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ELECTRICAL AND OPTICAL PROPERTIES OF SEMICONDUCTORS

Anomalous Scattering of Electrons in *n*-Si Crystals Irradiated with Protons

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Abstract—The aim of this study was to gain insight into the effect of irradiation with 25-MeV protons on the Hall mobility of electrons in *n*-Si crystals. Irradiated crystals with an initial electron concentration 6×10^{13} cm^{-3} were studied using the Hall method in the range of temperatures 77–300 K. The studies showed that, in crystals irradiated with the proton dose $\Phi = 8.1 \times 10^{12}$ cm^{-2}, the effective mobility of conduction electrons $\mu_{\rm eff}$ increases drastically. This effect is direct evidence that inclusions with relatively high conductivity and with nonrectifying junction at interfaces with semiconductor matrix are predominantly formed in *n*-Si crystals under these conditions. Agglomerations of interstitial atoms or their associations can represent such inclusions.

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1. INTRODUCTION

Irradiation with various particles or photons in a wide range of energies is used in radiation technology of solid-state electronics. In particular, irradiation of single-crystal or amorphous silicon with high-energy protons makes it possible to intentionally affect the electrical properties of materials [1–4].

In the case of irradiation with high-energy particles, complex structural imperfections appear in the semiconductor bulk; these imperfections are referred to as disordered regions (DRs), which represent the cause of specific variations in the electrical and galvanomagnetic properties. Kuznetsov and Lugakov [5] used the Hall and photo-Hall measurements to study the effect of irradiation with 30- and 660-MeV protons on the mobility of majority charge carriers μ_H and efficiency of introduction η of various radiation defects (RDs) into the *n*- and *p*-type silicon crystals. Measurements have shown that the mobility μ_H and electron concentration N decrease as the integrated proton flux Φ is increased. Infrared (IR) illumination or isochronous annealing of irradiated samples bring about an increase in μ_H and N, which is accounted for by ionization and annealing of secondary RDs in the peripheral parts of the regions of defect buildup (RDBs).

Kuznetsov and Lugakov [6] studied the efficiency of introduction η and nature of RDs formed in *n*-Si as a result of irradiation with 640-MeV protons at various temperatures ($T_{\rm irr}$ = 30–700°C).

An increase in $T_{\rm irr}$ leads to an increase in μ_H, which is accounted for by a decrease in η for secondary RDs in the peripheral part of an RDB and, correspondingly, by a decrease in the size of these agglomerations.

The results reported in [5] and [6] are complementary. An analysis of experimental data [5] and [6] made it possible to assume that RDBs consist of two parts: a central part (the core) and a peripheral part (the shell). The RDB cores consist of intrinsic structural defects (vacancy or interstitial associations), while the peripheral part of RDBs is formed of complexes of intrinsic defects with impurity atoms, i.e., the secondary RDs (*E* centers, *A* centers, the oxygen + divacancy centers, and so on).

If Kuznetsov and Lugakov [5, 6] had used IR illumination, an increase in the temperature of isochronous annealing $T_{\rm ann}$, or irradiation $T_{\rm irr}$ to completely release the RDB cores from the effect of the impurity–defect shell, the temperature dependence of mobility $\mu_H(T)$ would shift to larger values of μ_H. To this end, it is necessary that the RDB cores be in fact agglomerations of interstitial atoms or their associations and not be annealed before annealing of secondary RDs in the shell (the annealing temperature $T_{\rm ann} \geq 600$°C).

If a crystal contains macroscopic inclusions that are not penetrable for conduction electrons (dielectric inclusions), one may expect a decrease in the effective value of mobility of majority charge carriers $\mu_{\rm eff}$ due to a decrease in the real volume of the sample [7].

In the other limiting case where one can disregard the conductivity of the medium in comparison of the conductivity of inclusions (metallic inclusions), $\mu_{\rm eff}$ is an ascending function of volume fraction f of these inclusions.

Dielectric inclusions represent vacancy-type defects, while metallic inclusions belong to interstitial-type defects [7, 8].

