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INFLUENCE OF IR ILLUMINATION ON CONDUCTION ELECTRON SCATTERING IN CRYSTALS IRRADIATED WITH 25-MeV PROTONS

The photo-Hall effect is studied in specimens of n-Si single crystals with the electron concentration $N = 6 \times 10^{13}$ *cm*$^{-3}$ *irradiated with 25-MeV protons at a temperature of 300 K. The irradiated specimens revealed an anomalously high value of the electron Hall mobility, which can be explained by the formation of highly conducting inclusions in the crystal bulk with ohmic junctions at their interface with the crystal matrix. At some temperatures of the isochronal annealing, the specimens demonstrated an anomalously high electron scattering, which can be reduced by the monochromatic IR illumination with a given photon energy. The illumination deionizes electrostatically interacting deep secondary defects, which are formed in the course of isochronal annealing around the highly conducting inclusions, and screen them. A- and E-centers are shown to dominate among the screening defects.*

Keywords: *n*-silicon, proton irradiation, photo-Hall effect.

1. Introduction

A number of researches have been carried out concerning electric inhomogeneities created by high-energy radiation in crystalline silicon. For example, the features in the processes of accumulation and annealing of primary radiation-induced defects (RIDs) in almost dislocation-free silicon crystals can be interpreted [1] with regard for the presence of the bulk inclusions of interstitial atoms. In this case, the gettering properties of those inclusions depend in a complicated manner on the content of the main background impurity, oxygen, in a crystal. In particular, the study of the electric properties of silicon irradiated with electrons and thermally treated at 530 °C revealed a microscale-inhomogeneous spatial distribution of oxygen-containing thermodonors [2]. While studying the influence of the irradiation with electrons on the formation of electrically active centers in silicon, it was also found [3] that the annealing at 450 °C gives rise to the formation of regions with *n*- and *p*-types of conductivity. The concentration of charge carriers increases in the regions of both types of conductivity, as the irradiation dose and the annealing time grow, which testifies to the formation of not only thermodonors, but also thermoacceptors. Nonuniformities in the distributions of those centers correlate with the concentration fluctuations of background impurity atoms, oxygens. The results of researches of the electron states and electric parameters in *p*-Si specimens grown up by the Czochralski method, irradiated with high-energy neutrons, and isothermally annealed were explained [4] by the appearance of oxygen microprecipitates in the form of crystalline (cristobalite) or amorphous (quartz) phase, depending on the neutron flux. At the interfaces between those inclusions and the Si matrix, a bulk charge is accumulated, and a potential barrier emerges.

The researches of silicon irradiated with boron ions, B^+, and annealed at a high temperature [5] revealed that, at a high boron concentration exceeding the solubility threshold of boron in silicon, there emerge the additional maxima in the boron distribution profile. This clusterization is associated with the displacement of boron atoms from crystal sites by own interstitial Si atoms leaving disordered regions (DRs). The character of the boron precipitation in silicon at high-dose implantation depends on the concentration of boron atoms that were preliminary placed at the crystal lattice sites [6]. At boron concentrations close to the equilibrium value, the precipitation is mainly observed in the regions with a reduced content of RIDs, whereas, in the regions with the enhanced boron content, the boron atoms are involved into the clusterization with interstitial silicon atoms. By comparing the formation conditions of shallow acceptor centers in silicon irradiated with electrons, neutrons, and high-energy ions in the course of high-temperature annealing, it was shown [7] that the emergence of thermoacceptors is a result of the interaction between the boron atoms playing the role of acceptor impurities and the vacancies accumulated in multivacancy clusters. It was also demonstrated [8] that the level of preliminary doping of silicon crystals with boron considerably affects the distribution profile of another impurity, phosphorus, introduced into the material using the ionic implantation.

The features in the electric properties of γ-irradiated p-silicon can be explained [9] by the interaction between DRs and RIDs. More specifically, this is a result of the irradiation-induced growth of the potential barrier between the regions with relatively high and relatively low resistances, as well as the quick capture of primary RIDs by additional drains, whose role is played by DRs. The combined research of the processes of isothermal and isochronal annealings of divacancies in silicon irradiated with 8-MeV protons using the methods of IR and positron spectroscopies brought about a conclusion [10] that there exist two processes associated with the material inhomogeneity: the recombination with aggregates of interstitial atoms and the formation of vacancy agglomerates. Irradiation of silicon by Ge^+, Ar^+, and Ne^+ ions in extreme doses results in the almost total amorphization of the material, which contains, nevertheless, nano-crystalline inclusions [11]. At the interface between the nanocrystals and the amorphous matrix, there are numerous broken bonds giving rise to an enhancement of the EPR signal.

