Linewidth broadening of excitonic luminescence from quantum wells in pulsed magnetic fields

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Abstract

We investigate the effect of magnetic fields, $B$, up to 42 T, on the photoluminescence spectra of In$_{0.5}$Ga$_{0.5}$As/GaAs single quantum wells (QWs). We find that the full-width at half-maximum, $W$, of the excitonic recombination spectrum increases significantly at these high fields to an extent depending on the direction of $B$. The increase of $W$ with magnetic field is due to the squeezing of the exciton wave function, which increases the effect of the QW potential energy fluctuations on the line width. A statistical model for the QW interface disorder is used to explain these results. In turn, this allows us to probe the magnetic field dependence of the spatial extent of the exciton in the QW. © 2002 Elsevier Science B.V. All rights reserved.

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In recent years, there have been several experimental and theoretical investigations of magneto-excitons. Some of these studies have dealt with the magnetic field ($B$) dependence of the exciton binding energy [1–3], a quantity related to the spatial extent of the exciton wave function, $\rho_{\text{exc}}$. The $B$ dependence of $\rho_{\text{exc}}$ can, therefore, provide useful information about the interplay of magnetic field effects and carrier–carrier interaction effects in low-dimensional systems. Magneto-transport measurements were employed to investigate the effect of magnetic fields on the donor wave function in bulk GaAs [4], on the exciton wave function in bulk binary alloys [5] and in quantum wells (QWs) [6]. In particular, the decrease of the exciton size with $B$ has been related to the $B$-dependence of the line width of the exciton recombination spectrum [5,7,8].

In this paper, we report an experimental study of the magnetic field dependence of the exciton size in strained In$_{0.5}$Ga$_{0.5}$As/GaAs single QWs. We use photoluminescence (PL) spectroscopy in pulsed magnetic fields ranging from $B = 0$ to 42 T, applied parallel and perpendicular to the QW plane. We show that the full-width at half-maximum, $W$, of the spectrum of the excitonic recombination increases with increasing $B$ and that the extent of the line width broadening...
depends on the direction of \( B \). The increase of \( W \) with magnetic field is attributed to the squeezing of the exciton size induced by \( B \), which, in turn, leads to a reduction in the spatial averaging of the potential energy fluctuations of the QW due to the finite exciton size. By using a statistical model for the QW interface disorder, we account for the magnetic field dependence of the excitonic recombination line width and probe the variation of the exciton size with \( B \).

A series of In\(_{0.5}\)Ga\(_{0.5}\)As single QW structures were grown by molecular beam epitaxy on (311)B oriented GaAs substrates. The QW thickness are \( L = 0.5, 0.7, 0.8, \) and \( 1.0 \) nm. The strained layer was deposited at a substrate temperature \( T_\text{G} = 450^\circ\text{C} \) and covered by a 25 nm thick GaAs cap. The reflection high-energy electron-diffraction patterns indicated two-dimensional growth throughout the whole In\(_{0.5}\)Ga\(_{0.5}\)As deposition. PL measurements were performed at \( T = 4.2 \) K in pulsed magnetic fields up to 42 T. The laser beam (\( \lambda_{\text{exc}} = 488 \) nm) was chopped and the sample illuminated for 1 ms at the top of the field pulse, with the PL emission detected by a Si charge coupled device. The magnetic field was applied parallel or perpendicular with respect to the growth axis, \( z \).

Fig. 1 shows the PL spectra of a 0.7 nm thick QW taken at different magnetic field intensities for \( B \) parallel to \( z \). The PL band is due to the exciton recombination in the well. Increasing \( B \) has three effects on the QW PL spectrum: (i) the exciton recombination energy blue-shifts, consistent with the extra confinement exerted by the magnetic field on the carriers; (ii) the PL-integrated intensity increases consistent with an enhanced oscillator strength as predicted for two-dimensional excitons in a magnetic field [9]; the increase of the PL intensity could be also due to a faster capture rate of electrons and holes in the well and/or a \( B \)-dependence of non-radiative recombination processes; (iii) the PL line width (measured as full-width at half-maximum) increases significantly at these large fields. These effects are observed in all samples to an extent slightly dependent on the QW thickness.

