ENERGY SPECTRUM OF FREE EXCITONS IN GERMANIUM

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We use the absorption and photoconductivity measured at submillimeter wavelengths to plot the energy spectrum of free indirect excitons in germanium.

Experimental observation of free excitons in Ge in the submillimeter band with the aid of spectrometers using backward-wave tubes was reported in [1 — 3]. In the energy band $\varepsilon = 3.2 - 3.65$ meV, three well-resolved lines were observed in the absorption and photoconductivity spectra and were due to transitions of indirect free excitons from the ground to the excited state. In [4] are given results of an investigation of the absorption spectra in a wider range of frequencies, corresponding to $\varepsilon = 1.7 - 3.7$ meV. Two series of lines of exciton transitions to excited states (with strong and weak dependence on the temperature) were obtained, and the splitting of the ground state of the exciton ($\Delta = 0.7$ meV) was obtained from the temperature dependence of the line intensity.

We have performed experiments in which, besides measuring the absorption spectra, we investigated also the photoconductivity. This has enabled us to determine from the aggregate of the data not only the transition energies, but also the free-exciton energy spectrum itself. The measurements were performed on Ge samples with impurity concentration $\lesssim 10^{12}$ cm^{-3}in the range $\varepsilon = 2.5 - 5$ meV at $T = 1.6 - 4.2$°K at low levels of the optical excitation (the concentration n_e of the free exciton did not exceed 5×10^{12} cm^{-3}).

Figure 1a shows the characteristic absorption spectra at T = 4.2°K and T = 1.6°K, while Fig. 1b shows the corresponding photoconductivity spectra. The latter were obtained in weak electric fields (∿ 0.1 V/cm), where the lines of the transitions of the excitons into the excited state have low intensity [1], but the edge of the nonresonant photoconductivity can be clearly seen.

As seen from Fig. 1a, the absorption spectrum reveals a number of narrow lines; the energies of the intense lines coincide within the limits of experimental accuracy (∿ 0.01 meV) with the data of [4]. When the temperature is

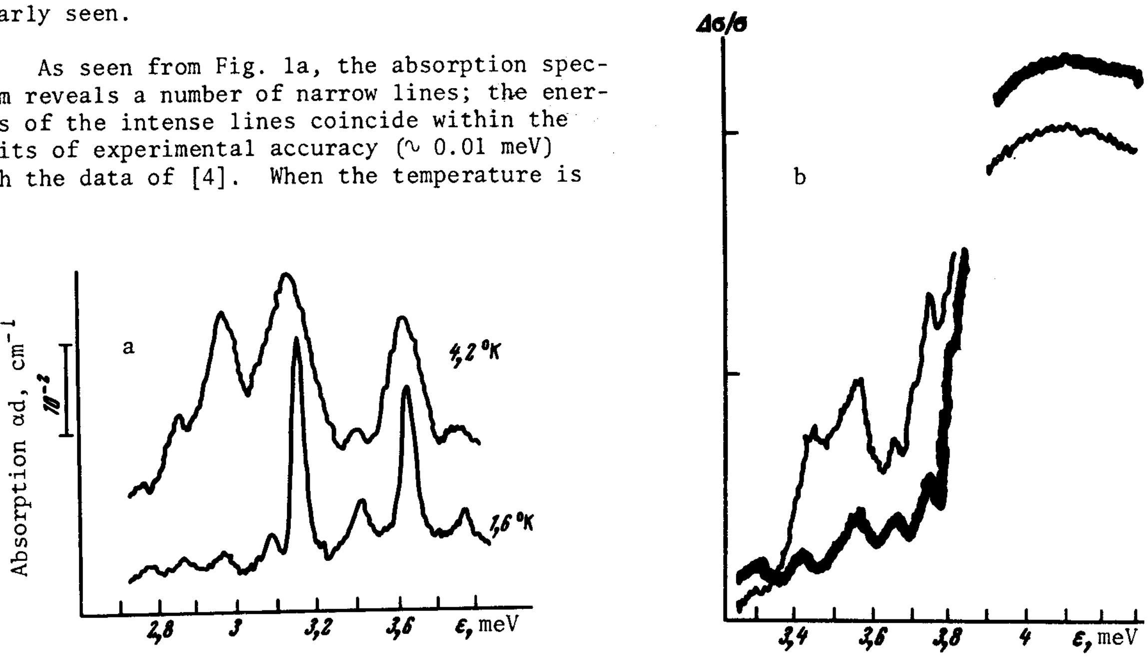

Fig. 1. a) Ge exciton-absorption spectrum (for convenience in the analysis, the individual curves are vertically separated, and the scale of αd is shown along the ordinate axis).
b) Photoconductivity spectrum of Ge (the thin and thick lines show the spectra at T = 4.2°K and 1.6°K, respectively).

