Magnetophotoluminescence of negatively charged excitons in narrow quantum wells

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We present the results of photoluminescence experiments on the negatively charged exciton X^- in $GaAs/Al_xGa_{1-x}As$ quantum wells (QW) in high magnetic fields ($\leqslant 50$ T). Three different QW widths are used here: 100, 120, and 150 Å. All optically allowed transitions of X^- are observed, enabling us to experimentally verify its energy-level diagram. All samples behave consistently with this diagram. We have determined the binding energy E_b of the singlet and triplet state of X^- between 23 and 50 T for the 120 and 150 Å QW, while only the triplet E_b is observed for the 100 Å QW. A detailed comparison with recent theoretical calculations shows an agreement for all samples across this entire field range.

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I. INTRODUCTION

A neutral exciton X_0 consists of one conduction-band electron and one valence-band hole bound by the Coulomb interaction. If X_0 binds a second electron (hole), one has a negatively (positively) charged exciton X^- (X^+), also called a trion. The neutral exciton is the solid-state analog of the hydrogen atom H, while X^- is the analog of the negatively charged hydrogen ion H^-. Since X^- consists of one hole and two electrons, the binding energy, E_b, is defined as the energy needed to remove the second electron and is expected to depend strongly on the confinement. Indeed, localizing the neutral exciton in a quantum well (QW) with excess electrons or holes increases the binding energy of the excess charge carrier sufficiently so that the trion can be observed experimentally. The behavior of charged excitons in a magnetic field B is currently of much interest and has been studied theoretically[1–6] as well as experimentally,[7–14] but is still a matter of intense debate. In particular, the behavior of E_b as a function of QW width and magnetic field has been the focus of much attention. Here we report a series of photoluminescence (PL) experiments, in which we have measured all the optically allowed transitions of X^- in magnetic fields up to 50 T. By taking the difference in PL energy between the X_0 and X^- transitions, we determine E_b for both singlet and triplet states as a function of field for different QW widths. Our experimental results are compared with recent theories[1,2] that consider the identification of the singlet and triplet states and calculate their binding energy.

Pauli's exclusion principle tells us that since the two electrons of X^- are identical, the total wave function must be antisymmetric, and consequently, it factorizes into a symmetrical (antisymmetrical) spin part with an antisymmetrical (symmetrical) space part. Taking this into account, there is only one possibility to construct the antisymmetrical spin wave function known as the singlet state of the negatively charged exciton, X_s^-. The three possibilities for constructing the symmetrical spin wave function correspond to the triplet state of the negatively charged exciton, X_t^-. By applying a magnetic field, the degeneracy of the energy levels of X_s^- and X_t^- is lifted by the Zeeman interaction determined by the exciton gyromagnetic ratio (g factor). Much theoretical effort has been put into predicting the field dependence of these states. There is now a consensus that the triplet state is unbound at low fields, while the singlet is bound at any field. (A recent theory has predicted that the triplet will be stable at zero field,[3] but this has not yet been observed experimentally.) A source of great debate has been the lowest-energy bound triplet, which is not expected to be observable experimentally in two-dimensional (2D) systems,[4] and is therefore called the ''dark'' triplet. Despite this, a number of experiments by different groups have shown a clear triplet transition for 2D QW spectra at finite field.[7–13] Recently, this apparent contradiction was resolved by the theoretical discovery of a new optically active ''bright'' triplet state,[2] which should be seen experimentally. This has motivated us to perform new experiments with polarization sensitivity on a series of samples and to make a fresh comparison between theory and experiment.

The present paper is organized as follows. In Sec. II we describe the sample details and our experimental setup. The experimental results and the field dependence of the PL transitions of all samples are discussed in Sec. III. In Sec. IV a revised energy-level diagram of X^- is constructed and the X_0 and X^- effective g factors are analyzed. We also determine the binding energy of X^- for all samples. A detailed comparison between our experimental results and available theoretical calculations is made in Sec. V. In the last section we summarize our results and present some conclusions.

II. EXPERIMENTAL SETUP

All $GaAs/Al_xGa_{1-x}As$ QW samples are grown by molecular beam epitaxy and asymmetrically doped with a Si

