

Luminescence of bound diamagnetic excitons in indium antimonide

I. V. Kavetskaya and N. N. Sibel'din

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

(Submitted 3 June 1983)

Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 2, 67–70 (25 July 1983)

A narrow line corresponding to the emission of exciton-impurity complexes appears in the luminescence spectrum of indium antimonide when a magnetic field $H \gtrsim 5\text{--}7$ kOe is imposed. In a strong magnetic field, this new line dominates the spectrum.

PACS numbers: 78.20.Ls, 71.35. + z

Even in a weak magnetic field (about 1 kOe), the excitons in indium antimonide are diamagnetic; i.e., the cyclotron energy of an electron exceeds the exciton rydberg.¹ Diamagnetic excitons are highly anisotropic: Their wave function is elongated along the field and compressed in the perpendicular direction. A system of diamagnetic excitons appears to be a convenient entity for modeling the properties of atoms, molecules, and substances in ultrastrong magnetic fields. However, essentially no information is available on the interactions and collective phenomena in a system of diamagnetic excitons. In Ref. 2 we reported observing a luminescence of an electron-hole liquid, stabilized by a magnetic field,³ in indium antimonide. Kharchenko⁴ has studied the localization of diamagnetic excitons at impurities. It was shown that in a magnetic field electron-hole complexes can form at defects which would not be capable of binding an exciton in the absence of a field. Like the electron-hole complexes in the absence of a magnetic field,⁵ bound diamagnetic excitons have a giant oscillator strength.

This letter reports a study of the low-temperature magnetophotoluminescence of pure indium antimonide crystals. The results show that the predominant mechanism for radiative recombination in a strong magnetic field is the recombination of bound diamagnetic excitons. Some corresponding studies have recently been published,⁶ but the results differ substantially from the results we are reporting here.

Most of the experiments were carried out with *n*-type InSb samples 5×5 mm² in area and 100–200 μ m thick with an electron density of $(1\text{--}2) \times 10^{14}$ cm⁻³ at liquid-nitrogen temperature and compensation of about 50%. After mechanical polishing the samples were etched in SR-4A etchant. The source of the quasisteady photoexcitation was a He-Ne laser (wavelength of 3.39 μ m, power ~ 15 mW). The luminescence and magnetoreflexion spectra were analyzed with an MDR-2 monochromator with a grating with 100 lines/mm and detected with either a Ge: Au photoresistance or an InSb photodiode, each device being cooled to ~ 100 K. The magnetic field was produced by a superconducting solenoid. Most of the measurements were carried out at 2 K in the Faraday geometry. The magnetic field was directed perpendicular to the wide face of the sample, along the $\langle 211 \rangle$ crystallographic axis.

Figure 1 shows the luminescence spectra at various magnetic fields. These spectra were recorded at an excitation intensity ~ 10 W/cm², which is roughly an order of

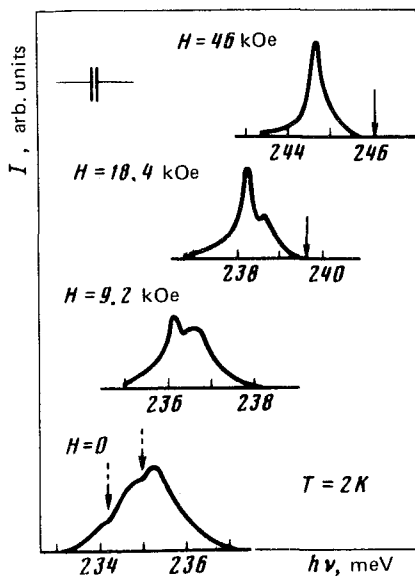


FIG. 1. Luminescence spectra in various magnetic fields. Solid arrows—position of the center of the long-wavelength component of the exciton magnetoreflexion spectrum; dashed arrows ($H = 0$)—positions of the absorption lines of atmospheric water vapor.

magnitude lower than that required for observation of an electron-hole liquid.² The emission line observed in the absence of a magnetic field is usually attributed to interband radiative transitions, but this line is shifted in the long-wavelength direction from the exciton absorption line ($h\nu_{ex} = 236.3$ meV; Ref. 7). The apparent reason for this long-wavelength shift is the Coulomb interaction between nonequilibrium carriers and between carriers and charged impurities.

