INFLUENCE OF A- AND E-CENTERS ON THE LIFETIME OF NONEQUILIBRIUM CHARGE CARRIERS IN γ-IRRADIATED n-Si

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The results of experimental comparison made for the recombination properties and the formation efficiencies (FEs) of A- and E-centers in γ-irradiated n-Si are reported. The conductivity of n-type was induced in Si by introducing there either chemical donors (phosphorus, n-Si⟨P⟩) or thermal oxygen donors (n-Si⟨TD⟩). The substitution of P by TDs, which are not sensitive to radiation, allows such n-Si to be obtained, in which irradiation does not give rise to the formation of E-centers. The A-centers have been shown to be dominant radiation-induced defects (RIDs) with almost identical FE values, as well as dominant recombination centers (RCs), in both n-Si forms with the doping levels of about $10^{14} \div 10^{16}$ cm^{-3}. The corresponding value of the hole-capture cross-section for A-centers was determined as $\sigma_A = (2.5 \pm 0.3) \times 10^{-13}$ cm^{-2}; and the corresponding value σ_E for E-centers was found not to exceed 1×10^{-14} cm^2.

1. Introduction

The lifetime τ of nonequilibrium charge carriers (NCCs) is the most sensitive parameter – among all electrophysical parameters of silicon – to the action of radiation. As a rule, the value of τ varies by several times (or even by an order of magnitude) under irradiation, whereas the specific electroresistance or the current carrier mobility changes insignificantly at such exposure doses. In this case, the lifetime of NCCs under irradiation becomes always shorter, irrespective of the conductivity type and the degree of silicon doping. Therefore, radiation is – on the one hand – a serious factor of degradation and – on the other hand – a convenient and simple way to control the parameters of those silicon-based devices (diodes, transistors, microcircuits, and so on), the functioning of which is governed by the lifetime τ of NCCs [1].

Degradation of the NCC lifetime in silicon under radiation occurs owing to the formation of RIDs, which are, at the same time, effective RCs. In n-Si irradiated with γ-quanta or electrons with an energy of a few megaelectronvolts, such RCs at room temperature are the acceptor RIDs "vacancy + oxygen impurity atom" (A-centers, the electron level of $E_c - 0.17$ eV) and "vacancy + donor impurity atom (mainly, phosphorus)" (E-centers, the electron level of $E_c - 0.44$ eV) [1–3]. Divacancies can also be regarded as main RCs; however, their contribution becomes noticeable at irradiation by electrons with an energy of about 10 MeV, when the FEs of primary divacancies and A-centers become close to each other [4]. In a specific case, the contribution of A- and E-centers to the τ-degradation of irradiated n-Si depends, first of all, on their FEs, which are determined by the concentrations of corresponding impurities and the constants of vacancy capture onto the latter, as well as by the cross-sections of current carrier capture by those RIDs. The literature data for those quantities are scattered within rather a wide range. For instance, the range of values for the cross-section of hole capture onto A-centers is $\sigma_A = (0.25 \div 5.5) \times 10^{-13}$ cm^{-2}; for E-centers, the corresponding value is $\sigma_E = (0.4 \div 2.7) \times 10^{-13}$ cm^{-2} [5]. The ratio χ_E/χ_A between the reaction constants for the formation of E- and A-centers at room temperature changes from about $10 \div 20$ [3,6] to 130 [7]. The availability of such a large body of data for the given parameters – which are, in addition, contradictory to one another in the case of σ_A and σ_E – means that the issue concerning the dominant recombination center in n-Si remains still unresolved. Therefore, the aim of our researches was to obtain the additional information about the dominant RC at room temperature in γ-irradiated n-Si.

In order to achieve this goal, the contributions of A- and E-centers to the τ-degradation of NCCs must be properly distinguished. For this purpose, in our experiments, we compared the recombination properties of two kinds of γ-irradiated n-Si. The donor properties of n-Si of the first kind were governed by phosphorus (n-Si⟨P⟩), and those of n-Si of the second kind by low-temperature thermal donors (n-Si⟨TD⟩). Such TDs are formed in the course of specimen annealing at $350 \div 550$ °C; they are double-charged donors, the depth of which – $E_c - (0.13 \div 0.16)$ eV or $E_c - (0.05 \div 0.07)$ eV –

