Strong temperature destabilization of free exciton recombination in a two-dimensional structures with hole gas

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Abstract. We have investigated polarisation resolved magneto-photoluminescence from 22 nm wide asymmetric GaAs quantum well. In contrast to previous studies we observed abrupt decrease of photoluminescence intensity of the neutral exciton line with increasing temperatures whereas photoluminescence intensity of the positively charged exciton remains unchanged. The effect is a clear evidence of different mechanisms of neutral and charged exciton recombination. We have also detected a coupling of two different radiative states: an acceptor-bound and an essentially free trions.

1. Introduction

The energy spectrum of quasi-two-dimensional excitons in quantum well semiconductor heterostructures has been extensively studied in recent decades [1]. Most experiments were conducted with 2D electrons with highest mobility. In our studies we have explored 2D holes. We have investigated low-temperature (T=2.0-18K), high-field (B<17T), polarization-resolved magneto- photoluminescence (PL) on a range of high-quality asymmetric GaAs quantum wells with different widths w, hole concentrations p and (high) mobility μ. In contrast to previous studies [2] we observed abrupt decrease of photoluminescence intensity of neutral exciton line (X) with increasing temperatures whereas PL intensities of positively charged excitons (X+) remain unchanged. We also detected a coupling of two different radiative states observed as an anti-crossing in the magneto- photoluminescence spectrum, of essentially-free and acceptor-bound trion states immersed in a magnetically quantized hole gas, aided by an additional cyclotron excitation.

2. Experimental results

Te effect reported here was most prominent in the asymmetric 22nm wide GaAs/Ga0.65Al0.35As quantum well. The sample was grown by molecular beam epitaxy on a (001) semi-insulating GaAs substrate and δ-Carbon doped in the barrier on one side. The well was separated from the doping layer by a 40nm wide spacer. The hole mobility measured at T=4.2K was equal to μ=1.71x105cm-2/Vs. The hole concentration measured at low temperatures (T=17 mK-4.2K) and estimated from the quantum Hall effect measured in van der Pauw configuration, was almost temperature independent. In the dark, it was equal to $p=1.43\times10^{11}cm^{-2}$. Under laser illumination it decreased linearly with excitation power density, by up to several percent. The PL was excited by the 632.8nm line of a Helium-Neon laser (above the band gap of the barrier). The optical experiments were performed in temperatures from T=2.3K up to 18K, in the Faraday configuration, in magnetic fields up to B=17T varied with a small step ΔB=0.05T. To switch between the σ- and σ+ polarisations the direction of the field was reversed. The spectra were analyzed in a high-resolution monochromator, with a Nitrogen-cooled 2048-pixel CCD camera.

The magnetic field evolution of PL spectrum in σ^- polarization is presented in Fig. 1. In the absence of a field a single line is observed. When magnetic field is applied this line splits into two distinct components. The energy positions of both lines can be resolved in the fields above B=6T. After the detailed analysis and comparison with our previous experiments we attribute the observed lines to the neutral exciton X (higher energy) and the spin-singlet state of a positive trion X^+s (lower energy) [3].

