# CONVERSION OF DIVACANCIES AT ISOCHRONOUS ANNEALING OF IRRADIATED *p*-Si CRYSTALS

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*p*-Si single crystals, fabricated by the Czochralski method and characterized by the hole concentration $p = 6 \times 10^{13}$ cm$^{-3}$, are studied. Specimens were irradiated with 8-MeV electrons at 300 K. Irradiated crystals were isochronously annealed in the temperature interval $T_{\rm ann} = 100 \div 500$ °C. The electrophysical parameters were measured by the Hall method in the temperature interval 77 − 300 K. The analysis of results obtained showed that, in the course of isochronous annealing (IA), the conversion of $V_2$-divacancies into B$_sV_2$-complexes following the reaction B$_s + V_2 \rightarrow$ B$_sV_2$ takes place in the temperature interval 270–300 °C. The B$_sV_2$-complex is associated with the energy level of $E_v + 0.22$ eV and is annealed in the temperature interval 360–440 °C.

## 1. Introduction

It is known [1] that a divacancy (DV) can be formed as a primary defect at the irradiation of silicon, if the bombarding particle transfers such energy to a lattice, which is sufficient for two atoms in neighbor sites to be displaced. It should be noted that the growth of the DV number in the vacancy annealing area and the dependence of the annealing on the oxygen concentration are in agreement with the assumption about the formation of DVs by joining two isolated vacancies.

DVs themselves are annealed in the temperature interval 250–300 °C [1]. The authors of works [2–4] observed an increase of the concentration of *A*-centers, which dissociate in the interval 300–400 °C, in the area of DV annealing. It testifies that the fragments of DV decay – monovacancies – enter into a quasichemical reaction with oxygen impurity atoms and form radiation-induced defects (RIDs), which are characterized by a high thermal stability. According to the results of work [5], a *K*-center is formed as a result of the trapping of a positive DV by a CO-center.

From the aforesaid, it follows that RIDs – in particular, DVs – can be formed as both primary and secondary defects, by joining two monovacancies. Annealing of a DV occurs through either its decay into monovacancies or its conversion into other, more stable, RIDs.

In this work, we consider the specific features of the formation and annealing of secondary RIDs in *p*-Si crystals irradiated with electrons.

## 2. Experimental Part

Specimens of single-crystalline silicon with the hole concentration $p = 6 \times 10^{13}$ cm$^{-3}$, fabricated by the Czochralski method, were studied; the density of growth dislocations was $10^3 - 10^4$ cm$^{-2}$. Specimens were irradiated with 8-Mev electrons at room temperature; the exposure dose was $\Phi = 5 \times 10^{15}$ cm$^{-2}$ and the flux density $\varphi = 5 \times 10^{12}$ cm$^{-2} \cdot$ s$^{-1}$. The irradiated crystals were isochronously annealed in the temperature interval 100–500 °C, with a step of 10 °C and the 10-min time of specimen holding at a fixed temperature. Every IA cycle was followed by the measurement of the hole concentration *p* by the Hall method in the temperature interval 77–300 K. Ohmic contacts, necessary for such measurements, were created by rubbing aluminum into the surfaces of studied specimens.

The variation of *p* in the course of IA was determined making use of the curves $p = f(10^3/T)$ at $T = 260$ K. The locations of the defect energy levels $E_i$ were determined in the assumption that $\varepsilon_{\rm F} = E_i$, where $\varepsilon_{\rm F}$ is the Fermi level, by the formula

$$p = N_v F_{1/2}(\varepsilon_{\rm F}/kT),$$

where $N_{\rm V}$ is the effective density of states in the valence band, and $F_{1/2}(x)$ is the Fermi–Dirac integral. The corresponding sections in the dependences $p = f(10^3/T)$ were selected taking into account the depletion degree of a definite level and the degeneracy order of the valence band in silicon (Fig. 1, curves *5* and *6*). In the strongly compensated specimens, the value of $E_i$ was determined from the slope of the dependences $p = f(10^3/T)$ (Fig. 1, curves *1* to *4*). The concentrations of various RIDs after every IA cycle were calculated with the help of step-like dependences $p = f(10^3/T)$ and $p = f(T_{\rm ann})$ in the

