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IMPURITY PHOTOCONDUCTIVITY SPECTRA OF p-TYPE GERMANIUM WITH Ga, Hg, Au, AND Ni IMPURITIES

I. A. KUROVA, N. N. ORMONT, and V. V. OSTROBORODOVA

Moscow State University

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The impurity photoconductivity spectra of p-type germanium with partially compensated for Ga (0.01 eV), Hg (0.087 eV), Au (0.15 eV), and Ni (0.2 eV) levels were investigated at temperatures between 6 and 10°K. Oscillations, i.e., a set of equidistant (0.037 eV) minima, were observed in the Ge with Ga spectra. The relative depth of the minima (K, %) depend on the lifetime of the holes τ_0 in the sample, decreasing with its increase. The dependences of K on the field strength and on the temperature agrees qualitatively with the respective dependences for τ_0. For equal recombination-center concentrations, the depth of the minima in the photoconductivity spectra of Ge with Hg is much less than that of Ge with Ga. No oscillations were observed in spectra of Ge with Au or Ni. The results obtained, together with those of a previous paper [1], indicate that for equal lifetimes the oscillation depth decreases with growth of the ionization energy of the impurity centers. Some suggestions are made regarding the possible causes of the effect.

In a preceding paper [1] we investigated the spectra of impurity photoconductivity of p-type Ge with partially compensated first acceptor levels (1A) of Cu (0.04 eV), Zn (0.03 eV) and Cd (0.05 eV) and donor level (D) of Au (0.04 eV) in order to establish the regularities of the oscillation effect [1-4]. It was found that there were no oscillations in the absorption spectra, and consequently the phenomenon was connected with singularities of the conductivity of the samples in the presence of excited holes with different energies in the band. For each group of samples with a given impurity, we observed a correlation between the relative depth of the oscillations and the concentration of the recombination centers, and also a difference in the depth of the oscillations for impurities with different ionization energies. It was deemed of interest to obtain additional data to confirm the connection between the depth of the oscillations and the carrier lifetime, and also to carry out investigations with samples in a broader interval of ionization energies of the impurity centers.

We have investigated in the present work the photoconductivity spectra of p-type germanium with partially compensated levels A Ga (0.01 eV), 1A Au (0.15 eV), 1A Hg (0.087 eV), and 1A Ni (0.3 eV). The characteristics of the investigated samples are listed in the table. The concentrations of the main impurity and of the recombination centers were determined from the temperature dependence curves of the Hall constant. The impurity-photoconductivity spectra were investigated with the same apparatus as in [1]. To increase the resolving power of the NaCl prism in the 0.26—0.6 eV photon energy range, the Littrow mirror in the IKS-21 was replaced with a replica.

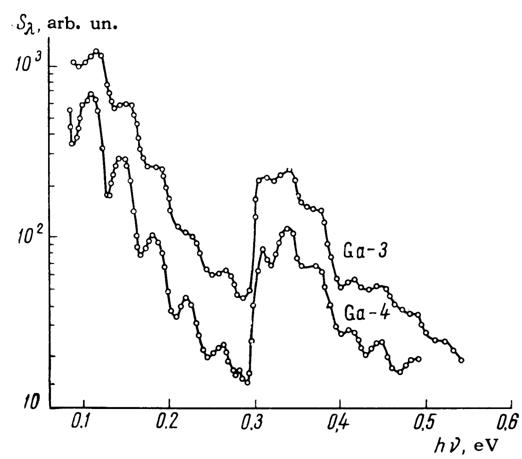

FIG. 1. Spectra of impurity photoconductivity of Ge with Ga, T ≈ 6.5°K, E = 1.5 V/cm.

