Energy relaxation and transport of indirect excitons in AlAs/GaAs coupled quantum wells in magnetic field

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The evolution of indirect exciton luminescence in AlAs/GaAs coupled quantum wells after excitation by pulsed laser radiation has been studied in strong magnetic fields ($B \leqslant 12$ T) at low temperatures ($T \geqslant 1.3$ K), both in the normal regime and under conditions of anomalously fast exciton transport, which is an indication of the onset of exciton superfluidity. The energy relaxation rate of indirect excitons measured in the range of relaxation times between several and several hundreds of nanoseconds is found to be controlled by the properties of the exciton transport, specifically, this parameter increases with the coefficient of excitonic diffusion. This behavior is qualitatively explained in terms of migration of excitons between local minima of the random potential in the plane of the quantum well. © *1998 American Institute of Physics.* [S1063-7761(98)02509-8]

Owing to their long lifetime, indirect excitons in coupled quantum wells (CQWs) can cool down to temperatures close to that of the crystal lattice. Therefore, condensation of excitons similar to the Bose–Einstein condensation is possible at low lattice temperatures.[1] It has been shown in some theoretical investigations that the critical conditions for exciton condensation can be greatly improved by applying a magnetic field perpendicular to the quantum well plane, mainly because of the full quantization of the electron and hole energy spectra[2] and lifting of the spin degeneracy. In recent investigations of indirect excitons contained in AlAs/GaAs CQWs, effects indicating condensation of excitons in strong magnetic fields have been detected, namely, an anomalous increase in the diffusion coefficient[3] and radiative decay rate[4] of excitons, which have been interpreted in terms of excitonic superfluidity and superluminescence of the excitonic condensate, together with anomalously large fluctuations in the total intensity of exciton photoluminescence interpreted as critical fluctuations in the region of the phase transition associated with instability of condensate domains.[5]

In the reported work, we have investigated the evolution of indirect exciton luminescence in AlAs/GaAs CQWs after termination of a laser pulse in both the normal regime and the regime of anomalously fast transport and high radiative decay rate of excitons, i.e., in the regime of the suggested condensation of excitons. We have studied the energy relaxation of indirect excitons in the time interval from several nanoseconds to several hundreds of nanoseconds and its relation to exciton transport.

The n^+-i-n^+ heterostructures with AlAs/GaAs CQWs tuned by a gate voltage V_g are similar to those studied in earlier experiments.[3–5] The *i*-layer consists of two quantum wells: an AlAs well with thickness 40 Å and a GaAs well 30 Å thick between $Al_{0.48}Ga_{0.52}As$ barriers. In the indirect regime ($V_g \lesssim 0.5$ V), electrons are confined in the AlAs quantum well and holes in the GaAs quantum well (Fig. 1a). The electron state in AlAs is constructed from states of the X_z minima in the conduction band, which ensures that the indirect excitons have long lifetimes. Carriers were generated in the GaAs well by a semiconductor laser ($\hbar\omega = 1.85$ eV) operated in the pulsed mode. The laser pulse had an approximately rectangular shape with a duration of 50 ns and rise and decay times of about 1 ns. The time resolution of the light detecting system was 0.3 ns.

Photoluminescence decay in magnetic fields $B = 0$, 4, 6, and 12 T at $V_g = 0$ and $T = 1.3$ K is illustrated by Fig. 2a (the signal was detected in a spectral range with a width of 3 meV centered at the photoluminescence line peak). These curves are similar to those measured in previous experiments.[3–5] In the indirect regime, the radiative lifetime of excitons is much longer than the nonradiative time τ_{nr}, and the total lifetime $\tau \approx \tau_{nr}$.[5] In narrow CQWs $\tau_{\rm nr}$ is determined by the exciton transport toward the centers of nonradiative recombination.[6] Direct time-of-flight measurements of exciton transport in the AlAs/GaAs CQWs studied[3,4] indicate that an increase (decrease) in τ really corresponds to a decrease (increase) in indirect exciton diffusion coefficient.