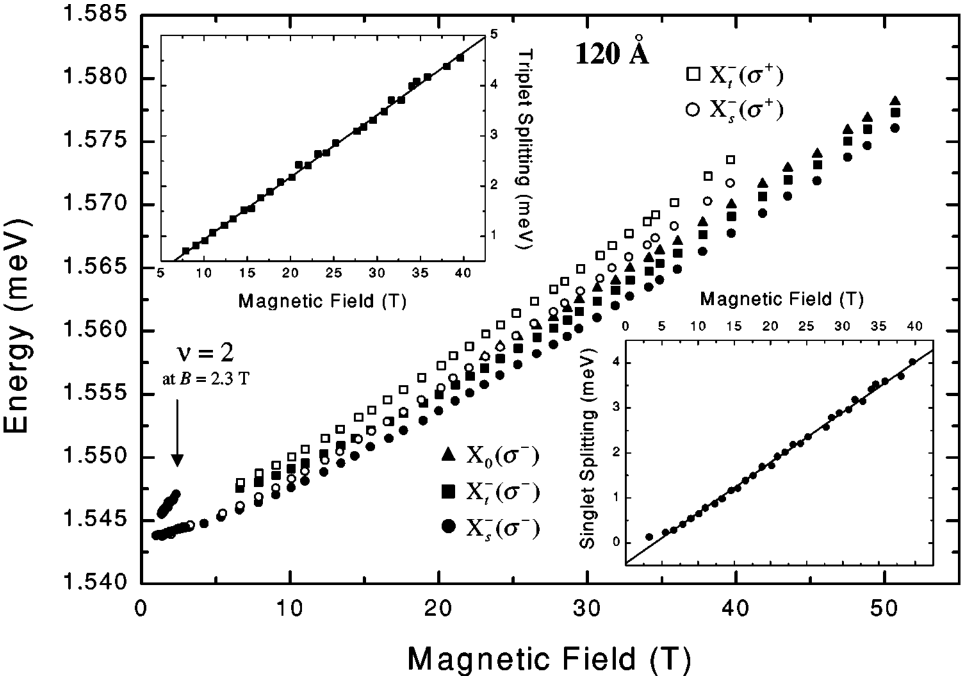

FIG. 1. Field dependence of the PL energy of the 120 Å QW at 4.2 K. The open [closed] symbols present the right- [left-] handed circularly polarized PL light. The lower [upper] inset shows the singlet [triplet] spin splitting obtained by taking the difference in PL energy between the two singlet [triplet] components $X_s^-(\sigma^+)$ and $X_s^-(\sigma^-)$ [$X_t^-(\sigma^+)$ and $X_t^-(\sigma^-)$].

density of 10^{18} cm^{-3}. A 100 Å thick $Al_xGa_{1-x}As$ barrier separates the donors from the QW. Three samples with different QW widths are used in our experiments: 100, 120, and 150 Å, i.e., in the narrow quantum-well regime. A description of the samples' band structure can be found elsewhere.[8] The optical experiments were carried out in a bath cryostat (1.2 K and 4.2 K) with B parallel to the growth direction of the QW. The optical excitation was achieved by the light of a solid-state laser at 532 nm with a maximum laser power density of 440 mW/cm^2. The observation of the second Landau level for the 120 and 150 Å QW samples enables us to determine the excess electron density, n_s. Above $Al_xGa_{1-x}As$ band-gap illumination was used to deplete the electron density in the GaAs QW (optical depletion) while reducing the disorder.[15] X^- is observed by an effective dilution of the two-dimensional electron gas using the magnetic field.[7–9,12] The laser light was transmitted to the sample in the cryostat via a single optical fiber. The PL was collected by six optical fibers arranged symmetrically around the central one. Our spectral resolution was better than 0.2 meV for the 120 and 150 Å QW, and 0.5 meV for the 100 Å QW. During the 25 ms magnetic field pulse, we achieved photon counting times of 0.65 ms for the 120 and 150 Å QW and a maximum of 2 ms for the 100 Å QW. This resulted in a field resolution of $\pm 0.1\%$ and $\pm 3\%$, respectively. The combination of an *in situ* polarizer and reversing the field direction enabled us to distinguish between the right- (σ^+) and left-handed (σ^-) circularly polarized PL light. A more detailed description of our experimental setup can be found in the literature.[16]

III. EXPERIMENTAL RESULTS

Figure 1 shows the field dependence of the PL energy for the 120 Å QW at 4.2 K. At low fields, we observe the second Landau level and locating $\nu=2$ at $B=2.3$ T gives $n_s = 1.1\times 10^{11}$ cm^{-2}. Four PL lines are observed for 7 T$<B<$23 T, two with a σ^+ and two with a σ^- polarization, while a third σ^- component appears at higher fields. The intensities of the σ^- components remain high up to 50 T, while those of σ^+ go gradually to zero and they become unobservable around 40 T. The assignment of the experimental PL lines is as follows. The splitting of the lowest energy line (circles) into a σ^+ and σ^- component in field is attributed to the Zeeman splitting of the singlet state of X^-, $X_s^-(\sigma^+)$, and $X_s^-(\sigma^-)$ respectively. A similar behavior is observed around 7 T (squares) and is assigned to the two components of the triplet state, $X_t^-(\sigma^+)$ and $X_t^-(\sigma^-)$. The triplet PL recombination is not observed at fields below 7 T, which is consistent with other experimental reports.[7–13] The highest energy line with σ^- polarization for $B>23$ T corresponds to the neutral exciton, $X_0(\sigma^-)$. The σ^+ component, $X_0(\sigma^+)$, is not observed, probably due to its high energy. Notice the clear crossing between $X_s^-(\sigma^+)$ and $X_t^-(\sigma^-)$ around 17 T, while the $X_s^-(\sigma^+)$-$X_0(\sigma^-)$ crossing at 24 T is less apparent due to the low intensity of $X_0(\sigma^-)$. Note also that all PL lines with the same polarization are parallel. This is consistent with our energy-level diagram as will be discussed in the next section.

