Charge conversion of nearly free and impurity bound magneto-trions immersed in 2D electron or hole gas with optically tunable concentration

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Abstract. We report collection of precise photoluminescence maps (emission intensity versus energy and magnetic field) of superior-quality two-dimensional hole gases. The maps reveal field evolution of both direct and cyclotron-assisted recombination lines attributed to various excitonic complexes, either moving nearly freely in the plane or bound to the acceptors placed inside or outside the quantum well. Under two-beam illumination (with photon energies below and above the band-gap in the barrier) we were able to control hole concentration (in the same well), and in particular to decrease it beyond the point of p- to n-type conversion. Our results demonstrate contrast between charge conversion of free and acceptor-bound positive trions resulting from the breaking of charge reflection symmetry by a fixed impurity.

1. Introduction

Two-dimensional (2D) electron gas subject to quantizing magnetic field is a paradigmatic system for the investigation of many-body interaction effects and as well as single-particle localization [1]. Most previous experiments were devoted to the electron systems due to their much higher mobility. However, recent advances in the growth of high purity semiconductor structures have also refocused attention onto the 2D hole systems. The magneto-optical spectra of the 2D holes are not equivalent to those of the 2D electrons mainly due to their much larger effective mass, which results in different relations between the binding energies of neutral and charged complexes. In presented studies we have recorded extremely precise photoluminescence maps as a function of excitation intensity and energy vs. magnetic field of high quality 2D hole gases, revealing field evolution of both direct and cyclotron-assisted recombination lines attributed to various excitonic complexes moving nearly freely in the plane or bound to residual acceptors positioned inside or outside the quantum well. Combining red and green laser excitation power, with photon energies below and above the band-gap of the barrier, we

were able to control the hole concentration and even decrease it beyond the point of conversion from p- to n-type (in the same structure) [2].

2. Experiment and results

The investigated samples were superior quality 15 nm wide GaAs/$Ga_{0.66}Al_{0.34}As$ quantum wells, grown by molecular beam epitaxy on a (001) semi-insulating GaAs substrate. The 2D hole gas was introduced into the quantum well by Carbon δ-doping in the barriers. Symmetric and asymmetric structures were fabricated with either the same or different doping dose in both barriers. In all samples, the hole mobility measured at $T = 4.2$ K was in the range of $\mu = 10^5$ cm^2/Vs and the hole concentration measured in the dark varied in the range of $p = (1.1 – 2.4) \times 10^{11}$ cm^{-2}. Photoluminescence (PL) was excited by a combination of two beams: a "red" 720-nm line of a titanium sapphire tunable laser and a "green" 514-nm line of an ion argon laser with the photon energy below and above the band gap of the barrier respectively. As it was demonstrated previously [1,2], the selective photoexcitation inside and outside of the quantum well allows control of the dynamical carrier population and even of the sign of majority carriers inside the well. The experiments were performed in the Faraday configuration, in magnetic fields up to $B = 23$ T changed with a small step $\Delta B = 0.05$ T at temperatures varied in the range of $T = 1.8$ to 30 K. Fiber optics geometry was used. The switch between the σ^- and σ^+ circular polarizations was achieved by reversing the direction of the field (current). The PL spectra were analyzed in a 0.7 m long monochromator, equipped with a Nitrogen-cooled charge coupled device.

