Available online at www.sciencedirect.com

ScienceDirect

Physica E 40 (2008) 1386–1388

PHYSICA E

www.elsevier.com/locate/physe

Energy and recombination spectra of free and impurity-bound positive trions in high magnetic fields

L. Bryja[a,*], A. Wójs[a], J. Misiewicz[a], P. Płochocka-Polack[b], M. Potemski[b]

[a]*Institute of Physics, Wrocław University of Technology, 50-370 Wrocław, Poland*
[b]*Grenoble High Magnetic Field Laboratory, CNRS, F-38042 Grenoble Cedex 9, France*

Available online 29 September 2007

Abstract

Recombination spectra of free and acceptor-bound positive trions in a quasi-two-dimensional hole gas are investigated by the combination of polarization-resolved photoluminescence and transport in high magnetic fields B and the realistic numerics. The whole family of free positive trions (the pair of bright and dark triplets in addition to the well-known singlet) is observed for the first time. Crossing of the singlet and triplet Coulomb energies is found at $B \approx 12\,\mathrm{T}$. Slight decrease of all trion emission energies is observed at $B = 14.2\,\mathrm{T}$, coincident with the formation of a $\nu = \frac{1}{3}$ Laughlin hole liquid. For the acceptor-bound trions, weak inter-Landau-level shake-up transitions are identified and explained by the breaking of translational invariance.
© 2007 Elsevier B.V. All rights reserved.

PACS: 71.55.Cc; 71.35.Ji; 73.21.Fg

Keywords: Photoluminescence; Two-dimensional hole gas; Magnetic field; Trion; Shake-up; Laughlin liquid

1. Introduction

Excitons ($X = \mathrm{e} + \mathrm{h}$) and trions ($X^{\pm} = X + \mathrm{e}$ or h) often determine photoluminescence (PL) spectra of low-dimensional semiconductor nanostructures [1,2]. In quasi-two-dimensional (2D) quantum wells subject to high magnetic fields B, the trion energy spectrum contains the following bound states labeled by the pair spin S and relative angular momentum M [3,4]: spin-singlet with $M = 0$ ($X_{\mathrm{s}}^{\pm}$) and a pair of triplets with $M = -1$ ($X_{\mathrm{td}}^{\pm}$) and $M = 0$ ($X_{\mathrm{tb}}^{\pm}$). For free trions, only the $M = 0$ states are optically active ("bright"); while recombination of states with $M \neq 0$ ("dark") requires breaking of the 2D translational invariance (e.g., by well width fluctuations or impurities).

In this paper we present investigations of the energy and recombination spectra of positive magneto-trions in p-doped quantum wells. Experimental PL and transport studies were supplemented with realistic configuration-interaction calculations. We report the first experimental detection of the entire family of X_{s}^{+}, X_{td}^{+}, and X_{tb}^{+} positive trions and the singlet-triplet crossing (at $B \approx 12\,\mathrm{T}$). Reduction of the trion emission energy was found at $B = 14.2\,\mathrm{T}$, coincident with condensation of the holes into an incompressible $\nu = \frac{1}{3}$ Laughlin liquid. We also determined the recombination spectrum of acceptor-bound trions, including weak shake-up transitions (with one of the left-over holes excited to a higher Landau level, LL) [5].

2. Experiment

We used a pair of MBE-grown, symmetrically C-doped $\mathrm{GaAs/Al_{0.35}Ga_{0.65}As}$ quantum wells of width $w = 15\,\mathrm{nm}$, hole mobilities (measured at low temperature $T = 4.2\,\mathrm{K}$) $\mu \sim 10^5\,\mathrm{cm^2/V\,s}$, and hole concentrations $p = 1.15$ and $1.89 \times 10^{11}\,\mathrm{cm^{-2}}$ (determined from quantum Hall measurements). Both samples showed similar behavior so we will only present the results obtained for the lower concentration. The PL was excited by a 720 nm red line (titanium sapphire tunable laser; below the energy gap in the barrier), and an additional 514 nm green line (ion argon laser; above the barrier gap) was used to decrease p. The spectra were recorded at $T \geqslant 1.8\,\mathrm{K}$ and $B \leqslant 23\,\mathrm{T}$ (corresponding to LL

*Corresponding author.
E-mail addresses: leszek.bryja@pwr.wroc.pl (L. Bryja), Arkadiusz.Wojs@pwr.wroc.pl (A. Wójs).

