Physics – Uspekhi **39** (7) 751 – 753 (1996)

CONFERENCES AND SYMPOSIA

PACS number: 01.10.Fv

Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (21 February 1996)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 21 February 1996 at the P L Kapitza Institute of Physical Problems. The following papers were presented at this session:

(1) **L V Butov** (Institute of Solid State Physics, RAS, Chernogolovka), **A Zrenner, M Hagn, G Abstreiter, G Böhm, G Weimann** (W Schottky Institute, Munchen Technical University, Munchen) *Evidence for condensation of excitons in double quantum wells*.

(2) **Yu E Lozovik** (Institute of Spectroscopy, RAS, Troitsk) *Ultrafast processes in superconductors and scopes for femtosecond spectroscopy*.

A summary of the first paper is given below.

PACS number: **71.35.+z**

Evidence for condensation of excitons in double quantum wells

L V Butov, A Zrenner, M Hagn, G Abstreiter, G Böhm, G Weimann

The electron-hole (e-h) interaction in a neutral e-h system may lead to the condensation of e-h pairs, i.e. excitons. In a dilute exciton gas, excitons may be considered as pointlike Bose particles and their condensation is similar to that of Bose–Einstein bosons, whereas in a dense e-h system a condensate is analogous to a BCS superconducting state [1].

One of the major difficulties in the experimental observation of exciton condensation in semiconductors lies in achieving a low-subcritical-exciton temperature. Due to the electron-hole recombination, the exciton temperature may exceed the lattice temperature considerably. Therefore, in looking for exciton condensation the semiconductors with a high exciton lifetime are taken. The degenerate Bose–Einstein exciton statistics, which is a precursor of exciton condensation in a bulk semiconductor, has been observed in Cu_2O [2] and Ge [3]. In recent work on Cu_2O, a crossing of the phase boundary for exciton condensation has been reported [4].

Quantum well (QW) semiconductor structures offer the possibility of experimental realization of a two-dimensional exciton condensate. The critical conditions for exciton condensation in a QW improve qualitatively in a strong perpendicular magnetic field [5] due to complete quantization of the electron and hole energy spectra, and also due to an increase in the exciton binding energy. A precursor of the condensation of two-dimensional excitons in a magnetic field, namely the formation of excitons in a dense e-h magnetoplasma, has been observed in the InGaAs/GaAs QW [6]. However, because of the fast electron-hole recombination, the carrier temperature was above the critical value. The rate of the electron-hole recombination can be substantially reduced in double quantum wells (DQWs), in which electrons and holes are spatially separated. Exciton condensation in a DQW must be accompanied by the onset of exciton superfluidity [5]. It is the analysis of the low-temperature, strong-magnetic-field optical and transport properties of indirect DQW excitons consisting of spatially separated electrons and holes which was the purpose of our study.

Indirect excitons in AlAs/GaAs DQWs rearranged by a gate voltage V_g were investigated at $T \geqslant 350$ mK and $B \leqslant 14$ T. The active part of the structure consists of 40-A AlAs and 30-A GaAS layers sandwiched between $Al_{0.48}Ga_{0.52}As$ layers (see insert to Fig. 1) [7]. In the indirect regime ($V_g < 0.5$ V) electrons are confined in the AlAs layer and holes in the GaAs layer. Carrier excitation was performed by a pulse laser ($\hbar\omega = 1.8$ eV).

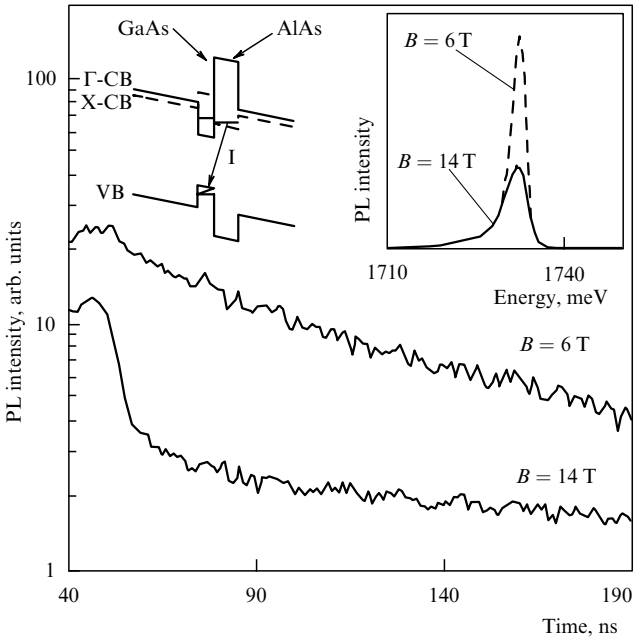

Figure 1. PL decay curves for $V_g = 0$, $T = 350$ mK, $B = 6$ and 14 T. Right insert: the corresponding time-integrated PL spectra. Left insert: band diagram of AlAs/GaAs DQW in an indirect regime.

