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OBSERVATION OF THE FREE-EXCITON SPECTRUM AT SUBMILLIMETER WAVELENGTHS

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Excitons are usually investigated at optical wavelengths. Nonetheless, special interest attaches to their investigation at submillimeter wavelengths corresponding to the characteristic frequencies of the exciton transitions from the ground to excited states [1]. A detailed analysis of such transitions reveals, besides the energy spectrum of the free exciton, entirely new possibilities of investigating their interaction with one another or with phonons or free carriers, etc. Such experiments, however, have just barely begun. A wide absorption band in the 2 - 6 meV range was observed for germanium in [2] by methods of long-wave infrared spectroscopy. This band is probably attributable to unresolved exciton-transition lines at a sufficiently high temperature (~7°K) under conditions when the excitons interact strongly. To detect the transitions from the ground to the excited states of free excitons at low exciton concentrations and at low temperatures it is necessary to have more sensitive spectroscopic apparatus.

We have observed in germanium narrow lines of exciton transitions from the ground to the excited state, using a backward-wave-tube submillimeter spectrometer of much higher sensitivity and resolution [2, 3]. We used Ge samples with total impurity concentration $N_d + N_a \lesssim 10^{12}$ cm^{-3}, since experiments [3, 5] have shown that otherwise the effects due to impurities make an appreciable contribution to the absorption and the photoconductivity; the energy interval in which exciton lines should be observed corresponds to transitions between the excited states of the impurity and photoionization of the donor and acceptor centers. The experiments were performed in the wave bands 2000 - 500, 400 - 345, and 310 - 250 μ (the gaps on the spectrum are the results of our not having the corresponding radiation generators). The temperature ranged from 4.2 to 1.6°K, and the level of the optical generation of the electron-hole pairs was 10^{15} - 10^{17} cm^{-2}sec^{-1}. The exciton concentration n_e averaged over the sample did not exceed 10^{13} cm^{-3} (the sample thickness was ~1 mm), and the spectra could be recorded to $n_e \approx 10^{10}$ cm^{-3}.

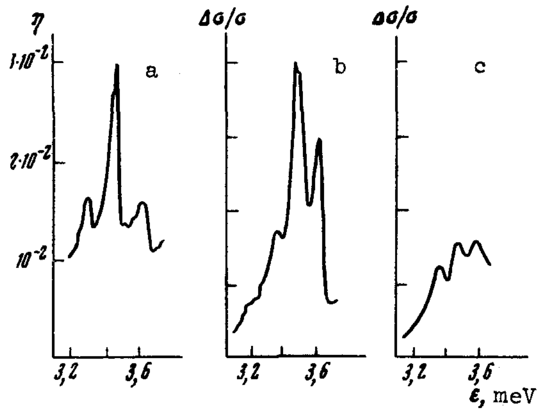

Fig. 1

Absorption and photoconductivity lines were observed in the energy interval 3.2 -

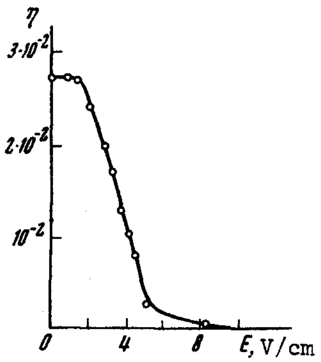

Fig. 2

3.6 meV, and nonresonant conductivity was observed in the interval 4 - 5 meV; both were due to the free excitons. Figure 1 shows the spectra of the absorption η (a) and of the photoconductivity $\Delta\sigma/\sigma$ (b) at T = 1.6°K, and the photoconductivity spectrum (c) at T = 4.2°K; the experiment was performed at $n_e \sim 10^{12}$ cm^{-3}.

The results show three well-resolved lines with energies 3.58, 3.42, and 3.3 meV, having a width ∿0.05 meV. The positions of the lines are the same in the absorption and photoconductivity spectra and do not depend on the temperature, but the relative intensities differ appreciably. The lines become broader when the temperature is increased.

The intensity of both the photoconductivity and of the absorption lines depends strongly on the electric field applied to the Ge sample. Figure 2 shows the dependence of the coefficient of absorption of the radiation by the sample, $\eta = P_{abs}/P_{inc}$ (P_{abs} and P_{inc} are the power absorbed by the sample and the incident power) on the electric field intensity, obtained for the 3.42-meV line at T = 1.6°K. Up to fields E ≃ 2 V/cm the absorption remains unchanged, and in the interval from 2 to 8 V/cm it increases by approximately two orders of magnitude. Reduction of the exciton concentration by one-half corresponds to E = 3 V/cm, which agrees well with the published data on impact ionization of excitons (e.g., [6]). The intensity of the photoconductivity lines at T = 1.6°K increases strongly when E is increased to 3.5 V/cm, after which it decreases. At T = 4.2°K one observes in weak fields only a slight growth of the line intensity.

An increase of the exciton concentration from 10^{10} to 10^{13} cm^{-3} does not lead to noticeable changes in the spectra, and the absorption of the radiation by the sample increases linearly and reaches 15%. The same results are obtained if the level of the optical excitation is kept constant and various samples with different exciton lifetimes are used.

The nonresonant photoconductivity in the energy interval from 4 to 5 meV is larger by approximately one order of magnitude than the photoconductivity line, and decreases strongly when E ∿ 3.5 V/cm is applied.

An analysis of the experimental results shows that the observed lines correspond to transitions of free excitons from the ground to excited states. The resonant photoconductivity is realized if the excitons excited by the submillimeter radiation dissociate under the action of phonons or of an electric field. The nonresonant conductivity is apparently connected with photoionization of free excitons.

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