One-Dimensional Magnetoexcitons in $GaAs/Al_xGa_{1-x}As$ Quantum Wires

M. Kohl, D. Heitmann, P. Grambow, and K. Ploog
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 7000 Stuttgart 80, Federal Republic of Germany
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$GaAs/Al_xGa_{1-x}As$ quantum-well wires with lateral dimensions of 70 nm have been prepared by mesa etching of 14-nm-wide quantum-well systems. In photoluminescence excitation two heavy-hole (hh) exciton transitions, hh_{11} and hh_{12}, separated by 2.5 meV, were observed. These transitions result from 1D quantum-confined energy states in the narrow wires. The 1D character was reflected in a strong polarization dependence and in a unique magnetic field behavior indicating an enhancement of the excitonic interaction of the 1D ground state by about 15%.

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The investigation of low-dimensional electronic systems has gained great interest since it has become possible to fabricate heterostructures with sharp interfaces by molecular-beam epitaxy (MBE), leading to the observation of interesting new physical phenomena and novel device applications. The optical properties of quantum wells (QW), for instance, are governed by intrinsic excitonic recombination, enhanced oscillator strengths, and exciton binding energies.[1,2] These effects are theoretically predicted to be even more pronounced in one-dimensional (1D) and 0D systems; e.g., Refs. 3 and 4. Recent experiments on low-dimensional systems yielded interesting new results, which were related to additional lateral quantum confinement,[5-11] but so far no experimental values about exciton binding energies in QW wires (QWW) have been reported.

In the current work we have realized $GaAs/Al_xGa_{1-x}As$ QWW's and studied photoluminescence (PL) and PL excitation (PLE) with and without magnetic fields. Using optimized preparation processes we could reduce the influence of nonradiative surface recombination and thus investigate etched GaAs QWW's as narrow as $t=70$ nm. The PL efficiency of the active QWW area was in this case only reduced by a factor of 30 with respect to the reference QW's. For $t\approx 70$ nm we observed a new transition in the regime of the ground-state heavy-hole (hh) exciton, hh_{12}, which was related to the second hh- and second electron-1D subbands. (The first and second index denote the quantization number in the growth direction, z, and in x direction perpendicular to the wires, respectively.) In PL and PLE measurements the observed transitions were strongly dependent on the polarization of the exciting light. The 1D behavior was, in particular, manifested in a unique dependence on a magnetic field, B. From the shift of the inter-Landau-level transitions with increasing B and the diamagnetic shifts of the ground-state exciton transitions we determined reduced masses and exciton binding energies.

The samples were grown by MBE at 560 °C. They consisted of three GaAs QW's of 14-nm thickness, separated by 10-nm-thick $Al_{0.26}Ga_{0.74}As$ barriers and of 50-nm-thick $Al_{0.26}Ga_{0.74}As$ layers below and above the multi-QW region. The high quality of the starting material was demonstrated by PL linewidths smaller than 0.4 meV at 4.2 K. By holographic lithography we prepared a mask consisting of photoresist lines with 250-nm periodicity oriented parallel to the $[\bar{1}10]$ direction. The width of these lines could be adjusted by the development time. With reactive ion etching (RIE) in a $SiCl_4$ plasma rectangular grooves of 130-nm depth were etched through the multi-QW layers. We prepared samples with lateral extensions t ranging from 70 to 120 nm, which were determined with a scanning electron microscope. On each QWW sample a small unpatterned part was left to take reference spectra. The PLE spectra were excited with normally incident light of a Styryl 9 dye laser, which was pumped by an Ar^+ laser. The magneto-optic measurements were performed in a superconducting magnet. The excitation light and the luminescence signal were transmitted through an optical fiber. The PL was analyzed with a 1-m Jobin-Yvon monochromator and a photon-counting system. The temperature was 4.2 K if not otherwise stated.

