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PHOTOLUMINESCENCE OF IMPURITY-BOUND EXCITONS AND TRIONS IN MAGNETIC FIELDS

ARKADIUSZ WÓJS, LESZEK BRYJA, ANNA GŁADYSIEWICZ and JAN MISIEWICZ
Institute of Physics, Wroclaw University of Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland

MAREK POTEMSKI
Grenoble High Magnetic Field Laboratory, CNRS, F-38042 Grenoble Cedex 9, France

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Recombination spectrum of excitons and positive trions is studied by two-beam magneto-photoluminescence of a two-dimensional hole gas. For acceptor-bound trions a low-energy cyclotron replica is observed, corresponding to a hole shake-up process. The experiment is supplemented by realistic numerical calculations, allowing for identification of individual transitions and connecting the splitting of the shake-up line directly with the hole mass.

Keywords: Photoluminescence; trion; shake-up.

1. Introduction

Photoluminescence (PL) is a powerful tool in experimental studies of two-dimensional (2D) systems of carriers in high magnetic fields[1]. The bound states dominating the spectra at sufficiently low density are neutral excitons ($X = e + h$) and trions ($X^+ = X + h$ for the gas of holes).[2,3] The trions involving (only) heavy holes are distinguished by the pair (pseudo)spin $S = 0$ or 1 and total angular momentum M. The most stable trions are the singlet $X_{\rm s}^+$ ($S = M = 0$) and two triplets $X_{\rm tb}^+$ and $X_{\rm td}^+$ ($S = 1$ and $M = 0$ and 1 for the "bright" and "dark" state).[4]

In this paper we investigate the shake-up process in which the e–h pair radiative recombination ($e + h \to \gamma$) is accompanied by a (cyclotron) excitation of another hole to a higher Landau level (LL), $h \to h^*$.[5] Such process must involve at least two holes, i.e., a trion. Moreover, shake-up recombination of *free* trions is forbidden due to angular momentum conservation,[6] which leads to the requirement of an additional collision to break the 2D translational symmetry.[7] Free holes turn out rather inefficient at relaxing the selection rule in exciton ($X + h \to \gamma + h^*$) or trion ($X^+ + h \to \gamma + h + h^*$) scattered emission. However, we show that even a small number of impurities (allowing for a still high mobility) enables shake-up detection.

We present polarization-resolved PL measurements of a 2D hole gas at low temperatures $T \geq 1.8$ K and in high magnetic fields $B \leq 23$ T. We also report numerical

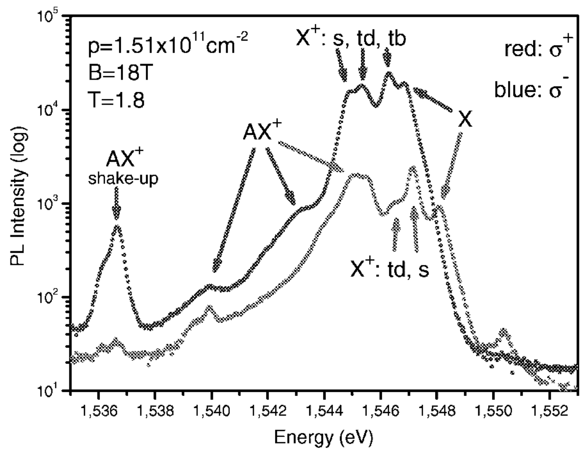

Fig. 1. Polarized PL spectra of a 2D valence hole gas in a $GaAs/Ga_{0.65}Al_{0.35}Al$ quantum well of width $w = 15$ nm at magnetic field $B = 18$ T. Note the logarithmic scale on vertical axis.

calculations taking into account quantum well width and LL/subband mixing. The role of neutral acceptors $A = A^- + h$ located inside the well is understood by identification of the weakly bound $AX_{\rm d}^+ = A^- + e + 3h$ doublet ($S = 1/2$) ground state and its recombination spectrum into different $A^+ = A^- + 2h$ states.

2. Experiment

The studied sample was a $w = 15$ nm $GaAs/Ga_{0.65}Al_{0.35}Al$ quantum well MBE grown on a (001) semi-insulating GaAs substrate δ C-doped in the barrier on both sides. The concentration and mobility of the holes (at $T = 4.2$ K) were $p = 1.51 \cdot 10^{11}$ cm^{-2} and $\mu = 1.01 \cdot 10^6$ cm^2/Vs. The PL spectra were recorded in Faraday configuration, with a small field step $\Delta B = 0.1$ T. To switch between σ^- and σ^+ light polarizations, the field direction was changed. PL was excited by the 750 nm line of Titanium Sapphire tuneable laser, and an additional ion Argon line 514 nm was used to increase the 2D electron concentration.