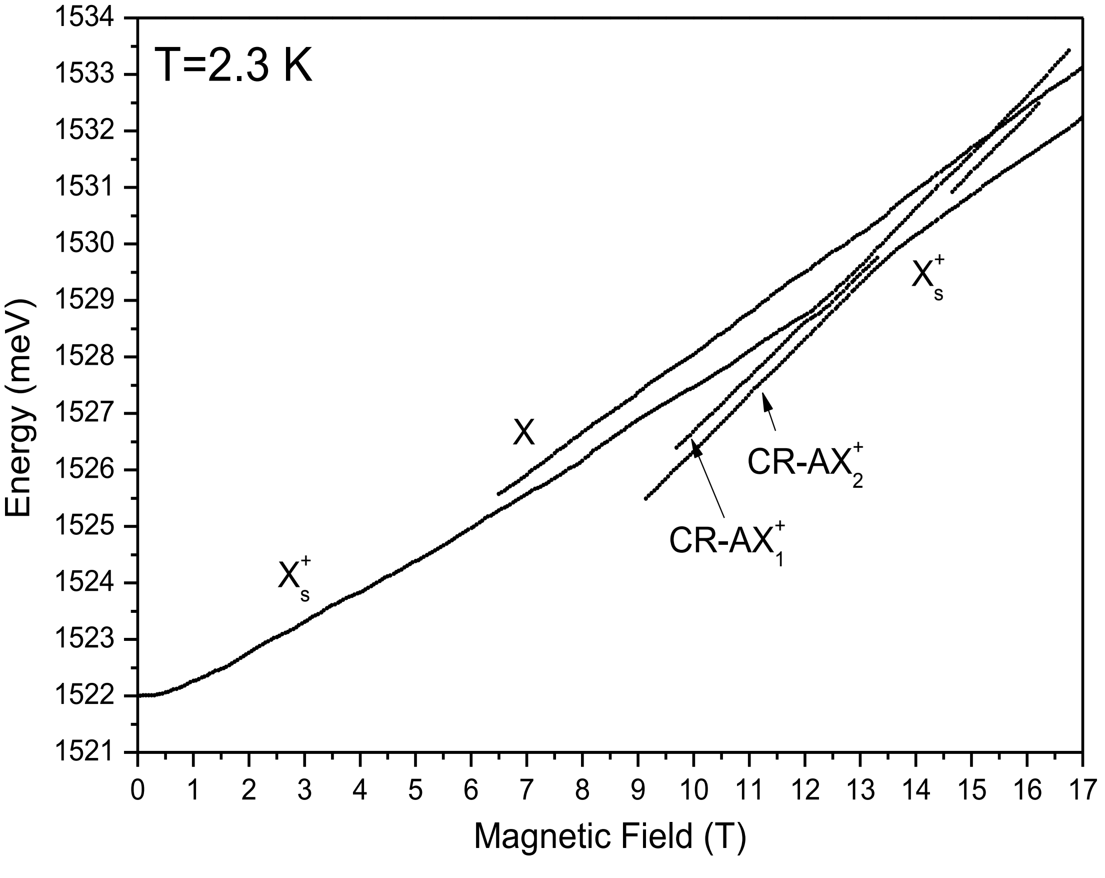

Fig.1 Energy position of all observed lines in photoluminescence in σ^- polarization.

In the lower energy part of the spectrum we detect the whole group of lines of very weak intensity. Two of them shift from the remaining ones toward higher energy, linearly with the increase of the magnetic field (with the slope of ~1.0meV/T). This effect is similar to the “shake-up” process [4] observed previously also by us [3] in a symmetric 15nm wide GaAs quantum well, but here the cyclotron shift is in the opposite energy direction. The magnetic field slope for the rest of weak lines (not marked in Fig. 1) is about 0.65meV/T. We interpreted the weak lines as follows: those lines with the smaller energy vs. field slope are due to the recombination of the trion bound on acceptor AX^+ (inside the well), whereas the two other lines with the higher slope are their hole cyclotron replicas. We named them $CR\text{-}AX^+_1$ and $CR\text{-}AX^+_2$ in analogy to a previous observation of an electron cyclotron replica of the free exciton line [5]. The presence of a pair of cyclotron replicas is a consequence of the fact that the allowed (by the conservation of angular momentum and spin) recombination of the AX+ ground state (labelled by the 3h spin of 1/2 and the total 3h+e angular momentum projection of -1) occurs to a pair of spin-singlet and triplet states of the A+, separated by an exchange gap [3]. Comparison of the slopes of $CR\text{-}AX^+$ and AX^+ gives a difference of 0.35meV/T, which agrees very well with the hole cyclotron energy determined earlier from the cyclotron resonance of 22 nm GaAs/AlGaAs quantum wells by Cole and co-workers [6] equal to 0.28meV/T). The effective mass determined from measured slope is m_{hh}=0.33. In σ^+ polarisation the cyclotron replicas are not observed in PL spectra. In this polarisation we detect only neutral and charged excitons lines.

