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**Abstract**

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# PHOTOCONDUCTIVITY IN GERMANIUM DOPED WITH GROUP-V IMPURITIES AT PHOTON ENERGIES LOWER THAN THE IMPURITY IONIZATION ENERGY

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As is known, the ionization energy of shallow donors in germanium differs somewhat for different impurities and has a value from $\sim 10$ to 14 meV. In particular, for antimony in germanium the ionization energy of the ground state, according to various authors, lies within the range $9.9 \div 10.2$ meV ([1,2]). Correspondingly, impurity photoconductivity in such a material should have a long-wavelength edge near $120\,\mu$. We investigated impurity photoconductivity in samples of germanium doped with antimony (Sb concentration $\sim 3 \cdot 10^{15}$ cm$^{-3}$) and germanium doped with arsenic (As concentration $\sim 1 \cdot 10^{15}$ cm$^{-3}$). As it turned out, photoconductivity is also observed at photon energies substantially smaller than the impurity ionization energy. In Fig. 1 a portion of the spectral-dependence curve of photoconductivity is shown for samples doped with antimony for wavelengths $\lambda$ greater than $120\,\mu$ ($h\nu < 10$ meV); the sample temperature was $T \approx 10^{\circ}$ K.

As can be seen from the figure, a series of maxima appears distinctly on the curve. The same figure gives the optical-absorption spectrum for germanium doped with antimony ($N_{\mathrm{Sb}} \sim 7 \cdot 10^{14}$ cm$^{-3}$), taken by us from Ref. ([2]), as well as a scheme of optical transitions of an electron to excited states of Sb atoms in Ge. The positions of the maxima on the photoconductivity curve correspond to peaks on the optical-absorption curve. In the photoconductivity, optical transitions are manifested both from the ground singly degenerate state and from the split-off triply degenerate state. The photoconductivity maxima are shifted toward longer wavelengths relative to the absorption peaks by approximately 0.1 meV, which may be connected with measurement errors.

A similar picture also occurs for the photoconductivity of germanium samples doped with arsenic. In this case as well, photoconductivity is observed at photon energies lower than the ionization energy of As (14 meV), and maxima appear on the spectral curve whose positions correspond to the peaks of optical absorption in this material. Thus, the photoconductivity described must be attributed to optical transitions of electrons to excited states within the impurity centers.

Figure 1

Figure 1: Figure 1

Concerning the mechanism of such photoconductivity, several assumptions may be put forward. It may be connected with conduction through partially overlapping excited states. In the present case this is doubtful, since the lifetime of electrons in the excited states is apparently too short to provide appreciable photoconductivity. Nor is it possible to connect the phenomenon described with the ejection of electrons from excited states by an electric field (similar to what was observed in Ge doped with copper ([3])), since changing the field strength from 0.5 to 7 V/cm does not lead to a change in the form of the photoconductivity curve. We believe that the contribution of excited states to impurity photoconductivity is provided by the participation of phonons in transitions of electrons from impurity levels into the conduction band. In

this may involve either sequential or simultaneous absorption of a photon and a phonon (in the latter case the transition to excited states should be regarded as virtual). The strong temperature dependence

**Fig. 1.** **a**—long-wavelength region of the spectral dependence of the photoconductivity of Ge:Sb ($N_{Sb} \sim 3 \cdot 10^{15}$ cm$^{-3}$); **b**—spectrum of optical absorption of Ge:Sb ($N_{Sb} = 7 \cdot 10^{14}$ cm$^{-3}$) ([2]); **c**—scheme of optical transitions from the ground states of shallow donors in Ge ($E_0$—ground state of an electron at a donor center in the effective-mass approximation; $\lambda$—displacement of the center of gravity; $4\Delta$—splitting of the ground state)

of the photoconductivity described here argues in favor of such a mechanism. A more detailed investigation of this phenomenon will make it possible to refine the mechanism of its occurrence.

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*Note: Figure translations are in progress. See original paper for figures.*