Vol. 116 (2009) ACTA PHYSICA POLONICA A No. 5

Proceedings of the XXXVIII International School and Conference on the Physics of Semiconductors "Jaszowiec" 2009

Combined Exciton–Cyclotron Resonance in Photoluminescence of a Two-Dimensional Hole Gas

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A two-dimensional hole gas in an asymmetric GaAs/$\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ quantum well is studied by polarization-resolved photoluminescence in high magnetic fields (up to $B = 20$ T) and at low temperatures (down to $T = 50$ mK). In addition to the previously reported dominant emission channels of various free and acceptor-bound trions, the high-energy hole cyclotron replicas of the bound states are now also observed, corresponding to the combined exciton–cyclotron resonance. Identification of different transitions in the rich, multi-peak spectra was possible by the analysis of optical selection rules and comparison of the experimental spectra with realistic numerical calculations.

PACS numbers: 73.20.Mf, 71.35.Ji, 71.35.Pq, 78.20.Ls

1. Introduction

The many-body quantum processes in two-dimensional (2D) gases composed of electrons or holes in strong magnetic fields can be observed as characteristic features in their optical spectra. Great variety of magneto-optical excitations have been studied in great detail over the last decade. Both negative and positive trions (also called charged excitons and consisting of either two electrons bound to a hole, or of two holes bound to an electron, respectively) have been observed in such systems [1, 2]. In photoluminescence (PL) spectra the shake-up process, in which radiative recombination of an electron–hole pair is accompanied by excitation of another carrier to a higher Landau level (LL), were also reported in both systems [3, 4]. They manifest themselves as a characteristic reduction of the transition energy by the cyclotron energy $E = \hbar\omega_{\mathrm{c}}$. A closely related phenomenon of a combined exciton–cyclotron resonance (ExCR) was also identified, but so far only in the electron systems. In this case an incident photon creates an exciton and simultaneously promotes one electron to a higher LL [5], leading to an *increase* of the transition energy by a quantum of cyclotron energy.

In this article we report on the first observation of a combined exciton–cyclotron resonance in a two-dimensional hole system. In contrast to the earlier observation reported in Ref. [5], we detect ExCR in the PL spectra, in form of a hole cyclotron replica of the emission line of an acceptor-bound positive trion, AX^+CR. In low magnetic fields, AX^+CR is observed below the neutral and positively charged exciton lines. With an increase of the magnetic field the line shifts toward higher energies, consecutively crossing all exciton lines, and in the highest magnetic fields it becomes the highest energy line in the PL spectrum.

2. Experimental results and discussion

The studied sample was an asymmetric $w = 22$ nm wide GaAs/GaAlAs quantum well (QW). The structure was fabricated by molecular beam epitaxy, and the two-dimensional hole gas was obtained by carbon δ-doping in one of the barriers of the well. The sample was of a very good quality, with the low-temperature 2D hole concentration (in the dark) $p = 1.92 \times 10^{11}$ cm^{-2} and mobility of $\mu = 1.71 \times 10^5$ cm^2/(V s). The optical emission was excited above the barrier by the $\lambda = 514$ nm line of an ion argon laser. By increasing laser excitation power density we were able to decrease slightly the 2D hole concentration. The actual concentration was determined from the parallel transport measurements in van der Pauw configuration. The PL measurements were carried out at low temperatures (from $T = 1.8$ K down to 50 mK) and in high magnetic fields (up to $B = 20$ T) applied perpendicular to the structure. The fiber glass optics was applied. Experiments were performed in the Faraday configuration, with a linear polarizer and wave quarter placed in the liquid helium close to the sample. To switch between the σ^- and σ^+ polarizations, the direction of magnetic field was changed.

In Fig. 1 evolution of the PL spectrum of the studied sample in σ^- polarisation is presented. In the absence of magnetic field, a single fairly broad line is observed independently of the laser power density. This is opposite to our previous studies of symmetric 15 nm wide QW with