Fig. 2 shows the magnetic field dependence of \( W \) for \( B \) applied parallel and perpendicularly to the growth direction for the same QW whose PL spectra are shown in Fig. 1. For \( B \parallel z \), \( W \) follows a roughly linear dependence with magnetic field. We attribute this behavior to the compression of the exciton wave function by the applied field [10]. The effect of increasing \( B \) is to decrease the electron–hole mean distance, in turn leading to an enhanced sensitivity of the exciton to the QW potential disorder. For \( B \perp z \), a much smaller increase of \( W \) is found. This suggests that the line width broadening is determined mainly by the potential fluctuations of the QW. In fact, since the in-plane exciton size is relatively unchanged for small \( B \perp z \), the exciton experiences the same in-plane disordered QW potential at different

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1 We neglect additional broadening of the PL spectrum with increasing \( B \) due to spin-splitting effects. In fact, the PL line shape can be reproduced by a single gaussian function even at the highest field. Also, previous studies suggest that the spin-splitting of the excitonic recombination in GaAs does not exceed 1 meV at \( B = 40 \) T which is much smaller than the line width in these narrow QW structures.
its contribution to the statistical model of Singh and Bajaj [13], two of the well thickness, respectively [12]. By using the inhomogeneous broadening of the excitonic energy is mainly due to alloy and interface disorder arising from local variations of the In content in the well and fluctuations of the well thickness, respectively [12]. By using the statistical model of Singh and Bajaj [13], two of the current authors previously showed that interface roughness has a crucial role at low $L$ (  < 1.0 nm) and high $x$ ( > 0.15) [12]. For the present samples ($x = 0.5$, $L = 0.5$–1.0 nm), we find that the contribution of alloy broadening to the line width is negligible ($ < 0.3$ meV) with respect to that due to interface roughness $^2$ according to this model. For an exciton recombining with energy $h\nu_{\text{exc}}$, the line shape of the PL spectrum is a gaussian function with full-width at half-maximum given by [12]

$$W = (0.42 \text{ eV}) \frac{\delta_1}{\rho_{\text{exc}}} (A_+ + A_-) \delta_1. \quad (1)$$

Here $\delta_1$ is equal to one monolayer ($\delta_1 = 0.3$ nm for $x = 0.5$, including distortion due to strain) and represents the minimum fluctuation of the well thickness along the growth axis, $\delta_2$ is the characteristic in-plane extent of morphological disorder (or interface roughness) at the QW interfaces, $A_\pm = (\partial h\nu_{\text{exc}}/\partial L)_{L \pm \delta_1}$, and $\rho_{\text{exc}}$ is the radius of the exciton in the QW plane. We point out that the above expression is valid in the limit that $\delta_2 < \rho_{\text{exc}}$ and for a random distribution of interface islands.

According to Eq. (1), the squeezing of the exciton wave function induced by the magnetic field should lead to a corresponding broadening of $W$ ($W \sim 1/\rho_{\text{exc}}$) and we can express the $B$-dependence of the in-plane extent of the exciton wave function as

$$\rho_{\text{exc}}(B) = \frac{W(0)}{W(B)} \rho_{\text{exc}}(0). \quad (2)$$

The above discussion implies that we can determine the magnetic field dependence of the lateral extent of the exciton wave function using the values of $W$ at different $B$. However, two important points need to be considered: first, it is necessary to verify that Eq. (1) accounts for the experimental values of $W$; and, secondly, it is necessary to estimate $\rho_{\text{exc}}$ at zero magnetic field.