The dependences of DR sizes and configurations in a Si crystal on the energy of a primarily knocked-out atom was demonstrated in work [12]. From the dependence of the number of interactions on the proton energy, it follows that the majority of interactions have a Coulomb nature, and, under those conditions, isolated point-like RIDs are mainly formed. If the recoil energy exceeds $\sim$2 keV, one-cascade or subcascade destructions appear in the crystal. As the energy of protons grows ($E > 20$ MeV), subcascade destructions transform into multicascade ones, i.e. the formation of DRs begins. The DR core consists of vacancies, divacancies, and various vacancy associates, whereas defects of the type “impurity + vacancy” take part in the formation of its periphery, the shell.

DRs are characterized by the conductivity of the p-type in n-Si crystals and by the conductivity of the n-type in p-Si crystals, i.e. DRs are isolated from the matrix by a potential barrier for the majority charge carriers. Accordingly, they are “dielectric” inclusions and stimulate a reduction of the effective value of Hall mobility μ_{eff} both in the region of phonon scattering and in the region of scattering by charged defects [13–17].

The authors of works [16, 17] supposed that DR cores in silicon mainly consist of intrinsic interstitial atoms. We proved experimentally [18–20] that, in n-Si crystals irradiated with 25-MeV protons, the “metallic”(i.e. highly conducting, if compared with the matrix) inclusions with an ohmic junction at the interface with the semiconductor matrix are predominately formed. As a result, μ_{eff} drastically imcreases. In the course of isochronal annealing, a shell composed of negatively charged acceptor RIDs and opaque for conduction electrons is formed around the “metallic” inclusions (probably, the latter may be aggregates of interstitial atoms). This scenario can explain a drastic reduction of μ_{eff} after the annealing of irradiated specimens at $T_{\mathrm{ann}} = 110$ °C or in the course of their natural aging for 30 days at 300 K.

In work [20], the assumption was made that E-centers are responsible for the screening of “metallic” inclusions in the high-temperature interval (200–300 K). At low temperatures, these are E-centers and A-centers; the latter start to charge below 200 K. After the annealing of E-centers ($T_{\mathrm{ann}} = 160$ °C), the screening shell apparently consists of only negatively charged A-centers at low temperatures ($T < 200$ K). It should be noted that, due to the Coulomb attraction between positively charged phosphorus atoms and negatively charged vacancies, the efficiencies of the introduction of A-centers, η_{A}, and E-centers, η_{E}, under conditions when the oxygen concentration is two orders of magnitude higher than the phosphorus one are almost identical: $\eta_{\mathrm{A}} \approx \eta_{\mathrm{E}}$ [21, 22].

If A- and E-centers are really formed around the “metallic” inclusions and if just they are responsible for a drastic reduction of μ_{eff} for electrons in n-Si crystals irradiated with 25-MeV protons, then, using the monochromatic selective illumination, it would be possible to substantially affect the behavior of the dependence $\mu_{\text{eff}}(T)$ by deionizing some of those centers.

This work aimed at studying the influence of the selective photoexcitation of some A- and E-centers in n-Si specimens with the use of the IR illumination on μ_{eff}.

2. Experiment

In our researches, we used phosphorus-doped n-Si single crystals with the electron concentration $N = 6 \times 10^{13}$ cm^{-3}. The crystals were fabricated by the zone melting. The oxygen concentration in them was $N_{\text{O}} \approx 10^{16}$ cm^{-3}, and the density of growth dislocations $N_{\text{Dis}} \approx 10^3 \div 10^4$ cm^{-2}. The specimens were cut out in the form of bars $1 \times 3 \times 10$ mm^3 in dimensions, with the surface (111) being the largest one.

