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Magneto optics of the spatially separated electron and hole layers in GaAs/AlGaAs coupled quantum wells

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Abstract

We report on the photoluminescence (PL) study of the spatially separated electron and hole layers in GaAs/AlGaAs coupled quantum wells at low temperatures $T \geqslant 50$ mK. At high magnetic fields cusps are observed in the energy and intensity of the indirect (interwell) exciton PL. We tentatively attribute these to the commensurability effects of the magnetoexciton with island structures in the sample. Strong nonlinearities in the indirect exciton PL kinetics are observed: right after the excitation is switched off, the indirect exciton PL intensity jumps up, and the consequent PL intensity decay rate increases strongly with excitation density. The effects can be attributed to stimulated exciton scattering to the optically active exciton states (the boser effect) and exciton superradiance.

Keywords: Magneto optics; Coupled quantum wells

The system of spatially separated electron (e) and hole (h) layers in coupled quantum wells (CQWs) is remarkable by the fact that because of much longer e–h recombination time compared to single-layer e–h systems one can reach lower e–h temperatures that are close to the lattice temperature. Therefore, CQWs provide a unique opportunity for studying low-temperature 2D neutral e–h systems.

We report on the cw and time-resolved photoluminescence (PL) study of the spatially separated e and h layers in GaAs/AlGaAs CQW at low-temperatures $T \geqslant 50$ mK and high magnetic fields $B \leqslant 16$ T. The electric-field-tunable $n^+ - i - n^+$ GaAs/AlGaAs CQW structure was grown by MBE. The *i*-region consists of two 8 nm GaAs QWs separated by a 4 nm $Al_{0.33}Ga_{0.67}As$ barrier and surrounded by two 200 nm $Al_{0.33}Ga_{0.67}As$ barrier layers. The n^+-layers are Si-doped GaAs with $N_{Si} = 5 \times 10^{17}\ cm^{-3}$. The electric field in the *z*-direction is monitored by the external gate voltage V_g applied between n^+-layers. The small disorder in the CQW is indicated by the

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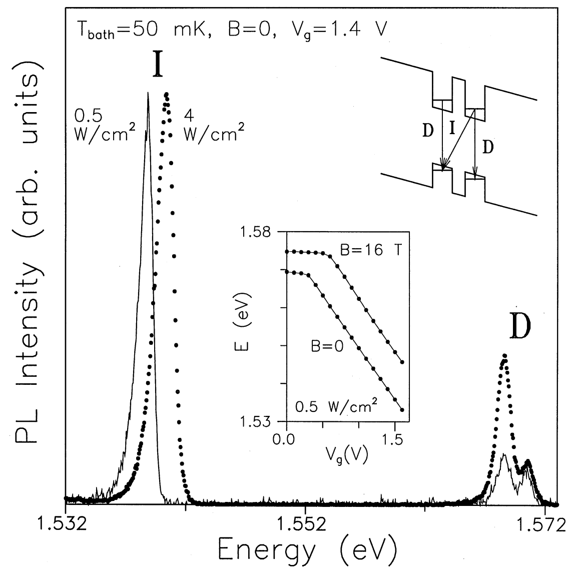

Fig. 1. PL spectra in the indirect regime. Top inset: band diagram of the GaAs/AlGaAs CQW structure under applied gate voltage; the direct (D) and indirect (I) exciton transitions are indicated. Bottom inset: the ground state PL line energy as a function of gate voltage.

indirect exciton PL line width of about 1 meV. Carriers were photoexcited by either a HeNe laser ($\hbar\omega = 1.96$ eV) or a pulsed semiconductor laser ($\hbar\omega = 1.85$ eV, the pulse duration was about 50 ns, the edge sharpness including the system resolution was ≈ 0.2 ns, and the repetition frequency was 1 MHz). The PL measurements were performed in a He^3/He^4 dilution refrigerator by means of an optical fiber with diameter 0.2 or 0.6 mm positioned 0.3 to 0.6 mm above the mesa.

