Magnetoexcitons in narrow GaAs/$Ga_{1-x}Al_xAs$ quantum wells

M. Potemski*
Max-Planck-Institut für Festkörperforschung, Hochfeld Magnetlabor, Boîte Postale 166X, F-38042 Grenoble, France

L. Viña
Instituto de Ciencia de Materiales del Consejo Superior de Investigaciones Cientificas y Departamento de Fisica Aplicada C-IV, Universidad Autónoma, Cantoblanco, E-28049 Madrid, Spain

G. E. W. Bauer
Philips Research Laboratories, P. O. Box 80.000, 5600 JA Eindhoven, The Netherlands

J. C. Maan
Max-Planck-Institut für Festkörperforschung, Hochfeld Magnetlabor, Boîte Postale 166X, F-38042 Grenoble, France

K. Ploog
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-7000 Stuttgart 80, Federal Republic of Germany

G. Weimann
Walter-Schottky-Institut, Technische Universität München, D-8046 Garching, Federal Republic of Germany
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We present results of our magneto-optical studies of excitonic transitions in narrow GaAs quantum wells, i.e., in the case when the heavy-hole–light-hole splitting is significantly larger than the heavy-hole exciton binding energy. The main (s-type) heavy-hole transitions can be simply understood in terms of two-dimensional hydrogeniclike magnetic levels. A giant repulsion occurring between the $3d^-$ heavy-hole and the $1s$ light-hole states demonstrates the importance of Coulomb interaction in the mixing of magnetoexcitonic levels.

As a result of its complicated valence-band structure,[1] GaAs quantum wells (QW's) show usually very rich interband-absorption spectra when a magnetic field is applied along the confinement direction.[2–8] These spectra reflect in fact the magnetoexcitonic levels[7–10] and it is tempting to interpret the main features of these spectra in terms of a *simple* model of a two-dimensional hydrogen atom in a magnetic field.[11] In the experiments reported so far QW's of rather large thicknesses have been studied.[2–8] With increasing well thickness, the energy separation between heavy- and light-hole states becomes smaller and the number of confined subbands increases. For wide QW's, in the accessible range of magnetic fields, there are many magnetoexcitonic states of a mixed (heavy, light-hole) character. The fan chart of magnetoexcitonic resonances is very complicated and it is often difficult to follow the transitions with magnetic field, since the mixing occurring under a magnetic field leads to an anticrossing (repulsion) behavior between the magnetoexcitonic states.

In this paper we present a magneto-optical study of narrow QW structures with well thicknesses $d=30$ and 45 Å. In these structures only one electronic and one light-hole subband are confined. In comparison with the case of wider QW's, the observed magnetoexcitonic fan chart is much simpler. As we will show, it can be described quite satisfactorily in terms of the magnetic levels of a two-dimensional hydrogen atom, using appropriate reduced masses and exciton binding energies. The only feature that is beyond this approximation is a very strong repulsion (anticrossing behavior) between the $3d^-$ state of the heavy-hole exciton and the $1s$ light-hole exciton. This interaction has been observed before only when an electric field was used to tune the heavy-hole exciton excited states closer to the ground state of the light-hole exciton.[12] However, it was not accessible previously in flat-band conditions, since for wide QW's, already at zero magnetic field, the excited states of the heavy-hole exciton are at higher energy than the light-hole ground state, and therefore those states will separate from each other in the presence of the field. Conversely, in the case of narrow QW's the energy separation between the heavy-hole and light-hole ground states is smaller than the exciton binding energy. The observed repulsion between heavy-hole $3d^-$ excitonic state and the $1s$ light-hole state is surprisingly large (≥ 10 meV) and a possible interpretation of this effect is proposed.

The samples studied are undoped, triple GaAs QW's of thicknesses $d=45$ and 30 Å, sandwiched between 1000-Å-thick $Ga_{1-x}Al_xAs$ barriers with $x=0.43$. Magneto-optical spectra were measured using dye lasers, with LD700 or DCM as dyes, pumped by Kr^+- or Ar^+-ion lasers, respectively. The experiments were performed in Faraday configuration, with σ^+ and σ^- helicities of the exciting light, at pumped helium temperature ($T=1.8$ K) and in magnetic fields up to 19 T produced by Bitter coils. The emission light was detected with a double spectrometer using a Peltier-cooled GaAs photomultiplier.

