Excitonic and free-carrier recombination of a two-dimensional electron gas in high magnetic fields

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Abstract

We have studied the low temperature photoluminescence (PL) of the two-dimensional electron gas in a 100 Å quantum well at fields up to 50 T over four orders of magnitude of laser power. At our highest laser powers we observe excitonic recombination via neutral and negatively charged (X−) excitons, and determine the X− binding energy to fields of 50 T. The binding energies of both singlet and triplet states increase monotonically with field above 15 T. At lower laser powers, in which recombination from the second Landau level is observed at fields up to 2.5 T, a splitting appears at high fields (>10 T) due to the recombination from the singlet and triplet states of X−. These data are inconsistent with a universal transition from free-carrier to excitonic recombination at Landau-level filling factor ν = 2, but imply that the onset of excitonic recombination is dependent on the illumination conditions.

Keywords: Photoluminescence; 2DEGs; Negatively charged excitons; Pulsed fields

1. Introduction

The identification of negatively charged excitons (X−) [1], formed when two electrons bind with a single hole, has done much to advance our understanding of the photoluminescence (PL) spectra of two-dimensional electron gases (2DEGs) [1–6]. In samples with a small excess electron density (<5 × 10^10 cm^−2), X− are observed at zero magnetic field [2]. However, even for samples in which the 2DEG density is larger, the application of a magnetic field perpendicular to the plane of the 2DEG can promote the formation of X− [3,4]. Here we report PL measurements of the 2DEG in a 100 Å GaAs quantum well. At high powers, where the recombination is excitonic at all magnetic fields, we have measured the binding energy of the X− in fields up to 50 T.

2. Experimental details

The sample used was a single 100 Å GaAs quantum well grown by molecular beam epitaxy with density 3.7 × 10^11 cm^−2 and mobility 5 × 10^5 cm^2/V s subsequent to saturation of the persistent photoconductivity effect [7]. Two experimental set-ups were used. In one the sample was placed in the
mixing chamber of a dilution refrigerator, and a superconducting magnet provided fields up to 15 T. The sample was excited by an Ar$^+$ laser via a single optical fibre with a core diameter of 125 μm. The same fibre was also used to collect the PL. The other set-up used a $^4$He bath cryostat in the bore of a pulsed magnet capable of achieving 50 T with pulse durations of about 20 ms. Optical access was provided using a bundle of 400 μm-core optical fibres. Light from a CW frequency-doubled solid-state laser operating at 532 nm was transmitted down the centre fibre of the bundle, whilst the six outer fibres were used to collect the PL. A multichannel analyser was exposed at the peak of the pulse for $\leq 1.84$ ms, giving a field resolution of $\pm 1\%$. The spectral resolution of the experiments was better than 0.5 meV.

3. Experimental results

Fig. 1 shows the energy dependence of the quantum well luminescence peaks taken in the pulsed field magnet at 4.2 K at laser power densities of 1300 and 3800 mW cm$^{-2}$. Three lines, labelled X, T and S, are observed at high magnetic field, which we identify as the neutral exciton and the triplet and singlet states of the negatively charged exciton, respectively [5]. The data of Fig. 2 look rather different. Fig. 2(a) shows data taken in the DC magnet at an incident laser power of just 1.3 mW cm$^{-2}$ and a bath temperature of 20 mK, whilst the data of Fig. 2(b) were taken in the pulsed field magnet at a temperature of 4.2 K and a laser power of 380 mW cm$^{-2}$. It is noteworthy that the two sets of data in Fig. 2 look rather similar despite the large disparity in laser power and temperature. In both cases the decay of the second Landau-level identifies the 2DEG density as $1.2 \times 10^{11}$ cm$^{-2}$, and a splitting is observed at high magnetic fields. Comparison of the data of Fig. 2(b) to fields up to 50 T demonstrates that these lines are the same as S and T in Fig. 1, identified as recombination from the singlet and triplet states of X$^-$. 