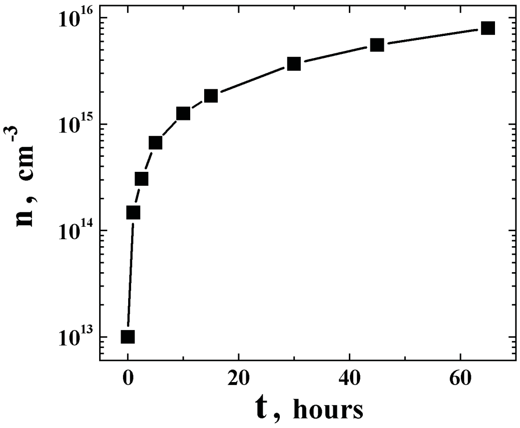

Fig. 1. Dependence of the n-variation in high-resistance n-Si on the period of heat treatment at 450 °C

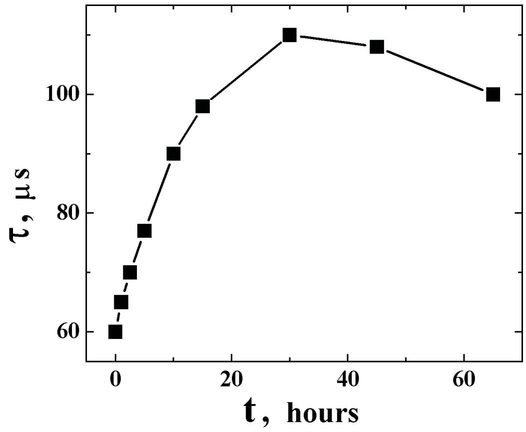

Fig. 2. Dependence of the τ-variation for NCCs in high-resistance n-Si on the period of heat treatment at 450 °C

depends on the heat treatment period [8]. This approach is based on the unique property of thermal donors: they are insensible to radiation. Unlike phosphorus atoms, thermal donors do not form acceptor complexes with radiation-induced vacancies (similar to E-centers) and do not lose their donor activity under irradiation [9]. If oxygen TDs rather than Ps are used in silicon to supply equilibrium charge carriers, E-centers do not emerge in such a material. That is, both A- and E-centers can be formed in n-Si⟨P⟩, and only A-centers in n-Si⟨TD⟩. Therefore, while comparing the recombination properties of the n-Si specimens of both kinds subjected to irradiation with γ-quanta, it becomes possible to distinguish between the contributions made by A- and E-centers into the degradation of τ. In such a manner, we can obtain an answer to the question about the dominant recombination center in n-Si, as well as the more accurate information concerning its recombination characteristics.

2. Experimental Part

For our researches, we used n-Si⟨P⟩ specimens grown by the Czochralski method and characterized by the following parameters: the phosphorus concentration $N_\mathrm{P} = 1\times10^{13}\div5\times10^{15}$ cm^{-3}, the oxygen concentration $N_\mathrm{O} = (7 \div 9) \times 10^{17}$ cm^{-3}, the carbon concentration $N_\mathrm{C} \leq 5 \times 10^{16}$ cm^{-3}, and $\tau_0 = 60 \div 130$ μs. The concentrations of oxygen and carbon were determined from IR-absorption spectra, and the concentration of free electrons n_0 by the Hall effect method. The formation of A- and E-centers was monitored by the DLTS method. The τ-value of NCCs was determined from the relaxation of nonequilibrium photoconductivity under conditions of low-level excitation ($\leq 5\%$) at room temperature. The error of τ-value determination did not exceed 10%.

In the experiment, we applied irradiation of the specimens with γ-quanta from a ^{60}Co source at a temperature of 30 °C and the exposure intensity $J_\gamma \approx 10^{11}$ γ-quanta/(cm^2 × s).

n-Si⟨TD⟩ specimens were fabricated from high-resistance n-Si ($N_\mathrm{P} \approx 1 \times 10^{13}$ cm^{-3}) by thermally treating the latter at a temperature of 450 °C, at which the efficiency of low-temperature TD formation is highest. Figure 1 demonstrates how the concentration of free electrons in those specimens changes depending on the duration of heat treatment at 450 °C. One can see that, within 65 hours, the concentration n increased by almost three orders of magnitude owing to the formation of TDs. In what follows, this dependence served as a reference point in the preparation of n-Si specimens with various TD concentrations, for which the condition $N_\mathrm{TD}/N_\mathrm{P} > 10$ was satisfied. The oxygen concentration practically did not change within such periods of heat treatment. It is known [10,11] that the lifetime of NCCs in the initial silicon is determined by deep impurities and is sensitive to the conditions of specimen cooling after heat treatment. Fast cooling of the specimens after their heat treatment can result in a drastic reduction of the τ-value, which would make, in its turn, the application of those specimens unpromising for subsequent irradiation. Therefore, specimens, after their heat treatment at 450 °C, were slowly – together with the oven – cooled down to room temperature. A typical behavior of τ for NCCs is depicted in Fig. 2. One can see that the lifetime first increases; in approximately 30 h, it reaches its maximal value; afterwards, a slight tendency of τ-

value reduction is observed. The increase of τ after short heat treatment is associated with the deposition of deep impurities at oxygen precipitates, while its reduction after long heat treatment with the accumulation of recombination-active oxygen precipitates [10,11]. In our experiments, the values of τ for both kinds of non-irradiated n-Si were close to each other.