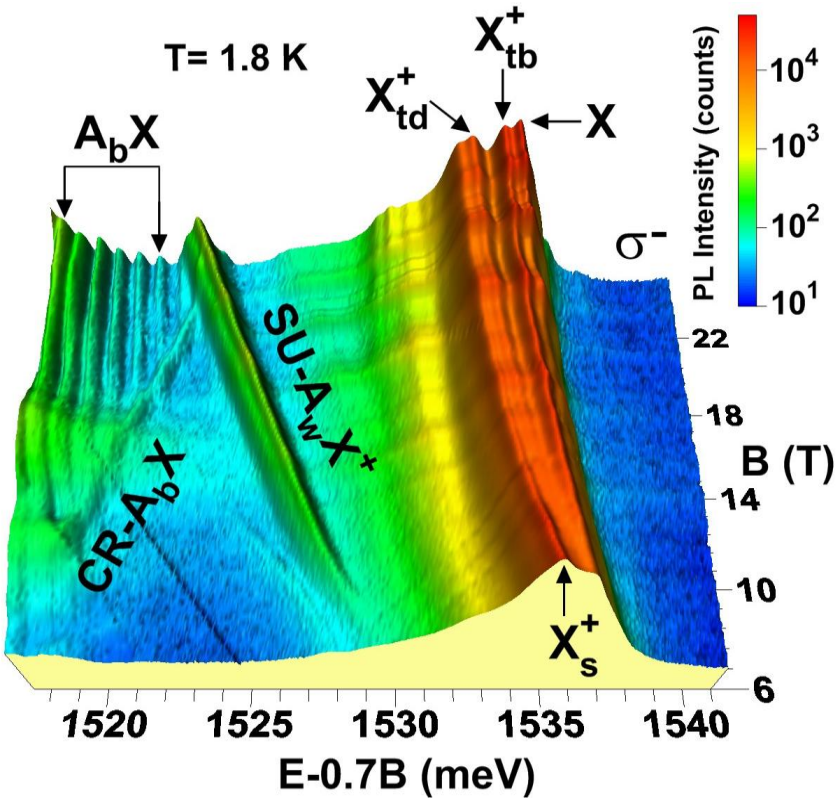

Figure 1. (color online) Evolution of the PL spectrum of the symmetric GaAs quantum well of (dark) concentration $p = 1.15 \times 10^{11}$ cm^{-2}, in magnetic field B varied from 0 to 23 T, in a strong intensity σ^- polarization, at $T = 1{:}8$ K, under power density $P = 30$ mW/cm^2 of the red laser. Photoluminescence intensity is presented in color logarithmic scale.

In the Fig. 1 evolution of PL spectra in σ^- polarization at temperature $T = 1.8$ K under excitation of red laser only are presented in magnetic field varied from $B = 6$ to 23 T.

In the Fig. 2 variations of the spectrum as a function of the power density of an additional green laser (decreasing 2D hole concentration), in magnetic field B = 23 T in σ+ polarization is presented.

Aided with the realistic numerical calculations [3,4] detailed analysis of the experimental data (field evolution of the emission spectra detected for different concentrations or holes or electrons), allowed us to interpret almost all observed emission lines related to the 2D gas. We divided them into two main groups.

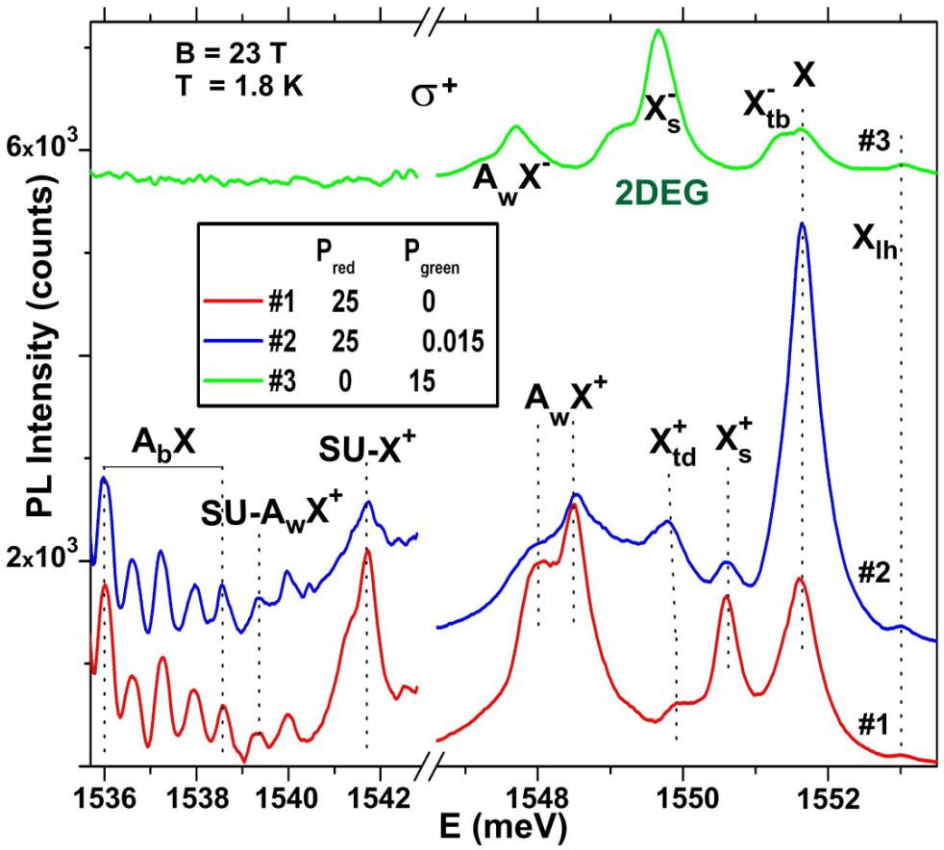

Figure 2. (color online) The PL spectra at B=23T, under different excitation of red and green lasers, in the symmetric GaAs quantum well.