Thus, in magnetic fields $B \lesssim 7$ T the diffusion coefficient monotonically increases with the temperature and decreases with the increasing delay time and magnetic field (Fig. 2a and 2c). This behavior can be well described in terms of one-exciton transport in random potential (the random potential in narrow quantum wells is largely controlled by interface roughness): (i) the increase in the diffusion coefficient with the temperature is due to thermal activation of excitons from local potential minima; (ii) the diffusion coefficient drops with the increasing delay since more and more strongly localized excitons dominate in the luminescence spectra (those which have not had enough time to travel to centers of nonradiative recombination and recombine there); (iii) the decrease in the diffusion coefficient with the increas-

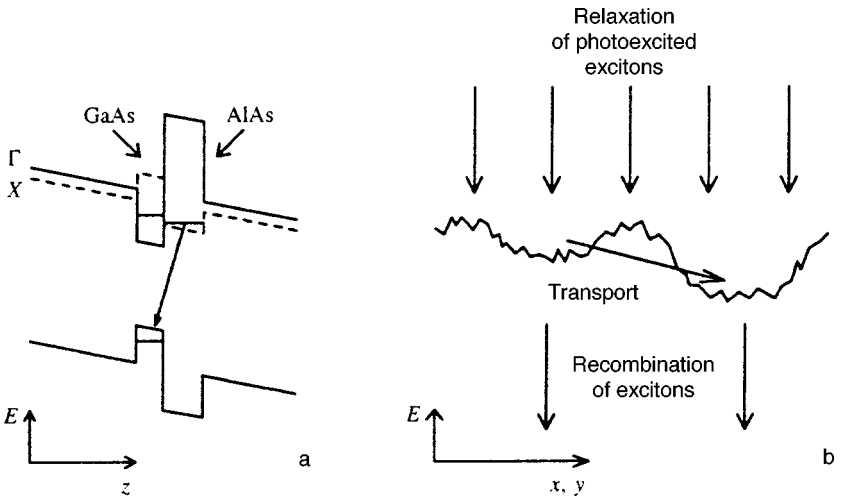

FIG. 1. (a) Band diagram of AlAs/GaAs CQWs; the solid (dashed) line represents energies of Γ (X) extrema in the Brillouin zone. (b) Scheme of a photogenerated exciton energy relaxation in the presence of random potential in the CQW plane.

ing field can be qualitatively explained by the increase in the magneto-exciton mass.[7]

For $B \lesssim 7$ T and $T \lesssim 5$ K, we have detected anomalous increase in the diffusion coefficient with the increasing magnetic field and a decrease in the diffusion coefficient with the increasing temperature at initial decay times (Fig. 2a and 2c). This behavior can not be explained in terms of one-exciton transport and is interpreted as the onset of exciton superfluidity owing to their condensation.[3] The fast decay of the exciton photoluminescence, which corresponds to fast exciton transport, is observed until the exciton density drops severalfold; the subsequent decay is slow and corresponds to slow exciton transport (Fig. 2a). The transition from the initially fast to the subsequent slower transport corresponds to elimination of excitonic superfluidity when the exciton density drops below the critical value, which is determined by the temperature, magnetic field, and random potential. In the general case of excitonic condensation in the presence of a random potential, domains of condensed (superfluid) excitons alternate with normal regions in a random manner, and the boundaries between these regions are determined by the potential relief. A superfluid domain may include several microdomains connected by weak bonds, which should lead to a coherence across the entire domain (it is an analogue of a network of the Josephson junctions in superconductors). Measurements of the photoluminescence decay time yield the parameters of the exciton transport averaged over normal and superfluid regions in the laser excitation spot.

Evolution of indirect exciton photoluminescence spectra with time and spectra integrated with respect to time at typical values of temperature and magnetic field are shown in Fig. 3. In integrated spectra, one can see a line of lower

