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The observation of exciton-cyclotron resonance in photoluminescence spectra of a two dimensional hole gas

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The detailed studies of two-dimensional hole gas in an asymmetric 22 nm wide GaAs/$Ga_{1-x}Al_xAs$ quantum well in polarization-resolved photoluminescence in high magnetic fields (up to B = 20 T) and at low temperatures (down to T= 50 mK) are reported. Additionally to the previously detected in symmetric quantum wells 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 a the exciton-cyclotron resonance. The identification of transitions in the reach spectra was performed by the analysis of optical selection rules and comparison of the experimental spectra with numerical calculations of the real structure.

1. Introduction

The optical experiments are the powerful tool for the study of many body quantum processes in two dimensional (2D) gases composed of electrons or holes in strong magnetic fields [1]. The varieties of magneto-optical excitations have been studied in great detail over last decades. The negatively and positively charged excitons (also called and trions consisting of either two electrons bound to a hole, or of two holes bound to an electron, respectively) have been detected in optical spectra in such systems [2,3]. 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 [4,5]. They are observed as a characteristic reduction of the transition energy by the cyclotron energy $E = \hbar\,\omega_c$. An opposite process with increase of transition energy called combined exciton-cyclotron resonance (ExCR) was also indentified, but only in the electron systems in II- VI compounds semiconductors structures [6]. The observation of such a process in two dimensional hole systems in III- V compounds semiconductors structures with lower exciton binding energy was a challenging task.

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. 6, we detect resonance in the PL spectra, as a hole cyclotron replica of the emission line of an acceptor-bound positive trion, AX^+CR. The line exhibit an intriguing feature. 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 investigated sample was an asymmetric $w = 22$ nm wide GaAs/GaAlAs quantum well (QW). The structure was elaborated by molecular beam epitaxy. 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 (measured in the dark) $p = 1.92\times10^{11}\,\mathrm{cm}^{-2}$ and mobility of $\mu = 1.71\times10^{5}\mathrm{cm}^{2}/\mathrm{Vs}$. The optical emission was excited above the barrier by the $\lambda = 514$ nm line of an ion Argon laser. Increasing laser excitation power density slightly decrease the 2D hole concentration. The actual concentration was determined from the parallel transport measurements in van der Pauw configuration. The photoluminescence 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 fibber 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. The switch between the σ^- and σ^+ polarizations was realized by invert of the direction of magnetic field.

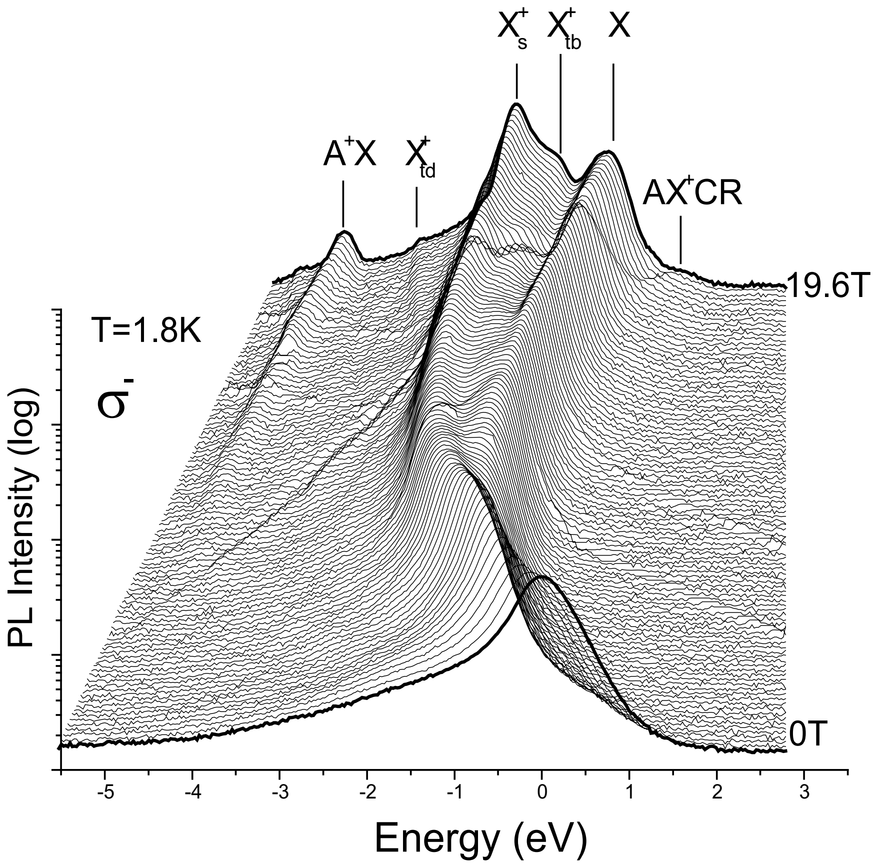

Fig. 1. Evolution of the photoluminescence spectrum in σ^- polarisation.