The PLE spectra obtained from a QWW sample with $t\approx 70$ nm at zero magnetic field are shown in Fig. 1 together with the corresponding reference sample. The transitions in the reference spectrum are the well-known hh_1 transitions (808.525 nm, 808.755 nm) and the lh_1 transitions (804.975 nm, 805.225 nm). From calculations we could ascribe the small splitting of the transitions of the reference PLE spectrum in Fig. 1 to QW-thickness fluctuations of one monolayer. The PLE spectra of the QWW in Fig. 1 show two transitions, hh_{11} and hh_{12}, in the wavelength regime of the hh_1 transition. The separation between these transitions was dependent on t of the investigated samples. The hh_{11} and lh_{11} transitions were blueshifted with respect to the corresponding transitions of the reference sample by about 0.2 nm (0.4 meV). We will show in the following that these transi-

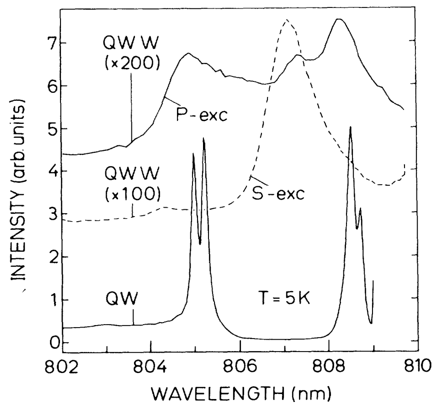

FIG. 1. PLE spectra at zero magnetic field of a QWW with $t \approx 70$ nm and of the corresponding reference QW. The spectra are shifted vertically with respect to each other for clarity and show the dependence on the polarization of the exciting laser light. For *s*-polarized (*p*-polarized) light **E** is parallel (perpendicular) to the wires. The excitation intensity was about 100 mW/cm^2.

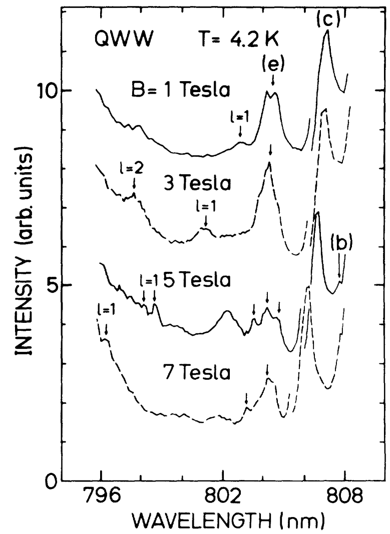

FIG. 2. Magnetic-field-dependent PLE spectra of a $t \approx 70$ nm QWW. (b), (c), and (e) denote the hh_{11}, hh_{12}, and lh_{11} transitions, respectively; the index l labels the order of the inter-Landau-level transitions. The spectra are shifted vertically with respect to each other for clarity. The excitation intensity was about 100 mW/cm^2.

tions are related to exciton transitions of 1D quantum-confined energy levels. For a quantitative understanding of the energy positions we performed calculations of the confinement energies for a 2D finite potential-well model. Taking the values for the exciton binding energies into account, which we deduced from magneto-optical experiments below, we obtained for $t = 70$ nm a value for the blueshift of the hh_{11} transition with respect to the hh_1 transition of about 0.5 meV. Since this value agreed very well with the experimental results, we could rule out possible stress effects in the QWW's. When we evaluated the energy separation between the hh_1 and h_{12} transitions we found good agreement with our measurements. The intrinsic nature of the hh_{12} transition was further confirmed by temperature-dependent PLE spectroscopy and a series of PLE measurements, where we set the detection wavelength to the different resonance positions. However, in all these measurements we were not able to resolve the lh_{12} transition, which should occur for $t = 70$ nm at about 803 nm. The weakness of transitions between higher 1D electron and lh subbands has also been observed for InP/InGaAs QWW samples.[9]

A second observation on the QWW's was a characteristic polarization dependence of the PLE spectra. When we excited the QWW with *p*-polarized laser light, i.e., the electric field vector **E** was perpendicular to the wires, we could observe very clearly the lh_{11} and hh_{11} transitions, while the hh_{12} transition was only weak. However, the shape of the spectra drastically changed when we excited with *s*-polarized light; i.e., **E** was parallel to the wires, see Fig. 1. In this case the lh_{11} transition was nearly absent and the spectrum was dominated by the hh_{12} transition such that the hh_{11} transition could only be observed as a shoulder. This strong polarization dependence, in particular the different behavior of the hh_{11} transition, on the one hand and the hh_{12}, on the other, shows that this is an intrinsic property of the 1D system which must be related to the symmetry of the 1D wave functions. We would like to note here that in QWW's with t in the order of 200 nm a strong polarized PL contribution about 0.3 meV on the high-energy side of the $e1$-hh1 transition was observed.[12] Since the 1D confinement energy of the lowest-energy states in such structures is small compared to the longitudinal-transverse (LT) splitting of the corresponding excitonic resonances, $\Delta E_{LT} \approx 0.3$ meV,[12] the polarization dependence of those systems can be understood electrodynamically in a polariton picture. The change in the polarization dependence of the PLE of the QWW's here, when the confinement energy is increased beyond ΔE_{LT}, thus directly reflects the breakdown of the polariton model. For a quantitative explanation of the observed polarization dependence one has to keep in mind that it depends, besides on the exciton wave-function symmetry,[11] also on electrodynamic effects; i.e., the neighboring wires are coupled via electromagnetic fields and exciting and emitted radiation are governed—polarization dependent—on the grating coupler effect[12] of the strong corrugation of our samples. Thus, without a complete grating coupler theory, which is a very complex problem, one cannot predict quantitatively the polarization.

