Shake-up replicas of excitons and trions in magneto-photoluminescence of two-dimensional hole gas

L. Bryja[1], A. Wójs[1], J. Misiewicz[1], M. Potemski[2], D. Reuter[3] and A. Wieck[3]

[1]*Institute of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2]*Grenoble High Magnetic Field Laboratory, CNRS, 25 av. Martrys, F38042 Grenoble*
[3]*Lehrstuhl fur Festkörperphysik, Ruhr Universität, Universitätstrasse 150, 44780 Bochum, Germany*

Abstract. Recombination spectra of excitons and trions in two-dimensional hole gas are studied in two-beam magneto-PL. The singlet, dark-triplet and bright-triplet trions are all identified, and their binding energies are determined. Below the trion energies, the cyclotron replica is identified. Based on the realistic numerical calculation, this peak is attributed to the shake-up process that involves a trion bound to a neutral acceptor located inside the quantum well.

Keywords: Shake-up, photoluminescence, trion, hole gas.
PACS: 71.35.Pq, 71.35.Ji

INTRODUCTION

Photoluminescence (PL) spectroscopy in magnetic fields is a powerful method to study two-dimensional (2D) electron (or hole) gas in the integral or fractional quantum Hall regime. Field evolution of the spectra carries information not only about the single-particle energy levels of 2D carriers, but also about the crucial role of exchange interaction. In this paper, we report low-temperature magneto-PL studies of a 2D hole gas. We observed recombination of neutral and positively charged excitons (trions): $X = e + h$, $X^+ = 2h + e$ [1,2], as well as of their cyclotron replicas. The analysis of optical selection rules and the numerical calculations allowed for (i) identification of all trion states and (ii) interpretation of the replica as a shake-up process [3] consisting of the recombination of a trion bound to a neutral impurity located in the quantum well, A^0X^+, accompanied by excitation of the impurity-bound hole to a higher Landau level (LL), $A^+ \rightarrow A^0 + h^*$. This demonstrates that interactions of 2D carriers with impurities are important even in high-quality samples, with mean free path comparable to that of electrons with the highest mobility $\mu \sim 10^6 cm^2/Vs$.

EXPERIMENT AND RESULTS

The sample was a $w = 15$ nm $GaAs/Ga_{0.65}Al_{0.35}Al$ quantum well fabricated by molecular beam epitaxy on a (001) semi-insulating GaAs substrate δ C-doped in the barrier on both sides. At low temperature $T = 4.2$ K

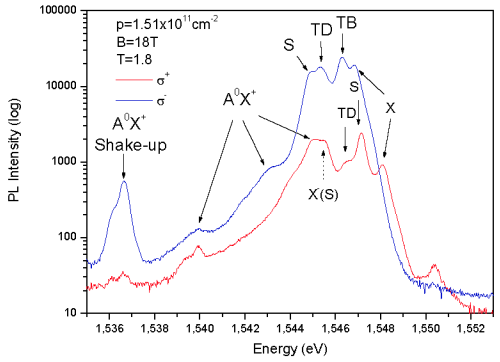

FIGURE 1. PL spectra of 15 nm $GaAs/Ga_{0.65}Al_{0.35}Al$ quantum well in magnetic field of $B = 19$T. Note that intensity on vertical axis is shown in logarithmic scale.

the sheet concentration and mobility of the holes were $p = 1.51 \times 10^{11}$ cm^{-2} and $\mu = 1.01 \times 10^6$ cm^2/Vs. The measurements were carried out at temperatures down to $T = 1.8$ K and in magnetic fields up to $B = 23$ T. We used Faraday configuration, with a linear polarizer and wave quater placed together with the sample in liquid helium. To switch between σ^- and σ^+ polarizations, the direction of the magnetic field was changed. PL was excited by the $\lambda = 750$ nm line of Titanium Sapphire tuneable laser. The additional ion Argon line $\lambda = 514$ nm was used to increase the 2D electron concentration.

In Fig. 1 the PL spectra in both polarizations at $B = 18$ T are presented. This particular value was

CP893, *Physics of Semiconductors, 28th International Conference*
edited by W. Jantsch and F. Schäffler

choosen for illustration because all lines detected also at lower and higher B are here visible simultaneously. In the spectra at $B = 0$ (not shown) there is only one peak. The characteristic exponential low-energy tail allows its attribution to the positive singlet trion X^+ [4]. With additional excitation by λ = 514 nm Argon ion laser, the free exciton line X emerges above the singlet trion energy. Application of the magnetic field reveals rich structure of the PL spectra, with a big difference between the two polarizations. For σ^-, the exciton and the bright [5] and dark [6] triplet trions emerge succesively (in the growing field) on the high-energy side of the singlet trion. Also on its low-energy wing, even more new lines emerge in the PL spectra.

