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PHOTOLUMINESCENCE STUDIES OF POSITIVELY CHARGED EXCITONS IN ASYMMETRIC GaAs/Ga$_{1-x}$Al$_x$As QUANTUM WELLS WITH A TWO-DIMENSIONAL HOLE GAS

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Positive trions in a quasi-two-dimensional hole gas confined in symmetric and asymmetric GaAs quantum wells are studied by a combination of polarization-resolved photoluminescence and transport measurements in high magnetic fields B (up to 23 T) and low temperatures (down to 30 mK). The experiments are accompanied by realistic numerical calculations. The whole family of trions (the singlet and a pair of triplets) are observed. The singlet-triplet crossing of Coulomb energies is found: hidden in symmetric and visible in asymmetric structures.

Keywords: Two-dimensional electron gas; photoluminescence; positively charged excitons.

1. Introduction

The two dimensional (2D) electron and hole gases are unique systems to study many body interactions.[1] Many works have been devoted to the study of negatively charged excitons (trions) in 2D electron gas whereas positively charged ones in 2D hole gas are decidedly less explored. Excitons (X = e+h) and trions ($X^{\pm}$ = X + e or h) often determine photoluminescence (PL) spectra of low-dimensional semiconductor nanostructures.[2,3] In 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:[4,5] spin-singlet with M = 0 ($X^{\pm}_{s}$) and a pair of triplets with M = −1 ($X^{\pm}_{td}$) and M = 0 ($X^{\pm}_{tb}$). For free trions, only the M = 0 states are optically active ("bright"); while recombination of states with M ≠0 ("dark") requires breaking of the 2D translational invariance (e.g., by well width fluctuations or impurities).

In this article we report on the studies of positively charged excitons in symmetric and asymmetric GaAs/$Ga_{1-x}Al_xAs$ quantum wells with a two-dimensional hole gas. The investigations were performed in parallel polarization resolved photoluminescence (PL) and transport experiments in high magnetic fields (up to B=23 T) and at low temperatures (down to T=30 mK). Experimental photoluminescence and transport studies were supplemented with realistic configuration-interaction calculations. We report on the experimental detection of the entire family of positively charged excitons: the pair of bright and dark triplets and the singlet. Crossing of the singlet and triplet Coulomb energies is found: hidden in symmetric and visible in asymmetric structures.

2. Experiment, Results and Discussion

The studied samples were GaAs/$Ga_{0.65}Al_{0.35}Al$ quantum wells fabricated by molecular beam epitaxy on a (001) semi-insulating GaAs substrate and δ C-doped in the barrier. We studied two types of samples. The symmetric structure was a 15 nm GaAs/AlGaAs quantum well, symmetrically carbon delta-doped in both barriers, with the 2D hole concentration (measured in dark) $p=1.15\times10^{11}\,cm^{-2}$ and mobility $\mu=1.01\times10^{5}\,cm^{2}/Vs$. The symmetric structures were 22 nm and 25 nm GaAs/AlGaAs quantum wells, carbon delta-doped on one side, with 2D dark concentration and mobility equal to, respectively, $p_1=1.75\times10^{11}\,cm^{-2}$, $p_2=1.8\times10^{11}\,cm^{-2}$ and $\mu_1=1.2\times10^{5}\,cm^{2}/Vs$, $\mu_2=1.7\times10^{5}\,cm^{2}/Vs$. From the measurements of longitudinal and Hall resistance (with van der Pauw contact geometry), performed on the same experimental conditions as PL ones, we determined precisely the magnetic fields corresponding to the relevant integer and fractional filling factors as well as actual 2D hole gas concentration. Under illumination, the concentration decreased to the extent dependent on the density of light. The photoluminescence measurements were carried out at low temperatures from T = 30 mK to T = 1.8 K and in high magnetic fields up to B = 23 T applied perpendicular to the structure. The fiber glass optics was applied. We used the Faraday configuration, with a linear polarizer and wave quarter immersed in the liquid helium close to the sample. To switch between the σ^- and σ^+ polarizations, the direction of magnetic field was changed. PL was excited by the λ = 514 nm line of ion Argon laser.

In the photoluminescence spectra of all studied samples in zero magnetic field one line attributed to radiative recombination of photo-excited electrons with 2D holes is observed. The line exhibit exponential decay towards low energy characteristic for charged excitons recombination. In the studied samples they are positively charged excitons, it is they consist of 2 holes and one electron bound by Coulomb interaction. According to theoretical calculation at B = 0 the holes are in a singlet state. When magnetic field is applied the photoluminescence spectra revealed to a very reach one.