Figure 1 shows the impurity-photoconductivity spectra of the samples with Ga. By virtue of the factors noted in [1], the spectra start from 0.09 eV. It is seen from the figure that the spectra have a series of equally-spaced minima 0.037 eV apart. The photoresponse in the photon energy region

Sample	Concentrations*, cm^{-3} $10^{-14}N$	$10^{-14}N_{rc}$	$10^{-14}N_{sc}$	K_3, %
Ga-1	2.2	0.7	1.4	15
Ga-2	12.0	1.1	2.2	36
Ga-3	38.0	1.3	2.6	40
Ga-4	15.7	13.7	27.4	68
Hg-1	5.5	1.5	3.0	9
Ni-1	46.0	10.0	20.0	0
Au-1	2.5	1.8	3.6	0
Au-2	8.7	5.4	10.8	0

*N – concentration of main impurity, N_{rc} – concentration of recombination centers, N_{sc} – of scattering centers.

$h\nu \geq 0.3$ eV shows a growth which is apparently connected with the fact that the split-off valence band participates in the photoconductivity processes [5]. However, the oscillations form one system of minima over the entire spectrum. The last column of the table gives the relative depth of the third minimum (the second on Fig. 1) for different samples. It is seen from the table that the depth of the oscillations increases with increasing concentration of the recombination centers, thus confirming the previously expressed assumption that they are connected with the carrier lifetime.

We have investigated the photoconductivity spectra under conditions when the lifetime in the given sample changed under the influence of the temperature or the field. It is known[6-8] that in the case of capture by an attracting center the carrier lifetime increases with increasing temperature and consequently the depth of the oscillations should decrease. Figure 2 shows the temperature dependence of the relative depth of the third minimum K_3 for one of the sample. The same figure shows the temperature dependence of the specific resistivity, which was measured simultaneously with the photoconductivity spectra. It is seen from the figure that the depth of the oscillations decreases with

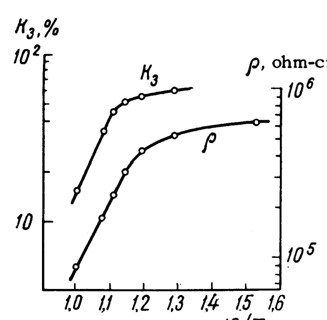

FIG. 2. Temperature dependence of the depth of the third minimum on the spectrum of the sample Ga-4 and temperature dependence of the specific resistivity of this sample under the same conditions, E = 1.5 V/cm.

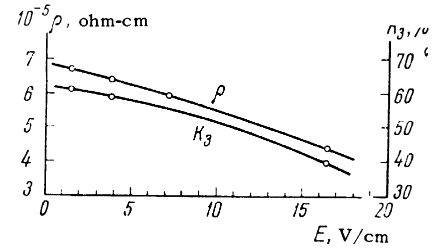

FIG. 3. Dependence of the relative depth of the third minimum on the spectrum of sample Ga-4 and of the specific resistivity of this sample on the electric field intensity ("breakdown" field E ≈ 19 V/cm), T ≈ 7°K.

increasing temperature. The weakening of the temperature dependence in the region of the background generation of carriers may be connected with the weakening of the temperature dependence of the lifetime. It must be noted that similar results were obtained with samples with 1A Zn and 1A Cd.

Koenig and Gunther-Mohr [9] and Abaulina-Zavaritskaya [10] have shown that in Ge samples with shallow impurities the mobility remains constant with increasing field intensity, and the lifetime increases. We have carried out simultaneous investigations of the dependence of the specific resistivity and depth of the third minimum on the field intensity. The results of the investigations for one of the samples are shown in Fig. 3. Assuming that the decrease in ρ is due to the increase of the lifetime, we can propose that the decrease in K_3 is caused by the same factors.

The relative depth of the oscillations as a function of the lifetime $\tau_0 = 1/\alpha_p^- N_{rc}$ is shown in Fig. 4. The coefficient α_p^- for the capture of a hole by a negatively charged Ga atom at 8°K was assumed close to the coefficient for the capture of an electron by shallow donor centers[11]. We have based ourselves here on the fact that, according to Lax's cascade theory of capture[6], the capture coefficients for hydrogenlike centers should differ little, in qualitative agreement with the experimental data on silicon[12,13]. The same figure shows the analogous relations obtained in[1] for Ge with impurities 1A Zn, D Au, and 1A Cu. We see from the

