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THE EFFECT OF THERMAL AND RADIATION DEFECTS ON THE RECOMBINATION PROPERTIES OF THE BASE REGION OF DIFFUSED SILICON p–n STRUCTURES

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Abstract—The effect of thermal and radiation defects on the minority-charge-carrier recombination in the base region of a diffused silicon p-n structures with doping levels of 10^{14}–$10^{18}\,cm^{-3}$ was studied. The parameters of thermal defects responsible for the change of the carrier lifetime in Si following its thermal treatment during the production of p-n structures are determined. The effective minority-charge-carrier trapping is observed in heavily-doped structures at $T \leqslant 100$ K. The dependence of the coefficient of the radiation-induced change in the carrier lifetime on the base-region doping level was found. Using this data and the results obtained by the capacitance spectroscopy technique the analysis of recombination properties of defects has been done. At carrier concentrations $n_0, p_0 > 10^{16}\,cm^{-3}$ the coefficient of the radiation-induced change in the carrier lifetime (K_τ) is shown to be determined by the introduction of the E-center in n-Si and the defect level $E_c - 0.27$ eV in p-Si. At a low excitation level in heavily-doped p-n structures a significant decrease in K_τ is observed at $T = 78$ K as compared to the value at 300 K.

1. INTRODUCTION

Physical phenomena defining the work of many semiconductor devices are based on the processes of the minority-charge-carrier recombination. Since the active layers of the device crystals have doping impurity concentrations of the order $10^{19}\,cm^{-3}$, the study of recombination mechanisms in heavily-doped silicon is of great practical interest. Recently, the processes of recombination in heavily-doped silicon are being widely discussed in connection with investigations of the Auger processes in bulk material[1–5]. The high-temperature treatments of monocrystals during the device growth result in defect generation and can significantly influence the ratio between the contributions of different recombination mechanisms (recombination through deep centers, Auger recombination, recombination through shallow impurity centers). Therefore, the results of the investigations performed on bulk material cannot be directly applied to the analysis of the phenomena taking place in devices.

The aim of the paper was to study the effect of thermal and radiation defects on the minority-charge-carrier recombination in the base region of the diffused asymmetrical silicon p–n structures with doping level in the range of 10^{14}–$10^{18}\,cm^{-3}$.

2. EXPERIMENTAL METHODS

We used p^+–n (n^+–p) structures prepared from bulk CZ silicon doped with phosphorus (boron) in the range of 10^{14}–$10^{18}\,cm^{-3}$. The p–n junction was formed by 2–3 μm boron or phosphorus diffusion into the (111) plane at 1100°C. The dislocation densities in the original Si wafers did not exceed $10^3\,cm^{-2}$. Before diffusion mechanical and chemical treatments were used to remove defects and minimize surface contaminations. The surface boron and phosphorus concentrations in diffused layers approximated $10^{20}\,cm^{-3}$. Ohmic contacts were formed by the vacuum evaporation of Al (10^{-5} Torr) on p-Si or by chemical deposition of Ni on n-Si with their subsequent annealing-in at 500°C for 20 min. The width of the base region was 300–450 μm. The abruptness of p–n junctions was determined from their C-V characteristics.

The minority-charge-carrier lifetime in the base region of p–n structures was determined from the transient characteristics during the switching of the junction on the instrument with time resolution 10^{-9} sec. Defect parameters and concentrations were obtained using the DLTS technique. The actual sensitivity of the setting at determination of the deep center concentration was $3.10^{-3}\,N_M$ (where N_M is the shallow doping impurity concentration). The spectrometer time constant approximated 100 sec and allowed the study of defects with $E_t \geqslant 0.10$ eV for the carrier cross sections $10^{-15}cm^2$.

Capacitance and carrier lifetime measurements were carried out in the temperature range of 300–78 K.

Irradiation with gamma rays from a ^{60}Co source was carried out at a dose rate of 600 R/sec. The linear pulse accelerator was used for irradiation of p–n structures by 7 MeV electrons. The electron flux intensity was $5 \times 10^{11}\,cm^{-2}\,sec^{-1}$. The electron energy was measured with an accuracy to 0.5 MeV. The dosimetry error for electron and gamma ray irradiation did not exceed 10%. The sample temperature at irradiation was not higher than 50°C.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 The minority-charge-carrier lifetime in lightly-doped samples

Measurements of the minority-charge-carrier lifetime $\tau_{n,p}$ in the base region of p–n structures with carrier concentration $n_0, p_0 \approx 10^{14}$–$10^{15}\,\mathrm{cm}^{-3}$ show that after thermal treatment during the formation of the p–n junction the carrier lifetime does not exceed 10^{-6}–10^{-5} sec at 300 K. It should be noted that in the original crystals its value approximated 10^{-4} sec. Therefore, one can conclude that thermal treatment of oxygen-containing Si results in the formation of effective recombination centers. However, thermal defects and impurities with $N_t \geqslant 3 \times 10^{-3} N_M$ were not detected in n- and p-type samples studied by DLTS.

With the increase of doping impurity in both n- and p-type base regions a decrease in the carrier lifetime is observed [Fig. 1(a) and (b); the injection level $\gamma = p_e/(n_0 + p_0) \approx 5 \times 10^{-2}$ and $T = 300$ K].

As is seen from the figure, with decreasing temperature the charge-carrier-lifetime dependence on doping level becomes weaker and is practically independent of it at 78 K.

Taking into account that thermal defects introducing levels into the gap have not been detected within the detection limit, one can use the information about structural perfection of the base region around the p–n junction to interpret the significant decrease in the minority-charge-carrier lifetime. In the course of a high-termperature treatment and impurity diffusion, besides point-defect introduction, the formation of dislocations can occur in the substrate[6].

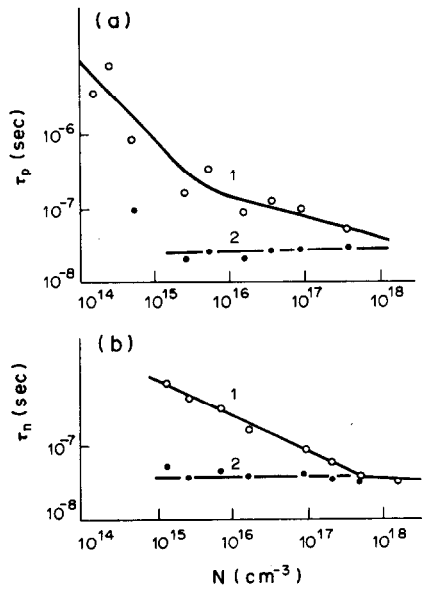

Fig. 1. The minority-charge-carrier lifetime as a function of shallow doping-impurity concentration for n- (a) and p-type (b) base region. 1—300 K; 2—78 K.