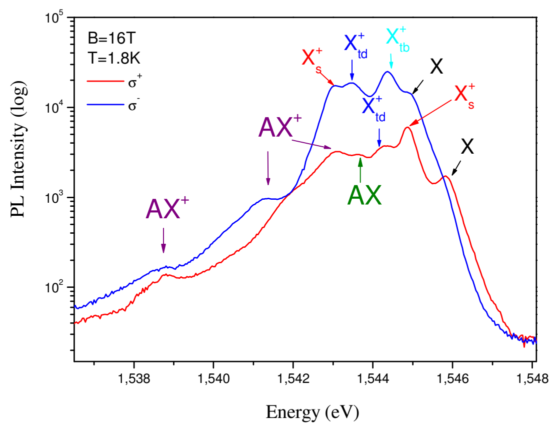

Fig. 1. Photoluminescence spectra for symmetric 15 nm QW in magnetic field B = 16 T.

In Fig. 1 the PL spectra for symmetric structure in both $\sigma^{\pm}$ are presented. From the detailed analysis of the evolution of PL spectr a as a function of the magnetic field (not presented) and comparision of experimental data of Coulomb binding energies in the trion complex with realistic numerical calculations we were able to identify all observed lines (for more detailed explanation see Ref. 6). In both polarization the exciton line X is the highest energy one. The order of energy positions of the trion lines in respect to X is different in both polarizations. In σ^- descending energy from X we detect: the triplet bright - X^+_{tb}, the triplet dark - X^+_{td} and finally the singlet - X^+_S. In σ^+ we detect reverse order of the singlet and the dark triplet lines. The bright triplet line is not observed in this polarization. In the PL spectra we observe also radiative recombination of excitons bound to neutral and positively charged acceptor – AX and A^+X (AX^+).

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 Land´e g-factor. Note that it causes reversal of the order of X^+_{td} and X^+_s peaks in the σ^+ and σ^- spectra. To remove Zeeman contribution from the trion binding energy $\Delta = E[X]+E[h]-E[X+]$, the X/X^+ peak separations measured in PL must be averaged over both $\sigma^{\pm}$ polarizations. The resulting curve Δ (B) of X^+_s and X^+_{td} is displayed in Fig. 2. In this figure the results of realistic numerical calculations are also plotted. The singlet–triplet crossing is found at $B \approx 12$ T (relatively low field compared to the crossing of negative trions in typical n - doped wells). Due to the strong difference in the Zeeman splitting this crossing is hidden in PL spectra. Notice that nevertheless the numerical calculations gives a slightly lower binding energy for the additional hole the singlet – triplet crossing is obtained almost in the same magnetic field.

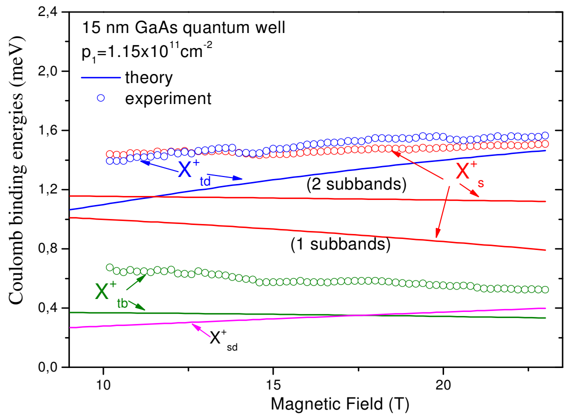

Fig. 2. The second-hole Coulomb binding energies: symbols – experiment, solid lines calculated numerically for the 15nm symmetric GaAs quantum well.

In the evolution of PL spectra for the asymmetric 22 nm QW in σ^- polarization in the magnetic field from B = 11 T to B = 16 T (not shown), we clearly see the crossing of two lines at B ≈ 13.5 T. From the comparision of experimental data of Coulomb binding energies in the trion complex with numerical calculations and detailed analysis of PL spectra evolution in magnetic field we assesses this feature to singlet triplet crossing.

In Fig. 3 the energy distance of singlet X^+_s and triplet X^+_{td} lines from excitons X is shown as a function of B. This energies agree well with theoretical calculations of Coulomb binding energies of additional hole in the asymmetric sample with lower concentration which satisfied experimental conditions. Due to high density of laser power excitation we decreased strongly the 2D hole concentration to $p_1=1.23\times10^{11}$ cm^{-2}.

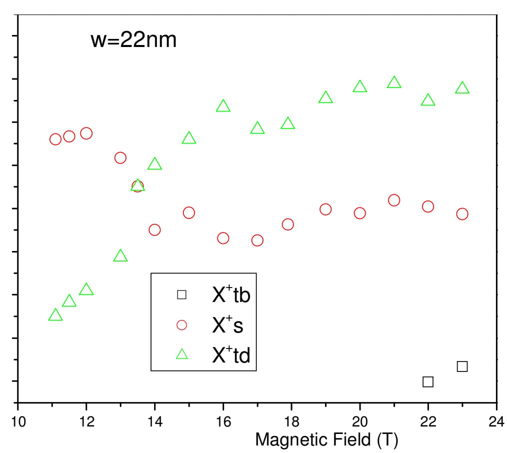

Fig. 3. The second-electron binding energies of the singlet and dark-triplet trion states for the sample with 2DEG concentration $n=1.8\times10^{11}$cm^{-2} (dark $n=1.7\times10^{11}$cm^{-2}).

Acknowledgments

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