Representative photoluminescence-excitation (PLE) spectra obtained for the sample with 45-Å-thick QW's are shown in Fig. 1, (a) for the extreme values of the field, (b) in the low-field regime, and (c) in the intermediate-field regime. In the PLE measurements the intensity was detected at the low-energy tail of the luminescence, which lies slightly below the lowest transition observed in the PLE spectra. These spectra are expected to reflect the absorption ones. As can be seen in Fig. 1(a), the zero-field pseudoabsorption spectrum shows only *two* well-pronounced transitions, which are associated with the heavy-hole and light-hole excitonic ground states. There is also a weak feature in the high-energy range ($\hbar\omega \simeq 1.81$ eV), which is related to the weakly forbidden E_1-H_3 transition (E_1 and H_3 are the first conduction and the third heavy-hole subbands, respectively). The energy position of this structure is in good agreement with a simple level-structure calculation performed within the Kronig-Penney model, which also shows that in this QW (as well as in the case of the 30-Å-thick QW) only one conduction band and one light-hole subband are confined. In contrast with the zero-field case, at high magnetic fields the PLE spectra reveal many absorption peaks, which are quite regularly spaced in energy [see Fig. 1(a)]. All the peaks, with the exception of the second one, correspond to the $1s, 2s, 3s, \ldots$, heavy-hole excitonic states.

A clear step observed at $B=0$ T between the ground-state heavy-hole and light-hole excitons is related to the continuum of the heavy-hole states, i.e., to the $2s$ exciton state overlapping with higher excited states. At relatively low magnetic fields, this structure evolves in the excitonic

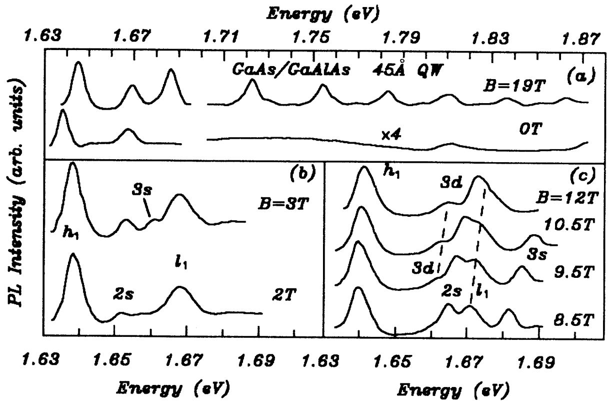

FIG. 1. Photoluminescence excitation spectra of a 45-Å-thick $GaAs/Ga_{0.57}Al_{0.43}As$ QW. (a) Spectra at the lowest and highest values of the applied field; the high-energy region of the zero-field spectrum is enlarged by a factor of 4. (b) Low-field regime showing the appearance of excited states. (c) Intermediate-field regime demonstrating the interaction between the $h_1(3d^-)$ state and the ground-state light-hole exciton $[l_1(1s)]$. The lines are an aid to the eye.

excited states and the $2s$ and $3s$ heavy-hole states become clearly resolvable, due to the enhancement of their oscillator strength by the magnetic field [see Fig. 1(b)]. The second transition, the ground state of the light-hole exciton, $l_1(1s)$, shows a conspicuous behavior as a function of magnetic field. This occurs at intermediate fields, as depicted in Fig. 1(c), and it will be discussed later.

The fan charts of the absorption peaks obtained with σ^- polarization of the exciting light for the 30-Å- and 45-Å-thick QW's are shown in Figs. 2(a) and 2(b), respectively. Contrary to previously reported studies,[2-8] the