To clarify the picture of dislocation propagation into the bulk of the base region the selective Sirtl-etch with the successive thin layer removal on the side of emitter was carried out. In the original crystals the dislocation density before diffusion was $\lesssim 10^3\,\mathrm{cm}^{-2}$. After the formation of the p–n junction the density of dislocations in the base region increased in all the materials. Thus, for the p-type base region the dislocation density was $5 \times 10^4\,\mathrm{cm}^{-2}$ at doping level $4 \times 10^{17}\,\mathrm{cm}^{-3}$, while for doping levels of $10^{15}\,\mathrm{cm}^{-3}$ the density of dislocations was an order of magnitude lower. The distribution of dislocations along the base region shows that their density is practically constant.

As shown in Refs.[7, 8], the introduction of dislocations with a density N_d of 10^3–$10^4\,\mathrm{cm}^{-2}$ results in a decrease in the carrier lifetime which decreases linearly with the increase in N_d. At dislocation density $10^5\,\mathrm{cm}^{-2}$ the charge-carrier lifetime in p-Si with doping level $10^{15}\,\mathrm{cm}^{-3}$ is $\tau \geqslant 10^{-4}$ sec, irrespective of the type of dislocations[7]. In our case the carrier lifetime at 78 K depends neither on dislocation density in the base region nor on doping level, and for $p_0 = 10^{15}\,\mathrm{cm}^{-3}$ is 10^{-6} sec. Thus, one may conclude that in this case the introduction of dislocations by thermal diffusion does not control the lowering of the charge-carrier lifetime.

The analysis of the data presented in Refs. [1, 4, 5] shows that for bulk Si the charge-carrier lifetime does not depend on doping impurity concentration in the range $10^{14} \leqslant n_0$ or $p_0 \leqslant 10^{17}\,\mathrm{cm}^{-3}$, and the absolute value of the lifetime is defined by the introduction of traps in the process of material growth. At the same time, the base region of p–n structures is characterized by a decrease in the minority-charge-carrier lifetime with an increase in doping level from 10^{14}–$10^{18}\,\mathrm{cm}^{-3}$ which is not determined by introduction of dislocations during the formation of the p–n junction. With the account of the above-stated facts one can treat the experimental data within the limits of the Hall–Shockley–Read model after the trap concentration determined from the sensibility of the setting is found, i.e. $N_t \lesssim 3 \times 10^{-3} N_M$. Let us assume the carrier recombination to be determined by defects of a definite type with concentration N_t much lower than that of majority carriers; that is reasonably justified in our case. Then we can write for the n-type base

$$\tau = \tau_{p0}\left(1 + \frac{n_1}{n_0 + n_e}\right) + \tau_{n0}\left(\frac{p_1 + n_e}{n_0 + n_e}\right), \tag{1}$$

and for the p-type base

$$\tau = \tau_{no}\left(1 + \frac{p_1}{p_0 + n_e}\right) + \tau_{p0}\left(\frac{n_1 + n_e}{p_0 + n_e}\right) \tag{2}$$

where

$$\tau_{n0} = (C_n N_t)^{-1}, \quad n_1 = N_c \exp\left(-\frac{E}{kT}\right),$$

$$\tau_{p0} = (C_p N_t)^{-1}, \quad p_1 = N_v \exp\left(-\frac{E_g - E_t}{kT}\right),$$

Table 1. The thermal defect parameters in silicon

Type of conductivity	Energy position (eV)	σ_n (cm^2)	σ_p (cm^2)	References
n-Si	$E_c - 0.19$	4×10^{-14}	4×10^{-13}	This paper
	$E_c - 0.20$	1×10^{-12}	1×10^{-19}	[11]
	$E_c - 0.18$	$C_n = 1 \times 10^{-14}$	$C_D = 1 \times 10^{-9}$	[9]
	$E_c - 0.22$	2×10^{-14}	—	[10]
p-Si	$E_v + 0.14$	3×10^{-13}	3×10^{-14}	This paper
	$E_v + 0.16$	1×10^{-19}	4×10^{-13}	[11]
	$E_v + 0.22$	$C_n = 3 \times 10^{-11}$	$C_p = 2 \times 10^{-14}$	[9]

n_e is the nonequilibrium carrier concentration; E_t is the energy level position for the recombination center; C_n, C_p are the capture coefficients for electrons and holes, respectively.

Analysis of the experimental dependence of τ† on the Fermi-level position using eqns (1) and (2) (Fig. 2), allowed one to determine the energy level positions of the recombination centers and their cross sections. For n-Si $E_{t1} = E_c - 0.19$ eV and $\sigma_p \geqslant 4 \times 10^{-13}$ cm^2, and for p-Si $E_{t2} = E_v + 0.14$ eV and $\sigma \geqslant 3 \times 10^{-13}$ cm^2. The fact that at high doping levels the lifetime is practically independent of temperature shows that the cross sections for the minority-carrier capture by recombination centers do not depend on temperature.

To confirm the results obtained, measurements of temperature and injection dependences of the lifetime were carried out. Figure 3 gives the temperature dependence of the carrier lifetime in the n-type base region ($n_0 = 2.5 \times 10^{15}$ cm^{-3}]. The results of the study of the carrier lifetime dependence on injection level at 330 and 77 K are given in Fig. 4 for the same samples. The temperature and injection dependences of τ are satisfactorily described by (1) for $E_t = E_c - 0.20$ eV, $\sigma_p = 4 \times 10^{-13}$ cm^2 and $\sigma_p/\sigma_n = 10$. The value of τ_{p0} was obtained directly from the experimental data given in Fig. 2.

The character of the dependences of the lifetime on temperature, excitation and doping levels shows the lifetime to be determined by thermal defects which give the energy levels mentioned, and are the main recombination centers in diffused p–n junctions.

Thermal defects with energy levels close to those obtained in our case and concentrations 10^{11}–10^{12} cm^{-3} were observed elsewhere[9–11] (Table 1). At high-temperature treatments a possible penetration of the rapidly diffusing impurities from the surface into the bulk of the crystal is suggested[11]. However, the comparison of the results obtained and the data available for the impurities[12] which are effective recombination centers in Si makes it possible to conclude that the recombination centers observed are not due to contaminating of crystals with impurities in the course of the diffusion process. Thermal defects with the energy positions $E_c - 0.20$ and $E_v + 0.16$ eV observed in Ref. [11] are related to complexes consisting of a shallow donor (acceptor) and an impurity which has diffused from the surface. However, it should be noted that defects observed in Ref. [11] differ greatly by the carrier cross sections ($\sigma_p/\sigma_n = 10^7$), which makes it impossible to identify these with thermal defects observed in our case. In

†The value of $\tau_{n,p}$ was defined as an average one for the number of the samples investigated ($n \geqslant 10$).