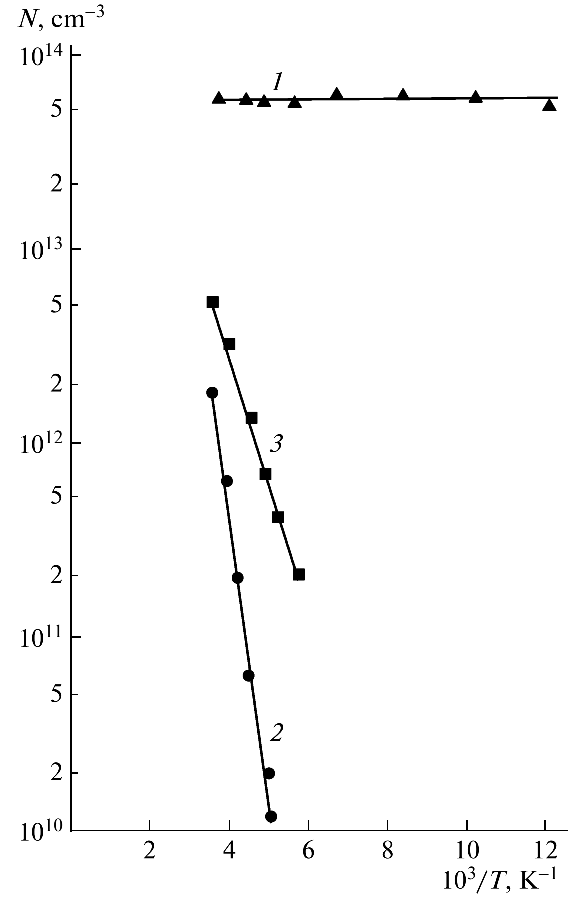

Fig. 1. Temperature dependences of the electron concentration in n-Si (*1*) before and (*2*, *3*) after irradiation with 25-MeV protons with the dose $\Phi = 8.1 \times 10^{12}$ cm^{-2} (*2*) immediately after irradiation and (*3*) after annealing at 90°C and aging of the sample for 30 days at 300 K.

The radiation defects of the vacancy and interstitial types in silicon crystals interact with each other. Heat treatment at temperatures of 200–300°C brings about the removal of all vacancy complexes. In the opinion of Antonova et al. [9], this happens owing to decomposition of interstitial complexes and annihilation of them with vacancy defects.

The efficiency of the introduction and the nature of RDs in silicon crystals are mainly determined by the impurity composition and the energy of irradiation [10].

The aim of this study is to gain insight into the effect of irradiation with 25-MeV protons on the RD nature in n-Si crystals.

2. EXPERIMENTAL

We studied the n-Si samples obtained by zone melting with phosphorus concentration $N_P = 6 \times 10^{13}$ cm^{-3}, oxygen concentration $N_O \approx 2 \times 10^{16}$ cm^{-3}, and density of growth dislocations no higher than 10^3–10^4 cm^{-2}. The samples under study had sizes of 1 × 3 × 10 mm and were irradiated with 25-MeV protons. The proton-flux density was $\varphi = 10^{11}$ cm^{-2} s^{-1}. Irradiated samples were annealed at a temperature $T_{\text{ann}} = 90$°C; the annealing duration was 10 min. The electron concentration N, the Hall coefficient R, and the electrical conductivity σ were measured in the temperature range $T = 77$–300 K. The Hall electron mobility was calculated using the formula $\mu_H = \sigma R$. In highly compensated samples, the energies of the defect levels ΔE were determined from the slope of dependences $N = f(10^3/T)$ in logarithmic coordinates. The error in determining these quantities was no larger than 10%.

3. RESULTS

In the initial samples, the dependence $N = f(10^3/T)$ in the range $T = 77$–300 K, corresponds to the complete ionization of shallow donors (phosphorus atoms): $N = 6 \times 10^{13}$ cm^{-3} = const (Fig. 1, curve *1*). After irradiation with protons with the dose $\Phi = 8.1 \times 10^{12}$ cm^{-2}, the temperature dependence of the electron concentration corresponds to depletion of acceptor centers with a level at $E_c - 0.38$ eV (Fig. 1, curve *2*). A rectilinear section is observed in the dependence $N = f(10^3/T)$ for the same sample annealed at 90°C and aged for 30 days at 300 K; this section corresponds to depletion of acceptor centers with the level at $E_c - 0.13$ eV (Fig. 1, curve *3*). In Fig. 2, we show the corresponding temperature dependences of the Hall mobility of electrons in the initial and proton-irradiated crystals (curves *1*, *2*, and *3*, respectively).

In Fig. 2, curve *1* corresponds to scattering of electrons by phonons in the initial crystal. Curves *2* and *3* in Fig. 2 represent the dependences $\mu_H(T)$ in the samples irradiated with the dose $\Phi = 8.1 \times 10^{12}$ cm^{-2}. Immediately after irradiation, the Hall mobility is noticeably higher than in the initial sample (compare curves *1* and *2*) and increases drastically as temperature is decreased. After low-temperature heat treatment at 90°C and aging of the sample for 30 days at 300 K, the curve $\mu_H(T)$ runs below the curve for the initial material and descends sharply as temperature is decreased (curve *3*).