With increasing magnetic field, the luminescence line shifts in the short-wavelength direction, contracts, and decreases in intensity. At $H \cong 5-7$ kOe, a narrow line appears on its long-wavelength wing, and when the field is raised to a sufficient level this narrow line begins to dominate the spectrum.

In order to determine the energies of the transitions to the state of a free diamagnetic exciton, we measured the magnetoreflexion spectra (Fig. 2). The solid arrows in Fig. 1 show the long-wavelength components of the magnetoreflexion spectrum.

Figure 3 shows the spectral position of the two long-wavelength lines of the exciton magnetoreflexion and the position of the peak of the emission line which arises in a magnetic field (except for the first three points near $H = 0$, which show the position of the peak of the short-wavelength emission line) vs the magnetic field. It can be seen from Figs. 2 and 3 that the luminescence spectrum is shifted in the lower-energy direction from the red boundary of the exciton spectrum. The shift of the narrow long-wavelength emission line is $\cong 1$ meV in a field $H = 23$ kOe.

Measurements taken at various excitation intensities and temperatures show that the intensity of the long-wavelength emission line initially increases linearly with in-

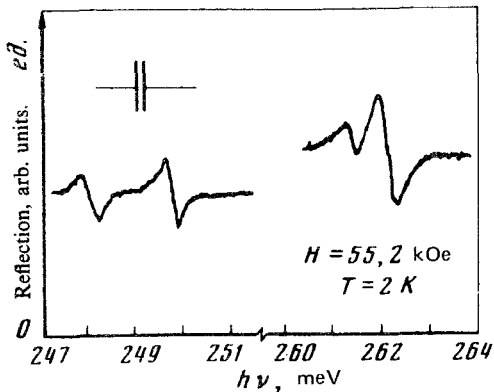


FIG. 2. Exciton magnetoreflexion spectrum.

creasing excitation level, but the increase then slows substantially. As the temperature is raised from 2 to 4.2 K, the intensity of the long-wavelength line drops off sharply, while that of the short-wavelength line increases slightly.

We conclude from these experimental results—the spectral position of the long-wavelength emission line, its high intensity, its small half-width ($\cong 0.3 \text{ meV}$), the approximately quadratic short-wavelength shift with increasing magnetic field (at low values of H), the dependence of the intensity on the pump level and the temperature, and the behavior in an electric field²—that this line is caused by the recombination of an electron-hole complex. The observed electron-hole complex is apparently a diamagnetic exciton bound to a neutral acceptor, Zn or Cd, whose ionization energies are $\sim 9 \text{ meV}$. Indirect evidence for the possible involvement of these acceptors in the formation of the electron-hole complexes comes from the circumstance that in the samples studied we observed a faint emission line corresponding to electron-hole transitions from the conduction band to acceptor levels with approximately the same energy. It should be noted that since the electronic g factor is very large ($g_e \cong 50$) in indium antimonide, electron-hole complexes at neutral donors could hardly be stable in a

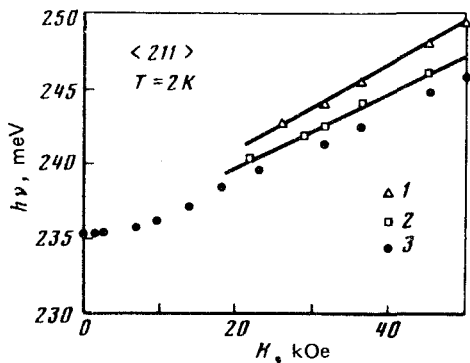


FIG. 3. 1, 2—Spectral position of the long-wavelength exciton magnetoreflexion lines; 3—spectral position of the peak of the luminescence line of the electron-hole complex vs the magnetic field. The curves are theoretical.⁸

magnetic field; this situation is similar to that which prevails for biexcitons in germanium⁹ when the energy of the unbound triplet state of a molecule falls below the singlet energy as the field is increased.