The PL recombination of the 150 Å QW at 4.2 K is very similar to that of the 120 Å QW and is presented in Fig. 2. Here we observe an electron density of $n_s = 1.3\times 10^{11}$ cm^{-2} by locating $\nu=2$ at $B=2.7$ T. The assignment of the PL lines is analogous to that in Fig. 1, and all recombination remains visible up to 50 T. $X_0(\sigma^-)$ is detected starting at $B=23$ T. Again, the σ^+ component of X_0 is not found except, possibly, as a mixture between $X_t^-(\sigma^+)$ and $X_0(\sigma^+)$ for $B>32$ T. This is seen as a change in slope of the highest energy line around 30 T. Again, analogous comments about

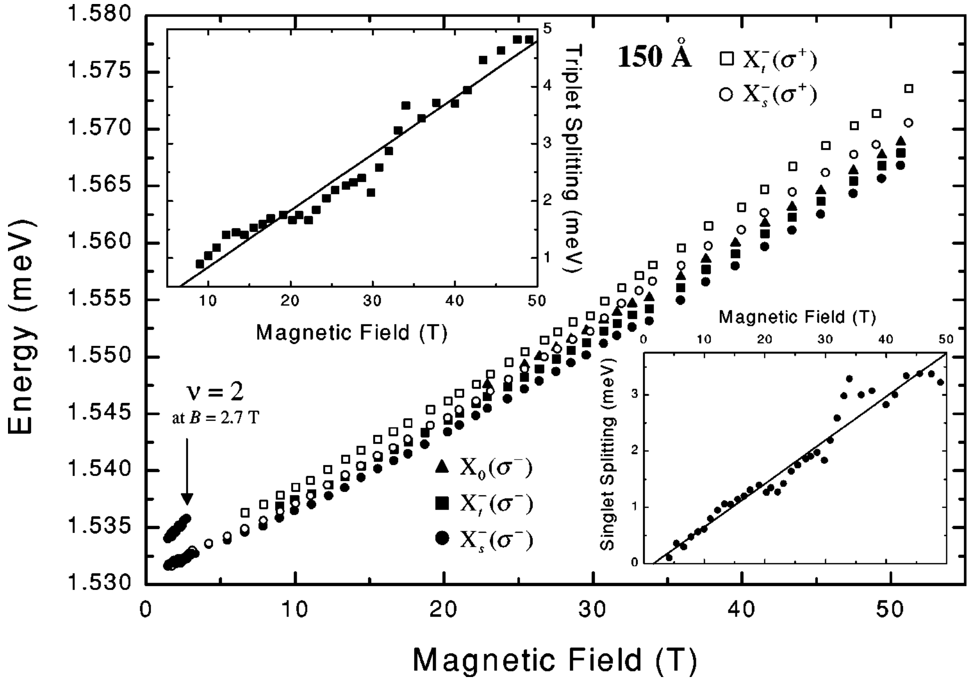

FIG. 2. Field dependence of the PL energy of the 150 Å QW at 4.2 K. The same notation has been used as in Fig. 1. The lower (upper) inset shows the singlet (triplet) spin splitting as a function of field.

the singlet-triplet and singlet–neutral-exciton crossings observed in the 120 Å QW can be made here.

Figure 3 shows the field dependence of the PL energy for the 100 Å QW at 1.2 K. In contrast to the other samples, only two σ^- components are observed here but the intensities of the two σ^+ components behave similarly to the other samples. The assignment of the PL lines for the 100 Å QW sample is not as straightforward as for the other samples. Since it is not obvious how to make an experimental distinction between the different states of X^- (see Sec. IV), the two lowest-energy components at low field (circles) are assigned to the Zeeman splitting of one of the X^- states and therefore labeled as $X^-(\sigma^+)$ and $X^-(\sigma^-)$. In contrast to our previous report,[7] the two other lines are now assigned as the two components of the neutral excitonic recombination, $X_0(\sigma^+)$ and $X_0(\sigma^-)$. This is motivated by a lack of observation of the second Landau level, implying a lower electron density in the QW, which would favor the formation of the neutral exciton in this sample. Both assignments are also driven by a comparison of the binding energy with the other samples and with recent theory, as will be explained in detail in Sec. V. Note that the same PL energies are observed for $X^-(\sigma^+)$

