Direct and indirect magnetoexcitons in symmetric $In_xGa_{1-x}As/GaAs$ coupled quantum wells

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Spatially direct (intrawell) and indirect (interwell) excitons in symmetric $In_xGa_{1-x}As/GaAs$ coupled quantum wells were studied by photoluminescence and photoluminescence excitation spectroscopy at magnetic fields $B \leq 14$ T. The regimes of zero and high electric fields in the growth direction as well as the transition between them were examined. The magnetic field changes the ratio between the one-particle symmetric-antisymmetric splittings and the exciton binding energies. This was found to result in a strong influence on the energies and oscillator strengths of the optical transitions both at zero and finite electric fields. The direct-indirect exciton crossover under applied electric field was found to be markedly modified by the magnetic field due to the increase of the exciton binding energy.

The study of excitons in coupled quantum wells (CQW's) has attracted considerable interest in the past. In particular, this is connected with the possibility of the formation of spatially indirect (interwell) excitons in CQW's with controllable overlap between electrons and holes. Due to the long recombination lifetime of indirect excitons, the exciton condensation (analogous to the Bose-Einstein condensation of bosons) is expected to occur in CQW's.[1,2] Recently, strong evidence for the condensation of indirect excitons in GaAs/AlAs CQW's has been observed at high perpendicular magnetic fields which improve critical conditions for the exciton condensation.[3]

In the present paper we study the properties of excitons in CQW's at high magnetic fields in the limit of low exciton densities (one-exciton problem). The excitons in symmetric $In_xGa_{1-x}As/GaAs$ CQW's characterized by light electron and hole masses and a simple valence band structure are studied. At zero magnetic field direct (intrawell) and indirect excitons in symmetric CQW's were studied both experimentally and theoretically.[4–11] The experimental work was performed on $GaAs/Al_xGa_{1-x}As$ CQW's. The optical transitions were studied as a function of the barrier/well width[4,8] or electric field in the growth direction.[5–7]

Theoretical analysis has shown that symmetric CQW's can be divided into regimes of narrow barriers and wide barriers where the classification of exciton states at zero electric field is concerned.[10,11] The regime can be parametrized by the ratio between one-particle symmetric-antisymmetric splittings (Δ_{SAS}) and exciton binding energies $\alpha = (\Delta_{SAS}^{(e)} + \Delta_{SAS}^{(h)})/(E_D - E_I)$, where E_D (E_I) is the binding energy of exciton made from an electron and a hole in the same (different) well. For CQW's with a wide barrier $\alpha \ll 1$. In this limit the exciton states are essentially direct (D) or indirect (I) in character. In order of increasing energy, the exciton states are D symmetric, D antisymmetric, I antisymmetric, and I symmetric. Antisymmetric exciton states are optically inactive; the oscillator strength (f_{osc}) of the I symmetric exciton is much smaller than that of the D symmetric exciton due to the smaller overlap between electron and hole. The energy splitting between the D and I exciton transitions is equal to the difference between the D and I exciton binding energies.[12] In CQW's with a narrow barrier, $\alpha \gg 1$, the exciton states have mixed direct-indirect character. In the limit of zero Coulomb interaction the exciton states can be classified as electron-hole single-particle pair states: $S_eS_h, S_eA_h, A_eS_h, A_eA_h$, where S and A are symmetric and antisymmetric one-particle electron/hole states. S_eS_h and A_eA_h transitions have equal f_{osc} while S_eA_h, A_eS_h are optically inactive. The energy splitting between the optical transitions is equal to $\Delta_{SAS}^{(e)} + \Delta_{SAS}^{(h)}$. For CQW's with arbitrary α always the first and the fourth exciton state in order of increasing energy are optically active while the second and the third have zero f_{osc}. The ratio between f_{osc} of the first and the fourth exciton states is monotonically increased with decreasing

α.

At high electric fields (F) the excitons become purely direct or indirect for CQW's both with wide and narrow barriers. The transition from zero to high electric field regime, however, is expected to be different for these two cases as it is strongly determined by the Coulomb interaction.[10,11]

A magnetic field (B) perpendicular to the plane of the CQW results in a strong modification of the exciton states. The electron-hole Coulomb interaction is monotonically increased with the increase of B, which results in a reduction of α. In particular, this opens the possibility to analyze a transition from the narrow to the wide barrier regime in one and the same CQW structure.

