OSCILLATORY DEPENDENCE OF ELECTRON HALL MOBILITY ON THE ANNEALING TEMPERATURE FOR IRRADIATED SILICON

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Temperature dependences of the electron Hall mobility $\mu_{\rm H}$ in n-Si single crystals before and after proton irradiation and thermal treatment have been measured. The value of $\mu_{\rm H}$ was found to oscillate at a given temperature after the isochronous annealing (IA) at elevating temperatures. The effect is explained as a competition of a dissociation of radiation-induced complex defects and a decay of defect clusters.

The variations of the behavior of the temperature dependences of the electron Hall mobility, $\mu_{\rm H}$, in irradiated silicon crystals on the isochronal annealing temperature $T_{\rm ann}$ are studied. Experimental specimens involved single crystals doped by phosphorus (P) up to the concentration $N_{\rm P} \approx 6 \times 10^{13}$ cm^{-3}. They were irradiated by high-energy (25 MeV) protons to provide a dose of 8.1×10^{12} cm^{-2} and then were annealed during 10 min at various temperatures with a step of 10 °C. The temperature dependences of $\mu_{\rm H}$ and of the electron Hall concentration $n_{\rm H}$ were recorded in an interval from the nitrogen boiling point up to ambient temperature.

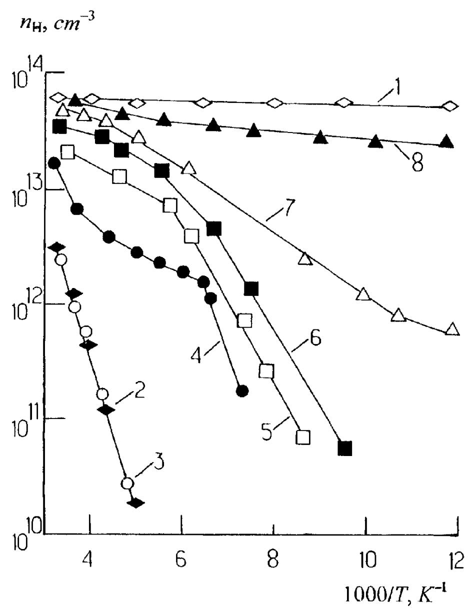

Fig. 1. Temperature dependences of the electron Hall concentration in silicon crystals before irradiation (*1*), after irradiation by 25-MeV protons to a dose of 8.1×10^{12} cm^{-2} (*2*), and after 10-min annealing at 80, 110, 120, 150, 290, and 380 °C (curves *3*—*8*, respectively)

The dependences of the electron concentration on the reciprocal temperature were monotonous in all investigated specimens (Fig. 1). At relatively low $T_{\rm ann}$, they have little variations, but, if the annealing temperature of the IA increases further, they shift upwards gradually. In contrast to $n_{\rm H}$, the values of $\mu_{\rm H}$, measured at a certain temperature T, manifest a nonmonotonous behavior, being regarded as a function of the annealing temperature (Fig. 2). For example, the electron Hall mobility in the irradiated specimen occurs markedly higher after the annealing at 80 °C (curve *3*) than that in the initial one (curve *1*) and decreases abruptly if the temperature of the specimen increases. At the same time, the annealing at 110 °C (curve *4*) results in the appearance of two minima on the curve $\mu_{\rm H}(T)$, where the values of $\mu_{\rm H}$ is about one tenth as much. The annealing at 120 °C (curve *5*) increases $\mu_{\rm H}$ again, and so on until the annealing temperature $T_{\rm ann}$ reaches the value of 380 °C, where, in essence, the temperature dependence of the electron Hall mobility, characteristic of a non-irradiated crystal, is restored and does not change more.

One can understand the revealed oscillation of the electron Hall mobility vs. the annealing temperature taking into account the concentration variations of those radiation-induced defects that are capable to affect the mobility of current carriers in silicon.