The first group of line, detected in the high energy region of the PL spectra, are strongly dependent on the quantum well width [5]. In this group we detected emission (highest in energy and intensity) from all theoretically predicted trions: the singlet X^+_s and two triplet states (bright X^+_{tb} and dark X^+_{td}) as well as the neutral excitons ($X_{hh} \equiv X$ and X_{lh} containing a heavy or light hole, respectively). Below, in energy sequence, to these lines, we detected the following lines in PL spectra: doublet of acceptor bound trion A_wX^+ (Fig. 2), hole cyclotron replicas of almost free and bound trions (SU – X^+ and SU – A_wX^+) related to well known "shake-up" processes [6]. We interpreted all above lines as radiative recombination of the electron-hole complexes whose wave functions are predominately located inside the quantum well. With increase of the power density of green laser the structure converts from p to n type. All positively charged complexes disappear from the PL spectra and are replaced by negatively charged ones: X^- and A_wX^- (Fig. 2). The former transition: charge conversion between the positive and negative excitonic complexes bound to acceptors ($A_wX^+ \rightarrow A_wX^-$) are the most spectacular observation in our investigation. This effect is essentially distinct from the previously observed charge conversion of free trions [7]. In the $A_wX^+ \rightarrow A_wX^-$ conversion two holes are subtracted whereas in $X^+ \rightarrow X^-$ conversion one hole in trion complex is substituted by one electron.

The second group of lines are detected in the lower energy sector of the PL spectrum. Their energy positions are insensitive to the width of the quantum well. We have attributed them to the radiative recombination of positive trions strongly localized by Coulomb potentials of remote ionized acceptors located in the barriers: $A_bX=A^-+X^+$. The multiple, parallel lines correspond to the A_bX complexes with acceptors placed in the barrier at subsequent crystalline layers. Above interpretation is supported with the following observation. In the studied the high-quality structure the residual bulk acceptor density in the barrier is on the order of 10^{15} cm^{-3}. This gives the average acceptor density per crystalline layer of 0.28×10^8 cm^{-2},which is over three orders of magnitude lower then 2D hole concentration in the well yielding considerably weaker intensity of each single A_bX^- line in comparison to X^+.

3. Conclusions

In polarization-resolved two-beam magneto-photoluminescence experiments performed on high-mobility 15 nm wide GaAs/$Ga_{0.66}Al_{0.34}As$ quantum wells we have identified and understood several optical transitions, including the nearly free excitons and trions, excitonic complexes bound to charged impurities placed in the well and in the barriers, and also their cyclotron replicas. In particular we have observed coexistence of nearly free and strongly bound trions as well as charge conversion between the positive and negative exciton complexes (both free and bound to acceptors in the well).

Acknowledgements

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References

[1] Jain J K, *Composite Fermions* (Cambridge University Press, Cambridge, 2007); Ihn T, *Semiconductor Nanostructures: Quantum States and Electronic* Transport (Oxford University Press, Oxford, 2010)
[2] Bartsch G et al., *Phys. Rev.* B **83,** 235317 (2011).
[3] Bryja L, Wójs A, Misiewicz J, Potemski M, Reuter D, Wieck A, *Phys. Rev.* B **75**, 035308 (2007).
[4] Wójs A, Quinn J J, Hawrylak P, *Phys. Rev.* B **62**, 4630 (2000); Wójs A, *Phys. Rev.* B **76**, 085344 (2007).
[5] Bryja L et al., *Phys. Rev.* B **85**, 165308 (2012)
[6] Glasberg S, Finkelstein G, Shtrikman H and Bar-Joseph I, *Phys. Rev.* B **59**, 10425R (1999).
[7] Glasberg S, Shtrikman H and Bar-Joseph I, *Phys. Rev.* B **63** 201308(R) (2001).