1386-9477/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physe.2007.09.128

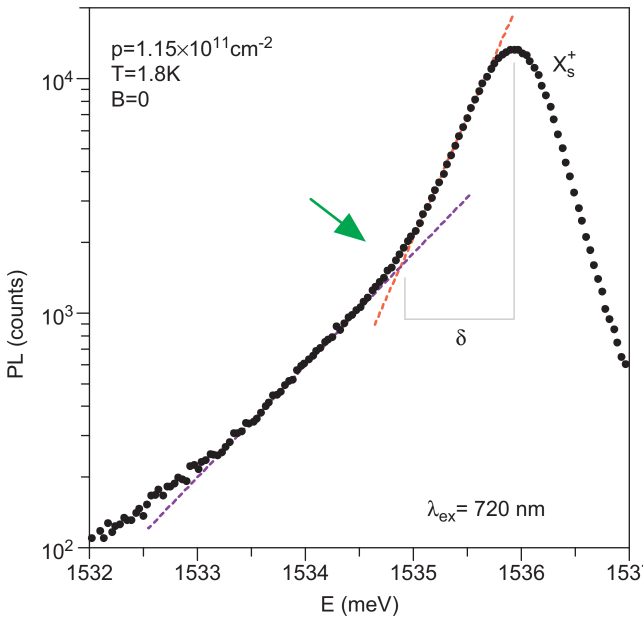

Fig. 1. PL spectrum of a 2D hole gas at $B=0$. Arrow marks the slope change in the trion emission tail, corresponding to the passing of the left-over hole through the Fermi surface.

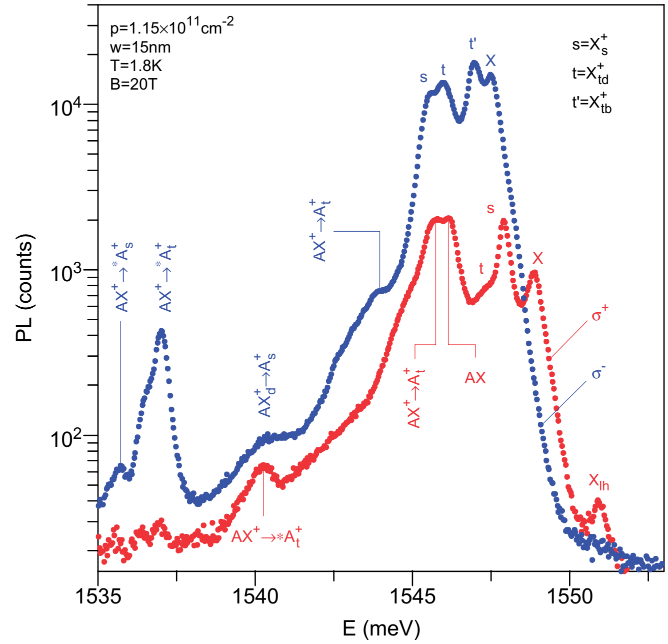

Fig. 2. Polarization-resolved PL spectrum of a 2D hole gas at $B=20\,\mathrm{T}$. Recombination of free and acceptor-bound excitons and trions is identified (incl. shake-up transitions).

filling factors $\nu \geqslant \frac{1}{5}$). We used Faraday configuration with the linear polarizer and wave quarter placed together with the sample in liquid helium.

The PL spectrum at $B=0$ shown in Fig. 1 consists of a single X_s^+ line. When plotted in logarithmic scale, the long low-energy tail $I(E)$ changes slope at the energy E about $\delta = 1\,\mathrm{meV}$ below the peak maximum. This effect is a consequence of the finite radius k_F of the 2D hole Fermi sphere. In recombination of a free X^+ its total initial momentum $\hbar k$ shared by the three bound particles equals the momentum of the single left-over hole. Depending on whether k is larger or smaller than k_F, the hole is left either outside or inside the Fermi sphere. For $k > k_F$, decay of $I(E)$ is exponential [6]. In the opposite case, Pauli exclusion principle considerably weakens the transition, causing relatively more rapid decrease of $I(k)$. Combining expressions for $k_F = \sqrt{2\pi p}$ and the hole Fermi energy $E_F = \delta/[1-(2+m_e/m_h)^{-1}]$ we obtained $E_F = 1.6\,\mathrm{meV}$ and $m_h = 0.13$.

An example of a much richer PL spectrum revealed at $B>0$ is shown in Fig. 2. Convincing identification of all marked peaks was possible by studying dependence of the spectra on p (tuned by the green laser) and comparison with extensive numerics [7]. Among the resolved peaks are free and acceptor-bound excitons (X, AX, and the light-hole X_{lh}), three states of a free trion (X_s^+, X_{td}^+, and X_{tb}^+), and the four-line emission spectrum of the acceptor-bound trion (AX^+) including a pair of $AX^+ \to {}^*A^+$ "shake-up" transitions involving excitation of one of the left-over holes to a higher LL.

From the comparison of σ$^+$ and σ$^-$ spectra we also extracted the Zeeman splitting for the recombination of different states. Interestingly, they are nearly identical for X and X_{td}^+, considerably lower than for X_s^+ or AX^+. This is traced to the k-dependence of the hole Landé g-factor. Note that it causes reversal of the order of X_{td}^+ and X_s^+ peaks in the σ$^+$ and σ$^-$ spectra.