Some of the researched specimens were irradiated only with 25-MeV protons (to the dose $\Phi \approx 8.1 \times 10^{12}$ cm^{-2}), and the others first by protons to a small dose ($\Phi \approx 5 \times 10^{11}$ cm^{-2} at $\varphi \approx 1.5 \times 10^{11}$ cm^{-2}s^{-1}) and then by 2-MeV electrons (to $\Phi \approx 10^{14}$ cm^{-2} at $\varphi \approx 5 \times 10^{12}$ cm^{-2}s^{-1}). The specimens were irradiated at a temperature of 300 K.

The influence of the deep center deionization on μ_{eff} was studied with the help of the photo-Hall effect. Electrons from the levels of the given type were excited into the conduction band using IR light and with the help of an IKS-21 monochromator. A-centers were excited by light with the quantum energy $h\nu_1 = 0.17$ eV (the wavelength $\lambda_1 = 7.3$ μm), and E-centers by light with the quantum energy $h\nu_1 = 0.44$ eV (the wavelength $\lambda_2 = 2.8$ μm). To obtain light rays, a LiF prism was used in the former and a NaCl one in the latter case. The injection level ΔN was estimated from the intensity of their illumination and did not exceed $\Delta N \approx 5 \times 10^{10}$ cm^{-3}. In log coordinates, the curves of the dependence $\lg N(10^3/T)$ obtained in dark and under illumination are practically superimposed on each other. Therefore, in Fig. 1, they are plotted together (the influence of illumination can be clearly seen from the plots for the mobility).

The temperature dependences of the charge carrier concentration N, specific resistance ρ, and effective Hall mobility μ_{eff} were analyzed in the interval $T = 77 \div 300$ K. The concentration N was measured using the compensation method in a magnetic field with the strength $H = 10$ kOe, ρ was measured using the two-probe method, the Hall factor was taken equal to 1, and μ_{eff} was calculated by the formula $\mu_{\text{eff}} = 1/(eN\rho)$, where e is the electron charge. In order to reorganize the environment of point defects formed around "metallic" inclusions, the isochronal annealing was applied in the temperature interval from 80 to 550 °C with a step of 10 °C and the 10-min period of specimen holding at every fixed temperature.

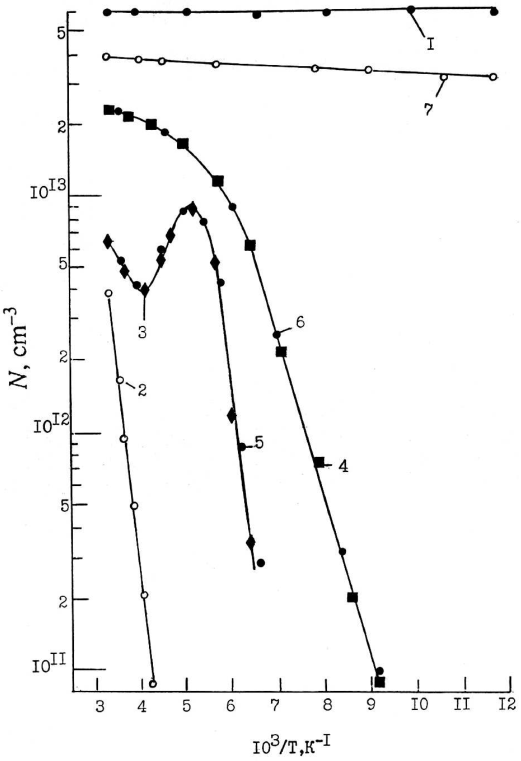

Fig. 1. Temperature dependences of the electron concentration in n-Si crystals irradiated with 25-MeV protons at 300 K: (*1*) before irradiation, (*2*) after irradiation to a dose of 8.1×10^{12} cm^{-2}, (*3*) after annealing at 110 °C, (*4*) after annealing at 160 °C, (*5*) after annealing at 110 °C together with IR illumination with 0.44-eV photons, (*6*) after annealing at 160 °C together with IR illumination with 0.17-eV photons, and (*7*) after annealing at 350 °C

3. Research Results and Their Discussion

Figure 1 exhibits the dependences $N = f(10^3/T)$ for the initial crystal (curve *1*), after its irradiation with 25-MeV protons to an integrated dose of 8.1×10^{12} cm^{-2} (curve *2*), and after the annealing

