Magnetophotoluminescence of positively-charged excitons in GaAs quantum wells

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Abstract

We have studied the low-temperature photoluminescence of high-mobility two-dimensional hole gases in GaAs quantum wells in magnetic fields up to 50 T. We have observed both spin states of the neutral ($X_0$) and of the singlet state of the positively charged exciton ($X^+$), allowing us to determine their $g$-factors and the binding energy of $X^+$. We find that the $g$-factor of the $X^+$ is larger than that of $X_0$ by a factor of 1.6. In very high fields, we expect the low-energy spin-state of $X^+$ to be bound only because of the Zeeman interaction. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Charged excitons, or trions, are formed when the electron–hole pair in a neutral exciton, $X_0$, bind a third charge carrier. After a period of intense theoretical [1–3] and experimental investigation [4–7], a consensus on the physics of the negatively-charged exciton ($X^-$), the bound state of two electrons and a hole, is now emerging [2,3,5,6]. In contrast, its positively-charged analog ($X^+$), the bound state of two holes and one electron, has received comparatively little attention [7–10]. On the theoretical side, this is probably due to the complexity of the valence band in III–V semiconductors, whilst on the experimental side, this issue is compounded by the difficulty of growing high-quality two-dimensional hole gases. Here, we describe a series of low-temperature photoluminescence experiments on $X^+$ in high mobility GaAs quantum wells (QWs) at magnetic fields, $B$, up to 50 T. We present measurements of the binding energy, $E_b$, of the excess hole across this entire field range, and derive a value for the $X^+$ effective $g$-factor, $g^+$. Our data clearly show the important role played by the Zeeman interaction in the physics of charged excitons.

2. Experimental details

The samples studied here are from the same wafers as those investigated by Ponomarev et al. at lower fields and in the absence of polarisation sensitivity [9]. They consist of GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As quantum wells grown on a (3 1 1)A substrate by
molecular beam epitaxy, with mobilities in excess of $10^5$ cm$^2$ V$^{-1}$ s$^{-1}$ in the dark, and were modulation doped in the Al$_x$Ga$_{1-x}$As with Si acting as an acceptor. Further details of the samples may be found in Ref. [9]. The experiments were undertaken at 1.2 and 4.2 K in a bath cryostat with optical access via a fibre-optic bundle. Green laser-light (532 nm) was used to excite the sample and to deplete the hole gas [11]. Magnetic fields up to 50 T were provided by a pulsed magnet system with a pulse duration of about 27 ms. Photon integration was performed for 2.2 ms at the peak of the pulse giving a field resolution of $\pm 1\%$. Left- ($\sigma^-$) or right- ($\sigma^+$) handed circularly polarised photoluminescence was selected via an in-situ polariser and reversing the direction of the magnetic field. The spectral resolution was better than 0.3 meV. In total three samples were studied, Samples A and B had 150 Å wide QWs with 800 and 200 Å, spacer widths, respectively, whilst Sample C had a 200 Å QW and an 800 Å spacer. The results from all three samples are similar, so here we shall concentrate on Sample A.

3. Results and analysis

The zero-field spectra for Samples A and B (Fig. 1) reproduce those previously obtained by Ponomarev et al. on samples from the same wafers. Sample A shows a clear doublet peak centred around 1.530 eV with a separation of 1.1 ± 0.1 meV. In accordance with Ref. [9], we assign the high-energy peak to recombination from $X_0$ and the low-energy peak to the singlet state of $X^+$. Sample B also shows two peaks with the same splitting; they are less well resolved due to the reduced intensity of $X_0$, but clearly revealed by Lorentzian curve fitting, as shown in Fig. 1. The increase in relative intensity of $X^+$ for Sample B indicates a higher hole gas density in the QW, as is expected for a sample with a smaller spacer width in which the density is optically depleted [11]. The intensities of the $X_0$ and $X^+$ peaks in the zero field spectra for Sample C (not shown) are also of nearly equal intensity, consistent with the fact that this sample also has an 800 Å spacer. In fact, the data from all three samples only differ in the relative intensities of the $X^+$ and $X_0$ peaks.