Many repeated pairs of symmetric CQW's form a superlattice (SL). Optical transitions in SL's at magnetic fields were studied experimentally and theoretically.[14–16] Below, we discuss briefly similarities and differences between the exciton states in symmetric CQW's and SL's (for extended comparison see Refs. 10, 17, and 18). Due to the SL miniband formation, the carrier energy spectrum is three dimensional (3D) at zero B and quasi-1D at high B. The singularities in the density of states at the electron/hole miniband minima and maxima result in the double peak structure in the absorption spectra; at high B this double peak structure is connected with each pair of the Landau subbands.[14] Electric field localizes the carrier wave functions, resulting in destroying of the miniband structure, which is replaced by the Stark ladder. Therefore, at high F the exciton states in SL's are analogous to that in CQW's. However, at zero F the excitons in CQW's differ from that in SL's due to the lower dimensionality. Correspondingly, the transition from zero to high F regime is also different for CQW's and SL's.[10,17,18]

To study magnetoexcitons in symmetric CQW's we have chosen strained $In_{0.2}Ga_{0.8}As$/GaAs CQW structures in which, due to the simple valence band structure, the direct and indirect magnetoexciton transition from different Landau levels are easily identified. The samples are designed as electric field tunable n^+-i-p^+ structures. They have been grown by molecular beam epitaxy. The active part of the structure is the i region, which consists of two 60 Å $In_{0.2}Ga_{0.8}As$ QW's separated by a 60 Å GaAs barrier and surrounded by 2000 Å GaAs barrier layers (Fig. 1). With increasing external gate voltage (V_g) the internal electric field in the structure is reduced and at $V_g \approx 1.52$ V the flat band regime is realized. The transition to the flat band regime is characterized by an abrupt increase of the current across the structure (by several orders of magnitude) and by the onset of strong electroluminescence. Further increase of V_g results only in a weak change of the electric field in the structure due to the large current through the device. Photoluminescence excitation (PLE) and photoluminescence (PL) spectra were recorded with the use of a cw Ti-sapphire laser (excitation density ≈ 0.1 W/cm^2) at low temperature ($T \approx 350$ mK) and high perpendicular magnetic fields ($B \leq 14$ T).

We first consider the regime of zero electric field. Figure 1 presents PLE spectra recorded with detection on the maximum of the PL line at $V_g = 1.55$ V versus B in steps of 1 T. The inset presents the PLE spectra recorded with detection on the low energy tail of the PL line at $B = 0$ and 14 T. The PLE line positions are presented in Fig. 2 by solid dots. At zero magnetic field two heavy-hole exciton transitions are observed in the PLE spectra (see inset). The energy splitting between them, $\simeq 8.5$ meV, slightly exceeds the calculated value of $\Delta_{\rm SAS}^{(e)} + \Delta_{\rm SAS}^{(h)}$=5.9+0.6=6.5 meV.[13] The oscillator strengths of the transitions are approximately equal. Therefore at B=0 the parameters of our CQW correspond to the narrow (or intermediate) barrier regime. The excitons have mixed direct-indirect character. For assignment, however, we label the transitions as D and I. Pure D and I excitons are shown schematically in the inset. The light-hole exciton absorption is observed at approximately 1443 meV.

At high magnetic fields direct (D_N) and indirect (I_N) excitons composed from electrons and holes with equal Landau level numbers (Nth) are optically active. The exciton energies are $\mathcal{E}_{D(I)_N} = (\hbar\omega_{\rm ce} + \hbar\omega_{\rm ch})(N + 1/2) - E_{D(I)_N}$, where $\hbar\omega_{\rm ce}$ and $\hbar\omega_{\rm ch}$ are electron and hole cyclotron energies and $E_{D(I)_N}$ is the binding energy of the D (I) exciton.[19] Both D_N and I_N excitons from different Landau levels are observed in the spectra (see Fig.