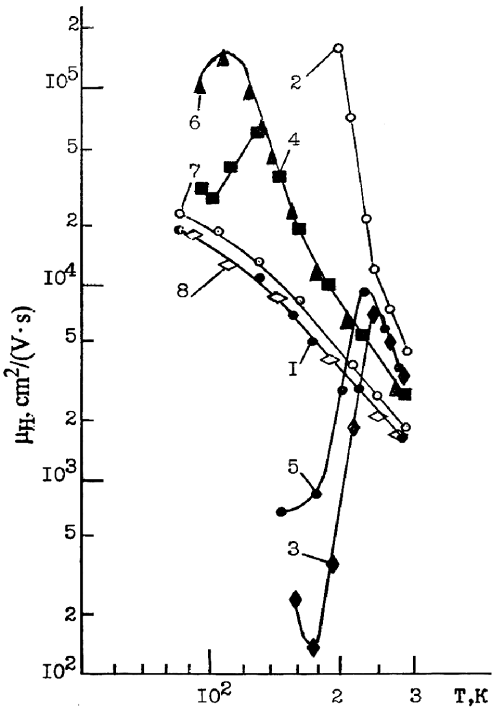

Fig. 2. Temperature dependences of the electron mobility in n-Si crystals irradiated with 25-MeV protons at 300 K: (*1*) before irradiation, (*2*) after irradiation to a dose of 8.1×10^{12} cm^{-2}, (*3*) after annealing at 110 °C, (*4*) after annealing at 160 °C, (*5*) after annealing at 110 °C together with IR illumination with 0.44-eV photons, (*6*) after annealing at 160 °C together with IR illumination with 0.17-eV photons, (*7*) after annealing at 350 °C, and (*8*) after annealing at 550 °C

of irradiated specimens at temperatures of 110, 160, and 350 °C (curves *3*, *4*, and *7*, respectively). Curves *5* and *6* correspond to annealing temperatures of 110 and 160 °C, respectively, and the IR illumination with 0.44-eV and 017-eV photons, respectively. Curve *2* in Fig. 1 corresponds to defects of the acceptor type with the ionization energy $E_C - (0.38 \pm 0.01)$ eV, i.e. divacancies [23].

Right after irradiation, all conduction electrons are located at deep levels (E-centers, divacancies, and so on). After the thermal treatment of irradiated specimens at $T_{\text{ann}} = 110$ °C, some of the E-centers become annealed. The annealing of one E-center gives rise to the appearance of two electrons in the conduction band. Free electrons charge some of the A-centers. The result of all those processes is shown in Fig. 1 by the nonmonotonic curve *3*, which corresponds to the exhaustion of A-centers. However, the deionization energy of A-centers turns out a little changed, which may be associated with the electrostatic interaction between various charged RIDs [19, 24].

The matter is that DR shells contain not only A-centers, but also a number of other centers, which are also charged in a wide temperature interval. Therefore, the average distance between all charged defects is definitely shorter than the average distance between A-centers. Accordingly, the variation of the A-center ionization energy owing to the electrostatic interaction is larger. The proton irradiation increases the fraction of electrostatically interacting centers (A- and E-centers, divacancies, and so on), because it creates primary RIDs located along the proton tracks and capable to condense with the formation of closely located vacancy complexes and clusters [22]. According to our estimations, the distance between electrostatically interacting RIDs changes within the interval from 10^{-7} to 10^{-6} cm.

If the energy of electrostatic interaction $\varepsilon \geq \geq 0.17$ eV, electrons seem to transit from the levels corresponding to A-centers into the conduction band at lower temperatures than usually (Fig. 1, curve *3*). The electrostatic interaction stimulates the electron transition into the conduction band not only from A-centers, but also from deeper levels. As a result, the slope of curve *3* in Fig. 1 grows, and the concentration of electrons at $T = 200$ K exceeds the equilibrium one (9×10^{12} cm^{-3}). After the thermal deionization of A-centers (at temperatures $T \geq 200$ K), the forces of electrostatic interaction between various RIDs diminish, and, at 250 K, only equilibrium electrons remain in the conduction band (4×10^{12} cm^{-3}). If the measurement temperature increases further, the concentration of equilibrium electrons starts to grows, which gives rise to the appearance of a minimum in curve *3*.

