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Strong red shift of indirect exciton luminescence in low magnetic field

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Abstract

We have studied the effect of the magnetic field on the indirect excitons in coupled quantum wells in GaAs at magnetic fields up to 25 T. An unexpectedly large red shift of the indirect exciton line occurs at relatively low magnetic field. This shift depends strongly on the electric field applied parallel to the growth direction. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Numerous experiments and theoretical studies on carriers in double quantum wells have indicated interesting phenomena, in particular, the possibility for Bose condensation into a superfluid state [1–4]. As reported previously [5,6], we have developed a method for creating an in-plane harmonic potential trap for indirect excitons in coupled quantum wells, and we have observed a strong dynamical Stark shift of the indirect exciton line [7]. The present work studies the behavior of the indirect excitons in symmetric coupled quantum wells in magnetic field. Magnetic field has several possible advantages for the goal of excitonic superfluidity. First, magnetic field could be used to create a potential trap for indirect excitons using an inhomogeneous magnetic field. Another effect is the splitting of the different spin states, which reduces the spin degeneracy of the ground state. Since Bose condensation requires high occupation of a single quantum state, a nondegenerate ground state favors Bose condensation. Areseev and Dzyubenko have also suggested an increased diffusion constant for two-dimensional excitons in magnetic field [8]. Experimentally, Akiyama et al. [9] found a decrease of the diffusion constant of two-dimensional direct excitons due to magnetic field, while Butov et al. [10] have observed faster diffusion of two-dimensional indirect excitons at high magnetic field.

2. Experiment

Our samples were grown via molecular-beam epitaxy at the Max Planck Institute. Two similar samples were used. The first one (60-42-60) consists of two 60 Å undoped GaAs wells with a 42 Å $Al_{0.3}Ga_{0.7}As$ barrier. The second sample (80-42-80) consists of two 80 Å undoped GaAs wells with a 42 Å $Al_{0.3}Ga_{0.7}As$ barrier. Both were grown on a heavily p-doped GaAs substrate and had a heavily n-doped GaAs capping layer to allow electric field perpendicular to plane of the quantum wells. A DC bias was applied perpendicular to the plane of the quantum wells, as shown in Fig. 1(a). The band offset due to the doping gives a built-in field of 24 kV/cm, while an applied reverse-bias voltage of 1 V gives an additional field of 15.2 kV/cm.

As reported earlier [5] and as observed by many authors [11–13], the electric field gives rise to a strong DC red shift due to the quantum-confined Stark shift, as illustrated in Fig. 1(b) The samples were excited with a He–Ne laser ($P = 14$ mW, $\lambda = 632.8$ nm) and the luminescence was observed with a Princeton CCD camera coupled to a spectrometer. The temperature was about 2.8 K, and the magnetic field was increased up to 25 T. At high magnetic field, the indirect exciton luminescence shifts toward higher energy, as

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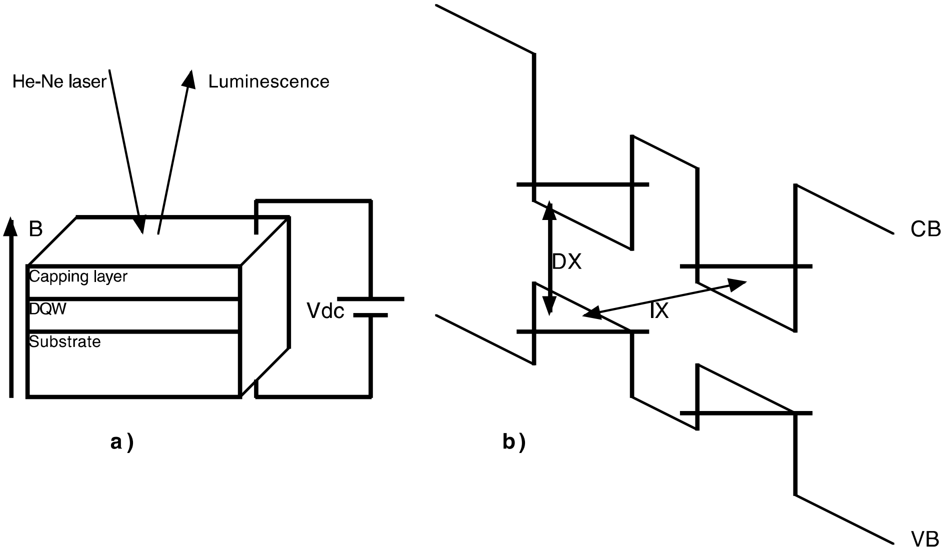

Fig. 1. (a) The experimental geometry. (b) The band structure. The IX energy drops as the external electric field (the bias voltage) increases.

expected from previous observations [14,16,17]. At low magnetic field, however, we see a strong red shift.