3. Experimental Results and Their Discussion

3.1. General approach

The irradiation-induced variation of τ can be written down as a sum of contributions given by every recombination RID:

$$\frac{1}{\tau_\gamma}-\frac{1}{\tau_0}=\sum_i\frac{1}{\tau_i}, \tag{1}$$

where τ_i is the NCC lifetime connected with the RIDs of the i-th type; and τ_0 and τ_γ are the lifetimes before and after irradiation, respectively.

For n-Si, provided that the excitation level is low (i.e. the concentration of nonequilibrium carriers Δn is much lower than the concentration of equilibrium ones n_0) and recombination occurs through a level located in the upper half of the energy gap (for both A- and E-centers), the lifetime of nonequilibrium charge carriers is determined by the lifetime of holes. In such a case, for every recombination center, the following expression is valid:

$$\tau_i=(\sigma_i v_p N_i)^{-1}\left[1+\frac{N_c\exp(-E_i/kT)}{n_0}\right], \tag{2}$$

where σ_i is the cross-section of hole capture by the i-th recombination center; N_i and E_i are the RC concentration and the electron level depth reckoned from the bottom of the conduction band, respectively; v_p is the thermal velocity of holes; and N_c is the effective density of states in the conduction band.

To estimate the influence of radiation on the recombination in silicon, the following relation is used:

$$\frac{1}{\tau_\gamma}=\frac{1}{\tau_0}+k_\tau\Phi, \tag{3}$$

where Φ is the exposure dose; and k_τ is the constant of lifetime degradation, it is a parameter which characterizes the sensitivity of silicon to radiation. Expression (3) can be used, when the concentration of defects linearly depends on the exposure dose, i.e. if the concentration of defects is much lower than that of impurities atoms which take part in defect formation. In the case where the recombination parameters are measured, this condition is always fulfilled.

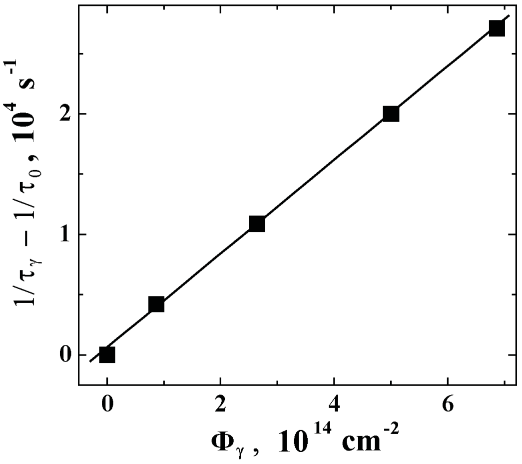

Fig. 3. Dependence of the quantity $\Delta(1/\tau)$ on the dose of γ-radiation from a ^{60}Co source for an n-Si specimen with $N_P = 1\times10^{15}$ cm^{-3} (points denote experimental data, the solid curve corresponds to the linear approximation)

Taking Eqs. (1) and (2) into account, we obtain an expression for the calculation of k_τ in irradiated n-Si in our case, i.e. provided that the excitation level is low and recombination occurs through RID levels located in the upper half of the silicon energy gap:

$$k_\tau=\sum_i\sigma_i v_p\,(dN_i/d\Phi)\left[1+\frac{N_c\exp(-E_i/kT)}{n_0}\right]^{-1}. \tag{4}$$

It follows from this equation that, in order to estimate the efficiency of NCC recombination through A- and E-centers by means of comparing the recombination properties of γ-irradiated n-Si⟨TD⟩ and n-Si⟨P⟩, it would be enough

– to have the experimental dependences $k_\tau(n_0)$ for both kinds of n-Si, as well as the P- and TD-concentrations varying in sufficiently wide ranges, and

– to carry out a simultaneous monitoring of FEs for given RIDs.