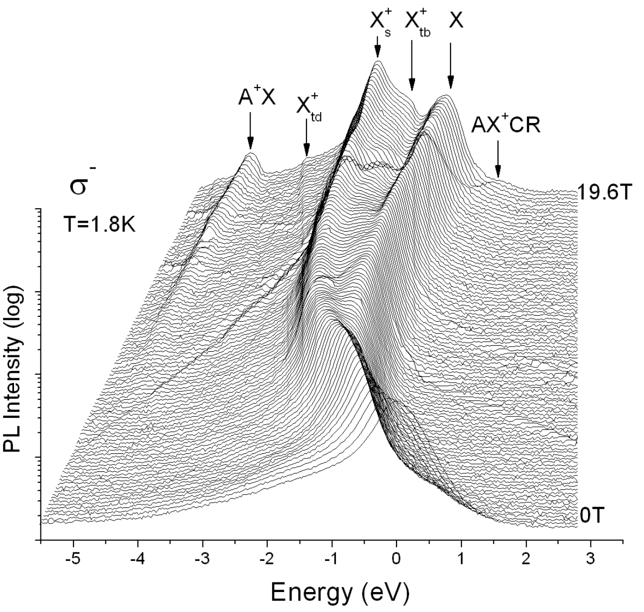

Fig. 1. Evolution of the photoluminescence spectrum of an asymmetric 22 nm wide quantum well as a function of magnetic field, in σ^- polarisation.

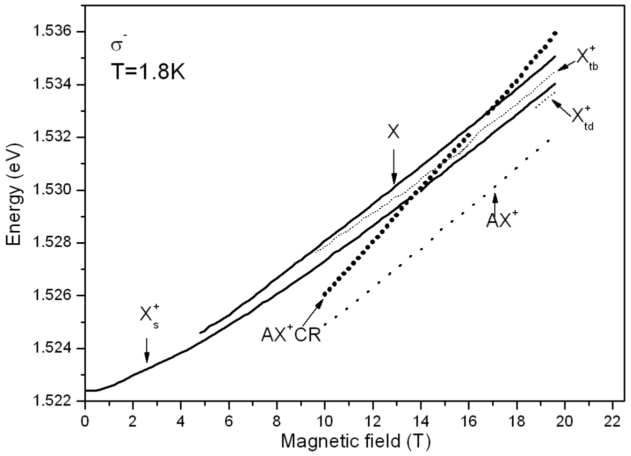

Fig. 2. Fan chart of all observed lines in photoluminescence spectra of an asymmetric 22 nm wide quantum well in σ^- polarisation.

similar 2D hole concentration, where a pair of lines assigned to the neutral and charged exciton were detected at zero field. Their relative intensities in the symmetric QW were changed by tuning the excitation power (up to reversed order). Under low excitation only the trion was observed, whereas at higher excitations only the neutral exciton was detected. For the asymmetric QW we were not able to distinguish between the neutral and charged exciton, because the Coulomb binding energy of an additional hole is decreased due to the separation of the photoexcited electrons from the hole gas, induced by the strong electric field caused inside the structure by one-sided doping. When the magnetic field is applied, the PL spectra gradually become rich and complicated. From the detailed analysis of the evolution of PL spectra and the comparison of experimental data of the Coulomb binding energies of the trion with realistic numerical calculations, we were able to identify all of the observed lines (for more detailed explanation see Refs. [4, 6]). In the highest magnetic fields when the most lines are observed, going in the order from the highest to the lowest energy, we detect the exciton X, "bright triplet" trion $\mathrm{X}_{\mathrm{tb}}^{+}$, singlet trion $\mathrm{X}_{\mathrm{s}}^{+}$ and finally "dark triplet" trion $\mathrm{X}_{\mathrm{td}}^{+}$.

The most intriguing line emerges in the PL spectra only at sufficiently high fields ($B \geq 5$ T, see also Fig. 2), initially below the singlet trion. When the field is increased, the line shifts linearly to higher energies (in contrast to the "shake-up" line [3, 4]). In high fields, it crosses all trions and the exciton lines. Its intensity decreases at lower temperatures (from $T = 4.2$ K down to 50 mK in our experiment) and increases with increase of excitation power. Aided with the exact diagonalization calculations of the binding energies, we attribute this transition to the combined exciton–cyclotron resonance (hole cyclotron replica of an acceptor-bound positive trion, AX$^+$CR). A similar effect was previously observed in pseudo-absorption experiments in PL excitation and reflectivity of a low-density electron gas in II–VI compound two dimensional quantum wells [5]. We also observe the same lines in PL spectra in σ^+ polarisation including combined exciton–cyclotron resonance but with much lower intensity in high magnetic fields.

Acknowledgments

Work supported by grants RITA-CT-2003-505474 from EC and by grant N202-071-32/1513 from Polish MNiSW.

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