4. DISCUSSION

The temperature dependence of the electron Hall mobility in the initial sample indicates that the phonon mechanism of scattering of charge carriers is dominant within the temperature range 77–300 K. Therefore, a shift of the dependence $\mu_H(T)$ upward or downward as a result of irradiation cannot be accounted for by a variation in the concentration of some scattering centers in the crystal. Large values of mobility obtained in the Hall experiments are indicative of the formation of inclusions with relatively high conductivity in the sample; these inclusions feature nonrectifying junction at interfaces with the semiconductor matrix. If the high-conductivity inclusions are spherical, the effective mobility is given by

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

where μ_{H} is the Hall mobility in the matrix and f is the total volume fraction of agglomerations of interstitial atoms [8]. If the Hall mobility in the initial material (equal approximately to 1.4×10^3 cm^2 V^{-1} s^{-1}) is used as the parameter μ_{H} and the postirradiation room-temperature Hall mobility (nearly equal to 4.4×10^3 cm^2 V^{-1} s^{-1}) is used as the parameter μ_{eff}, we obtain $f \approx 0.1$.

The obtained value of f is a reasonable estimate of the total volume fraction of agglomerations of interstitial atoms characteristic of a real silicon structure after irradiation with light ions [11].

Vacancy-type disordered regions, which are undoubtedly present in a small amount in the samples under study, consist of a core saturated with multivacancy complexes and a shell containing complexes of monovacancies with impurity atoms. The DR shells are formed as a result of diffusion of monovacancies from the core to the matrix and as a result of interaction of these monovacancies with impurity atoms. The depth of penetration of monovacancies into the matrix and, consequently, the sizes of the DR shells are determined by the impurity concentration in the matrix [12]. In our experiment, the irradiated samples were subjected to heat treatment in order to increase the depth of penetration of monovacancies into the matrix beyond the shell. The heat-treatment temperature ($T_{\text{ann}} = 90$°C) was limited by the onset of annealing of the E centers and DRs (100 and 200°C, respectively [13]). Apparently, in the course of heat treatment and aging of irradiated samples at 300 K, monovacancies emerge from the DR shell and move toward agglomerations of interstitial atoms, which give rise (like dislocations in the crystal lattice) to elastic stresses around them. Vacancies become involved in a quasi-chemical reaction with impurity atoms, which are located around agglomerations of interstitial atoms; as a result, screening impurity–defect shells consisting of the A centers, E centers, divacancies, and other acceptor-type RDs and also of the atoms of doping (phosphorus) and background (oxygen, carbon) impurities are formed around these agglomerations. Some fraction of vacancies undergo annihilation with interstitial atoms of metallic inclusions.

At temperatures of 300 K and below, the majority of acceptor-type RDs in n-Si crystals are charged negatively. Consequently, agglomerations of interstitial atoms become impenetrable for conduction electrons and act as dielectric inclusions along with agglomerations of vacancies. As a result, we experimentally observe a decrease in the effective value of mobility of majority charge carriers after aging of irradiated samples (Fig. 2, curve *3*).