4. Discussion

A number of workers studying the photoluminescence of relatively dense ($>1 \times 10^{11}$ cm$^{-2}$) 2DEGs have reported a transition from free carrier to excitonic recombination [3,4]. Furthermore, Yoon et al. suggested that there is a well-defined Mott metal–insulator transition from free-carrier to excitonic recombination involving X$^-$ as the

Fig. 1. Dependence of the peak energy on magnetic field at a power of 1300 mW cm$^{-2}$ (squares). Also shown are data taken at 3800 mW cm$^{-2}$ (circles). The bath temperature is 4.2 K. The inset shows the binding energy of the X$^-$ singlet (closed symbols) and triplet (open symbols) states.

Fig. 2. Dependence of the peak energy on magnetic field at a power of (a) 1.3 mW cm$^{-2}$ and (b) 380 mW cm$^{-2}$. In the former case the data were taken at a bath temperature of 20 mK in a superconducting magnet, and in the latter case at 4.2 K in pulsed fields. The lines are guides to the eye. The data shown in (b) have been shifted up in energy by 4 meV for clarity.
field is increased above Landau-level filling factor \( v = 2 \) \[4\]. The data of Fig. 2(b) are very similar to that reported in Refs. \[3,4\]. At \( v = 2 \) there is a kink in the energy of the lowest Landau-level recombination, and as the field is increased further it develops a distinct curvature, indicative of excitonic recombination. At yet higher fields the splitting confirms the formation of \( \text{X}^- \). Despite its similarities the data of Fig. 2(a) show different behaviour. There is no obvious kink in the lowest Landau-level recombination line at \( v = 2 \), and it shows a linear field dependence right up until the point where it splits at high field. The fact that the 2DEG density is the same in both cases, yet there is a clear transition to excitonic behaviour in Fig. 2(b) and not in 2(a) strongly argues against a universal transition. Rather, our data imply that the nature of the recombination is dependent on the illumination intensity, which varies by a factor of nearly 300 between the two sets of data. Since the photoexcited hole density in the QW is proportional to the laser power it is possible that the change between the two sets of data is a direct result of the rise in the hole population. An additional factor might be the flattening of the bands caused by the increased illumination, which would bring the electrons and holes in the quantum well closer together strengthening their interaction. However, since there is no discernible change in the 2DEG density, this implies that the change in band structure is quite small. Whichever effect is the dominant one, the dependence of the nature of the recombination on the illumination conditions implies that a number of factors, rather than just a single parameter like the filling factor, will have to be taken into account in order to understand the change from free-carrier to excitonic recombination in a magnetic field.

We now discuss the field dependence of the \( \text{X}^- \) binding energy, as given by the separation of the singlet and triplet recombination lines from the neutral exciton line. Whittaker and Shields have measured the binding energy of the excess electron in a 300 Å quantum well at fields up to 20 T \[6\]. They find that both singlet and triplet binding energies increase with field up to about 10 T, and then tend to saturate. Calculations of the triplet binding energy showed good agreement with their experimental data, however the agreement for the singlet was rather poor. In the same work, they also calculated the binding energy for a 100 Å quantum well, such as the one studied here. This predicted a decrease of the singlet binding energy at fields above 10 T, with a crossover from singlet to triplet ground state at 30 T. The inset to Fig. 1 shows the singlet and triplet binding energy as measured from our experimental data by the separation of the S and T lines from the X line. Due to the width of the luminescence lines we cannot resolve the data properly below 15 T, but in any case, it is clear that above 15 T both binding energies show a monotonic increase with magnetic field. Our data are clearly in strong qualitative disagreement with the theoretical prediction of Ref. \[6\]. The reason for this discrepancy is not known; however, calculations using a modified theory developed for the study of negative donor centres show reasonable agreement with our experimental results \[5\].

5. Conclusions

We have studied the PL of a 2DEG in a 100 Å QW to magnetic fields up to 50 T with laser power densities that vary by four orders of magnitude. At the highest laser powers, where the recombination is excitonic at all fields, we have measured the binding energy of the negatively charged exciton. Contrary to a recent theoretical prediction, we find that the binding energies of both the singlet and triplet states increase monotonically with magnetic field, and that the singlet remains the ground state. At lower laser power, where recombination from the first two Landau-levels are observed at low fields, the onset of excitonic recombination is dependent on the illumination conditions. This contradicts the recent suggestion of a Mott transition involving the formation of negatively charged excitons at a critical Landau-level filling factor of 2.

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