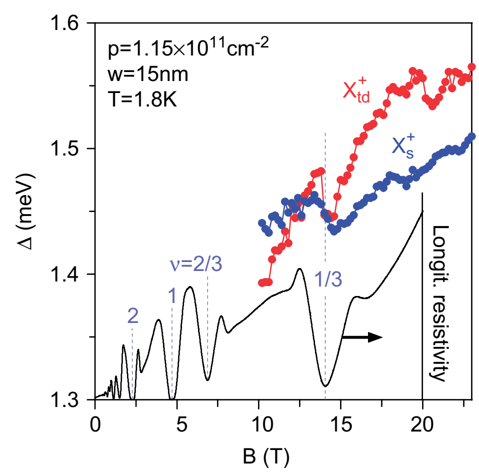

Fig. 3. Binding energy of singlet and triplet positive trions as a function of magnetic field. The quantum Hall curve confirms formation of the Laughlin hole liquid at $B \approx 14.2\,\mathrm{T}$.

To remove Zeeman contribution from the trion binding energy $\Delta = E[X] + E[\mathrm{h}] - E[X^+]$, the X/X^+ peak separations measured in PL must be averaged over both σ$^\pm$ polarizations. The resulting curve $\Delta(B)$ of X_s^+ and X_{td}^+ is displayed in Fig. 3. The singlet–triplet crossing is found at $B \approx 12\,\mathrm{T}$ (relatively low field compared to the crossing of negative trions in typical n-doped wells). Note also downward cusps at $B = 14.2\,\mathrm{T}$ in both curves. From the

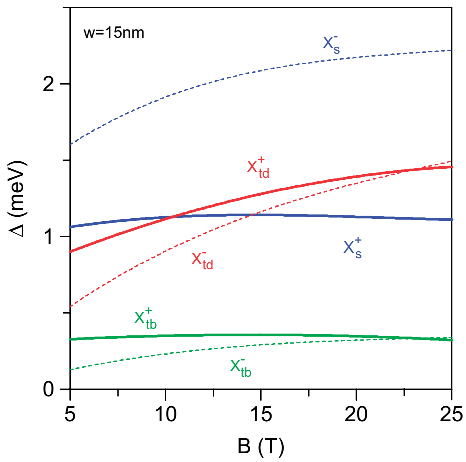

Fig. 4. Calculated magnetic field dependence of trion binding energies in a symmetric 15 nm quantum well. Big difference between positive and negative singlet states is evident.

quantum Hall measurements [see the longitudinal resistance curve $\varrho_{xx}(B)$] it is clear that $B = 14.2\,\mathrm{T}$ corresponds to $\nu = \frac{1}{3}$, i.e., to the formation of a Laughlin incompressible hole fluid.

3. Theory

The numerical (exact diagonalization) calculations of the binding energies of the relevant excitonic complexes (X, X^+, AX, and AX^+) were done in Haldane spherical geometry, with the configuration interaction (CI) basis containing up to five LLs and three quantum well subbands for both electrons and holes [7]. Inclusion of Coulomb dynamics in all three dimensions was essential for reaching sufficient numerical accuracy for reliable interpretation of the experiment.

In Fig. 4 we compare $\Delta(B)$ of different trions in a symmetric $w = 15\,\mathrm{nm}$ quantum well. In comparison of X^+ with X^-, binding of the singlet state weakens the most of all trions. This leads to the shift of the singlet–triplet crossing to a lower $B \approx 11\,\mathrm{T}$. Note that this transition field agrees very well with our experiment (better than the binding energies themselves).

Similar calculations were also performed with an ionized acceptor located inside the quantum well. The AX^+ ground state is a spin-doublet with $M = -1$. It can recombine to any of the A^+ eigenstates with the same $M = -1$. Transitions to the lowest spin-singlet (A_s^+) or triplet (A_t^+) dominate, but the shake-up processes to the excited states ($^*A_s^+$ and $^*A_t^+$) are also allowed. Calculated positions and relative intensities of these four peaks agree rather well with Fig. 2.

Acknowledgment

The authors acknowledge support from Grant N202-104-31/0771 of the Polish MNiSW.

References

[1] K. Kheng, R.T. Cox, Y. Merle d'Aubigne, F. Bassani, K. Saminadayar, S. Tatarenko, Phys. Rev. Lett. 71 (1993) 1752.
[2] M. Byszewski, B. Chwalisz, D.K. Maude, M.L. Sadowski, M. Potemski, T. Saku, Y. Hirayama, S. Studenikin, D.G. Austing, A.S. Sachrajda, P. Hawrylak, Nature Phys. (London) 2 (2006) 239.
[3] A. Wójs, J.J. Quinn, P. Hawrylak, Phys. Rev. B 62 (2000) 4630.
[4] G. Yusa, H. Shtrikman, I. Bar-Joseph, Phys. Rev. Lett. 87 (2001) 216402.
[5] S. Glasberg, H. Shtrikman, I. Bar-Joseph, Phys. Rev. B 63 (2001) 201308.
[6] A. Esser, E. Runge, R. Zimmermann, W. Langbein, Phys. Rev. B 62 (2000) 8232.
[7] L. Bryja, A. Wójs, J. Misiewicz, M. Potemski, D. Reuter, A. Wieck, Phys. Rev. B 75 (2007) 035308.