A typical V_g dependence of the ground state PL line positions at low excitation densities is shown in the inset to Fig. 1. The crossover between the direct to indirect ground state proceeds from the V_g behaviour of the direct $\mathscr{E}_D = E_g + \hbar\omega_c/2 - E_D$ and indirect $\mathscr{E}_I = E_g + \hbar\omega_c/2 - E_I - eFd$ exciton energies, where E_g is the energy gap including the e and h confinement energies in the CQW, E_D and E_I are the direct and indirect exciton binding energies, d is the separation between e and h layers, $F = V_g/d_0$ is the electric field in the z-direction, d_0 is the i-layer width, $\hbar\omega_c$ is the sum of the e and h cyclotron energies. The direct-to-indirect ground state crossover field, F_{D-I}, given by $eF_{D-I}d = E_D - E_I$, increases with magnetic field; also, the indirect line shifts with B to higher energies stronger than the direct line (inset to Fig. 1). This corresponds to the stronger enhancement of E_D compared to that of E_I with magnetic field [1,2]; particularly, in the high magnetic field limit these energies are evaluated as $E_D \sim 1/l_B$ and $E_I \sim 1/(l_B^2 + d^2)^{1/2}$, where $l_B = \sqrt{\hbar c/eB}$ is the magnetic length.

Fig. 1 shows that, unlike the direct exciton, the indirect exciton energy increases with excitation density. This observation is consistent with the theoretically predicted enhancement of the indirect exciton energy with e–h density: it can be understood in terms of the net repulsive interaction between indirect excitons caused by the dipole–dipole repulsion for low exciton densities, and in terms of the energy shift originated from the electric field between the separated e and h layers for high e–h densities [3,4]. In the latter case the energy shift can be roughly estimated using the plate capacitor formula $\delta E = 4\pi n_{eh} e^2 d/\varepsilon$, which allows the estimation of the exciton density $\approx 9\times 10^9\ cm^{-2}$ at $W_{ex} = 4\ W/cm^2$ for the data of Fig. 1.

We analyze both the integrated indirect exciton PL intensity $M_0 = \int I(E)\,dE$ and the PL line position given by the line gravity center $M_1 = M_0^{-1}\int EI(E)\,dE$ as a function of magnetic field. The energy shift of the indirect exciton PL line with magnetic field reflects the excitonic recombination: a quadratic shift at low fields changes to an approximately linear shift at high fields (Fig. 2(a)) [5,6]. The magnitude of the linear shift 0.8 meV/T corresponds to the zero Landau level energy $\hbar eB/2mc$ with $m = 0.072m_0$ which is higher compared to the reduced e–h mass because of the magnetic field dependence of E_I discussed above. For visualization purpose this shift is subtracted from the dependences $M_1(B)$ to obtain $\Delta(B)$. As seen from Fig. 2(b), pronounced well-reproducible cusps in energy occur at high fields $B \gtrsim 7$ T. Also, the integrated indirect exciton PL intensity exhibits a similar oscillating behavior that is correlated to a certain extent with the energy variations (Fig. 2(c)): some of the energy maxima coincide with the maxima of M_0 (dashed lines in Fig. 2), whereas the others coincide with the minima of M_0 (dotted lines in Fig. 2). The cusp position is insensitive to both excitation density and V_g, and their amplitude drops with temperature [7].

