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Renormalization of effective mass in self-assembled quantum dots due to electron-electron interactions

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Abstract. Magnetic-field dispersion of the multiexcitons related to the p shell of a single quantum dot (QD) is analysed in this work. The reduced cyclotron effective mass of carriers is determined from the energy splitting between the p_+- and p_-- related multiexcitonic emission lines. The reduced mass in the occupied QD was found to be larger than the mass related to the QD's single particle structure. The apparent increase of the reduced mass with increasing excitonic occupation of the dot is related to the mass renoralization due to electron-electron interactions within a multiexcitonic droplet.

1. Introduction

Semiconductor self-assembled quantum dots (QDs) have been intensely studied for almost 20 years. This interest is triggered by both scientific curiosity and possible applications [1]. The confinement of carriers within a space of the size comparable to their de Broglie wavelength allows to study electronic properties of strongly interacting carriers. Important for theoretical description of QDs properties is their single-particle (SP) energy structure. It has been shown that the structure can be well described using the harmonic lateral confinement potential [2], with characteristic confinement energy and effective mass of carriers. One of the approaches to determine the reduced effective mass $\mu^*_\pm$ of an electron-hole pair confined to a dot relies on the magnetic field-induced energy splitting between the resonances related to the p_+ and p_- subshells of a dot [3, 4, 5, 6]. In this communication we report on determination of the reduced mass using the single-dot optical magnetospectroscopy. We compare the result to the reduced mass μ^*, which characterizes the SP structure of the dot and we discuss the effect of electron-electron interactions on the reduced cyclotron mass in a highly occupied QD.

2. Experimental procedure

The structure investigated in this work comprised InAs/GaAs QDs grown using molecular beam epitaxy with application of the In-flush procedure [7]. The sample contains a single layer of dots, grown on a 600 nm undoped GaAs buffer layer, In-flushed at 5 nm and capped with a 100 nm GaAs layer [8]. Dots in the as-grown structure were found to be flat disks of 3.5 nm height and approx. 10 nm radius. This morphology results in vertical confinement significantly larger than the lateral confinement, which allows to assume the investigated dots to be two-dimensional. The structure was annealed after growth (30 s at 850 °C) in order to shift the emission energy into the sensitivity range of a CCD camera [9]. The sample was placed on top of piezo-driven attocube positioners and kept in gaseous helium at T=4.2 K [10]. A confocal microscope with a Y-shaped single mode fiber assembly was used in the measurements. Excitation was provided by laser light (λ=647 nm) coupled to one branch of the fiber and transmitted to the microscope located directly above the sample. The photoluminescence (PL) was collected by the microscope objective and extracted from the other branch of the fiber, dispersed by a 0.5 m monochromator, and detected by a liquid nitrogen-cooled CCD camera. The sample was placed inside a resistive magnet at National Laboratory of High Magnetic Fields in Grenoble, France. Magnetic field in Faraday configuration up to 19T was applied during measurements.

3. Experimental results

The PL spectra of a single QD excited with increasing laser-power density measured at zero magnetic field are shown in Fig.1. The weakly excited PL spectrum consists of two emission lines attributed to a neutral exciton (X) and a trion (X^*). Both: X and X^* excitonic emission lines are often observed in non-resonantly excited spectra of QDs, which charge state fluctuates during the spectrum collection. The double-line pattern is characteristic for the investigated structure [8] and the charge state attribution of the observed lines is based on results of polarization-sensitive measurements of the sample. Weak features accompanying main lines are due to respective biexcitons.