In Fig. 2 we have plotted PLE spectra of the $t \approx 70$ nm QWW sample for various magnetic fields B. Since we could not set a defined polarization of the exciting light by the transmission through the optical fiber, the

hh_{12} transition was always dominant in the spectra. The hh_{11} transition was in this case very weak and could only be observed when the detection wavelength was set close to its peak wavelength. The inter-Landau-level transitions, on the other hand, could be best observed when we detected resonantly at the hh_{12} transition. The energy positions in the PLE spectra, which we recorded up to 1.56 eV for B between 0 and 10 T, are summarized in Fig. 3. For clarity, the B dispersions of the reference transitions are not drawn in discrete data points but as solid lines in the same plot. We have only plotted the low-energy component of the transitions for the reference sample, which were split into two components due to QW-thickness fluctuations. Also not shown are the $l=1$ inter-Landau-level transition energies of the lh excitons of the reference sample, which could be resolved between 2 and 5 T.

The magnetodispersion for the reference sample was very similar to earlier measurements on comparable systems; e.g., Refs. 13–15. The lowest hh_1 and lh_1 transitions (a) and (b) in Fig. 3 showed only a weak-B dispersion, the diamagnetic shift. This demonstrates the strong Coulomb interaction and excitonic character of these transitions. For the lh_1 transition the spin splitting[15] was resolved. The higher-energetic transitions shifted linearly with increasing $B > 3$ T which is characteristic for inter-Landau-level transitions. Our investigation of the

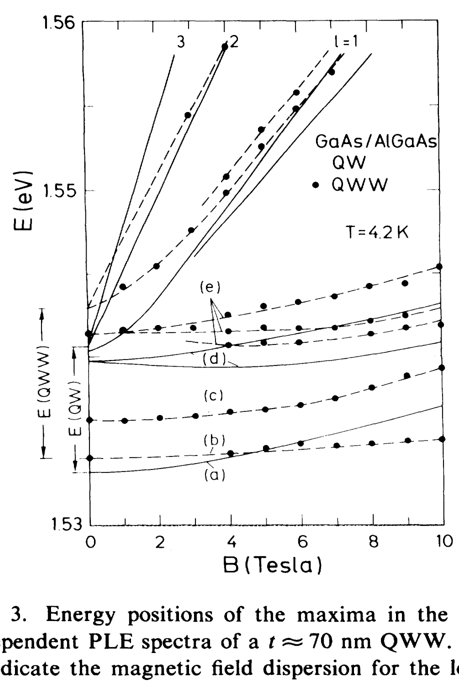

FIG. 3. Energy positions of the maxima in the magnetic-field-dependent PLE spectra of a $t \approx 70$ nm QWW. The solid lines indicate the magnetic field dispersion for the low-energy component of the transitions of the corresponding reference QW. (a), (b), (c), (d), and (e) denote the hh_1, hh_{11}, hh_{12}, lh_1, and lh_{11} transitions, respectively; the index l labels the order of the inter-Landau-level transitions. In addition, the exciton binding energies, E(QW) and E(QWW), deduced from zero-field extrapolations are indicated.

QWW's revealed drastic differences compared to the reference QW. (i) The hh_{11} ground-state transition Fig. 3(b) showed a smaller diamagnetic shift, indicating a stronger excitonic interaction. (ii) The hh_{12} transition Fig. 3(c) was still strongly excitonlike, but the diamagnetic shift was larger than for the hh_{11} transition. (iii) The inter-Landau-level separation was smaller as compared to the reference sample. All these features are qualitatively expected for 1D magnetoexcitons and confirm our interpretation of the hh_{11} and hh_{12} transitions. Within the remaining space of this Letter, we can only present some of the results, which we have derived from a quantitative analysis of the B dispersion.