Uspekhi Fizicheskikh Nauk **166** (7) 801 – 803 (1996)
Translated by E G Strel'chenko, edited by A Radzig

It was found that magnetic field markedly changes the exciton photoluminescence (PL) decay time. Decay curves at $T = 350$ mK and $B = 6$ and 14 T are shown in Fig. 1. The dependence of the initial decay time τ on B is displayed in Fig. 3a. At $B \lesssim 7$ T, the decay is weakly nonexponential, with a long lifetime of about 50 ns. In large magnetic fields the rapid initial decay is followed by a slow decay at large times. In the indirect regime the integrated exciton PL intensity is by more than an order of magnitude less than in the direct regime.

Hence, in the indirect regime the radiative lifetime is much longer than the nonradiative lifetime τ_{nr}, and $\tau \approx \tau_{nr}$. Thus, as the magnetic field grows, τ_{nr} first increases and then decreases. The growth (drop) in τ_{nr} is accompanied by an increase (decrease) in the integrated PL intensity (see spectra in the insert to Fig. 1). In the narrow DQWs studied, τ_{nr} is determined by the transport of excitons to centres of nonradiative recombination. Thus, changes in τ_{nr} indicate that increasing magnetic field leads first to a small decrease and then to a strong increase in the exciton mobility.

For direct exciton transport measurements, the time-of-flight technique was used, in which the decay of the PL signal from an open portion of the specimen was compared with that from a portion covered by an opaque mask. The mask involved transparent 4-μm-wide strips 32 μm apart. Figure 2 shows examples of decay curves for an open and a masked portions. In the latter case, the variation of the exciton density is given by $\partial n/\partial t = D\,\partial^2 n/\partial x^2 - n/\tau$ due to exciton diffusion underneath the opaque portions of the specimen, where D is the exciton diffusion coefficient describing the exciton transport at early stages of PL decay. For PL decay from an open portion, the $D\,\partial^2 n/\partial x^2$ term may be neglected due to a large size of the excitation spot. A comparison of the initial PL decays from the open and masked portions allows an independent determination of τ and D. The fitting curves are shown as straight lines in Fig. 2.

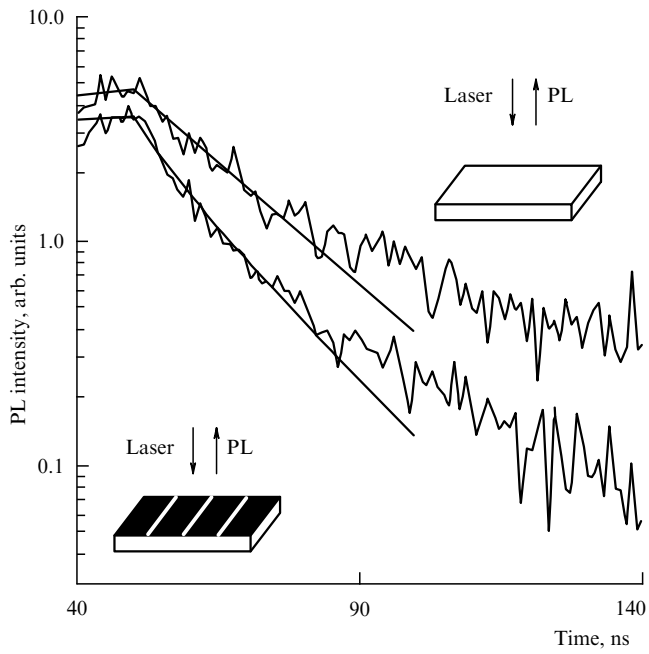

Figure 2. PL decay for a masked (lower curve) and open (upper curve) portions of the specimen for $V_g = 0$, $B = 6$ T, and $T = 5$ K.

The dependence of D on magnetic field at $T = 350$ mK is shown in Fig. 3b. D first decreases slightly with increasing B, and then rapidly grows. The temperature dependences of τ and D at $B = 6$ and 14 T are presented in Figs 3c and 3d. The 6 T-dependence is typical for weak magnetic fields, and that for 14 T is characteristic of strong fields, in which rapid exciton transport is observed at low temperatures. At $B = 6$ T, an increase in temperature leads to a monotonic increase in D and decrease in τ. In contrast, at $B = 14$ T increasing temperature causes a decrease in D and an increase in τ. Only at $T \gtrsim 5$ K does τ start to drop (and D to increase), approaching the dependence observed in weak magnetic fields. In all the experiments, changes in τ describing the exciton transport to nonradiative recombination centres correspond to variations in D as measured by a time-of-flight technique: an increase (decrease) in τ corresponds to a decrease (increase) in D.