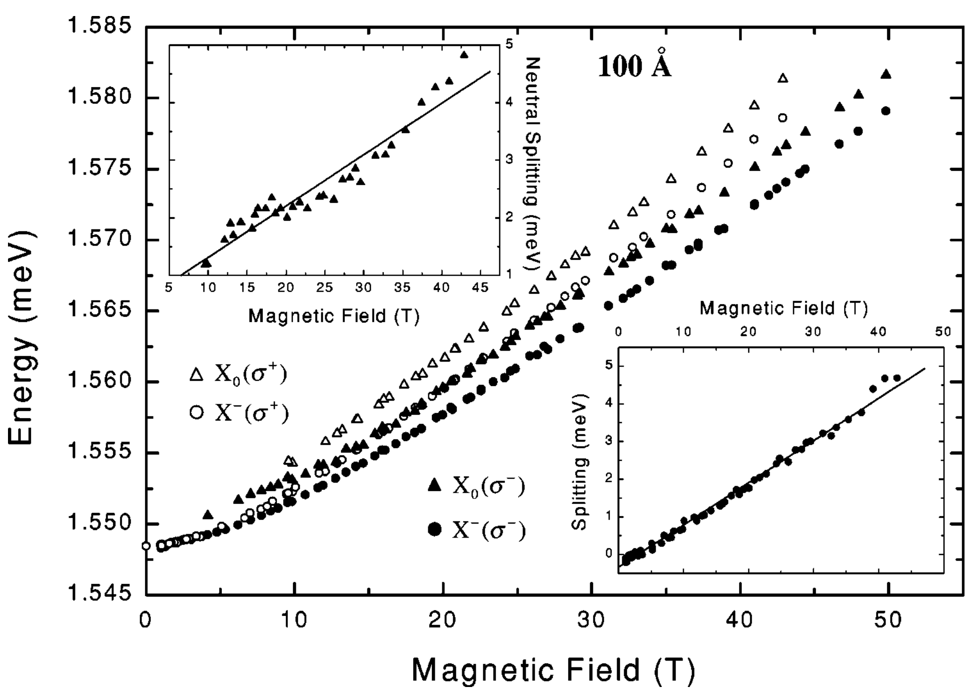

FIG. 3. Field dependence of the PL energy of the 100 Å QW at 1.2 K. $X^-(\sigma^+)$ and $X^-(\sigma^-)$ present the two components of one of the X^- states with a spin splitting shown in the lower inset. The upper inset shows the spin splitting of the neutral exciton.

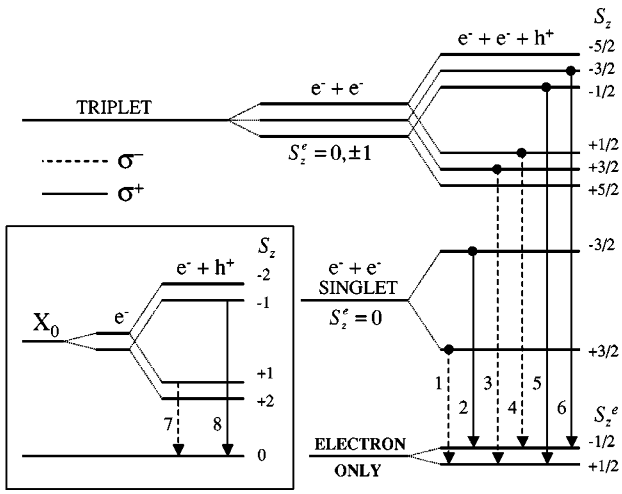

FIG. 4. Energy-level diagram of the singlet and triplet state of the negatively charged exciton with total spin z component S_z and six optically allowed PL transitions. The inset shows the energy-level diagram of the neutral exciton with two optically allowed PL transitions.

and $X_0(\sigma^-)$ between 15 and 23 T. Since the PL line $X_0(\sigma^-)$ is very weak, we believe that this is caused by a lack of resolution rather than by an intrinsic physical phenomenon.

IV. DISCUSSION

A. Energy-level diagram

Before discussing the different aspects of our experimental results, we outline the main elements of the construction of the energy-level diagrams for both the neutral and negatively charged exciton (Fig. 4).[7,8] As mentioned in Sec. I, the singlet spin wave function is antisymmetrical, with the total z component of the spin for the two electrons of X_s^- $S_z^e=0$. Including the hole with spin $S^h=3/2$, the total exciton spin $S=3/2$ for X_s^-. As a result of this the Zeeman splitting of the singlet is only determined by the spin and the g factor g_h of the hole, giving two energy levels for X_s^- with exciton spin z component $S_z=\pm 3/2$ (Fig. 4).