The spectrum of the indirect exciton recombination luminescence (60-42-60 sample) for a bias voltage of 1.0 V for several magnetic fields is presented in Fig. 2. The sample was about 2 mm by 4 mm, and the current through the sample was $I = 0.1$ mA, which remained roughly constant.

The peak energy of the indirect exciton recombination luminescence vs. magnetic field for different voltages is presented in Fig. 3(a). The luminescence energies at zero magnetic field simply give the effect of the DC quantum-confined Stark shift with electric field. As magnetic field increases, a strong red shift with magnetic field is seen, which increases with the applied voltage. Then, at high magnetic field, the luminescence peak shifts toward higher energy, similar to the blue shift of exciton luminescence in quantum wells seen in previous experiments [14–17].

A detailed dependence of the indirect exciton luminescence energy vs. magnetic field an applied voltage of 1.0 V is presented in Fig. 3(b). We checked that the shift with magnetic field is symmetric with respect to direction of the magnetic field by reversing the current in the magnet. For both directions of magnetic field, the luminescence peak shifts first to the red and then back to the blue in the same way as shown in Fig. 3(a). We also found no evidence for hysteresis in these measurements. We also have found no dependence of this effect on the laser intensity, although we

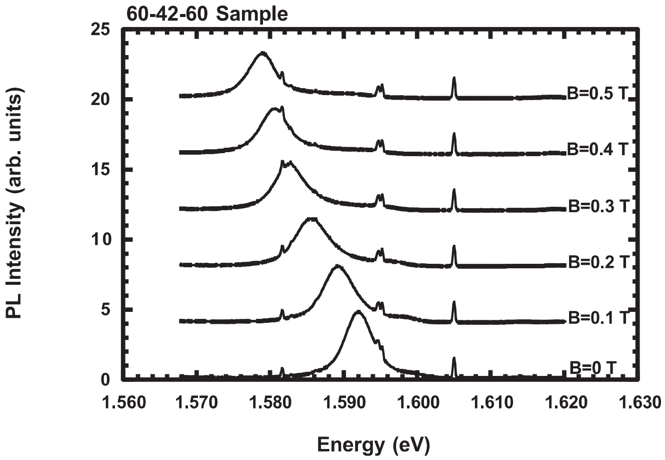

Fig. 2. The indirect exciton luminescence for an applied voltage of 1.0 V and different magnetic fields. The peak shifts to lower energy as the magnetic field is increased. The three peaks that don’t shift are He–Ne laser plasma lines.

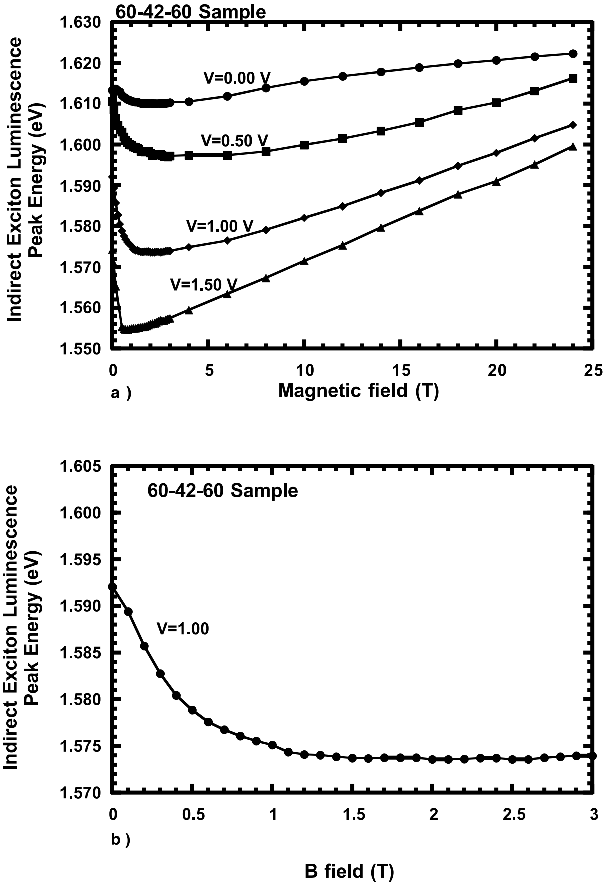

Fig. 3. (a) The indirect exciton peak energy vs. magnetic field for several voltages for 60-42-60 sample. Notice the low energy shift at low magnetic field, which becomes larger at higher bias voltages. (b) Detail of the IX PL peak vs. magnetic field for an applied voltage of 1.0 V.

have not performed a comprehensive study as a function of excitation density.