We now go on to discuss the in-field data. Fig. 2 shows the energy of the $\sigma^+$ (open symbols) and $\sigma^-$ (closed symbols) recombination peaks for Sample A at 1.2 K. As the field is increased, there is a clear diamagnetic shift of the $\sigma^-$ components of both the $X_0$ and $X^+$ peaks (denoted $X_0$ ($\sigma^-$) and $X^+$ ($\sigma^-$), respectively), characteristic of excitonic recombination. Although much weaker in intensity, particularly at high fields, a $\sigma^+$ component is seen to split from both the $X_0$ and $X^+$ lines (denoted $X_0$ ($\sigma^+$) and $X^+$ ($\sigma^+$), respectively) as a result of the Zeeman interaction. Between 16 and 35 T, these two lines are not resolved because $X^+$ ($\sigma^+$) crosses $X_0$ ($\sigma^+$) as a result of the large Zeeman energy of $X^+$. This is demonstrated in the inset of Fig. 2, which gives the difference in energy between the $\sigma^+$ and the $\sigma^-$ components of the $X^+$ and the $X_0$ recombination in the field regions where they are well resolved, i.e. below 16 T and above 35 T. In both cases, the high and low field regions for each fall on the same straight line with an intercept that is very close to zero. From this data we obtain an effective $g$-factor of $g_0 = 1.7$ for $X_0$ and $g^+ = 2.8$ for $X^+$, which is more than sufficient difference for the two $\sigma^+$ lines to cross at high fields. The large difference in $g$-factors confirms previous reports that the assumption of identical $g$-factors for neutral and charged excitons is not valid [6,7]. This has interesting implications for determining the charged exciton binding energy, as we discuss below.
Fig. 2. Magnetic field dependence of the left- and right-handed circularly polarised photoluminescence peaks recombination of $X_0$ and $X^+$. The open squares represent the unresolved $\sigma^+$ components of $X_0$ and $X^+$. The meanings of the other symbols are given in the legend. The inset shows the Zeeman splitting of the $X^+$ and $X_0$ as a function of field. In both cases a linear splitting is observed, indicating a constant $g$-factor. No data is shown in the mid-field region because the $\sigma^+$ components cross and so cannot be resolved.

4. Binding energy of $X^+$

The binding energy of a charged exciton, $E_b$, is defined as the energy needed to remove the excess charge carrier. In the absence of magnetic field, it is equal to the energy separation of the charged and neutral exciton recombination peaks. At $B = 0$ we find values of $1.0 - 1.1 \pm 0.1$ meV for all three samples, in good agreement with other experimental values quoted in the literature [7–9]. At finite $B$ things are not so straightforward as the role of the Zeeman interaction must be considered. One can either take the difference between the $\sigma^+$ components of the $X^+$ and $X_0$ recombination, or the difference between the mean energies of the $\sigma^+$ and $\sigma^-$ components of the $X^+$ and $X_0$. The former method fully includes the Zeeman contribution to the energies of the lowest lying state, and is often adopted in experimental analysis where the $\sigma^+$ components are either not measured or not observable. The latter approach effectively switches off the Zeeman interaction and allows comparison with theoretical calculations.

In order to explore this further, we first take the difference between $X_0 (\sigma^-)$ and $X^+ (\sigma^-)$, plotted as closed circles in Fig. 3. This data looks rather reminiscent of the binding energy of the $X^-$, with a fast increase at low field and then a slower increase or saturation at higher fields [1,3,5,7]. However, when the correction for the spin-splitting, given by $0.5(g^+ - g_0)\mu_B B$, is included things change substantially (open circles, Fig. 3). Rather than an initial increase and then a flattening off, the ‘Zeeman-corrected’ binding energy remains roughly constant at $1.0 - 1.2$ meV between 0 and 10 T, but then shows a slow decrease as the field is increased, falling to around 0.4 meV at 50 T. Glasberg et al. measured the binding energy of $X^+$ from 0 to 7 T in a 200 Å QW [7]. They also included the correction for the Zeeman energy, and found that $E_b$ was essentially field independent in this regime with values between 1.0 and 1.1 meV, i.e. in agreement with our data. Very recent calculations using a variational technique in which the Zeeman interaction is not included, also predict the same behaviour over the same field range [12]. There are no other studies, either theoretical or experimental, of $X^+$ at higher fields than 15 T. In this regime the ‘Zeeman-corrected’ binding energy shows a steady decrease (Fig. 3).
this trend were to continue it would reach zero at around 75 T, the implication being that the $X^+$ becomes unbound. This interpretation is confounded by an examination of the data in Fig. 2. The low-energy (field-aligned) spin-state of the $X^+$ singlet remains the lowest-energy state, and in high fields it remains bound (closed circles, Fig. 2). Such a situation clearly highlights the question of what we should consider the binding energy of the charged exciton to be [10]. In the case of $X^+$ it becomes an unavoidable issue as $g^+ \gg g_0$. Indeed, as we have shown above, the large Zeeman splitting of the $X^+$ is a direct result of the fact that $X^+$ is a many body object, and thus an intrinsic part of the problem which should be fully included.

5. Conclusions

We have studied the low-temperature photoluminescence of dilute two-dimensional hole gases in magnetic fields up to 50 T. We find that the $g$-factor of the positively charged exciton is enhanced over that of the neutral exciton by a factor of 1.6. This leads to the situation where the ‘Zeeman-corrected’ binding energy shows a decrease which would predict that the singlet state of the $X^+$ becomes unbound at $\sim 75$ T, whereas in reality the spin-aligned state remains bound because of the large Zeeman interaction. We therefore conclude that the full physics of the charged exciton, i.e. including the spin splitting, must be considered in order to understand its properties.

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References