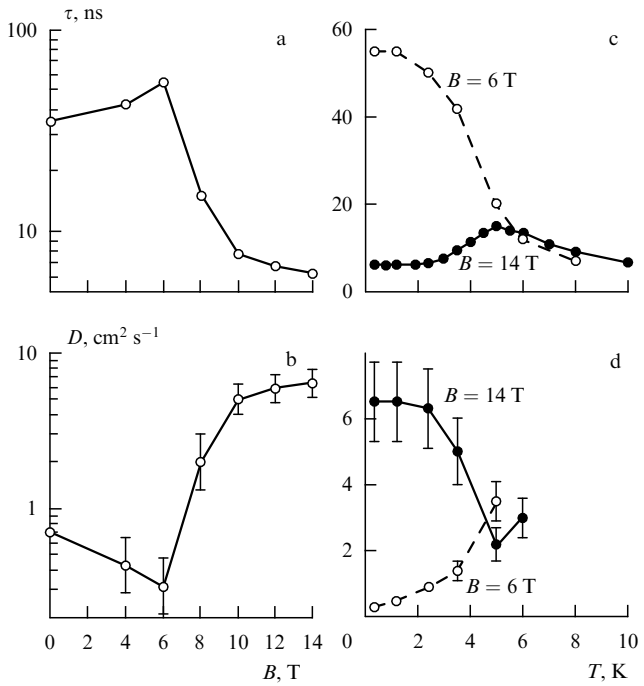

Figure 3. The magnetic field dependences of τ (a) and D (b) for $V_g = 0$, $T = 350$ mK. The temperature dependences of τ (c) and D (d) for $V_g = 0$, $B = 6$ and 14 T.

In weak magnetic fields the temperature and magnetic-field dependences of D are characteristic of the thermal-activated exciton transport in a random potential (due mainly to QW width fluctuations in the structures studied): in zero magnetic field an analogous increase in D and decrease in τ with increasing T were observed in a number of studies on type II AlAs/GaAs sublattices. The monotonic decrease in D with increasing B is qualitatively explained by a growth in the magnetoexciton mass and is in qualitative agreement with the theoretical picture of exciton transport in the AlAs/GaAs DQW [8]. The slow PL decay at large time delays corresponds to the recombination of strongly localized excitons.

Rapid exciton transport is observed in strong magnetic fields at low temperatures, i.e. under conditions when exciton superfluidity is expected. With increasing temperature, rapid exciton transport disappears and an ordinary picture of D increasing with temperature is restored. The time-of-flight

technique yields averaged characteristics of exciton transport, the diffusion coefficient being averaged over the strip length. For exciton condensation in the presence of a random potential, superfluid domains are expected to appear, whose boundaries are determined by the in-plane potential profile. Thus, on a large scale the averaged exciton transport is that in a disordered array of normal and superfluid regions. The relatively small value of D, which corresponds to the observed rapid exciton transport, finds an explanation in terms of such a picture (since the fractions of the normal and superfluid regions are unknown, a single value of diffusion coefficient was used in the data processing procedure).

With decreasing exciton density, the superfluidity must disappear at a certain critical density whose value depends on T. Because of the weak PL signal from a masked portion of the sample, only the maximum laser excitation power, corresponding to the initial average exciton density of $\sim 10^{10}$ cm^{-2}, was used in experiments, which made it impossible to measure the dependence of D on the excitation power. Indirectly, the dependence on the exciton density manifests itself in the time evolution of the PL decay. At low T and large B, a rapid initial decay compatible with rapid exciton transport is observed until a severalfold decrease in the exciton density is reached (see Fig. 1), after which the PL decay is slow and corresponds to slow exciton transport. The crossover from the initial rapid to the subsequent slow exciton transport is sharp, in accord with the expected disappearance of exciton superfluidity. Notice, however, that a decrease in the exciton density during the recombination process is not the sole factor to determine the crossover; another one is the gradual increase of the exciton localization due to relaxation in energy (localization of excitons below the mobility threshold must suppress superfluidity).