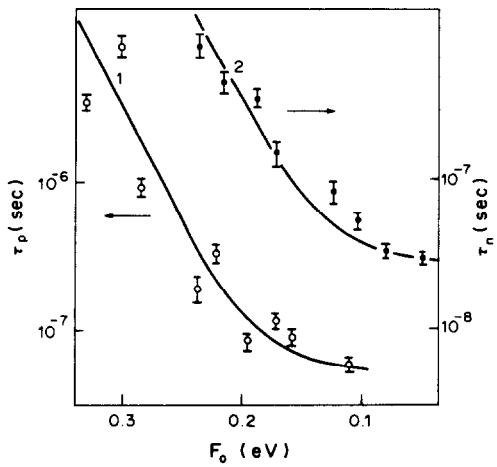

Fig. 2. The minority-charge-carrier lifetime as a function of the Fermi-level position ($T = 300$ K) for n- (1) and p-type (2) base region. The calculated dependences are given by full lines.

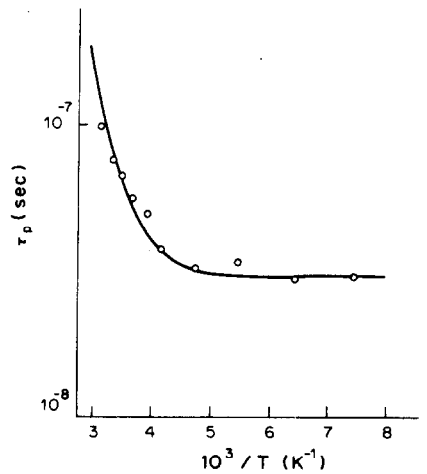

Fig. 3. The temperature dependence of the minority-charge-carrier lifetime in the n-type base region ($n_0 = 2.5 \times 10^{15}$ cm^{-3}). The calculated dependence is given by the full line.

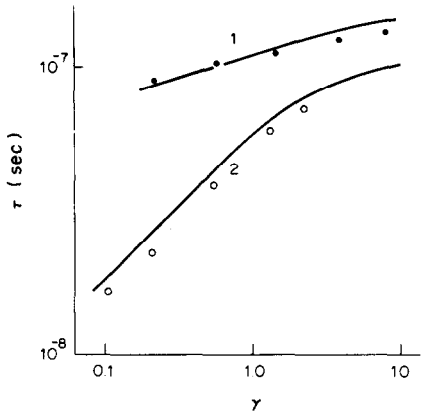

Fig. 4. The minority-charge-carrier lifetime as a function of excitation level ($n_0 = 2.5 \times 10^{15}\,cm^{-3}$). The calculated dependences are given by full lines. 1—300 K; 2—78 K.

Ref. [9] thermal defects with the energy level positions close to those observed in our case and in Ref. [11] are related to oxygen-vacancy complexes (e.g. $V + O_2$). It should be noted that the thermal treatment of the crystals was performed in the temperature range 200–600°C[9], which is typical for generation of oxygen-containing complexes. However, the introduction of thermal defects with the energy level positions close to those determined in Ref. [9] is observed at the high-temperature treatment at 1100°C also[10]. The detailed investigation of the complex origin carried out in Ref. [10] allowed one to conclude that the complexes consist of vacancies and do not contain oxygen.

Additionally, it should be noted that the value of the majority-charge-carrier capture cross section for thermal defects with $E_c - 0.22$ eV, $\sigma_n = 2 \times 10^{-14}\,cm^2$, determined by DLTS technique in Ref. [10], correlates reasonably well with our value $\sigma_n = 4 \times 10^{-14}\,cm^2$ obtained from the recombination process study.

Thus, the change in the carrier lifetime in silicon after its thermal treatment in the course of p–n structure formation is due to the introduction of thermal defects with the energy level positions $E_{t1} = E_c - 0.19$ eV in n-Si and $E_{t2} = E_v + 0.14$ eV in p-Si. The analysis of the results obtained and their comparison with the data available in the literature make it possible to conclude that the above-stated thermal defects are not impurity centers and do not contain oxygen. The damaged surface layer on the nonplanar side of the crystal and the diffused region with high surface concentrations of boron and phosphorus are likely to be sources of such defects. The results presented show the above-stated thermal defects to be intrinsic structural damage, perhaps vacancy complexes coagulating on defect clusters. The latter follows from the anomalously high capture cross sections for minority-charge carriers. However, an additional study of needed to give a final conclusion concerning the origin of thermal defects.

3.2 *Peculiarities of recombination processes in the base region of the diffused* p–n *junctions at high doping levels*

With the increase in doping level, besides recombination at thermal defects, other recombination mechanisms could be expected, for example, band-to-band Auger recombination or recombination where shallow impurities are involved. In this case the minority-carrier lifetime $\tau_n = C_n^0 p_0^{-2}$ ($\tau_p = C_p^0 n_0^{-2}$) and is practically independent of temperature in the range from 77 to 440 K for carrier concentrations exceeding $10^{18}\,cm^{-3}$[1,3,5].

Figure 1 shows that at 78 K the carrier lifetime is independent of equilibrium charge-carrier concentration through the total interval of doping levels. The dependence of τ on doping level at 300 K is defined by the overfilling of thermal defects with $E_c - 0.19$ eV and $E_v + 0.14$ eV. The analysis of our data and the data available in the literature[1,3,5] shows that at doping level $1–2 \times 10^{19}\,cm^{-3}$ for the n-type base region and $2–9 \times 10^{19}\,cm^{-3}$ for the p-type base region equal contribution of Auger processes and carrier capture by thermal defects into recombination will be observed. Consequently, in the structures studied the Auger recombination will be dominant only at doping levels exceeding those mentioned above.

When doping impurity concentrations in the base region of the diffused p–n structures exceed $10^{17}\,cm^{-3}$, one can observe rather peculiar temperature and injection dependences of the carrier lifetime. As was shown already, in lightly-doped samples the carrier lifetime decays with decreasing temperature, while in heavily-doped ones an increase in the lifetime, irrespective of the type of conductivity in the base region (Fig. 5), is observed at low excitation levels.

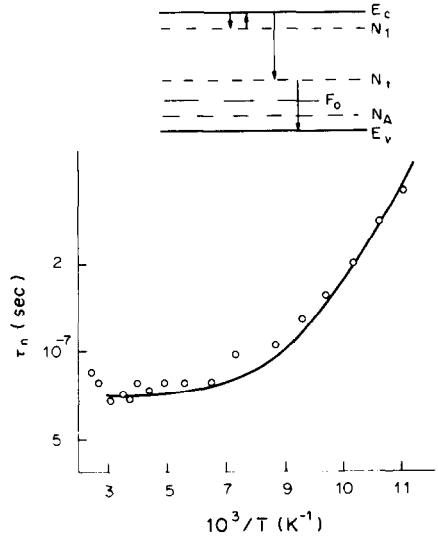

Fig. 5. The temperature dependence of the minority-charge-carrier lifetime in the p-type base region ($N_A = 9 \times 10^{16}\,cm^{-3}$). By the full line the calculated dependence for $N_t = 1.6 \times 10^{16}\,cm^{-3}$ and $E_t = 0.05$ eV [according to (5)] is given.

