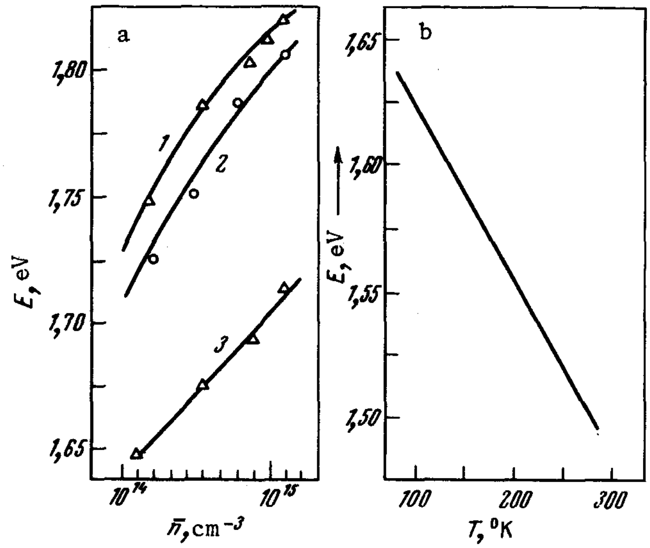

Fig. 3. Position of luminescence maximum vs exciting-light intensity (a) and temperature (b): a - 1) $CdIn_2S_4$ (300°K), 2) $CdIn_2S_4$ (77.3°K), 3) $AgIn_5S_8$ (77.3°K). b - $CdIn_2S_4$ [1]; excitation with xenon-lamp light; λ_{exc} = 400 - 500 nm.

the short-wave region of the spectrum, or in a direction opposite to the shift that occurs when the temperature is raised.

We know of no experiments on observation of giant (above several hundredths of an electron-volt) smooth shifts of the luminescence spectrum of a semiconductor towards the short-wave side; nor do we know the reason for such a shift. In our case the shift reaches 0.2 eV at 77.3°K and ~0.3 eV at 300°K. The data shown in Fig. 3 offer evidence that the observed effect cannot be attributed to heating of the sample.

In our opinion, the possible causes of the observed effect can be: 1) a change in the elastic constants of the lattice; 2) generation of non-equilibrium phonons and their participation in the optical transitions, 3) collective effects in a high-density system of luminescence centers.

We note that concrete calculations entail certain difficulties, since they must be based on detailed information concerning the structure of the luminescence centers; no such information is available at present.

The observed effect can find very interesting practical applications; one of them is the development of light sources whose emission band can be varied continuously.

[1] I. A. Damaskin, S. L. Pyshkin, S. I. Radautsan, and V. E. Tazlavan, Phys. Stat. Sol. (a) 6, 425 (1971).
[2] S. I. Radautsan, N. N. Syrbu, V. E. Tazlavan, K. F. Sherban, and E. E. Strumban, ibid. 15, 295 (1973).

BIEXCITON LUMINESCENCE POLARIZATION IN UNIAXIALLY DEFORMED GERMANIUM

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Strong linear polarization of the 0.709-eV emission line of germanium was observed under weak uniaxial deformation. This confirms that this line is due to biexcitons.

Experimental investigations of the properties of excitons when their density in germanium or silicon is high have shown that at relatively low densities the exciton system is a gas of exciton molecules, which condenses into a liquid phase at sufficiently high excitation levels [1]. There is, however, another point of view, according to which no biexcitons can be produced in these semiconductors, and the emission line ascribed to biexcitons ($h\nu$ = 0.709 eV in Ge and 1.08 eV in Si) actually belongs to the electron-hole condensate that exists even at very low concentrations [2].

To verify the existence of biexcitons, it may be very useful to investigate the polarization of the recombination radiation in these semiconductors under uniaxial deformation.

The idea of the experiments reported here is as follows: At sufficiently low temperature, the majority of the excitons and biexcitons in a uniaxially deformed crystal is at the lowest level produced upon splitting of the ground state. It is important that the splitting sufficient for such a particle redistribution should be close to kT. Since the split levels correspond to different grees of polarization of the radiation [3 - 5], the fact that the excitons and biexcitons are predominantly at the lowest level can be established by investigating the degree of polarization of the corresponding recombination radiation as a function of the direction and magnitude of the pressure and temperature. The main channel of radiative recombination in germanium is the passage of the electrons through the Γ extremum with emission of an acoustic phonon. Therefore, if the ground state of the exciton were fourfold degenerate in terms of the angular momentum of the hole, the shoft of the extrema of the conduction band as a result of the uniaxial pressure would not lead to polarization of the exciton luminescence, and the latter could be due only to the splitting of the valence band. However, owing to the anisotropy of the electron effective mass, the ground state of the exciton is split and an appreciable polarization appears even at pressures at which the splitting of the valence band is much smaller than the initial splitting of the exciton state. Similar considerations are valid also for biexcitons [5]. Unlike biexcitons, the luminescence polarization of the condensed phase should be observed at pressure many times larger, when the splitting of the valence band is comparable with the electron and hole Fermi energy, which exceeds kT by dozens of times at helium temperature[1)] [2].

We used for the experiments oriented germanium samples with total impurity-center concentration of about 10^{12} cm^{-3}, placed in an optical cryostat together with a device for uniaxial compression of the sample. The experiments were performed at low ($\leq 10^{14}$ cm^{-3}) and high (up to 5×10^{16} cm^{-3}) concentrations of the non-equilibrium electron-hole pairs.