3.2. Experimental results and their analysis

At the first stage, we obtained the dependences $k_\tau(n_0)$ for γ-irradiated n-Si of both kinds. The experimental values of k_τ were determined from the linear sections of the dose dependences of the quantity $\Delta(1/\tau) = (1/\tau_\gamma - 1/\tau_0)$. In Fig. 3, such a dependence is depicted,

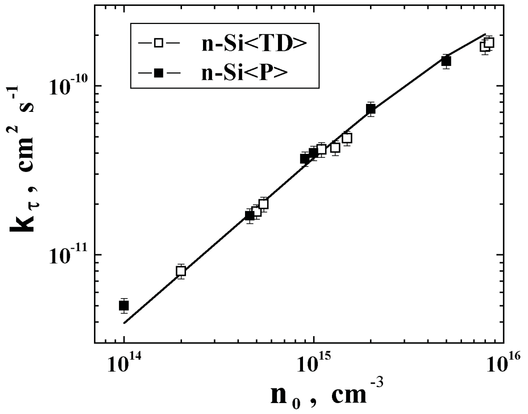

Fig. 4. Dependences of k_τ on the concentration of free electrons in γ-irradiated n-Si⟨P⟩ and n-Si⟨TD⟩ specimens (points denote experimental data, the solid curve is the result of calculations)

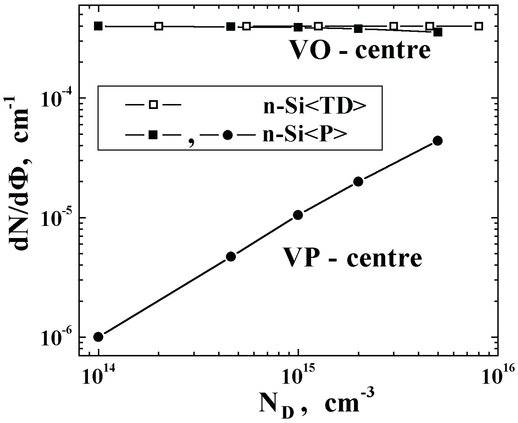

Fig. 5. Dependences of the formation efficiency of A- and E-centers on the concentration of phosphorus atoms or thermal donors

as an example, for an n-Si specimen with $N_\mathrm{P} = 1 \times 10^{15}$ cm^{-3} (here, points denote experimental results, and the solid curve is their linear approximation). It is evident that the increment $\Delta(\tau)^{-1}$ depends linearly on Φ; and this circumstance allows one to determine the value of k_τ with the help of Eq. (3). Similar dependences for the determination of k_τ were obtained for all studied specimens.

In Fig. 4, the dependences $k_\tau(n_0)$ for n-Si⟨P⟩ and n-Si⟨TD⟩ specimens irradiated with γ-quanta, in which n_0 varied in the range $1 \times 10^{14} \div 8.5 \times 10^{15}$ cm^{-3}, are exhibited. It is evident that experimental points for both kinds of n-Si lie in the same curve. In order that the given dependence be used for the estimation of recombination properties of A- and E-centers, it is necessary to know the FE values for those RIDs in the specimens. The corresponding results, which were obtained with the help of the DLTS method, are presented in Fig. 5. From this figure, one can see that:

— as the phosphorus concentration in n-Si⟨P⟩ grows, the FE of E-centers substantially increases (by one and a half order of magnitude), while the FE of A-centers becomes somewhat lower (by 20%). The ratio between the reaction constants of the formation of those RIDs at room temperature amounts to $\chi_E/\chi_A = 15 \pm 3$ at that; this value agrees well with the results of works [3, 6] which were also obtained making use of the DLTS method. Data for the ratio χ_E/χ_A, which are an order of magnitude higher – for instance, in work [7], the value $\chi_E/\chi_A = 130$ was obtained from Hall measurements, – seem overestimated;

— in n-Si⟨TD⟩, the presence of TDs does not affect the FE of A-centers. This result is similar to that obtained in work [9]. It is expectable, because just this result underlies our comparative experiment. Owing to the presence of phosphorus in this material with an insignificant concentration (of about 1×10^{13} cm^{-3}), E-centers are also formed, but their FE does not exceed 1×10^{-7} cm^{-1}. Such a value is, at least, an order of magnitude lower than the FE of E-centers in n-Si⟨P⟩, so that these data are not presented in the figure;

— A-centers are dominant RIDs in n-Si of both kinds, for which the FE values are practically identical within the studied range of donor concentration.