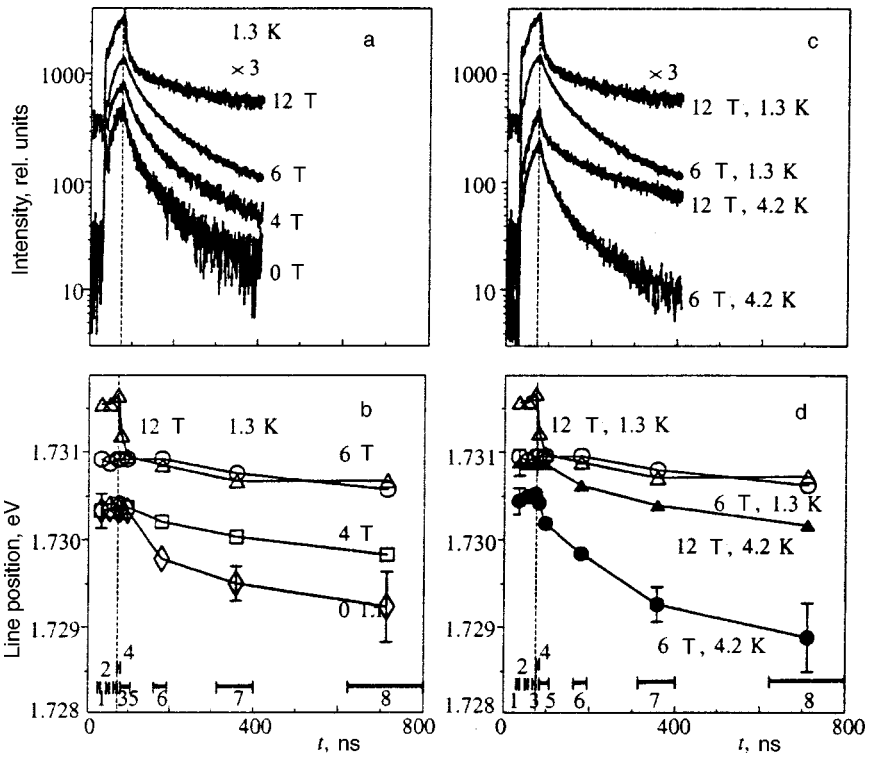

FIG. 2. (a,c) Decay and (b,d) photoluminescence line positions of indirect excitons at $V_g = 0$, $B = 0$, 4, 6, and 12 T, $T = 1.3$ and 4.2 K. The dashed vertical line shows the position of the 50-ns laser pulse end. The positions of the luminescence line (b,d) were derived from spectra measured in time intervals 1–8 shown at the bottom of the graph.

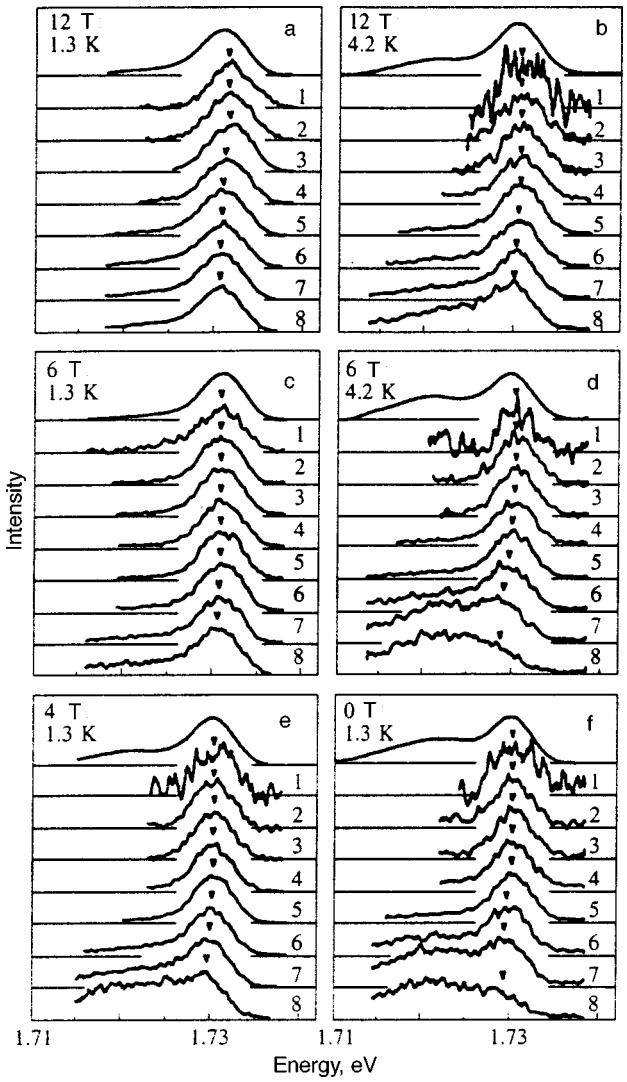

FIG. 3. Evolution of photoluminescence spectra of indirect excitons with time. Spectra 1–8 were recorded in time intervals shown in Fig. 2b and 2d. The positions of the photoluminescence line of mobile excitons are marked by ticks. Spectra integrated over time are shown at the tops. The spectra are normalized so that have almost the same peak intensities.

intensity on the low-energy side of the dominant line (Fig. 3b and 3d–f). The magnitudes of the shifts of these lines toward lower energy with the gate voltage V_g indicate that both of them are due to recombination of indirect excitons. The relative intensity of the low-energy line increases with the delay time (Fig. 3). Therefore, we associate this line with the recombination of strongly localized indirect excitons, whose nonradiative recombination rate is small owing to their lower mobility (it is likely to be smaller than their radiative recombination rate). The high-energy line is due to recombination of indirect excitons with a higher mobility (even though the localization radius of such excitons is finite, we dub them mobile for definiteness). These are the excitons which demonstrate the variations in the diffusion coefficient and radiative decay rate[4] with the magnetic field and temperature discussed above.

