different form [6]:

$$\Delta L^{(e^2)} (CP = +1, P = +1, |\Delta S| = 1 \approx a_3 27_{3/2} + a_2 27_{1/2} + a_1 8^*_{1/2} + h. c.,$$

where

$$a_3 = 1, \quad a_2 = \frac{1}{\sqrt{5}}(4 - 3x), \quad a_1 = \frac{1}{\sqrt{5}}(7 - 4x).$$

PHOTOELECTRIC SPECTROSCOPY OF IMPURITIES IN SEMICONDUCTORS

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Photothermal ionization of impurities, a phenomenon observed and investigated in germanium doped with impurities of group III or V, was reported in [1-4]. We recall that the gist of this phenomenon consists in optical excitation of the impurity center with subsequent absorption of one or several photons. As a result of such a process, the carrier goes over into one of the free bands of the crystal, where it can take part in the charge-transport processes. Thus, the photothermal ionization of the impurities leads to the occurrence of photoconductivity whose spectral distribution constitutes under certain conditions a system of lines located in the photon energy region below the impurity ionization energy. The number of these lines and their arrangement on the wavelength scale is a reflection of the energy spectrum of the states produced by an impurity of a given type in the crystal.

In the present note we wish to point out one feature of the photoconductivity, connected with photothermal ionization of the impurities. This feature makes it possible to use this ionization to reveal very small amounts of impurities in a semiconductor and to establish their chemical nature.

It is known that the energy spectrum of an impurity center in a crystal can be determined by measuring the optical absorption spectra of the corresponding materials. However, the magnitude of the impurity optical absorption is connected linearly with the concentration of the impurities, and decreases with decrease of the latter. Therefore such measurements can be made in materials having not too low an impurity concentration. For example, in germanium with impurities of groups III and V, the impurity absorption is small even at a concentration $\sim 10^{14}$ cm^{-3}, and its measurement is a difficult task, which becomes practically impossible at a concentration $\sim 10^{13}$ cm^{-3}.

To the contrary, the photoresponse of the impurity photoconductivity (the ratio of the signal voltage to the power of the incident radiation), which is proportional to the relative change of the carrier density upon irradiation, $\Delta n_{phot}/n_{dark}$, does not depend on the impurity concentration or on the method of impurity compensation (see [5]). The photoconductivity due to photothermal ionization, on the other hand, even increases noticeably when the impurity concentration decreases, and its spectral lines, which characterize the chemical nature of
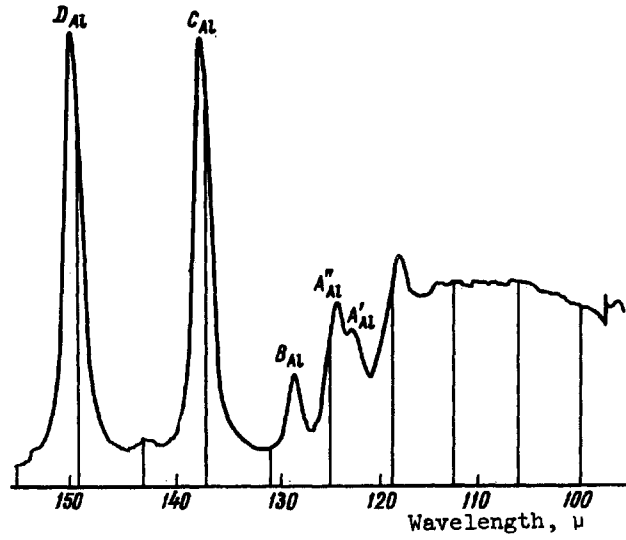
Fig. 1. Long-wave section of the photoconductivity spectrum of germanium with a differential impurity concentration $N_a - N_d = 3 \times 10^{11}$ cm^{-3}, $T = 8°$K.

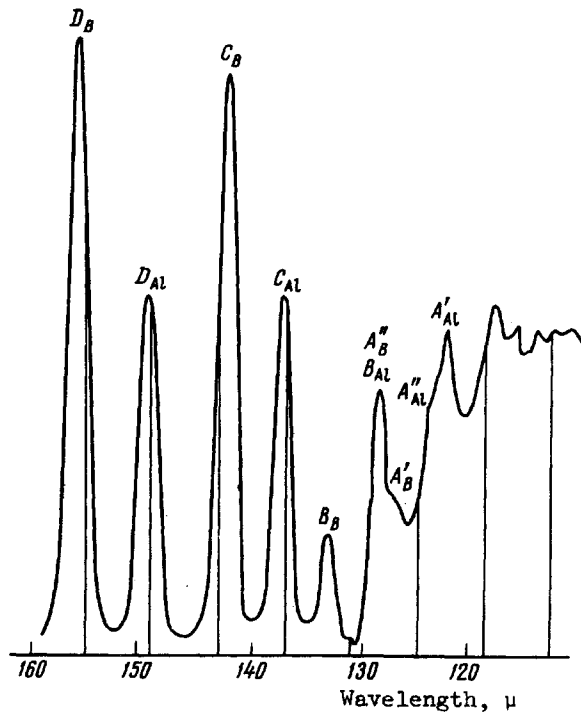

Fig. 2. Long-wave section of the photoconductivity spectrum of germanium with a differential impurity concentration $N_a - N_d = 1 \times 10^{12}$ cm^{-3}, $T = 10°$K.

the impurities, become narrower and their height increases. This is a manifestation of the decrease in the action exerted on the impurity centers by the fields of the randomly arranged neighboring impurity atoms. Whereas in samples with relatively high impurity concentration $(10^{13} - 10^{14}$ cm$^{-3})$ the lines in the photoconductivity spectrum are produced only when the sample temperature exceeds that of liquid helium by several degrees, in samples in which the impurity concentration is very small $(10^{11} - 10^{12}$ cm$^{-3})$ these lines are clearly visible even at a temperature 4.2°K, and when the temperature is raised to 10°K their height becomes larger than the signal at the maximum of the ordinary impurity conductivity.

