# Existence of bi-excitons and trions in germanium

A. E. Zhidkov[1)] and Ya. E. Pokrovskii
*Institute of Radio Engineering and Electronics, USSR Academy of Sciences*

(Submitted 9 August 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **30**, No. 8, 499–502 (20 October 1979)

The photoluminescence of germanium has been investigated near the exciton condensation threshold at a temperature of 2–5.2 K, for uniaxial compression and in the presence of an electric field. It is shown that the broadening of the long-wavelength exciton band edge is not due to the formation of molecular-type states.

PACS numbers: 71.35. + z, 78.55.Hx

Attempts to discover in germanium molecular-type collective states of nonequilibrium charge carriers (bi-excitons, trions) have been underway now for about ten years (see, for example, Ref. 1). In particular, in Ref. 2 the broadening of the long-wavelength free-exciton radiation band edge at 6.5 K and a high excitation level was associated with the decay of trions or bi-excitons. It is possible to facilitate the formation of molecular collective states by a uniaxial compression of germanium in the (111) direction, leading to a decrease in the binding energy of the electron-hole fluid (EHF)[3] and, consequently, to an increase in the density of excitons and free carriers at a fixed excitation level and temperature. An analogy with silicon, in which bi-excitons were found when the crystals were deformed uniaxially,[4] is appropriate here. It must be expected, however, that the exciton and molecular radiation bands in germanium, unlike silicon, must overlap considerably since the exciton binding energy, determining the shift of the molecular band,[5] is considerably lower in germanium than in silicon.[1] An attempt to find molecular radiation in germanium, compressed in the (111) direction, was made by G.A. Thomas, V. B. Timofeev and Ya.E. Pokrovskii in 1977 at Harvard University; however, they were unable to obtain unequivocal results. The effect of deformation, temperature, excitation level and an electric field on the photoluminescence of pure germanium near the exciton condensation threshold is investigated in more detail in the present paper.

A germanium specimen with dimensions of $15\times2.5\times1.8$ mm$^3$, cut in the (111) direction, was used; it was subjected to uniaxial compression in a helium bath using the device described in Ref. 6. The bath temperature was regulated by the helium vapor pressure in the 2–5.2 K interval (2.25 atm). Two narrow indium strips, applied 3.5 mm apart on one of the crystal faces perpendicular to the (111) direction, served as electrodes to which a d-c voltage could be applied. The modulated radiation of an argon laser was focused onto the sample surface in the form of a $5\times0.2$ mm$^2$ band, spanning the interelectrode gap, for photoexcitation.

Figure 1 shows the germanium radiation spectra for uniaxial compression, a fixed excitation level and different temperatures. It is seen from the figure that the long-

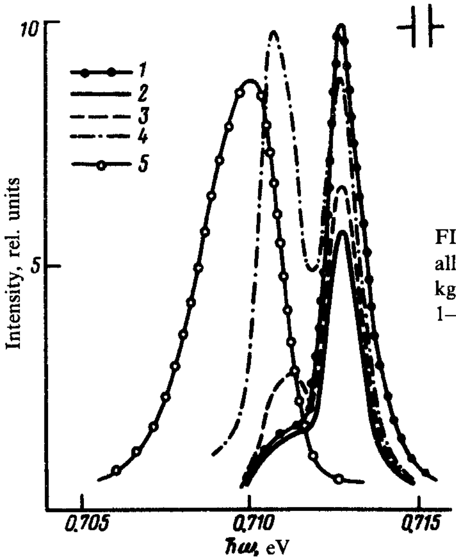

FIG. 1. Radiation spectra of pure germanium when uniaxially compressed in the (111) direction, at pressure of 370 kg/cm$^2$, photoexcitation power of 90 mW, temperature, K: 1—4.2; 2—3.73; 4—2.71; 5—2.

