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Abstract

Full Text

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PHYSICS

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ENERGY SPECTRUM OF RADIATION DEFECTS

IN SILICON SINGLE CRYSTALS

The energy spectrum and concentration of radiation defects arising in silicon single crystals when they are irradiated with γ -quanta, fast electrons, and fast neutrons depend both on the dose and type of hard radiation and on the impurity composition of the material (¹⁻³). The presence of residual chemical impurities in many cases determines the spectrum of stable radiation defects that introduce deep energy levels into the forbidden band (⁴). To date, the largest number of local energy levels in irradiated silicon crystals has been detected by analyzing photoconductivity spectra (⁵). This is explained by the high sensitivity of the photoelectric-measurement method, since in irradiated silicon crystals an increase is usually observed in the signal corresponding to the relative photoconductivity $\Delta\sigma/\sigma I$ (where $\Delta\sigma$ is the change in conductivity under illumination, σ is the dark conductivity, and I is the power of the exciting light flux).

The aim of the present work was to determine the energy spectrum of levels appearing in silicon single crystals after their irradiation with various integral fluxes of fast electrons, neutrons, and γ -quanta. The fluxes of fast electrons with an energy of 1 MeV were $10^{13} \div 10^{18}$ el/cm², those of fast reactor neutrons $10^{12} \div 10^{19}$ n/cm², and those of γ -quanta $10^{15} \div 10^{19}$ quanta/cm² from a Co⁶⁰ source. The initial silicon crystals of *n*- and *p*-type had specific resistivities from 0.03 to 150 ohm · cm and contained residual chemical impurities introducing deep energy levels into the forbidden band at concentrations not exceeding $5 \cdot 10^{12}$ cm⁻³ (⁶). Both in unirradiated crystals and in crystals irradiated with various fluxes of hard radiation, the temperature dependence of conductivity, the temperature dependence of the Hall coefficient, and the spectral distribution of the photoconductivity signal were measured.

Measurement of the temperature dependence of conductivity and of the Hall coefficient showed that, in *n*-type silicon crystals, irradiation with γ -quanta, fast electrons, and neutrons most effectively introduces acceptor centers $E_c - 0.16$

Fig. 1. Photoconductivity spectra for n-type silicon

Figure 1: Fig. 1. Photoconductivity spectra for n-type silicon

Fig. 2. Photoconductivity spectra for p-type silicon ($T = 80^\circ\text{K}$)

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and -0.40 eV. Moreover, the rate of introduction of the $E_c - 0.40$ eV centers increases as the initial specific resistivity of the crystals decreases, whereas the rate of introduction of the $E_c - 0.16$ eV centers (an association of a vacancy with oxygen) does not depend on the specific resistivity. In p -type crystals, donor centers $E_v + 0.30$ and $+0.35$ eV were observed. The rate of introduction of the $E_v + 0.35$ eV centers is considerably higher in crystals grown in quartz crucibles than in crystals obtained by the zone-melting method in vacuum. Thus, in the case of neutron irradiation, for crystals with a specific resistivity of $24 \text{ ohm} \cdot \text{cm}$, the rate of introduction of $E_v + 0.35$ eV centers in zone-refined silicon is about $3 \cdot 10^{-2}$ centers per 1 cm^3 , whereas in pulled silicon it is $\sim 10^{-4}$ centers per 1 cm^3 for each neutron. It may therefore be assumed that the $E_v + 0.35$ eV centers are associated with associations of point defects with oxygen, the concentration of which in stretched crystals was $8 \cdot 10^{17} \text{ cm}^{-3}$, and in zonal crystals $2 \cdot 10^{16} \text{ cm}^{-3}$.