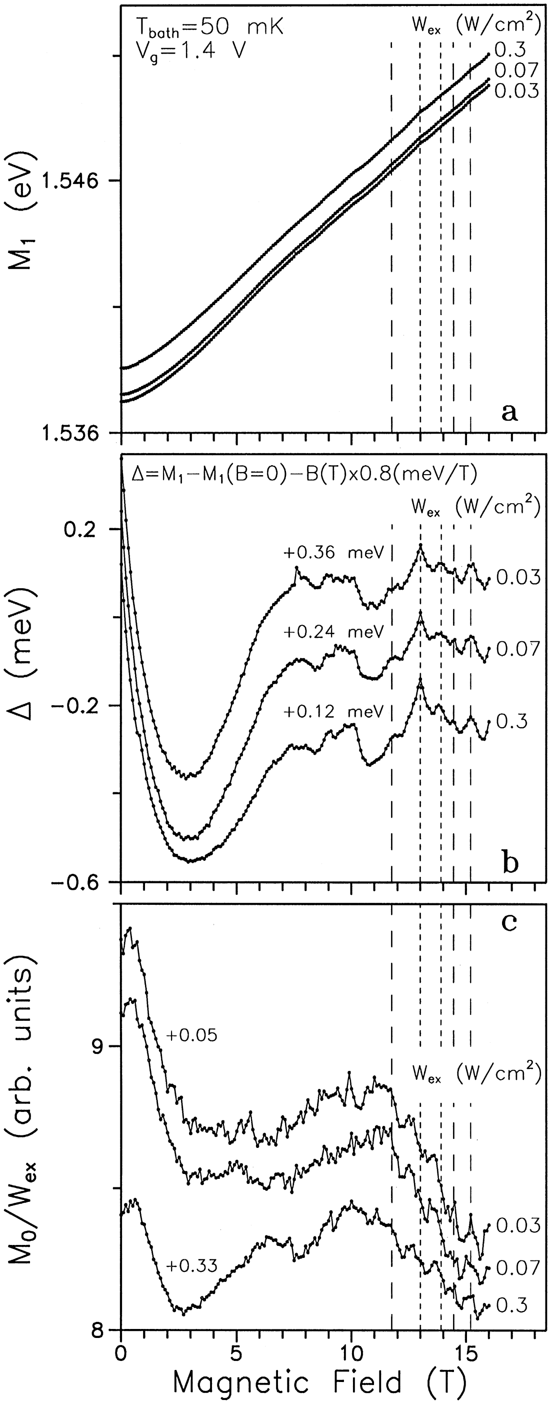

Fig. 2. Magnetic field dependences of the indirect exciton PL line position M_1 (a), its deviation from the linear shift Δ (b), and the integrated indirect exciton PL intensity M_0 normalized by the excitation density (c) versus excitation density. Some of the curves are shifted vertically for clarity, the shift magnitudes are indicated.

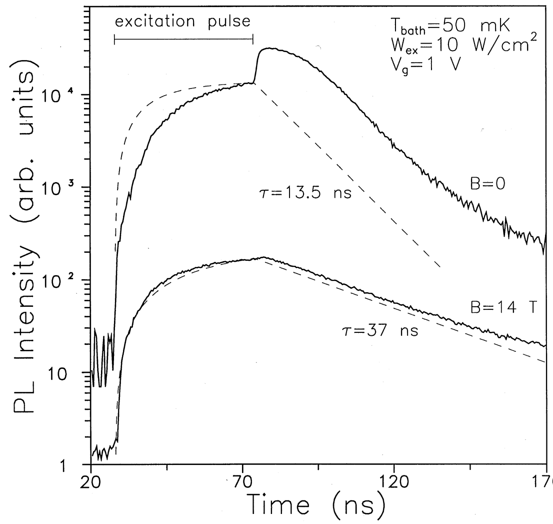

Fig. 3. Kinetics of the indirect exciton PL. The dashed lines represent the monoexponential PL rise/decay with time constants corresponding to the fastest PL decay rate.

Since the position of the cusps in the energy and intensity of indirect exciton PL is independent of the excitation-controlled exciton density (Fig. 2(b)), the cusps are not related to either filling-factor-sensitive collective states (contrary to cusps in the energy and intensity of 2DEG or 2DHG PL observed at fractional filling factors [8]) or magnetic-field-dependent screening and are likely to be of one-magnetoexciton origin. At the same time no cusps in energy and intensity are expected for both the indirect and direct one-magnetoexciton PL in ideal single- or double-layer e–h systems [2,5,6,9,10]. Therefore, we tentatively attribute the observed cusps to the commensurability effects of the magnetoexciton with island structures in the sample. (If an in-plane potential were periodic with a period a when cusps in the energy of the zeroth Landau level electron/hole/exciton state are expected whenever an energy gap formed by the potential is crossed; this happens if $a \sim \pi l_B(2N+1)$, where N is integer.) The cusp presence may reveal the potential correlations in the CQW.