For the triplet, the spin wave function is symmetrical, and the total z component of the spin $S_z^e=0$ or ± 1 for the two electrons. The degeneracy of the two electron energy levels is lifted by the Zeeman interaction determined by S_z^e and the electron g factor g_e. This already results in three energy levels without taking the hole into account. When the hole is included each electron level splits in two sublevels with an exciton spin z component $S_z=\pm 5/2$, $\pm 3/2$ and $\pm 1/2$ as can be seen in Fig. 4. There are in total eight different energy levels for the negatively charged exciton in a magnetic field, two for the singlet and six for the triplet state. The arrows in Fig. 4 indicate the six optically allowed PL transitions according to the selection rules $\Delta S_z\text{-}S_z^e=\pm 1$, i.e., a total spin change of $+1$ (-1) for right- (left-) handed circularly-polarized PL light indicated by a solid (dotted) arrow. These transitions recombine one electron-hole pair and leave the excess electron with spin z component $S_z^e=\pm 1/2$ in the QW. The experimentally observed Zeeman splitting is given by $\Delta E=(g_e+3g_h)\mu_B B$, with μ_B the Bohr magneton, for both singlet and triplet. Although the singlet splitting is only caused by the hole, we have to take into account g_e since the final levels of the singlet transitions 1 and 2 differ by the electron splitting. Since we cannot make an experimental distinction between the electron and hole g factor by using PL, g_e+3g_h will be labeled as the effective exciton g factor g_{eff} resulting in $\Delta E=g_{eff}\,\mu_B B$.

For the triplet, the difference in energy between level $S_z=+1/2$ and $S_z=+3/2$ equals the electron Zeeman splitting for all fields, so transitions 3 and 4 have the same PL energy and are therefore not distinguishable experimentally. The same is true for transitions 5 and 6. This results in four distinguishable PL transitions, two for the singlet and two for the triplet. Note that our energy-level diagram differs from the one in the literature[11] by the order of the PL transitions, which is essential for the correct assignment of the PL lines in the experimental data. Note also that the energy-level diagram in Fig. 4 is drawn for $2g_e<0<g_h$ and $|g_e|<|3g_h|$. In all other cases, a similar approach can be used to obtain the correct result. The energy-level diagram for X_0 is shown in the inset of Fig. 4, constructed in the same way. It has four energy levels with exciton spin z component $S_z=\pm 1$, ± 2 and two optically allowed PL transitions with different polarization. Both energy-level diagrams tell us that in total we should expect six PL transitions, two for X_0 and four for X^-.

The assignment of the experimental data in Figs. 1 and 2 is performed according to the energy-level diagram in Fig. 4, where the singlet, triplet, and neutral exciton lines correspond to transitions 1-2, 3(4)-5(6), and 7-8, respectively. Assuming that the g factors are identical for X_s^-, X_t^-, and X_0, it is difficult to make a definitive distinction between the neutral and negatively charged exciton recombination lines. This partially explains the reassignment of the triplet[7] to the neutral exciton recombination for the 100 Å QW and the labeling for $X^-(\sigma^-)$ and $X^-(\sigma^+)$ (see Fig. 3). The triplet level $S_z=+3/2$ remains parallel with singlet $S_z=+3/2$ for all fields, and only triplet level $S_z=+5/2$ can become the lowest-energy level at very high fields. However, since no optical transition is allowed from triplet level $S_z=+5/2$, such a triplet ground state can never be observed experimentally.

We now compare our experimental data of Figs. 1–3 with the energy-level scheme of Fig. 4. According to this level scheme, the difference in PL energy between the σ^+ and σ^- components of the singlet, triplet and neutral exciton should be linear in field given by $\Delta E=g_{eff}\,\mu_B B$. The differences in PL energy for the singlet are shown in the lower insets of Figs. 1 and 2, while the lower inset of Fig. 3 presents the splitting of X^- for the 100 Å QW. A very clear linearity can be found for the 100 and 120 Å QW, whilst for the 150 Å QW it becomes poor above 30 T. This is probably due to low intensity of $X_s^-(\sigma^+)$ at these fields, which prevents us resolving $X_s^-(\sigma^+)$ with the same resolution as the σ^- component. Taking the slope of the splittings, we determine g_{eff} for all three samples as reported in the second column of Table I. Since we cannot make an experimental distinction between the states of X^- in the 100 Å QW, this

TABLE I. Experimental values of the singlet, triplet, and neutral exciton effective g factors for three different QW widths. The maximum experimental error is $\pm 5\%$.

QW	Singlet	Triplet	X_0
100 Å	$g_{eff}=1.9$		$g_{eff}=1.5$
120 Å	$g_{eff}=1.9$	$g_{eff}=2.1$	
150 Å	$g_{eff}=1.3$	$g_{eff}=1.4$	

value is reported in Table I as either the singlet or triplet. g_{eff} is found to be the same for the 100 and 120 Å QW, whilst it is about 30% lower for the widest QW.

The same can be done for the triplet by taking the difference in PL energy between $X_t^-(\sigma^+)$ and $X_t^-(\sigma^-)$, as shown in the upper insets of Figs. 1 and 2. Again, the linearity is slightly worse for the 150 Å QW. In contrast, the linearity of the triplet splitting for the 120 Å QW is impressive, as can be seen in the upper inset of Fig. 1. The slopes of the triplet splittings are determined and the values of g_{eff} are reported in the third column of Table I. Again, the triplet g_{eff} is about 30% lower for the widest QW, as it was for the singlet. This indicates a dependency of g_{eff} on the QW width. Although it was reported that g_e and g_h depend strongly on the QW width,[17] the behavior is different to that observed in our experiments, at least for these QW widths.[18] We find that g_{eff} does not depend on the magnetic field, as is discussed in more detail in Ref. 8. The singlet g_{eff} values are slightly lower than those of the triplet. As we do not see both components of X_0 in the 120 and 150 Å QW samples, a comparison of the X_0 effective g factors for these samples cannot be made.