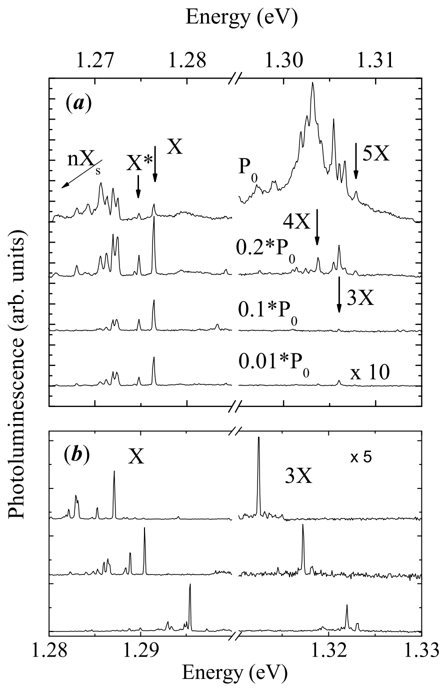

Figure 1. (a) Photoluminescence from a single InAs/GaAs QD at $B = 0T$ as a function of excitation power. The estimated excitation power density $P_0 \approx 70W/cm^2$.(b) Emission spectra from several weakly excited single dots in the investigated structure.

Excitation of the dot with higher power density results in the increase of the X and X^* lines intensities and in the appearance of additional emission lines. In particular an emission line $3X$

related to the higher lying SP level (p-shell) can be observed at the energy approximately 30 meV higher than the s-shell emission energy. Additional spectroscopic measurements confirmed the $3X$ attribution to the neutral charge state of a QD. This allows us to relate the $3X$ line to a complex of three excitons (triexciton) in the QD. Two carriers of each sign (electron and hole) occupy the lowest s-shell of a dot in such a complex. The third carrier of each sign occupies the p-shell because of the Pauli exclusion limiting the occupation of a particular SP level to two carriers of anti-parallel spins. The $3X$ emission line is related to the transition which leaves the dot in the ground state of a biexcitonic complex. The triexciton can also recombine to an excited state of a biexciton, which results in an additional emission line in the lowest energy region (s-shell) [11]. The occupation of the dot with more excitons further complicates the observed spectral pattern. The $4X$ ($5X$) emission line which emerges with increasing excitation power is attributed to recombination of four (five) excitonic complexes. The recombination leaves the dot in the ground state of a three (four) excitonic droplet. Both multiexcitonic configurations can also recombine leaving the $N-1$ excitonic complex in an excited state, therefore the number of possible transitions increases significantly with the number of confined excitons. This results in significant broadening of the observed emission spectra.

The magnetic field evolution of the PL from a highly excited dot can be analyzed in order to determine the reduced effective mass of an electron-hole pair $\mu^*_\pm$ [3, 4, 5, 6]. The single-dot-resolved optical experiments uncover also another feature of the evolution [12, 13], which is the zero-field splitting of the $3X$ and $5X$ (see Fig. 2(a)). The evolution of the PL emission from the investigated dot is shown in Fig.2(a). The $3X-$ and $5X-$ related emission lines are denoted with open symbols for more clarity. The $3X$ ($5X$) emission line follows the p_- (p_+) shell structure of SP energy levels of a charge carrier confined in a harmonic lateral potential (referred to as the Fock-Darwin (FD) spectrum[14, 15]) except for the lowest magnetic fields. The low-field deviation is due to the scattering of the electron-hole pair between the equivalent SP p-shell configrations of a three (five) exciton complex [16]. The energy separation between the $3X$ and $5X$ emission lines 2 (b) in the intermediate magnetic field was fitted with a linear dependence: $\Delta E_\pm = \alpha + (\hbar eB/\mu^*_\pm)$ with the result of the fitting shown with a continuous line in Fig.2 (b). The resulted reduced effective mass is equal to $\mu^*_\pm = 0.061 \pm 0.0005 m_0$.

The obtained cyclotron mass $\mu^*_\pm$ can be compared to the reduced effective mass μ^*, which characterises the SP energy level structure of the dot. The latter reduced mass can be found from the analysis of the magnetic-field dispersion of the X and $3X$ emission lines in a broad magnetic field range [17]. The magnetic-field (Faraday configuration) evolution of the PL spectrum with those lines is shown in Fig.3 in the form of a surface plot. The spin Zeeman splitting of emission lines can be identified at highest magnetic fields. The splitting is a nonlinear function of magnetic field, which is characteristic for the investigated type of dots [8, 18]. Both X and $3X$ field-dispersions are analysed in within the approximation of equal spatial extents of electron and hole wavefunctions. As a result of the fitting procedure the reduced effective mass μ^* was determined to be equal to $\mu^* = 0.053 m_0$, which is lower than the cyclotron reduced effective mass $\mu^*_\pm$. The reduced effective mass well corresponds to the mass obtained from **kp** calculations for a similar structure [5]. If the usually observed in III-V materials 2:1 conduction band-valence band offset is assumed, the effective electron (hole) mass equals then to $m_e = 0.080 m_0$ ($m_h = 0.16 m_0$). The X and $3X$ dispersions fitted with the reduced mass μ^* are shown in Fig. 3 with dotted lines.