A similar shift of the indirect exciton luminescence is observed for the 80-42-80 sample. The position of the peak energy of the indirect exciton luminescence vs. magnetic field for this sample is presented in Fig. 4. As seen in this figure, at zero applied electric field, the shift of the luminescence in this wider quantum well sample is

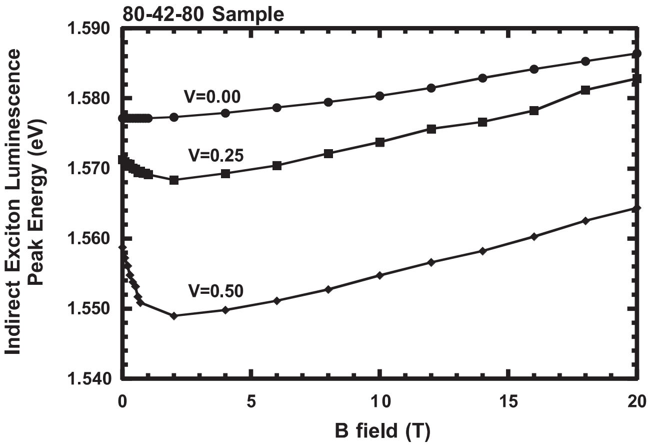

Fig. 4. The indirect exciton peak energy vs. magnetic field for the 80-42-80 sample.

very similar to the diamagnetic shift seen previously [16] in unbiased, wide (99 Å) GaAs coupled quantum wells.

3. Discussion

As mentioned above, previous experiments have observed a blue shift of the exciton luminescence at high magnetic field, both in single quantum wells [14,15] and coupled quantum wells [16,17]. At low magnetic field, this shift had a B^2 dependence [14,16], which was attributed to the diamagnetic shift of the excitons, while at high magnetic field, the shift had a linear dependence on magnetic field [14,17], which was attributed to the electron Landau level energy. In our experiment, at high magnetic field the indirect exciton photoluminescence peak shifts linearly with the magnetic field, with a slope which depends on the bias voltage. This indicates a Landau level shift with magnetic field. The energy of a free conduction-band electron in a Landau level is given by:

$$E = \left(l + \frac{1}{2}\right)\frac{\hbar eB}{m^*}. \qquad (1)$$

When m^* is the effective mass of the free conduction electron in bulk GaAs, $0.067m_0$ [18], the slope of the energy vs. magnetic field for the lowest Landau level is 0.88 meV/T, compared with the slope of 1.99 meV/T of our experimental data at 1.5 V. In the high-magnetic field experiments of Maan et al. [15], the ground state exciton line did not shift strongly with magnetic field, while the excited states shifted strongly with magnetic field. Maan et al. argued that the Coulomb energy of the excitons dominated their behavior, while the excited states were much more weakly bound, and therefore the electrons acted as nearly free electrons in the magnetic field. In this interpretation, the strong Landau shift which we see at high voltage implies that the binding energy of the indirect excitons at high electric field is very small.

A red shift at low magnetic field has been seen before in similar experiments [19], although with a different sample geometry. In those experiments, three sets of asymmetric GaAs/$Al_{0.33}Ga_{0.67}As$ coupled quantum wells were used with thicknesses 200.7/38.2/195, 101.8/38.2/96.1 and 82.0/38.2/76.3 Å, grown on a 1 μm GaAs substrate, separated by 200 Å $Al_{0.33}Ga_{0.67}As$ barriers. The excitation wavelength in that case was 730.3 nm (under-barrier excitation) and the power was less than 1 mW, and the temperature was 4.2 K. The red shift in that case was also electric field-dependent. However, the total magnitude of the shift was less than 5 meV, compared to 20 meV in our experiments.

Krivolapchuk et al. [19] attributed the anomalous red shift to blocking of the current across the wells, which would change the effective electric field across the wells, and therefore affect the DC quantum-confined Stark shift, which depends sensitively on the local electric field. In our experiments, we monitored the current across the wells and found no dependence on magnetic field. At present, we have no explanation for the anomalous red shift at low magnetic field, which seems to occur only in narrow coupled quantum wells with DC bias.

Future experiments will study this shift as a function of the temperature, as a function of the excitation wavelength, and over a wider range of well widths. A very appealing application of this effect is the possibility of trapping indirect excitons in a potential minimum. Since at low magnetic field, a magnetic field *maximum* corresponds to an energy *minimum* for the excitons, a trap can be created using a non-uniform magnetic field with a simple maximum. This may be done in addition to our previous method for creating an in-plane potential trap [5].

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