In Fig. 2, the temperature dependences of the Hall mobility, $\mu_{\text{H}}(T)$, in the initial crystal (curve *1*) after its irradiation with 25-MeV protons to a dose of 8.1×10^{12} cm^{-2} (curve *2*) and after the annealing at $T_{\text{ann}} = 110$, 160, 350, and 550 °C (curves *3*, *4*, *7*, and *8*, respectively) are shown. Curve *3* demonstrates a drastic reduction of μ_{eff} with a formation of a minimum at $T = 180$ K. An analogous minimum in curve *4* is observed at $T = 100$ K. The photoexcitation of electrons into the conduction band from the levels at 0.44 eV ($\lambda = 2.8$ μm) in specimens annealed at $T_{\text{ann}} = 110$ °C increases the μ_{eff} value by shifting the dependence toward lower temperatures (Fig. 2, curve *5*). After the annealing at $T_{\text{ann}} = 160\ ^\circ\text{C}$, the excitation of electrons from the levels at 0.17 eV ($\lambda = 7.3\ \mu\text{m}$) stimulates the growth of the maximum in the dependence $\mu_{\text{eff}}(T)$ and shifts it toward lower temperatures (Fig. 2, curve *6*). From Fig. 2, it follows that the illumination affects the behavior of the dependence $\mu_{\text{eff}}(T)$ not only at low temperatures ($\sim$100 K), i.e. in the interval of the scattering by charged centers, but also in the interval of the scattering of charge carriers by phonons (at temperatures $T \geq 180$ K).

The energy of an electron at the local level equals $E = E_T + \varepsilon$, where E_T is the thermal energy, and ε the average energy of electrostatic interaction between negatively charged defects in the environment around "metallic" inclusions. If $E = E_i$, where E_i is the center deionization energy, the electron transits from the local level into the conduction band. In the temperature interval of 230–300 K, the electrons seem to transit from the level $E = E_i = 0.44$ eV corresponding to E-centers into the conduction band, the degree of "metallic" inclusion screening decreases, and the Hall mobility, in accordance with the results of work [25], can be described by the expression

$$\mu_{\text{eff}} \approx \mu_{\text{H}} \frac{1 + 3f_1}{1 - 6f_1}, \tag{1}$$

where μ_{H} is the Hall mobility in the undamaged matrix, and f_1 the total volume fraction of interstitial atom aggregates. Formula (1) testifies that μ_{eff} is an increasing function of the inclusion volume fraction f_1, which is confirmed by the behavior of the dependence $\mu_{\text{eff}}(T)$ in the interval of 230–300 K (Fig. 2, curve *3*). As the temperature decreases, E diminishes, and E-centers begin to charge. As a result, the degree of "metallic" inclusion screening increases. The inclusions become opaque for electrons, and, according to the results of work [14], the Hall mobility decreases following the law

$$\mu_{\text{eff}} \approx \mu_{\text{H}} \frac{1 - f_2/4}{1 + f_2/2}, \tag{2}$$

where μ_{H}, as above, is the Hall mobility of electrons in the initial specimen, and f_2 is the volume fraction occupied by quasidielectric inclusions (see Fig. 2, curve *3*).

It should be noted that, in this case, the quantities f_1 and f_2 depend not only on the energy and the radiation dose, but also on the screening degree γ of "metallic" inclusions. If γ grows, the value of f_1 decreases, and that of f_2 increases, and *vice versa*.

The dependence $\mu_{\text{eff}}(T)$ reveals a minimum at $T \approx 180$ K. Its existence was explained in work [19] by the temperature-induced variation of the "metallic" inclusion screening degree in the course of measurements, although there is no common opinion on this issue at present [24–27].