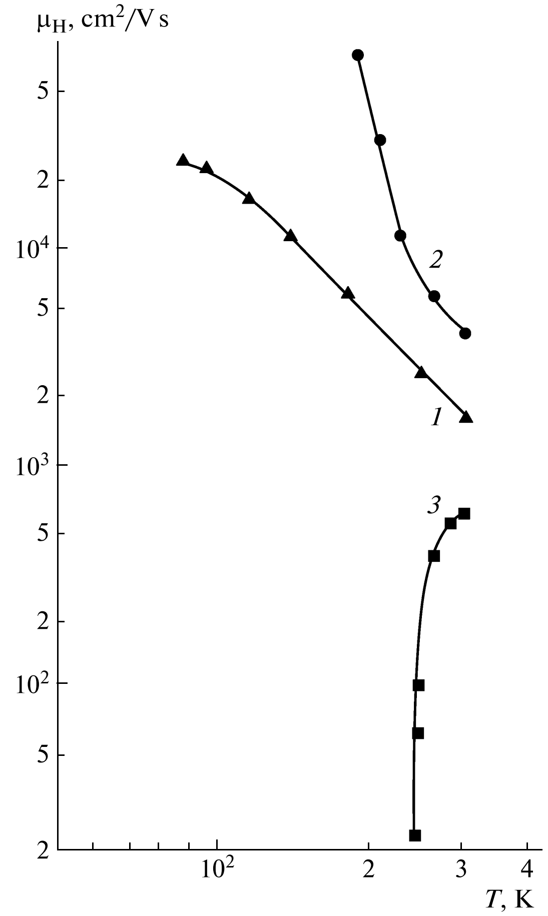

Fig. 2. Temperature dependences of the Hall electron mobility in n-Si crystals (*1*) before and (*2*, *3*) after irradiation with 25-MeV protons with the dose $\Phi = 8.1 \times 10^{12}$ cm^{-2} (*2*) immediately after irradiation and (*3*) after annealing at 90°C and aging of the sample for 30 days at 300 K.

A drastic decrease in the mobility with a minimum in the curve $\mu_{\text{eff}}(T)$ was also observed in plastically deformed n-Si crystals irradiated first with 25-MeV protons and then with 2.2-MeV electrons [14]. Exposure to IR radiation reduces the depth of the minimum. The observed effect is accounted for [14] by a buildup of secondary point defects at dislocations and RDs in the course of isochronous annealing, irradiation with electrons, and natural aging of the samples under study.

In order to assess the volume fraction of quasi-dielectric inclusions f_1, we can use the following expression in the crude approximation and in analogy with formula (1):

$$\frac{\mu_{\text{eff}}}{\mu_{\text{H}}} \approx \frac{1-f_1}{1+f_1}. \tag{2}$$

Substituting experimental values of μ_{eff} and μ_{H} (7×10^2 and 1.4×10^3 cm^2 V^{-1} s^{-1}, respectively), we obtain $f_1 \approx 0.3$ at 300 K.

The obtained values of f_1 are larger than those of f, since quasi-dielectric inclusions are formed on the basis of agglomerations of interstitial atoms.

As the sample temperature is decreased, the concentration of charged RDs in the impurity–defect shell of quasi-dielectric inclusions increases. This brings about an increase in the degree of screening of these inclusions and, consequently, an observed decrease in μ_{eff} as temperature is decreased (Fig. 2, curve *3*).

At a temperature of 240 K, $\mu_H = 2 \times 10^1$ cm^2 V^{-1} s^{-1}; consequently, we have $f_1 \approx 0.9$. As temperature is decreased further, the resistance of the sample drastically increases, so that it becomes impossible to carry out electrical measurements.

Taking into account the above-said, we may assume that agglomerations of interstitial atoms (in addition to vacancy-type DRs) are also formed in silicon samples as a result of irradiation with high-energy particles. Agglomerations and DRs affect differently the effective value of the Hall mobility of majority charge carriers μ_{eff}. The vacancy-type DRs (dielectric inclusions) bring about a decrease in the value of μ_{eff}, while agglomerations of interstitial atoms (metallic inclusions) lead to an increase in μ_{eff}. The value and the form of the temperature dependence of μ_{eff} depend on the quantitative relation between these inclusions. Agglomerations of interstitial atoms are predominantly formed in the *n*-Si crystals as a result of irradiation with 25-MeV protons, which brings about an increase in μ_{eff}. In the course of natural aging, negatively charged shells impenetrable for electrons form around metallic inclusions, which brings about a decrease in μ_{eff}.

In Fig. 1, curve *2* corresponds to depletion of the *E* centers or divacancies ($E_c - 0.38$ eV), while curve *3* corresponds to depletion of the *A* centers ($E_c - 0.13$ eV), the deionization energy of which is changed owing to electrostatic interaction between negatively charged centers in the impurity–defect shell; these centers are formed around a DR in the course of natural aging of irradiated samples at 300 K [14].

5. CONCLUSIONS

Thus, a drastic increase in the value of μ_{eff} is observed in the *n*-Si crystals after irradiation with 25-MeV protons (μ_{eff} is the effective mobility of the majority charge carriers). This effect is direct proof that metallic inclusions are predominantly formed in the samples under study as a result of irradiation. It appears that metallic inclusions are agglomerations of interstitial atoms or associations thereof.

Presumably, in the course of annealing (at $T_{\text{ann}} = 90°$C) and natural aging of irradiated samples for 30 days at 300 K, negatively charged impurity–defect shells, which are impenetrable for electrons, are formed around metallic inclusions; this results in a drastic decrease in the effective value of electron mobility μ_{eff}.

Apparently, preferential formation of dielectric or metallic inclusions depends on the energy and type of particles incident on the crystal.

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