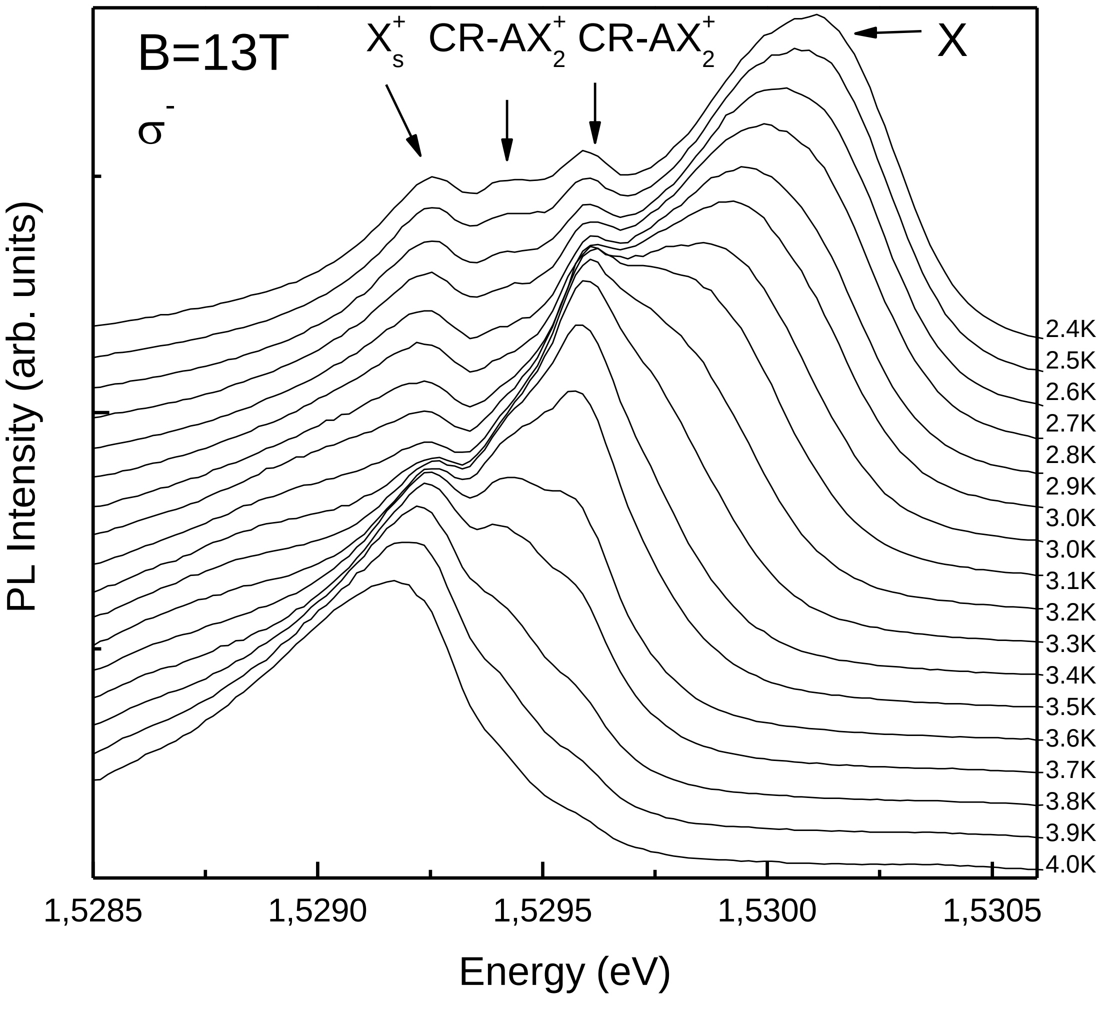

Fig.2. Temperature evolution of photoluminescence spectra.