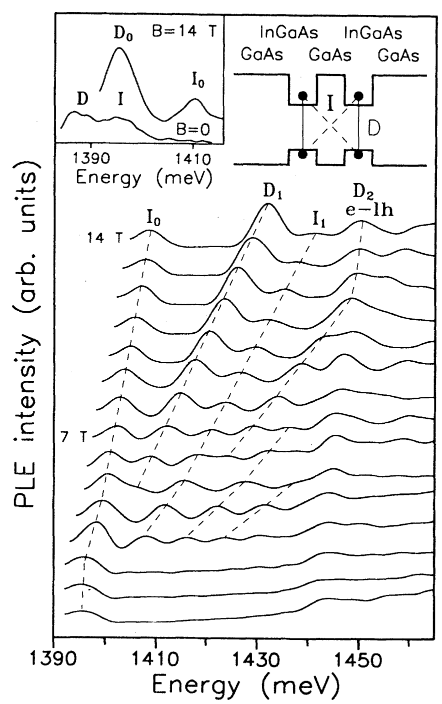

FIG. 1. PLE spectra recorded with detection on the maximum of the PL line at zero electric field regime ($V_g = 1.55$ V) for magnetic fields $B = 0 - 14$ T in 1 T steps. The dashed lines are a guide for the eyes. Left inset: PLE spectra recorded with detection on the low energy tail of the PL line at zero electric field at $B = 0$ and 14 T. Right inset: Schematic band diagram of the $In_xGa_{1-x}As$/GaAs CQW at $F = 0$.

1). Due to the simple valence band structure the excitons with energies below the light-hole exciton can be easily identified, while at higher energies the spectra are complicated and will not be further considered in the present paper (as well as the light-hole excitons).

At high B the exciton binding energies can be approximated by $E_D \sim 1/l_B \sim B^{1/2}$,[20] $E_I \sim (l_B^2 + d^2)^{-1/2}$ (l_B is a magnetic length, d is effective interwell electron-hole separation). Due to the spatial separation between electron and hole for the I exciton, the increase of E_I with B is slower than that of E_D. Therefore magnetic field results in an increase of the energy splitting between the D and I excitons, Δ_{I-D}, and in a reduction of the parameter α. The increase of Δ_{I-D} with B is directly observed in our experiments (see Figs. 1 and 2). At high magnetic fields $\Delta_{I_0-D_0}$ markedly exceeds $\Delta_{\rm SAS}^{(e)} + \Delta_{\rm SAS}^{(h)}$ and is determined by the difference in the D and I exciton binding energies. The reduction of α with B results in an increase of the ratio between the oscillator strengths of the direct and indirect excitons f_D/f_I. While at B=0, $f_D \approx f_I$,

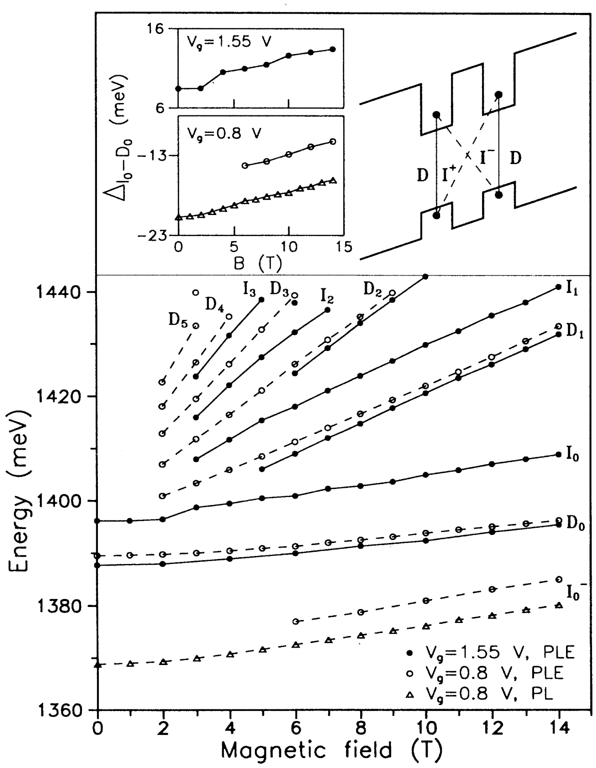

FIG. 2. Magnetic field dependence of the exciton transition energies for zero electric field (V_g = 1.55 V) and for high electric field ($F \approx$ 17.2 kV/cm, V_g = 0.8 V). PLE line positions at V_g = 1.55 V (0.8 V) are shown by solid dots (open circles). PL line positions for V_g = 0.8 V are shown by triangles. Left inset: Magnetic field dependence of energy splittings between I_0 and D_0 excitons for V_g = 0.8 (open circles) and 1.55 V (solid dots). The energy differences between the I_0 PL lines and the D_0 PLE lines at V_g=0.8 V are shown by triangles. Right inset: schematic band diagram for finite F.