The temperature dependence of the electron Hall mobility in the initial specimen testifies for that the phonon mechanism of current carrier scattering dominates in the temperature range of measurements. Therefore, the shifts of the initial curve $\mu_{\rm H}(T)$ upwards after the IA of the irradiated specimen cannot be explained on the basis of the concentration decrease of certain scattering defects in a crystal. Such high values for the mobility, obtained in Hall experiments, are an indicator of the formation of relatively high-conducting inclusions in a specimen with ohmic junctions at the interfaces with a semiconductor matrix [1]. In this case, according to the theory of effective medium, the Hall concentration of current carriers is determined, in essence, by the value of their concentration in a relatively low-conducting matrix, whereas the Hall mobility is an increasing function of the volume fraction c of inclusions. In particular, if inclusions, for the sake of simplicity, are assumed to have a spherical form, then $\mu_H/M_H \approx (1 + 3c)/(1 - 6c)$, where M_H is a Hall mobility of current carriers in the matrix. Since the point radiation-induced defects in silicon can only weakly affect the electron transport at ambient temperature, the corresponding value of the electron Hall mobility in the initial specimen, being approximately of 1600 $cm^2/(V \cdot s)$, may be used for the parameter M_H. At the same time, the Hall mobility value, measured at ambient temperature after the irradiation and annealing at 80 °C, equals about 4400 $^2/(V \cdot s)$. Therefore, $c \approx 0.09$, which is a reasonable assessment of the total volume fraction of interstitial atom clusters, characteristic of the real silicon structure after the irradiation by light ions and the thermal treatment [2]. We explain a high conductivity of those inclusions, with respect to the remaining part of the crystal, by the accumulating of doping phosphorus atoms in them and by a reduction of the electric activity of the latter in the matrix, i.e. by the formation of a E-center (the complex of a P atom and a vacancy V) in a neutral state rather than an ionized doping P atom. An especially effective reduction of the electron number in the matrix should be expected at large irradiation doses, when the concentration of the E-centers $N_{P+V} > N_P/2$, i.e. more than a half of doping impurities is disabled, while electrons supplied by other P atoms are captured by deeper centers. The dependence $n_H(T)$ for an irradiated, but not annealed, specimen corresponds to the exhaustion of acceptor centers, which are characteristic of such a material, with the energy level of $(E_c - 0.54)$ eV [3]. Since the energy level of $(E_c - 0.44)$ eV is attributed to the E-centers, the latter have to be in a neutral state under the conditions concerned. At the annealing of the E-centers, only one electron returns into the conduction band. That is why the variation of the electron concentration Δn at ambient temperature in the specimens subjected to the IA at temperatures up to $T_{ann} = 150$ °C, when the dissociation of the E-centers finishes, equals to concentration of the E-centers before annealing. According to Fig. 1, $N_{P+V} \approx 3.5 \times 10^{13}$ cm^{-3}

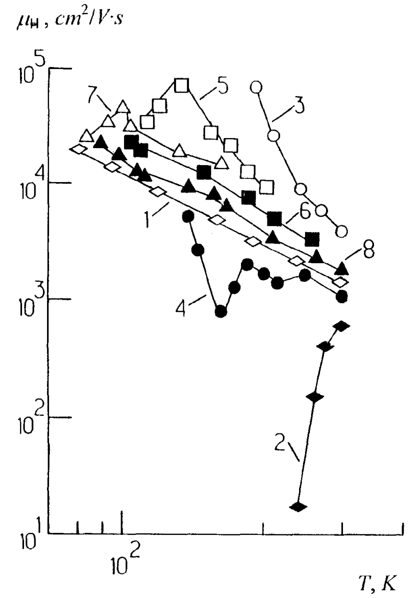

Fig. 2. The same as in Fig. 1 but for the electron Hall mobility

and, therefore, $N_{P+V} > N_P/2$ indeed. As the centers of that kind disappear, the impurity P-atoms become again free electron donors in the matrix, which is in agreement with a monotonous shift of the curve $n_H(T)$ upwards, when T_{ann} increases. A dissociation of the P+V complexes in the matrix and a decay of the cluster regions of interstitial atoms during the IA result in a leveling of the specimen inhomogeneities in the electrical conductivity and, hence, to an intensity moderation of the process leading to the growth of the effective value of the Hall mobility.

Concerning the phenomenon of the substantial reduction of the electron Hall mobility in irradiated silicon, which was also observed at the IA, it has a good qualitative substantiation in [4]. Namely, the radiation-induced defects affect the μ_H value in two ways, first, by a decrease of the drift mobility μ_D through the formation of scattering charged centers in groups and, second, by a variation of the Hall factor $r_H = \mu_H/\mu_D$ through the creation of the inhomogeneity of the potential distribution in the specimen. Moreover, we succeeded [5] in a quantitative description of the phenomenon in the framework of the model of thermal polarization of the pairs composed of electrically inactive radiation-induced defects. At a high concentration, such electric dipoles scatter current carriers rather effectively or lead to substantial fluctuations of the potential in the crystal. At the same time, the defect pair remains neutral as a whole in the polarized state as well and slightly affects the concentration of free electrons. In this case, two possible minima of the quantity $\mu_H = r_H\mu_D$ are inherited from those of r_H and μ_D. The indicated pairs of radiation-induced defects may be identified, e.g., as complexes of electrically inactive interstitial atoms. Similar complexes will be annealed with the increase of T_{ann}, which should increase the value of μ_H.

Thus, the observed oscillation of the electron Hall mobility values in irradiated silicon after the 10-min IA vs the annealing temperature can be regarded as a result of a simultaneous action of two mechanisms. The first one, being connected to the specimen inhomogeneity in electrical conductivity, leads to the growth of the effective value of the mobility, while the second one, resulting from radiation-induced complex defects, on the contrary, to its reduction.

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ОСЦИЛЯЦІЙНА ЗАЛЕЖНІСТЬ ХОЛЛІВСЬКОЇ РУХЛИВОСТІ ЕЛЕКТРОНІВ ВІД ТЕМПЕРАТУРИ ВІДПАЛУ В ОПРОМІНЕНОМУ КРЕМНІЇ

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Р е з ю м е

Температурні залежності холлівської рухливості електронів μ_H у монокристалах n-Si було виміряно як до, так і після їхнього опромінення протонами та проведення температурної обробки. Виявлено осциляції величини μ_H, виміряної при певній температурі у зразках, що піддавалися ізохронному відпалу при зростаючих температурах. Ефект пояснено конкуренцією між дисоціацією комплексних радіаційних дефектів і розпадом скупчень дефектів.