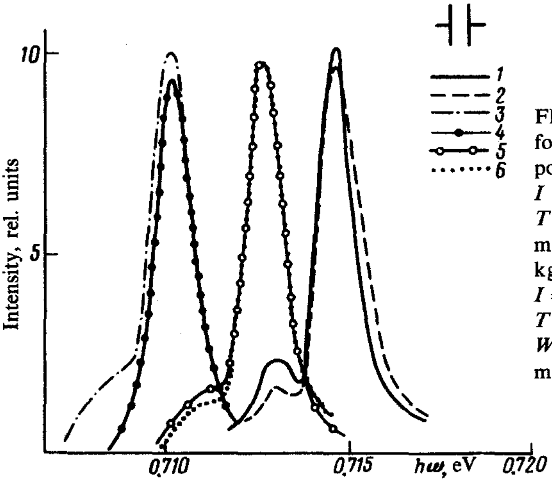

FIG. 2. Radiation spectra of pure germanium for pressure $P$ in (111) direction, photoexcitation power $W$, temperature $T$, voltage $U$ and current $I$ between contacts: 1—$P = 0$, $W = 90$ mW, $T = 4.2$ K, $U = 0$, $I = 0$; 2—$P = 0$, $W = 150$ mW, $T = 5.2$ K, $U = 0$, $I = 0$; 3—$P = 750$ kg/cm$^2$, $W = 150$ mW, $T = 5.2$ K, $U = 0$, $I = 0$; 5—$P = 370$ kg/cm$^2$, $W = 125$ mW, $T = 4.2$ K, $U = 0$, $I = 0$; 6—$P = 370$ kg/cm$^2$, $W = 125$ mW, $T = 4.2$ K, $U = 1.44$ V, $I = 14$ mA.

wavelength broadening of the exciton radiation band, close to that given in Ref. 2 at high temperatures, gradually develops into the well-known EHF radiation band as the temperature is lowered.[6] The short-wavelength shift of the EHF radiation band near the condensation threshold is due to a decrease in the energy of the small-size drops because of the strong influence of the surface.[7]

It should be expected that uniaxial compression of germanium leads to a lowering of the critical condensation temperature because of a decrease in the EHF binding energy, whereas the binding energy of the molecular states should not be significantly altered during crystal deformation.[5] It is seen from Fig. 2 that in undeformed crystals EHF radiation is observed both at 4.2 K and at 5.2 K, whereas uniaxial compression completely suppresses the long-wavelength broadening of the exciton band at 5.2 K. No broadening was observed even with a further increase of the excitation level to 300 mW. It can be concluded from this that the critical temperature for uniaxially compressed germanium is apparently less than 5.2 K. At the same time the formation of molecular states should not have such a sharp threshold, and the disappearance of the long-wavelength band with deformation or a slight temperature increase contradicts the assumption of the molecular nature of this band.

In undeformed germanium the critical temperature is estimated as 5–8 K.[1] The temperature of 6.5 K, at which the studies in Ref. 2 were performed, is apparently only slightly below the critical. Therefore EHF formation was evident in Ref. 2 only in the broadening of the long-wavelength exciton band edge since the binding energy of the EHF is reduced significantly near the critical temperature.[1] This leads to considerable overlapping of the exciton and EHF radiation bands.

Molecular states have an extremely small binding energy,[2] and therefore impact ionization in an electric field should lead first of all to a destruction of bi-excitons and trions and the disappearance of the corresponding radiation band. It is seen from Fig. 2, however, that in an electric field the intensity of both the exciton radiation and its broadened long-wavelength edge are reduced approximately identically (by a factor of five in Fig. 2). This also contradicts the molecular nature of the long-wavelength broadening.

Thus, the experimental results presented above indicate the trivial cause of the broadening of the long-wavelength edge of the exciton radiation band, namely, the formation of the EHF near the critical temperature and it contradicts the assumption of a molecular nature for this broadening.

The authors are grateful to G.A. Thomas and V.B. Timofeev for discussions that led to undertaking this work.

1)Deceased.

---

[1]J.C. Hensel, T.G. Phillips and G.A. Thomas, Solid State Physics, **32**, edited by H. Ehrenreich, F. Seitz and D. Turnbull, Academic Press, NY, 1977.

[2]G.A. Thomas and T.M. Rice, Solid State Commun. **23**, 359 (1977).

[3]V.S. Bagaev, T.I. Galkina, O.V. Gogolin and L.V. Keldysh, Pis'ma Zh. Eksp. Teor. Fiz. **10**, 304 (1969) [JETP Lett. **10**, 192 (1969)].

[4]V.D. Kulakovskii and V.B. Timofeev, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 487 (1977) [JETP Lett. **25**, 458 (1977)].

[5]V.D. Kulakovskii, V.B. Timofeev and V.M. Edel'shtein, Zh. Eksp. Teor. Fiz. **74**, 372 (1978) [Sov. Phys. JETP **47**, 193 (1978)].

[6]Ya.E. Pokrovskii and K.I. Svistunova, Zh. Eksp. Teor. Fiz. **68**, 2323 (1975) [Sov. Phys. JETP **41**, 1161 (1975)].

[7]B. Etienne, C. Benoît à la Guillaume and M. Voos, Phys. Rev. Lett. **35**, 536 (1975).