Now, let us analyze the obtained experimental results. For any value of n_0 from the studied range (see Fig. 4), we have

$$(k_\tau)_\mathrm{P} \approx (k_\tau)_\mathrm{TD} \,. \tag{5}$$

This means that the cumulative contribution of A- and E-centers to the variation of τ is approximately identical for both kinds of n-Si irradiated with γ-quanta. So that, according to Eqs. (1) and (3), we obtain

$$\left(\frac{1}{\tau_A} + \frac{1}{\tau_E}\right)_\mathrm{P} \approx \left(\frac{1}{\tau_A} + \frac{1}{\tau_E}\right)_\mathrm{TD} \,. \tag{6}$$

Since (see Fig. 5)

$$\left(\frac{dN_A}{d\Phi}\right)_\mathrm{P} \approx \left(\frac{dN_A}{d\Phi}\right)_\mathrm{TD}, \quad \text{a} \quad \left(\frac{dN_E}{d\Phi}\right)_\mathrm{P} \gg \left(\frac{dN_E}{d\Phi}\right)_\mathrm{TD},$$

the contributions of A-centers to the degradation of τ are close to each other in both materials, while the contribution of E-centers is much greater in n-Si doped with phosphorus (n-Si⟨P⟩):

$$\left(\frac{1}{\tau_A}\right)_\mathrm{P} \approx \left(\frac{1}{\tau_A}\right)_\mathrm{TD}, \quad \left(\frac{1}{\tau_E}\right)_\mathrm{P} \gg \left(\frac{1}{\tau_E}\right)_\mathrm{TD}. \tag{7}$$

Then, equality (5) can be rewritten, taking Eq. (7) into account, as follows:

$$\left(\frac{1}{\tau_A}+\frac{1}{\tau_E}\right)_{\mathrm{P}} \approx \left(\frac{1}{\tau_A}\right)_{\mathrm{TD}}. \tag{8}$$

So that, it can be valid only provided that the contribution of E-centers is small in comparison with that of A-centers and, therefore, can be neglected:

$$\left(\frac{1}{\tau_A}\right)_{\mathrm{P;TD}} \gg \left(\frac{1}{\tau_E}\right)_{\mathrm{P;TD}}. \tag{9}$$

This means that, in our case, A-centers must be dominant recombination centers in n-Si, the donor properties of which are governed by both Ps and TDs. Just this fact can explain why the dependence $k_\tau(n_0)$ presented in Fig. 4 is identical for both materials. The solid curve in this figure corresponds to the theoretical dependence $k_\tau(n_0)$ described by Eq. (4), where the cross-section σ_A of hole capture onto A-centers played the role of fitting parameter, and the value of $dN_A/d\Phi$ was taken from experimental data for n-Si$\langle$P$\rangle$ (Fig. 5). It turned out that the theory and the experiment are in satisfactory agreement, if $\sigma_A = (2.5 \pm 0.3) \times 10^{-13}$ cm^2 and the estimated value for the cross-section σ_E of hole capture onto E-centers does not exceed 1×10^{-14} cm^2.

4. Conclusions

The application of thermal donors, which are insensible to radiation, instead of impurities of group V for the creation of the conductivity of n-type in Si makes it possible to obtain a material, in which E-centers are not formed under irradiation. By comparing the recombination properties and the FEs of dominant RIDs in γ-irradiated n-Si$\langle$P$\rangle$, where both A- and E-centers are generated, and n-Si$\langle$TD$\rangle$, where only A-centers arise, we have proved that it is A-centers that are the dominant recombination centers in n-Si of both kinds with a degree of donor doping of the order of $10^{14} \div 10^{16}$ cm^{-3}. In addition, our approach allowed the value of σ_A to be determined more exactly and the threshold value for σ_E to be estimated.

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ВПЛИВ A- І E-ЦЕНТРІВ НА ЧАС ЖИТТЯ НЕРІВНОВАЖНИХ НОСІЇВ ЗАРЯДУ В n-Si ПРИ γ-ОПРОМІНЕННІ

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Резюме

Представлено результати експериментального порівняння рекомбінаційних властивостей і ефективностей утворення (ЕУ) A- і E-центрів в опроміненому γ-квантами ^{60}Co n-Si, в якому для створення n-типу провідності застосовували хімічні донори (фосфор, n-Si$\langle$P$\rangle$) або кисневі термодонори (n-Si$\langle$ТД$\rangle$). Заміна Р на ТД, які не чутливі до дії радіації, дозволяє отримати n-Si, в якому під дією опромінення не утворюються E-центри. Показано, що A-центри є домінуючими радіаційними дефектами (РД) із майже однаковими значеннями ЕУ і основними центрами рекомбінації (ЦР) в обох видах n-Si із ступенем легування донорами $\sim 10^{14} \div 10^{16}$ см$^{-3}$. При цьому отримано, що значення поперечного перерізу захоплення дірок A-центрами $\sigma_A = (2,5 \pm 0,3) \cdot 10^{-13}$ см^2, а для E-центрів σ_E не повинно перевищувати $1 \cdot 10^{-14}$ см^2.