OCCURRENCE OF A CONDENSED PHASE OF NONEQUILIBRIUM CARRIERS IN GERMANIUM

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It is known that in semiconductors such as germanium and silicon, the nonequilibrium electrons and holes combine at low temperatures into excitons [1]. At large exciton concentrations and at sufficiently low temperatures, the attraction between the excitons may turn out to be appreciable, so that the occurrence of a condensed phase in the exciton system is to be expected [2]. The results presented below, of an investigation of the recombination radiation of germanium at low temperatures, confirm the existence of such a phase.

Germanium samples with resistivity 50 ohm-cm at 300° K were immersed in liquid helium and excited either by modulated radiation from DRSh-250 mercury lamp, or by radiation pulses at different power and ∿ 1 μsec duration from an ISSh-100 xenon lamp. The excited radiation passed through a water optical filter and ensured surface generation of carriers in the germanium. The average power of the exciting radiation did not exceed several dozen milliwatts, thus precluding the heating of the samples [3]. The sample temperature was regulated by pumping off liquid helium. The recombination radiation was analyzed by a lattice spectrometer and registered with a small-area lead-sulfide photoresistor.

The number of nonequilibrium carriers introduced into the sample was determined from the sample photoconductivity at room temperature. We shall henceforth characterize the excitation level by means of the carrier density n_0 averaged over the volume of the sample. It was difficult to determine the true concentration of the nonequilibrium carriers in the samples at low temperatures, since we did not know the carrier spatial distribution. However, the total number of carriers introduced into the sample should not depend on the temperature, since the duration of the exciting light pulse was much shorter than the carrier lifetime $\tau > 10^{-5}$ sec at 4.2° K.

Figure 1 shows the recombination-radiation spectra of germanium at 4.2° K and at different excitation levels. We see that at the minimum excitation level the maxima of the radiation correspond to proton energies 714.2 and 706 meV. These maxima are connected with the recombination of the free excitons, accompanied by emission of longitudinal acoustic and transverse optical phonons [1]. The width of the maxima is ≈ 2 meV and is determined by the thermal motion of the excitons and by the insufficient resolution. With increasing n_0,new broad maxima appear in the spectra 4.6 meV lower in energy relative to the maxima in the free-exciton recombination spectrum. The half-width of these maxima is approximately 4 meV and exceeds the broadening that can be attributed to thermal motion or to insufficient resolution.

The photoconductivity of the germanium samples at 4.2° K in electric fields < 10 V/cm is quite small even at the maximum excitation levels, $n_0 < 3 \times 10^{15}$ cm^{-3}, used in the present investigation. In fields ≈ 10 V/cm the photoconductivity increases jumpwise [4]. In this case both the recombination-radiation peaks of the free excitons and the new long-wave maxima disappear.

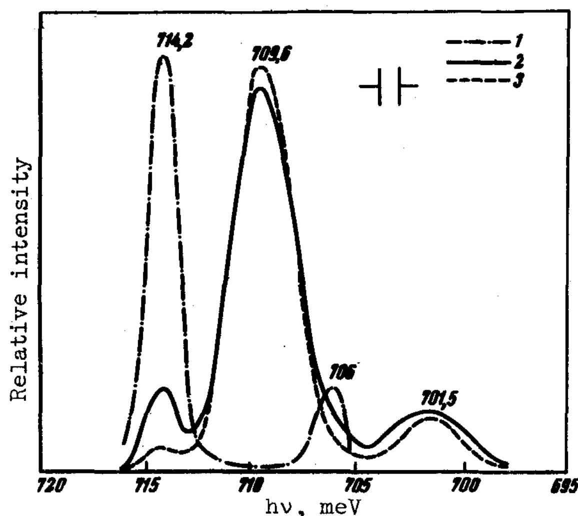

Fig. 1. Germanium recombination radiation spectra at 4.2°K and at various excitation levels. n_0 = 4×10^{12} cm^{-3}(1), 3×10^{14} cm^{-3}(2), and 3×10^{15} cm^{-3}(3).

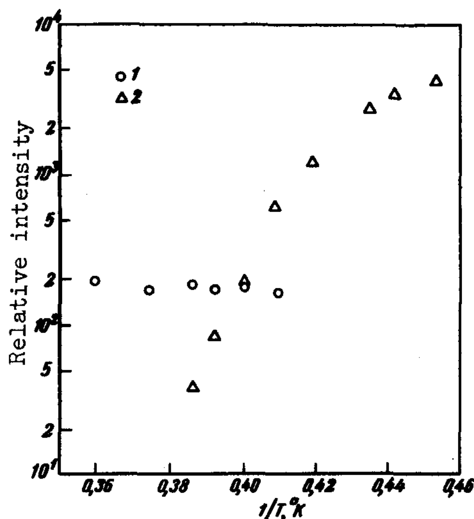

Fig. 2. Temperature dependence of the intensity of the peaks of recombination radiation in germanium: 1 - 714.2-meV peak, 2 - 709.6-meV peak. n_0 = 1.3×10^{13} cm^{-3}.

Figure 2 shows the temperature dependence of the radiation intensity of the free exciton at the 714.2-meV maximum and the intensity of the new radiation at the 708.6-meV maximum following excitation of the sample by a mercury lamp. It is seen from the figure that the intensity of the recombination radiation of the free excitons is practically independent of the temperature, whereas the intensity of the new radiation increases by approximately two orders of magnitude in a very narrow temperature interval. The region of temperatures in which this increase is observed depends very strongly on the excitation level. The growth of the intensity can be described by an exponential law with activation energy ≈10 Mev. However, this value may be greatly underestimated, since the concentration of the carriers changes in time during the registration of the radiation, and is not constant over the volume of the sample, so that the critical conditions inside the sample are reached at somewhat different temperatures. The integrated intensity of the new radiation exceeds by more than four orders of magnitude the intensity of the free-exciton radiation.

We can therefore conclude that when the critical exciton concentration and the critical temperature are reached in germanium, a new condensed phase of nonequilibrium carriers is produced jumpwise and is characterized by a high rate of radiative recombination. The binding energy of the carriers in this phase can be characterized by the energy difference between the peaks of the recombination radiation of the free excitons and the peaks of the new radiation, which amounts to approximately 4.6 meV. The large rate of radiative recombination indicates a large concentration of the nonequilibrium electrons and holes in this phase. It is quite possible that the phase has properties characteristic of the metallic state [5].

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