In the 100 Å QW we also observe both components of the neutral exciton. The upper inset of Fig. 3 presents the neutral exciton splitting by taking the difference in PL energy between $X_0(\sigma^+)$ and $X_0(\sigma^-)$. According to the level diagram of Fig. 4, this splitting should be the same as the singlet and triplet splitting of X^-. The linearity is slightly worse than the corresponding X^- splitting due to the weak $X_0(\sigma^+)$ PL line, but the neutral g_{eff} is seen to be about 20% lower than the corresponding singlet or triplet spin splitting for the same sample (Table I). This observation is consistent with the experimental data of Glasberg *et al.*,[13] who found a slightly reduced spin splitting for X_0 than for X_s^-. They have determined $g_{eff}=-1.1$ at 7 T for X_s^- in a 200 Å QW, which is very similar, apart from the sign, with the 1.3 found in our 150 Å QW. The difference in sign is a result of the fact that Glasberg *et al.* observed σ^- to be the highest PL energy line, rather than the σ^+. Though both splittings are expected to be the same in the noninteracting particle approximation of Fig. 4, the difference in configuration of the particles between X_0 and X^- could change their effective g factors.

B. Binding energy

The binding energy, E_b, of X^- is defined as the energy needed to remove the second electron. If one of the electrons of X^- recombines with the hole, then the other electron is

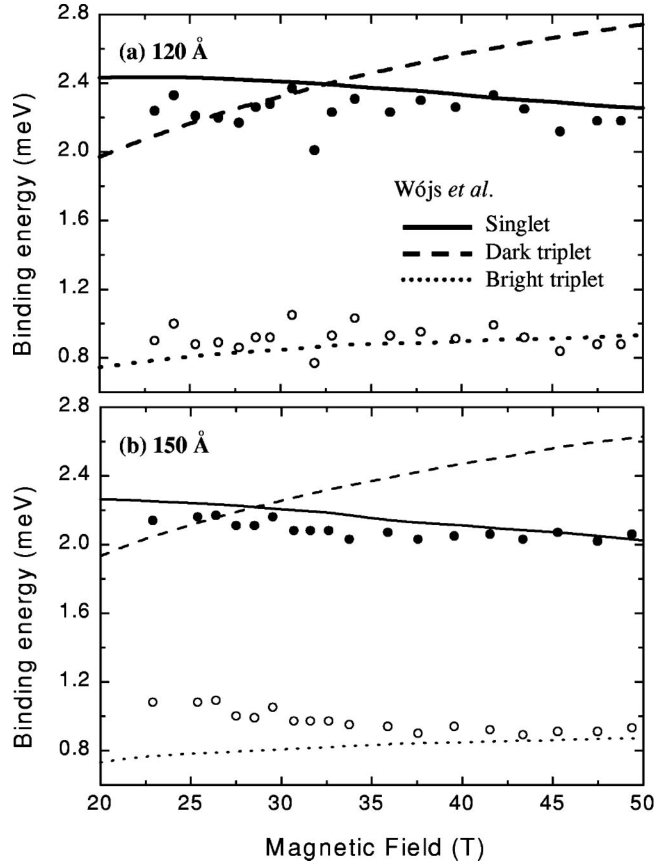

FIG. 5. Experimental results of the singlet (closed symbols) and triplet (open symbols) binding energies as function of field for the (a) 120 and (b) 150 Å QW The lines are the theoretical binding energies by Wójs *et al.* (Ref. 2) for the singlet (solid line), dark triplet (dashed line), and bright triplet (dotted line) (see text for details).

left in the lowest Landau level. Thus the difference in PL energy between $X_0(\sigma^-)$ and $X_s^-(\sigma^-)$ $[X_t^-(\sigma^-)]$ gives the experimental binding energy of the singlet [triplet], E_b^s $[E_b^t]$, assuming that X_0 and X_s^- $[X_t^-]$ have the same g_{eff}. Figure 5 presents E_b^s (closed symbols) and E_b^t (open symbols) for the 120 (a) and 150 Å QW (b). Since we are not able to resolve $X_0(\sigma^-)$ at low fields, E_b can only be determined between 23 and 50 T. Comparison between Figs. 5(a) and (b) shows that the singlet and triplet binding energies are very similar for the 120 and 150 Å QW, both qualitatively and quantitatively. For the 120 and 150 Å QW, E_b^s and E_b^t are also found to be constant in field with a separation of about 1.3 and 1.1 meV for the 120 and 150 Å QW, respectively. This is in agreement with recent theoretical calculations by Wójs *et al.*,[2] where E_b was found to be comparable for small QW's. This will be discussed in detail in the next section.