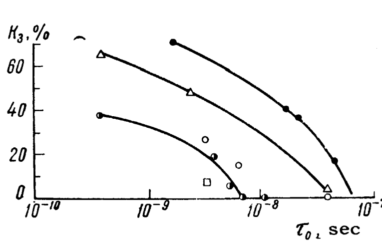

FIG. 4. Dependence of the relative depth of the third minimum on τ_0 for samples with impurities: ● – A Ga (0.01 eV), △ – 1A Zn (0.03 eV), ◑ – 1A Cu (0.04 eV), ○ – D Au (0.04 eV), □ – 1A Hg (0.087 eV); T ≈ 8°K, E = 1.5 V/cm.

figure that for the same value of τ_0 the relative depth of the oscillations is different for different impurities, decreasing with increasing ionization energy.

In order to obtain a more complete picture of this dependence, we have investigated the spectra of impurity photoconductivity of p-type Ge with partially compensated levels 1A Hg, 1A Au, and 1A Ni. Weak oscillations with $K_3 = 9\%$ were observed in the spectrum of the sample with Hg. Based on the data of Kaufman and Kulikov [14] concerning the capture cross section σ_p^{-1}(Hg) at T = 55°K, and assuming it to be $\sim 10^{-12}$ cm^2 at 7°K, we obtained $\tau_0 \approx 3 \times 10^{-9}$ sec and the corresponding point on Fig. 4. Figure 5 shows the impurity photoconductivity spectra of samples with 1A Au and 1A Ni. We see that there are no oscillations there. At the same time, the concentration of the recombination centers in them, given in the table, offers evidence of very small times τ_0 [12,13], smaller than in the samples with Ga, Zn, Cu and D Au, where oscillations were observed. These data agree with the observed general rule that the depth of the oscillations decreases with increasing ionization energy of the impurities.

One of the possible causes of the decrease in the depth of the oscillations, along with the increase of τ_0, may be the scatter of the energies of the holes (in the band) excited by the proton of given energy. This scatter may be connected, for example, with the presence of a certain interval ΔE_i [15] in the ionization energies of different impurity atoms, the absolute value of the interval increasing with increasing E_i. However, the decrease in the depth of the oscillations with increasing impurity ionization energy can be connected with processes of photoionization and recombination on deep centers and singularities of the oscillation phenomenon itself, whose mechanism has so far not been made clear. In this connection, we find it important to note the following.

According to Habegger and Fan [16], in order for oscillations to appear in the photoconductivity spectra it is necessary to satisfy the condition $\tau_0 < \tau_a$, where τ_a is the relaxation time of the carrier energy over the acoustic phonons. We have calculated this value for germanium by means of the formula [17]

$$\tau_a = \pi\hbar^4\rho / 2\sqrt{2}m^{*2.5}E_1^2\bar{\varepsilon}^{1/2}$$

with $m^* = 0.28m_0$, $E_1 = 10$ eV, and $\bar{\epsilon} = 0.02$ eV, and obtained $\tau_a = 10^{-10}$ sec. We have thus observed oscillations under the conditions $\tau_0 > \tau_a$. At the same time, if we use for the estimate the effective mass of the light holes ($m^* = 0.04m_0$), then $\tau_a = 10^{-8}$ sec.

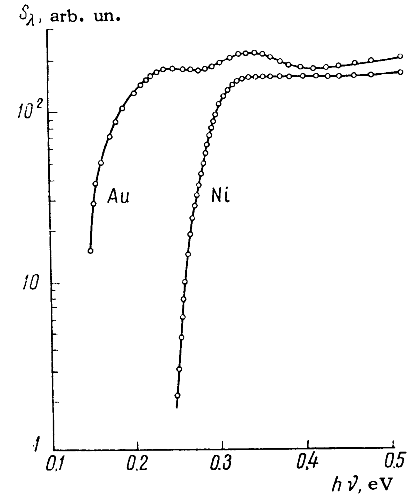

FIG. 5. Spectra of impurity photoconductivity of Ge with 1A Au and 1A Ni; T ≈ 8° K, E = 1.5 V/cm.

It therefore seems probable that the light holes participate in the processes responsible for the appearance of oscillations. This assumption, however, calls for serious theoretical and experimental investigations.

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