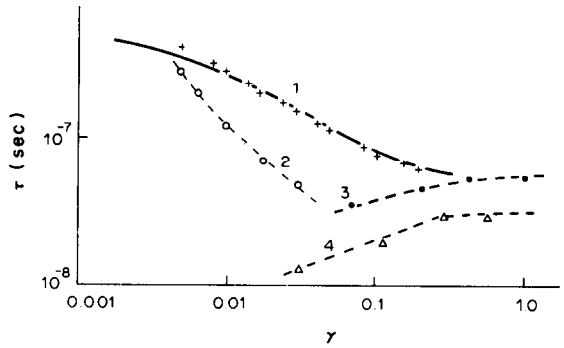

Fig. 6. The minority-charge-carrier lifetime as a function of excitation level for $T = 78$ K and the following base doping-impurity concentrations: 1—$N_A = 9 \times 10^{16}\,cm^{-3}$; 2—$N_D = 4 \times 10^{17}\,cm^{-3}$; 3—$N_A = 7 \times 10^{15}\,cm^{-3}$; 4—$N_D = 1.4 \times 10^{16}\,cm^{-3}$. The curve calculated according to (5) is given by the full line.

The investigation of the injection dependences of the carrier lifetime at 78 K also indicates the differences in the lifetime behavior for lightly- and heavily-doped samples. Figure 6 shows that in heavily-doped samples a decrease in the carrier lifetime with the increase in doping level is observed, while in lightly-doped ones the carrier lifetime shows a decrease both in n- and p-type base regions.

As will be shown below, the experimental results obtained can be interpreted through the trapping of the minority-charge carriers at shallow impurities.

4. MODELS AND DISCUSSION

Let us consider p-Si with high doping level containing recombination centers of concentration N_t and trapping centers of concentration N_1. Figure 5 gives the energy diagram of the transitions considered.

It suggests that the average time of the minority-charge carrier residence at the trapping center is much shorter as compared to that of the carrier capture by the recombination center which in our case is

$$\tau_{n0} = (c_n N_t)^{-1}. \tag{3}$$

In this case the process of nonequilibrium minority-charge-carrier recombination would occur under the quasiequilibrium between the conduction band and the trapping level. Furthermore, it suggests that the cross section of the majority-charge-carrier capture at the trapping center $\sigma_{p1} = 0$. In this case the kinetic equations describing the changes in the nonequilibrium carrier concentration after the generation has ceased ($G = 0$) have the forms

$$\frac{dp_e}{dt} = -\frac{n_e}{\tau_{no}},$$

$$\frac{dn_e}{dt} = -\frac{n_e}{\tau_{no}} - n_e C_{n1}\left(\frac{n_1 N_1}{n_0 + n_1} - n_{e1}\right) + n_{e1} C_{n1}(n_0 + n_1),$$

$$\frac{dn_{e1}}{dt} = n_e C_{n1}\left(\frac{n_1 N_1}{n_0 + n_1} - n_{e1}\right) - n_{e1} C_{n1}(n_0 + n_1), \tag{4}$$

$$n_e + n_{e1} = p_e$$

where

$$C_{n1} = v\sigma_{n1}, \quad n_1 = N_x \exp\left(-\frac{E_1}{kT}\right).$$

E_1 is the energy level position for the trapping level; n_e, p_e, n_{e1} are the nonequilibrium concentrations of free electrons, holes and electrons at the trapping level, respectively. To solve the set of equations (4) at an arbitrary excitation level is a matter of some difficulty. The case of low excitation level is considered in Refs. [13,14] for n- and p-type materials.

One can determine the momentary nonequilibrium carrier lifetime for an arbitrary value of excitation level. In this case taking into account that the reduction in the total number of nonequilibrium carriers in the conduction band and at the trap levels is caused solely by their capture by recombination centers from the C-band, we obtain from (4) the following expression for the quasistationary case:

$$\tau = -n_e\left(\frac{dn_e}{dt}\right)^{-1} = \tau_{n0}\left[1 + \frac{\tau_g}{\tau_t}\cdot\frac{1}{1 + n_e(n_0 + n_1)^{-1}}\right], \tag{5}$$

where

$$\tau_g = C_n^{-1}(n_0 + n_1)^{-1}, \quad \tau_t = (C_n N_1)^{-1}\left(1 + \frac{n_0}{n_1}\right).$$

τ_g, τ_t are the times of electron residence at the trapping center and in the conduction band before their capture by the trapping center.

The temperature and injection dependences of the lifetime given in Figs 5 and 6 for highly-doped p-Si are well described by (5) at the energy level position for the trapping center $E_1 = 0.05$ eV and its concentration $N_1 = 1.6 \times 10^{16}\,cm^{-3}$. The value of $\tau_{no} = 3.5 \times 10^{-8}$ sec was obtained using the data for $\tau(F_0)$, presented in Fig. 2. It is seen from Fig. 6 that with the increase in excitation level the carrier lifetime tends to τ_{no}.

Analogous calculations can also be performed for heavily-doped p–n structures based on n-Si. Measurements of the charge-carrier concentration in the base region of the p–n structures shows that it practically coincides with that obtained from the Hall measurements on bulk material up to the values of shallow doping impurities of boron and phosphorus $\sim 5 \times 10^{16}\,cm^{-3}$ (Fig. 7). At doping levels exceeding the above-stated value a deviation of n_0- and p_0-values, obtained from C-V measurements, from their Hall values is observed. Thus, for the Hall carrier concentration $n_0, p_0 \approx 10^{17}\,cm^{-3}$, its value obtained from C-V measurements is underestimated by 20–25% with respect to the mentioned value. This discrepancy in the values of carrier concentrations

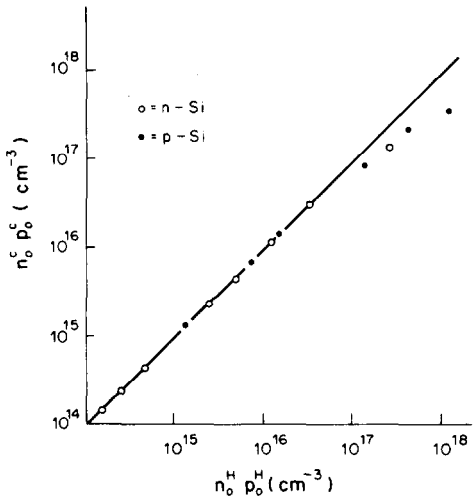

Fig. 7. The ratio between carrier concentrations determined by the Hall effect and from the capacitance measurements.

obtained from C-V measurements and Hall effect measurement can be explained by the presence of compensating impurities in the p–n junction base region.