The energy spectrum of radiation defects was studied in more detail by measuring the spectral dependences of photoconductivity. Thus, Fig. 1 shows the spectral dependences for zonal n -type silicon with $\rho = 100 \text{ } \Omega \cdot \text{cm}$, irradiated with a fast-electron flux of $5 \cdot 10^{16} \text{ el/cm}^2$. Curve 1 was recorded at a temperature of 300°K , and curve 2 at 80°K . The structure observed on both curves in the region from 1.3 to 2.5μ is associated with the formation, as a result of electron irradiation, of centers introducing deep energy levels $E_c - 0.33$, -0.35 , -0.38 , -0.40 , and -0.50 eV. In addition, on curve 2 there are photoconductivity "steps" in the region of 1.7 and

Fig. 1. Photoconductivity spectra for n -type silicon

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2μ , which can be associated with ionization of centers introducing levels $E'_c - 0.72$ and -0.62 eV.

The strong decrease in the photoconductivity signal in the region of 1.85 and 2.7μ on curve 1 is associated with the formation, under irradiation, of trapping centers for minority carriers (holes), introducing levels $E_v + 0.67$ and $+0.46$ eV. Excitation of electrons from the valence band to the levels of these trapping centers leads to the appearance of long-wavelength optical quenching of photoconductivity in the region 2.2 - 2.8μ and of negative photoconductivity in the region $1.6 \div 1.9 \mu$. The strong increase in photoconductivity in the region below 1.3μ is associated with bipolar excitation of carriers from the valence band into the conduction band through trapping centers for electrons $E'_c - 0.16$ eV. Sim-

Fig. 3. Diagram of the energy levels of radiation defects in silicon. *I* – electrical measurements; *II* – photoelectric measurements; *III* – levels of some residual chemical impurities

Figure 3: Fig. 3. Diagram of the energy levels of radiation defects in silicon. *I* – electrical measurements; *II* – photoelectric measurements; *III* – levels of some residual chemical impurities

ilar photoconductivity spectra were also observed on crystals irradiated with comparatively small integral fluxes of fast neutrons ($10^{14} \div 10^{16}$ n/cm²) and γ -rays ($10^{16} \div 10^{19}$ quanta/cm²).

As the irradiation dose increases, a “smearing” of the structure in the photoconductivity spectra is observed, and only several different centers can be clearly distinguished. Thus, Fig. 2 presents the spectral dependences of photoconductivity for *p*-type silicon with $\rho = 25 \Omega \cdot \text{cm}$ (curve 1) and $\rho = 100 \Omega \cdot \text{cm}$ (curve 2), irradiated with an integral neutron flux of $5 \cdot 10^{18}$ n/cm². In the spectra, rises of photoconductivity are clearly visible in the regions of 3.2, 2.8, and 1.8 μ , which can be associated with the transition of electrons from the valence band to the levels of centers $E_v + 0.38$, $+0.45$, and $+0.70$ eV. The large photoconductivity signal in the wavelength region

less than 1.5 μ can be explained by the fact that, at high irradiation doses, a significant concentration is formed of centers introducing energy levels in the upper part of the forbidden band.

The spectrum of energy levels of radiation defects, which can be determined from photoelectric and electrical measurements, depends strongly on the magnitude of the irradiation dose. Fig. 3 presents a diagram of the energy levels that are found in all the silicon crystals we studied when analyzing the photoconductivity spectra of *n*- and *p*-type samples irradiated with various integral fluxes of fast electrons, neutrons, and γ -quanta (11). Some centers are also detected by analyzing the temperature dependences of the specific conductivity and the Hall coefficient. However, it was not possible to detect the centers $E_c - 0.03$ and $+0.05$ eV (1), which had previously been attributed to point defects (7). Our experiments make it possible to suppose that point defects give an almost continuous set of local levels near the conduction band and the valence band, which is associated with different separations of vacancy-interstitial-atom pairs. These pairs, evidently, may be stable even at room temperatures in strongly irradiated crystals. Some of the observed deep centers may be associated with levels of residual chemical impurities, whose detection in irradiated crystals is facilitated both by the increase of $\Delta\sigma/\sigma I$ (as indicated above) and by the “manifestation” of residual impurities as a result of an increase in their electrically active component.

Fig. 3. Diagram of the energy levels of radiation defects in silicon. *I* – electrical measurements; *II* – photoelectric measurements; *III* – levels of some residual

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