The pair of $\sigma^\pm$ PL spectra at $B = 18$ T are shown in Fig. 1. The individual peaks labeled by arrows were identified by comparison with the numerical calculation and by analyzing the field evolution shown in Fig. 2.

3. Calculation

The exact diagonalization of model hamiltonians was carried out for the relevant e–h systems, with and without an additional acceptor (point charge) A^- located at an arbitrary distance d from the middle of the quantum well. We used Haldane geometry[8] and mapped the in-plane motion onto the sphere of radius R with Dirac monopole of strength $2Q$ placed in the center. $2Q\phi_0 = 4\pi R^2 B$ where $\phi_0 = hc/e$ is flux quantum, and $Q\lambda^2 = R^2$ where $\lambda = \sqrt{\hbar c/eB}$ is the magnetic length; in the

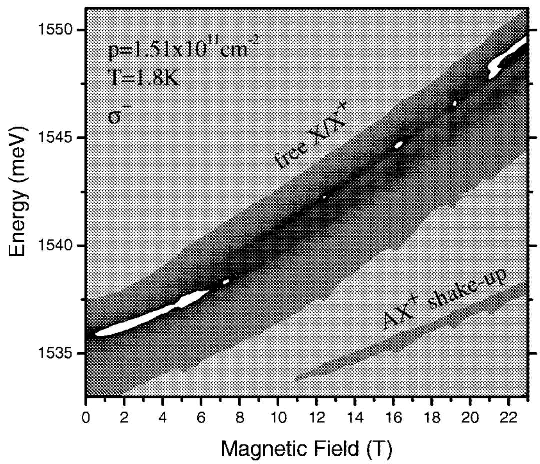

Fig. 2. Magnetic field evolution of the σ^- PL spectrum of Fig. 1. The lowest line is the shake-up recombination of the spin-doublet state of the acceptor-bound trion, $AX_{\rm d}^+ \to (A_{\rm t}^+)^*$.

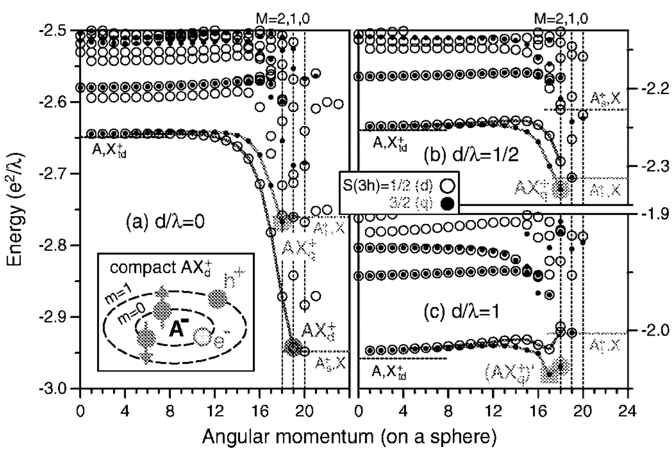

Fig. 3. Energy spectrum of a $3h+e$ system in the presence of an acceptor A^- at different distances d from the plane of the quantum well (λ is the magnetic length), calculated on a sphere for the magnetic monopole strength $2Q = 20$. Parameters adequate for an ideal system: $w = 0$ and lowest LL. Inset in frame (a): schematic of the "compact" $AX_{\rm d}^+$ state with angular momentum $M = 1$.

following we show data for $2Q = 20$. For the lack of space, let us focus on the AX^+.

We begin with an ideal case ($w = d = 0$, lowest LL, exact particle-hole e–h symmetry), shown in Fig. 3(a). The ground state occurs at $L = 2Q = 20$, i.e., at $M = 0$ (total angular momenta on a sphere L and on a plane M are related by $L = 2Q - M$). It is a "multiplicative" state,[9] degenerate with the unbound $A_{\rm s}^+ + X$ configuration. The "compact" $M = 1$ spin-doublet $AX_{\rm d}^+$ (see inset) at $L = 19$ is unbound. The spin-polarized quadruplet $AX_{\rm q}^+$ is also marked, but its stability

