with a level of $E_c$ – 0,07 are present only in the material processed at 600 ° C; this is due to the fact that the temperature is 600 °C is still insufficient for complete annealing of point oxygen-containing thermodonors, intensively formed during the decomposition of a solid oxygen solution in the temperature range 350-500 ° C [4,5,6].

3. When silicon is heat treated, inhomogeneities of two different scales occur. Macro-heterogeneities in the distribution of thermodefects with sizes of several microns, in turn, consist of single thermodefects and their clusters. There are no small clusters of thermodefects in the space between macro-heterogeneities.

The method of photoelectric registration of clusters does not reveal macro-heterogeneities, therefore, to obtain a complete picture of the distribution of impurities and defects, it is desirable to involve a combination of various methods for detecting clusters.

4. Visible (see fig. 3) that irradiation leads to an increase in the size of clusters of donor centers and to an increase in the concentration of clusters with a certain Z.

You can specify two possible reasons for the growth of clusters during irradiation:

1. There is a certain probability of the birth of structural defects inside the spatial charge region (SPD) of already existing clusters.

2. Defects born outside clusters (in the crystal matrix) can be captured by clusters by diffusion or drift.

In addition, it should be borne in mind that during irradiation, due to a decrease in the concentration difference between acceptors $N_A$ and donors $N_D$, the length of the shielding increases and, consequently, the radii of the OPZ.

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