The magnetic-field dependence of the position of the peak of the short-wavelength luminescence line is of nearly the same nature as that for the emission line of an electron-hole complex, and the distance between the corresponding peaks is less than 1 meV. Since the electrons in indium antimonide are much lighter than the holes, the exciton binding energy is approximately equal to the ionization energy of shallow donors. It may therefore be concluded that the short-wavelength component of the luminescence spectrum corresponds to transitions from donor levels to the valence band. The comparatively large half-width of this line (≥ 1 meV) is probably caused by a spread of the donor levels due to fluctuations in the concentration of charged impurities.

We are deeply indebted to L. V. Keldysh for constant interest and many discussions. We thank V. D. Kulakovskii, V. B. Stopachinskii, V. B. Timofev, and A. P. Shotov for a discussion; B. A. Dobysh, N. V. Zamkovets, and V. A. Tsvetkov for assistance in the experiments; Al. L. Éfros for calculating the exciton spectrum; and M. N. Kevorkov and A. N. Popkov for furnishing the samples.

¹B. P. Zakharchenya and R. P. Seĭsyan, *Usp. Fiz. Nauk* **97**, 193 (1969).

²I. V. Kavetskaya, Ya. Ya. Kost', N. Y. Sibel'din, and V. A. Tsvetkov, *Pis'ma Zh. Eksp. Teor. Fiz.* **36**, 254 (1982) [*JETP Lett.* **36**, 311 (1982)].

³L. V. Kaldysh and T. A. Onishchenko, *Pis'ma Zh. Eksp. Teor. Fiz.* **24**, 70 (1976) [*JETP Lett.* **24**, 59 (1976)]; E. A. Andryushin, V. S. Babichenko, L. V. Keldysh, T. A. Onishchenko, and A. P. Silin, *Pis'ma Zh. Eksp. Teor. Fiz.* **24**, 210 (1976) [*JETP Lett.* **24**, 185 (1976)].

⁴V. A. Kharchenko, *Zh. Eksp. Teor. Fiz.* **83**, 1971 (1982) [*JETP* **56**, 1140 (1982)].

⁵É. I. Rashba and G. É. Gurgenishvili, *Fiz. Tverd. Tela (Leningrad)* **4**, 1029 (1962) [*Sov. Phys. Solid State*]; É. I. Rashba, *Fiz. Tekh. Poluprovodn.* **8**, 1241 (1973).

⁶V. I. Ivanov-Omskii, S. I. Kokhanovskii, R. P. Seĭsyan, V. A. Smirnov, and Sh. U. Yuldashev, *Fiz. Tekh. Poluprovodn.* **17**, 532 (1983) [*Sov. Phys. Semicond.* **17**, 334 (1983)].

⁷L. M. Kanskaya, S. I. Kokhanovskii, and R. P. Seĭsyan, *Fiz. Tekh. Poluprovodn.* **13**, 2424 (1979) [*Sov. Phys. Semicond.* **13**, 1420 (1979)].

⁸B. L. Gel'mont, R. P. Seĭsyan, Al. L. Éfros, and A. V. Varfolomeev, *Fiz. Tekh. Poluprovodn.* **11**, 238 (1977) [*Sov. Phys. Semicond.* **11**, 139 (1977)].

⁹V. D. Kulakovskii, I. V. Kukushkin, and V. B. Timofeev, *Zh. Eksp. Teor. Fiz.* **81**, 684 (1981) [*Sov. Phys. JETP* **54**, 366 (1981)].

Translated by Dave Parsons

Edited by S. J. Amoretty