The experimental binding energy of the 100 Å QW behaves differently from the other samples as can be seen by the closed symbols in Fig. 6. Since in this sample we observe both components of X_0, the binding energy in Fig. 6 is obtained by taking the average in PL energy between the σ^+ and σ^- components of X_0 and X^-. For low fields ($B<15$ T) where the lines are more difficult to resolve, E_b

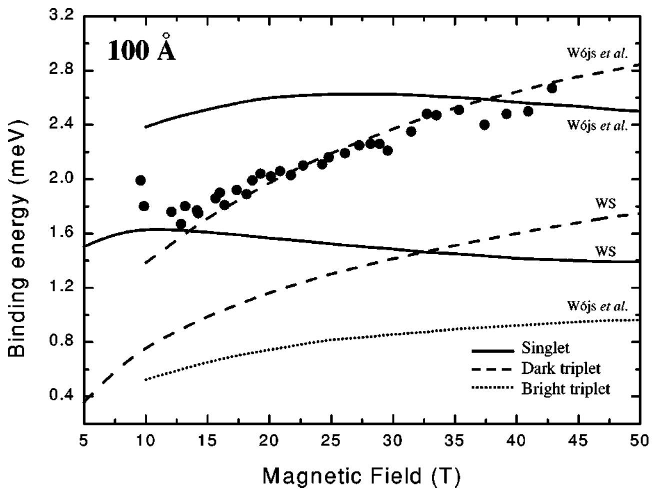

FIG. 6. Experimental result of the observed (closed symbols) binding energy for the 100 Å QW. The lines present theoretical calculations of Whittaker and Shields (WS) (Ref. 1) and Wójs *et al.* (Ref. 2) for the singlet (solid line), dark triplet (dashed line), and bright triplet (dotted line) (see text for details).

scatters from 1.7 to 2.0 meV while a monotonic increase is observed between 15 and 43 T. Since $X_0(\sigma^+)$ is not found above 43 T, we do not determine E_b at higher fields in this sample. Note that this binding energy is obtained in the assumption that the highest energy splitting observed in the 100 Å QW sample is the neutral exciton as discussed above. Recent theoretical[5] calculations indicate that at high fields this splitting might be the bright triplet rather than the neutral exciton. However, it was also found that the bright triplet and neutral exciton transition energies should be the same at these fields, so our experimentally determined binding energy would still be valid for the 100 Å QW.

V. COMPARISON WITH THEORETICAL RESULTS

We now compare our data with two different calculations of the binding energy of X^- at high magnetic fields.[1,2] Whittaker and Shields[1] (WS) have calculated E_b^s and E_b^t for a 100 and 300 Å QW up to 50 T using a variational technique. Comparison was made with experimental data up to 20 T (Refs. 1 and 10) for the 300 Å QW. Although the agreement for the singlet was very poor, with experimental values about 50% higher than the theory, the triplet binding energy corresponded relatively well. The 100 Å QW results of WS are presented in Fig. 6 by a solid and dashed line for the singlet and triplet respectively. As can be seen, they predicted a transition from the singlet to the triplet ground state around 30 T for a 100 Å QW by a crossing between E_b^s and E_b^t. This crossing was not observed experimentally by Hayne *et al.*,[9] resulting in a major disagreement between theory and experiment. In addition to this there was the long-standing mystery of the observation of the triplet state in experiments, when it was expected to be dark. Recently, Wójs *et al.*[2] have reported finite size calculations of E_b for three different narrow QW's (100, 115, and 130 Å). They discovered a new triplet state which should be observable experimentally and therefore called a ''bright'' triplet. Doing so, they removed the discrepancy between theory[1] and experiment,[9] saying that the triplet state calculated by WS is the ''dark'' triplet rather than the bright one, and also resolving the more general problem of the observation of a triplet in PL experiments. Wójs *et al.* also predicted a transition from the singlet to the dark triplet ground state by a crossing between E_b^s and E_b^t, similar to that proposed by WS for the 100 Å QW.[1] Therefore, there is no *qualitative* disagreement between experiment and theory. Here, we show a *quantitative* agreement between theory and experiment.

The theoretical results of Wójs *et al.* for a 100 Å QW are shown in Fig. 6 by a solid, dashed, and dotted line for the singlet, dark, and bright triplet, respectively. The binding energies in Ref. 2 are substantially larger than those calculated by WS for both states at all fields. This is explained by Wójs *et al.* by two important differences between the theories. First, the binding energy is expected to be strongly dependent on the symmetry of the hole mass, i.e., symmetrical[2] or asymmetrical.[1] Both groups report that the use of a symmetrical hole mass results in larger binding energies. Second, Wójs *et al.* claim that, in contrast to WS, they have found both good orbital quantum numbers, which is essential to resolve the bright triplet state. Though both theories are different, E_b^s behaves very similarly at high fields (see Fig. 6) where a saturation is found.