The evolution of the PL spectrum of the studied sample in σ^- polarisation is presented in Fig.1. In the absence of magnetic field, a single fairly broad line is observed independently of the laser power density. This is strongly different to our previous studies of symmetric 15 nm wide QW with similar 2D hole concentration, where a pair of lines: the neutral and charged exciton were detected at zero field. Their relative intensities were changed by tuning the excitation power density (up to reversed order). At low excitation only the trion was observed, whereas under 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 photo-excited electrons from the hole gas, induced by the strong electric field caused inside the structure by one-sided doping. Under application of the magnetic field the photoluminescence spectra gradually become very rich and complicated. The detailed analysis of the evolution of PL spectra and the comparison of experimental data of Coulomb binding energies of the trion with realistic numerical calculations enable us to identify most of the observed lines (for more detailed explanations see Refs. [5,7]). 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 X^+_{tb}, singlet trion X^+_S and finally “dark triplet” trion X^+_{td}.

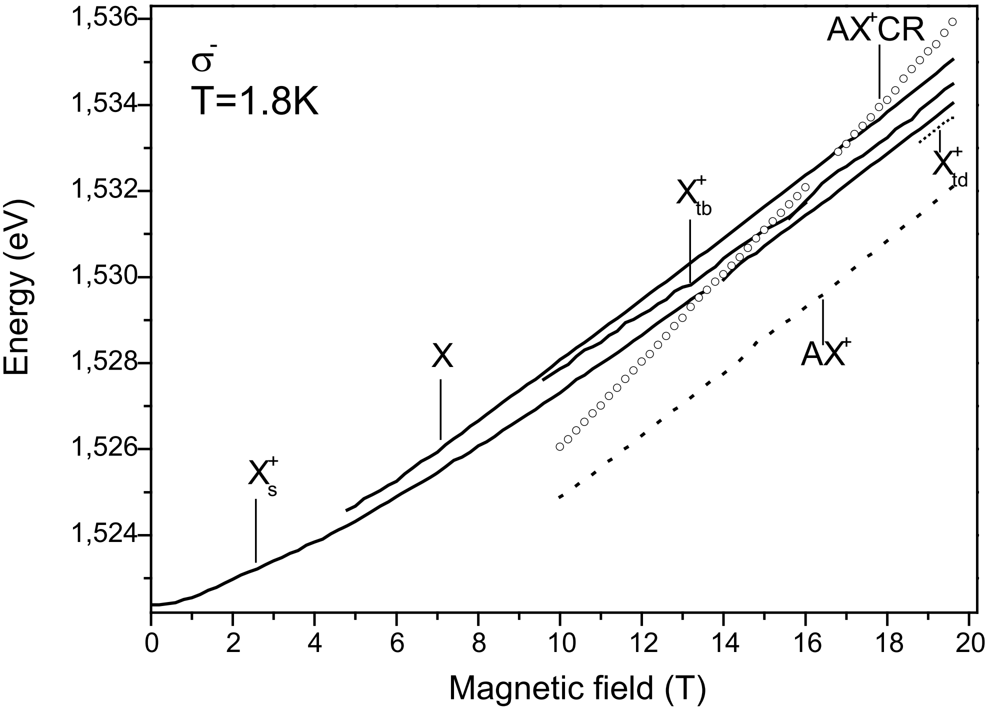

Fig.2. Fan chart of all observed lines in photoluminescence spectra in σ^- polarisation.

The most intriguing line emerges in the PL spectra at sufficiently high fields (B ≥ 5 T, see also Fig. 2), initially below the singlet trion. With increasing of the field the line shifts linearly to higher energies (in contrast to the “shake-up” line [4,5]) consecutively crossing 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 density. Under the detailed analysis and 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). Details of numerical calculations are described in Ref. [5,7].

In conclusion, in polarisation resolved magneto-photoluminescence spectra of two dimensional hole gas we observed exciton cyclotron resonance as a cyclotron replica of trion bound on acceptor line (AX^+CR). Following the work of Moskalenko et al [8] we interpret this effect as a dipole- active transition. From the slop of energy position of AX^+CR as a function of magnetic field we found a 2D hole effective mass equal to 0.31 m_e.

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