Following similar evaluations for 2D systems, e.g., Refs. 13 and, in particular, 14, we have analyzed the slopes of the inter-Landau-level dispersion in Fig. 3 above 3 T, where they are assumed to be proportional to the electron and hole Landau-level quantum number 1 and the inverse reduced mass μ^{-1}, which characterizes the combined electron and hole Landau levels. For the hh_1 exciton of the reference sample we found a value for the reduced mass of about $0.06m_0$. From this a zero-field exciton binding energy of 7.5 meV can be calculated, which is consistent with other published values.[14,16,17] There has been a long discussion on the determination of the exciton binding energy in magneto-optics. We have adopted the evaluation of Ref. 14, which takes into account the Coulomb interaction between electrons and holes at finite fields and yields good agreement with binding energies deduced by other methods. The exciton binding energy of a ground-state exciton can independently be determined by an extrapolation of the Landau-level peak positions to zero field. It was demonstrated that the extrapolation of the higher $l > 1$ inter-Landau-level transitions in the low-field regime between 0 and 6 T yields the onset energy of free-carrier absorption.[14] Therefore, one directly obtains the exciton binding energy by subtracting the energy of the corresponding excitonic transition at $B=0$. As indicated in Fig. 3 we thus obtained a value for the exciton binding energy which agrees very well with the result of our analysis of the magnetic-field-dependent shift of the inter-Landau-level transitions.

The slopes of the $l=1$ and $l=2$ inter-Landau-level dispersion in Fig. 3 of the QWW's are smaller than of the corresponding reference sample and a stronger bending of the $l=1$ inter-Landau-level transition in the low magnetic field regime is observed compared to the reference QW. Both observations indicate that the reduced mass of the hh_{11} exciton and the hh_{11}-exciton binding energy must be higher in the QWW systems as compared to the QW. A quantitative analysis yielded a reduced hh_{11}-exciton mass of about $0.076m_0$ and a hh_{11}-exciton binding energy of 8.7 meV, which is about 15% higher than of the reference QW. Again we found good agreement with the result obtained by zero-field extrapolation in the low magnetic field regime. The experimental error of these values is approximately 5% and is mainly due to the uncertainty of the slope of the $l=2$ line.

From the diamagnetic shifts of the ground-state exciton transitions we could determine reduced masses, which agree very well with our results from the inter-Landau-level transitions. It has been shown that the diamagnetic shift of the hh_1 excitons in a QW can alternatively be described by using only the 3D value of the reduced mass, $\mu=\mu(3D)$, independently of the QW width and expressing the shift in terms of the transverse extension of the exciton, ρ.[18] When we evaluate our data for the QWW's in this manner we find a decrease of ρ by about 13% with respect to the reference QW, which directly indicates the shrinkage of the excitonic wave function due to the additional lateral confinement. From the diamagnetic shift of the hh_{12} transition we determined a reduced mass, which is about 5% smaller than the ground-state value. As a consequence, the hh_{12}-exciton binding energy, which we determined from the reduced mass, is reduced by the same amount with respect to the hh_{11} binding energy.

The exciton binding energy of a QWW has so far only been calculated; e.g., Refs. 3 and 4. It was found that this energy is related to the cross-sectional area of the wire rather than to its shape.[4] Therefore, a wire with a cross section of 14×70 nm^2 should be equivalent to a cylindrically symmetric wire with a radius of 17.7 nm. Thus, we can directly compare our result with Ref. 3, where for the case of a finite barrier of $Ga_{0.9}Al_{0.1}As$ a value of 2.1 Ry is reported. For the case of an infinite barrier height the calculated binding energy is 2.4 Ry, so that the actual value to compare with is about 10% smaller than our experimental value of 2.5 Ry, which demonstrates a surprisingly good agreement.

In conclusion, we have prepared GaAs/AlGaAs QWW's with a lateral confinement length t down to 70 nm, which showed in PLE measurements transitions between 1D subbands. The 1D character of the transitions is manifested in a strong polarization behavior and a characteristic magnetic field dependence. Both from the inter-Landau-level transitions and from the diamagnetic shift of the ground-state excitonic transitions we found an enhancement of the reduced mass and of the exciton binding energy of the ground-state hh exciton of about 15%.

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