at B=14 T f_D is considerably larger than f_I (see inset of Fig. 1). The increase of f_D/f_I with decreasing α is in qualitative agreement with theoretical considerations of exciton oscillator strengths in CQW's.[10,11]

The parameter α depends also on the Landau level number N because the exciton binding energy is reduced with N. In particular, in the high field limit $E_{D_1} = \frac{3}{4}E_{D_0}$.[20] The reduction of E_{I_N} with N is smaller than that of E_{D_N}, again due to the electron-hole separation for the indirect exciton. Due to this reason, at high magnetic fields $\Delta_{I_1-D_1}$ is smaller than $\Delta_{I_0-D_0}$ (see Figs. 1 and 2).

At intermediate fields (B = 3 − 6 T) a complicated behavior of the exciton transitions is observed. Figure 1 shows that under reduction of the field $f_{\rm osc}$ of the D_N excitons start to drop quickly near $B \sim 6$ T; at the same time $f_{\rm osc}$ of the I_{N-1} excitons is increased ($N \geq 1$). This behavior is a consequence of the mixing between the direct and indirect excitons from different Landau levels. The mixing is strong at low fields $B \lesssim 6$ T at which the splitting between excitons from different Landau levels becomes comparable to Δ_{I-D}.

At high electric fields there are direct and two types of indirect (I^+ and I^-) excitons (see inset of Fig. 2). The PLE line positions for V_g = 0.8 V ($F \approx$ 17.2 kV/cm) are shown by open circles in Fig. 2. Due to the low oscillator strength of the indirect excitons only the direct excitons and I_0^- exciton (at high B) are observed in the spectra. The behavior of the I_0^- exciton at low B is presented by the PL line position, which is observed below the PLE line due to inhomogeneous line broadening. The magnetic field dependences of the D exciton energies and oscillator strengths at high F are similar to that at zero F. Deviations are observed at low fields ($B \lesssim 6$ T), where D and I excitons are mixed at F = 0. Similar to the zero electric field case, at high F the diamagnetic shift of the I_0 exciton is higher than that of the D_0 exciton (see Fig. 2 and inset of Fig. 2). The origin of this effect is the same as for the zero electric field case — the binding energy of the I exciton increases more slowly with B as compared to that of the D exciton. Note that at high F the magnetic field dependence of the exciton transitions is qualitatively similar to that observed in SL's.[16]

The evolution of the exciton states under applied electric field is shown in Figs. 3 and 4. Figure 3 presents PLE spectra recorded from the maximum and the low energy tail of the PL lines as well as PL spectra at B = 10 T. The PLE and PL line positions at B = 0 and 10 T are shown in Fig. 4. Under an applied electric field the D_N (I_N) magnetoexcitons split into D_N^+ and D_N^- (I_N^+ and I_N^-) excitons. With increasing electric field the I_N^- exciton anticrosses with the D_N^+ and D_N^- excitons. Therefore, at high electric fields the D_N^- exciton transfers to the I_N^- exciton, while the D_N^+ and I_N^- excitons form the D_N excitons (there are two D_N excitons at high F; the splitting between them is small and is not resolved in our experiment). The D_N excitons have high $f_{\rm osc}$ while I_N excitons have low $f_{\rm osc}$; the exciton anticrossing is accompanied by the corresponding redistribution of the oscillator strengths (see Fig. 3).[21]