Figure 1 shows the obtained degree of polarization of the 0.709-eV line in germanium as a function of the pressure applied in the 111 direction at T = 1.8°K. We see that the radiation becomes strongly polarized even at negligibly small stresses[2)]. The polarization reaches a maximum ∿50% at a pressure of merely 100 kg/cm^2. This indicates that the particles are almost completely redistributed on the lowest level as a result of the splitting of the ground state under conditions when this splitting is less than 1 meV [3]. The splitting of the valence band is smaller by almost one order of magnitude than the initial splitting of the exciton ground state due to the anisotropy of the electron effective mass [3]. At the same time, a strong temperature dependence of the degree of polarization of the radiation is observed (Fig. 2). The polarization vanishes when kT becomes larger than the expected splitting of the ground state.

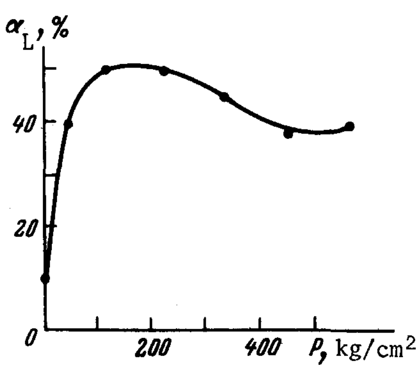

Fig. 1

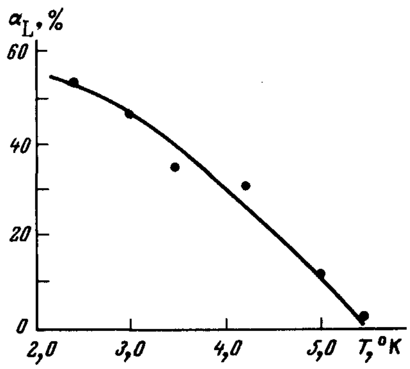

Fig. 2

Fig. 1. Degree of polarization of biexciton radiation in Ge at low excitation levels ($<10^{14}$ cm^{-3}) vs stress applied in <111> direction, T = 2°K.

Fig. 2. Temperature dependence of biexciton radiation polarization, P = 100 kg/cm^2.

In the same range of pressure variation, there appears a strong linear polarization of exciton radiation, increasing to 50 - 60% at stresses lower than 200 kg/cm^2. The polarization direction was parallel to thepressure axis, corresponding to a ground state with $J_z^h = 1/2$, i.e., $\Delta_c > 0$ [5].

Such a behavior of the lumnescence polarization demonstrates once more that the 0.709-eV line is due to exciton molecules at low excitation levels. In the case of the electron-hole condensate one should expect a negligibly low polarization of the radiation at such a small deformation of the crystal.

It was shown in [1, 6, 7] that condensation of the biexciton gas in germanium occurs at concentrations close to 5×10^{15} cm^{-3}. This agrees with the decrease we observed in the degree of polarization radiation when such excitation levels are reached. At non-equilibrium electron-hole concentrations larger than 2×10^{16} cm^{-3}; the luminescence was almost completely depolarized at pressures lower than 500 kg/cm^2. Simultaneously, a slight broadening of the 0.709-eV line was observed; this broadening, as shown in [7], is the consequence of formation of a condensed state in the sample.

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1) According to [2], the electron-hole pair concentration in the condensed phase is equal to 2.6×10^{17} cm^{-3}, corresponding to an approximate Fermi energy 5×10^{-3} eV.

2) Strong radiation polarization was observed in some of the investigated samples in the absence of external deformation. This phenomenon is apparently due to strains existing inside the crystal. These strains, however, are so small, that the hardly affect the position of the exciton emission line, which was shifted less than 0.25 meV in such samples.

[1] A. A. Rogachev, Izv. AN SSSR ser. fiz. 37, 229 (1973).
[2] Ya. E. Pokrovskii, Proc. 11th Internat. Conf. on Physics of Semiconductors, Warsaw, 1972, p. 69.
[3] I. Balslev, Phys. Rev. 143, 636 (1966).
[4] G. L. Bir and G. E. Pikus, Simmetriya i deformatsionnye effekty v poluprovodnikakh (Symmetry and Deformation Effects in Semiconductors), Nauka, 1972.
[5] G. L. Bir and G. E. Pikus, this issue, next article.
[6] V. M. Asnin and A. A. Rogachev, Proc. 3rd Internat. Conf. on Photoconductivity, Stanford University, 1969, p. 13.
[7] V. M. Asnin, A. A. Rogachev, and N. I. Sablina, Fiz. Tverd. Tela 14, 399 (1972) [Sov. Phys.-Solid State 14, 332 (197

POLARIZATION OF EXCITON AND BIEXCITON RECOMBINATION RADIATION IN DEFORMED GERMANIUM

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Results of calculations of the degree of polarization of exciton and biexciton radiation in germanium are presented. It is shown that at low deformations that disturb the equivalence of the electronic extrema this radiation can be strongly polarized.

The investigation of the polarization dependences of recombination radiation may serve as an effect-ve method of distinguishing, in principle, between the radiation of excitons, biexcitons, or drops, and of obtaining information concerning their structure.

Strong polarization of exciton absorption in deformed germanium was observed by Balslev [1]. Recently Asnin, Lomasov, and Rogachev have observed that exciton radiation of deformed germanium and the radiation in the band ascribed to biexcitons or drops is strongly polarized [2]. In this paper we give results of calculations showing that biexciton luminescence in deformed crystals cal, like exciton luminescence, be strongly polarized. In the case of drops one can expect an appreciable luminescence polarization only at large deformations, when the