The observed changes in the ratio I_m/I_l between the intensities of the mobile and strongly localized exciton luminescence lines with the magnetic field and temperature are related to variations in both the diffusion coefficient and radiative decay rate of mobile excitons. For example, in fields below 7 T the radiative decay rate of mobile excitons drops with the increasing temperature,[4] whereas the diffusion coefficient grows (Fig. 2c). Both these effects lead to a decrease in I_m/I_l (Fig. 3c and 3d). This effect of temperature indicates that the distribution of excitons between localized and mobile states is nonequilibrium. The effect would have an opposite sign if there were equilibrium between these states, namely, the relative intensity of higher energy mobile excitons would increase with temperature. The time of experiment (about 1 μs), which is limited by the necessity of detecting the decaying luminescence signal, is insufficient for establishing equilibrium between the mobile and localized indirect excitons.

As the delay time increases, one can see a shift of the mobile exciton luminescence line, which reflects energy relaxation of excitons (Fig. 2b and 2d and Fig. 3). In order to determine the spectral position the line shape was approximated by a Gaussian. In magnetic fields $B \lesssim 7$ T, the energy relaxation rate of mobile excitons gradually drops with the delay; in addition, it decreases with the field and grows with the temperature at all delay times (Fig. 2b and 2d). In magnetic fields $B \gtrsim 7$ T the energy relaxation rate of mobile excitons is considerably higher at smaller delays; in addition, it increases with the magnetic field and drops with the temperature at small delays, whereas it decreases with the field and rises with the temperature at longer delays (Fig. 2b and 2d). Thus, the energy relaxation of mobile excitons is faster, the higher the diffusion coefficient throughout the entire range of experimental parameters studied (magnetic field, temperature, and delay).

After photoexcitation, electron–hole pairs are rapidly bound in excitons and lose their kinetic energy by emitting phonons. In this ''fast'' relaxation stage, $\Gamma - X$ electron transfer from GaAs to AlAs takes place and indirect excitons are formed. The times of these processes are considerably shorter than the lifetime of indirect excitons, and they are not revealed in our measurements. The ''slow'' energy relaxation, which is observed in the range between several nanoseconds and hundreds of nanoseconds (Fig. 2b and 2d), is controlled by excitons migrating between local minima of the random potential in the plane of the CQWs (Fig. 1b). This migration of excitons in the random potential is characterized by a large spread of relaxation times,[8] and the long lifetime of indirect excitons allows us to trace the transport and energy relaxation of excitons in the range of long delay times. The speed of exciton transport to deeper local minima increases with the their mobility, which leads to a faster energy relaxation of excitons. The relationship between the energy relaxation and exciton transport persists with the onset of exciton superfluidity, when superfluid domains of excitonic condensate are formed at some local minima.

The diffusion coefficient and radiative decay rate of indirect excitons are sensitive to the bath temperature down to 1 K, which indicates that excitons in local minima thermalize down to ~ 1 K. The recombination line of indirect excitons of each local minimum cannot be much wider than the exci-

ton temperature (~ 1 K), so the measured line width of about 50 K (Fig. 3) indicates that the laser excitation spot covers a lot of local minima, and the distribution of excitons among them is nonequilibrium. The measurement time (about one microsecond) is insufficient for establishing equilibrium among all local minima of the random potential. The condensation of excitons should result in a narrowing of luminescence line from the condensate domain owing to the macroscopic filling of state with the lowest energy. In our experiments, we have not detected a narrowing of the exciton luminescence line in strong magnetic fields and at low temperatures when the diffusion coefficient and radiative decay rate of indirect excitons increased anomalously (Fig. 3). This can be explained by the presence of a large number of condensate domains in the laser excitation spot with a nonequilibrium distribution of excitons among them.

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