The growth of μ_{eff} in the interval of 140–230 K, when the electrons are excited into the conduction band from the level $E_C - 0.44$ eV by means of the IR illumination, is explained by a reduction of the screening degree of atomic clusters and, respectively, the increase of the volume fraction of "metallic" inclusions f_1 (see formula (1)). In the temperature interval of 230–300 K, E-centers around "metallic" inclusions are exhausted owing to the electrostatic interaction and high temperatures. Therefore, the IR illumination does not affect the magnitude of effective mobility μ_{eff}. A-centers are almost electrically neutral in the interval of the phonon scattering (200–300 K) and cannot change substantially the degree of "metallic" inclusion screening and, hence, μ_{eff}. As to divacancies, they are mainly formed in the course of irradiation following the cascade mechanism and are undoubtedly present in the crystal bulk. The formation of divacancies in the course of isochronal annealing following the diffusion mechanism is hardly probable owing to the electrostatic repulsion between negative monovacancies. Therefore, it seems that only a small number of them are present in the environment around "metallic" inclusions.

The reduction of μ_{eff} in the low-temperature interval (≈ 130 K) after a complete annealing of E-centers ($T_{\text{ann}} = 160\ ^\circ\text{C}$) was explained in work [20] by a change in the charge state of A-centers. At temperatures $T \leq 130$ K, the A-centers are charged negatively and increase the degree of "metallic" inclusion screening. In this temperature interval, the "metallic" inclusions with the negatively charged shell strongly scatter the conduction electrons and, hence, diminish μ_{eff} (Fig. 2, curve *4*).

The excitation of electrons into the conduction band from the level $E_C - 0.17$ eV with the help of the IR illumination gives rise to a reduction of the "metallic" inclusion screening degree γ. As a result, the influence of the electron scattering by negatively charged inclusions on μ_{eff} decreases. Hence, μ_{eff} con-

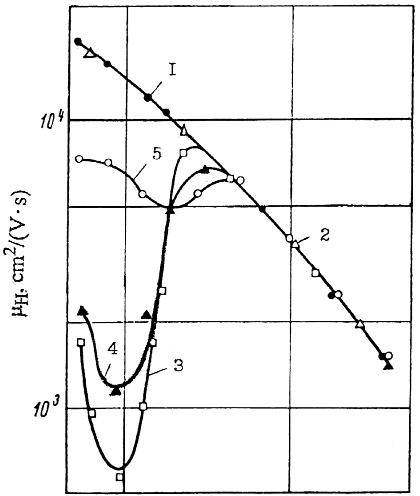

Fig. 3. Temperature dependences of the electron mobility in n-Si crystals firstly irradiated with 25-MeV protons to a dose of 5×10^{11} cm^{-2} and then with 2-MeV electrons to a dose of 10^{14} cm^{-2}: (*1*) before irradiation, (*2*) after the proton irradiation, (*3*) after the electron irradiation in dark, (*4*) after the electron irradiation at the IR illumination with 0.17-eV photons, and (*5*) after the electron irradiation at the IR illumination with 0.44-eV photons

tinues to grow almost to 100 K, and, as one can see, the minimum is shifted to the left, toward low temperatures ($T < 77$ K, Fig. 2, curve *6*).

After the complete annealing of A-centers at $T_{\rm ann} = 350$ °C, the dependence $\mu_{\rm eff}(T)$ becomes nonmonotonic in the temperature interval from room temperature to the nitrogen boiling point (Fig. 2, curve *7*). At $T_{\rm ann} = 550$ °C, the "metallic" inclusions are annealed completely (Fig. 2, curve *8*).

A drastic reduction of $\mu_{\rm eff}$ with a minimum at $T \approx 100$ K is also observed in specimens firstly irradiated with protons to small doses ($\Phi \approx 5 \times \times 10^{11}$ cm^{-2}) and then with electrons (to $\Phi \approx \approx 10^{14}$ cm^{-2}) (see Fig. 3, curve *3*). It seems that, after the specimens were irradiated with protons to the dose $\Phi \approx 5 \times 10^{11}$ cm^{-2}, a small number of "metallic" inclusions, besides point-like RIDs, is formed in the crystal bulk. Those inclusions practically do not affect the electron mobility (Fig. 3, curve *2*), but generate local elastic stresses in the crystal lattice. After the irradiation with electrons, primary RIDs–vacancies and interstitial atoms–emerge in the crystal. Nonequilibrium vacancies probably move to "metallic" inclusions [28]. Some of them recombine with interstitial atoms in "metallic" inclusions, whereas the others create shells around those inclusions, which are opaque for conduction electrons and consist of negatively charged A-centers, E-centers, divacancies, and other RIDs. As a result, the metal-like inclusions are transformed into quasidielectric ones, which scatter conduction electrons, and $\mu_{\rm eff}$ drastically diminishes (Fig. 3, curve *3*).