Thus, for the data given in Figs 5 and 6 for p-Si ($p_0 = 9 \times 10^{16}\,cm^{-3}$) the calculated value $N_1 = 1.6 \times 10^{16}\,cm^{-3}$, and the fraction of compensated acceptors in this case approximates, according to Fig. 7, the value of $2 \times 10^{16}\,cm^{-3}$.

The presence of shallow compensating impurities of such concentrations in the base region is related to a peculiar distribution of diffusing boron and phosphorus at their high surface concentrations and high doping level of the original crystal. Under these conditions diffusing impurity profiles are not described by a simple erfc function[6,15]. In this case we can observe the diffusing impurity compensation of the base region, adjacent to the p–n junction, which is much wider for highly-doped crystals than for lightly-doped ones. Consequently, the carrier diffusion length in heavily-doped samples becomes comparable to the width of the compensated base region, which leads to the effective trapping of the injected carriers.

Thus, the values of the energy level position of the trapping centers close to those of shallow doping-impurity ionization energy, very high concentrations of trapping centers, and the identity of the temperature and injection dependences of the carrier lifetime in structures based on n- and p-Si with high doping level allow one to suggest that the compensating shallow acceptors are the trapping centers in the n-base region of diffused structures, and in the p-base region the role of trapping centers is played by shallow donors.

It is known that the minority-carrier cross section for shallow donors and acceptors in Si is 10^{18}–$10^{-21}\,cm^2$; that is much lower than that for the majority carriers, which approximates $\sim 10^{-13}\,cm^2$ at 77 K[12]. In this case the estimation of τ_g and τ_t values is possible. For the case previously considered ($p_0 \approx 10^{17}\,cm^{-3}$) we obtained $\tau_g = 10^{-9}$ sec and $\tau_t = 10^{-10}$ sec, taking into account the certain values of N_1, E_1 and C_{n1}.

At low excitation level, when $n_e \ll n_0 + n_1$, (5) reduces to

$$\tau_l = \tau_{no}\left(1 + \frac{\tau_g}{\tau_t}\right). \tag{6}$$

With the increase in excitation level, when $n_0 + n_1 \ll n_e$ and $1 + n_e/(n_0 + n_1) > \tau_g/\tau_t$, we have for the carrier lifetime

$$\tau_h = \tau_{n0}. \tag{7}$$

The ratio of the carrier lifetimes experimentally determined for these two limits is

$$\frac{\tau_l}{\tau_h} = \frac{\tau_g}{\tau_t} + 1, \tag{8}$$

and as is seen from (8), it is determined by the ratio between the carrier residences at the trapping center and in the conduction band. Figure 6 shows that $\tau_l/\tau_h = 10$, which gives a good agreement with the calculated value.

5. RADIATION-INDUCED CHANGE OF THE CARRIER LIFETIME

5.1 Lightly-doped samples

The rate of the radiation-induced change in the lifetime can be determined if parameters of radiation defects and the efficiency of their formation are known. The calculation of the lifetime after the irradiation was performed on the basis of the DLTS data on energy spectrum, defect formation rates and cross sections for the majority carrier capture by centers[16,17]. Proceedings from the data on radiation defect introduction rates, it is advisable to analyze the lifetime temperature dependences for the case of irradiation by gamma rays from ^{60}Co†. This is due to the fact that in this case a preferential introduction of one type of radiation defects is observed both for n- and p-type samples.

Figure 8 shows that for the p-type base region a satisfactory agreement between the calcualted temperature dependence of the lifetime and the experimental one is observed when only one defect level $E_v + 0.35$ eV is taken into account. In this case the electron capture cross section $\sigma_n = 2.9 \times 10^{-14}\,cm^2$. Taking into account the fact that the introduction rate of the defect with $E_v + 0.35$ eV is nearly 30 times higher than that for the defect with $E_v + 0.21$ eV, we may suggest that the absence of the effect of the latter on the lifetime temperature dependence shows that

†The results were analyzed within the limits of the Hall–Shockley–Read model for the excitation level $\gamma \approx 10^{-2}$.

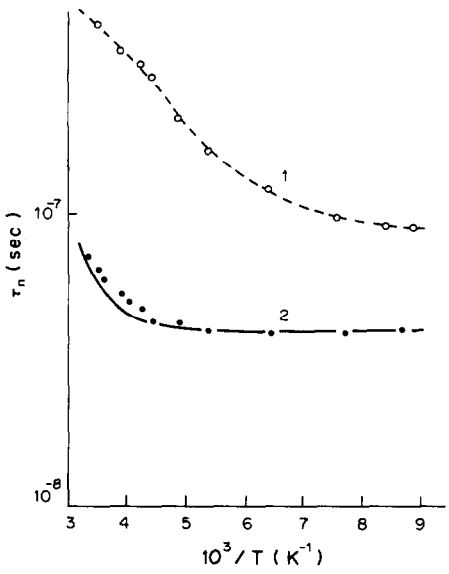

Fig. 8. The temperature dependence of the minority-charge-carrier lifetime in p-Si irradiated by gamma-rays from ^{60}Co. 1—before irradiation; 2—$\phi = 1 \times 10^{18}$ cm^{-2}. The calculated curve is presented by the full line.

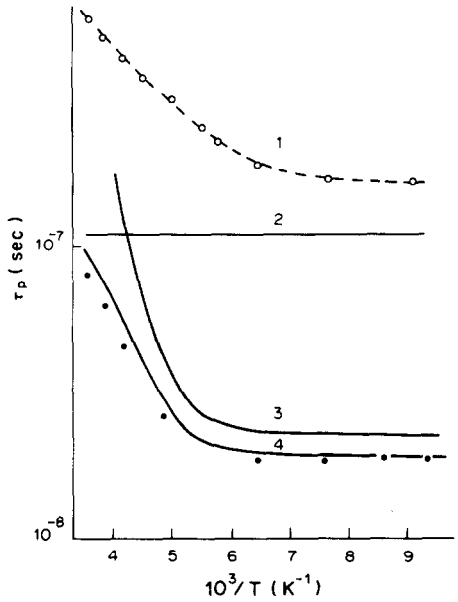

Fig. 9. The temperature dependence of the minority-charge-carrier lifetime in n-Si irradiated by gamma rays. 1—before irradiation; 2—the calculated curve is obtained taking account of the E-center alone ($\phi = 2 \times 10^{17}$ cm^{-2}); 3—the calculated curve is obtained taking account of the A-center alone ($\phi = 2 \times 10^{17}$ cm^{-2}); 4—the calculated curve is obtained taking account of both A- and E-centers.

the electron capture cross section by the center with $E_v + 0.21$ eV has the same or lower order of magnitude as the defect with $E_v + 0.35$ eV (Table 2).