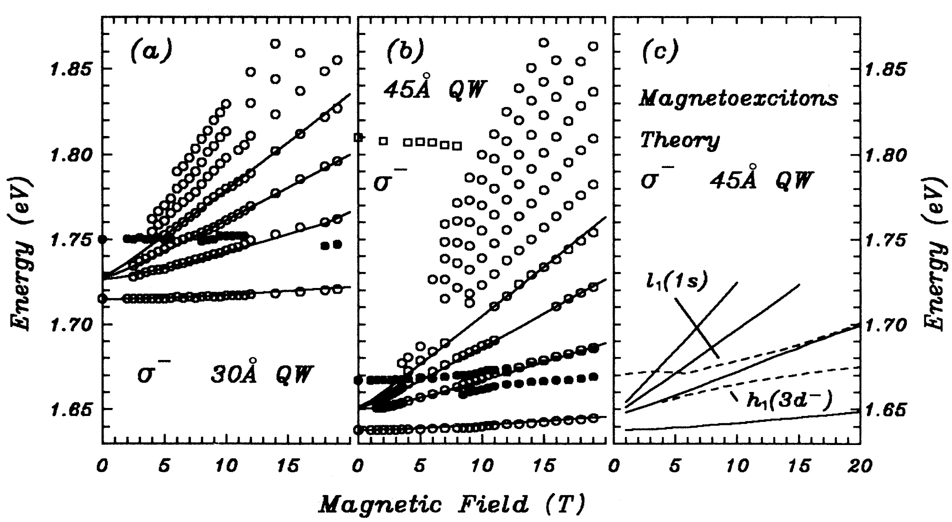

FIG. 2. Magnetic-field dependence of the excitons excited with σ^- polarization, for (a) a 30-Å-thick QW, and (b) a 45-Å-thick QW. The open circles depict heavy-hole excitonic states of Γ_7 symmetry, the full points Γ_6 states [light-hole and $h_1(3d^-)$]. The open squares represent the $h_{13}(1s)$ exciton. The solids lines in (a) and (b) are the results of a fit using a two-dimensional excitonic model. (c) Results of a full theory of excitonic mixing for the 45-Å QW. The solid (dashed) lines show states of Γ_7 (Γ_6) symmetry.

magnetoexcitonic states observed for narrow QW's show rather regular fan charts. The *s*-type heavy-hole transitions are an illustrative example of two-dimensional hydrogeniclike states. The ground state shows the typical behavior in a magnetic field, with very small diamagnetic shift. For higher excited states, the field range of the quadratic dependence becomes shorter and an almost linear dependence is observed at higher fields (small deviations at high fields are due to nonparabolicity of the bands). The slopes increase roughly as $n-1(n>1)$, where n represents the *principal* quantum number of the exciton. The lines drawn through the $h_1(1s)$ to the $h_1(4s)$ states correspond to the best fit of the experiments to a two-dimensional "hydrogeniclike" exciton, following the model of Ref. 11. From the simultaneous fit of the ground and excited states, we extract the binding energy of the ground state E_b, and the reduced effective mass m_r, of the heavy-hole exciton. These values are $E_b=13.5$ meV, $m_r=0.686$ and $E_b=13.5$ meV, $m_r=0.660$ for the 30-Å and 45-Å-thick samples, respectively.

The light-hole ground state shows a striking field dependence. This effect can be investigated better for the 45-Å-thick well (because of the narrower absorption lines), although both samples show quantitatively the same behavior. In the case of the 45-Å-thick well, at $B=9.5$ T, the transition $h_1(3d^-)$ appears below the $2s$ heavy-hole resonance [see Fig. 1(c)]. Simultaneously, the $1s$ light-hole state is pushed up in energy and loses oscillator strength. This characteristic feature indicates the interaction between states of the same symmetry. In the particular case considered here, the interaction between the $3d^-$ heavy-hole excited state $h_1(3d^-)$ and the $1s$ light-hole ground state $l_1(1s)$ is observed. The $h_1(3d^-)$ state has rather pure heavy-hole character at low magnetic fields and, in accordance to the selection rules, is not observed in absorption. With increasing magnetic field the energy separation between $h_1(3d^-)$ and $l_1(1s)$ decreases and they become of a mixed character. The state being initially $h_1(3d^-)$ borrows oscillator strength from $l_1(1s)$ and starts to be visible in absorption. This mixing leads to a repulsive interaction between these states, as can be seen clearly in Fig. 2(b) (full points). Unfortunately the higher component of this mixed exciton cannot be followed beyond 12 T, since it overlaps with $h_1(2s)$ (these two states have Γ_6 and Γ_7 symmetries,[10–12] respectively, and do not interact). However, from an analysis of the oscillator strength and a comparison with the spectra recorded with σ^+ polarization, where the $h_1(3d^+)$ is not observed, we can deduce that the interaction, although weaker, is still present at 19 T. At higher magnetic fields, the lowest component should recover its initially predominant light-hole character.