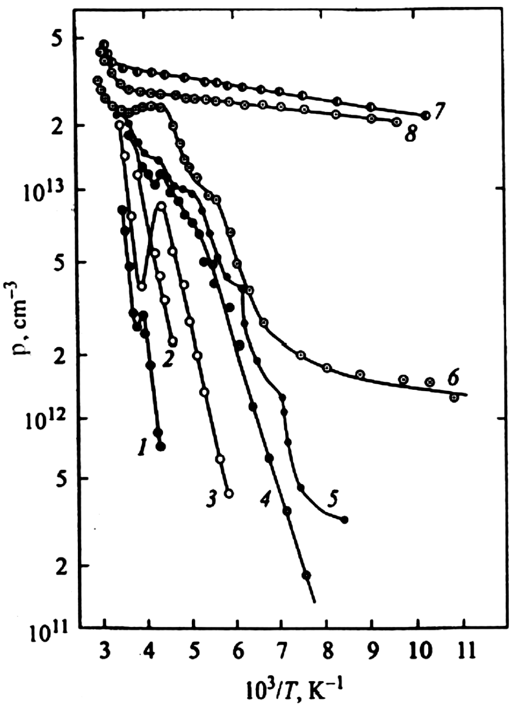


Fig. 1. Temperature dependences of the hole concentration $p$ for a $p$-Si crystal irradiated with electrons for various annealing temperatures $T_{\text{ann}}$: before annealing (*1*), 100 (*2*), 170 (*3*), 240 (*4*), 270 (*5*), 300 (*6*), 400 (*7*), and 500 °C (*8*)

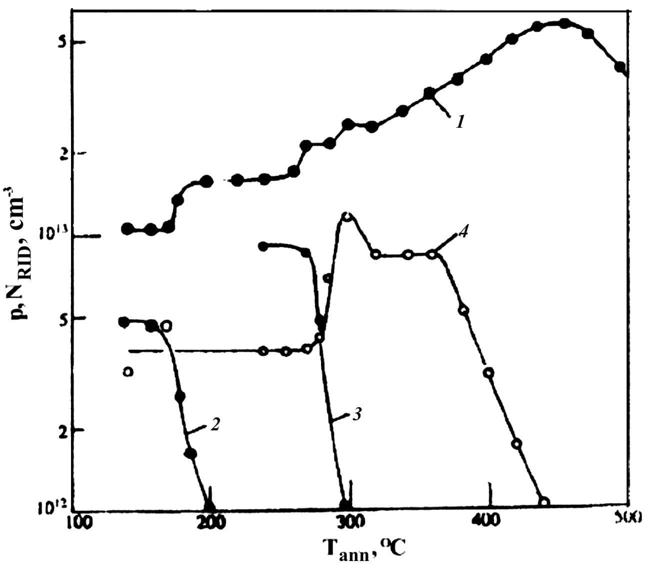


Fig. 2. Dependences of the hole concentration $p$ (*1*) and some radiation-induced defects (*2*–*4*) on the isochronous annealing temperature in the $p$-Si crystals irradiated with electrons

temperature intervals 77–300 and 100–500 K, respectively (Figs. 1 and 2). The measurement error for those quantities did not exceed 10%.

## 3. Results of Researches and Their Discussion

In Fig. 2, the concentration changes for the majority charge carriers $p$ and various RIDs with the variation of the IA temperature $T_{\text{ann}}$ are depicted (curves *1* and *2*–*4*, respectively).

In the interval $T_{\text{ann}} = 170 \div 200$ °C, the sharp increase of $p$ is associated with the annealing of defects with the energy level of $E_v + 0.45$ eV and the concentration $N_{\text{RID}} \approx 5 \times 10^{12}$ cm$^{-3}$ (Fig. 2, curves *1* and *2*). This level belongs to the complex of the doping impurity, i.e. boron, with the vacancy V + B [6].

In the interval $T_{\text{ann}} = 260 \div 300$ °C, a defect with the energy level of $E_v + 0.28$ eV and the concentration of about $8 \times 10^{12}$ cm$^{-3}$ is annealed (Fig. 2, curve *3*). According to the values of $T_{\text{ann}}$ and $E_i$, these centers are DVs [1]. In the course of DV annealing, a drastic increase of the concentration of defects with the level $E_i = E_v + 0.22$ eV ($H$-centers, (Fig. 2, curve *4*) is observed. Moreover, the concentrations of the DVs decayed in the interval 270–290 °C and the emerged $H$-centers with the donor level of $E_v + 0.22$ eV are equal to each other at that. It testifies that $H$-centers do contain DVs. In Fig. 1, the third step from below in the step-like curve *5* corresponds to the transition of electrons from the valence band onto a donor level with the energy of $E_v + 0.22$ eV, which leads to the increase of the hole concentration. Figure 2 demonstrates that this process comes to the end at approximately 220 K. It is natural that electrons cannot return back to the valence band at higher temperatures (for instance, at room temperature) to compensate holes.