The optical-absorption lines should also become narrower and higher with decreasing impurity concentration, as compared with the absorption maximum corresponding to optical ionization of the impurities. This effect, however, is not very significant against the background of the decreased absorption with decreasing concentration of the absorbing centers.

Figures 1 and 2 show the photoconductivity spectra of two of the purest germanium samples at our disposal.[*] Both samples were of the p-type. The concentration of the uncompensated acceptors, determined from measurements of the Hall coefficient at liquid-nitrogen temperature, was 3×10^{11} cm^{-3} and 1×10^{12} cm^{-3} in the first and second samples, respectively. The sections of the curves in the wavelength region $\lambda < 120$ μ correspond to ordinary impurity photoconductivity. The photoresponse upon irradiation of the sample with low-power radiation from a monochromator $(10^{-7}$ W) was 0.1 - 1 mV, a value easily measured with the aid, say, of a simple voltage amplifier for the audio band. Each of the spectra was obtained within a measurement time of approximately 10 min at an instrument time constant 2 sec.

The optical impurity absorption spectra are by now well known for all impurities of groups III and V in germanium [6,7]. It suffices to simply superimpose these spectra on the curves of Figs. 1 and 2 to see immediately that the first sample contains only one shallow acceptor, aluminum, and the second contains two, boron and aluminum.

Inasmuch as the total concentration of the uncompensated acceptors, as already mentioned, is known, we can determine the concentration of each of the impurities separately. Thus, the proposed method, which we call the method of photoelectric spectroscopy of impurities in semiconductors, is already shown by the obtained data to be superior in sensitivity to other known methods, at least for impurities of groups III and V in germanium. At the same time, the form of the spectra of Figs. 1 and 2 shows that this method can be used to detect and establish the chemical nature of impurities of groups III and V in germanium in those cases when their concentration is much lower than 10^{11} cm^{-3}. One can likewise not exclude the possibility of extending the use of the described method to other semiconductors and other impurities, as well as determining the total donor and acceptor concentration in the material by using the well known phenomenon of optical charge exchange of impurities.

[1]   T. M. Lifshitz and F. Ya. Nad', Dokl. Akad. Nauk SSSR 162, 801 (1965) [Sov. Phys.-Dokl. 10, 532 (1965)].
[2]   Sh. M. Kogan and B. I. Sedunov, Fiz. Tverd. Tela 8, 2382 (1966) [Sov. Phys.-Solid State 8, 1898 (1967)].
[3]   V. I. Sidorov and T. M. Lifshitz, ibid. 8, 2496 (1966) [8, 1998 (1967)].
[4]   T. M. Lifshitz, F. Ya. Nad', and V. I. Sidorov, ibid. 8, 3208 (1966) [8, 2567 (1967)].

[5] V. I. Sidorov and T. M. Lifshitz, Radiotekhnika i elektronika 7, 2076 (1962).
[6] R. L. Jones and P. Fisher, J. Phys. Chem. Sol. 26, 1125 (1965).
[7] I. H. Reuszer and P. Fisher, Phys. Rev. 135, 1125 (1964).
[8] S. M. Ryvkin, Fotoelektricheskie yavleniya v poluprovodnikakh (Photoelectric Phenomena in Semiconductors), Fizmatgiz, 1963, p. 267.

E R R A T A

The article by G. A. Askar'yan et al., V. 5, No. 5, p. 150 (transl. p. 121) calls for the following errata and comments:

1. The sweep durations on the oscillograms of Fig. 1 are incorrectly marked. Instead of 100 msec, 1 msec, and 10 msec read 100 nsec, 1 μsec, and 10 μsec (as written in the text).

2. The formula for the fireball lifetime (more accurately, the expansion time of the fireball, which should be compared with the duration of the diamagnetic perturbation) contains errors.

It should read $T_{FB} \simeq BE^{1/3}$, where $B \simeq 0.3 \, \text{sec}/(\text{kt})^{1/3}$ and E is the explosion energy in kilotons.

3. At high temperatures, when the adiabatic constant of the gas $\gamma \to 1$, the main energy of the shock wave is contained in the internal energy of the gas behind the compression layer, but since this energy is proportional to the kinetic energy, all the relative estimates (evaluation of conditions) of the detachment of the shock wave from the fireball, based on the assumed equality of the wave kinetic energy to the initial released energy, remain in force, but in absolute estimates of the velocity and time of detachment it is necessary to introduce a coefficient that takes into account the difference between the total and kinetic energies of the shock wave.

A more detailed theory of fireballs with allowance for the losses will be published soon.

In the article by L. I. Korsunov et al., V. 7, No. 2, p. 42 of the translation, the word "multiphonon" in the title and the first two sentences of the article should be "multiphoton."