We derive $\rho_{\text{exc}}(B=0)$ by using the diamagnetic shift of the PL spectra, $\Delta E_d = e^2 \langle \rho^2 \rangle B^2 / 8 \mu_{\text{exc}}$, where $\mu_{\text{exc}}$ is the exciton reduced mass (which we set to the value of GaAs, $\mu_{\text{exc}} = 0.04$, because of the sizable penetration of the carrier wave function into the GaAs barrier) and $\langle \rho^2 \rangle$ is the expectation value of the square of the electron–hole distance in the plane perpendicular to $B$. We find that $\rho_{\text{exc}} = \sqrt{\langle \rho^2 \rangle}$ decreases from 9.2 nm ($L = 0.5$ nm) to 7.5 nm ($L = 1.0$ nm) [14].

We now test the validity of the statistical model (Eq. (1)) for our data. We use the values of $\rho_{\text{exc}}$ at zero field determined above and calculate $A_\pm$ within the envelope function approximation. Finally, $\delta_2$ is left as a free parameter in the best fit of Eq. (1) to the experimental $W$ values. The inset of Fig. 2 shows the line width (•) as a function of the well thickness at zero magnetic field. The dashed line is a fit of Eq. (2) to the experimental data. The theoretical curve successfully

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$^2$ The total line width is given by $W = \sqrt{\gamma_{\text{int}}^2 + \gamma_{\text{all}}^2}$, where $\gamma_{\text{int}}$ and $\gamma_{\text{all}}$ are due to interface and alloy disorder, respectively. For the present samples, $\gamma_{\text{all}}$ does not exceed 0.3 meV and we discard its contribution to $W$. 

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**Fig. 2.** Dependence of the photoluminescence line width on magnetic field for $B$ applied along (●) and perpendicular to (■) $z$ for the 0.7 nm thick QW sample. Inset: Photoluminescence line width (●) at zero magnetic field as a function of the well thickness, $L$. The dashed line is a best fit of Eq. (1) to the data with $\delta_2 = 3.0$ nm.
Fig. 3. Exciton radius as a function of magnetic field intensity applied along the growth axis (z) for different QW thickness $L$. Dashed lines are a guide to the eye.

describes the experimental $W$’s with $\delta_2 = 3.0$ nm. Note that $\delta_2$ matches the length scale of interface roughness as measured in structures similar to ours using a scanning tunneling microscope [15].

Finally, Fig. 3 shows the dependence of $\rho_{\text{exc}}$ on $B$ applied perpendicular to the QW plane for various QW thickness. The data have been calculated using Eq. (2). It can be seen that $\rho_{\text{exc}}$ increases with decreasing $L$ due to the increasing spreading of the exciton wave function into the QW barrier [14]. As far as the magnetic field dependence of $\rho_{\text{exc}}$ is concerned, the in-plane Bohr radius of the exciton decreases by as much as 30% for the highest field employed (42 T). As a final remark, note that excitons in these narrow QW systems can be approximated as hydrogenic systems, but with a larger size ($\sim 10$ nm) and smaller binding energy ($<10$ meV). This implies that the magnetic field intensities employed in our experiment correspond to huge fields ($\sim 10^5$ T) if scaled to the hydrogen atom size [11]. Such fields can exist in stellar objects, such as white dwarfs and neutron stars, so the modifications of the hydrogenic wave functions measured in our experiment may be used as a test of theories of hydrogen in the vicinity of such objects.

In conclusion, we have studied the PL properties of In$_{0.5}$Ga$_{0.5}$As/GaAs single QWs in magnetic fields ranging from $B = 0$ to 42 T, applied either perpendicular or parallel to the plane of the QW. We observe a sizeable increase of the PL line width with increasing $B$. This is described in terms of the lateral squeezing of the exciton size in the plane perpendicular to $B$. By a quantitative analysis of the PL line shape, we determine the $B$ dependence of the exciton size. This study shows that the dependence of the luminescence line width broadening on magnetic field intensity and orientation can be used as a means of probing the exciton properties in low-dimensional heterostructures.

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References