In n-Si the introduction rate for defects with $E_c - 0.18$ eV (A-center) is 30 times higher than that for defects with $E_c - 0.44$ eV (E-center) and 100 times higher than that for defects with $E_c - 0.23$ eV (divacancy). However, as it is seen from Fig. 9, one cannot satisfactorily describe the lifetime temperature dependence only by accounting for the A-center participation in the recombination process. A satisfactory agreement between the calculated lifetime temperature dependence and the experimental one is observed only when the carrier recombination through the E-center is taken into account, and independence of channels for recombinations through A- and E-centers with carrier capture cross sections $\sigma_p = 5 \times 10^{-14}$ cm^2 and $\sigma_p = 2.7 \times 10^{-13}$ cm^2, respectively, is suggested. Figure 9 shows that at temperatures lower than 200 K the lifetime in n-Si is controlled by the introduction of A-centers. It should be noted that for recombination of both types, through A-centers and through defects with $E_v + 0.35$ eV, the lifetime in p-Si does not depend on temperatures below 200 K, i.e. when centers are practically filled. Hence the carrier capture cross sections for the centers mentioned above are temperature independent from 77–200 K.

In both n- and p-type Si the radiation-induced change in the carrier lifetime is described by the well-known expression

$$\tau^{-1} = \tau_0^{-1} + K_\tau \phi \tag{9}$$

where τ_0 is the initial value of the carrier lifetime; K_τ is the coefficient of the radiation-induced change in the carrier lifetime.

For n-Si the expression for K_τ has the form

$$K_\tau = \sum_i \delta N_i v \frac{n_0 + n_e}{\sigma_{ni}^{-1}(p_{1i} + n_e) + \sigma_{pi}^{-1}(n_0 + n_{1i} + n_e)}, \tag{10}$$

where δN_i is the efficiency of the ith recombination center formation. An analogous expression can also be written for p-Si. The calculation of

Table 2. Radiation defect parameters in silicon obtained in this paper and in [16,17]

	E_t (eV)	σ_n (cm^2)	σ_p (cm^2)	References
n-Si	$E_c - 0.18$	1.5×10^{-14}	4.9×10^{-14}	
	$E_c - 0.23$	3.6×10^{-15}	3.5×10^{-14}	
	$E_c - 0.39$	2.9×10^{-16}	3×10^{-15}	
	$E_c - 0.44$	5×10^{-15}	2.7×10^{-13}	
p-Si	$E_v + 0.35$	3×10^{-14}	2×10^{-15}	
	$E_v + 0.21$	3.9×10^{-14}	1.8×10^{-15}	
	$E_c - 0.27$	1×10^{-13}	2×10^{-14}	[18]

The data on energy levels and majority carrier cross-sections are taken from Ref. [16, 17].

K_τ for gamma-irradiated p-Si, providing that the change in the carrier lifetime is defined by a defect with $E_v + 0.35$ eV, gives the value $K_\tau = 1.8 \times 10^{-11}$ cm^2 sec^{-1} for $T = 300$ K and excitation level $\gamma \approx 10^{-2}$. This value gives a good agreement with the K_τ value which is experimentally determined using (9) and is 1.6×10^{-11} cm^2 sec^{-1} (300 K). Measurement of K_τ at 78 K gives the value 2×10^{-11} cm^2 sec^{-1}. The increase in K_τ by 25% at a tempeature change from 300 to 78 K can be explained by the contribution to the radiation-induced change in the minority-charge-carrier lifetime of the defect with $E_c - 0.27$ eV[18], which, as it will be shown later, is an effective recombination center in heavily-doped p-Si. Thus, the results obtained confirm the above-given conclusion that in p-Si the main change in τ_n ($p_0 \approx 10^{15}$ cm^{-3}) is determined by introduction of defects with the level $E_v + 0.35$ eV.

According to the results of the lifetime temperature dependence study, the analysis of K_τ for gamma-irradiated n-Si was performed taking of A- and E-center introduction. It was found that at 300 K for $n_0 = 10^{14}$–10^{15} cm^{-3} and high excitation levels ($\gamma \approx 10$) the value of K_τ is determined by the A-center introduction. Thus, for samples with $n_0 = 1.5 \times 10^{14}$ cm^{-3} the experimentally determined value of K_τ is 1.3×10^{-11} cm^2 sec^{-1} and the calculated one is 1.1×10^{-11} cm^2 sec^{-1}. With the increase in excitation level the E-center begins to make a notable contribution recombination. At $\gamma \leqslant 10^{-2}$ the coefficient for the radiation-induced change in the lifetime is largely determined by the E-center introduction. The value of K_τ increases with the decrease in temperature from 300 to 78 K. Thus, for Si with $n_0 = 4.8 \times 10^{14}$ cm^{-3} $\kappa_\tau = 4 \times 10^{-11}$ cm^2 sec^{-1} at 300 K and $K_\tau = 2.2 \times 10^{-10}$ cm^2 sec^{-1} at 77 K. Such an increase in K_τ with the decrease in temperature is defined by the A-center filling.

For irradiation by electrons with $E = 7$ MeV[17] the introduction rates for irradiation defects of all types are of the same order. Therfore in this case the quantitative estimations of K_τ for both n- and p-type Si were performed according to (10) taking account of all centers observed.

For p-Si ($p_0 \approx 10^{15}$ cm^{-3}) the calculations were carried out taking account of defects with $E_c - 0.27$ eV, the rate of introduction and the capture cross section of which were 5×10^{-3} cm^{-1} ($E_e = 7$ MeV) and $\sigma_n = 1 \times 10^{-13}$ cm^2, respectively. The calculations show that for this doping level of p-Si the value of K_τ at 300 K is defined by the introduction of defects with $E_v + 0.35$ eV and K_τ is practically independent of temperature in the range of 78–300 K, in agreement with the experimental data (Fig. 10). The analogous conclusion was made for gamma-ray ^{60}Co irradiation.

For the n-type base region with $n_0 = 10^{14}$–10^{15} cm^{-3} a good agreement of the calculated value of K_t with the experimental one is observed when defects of three types (A-center, E-center, divacancy) introduced (Fig. 11). In this case, as well as for gamma irradiation, at high excitation levels K_τ is defined by the A-center introduction. The increase of K_τ from 3.5×10^{-8} cm^2 sec^{-1} to 2.1×10^{-7} cm^2 sec^{-1}, for $n_0 = 4.8 \times 10^{14}$ cm^{-3}, with the decrease in temperature is due to the growth of the A-center occupancy.