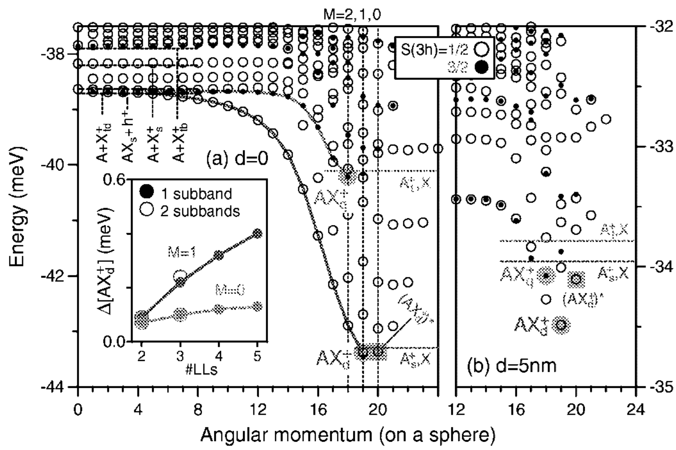

Fig. 4. Similar to Fig. 3 but for $w = 15$ nm and $B = 15$ T, including the lowest subband and two LLs. Two frames correspond to diferent positions of the acceptor A^- inside the quantum well. Inset in frame (a): Binding energies obtained including more subbands and more LLs.

requires high Zeeman gap. The solid lines connect states going from AX^+ towards higher M's and describing an X^+ orbiting around an A with different M (note that $X^+_{\rm td}$ is the only bound trion in the lowest LL). The spectra for off-center acceptors in frames (b) and (c) demonstrate sensitivity to the acceptor position.

More realistic AX^+ spectra in Fig. 4 were obtained by using the lowest-subband wavefunctions for $w = 15$ nm and including two LLs for both e and h, with the cyclotron gaps and magnetic length appropriate for $B = 15$ T. For $d = 0$ (a) we find weak binding of two $AX^+_{\rm d}$ states at $M = 0$ and 1. Stability of the "compact" $M = 1$ state is enhanced by inclusion of even more LLs and higher quantum well subbands (see inset). It is difficult to estimate reliably its binding energy Δ, but we conclude that (i) it is the lowest state for an excitonic complex in the presence of acceptors inside the well, and (ii) it is rather weakly bound, observable only at low temperatures. Sensitivity to acceptor position is exaggerated in frames (b) and (c) due to the lowest-subband approximation, but it allowed us to identify acceptors located *inside* the well as responsible for shake-up observed in our experiment.

The A^+ energy spectrum (final state in the $AX^+_{\rm d}$ recombination) in Fig. 5 was was calculated accurately, including five LLs and three subbands for each e and h. The $\Delta M = 0$ selection rule defines $M = 1$ as the active optical channel. The lowest $M = 1$ states are one singlet and one doublet for either both holes in the lowest LL: $A^+_{\rm s}$ and $A^+_{\rm t}$, or for one of the holes in the excited LL: $(A^+_{\rm s})^*$ and $(A^+_{\rm t})^*$. The indicated binding energy Δ of each of these states is measured from an unbound $A+h$ or $A+h^*$ state (h^* is a hole in the excited LL). Both triplets have essentially the same $\Delta_{\rm t} = \Delta^*_{\rm t} = 1.35$ meV, while both singlets are unbound.

Different final states yield distinct lines in the PL spectrum. The oscillator strengths evaluated relative to X are: $I_{\rm t} = 0.0061$, $I_{\rm s} = 0.0012$, $I^*_{\rm t} = 0.0008$, and

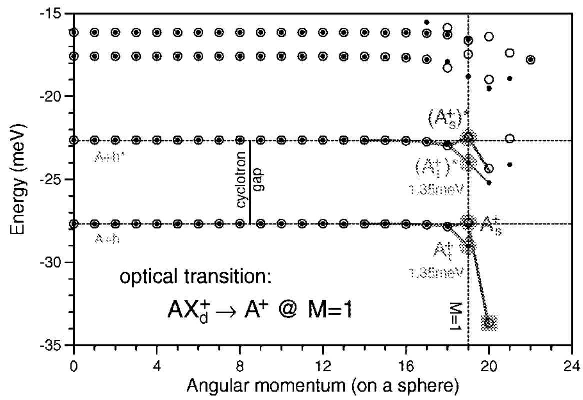

Fig. 5. Energy spectrum of $2h$ with an acceptor A^- in the middle of quantum well, calculated for $w = 15$ nm and $B = 15$ T, including three subbands and five LLs.

$I_s^* \approx 0$, in good agreement with our experiment. Remarkably, since $\Delta_t = \Delta_t^*$, the shake-up $AX_d^+ \to (A_t^+)^*$ transition occurs at exactly the (hole) cyclotron energy below its $AX_d^+ \to A_t^+$ parent transition. Generally, the lack of Coulomb contribution to this peak splitting allows for extraction of the hole cyclotron mass from PL.

Acknowledgments

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