We now compare our experimental results for the 100 Å QW with the two calculations[1,2] presented in Fig. 6. No agreement can be found between the experimental data and theoretical results of WS for any state. However, it turns out that our experimental data very closely follow the theoretical dark triplet binding energy of Wójs *et al.* for fields between 15 and 35 T. We also note that the observed increase in binding energy with field in this sample is characteristic of the dark triplet state according to recent theories.[2,5] Such a dark triplet correspondence is remarkable since it should not be observable in experiment. It was found that breaking of symmetry rules,[2,4] e.g., by an enhanced electron-exciton interaction or localization, could make the dark-triplet state visible. Since QW potential fluctuations play an important role in small QW's, breaking of symmetry rules is expected to be more likely for the 100 Å QW. We believe that more investigation is needed here. At fields lower than 15 T, the agreement becomes rather bad, which is probably due to our low resolution in this field range. Above 35 T no conclusion can be made whether the experimental results follow the theoretical dark triplet or singlet binding energy. The correspondence between experiment and theory is similarly striking with the other samples as we now discuss.

We compare our experimental results for the 120 Å QW with the theoretical results obtained by Wójs *et al.* for a 115 Å QW in Fig. 5(a). The same notation is used as in Fig. 6. For fields above 32 T, the agreement for the singlet is good, except for the theoretical values being slightly overestimated. At lower fields, it is not clear whether our experimental results follow the singlet or dark-triplet line. A similar remark about the experimental observation of a dark triplet can be made here. For the triplet, the agreement between our experimental data and the theoretical bright-triplet energy is very good for all fields.

Since there are no theoretical calculations for a 150 Å QW available, we compare our experimental results with predictions[2] for a 130 Å QW shown in Fig. 5(b). This is motivated by the fact that the binding energy was found by Wójs *et al.* to be similar for small QW widths, especially for the bright triplet. The agreement between experiment and theory is good for the singlet state for $B>30$ T (solid line), though the theoretical values are a bit overestimated. Since these calculations are for a 130 Å QW, this is consistent with the fact that the singlet binding energy is expected to become slightly lower for wider QW's as can be extracted from Figs. 5(a) and 6 and Ref. 2. At fields below 30 T, no firm conclusion can be made about whether the experimental results follow the theoretical singlet or dark-triplet energy line, as was the case for the 120 Å QW. A transition of the PL assignment from the singlet to the dark triplet by decreasing field would be consistent with the other samples, though such a transition is less clear here. For the triplet, the correspondence is good at high fields ($B>35$ T), while a substantial deviation is found for lower fields where the theoretical energy is too low. The binding energy of the bright triplet is almost independent or slightly lower for wider QW's (see Figs. 5(a) and 6 and Ref. 2); therefore a closer agreement between the 150 Å QW data and an explicit calculation for a 150 Å well width is not expected. Note that our experimental binding energies for the 120 and 150 Å QW are determined by taking the difference in PL energy between the σ^- components of X_0 and X_s^- (X_t^-). This assumes the g factors to be the same for X_0 and X_s^- (X_t^-). A difference in g factors between X_0 and X^- as observed in the 100 Å QW should *decrease* the binding energy by a maximum of 0.2 and 0.6 meV at 20 and 50 T, respectively, for the 120 and 150 Å QW. This would reduce the agreement between theory and experiment. The situation is different for the 100 Å QW where the difference in g factors is included by taking the average in PL energy between the σ^+ and σ^- components of X_0 and X^-, and a direct comparison between theory and experiment can be made. We further note that a more recent theory by the same group[6] points out that the results of the calculations are very sensitive to the parameters and approximations used, and in particular that going beyond the lowest subband approximation should *increase* their binding energies by up to 0.5 meV. With these factors in mind, although we are convinced that we have identified the observed states in our samples with some certainty, we believe that the very impressive agreement between theory and experiment is slightly fortuitous, and that further theoretical work may clarify the situation considerably.

VI. CONCLUSIONS

We have studied three different GaAs/Al_xGa_{1-x}As QW samples (100, 120 and 150 Å) using photoluminescence in magnetic fields up to 50 T. By using an *in situ* polarizer, we are able to distinguish between all optically allowed transitions for the singlet and triplet state of the negatively charged exciton in the 120 and 150 Å QW. A comparison between our experimental results and the energy-level diagram of X^- and X_0 allows us to assign all observed PL transitions. The spin splittings and g factors for X^- are determined. Our experimental values of the binding energy are compared with two different theoretical calculations from the literature.[1,2] Very recent calculations of the binding energy by Wójs *et al.* agree well with our experimental data across a very wide range of fields. For the 100 Å QW, a comparison with theory reveals the assignment of the experimental lowest-energy recombination to the dark-triplet state.

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[18] Since Snelling *et al.* (Ref. 17) use an effective hole spin $\Sigma^h = 1/2$, their g_{eff} is different from the one used in this work.