5.2 Radiation-induced change in the carrier lifetime in p–n junctions with high doping level of the base region

As shown in Refs. [16,17], the introduction rates of vacancy-type defects, determining the radiation-induced change in the lifetime in highly-doped crystals, depend significantly on Si doping level. At high doping level compensation of Si is not determined by the vacancy center introduction[17]. Therefore, to determine parameters and the nature of the centers responsible for the radiation-induced change in the lifetime in n- and p-Si with high doping level was of great interest. With increasing doping level there is a change in correlation between the introduction rates of the radiation defects and their contributions to recombination.

The experimental dependences of K_τ at $\gamma \approx 10^{-2}$ for electron-irradiated p-Si are given in Fig. 10. It is seen that in the range from 10^{15} to 10^{16} cm^{-3} K_τ is practically independent of temperature and increases with doping level of the base region. However,

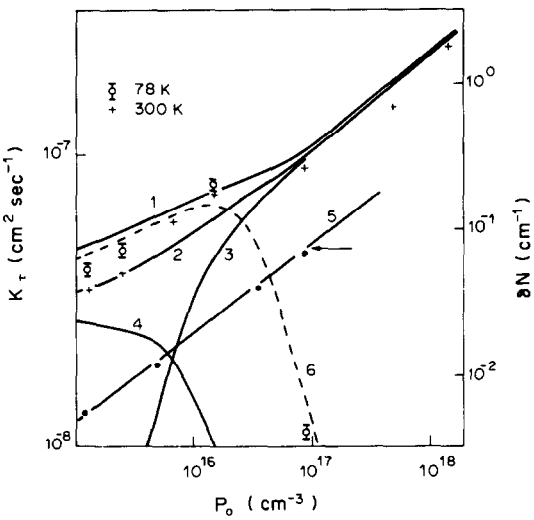

Fig. 10. The dependence of the coefficient of the radiation-induced change in the minority-charge-carrier lifetime (curves 1, 2, 3, 4 and 6) and the effectiveness of the introduction of defects with the level $E_c - 0.27$ eV (curve 5) on carrier concentration in p-Si irradiated by electrons with $E = 7$ MeV. The full lines present the calculated dependences $K_\tau(p_0)$ for: 1—recombination through centers with $E_c - 0.27$ eV, $E_v + 0.35$ eV, $E_v + 0.21$ eV; $T = 78$ K. 2—recombination through centers with $E_c - 0.27$ eV, $E_v + 0.35$ eV, $E_v + 0.21$ eV; $T = 300$ K. 3—recombination through radiation defects with $E_c - 0.27$ eV; $T = 300$ K. 4—recombination through radiation defects with $E_v + 0.35$ eV; $T = 300$ k. The experimental results are $-+-$ 300 K, $-\circ-$ 77 K (curve 6).

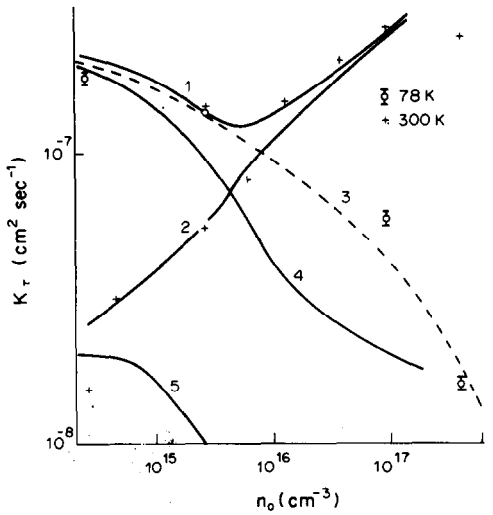

Fig. 11. The dependence of the coefficient of the radiation-induced change in the lifetime on carrier concentration in n-Si irradiated by electrons with $E = 7$ MeV. The full lines present the calculated dependences $K_\tau(n_0)$ for: 1—recombination through radiation defects with $E_c - 0.18$ eV, $E_c - 0.23$ $(E_c - 0.39)$ eV, $E_c - 0.44$ eV; $T = 78$ K. 2—recombination through centers with $E_c - 0.18$ eV, $E_c - 0.23$ $(E_c - 0.39)$ eV, $E_c - 0.44$ eV; $T = 300$ K. 4—recombination through A-center, $T = 78$ K. 5—recombination through divacancies, $T = 78$ K. The experimental results are: $-+-$ 300 K, $-\bigcirc-$ 77 K (curve 3).

this increase of K_τ cannot be described by recombination at defects with the levels $E_v + 0.35$ and $E_v + 0.21$ eV[16].

It is shown in Ref. [18] that upon electron irradiation, beside defects with the above-stated levels, centers with $E_c - 0.27$ eV are effectively introduced in B-doped p-Si. The introduction rates of these centers increase with doping impurity concentration. The final conclusion concerning the nature of these defects has not been made yet. It is suggested that they are $B_i - B_s$ or $B_i - O_i$ complexes[18], and the fact that these complexes include doping impurity atoms of boron is the most convincing one.

The calculation of K_τ dependence on the equilibrium carrier concentration was carried out using the data on the effectiveness of introduction of defects with $E_c - 0.27$ eV†; the results of the calculations are given in Fig. 10. It is seen that for $E_c - 0.27$ eV the calculated dependence agrees well with the experimental one at $\sigma_n = 1 \times 10^{-13}$ cm^2. This value of the electron capture cross section obtained from the radiation-induced change in the lifetime gives a satisfactory coincidence with the value $\sigma_n = 2 \times 10^{-13}$ cm^2 for the stated center, obtained using capacitance spectroscopy[18]. It should be noted that for $p_0 > 10^{16}$ cm^{-3} the radiation-induced change in the lifetime in p-Si is determined mainly by introduction of defects with the level $E_c - 0.27$ eV.

Figure 11 gives the dependence of K_τ on the equilibrium carrier concentration in the base region for electron-irradiated n-Si. Unlike p-Si, in n-Si the coefficient of the radiation-induced change in the lifetime for the concentration range 10^{14}–10^{15} cm^{-3} is largely dependent on temperature. At electron irradiation the growth of K_τ with temperature decreasing within the stated concentration interval is defined by the occupancy of A-center and divacancy.

The increase in K_τ with carrier concentration can be determined by two factors: occupancy of centers and increase in the effectiveness of E-center introduction. The calculation of K_τ dependence on doping level was carried out taking into account A-, E-center and divacancy. The radiation-induced change in the lifetime determined by divacancy, was calculated within the framework of the recombination statistics for multicharge centers according to Ref.[19]:

$$K'_\tau = \delta N_W v n_0 \left[\frac{\sigma_{n2} f_1 \sigma_{p2} f_2}{\sigma_{ns} f_1 n_0 + \sigma_{p2} f_2 p_0} + \frac{\sigma_{n1} f_0 \sigma_{p1} f_1}{\sigma_{n1} f_0 n_0 + \sigma_{p1} f_1 p_0} \right] \tag{11}$$

where

$$f_0 = 1 - f_1 - f_2,$$

$$f_1 = \left\{ 1 + \exp\left[\frac{1}{kT} (-F - E_1) \right] + \exp\left[\frac{1}{kT} (F + E_2) \right] \right\},$$

$$f_2 = \left\{ 1 + \exp\left[\frac{1}{kT} (-F - E_2) \right] + \exp\left[\frac{1}{kT} (2F - E_1 + E_2) \right] \right\},$$

and $E_1 = E_c - 0.39$ eV, σ_{n1} and σ_{p1} are the energy level and carrier cross sections for the divacancy at the transition $W^- \to W^0$; $E_2 = E_c - 0.23$ eV, σ_{n2} and σ_{p2} are the energy level and carrier cross sections for the divacancy at the transition $W^{2-} \to W^-$.