The exciton PL under cw laser excitation ($\hbar\omega = 1.85$ eV) was also investigated. Anomalously large fluctuations (noise) in the integrated indirect-exciton PL intensity I_{PL} were found in strong magnetic fields at low temperatures. A typical B-dependence of I_{PL} is shown in Fig. 4. As B increases, the average value of I_{PL} first grows and then falls off. As in the pulsed photoexcitation case, the larger (smaller) average value of I_{PL} corresponds to a smaller (larger) exciton diffusion coefficient. The noise is observed against the background of increasing average I_{PL}. It is appeared at low temperatures; a typical T-dependence of the noise amplitude is shown in the insert to Fig. 4. The noise spectrum is of a wideband nature, $\propto 1/f$.

The large noise is evidence for the existence of coherence in the exciton system. It is known that noise amplitude is inversely proportional to the number of statistically independent entities in a system. A large noise amplitude implies that in a macroscopically large photoexcited region (with $\sim 10^6 - 10^7$ excitons) the number of independent entities is small. We may consider a condensate domain as such an independent entity. The PL signal from condensed excitons is much stronger than that from normal ones, since the exciton transition oscillator strength is proportional to the coherent volume of the exciton, which is determined by the size of the exciton condensate domain for having condensed excitons. The I_{PL} noise is associated with the appearance and disappearance of condensate domains (their size fluctuations). Since noise is observed at lower magnetic fields as compared to a rapid exciton transport, the former may be thought of as critical fluctuations near a phase transition.

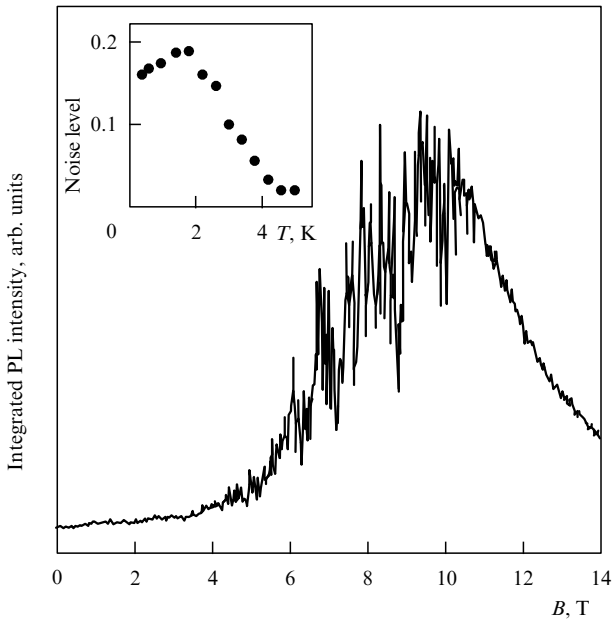

Figure 4. Integrated PL intensity for $V_g = -0.5$ V, $T = 350$ mK as a function of B. Insert: the temperature dependence of the noise level $\langle \delta I_{\mathrm{PL}} \rangle / \langle I_{\mathrm{PL}} \rangle$ for $V_g = -0.5$ V, $T = 350$ mK, and $B = 9$ T.

In summary, the e-h system in the AlAs/GaAs DQW exhibits effects indicative of the condensation of indirect excitons in strong magnetic fields at low temperatures. These are a large increase in the exciton diffusion coefficient, interpreted as being due to the onset of exciton superfluidity; and a noise in the integrated exciton PL intensity interpreted as critical fluctuations in the vicinity of the phase transition due to the large oscillator strength conforming to the exciton condensate.

The authors are grateful to A B Dzyubenko, Yu M Kagan, V D Kulakovskiĭ, and Yu E Lozovik for helpful discussions. The financial support of the Volkswagen Foundation is highly acknowledged.

References

1. Keldysh L V, Kopaev Yu V *Fiz. Tverd. Tela* (Leningrad) **6** 2791 (1964)
2. Hulin D, Mysyrowicz A, Benoit a la Guillaume *Phys. Rev. Lett.* **45** 1970 (1980)
3. Timofeev V B, Kulakovskiĭ V D, Kukushkin I V *Physica* **117-118 B+C** 327 (1983)
4. Lin J L, Wolfe J P *Phys. Rev. Lett.* **71** 1222 (1993)
5. Kuramoto Y, Horie C *Solid State Commun.* **25** 713 (1978); Lerner I V, Lozovik Yu E *Zh. Eksp. Teor. Fiz.* **80** 1488 (1981) [*Sov. Phys. JETP* **53** 763 (1980)]
6. Butov L V, Kulakovskiĭ V D *Pis'ma Zh. Eksp. Teor. Fiz.* **53** 444 (1991) [*JETP Lett.* **53** 466 (1991)]
7. Butov L V, A Zrenner, G Abstreiter, G Böhm, G Weimann *Phys. Rev. Lett.* **73** 304 (1994)
8. Dzyubenko A B, Bauer G E W *Phys. Rev. B* **51** 14524 (1995)