decreased below 4.2°K, the intensities of the absorption lines with energies ε = 2.76, 3.14, 3.29, 3.42, 3.56 meV does not change noticeably. The intensities of the remaining lines (ε = 2.85, 2.97, and 3.07 meV) decreases, just as in [4]. The photoconductivity spectra show at T = 1.6°K a long-wave photoconductivity edge with energy 3.8 meV 1), and when T is raised to 4.2°K an additional nonresonant photoconductivity band appears, with a long-wave edge 3.4 meV.

The presence of two groups of lines with different temperature dependences and the appearance of a second long-wave photoconductivity edge when the temperature is raised suggest that the ground state of the free exciton in Ge is split into two levels with energies 3.8 and 3.4 meV.

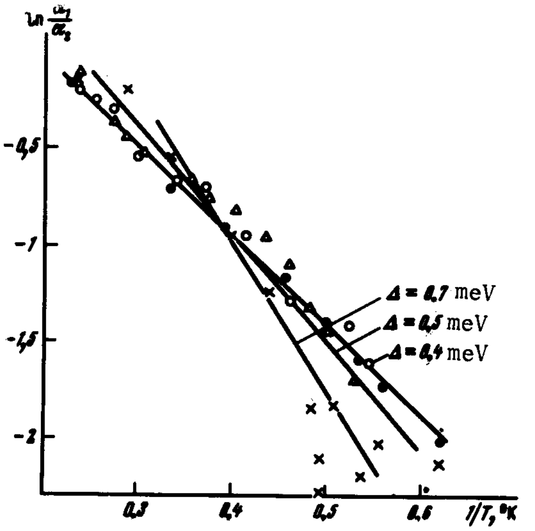

Fig. 2. Temperature dependence of the absorption α_1/α_2: ● — for the 2.97-meV line (sample 1), Δ — for the 2.87-meV line (sample 1), ○ — for the s.87-mev line (sample 2), × — results of [4].

The splitting of the ground state can also be determined from the temperature dependence of the absorption-line intensity, as was done in [4]. Figure 2 shows the measured temperature dependence of the absorption coefficient for the 2.85 and 2.97 meV lines for two Ge samples. The figures show also the data of [4]. We see that our measurements and the data of [4] agree well. However, the experimental points obtained in independent measurements have such a spread that it is impossible to determine uniquely, in such a small temperature interval, the character of the dependence of $\ln(\alpha_1/\alpha_2)$ on $(1/T)$, (α_1 is the absorption coefficient for the lines whose intensity depends on T, and α_2 is the absorption coefficient for one of the T-independent lines with ε = 3.42 meV). Nonetheless, the majority of the points fit a straight line with slope 0.4 — 0.5 meV, in good correlation with the photoconductivity data, which yield a splitting $\Delta \approx 0.4$ meV.

From the aggregate of the data on the photoconductivity and absorption, putting Δ = 0.4 meV, we constructed the energy spectrum of the free excitons in Ge. The obtained energies of the states are listed in the table:

Ground state	Excited states				
3,8 meV	**1,04**	**0,66**	**0,51**	**0,38**	**0.24**
3,4 meV	**0,55**	**0,43**	**0,33**	–	–

We note in conclusion that when the level of the optical excitation is increased ($n_e > 10^{13}$ cm^{-3} at 4.2°K), the intensity of the lines due to transitions from the lower level of the ground state begins to decrease sharply with decreasing temperature, thus evidencing the appearance of collective effects for the excitons. When T drops to 1.6°K, the intensity of this series of absorption lines changes by a factor as much as ~ 10 (when $n_e \approx 5\times10^{14}$ cm^{-3} at T = 4.2°K) for samples of thickness d = 2 mm. The $\alpha d(T)$ dependence changes significantly when the sample thickness is decreased, possibly as a result of the non-uniform distribution of the excitons over the sample and as a result of the influence of the sample surface.

At the same time, additional experiments performed by us at $n_e \lesssim 10^{12}$ cm^{-3} down to T = 0.5°K show that at such exciton concentrations αd does not depend on T in samples with different thicknesses, and no collective effects take place.

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1) In [5], using a long-wave IR grating spectrometer, the Ge exciton binding energy was found to be 4.15 meV.

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