The most intriguing effect is observed when the pair of $CR\text{-}AX^+_1$ and $CR\text{-}AX^+_2$ lines approach the positive trion X^+_s which results in a clear anticrossing. Furthermore, the intensity of both lines is greatly enhanced in the narrow anticrossing region. Beyond this region all lines return to a similar behaviour as in the lower fields (both in terms of energy and intensity).

Interpretation of this anticrossing was aided by the numerical calculation of the energy and recombination spectra of the involved radiative complexes [3, 7]. The conclusion is that the X^+ and AX^+ states are brought into resonance by an additional cyclotron excitation of a nearby free hole. The coupling mechanism for this pair of quasi-degenerate states is the resonant exciton transfer between the localized and (essentially) free trion states. The coupling strength (dependent on, e.g., the relative acceptor and hole concentrations) extracted from the energy splitting at the point of anticrossing is about 0.1meV.

The coincidence of the degeneracy of the initial radiative states X^+ and AX^+ (required for their efficient mixing) and of the transition energies (whose anticrossing has been directly observed in the PL spectrum) is explained by the near degeneracy of the optically active A^+ channel (corresponding to the angular momentum -1 of the AX^+ ground state) with the free hole state, the two serving as the final states in the radiative recombination of either X^+ or AX^+ [3]. The above interpretation is well supported by a simple calculation involving the set of constant X^+ and AX^+ oscillator strengths and the linear field dependences of the uncoupled initial and final states (extracted from the spectrum outside of the anticrossing region) and the constant coupling strength (determined at the point of anticrossing).

In the Figure 2 the temperature evolution of photoluminescence spectra at magnetic field B=13T are presented. In contrast to previous studies we observed abrupt decrease of photoluminescence intensity of neutral exciton line (X) with increasing temperature whereas PL intensities of positively charged excitons (X^+) remain unchanged [2]. We interpret this effect as a different mechanism of neutral and charged exciton recombination. During the recombination of charged exciton the total momentum can be transferred to left over hole whereas neutral exciton recombine with the total momentum close to zero. This is realized by the neutral exciton localization on a shallow lateral potential. With increasing temperature the recombination of excitons bound on lower potentials consecutively disappear from the PL spectra. This is observed as a low energy shift and narrowing of neutral exciton line and finally its complete disappearance from the PL spectra.

3. Conclusion

We have observed an anomalous effect of abrupt decrease of photoluminescence of neutral exciton recombination with increasing temperature, which is interpreted in terms of different dynamics of neutral and charged excitons. We have also detected the anticrossing of the nearly free trion lines with a pair of cyclotron replicas of an acceptor-bound trion line. The effect has been observed here in a 2D hole gas; it has not been earlier detected in an electron system. The coupling is interpreted as a resonant exciton exchange between free and bound trions assisted by the cyclotron hole excitation.

4. References

[1] Heiman D et al. 1998, Phys. Rev. Lett. **61**, 605; Goldberg B B et al. 1990, ibid. **65**, 641; Kheng K et al. 1993, ibid. **71**, 1752; Yusa G et al. 2001, ibid. **87**, 216402; Buhmann H et al. 1995, Phys. Rev. B **51**, 7969; Byszewski M et al. 2006, Nat. Phys. (London) **2**, 239.
[2] Esser A et al. 2000, Phys. Rev. B **59**, 8231.
[3] Bryja L et al. 2007, Phys. Rev. B **75**, 035308.
[4] Finkelstein G et al. 1996, Phys. Rev. B **53**, 12593; 1997 ibid. **56**, 10326; Dzyubenko A B, 2004 ibid. **69**, 115332.
[5] Yakovlev D et al. 1997, Phys. Rev. Lett. **79**, 3974.
[6] Cole B E et al. 1997, Phys. Rev. B **55**, 2503.
[7] Wójs A and Quinn J J 2007, Phys. Rev. B **75**, 085318; Wójs A, 2007 ibid. **76**, 085344.
Glasberg S et al. 1999, Phys. Rev. B **59**, R10425.

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