As is seen from Fig. 11, there is a good agreement between the calculated values of $K_\tau(n_0)$ and the experimental data. In addition the figure shows the calculated dependences of the partial contributions of different centers to the radiation-induced change in the lifetime with the increase in the equilibrium carrier concentration. It is seen that at $n_0 > 10^{16}$ cm^{-3} the radiation-induced change in the lifetime is caused by the E-center, and this very fact determines the increase in the above-stated range of carrier concentrations.

Thus, though the carrier removal rate at high doping levels ($> 10^{16}$ cm^{-3}) is not defined by the centers observed (Table 2), in n-Si the radiation-induced change in the lifetime is determined by the E-center, and in p-Si by the center with $E_c - 0.27$ eV.

†The introduction rate of $E_c - 0.27$ eV centers was corrected to the energy of bombarding electrons which is 10 MeV.

Analogous results were also obtained for the heavily-doped Si irradiated by gamma-rays from ^{60}Co.

Table 2 gives the parameters of the main radiation defects in n- and p-Si, determined by the capacitance spectroscopy and from the radiation-induced change in the lifetime.

As was shown in Sec. 3.2, in p–n-structures with a high doping level of the base region the effective carrier trapping at shallow compensating impurities of boron and phosphorus is observed at low temperatures. This results in some peculiarities in the radiation-induced change of the lifetime at low temperatures ($T \leqslant 100$ K). As is seen from Figs 10 and 11, at $\gamma \leqslant 10^{-2}$ the value of K_τ in n- and p-type base regions can be an order of magnitude lower than that for the case where there is no carrier trapping. In fact, when carrier trapping occurs, we may write, using (5), for p-Si,

$$K_\tau = \frac{d(1/\tau)}{d\phi} = \left[1 + \frac{\tau_g}{\tau_t}\cdot\frac{1}{1 + n_e(n_0 + n_1)^{-1}}\right]^{-1} \sum_i \delta N_i \sigma_{ni} v. \quad (12)$$

Then for a low excitation level, when $n_e \ll n_0 + n_1$, we have

$$K_\tau = \left[1 + \frac{\tau_g}{\tau_t}\right]^{-1} \sum_i \delta N_i \sigma_{ni} v. \quad (13)$$

Thus, it is seen that at low excitation levels in heavily-doped crystals the value of K_τ in the case of effective trapping is $(1 + \tau_g/\tau_t)$ times lower than that for the case of absence of trapping centers.

As was already shown, the value of τ_g/τ_t is about 10. Thus, in samples where effective trapping occurs, at a relatively low excitation level the value of K_τ at 78 K should be an order of magnitude lower than that at 300 K, and, as it is seen from Figs 10 and 11, this is well observed experimentally.

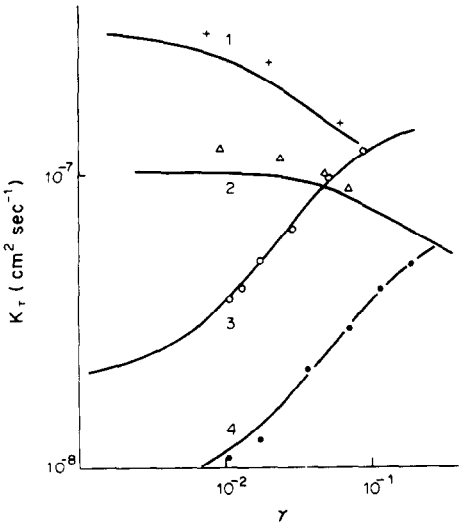

Fig. 12. The dependence of K_τ on excitation level in n-Si (curves 1 and 3) and p-Si (curves 2 and 4) irradiated by electrons with $E = 7$ MeV at 300 K (curves 1 and 2) and 78 K (curves 3 and 4). The full lines present the calculated dependences ($N_A \approx N_D = 9 \times 10^{16}$ cm^{-3}).

Figure 12 gives K_τ as a function of excitation level at 300 and 78 K for n- and p-structures with effective trapping. The experimentally observed increase in K_τ with excitation level is well described by the calculated $K_\tau(\gamma)$ dependences, obtained using (12) and given by full lines in the figure. It is seen that the value of K_τ tends to its limit with excitation level, $K_\tau \to \Sigma_i \delta N_i \sigma_{ni} v$, when there is no trapping.

6. CONCLUSIONS

The lifetime dependences on doping level of the base region in diffused p–n structures are obtained for the concentration range 10^{14}–10^{18} cm^{-3}. The lifetime change in n- and p-Si after its thermal treatment during the formation of p–n structures is shown to be caused by the introduction of thermal defects with the ionization energies $E_c - 0.19$ and $E_v + 0.14$ eV, respectively. The results obtained allow one to conclude that thermal defects with the stated levels are due to the intrinsic structural damage, possibly vacancy complexes. It is found that in heavily-doped diffused p–n junctions at low temperatures ($T \leqslant 100$ K) and small excitation levels the minority-carrier effective trapping at shallow compensating impurities of boron and phosphorus is observed.

From the lifetime temperature dependences and the coefficients of the radiation-induced change in the lifetime with irradiation by electrons with $E \leqslant 7$ MeV, it was concluded that in lightly-doped Si the radiation-induced change in the carrier lifetime is largely determined by the introduction of A- and E-centers in n-Si and by the defect with $E_v + 0.35$ eV in p-Si. At $n_0, p_0 > 10^{16}$ cm^{-3} the coefficient of the radiation-induced change in lifetime in n-Si is determined by the introduction of E-centers and in p-Si by defects with the level $E_c - 0.27$ eV.

In heavily-doped samples a significant decrease in K_τ at $T \leqslant 100$ K and low excitation levels, as compared to its value at 300 K, can well be explained by the model of the minority-carrier trapping at shallow compensating impurities of B and P.

Certain parameters of recombination centers together with the observed effectiveness of their formation can be calculated in n- and p-Si in the temperature range from 78 to 300 K for any doping level n_0, $p_0 \lesssim 10^{18}$ cm^{-3} and an arbitrary level of excitation.

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