An effective-mass calculation of the excitons, which takes into account valence-band mixing and the effects of the magnetic field,[10] is presented in Fig. 2(c) for the 45-Å-thick QW. The solid lines correspond to the s states of the heavy-hole exciton (Γ_7 symmetry), while the dashed lines depict the magnetic-field dependence of the $l_1(1s)$ and $h_1(3d^-)$ excitons (Γ_6 symmetry). A strong interaction between these states is also obtained in the calculations, in very good agreement with the experiments. The weaker dependence of $h_1(3s)$ and $h_1(4s)$ as compared with the experimental results is due to basis-set limitations for this narrow QW. The strength of the interaction, seen in the magnitude of the gap between the two excitons and in the fact that they are still interacting even when their energy separation is as large as $\simeq 25$ meV (19 T), is rather striking. By comparison with the previous observation of this interaction,[12] where the strength of the applied magnetic field was only 0.5 T and the gap of the interaction $\simeq 1.5$ meV, we speculate that the origin of the enhancement lies in the larger field strength needed in the present experiment, which in this case produces a shrinkage of the excitonic wave functions and therefore an increase in their overlap.

It has been shown[10,13] that in the limit of high magnetic fields, the magneto-optical spectra of GaAs QW's can be explained well by calculations of interband transitions which are *a posteriori* corrected for excitonic effects (shifted down by appropriate energies). In the case of narrow quantum wells, this limit corresponds to very high magnetic fields (above 20 T). We believe that the anticrossing behavior between the $h_1(3d^-)$ and the $l_1(1s)$ states is an illustrative example of mixing involved by Coulomb interaction and not only by hybridization of valence-band Landau levels. This anticrossing is observed only when the real (i.e., experimentally observed) excitonic states tend to intersect, i.e., for narrow QW's. Conversely, there is no peculiar behavior observed in the field dependence of the $l_1(1s)$ state in the case of wide QW's, for which this state is, already at zero field, below the heavy-hole excited states. If one would interpret the Landau fans in terms of interband transitions, similar effects would be expected for samples with different well widths since, within this interpretation, the mixing originates only from the hybridization of valence-band levels independently of the Coulomb interaction.

In summary, we have shown that the magneto-optical spectra of thin QW's constitute a clear and valuable example of quasi-two-dimensional "hydrogeniclike" excitons, where most of the complications present in wider wells, due to the complexity of the valence-band structure, can be avoided. A giant interaction between excited states of the heavy-hole exciton and the ground state of the light-hole exciton is demonstrated, and its strength correlated with the magnetic-field strength. The results are also in good agreement with calculations of magnetoexcitons mixing.

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*Also at the Institute of Physics, Polish Academy of Sciences, PL-02668 Warsaw, Poland.

[1]See, for example, R. Eppenga, M. F. H. Schuurmans, and S. Colak, Phys. Rev. B **36**, 1554 (1987).

[2]J. C. Maan, G. Belle, A. Fasolino, M. Altarelli, and K. Ploog, Phys. Rev. B **30**, 2253 (1984).

[3]N. Miura, Y. Isawa, S. Tarucha, and H. Okamoto, in *Proceedings of the 17th International Conference on the Physics of*

Semiconductors, edited by J. D. Chadi and W. A. Harrison (Springer, New York, 1984), p. 359.
[4]D. C. Rogers, J. Singleton, R. J. Nicholas, C. T. Foxon, and K. Woodbridge, Phys. Rev. B **34**, 4002 (1986).
[5]W. Ossau, B. Jäkel, E. Bangert, G. Landwehr, and G. Weimann, Surf. Sci. **174**, 188 (1986).
[6]L. Viña, G. E. W. Bauer, M. Potemski, J. C. Maan, E. E. Mendez, and W. I. Wang, Phys. Rev. B **41**, 10 767 (1990).
[7]L. Viña, in *Spectroscopy of Semiconductor Microstructures,* Vol. 206 of *NATO ASI Series B,* edited by G. Fasol, A. Fasolino, and P. Lugli (Plenum, New York, 1989), p. 367.
[8]Y. Iimura, Y. Segawa, G. E. W. Bauer, M. M. Lin, Y. Aoyagi, and S. Namba, Phys. Rev. B **42**, 1478 (1990).
[9]S.-R. Yang and L. J. Sham, Phys. Rev. Lett. **58**, 2598 (1987).
[10]G. E. W. Bauer and T. Ando, Phys. Rev. B **38**, 6015 (1988).
[11]A. H. MacDonald and D. S. Ritchie, Phys. Rev. B **33**, 8336 (1986).
[12]L. Viña, G. E. W. Bauer, M. Potemski, J. C. Maan, E. E. Mendez, and W. I. Wang, Phys. Rev. B **38**, 10 154 (1988).
[13]F. Ancilotto, A. Fasolino, and J. C. Maan, Phys. Rev. B **38**, 1788 (1988).