The apparent difference between the cyclotron reduced effective mass $\mu^*_\pm$ and the "SP-structure" reduced effective mass of the QD μ^* results in our opinion from the effect of magnetic field on electron-hole interactions within a multiexcitonic droplet. The effect coresponds to the previously observed effective mass renormalization due to many-body interactions in two-dimensional electron-hole systems systems [19, 20]. The renormalization of the reduced effective mass makes the system different from a dot occupied with electrons. If only electrons are present in the dot, the optical spectra are insensitive to the electron number and to details of electron-

electron interactions [21]. This results from the coupling of electromagnetic radiation to the center-of mass degrees of freedom only [22]. Moreover if the QD confinement is well approximated by a parabolic potential, the center-of-mass and relative motion separate due to the generalized Kohn's theorem and the intraband absorption spectra are those of a single particle [23].

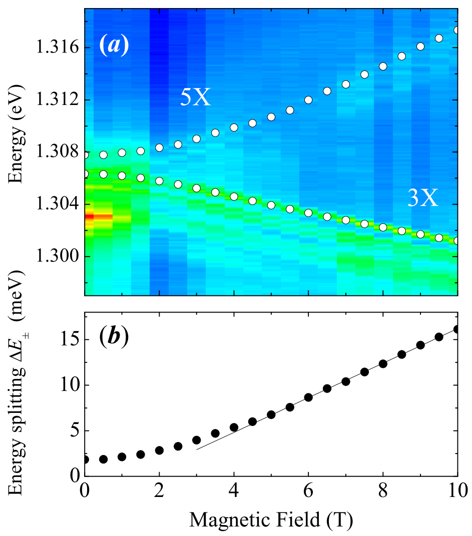

Figure 2. (color online) (*a*) Photoluminescence of a highly excited single dot with energies of the $3X$ and $5X$ emission lines denoted with open points. (*b*) The energy difference between the $3X$ and $5X$ emission (points) and the fit to the dependence (line).

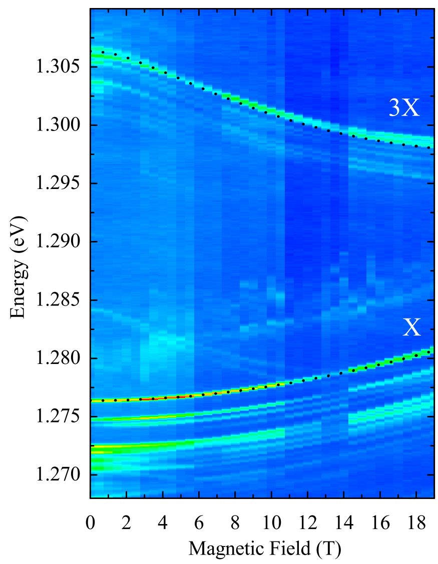

Figure 3. (color online) The evolution of the emission spectrum from a single InAs/GaAs quantum dot in perpendicular magnetic field. Simulations of the X and $3X$ emission lines obtained with parameters described in the text are denoted with dotted lines.

4. Summary

In conclusion, we have investigated the s- and p-shell related emission from a single InAs/GaAs QD in magnetic fields. We have shown that the cyclotron reduced effective mass $\mu^*_\pm$ obtained from the analysis of the dot occupied with at least five excitons is higher than the reduced mass μ^* resulting from the SP structure of the dot. We relate the difference to the effect of magnetic field on the Coulomb interactions within a dot.

Acknowledgments

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