The indirect exciton PL kinetics is shown in Fig. 3. At high excitation densities, low temperatures, and low magnetic fields the indirect exciton PL kinetics strongly differs from monoexponential PL rise/decay: right after the excitation is

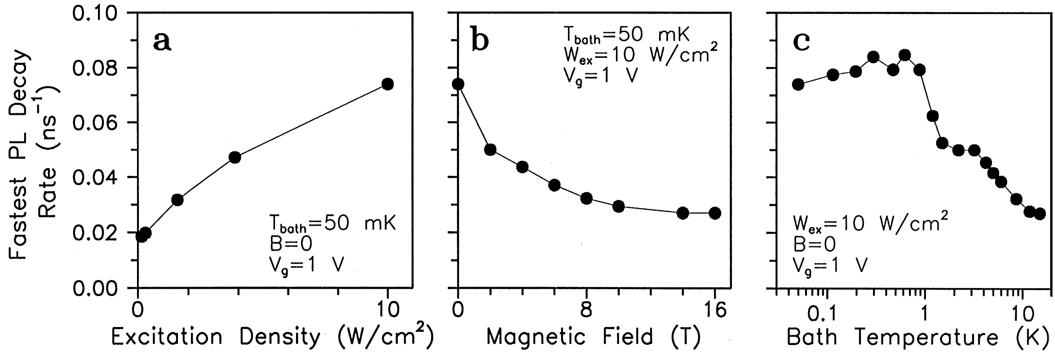

Fig. 4. The fastest PL decay rate versus excitation density, magnetic field and temperature.

switched off, the indirect exciton PL intensity first jumps up and then decays with a rate that changes non-monotonously with time. On the contrary, at low excitation densities [11], high magnetic fields (Fig. 3), and high temperatures [11] the indirect exciton PL kinetics are close to monoexponential with long-time constants.

The integrated exciton PL intensity remains almost constant with V_g variation while the decay time varies by several orders of magnitude [11]. Hence, the radiative recombination is dominant in the CQW studied. For delocalized 2D excitons only the states with small center-of-mass momenta $k \leqslant k_0 \approx E_g/\hbar c$ (where c is the speed of light in the medium) can decay radiatively [12]. The exciton PL kinetics is determined by the kinetics of occupation of the optically active exciton states with $E \leqslant E_0 = \hbar^2 k_0^2/2m \approx 1$ K. The occupation of these states is increased through the energy relaxation of photoexcited high-energy excitons and decreased as a result of exciton recombination. The PL-jump denotes a sharp increase of the occupation of the optically active exciton states just after the excitation is switched off [11].

We emphasize that the fastest PL decay rate is increased with excitation density (Fig. 4a) and discuss this below. The exciton radiative decay rate is proportional to the dipole matrix element connecting Bloch states in the valence and conduction bands, the overlap between the e and h wave functions describing e–h relative motion, the lateral size of the exciton center-of-mass wave function (the so-called exciton coherent area as determined by the exciton localization length and scattering length), and the occupation of the optically active exciton states [12]. The observed increase of the fastest PL decay rate can be attributed to two distinct effects. The first is related to the increase of the exciton coherent area (the exciton superradiance effect) [13]. The increase of the exciton coherent area with increasing exciton density is due to the enhanced exciton screening of random potential fluctuations and filling of low energy strongly localized states which originates from the repulsive interaction between indirect excitons (see above). The second is related to the superlinear increase of the occupancy of the optically active exciton states with excitation density caused by stimulated exciton scattering (the boser effect) [14]: it occurs when the occupation numbers of the states approach and exceed unity. The exciton accumulation is promoted by the long lifetime of indirect excitons [11].

The fastest radiative decay rate is reduced with increasing magnetic field (Fig. 4b). We note that this is qualitatively different from the case of AlAs/GaAs CQWs where the indirect exciton radiative and nonradiative decay rates were observed to increase abruptly at low temperatures and high magnetic fields which was related to the exciton condensation [15]. In the studied GaAs/AlGaAs CQW, where no exciton condensate is expected at high magnetic fields because of large separation between e and h layers ($d \gtrsim l_B$ at $B > 4$ T) [3,16], no such increase of the decay rate is observed. The observed reduction of the indirect exciton radiative decay rate with magnetic field (Fig. 4b) can be explained by reduction of the exciton coherent area and of the occupation numbers of optically active exciton states. The origin for both effects is an order of magnitude increase at the highest magnetic fields of the magnetoexciton mass for the interwell excitons with large $d \approx 12$ nm, as calculated in Ref. [10]. The competitive increase of the magnetoexciton radiative decay rate due to the shrinkage of the in-plane exciton radius (given by l_B at high fields [9]) is, apparently, a weaker effect.

With increasing bath temperature the occupation of the low energy optically active states reduces, which results in the observed reduction of the PL decay rate (Fig. 4c).

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