To understand the numerous features observed in the spectra, we performed detailed realistic numerical calculations and additional experiments. Numerically, we calculated energy spectra of various electron-hole bound states, with and without an additional acceptor (placed at arbitrary position in the growth direction). Experimentally, we studied dependence of the spectra on red/green laser power density and on temperature. This led to the identification of peaks marked in Fig. 1.

Two lines named A^0X^+ are due to recombination of a trion bound to a neutral acceptor, i.e., one electron and three (unpolarized) holes bound to a point charge A^- located inside the quantum well. The ground state of this configuration has relative angular momentum $M = -1$, and it is only weakly bound against breakup into A^+ and X. Our best theoretical estimate of the A^0X^+ binding energy is below 0.5 meV. This agrees rather well with the observation that the shake-up replica disappears when the liquid helium temperature is increased from $T = 1.8$ to 4.2 T.

Upon recombination, the A^0X^+ ground state leaves behind an excited state of A^+ (with the same $M = -1$), with the two holes in either singlet or triplet spin state. The A^+ energy spectrum is shown in Fig. 2. For either spin configuration, the lowest A^+ state at $M = -1$ corresponds to both holes in the lowest LL; in the excited state one of the holes is in the excited LL. The possible recombination processes starting from the A^0X^+ ground state and ending in the A^+ with $M = -1$ were predicted from realistic numerical calculations. Comparison of energy positions and relative intensities with experiment allowed for identification of the peaks marked in Fig. 1. The most interesting is the shake-up process: $A^0X^+ \rightarrow A^+$ (spin-triplet; excited). Curiously, the calculations predict that its energy difference from the "main" transition (to the lowest spin-triplet A^+) is almost exactly the hole cyclotron gap. This connects the hole cyclotron mass with the PL spectrum.

Let us add that the shake-up process found here requires the presence of impurities. Conservation of angular momentum in translationally invariant systems

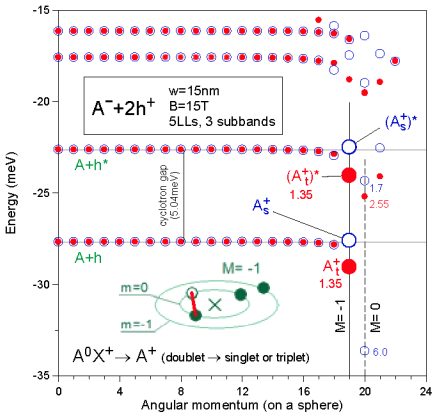

FIGURE 2. The energy spectrum of A^+ (two holes bound to an acceptor in the middle of a quantum well) calculated on a sphere for realistic sample parameters (GaAs, w = 15 nm, B = 15 T) and including five LLs and three quantum well subbands. A^+ is the final state for recombination of acceptor-bound trions (optically active channel is $M = -1$). Subscripts "s" and "t" in A^+ denote singlet and triplet (open and full dots). Binding energies from A + h or A + h* (in meV) are indicated.

[6] leads the optical selection rules that exclude shake-up recombination of any *free* bound trion states [7]. On the other hand, we have checked (numerically) that shake-up emission from the continuum of scatterred X + h states is inefficient and it cannot explain Fig. 1.

ACKNOWLEDGMENTS

Work supported by grants: RITA-CT-2003-505474 from EC and N20210431/0771 (LB) and 2P03B02424 (AW) of Polish MENiS.

REFERENCES

1. M. A. Lampert, *Phys. Rev. Lett.* **1**, 450 (1958).
2. K. Kheng et al., *Phys. Rev. Lett.* **71**, 1752 (1993); G. Yusa, H. Shtrikman, I. Bar-Joseph, *ibid.* **87**, 216402 (2001); H. Buhmann et al., *Phys. Rev. B* **51**, 7969 (1995).
3. G. Finkelstein, H. Shtrikman, I. Bar-Joseph, *Phys. Rev. B* **53**, 12593 (1996); *ibid.* **56**, 10326 (1997); S. Glasberg, H. Shtrikman, I. Bar-Joseph, *ibid.* **63**, 201308 (2001).
4. B. Stebe, A. Ainane, *Superlatt. Microstruct.* **5**, 545 (1989); C. Riva, F. M. Peeters, K. Varga, *Phys. Rev. B* **61**, 13873 (2000).
5. A. Wójs, J. J. Quinn, P. Hawrylak, *Phys. Rev. B* **62**, 4630 (2000); C. Riva, F. M. Peeters, K. Varga, *ibid.* **63**, 115302 (2001).
6. A. Wójs, P. Hawrylak, *Phys. Rev. B* **51**, 10880 (1995); J. J. Palacios, D. Yoshioka, A. H. MacDonald, *ibid.* **54**, 2296 (1996); A. B. Dzyubenko, A. Y. Sivachenko, *Phys. Rev. Lett.* **84**, 4429 (2000).
7. A. B. Dzyubenko, *Phys. Rev. B* **69**, 115332 (2004).