Similarly to the phosphorus atom, which takes away its fifth electron from the conduction band at the formation of an $E$-center ($V$ + P) [7], DV-donors also take away their electrons from the valence band in the course of formation of the donor center with the level at $E_v$+0.22 eV. Therefore, the value of $p$ should grow at DV annealing, although we have practically $p$ = const in the interval $T_{\text{ann}} = 270 \div 290$ °C (Fig. 2, curve *1*). Probably, the complexes which are formed at DV annealing contain boron atoms. The concentrations of the boron atoms, which become locked at the formation of $H$-centers, $N_{\text{B}}$, and of the majority charge carriers, which are formed at DV annealing, $p$, are equal. Therefore, the variation of the hole concentration is zero, $\Delta p = 0$, in the annealing interval $T_{\text{ann}} = 270 \div 290$ °C. The results obtained confirm the opinion stated by the authors of work [8] about the existence of $B_sV_2$-complexes in irradiated $p$-Si crystals which are annealed in the temperature interval 350–400 °C.

The activation energy of the DV migration process amounts to about 1.3 eV, and the bond energy of defect is equal to 1.47 eV [1, 9]. Therefore, a DV can migrate without decaying over the crystal. It is also known that BV-complexes are annealed at a temperature of about 180 °C (Fig. 2, curve *2*) and, consequently, cannot participate in the formation of $B_sV_2$-complexes in the temperature interval 270–290 °C. On the basis of the aforesaid, it is possible to assume that $B_sV_2$-complexes are formed by means of DV conversion following the reaction

$$B_s + V_2 \rightarrow B_sV_2,$$

rather than the consecutive trapping of radiation-generated vacancies $V$ by a boron ($B_S$) at the lattice site, as was supposed in work [8].

Figure 2 demonstrates that $H$-centers are annealed in two stages: in the intervals $T_{\rm ann} = 300 \div 320$ and $360 \div 440$ °C. The initial concentration of $H$-centers is equal to $3.5\times10^{12}$ cm$^{-3}$, and the same number of centers are annealed at the first stage of annealing. At the second stage of annealing, the concentration of decayed centers coincides with that of $B_sV_2$-complexes formed at DV annealing ($3.5 \times 10^{12}$ cm$^{-3}$).

The results obtained allowed us to assume that $B_sV_2$-complexes are formed in the interval 270–290 °C in the course of DV annealing and dissociate at a temperature of 400 °C ($H_1$-centers). Concerning the centers annealed at the first stage, they are identical to $B_sV_2$-complexes by the ionization energy and are annealed in the temperature interval $T_{\rm ann} = 300 \div 320$ °C ($H_2$-centers).

The variation of the hole concentration after the annealing at 300 °C is associated with the decay or formation of $V_2O_2$-complexes, $K$-centers, and other deep centers characterized by a high thermal stability [10].

## 4. Conclusion

Our researches have shown that defects with the energy level of $E_v + 0.22$ eV are annealed in two stages: in the temperature intervals $T_{\rm ann} = 300 \div 320$ ($H_2$) and $360 \div 440$ °C ($H_1$). At the first and second stages, the center of unknown nature, which is created during irradiation, and the $B_sV_2$-complex, which is formed as a result of the DV conversion in the temperature interval 270–290 °C following the reaction $B_s + V_2 \rightarrow B_sV_2$ are annealed, respectively.


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КОНВЕРСІЯ ДИВАКАНСІЙ У ПРОЦЕСІ ІЗОХРОННОГО ВІДПАЛУ ОПРОМІНЕНИХ КРИСТАЛІВ $p$-Si

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Р е з ю м е

Досліджено монокристали $p$-Si, отримані методом Чохральського, з концентрацією дірок $p = 6 \cdot 10^{13}$ см$^{-3}$. Зразки опромінювали електронами з енергією 8 МеВ при температурі 300 К. Ізохронний відпал опромінених кристалів проводили в інтервалі температур $T_{\rm відп} = 100 \div 500$ °C. Електрофізичні параметри вимірювали методом Холла в інтервалі температур 77–300 К. Проведені дослідження показали, що в процесі ізохронного відпалу при температурі 270–300 °C відбувається конверсія дивакансій $V_2$ згідно з реакцією $B_s + V_2 \rightarrow B_sV_2$. Комплексу $B_sV_2$ відповідає рівень з енергією $E_v + 0,22$ еВ, він відпалюється в інтервалі температур 360–440 °C.