Under the IR illumination with a photon energy of 0.17 eV in the course of Hall measurements, A-centers are deionized. Accordingly, the degree of "metallic" inclusion screening decreases, which results in an increase of $\mu_{\rm eff}$ in a vicinity of $T = 100$ K (see Fig. 3, curve *4*). The photoexcitation of electrons from the level $E_C - 0.44$ eV into the conduction band results in an increase of $\mu_{\rm eff}$ in a wider temperature interval (Fig. 3, curve *5*), because E-centers are charged negatively in the interval of 77–300 K.

The obtained experimental results confirm the opinion stated earlier in work [20] that it is A- and E-centers that are mainly responsible for the screening of "metallic" inclusions.

The minimum in the dependence $\mu_{\rm eff}(T)$ (see Fig. 3) is explained by the dependence of the charge state of the screening shells around the atomic clusters on the measurement temperature T and the energy ε of electrostatic interaction between charged RIDs in those shells. As the measurement temperature T decreases, RIDs around atomic clusters begin to charge negatively. Accordingly, the screening degree of atomic clusters becomes lower, and the latter are transformed into quasidielectric inclusions, which results in that $\mu_{\rm eff}$ decreases. At a certain temperature, the energy ε of electrostatic interaction between negatively charged RIDs in the shell becomes larger than their ionization energy, and RIDs begin to deionize [19, 29]. Accordingly, the screening degree of atomic clusters by charged RIDs decreases. Quasidielectric inclusions are transformed again into atomic clusters with a high conductivity, $\mu_{\rm eff}$ increases, and there appears a minimum in the dependence $\mu_{\rm eff}(T)$.

4. Conclusions

To specify which radiation-induced defects are responsible for a reduction of the effective Hall mobility $\mu_{\rm eff}$ in n-Si crystals irradiated with 25-MeV protons at various temperatures, the photo-Hall effect was studied. The researches demonstrated that the selective excitation of E-centers ($E_C - 0.44$ eV) affects the minimum at about 180 K in the dependence $\mu_{\rm eff}(T)$. At the same time, the excitation of A-centers ($E_C - 0.17$ eV) varies the minimum at about 100 K in the same dependence.

The obtained results confirm the conclusion made earlier that the screening of "metallic", i.e. relatively highly conducting, inclusions in proton-irradiated n-Si crystals is performed by E-centers only in the temperature interval of the phonon scattering and due to the common action of A- and E-centers at low temperatures. After the complete annealing of E-centers ($T_{\rm ann} = 160$ °C), only A-centers are responsible for the minimum in the dependence $\mu_{\rm eff}(T)$.

In general, the minimum in the dependence $\mu_{\rm eff}(T)$ is explained by the dependence of the screening degree of atomic clusters on the measurement temperature and the energy of electrostatic interaction between charged RIDs that compose a screening shell around atomic clusters.

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ВПЛИВ ІЧ ПІДСВІЧУВАННЯ НА РОЗСІЮВАННЯ ЕЛЕКТРОНІВ ПРОВІДНОСТІ В ОПРОМІНЕНИХ ПРОТОНАМИ З ЕНЕРГІЄЮ 25 МеВ КРИСТАЛАХ N-Si

Резюме

Досліджувані зразки монокристалів n-Si з концентрацією електронів $N = 6\cdot10^{13}$ см$^{-3}$ опромінювались протонами з енергією 25 МеВ при 300 К. Для дослідження застосовували метод фото-Холл-ефекту. В опромінених зразках спостерігається аномально високе значення холлівської рухливості електронів, що пояснюється утворенням в об'ємі кристала високопровідних включень з омічним переходом на межі з матрицею кристала. При деяких температурах ізохронного відпалу спостерігається аномально високе розсіювання електронів, яке зменшується монохроматичним ІЧ підсвічуванням із заданою енергією фотонів. Підсвічування деіонізує вторинні глибокі дефекти, які електростатично взаємодіють та утворюються в процесі ізохронного відпалу навколо високопровідних включень і екранують їх. Показано, що такими екрануючими дефектами є, в основному, A- і E-центри.