At B = 10 T the shifts of the D_N and I_N excitons

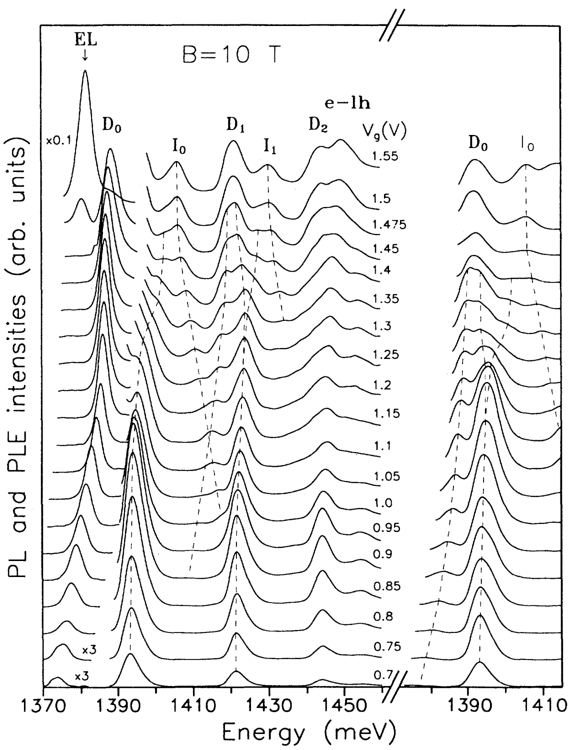

FIG. 3. Electric field dependences of PL and PLE spectra at B = 10 T. PLE spectra recorded with detection on the maximum (low energy tail) of the PL lines are shown on the left (right). The dashed lines are a guide for the eyes.

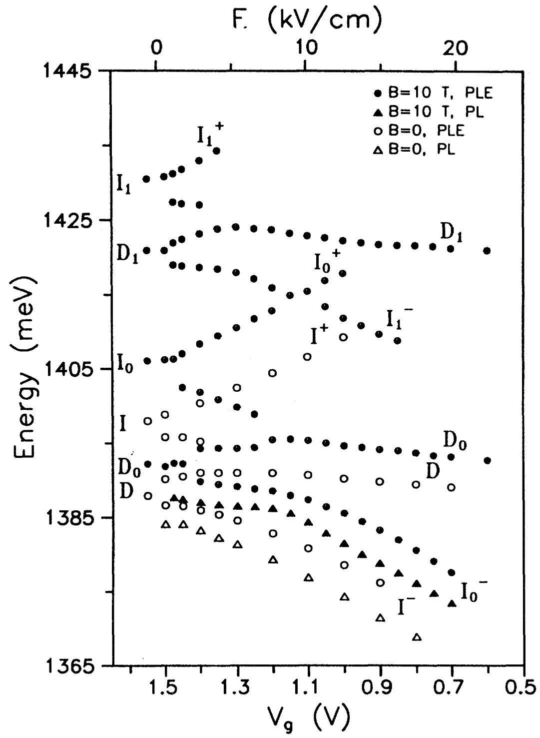

FIG. 4. Electric field dependences of the exciton transition energies at $B = 0$ and 10 T. PLE line positions at $B = 0$ (10 T) are shown by open circles (solid dots). PL line positions at $B = 0$ (10 T) are shown by open (solid) triangles.

with F are essentially different, which is clearly seen on the example of the 0th Landau level (see Figs. 3 and 4). While the I_0^+ and I_0^- excitons experience a strong energy shift with F, the position and oscillator strength of D_0^- exciton are changed weakly at small electric field, and start to drop quickly only at $F \approx 8.9$ kV/cm ($V_g \approx 1.15$ V). This electric field, F_{D-I}, corresponds to the anticrossing between the D and I excitons and, therefore, to the direct-indirect exciton crossover. At F_{D-I} the energy difference between the single-particle direct and indirect pair states become equal to the difference in the D and I exciton binding energies: $eF_{D-I}d \approx E_D - E_I$ (e is the electron charge). The increase of the difference between the D and I exciton binding energies should result in an increase of F_{D-I}. This effect is observed with increasing B. At $B = 0$ (see Fig. 4) the ground state exciton becomes essentially indirect already at $F \approx 4.1$ kV/cm ($V_g \approx 1.35$ V). Thus the magnetic field strongly modifies the direct-indirect exciton crossover due to the increase of the Coulomb interaction. In particular at $F \approx 7.7$ kV/cm ($V_g = 1.2$ V) the ground state exciton is indirect at $B = 0$ but direct at $B = 10$ T. Similarly, F_{D-I} for the excitons from the first Landau level is smaller than F_{D-I} for the excitons from the 0th level (see Figs. 3 and 4), also due to the smaller Coulomb interaction for the former.

In conclusion, we have studied direct and indirect magnetoexcitons in symmetric $In_xGa_{1-x}As/GaAs$ CQW's at zero and finite electric fields. The exciton energy splittings and relative oscillator strengths were found to be strongly determined by the electron-hole Coulomb interaction, which is increased with magnetic field and reduced with Landau level number. The evolution of the magnetoexciton states under applied electric field was studied. The direct-indirect exciton crossover under increased electric field was found to be strongly modified by the magnetic field due to the increase of the exciton binding energy.

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