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Optical spectroscopy of a single InAs/GaAs quantum dot in high magnetic fields

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Abstract

We report on the measurements of the photoluminescence from the *s*-shell of a single InAs/GaAs quantum dot in magnetic fields up to 23 T. The observed multiline emission is attributed to different charge states of a single dot. Characteristic anticrossing of emission lines is explained in terms of hybridization of final states of a triply charged exciton (X^{-3}).

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Optical control and manipulation of spatially confined carriers in self-assembled quantum dots (QDs) requires developing our understanding of highly charged exciton complexes [1]. In particular, an unusual pattern caused by resonant configuration mixing in emission from a triply charged exciton in dots with at least three confined shells (*s*-, *p*- and *d*-) has been predicted [1]. A similar effect has been observed in emission from spin-polarized 2DEG at filling factor $\nu = 3$ [2] and in quantum dots where the continues states in the wetting layer play the role of the *d*-shell [3,4].

In this communication we present experimental results which can be explained in terms of the anomalies in the triply charged exciton emission spectrum.

The sample investigated in this work was grown by molecular beam epitaxy using In-flush technique [5]. It contains a single layer of InAs QDs In-flushed at 5 nm, grown on n^+GaAs substrate, 800 nm GaAs buffer layer and covered with 100 nm GaAs top layer. The structure was annealed after growth (30 s at 850 °C) to shift the emission from QDs within the sensitivity range of a CCD camera. A set of mesa structures were prepared on the sample in order to limit the number of dots addressed optically. The sample was placed on Attocube nano-positioners and immersed in liquid helium ($T = 4.2$ K) within the tail of a cryostat, which was installed in the bore of a Bitter magnet in the Grenoble high magnetic field laboratory [6]. The Ar^+ laser ($\lambda = 514.5$ nm–referred to as the green illumination) and Ti-sapphire tunable laser ($\lambda = 724$ nm–referred to as the red illumination) were used for the excitation. Laser light was coupled to a single-mode fiber, delivered to the sample and focussed by two aspheric microlenses. The obtained spot was of the order of 10 μm, which assured excitation of a single mesa. The photoluminescence was collected by a multimode fiber (600 μm). The relative position of the sample with respect to the optical setup was controlled by the nano positioners. Their independent movement allowed for the precise adjustment of a focus and a spatial position of the sample. The photoluminescence was transmitted to a 1 m double-grating monochromator and detected by a liquid nitrogen-cooled CCD camera.

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Power dependence of the spectrum excited with the green light at zero-magnetic field is shown in Fig. 1. At the lowest excitation power the spectrum is dominated by a single line denoted with X1. With increasing power the intensity of the X1 line increases and a new line X2 emerges at lower energy. The X2 line becomes the main feature of the spectrum at moderate excitation power density. Further increase of excitation power results in additional lines, which appear approx. 30 meV above the X1 and X2 (not shown in Fig. 1) , as well as additional weak lines within 8 meV below X1 and X2. At even higher excitation power the line X3 emerges below the X2 emission line.

At the lowest power density of the red-light excitation only the X3 line can be observed. At higher intensities additionally the X2 line as well as two weak features emerge at lower energy. Surprisingly neither the X1 line nor weak satellites of the X1 line can be seen in the red-light excited spectra (comparison of the spectra obtained with the green- and red-light excitation spectrum is shown in Fig. 2).

The weakest excitation with the red light results in the X3 emission line, whereas the weakest excitation with the green light results in the X1 emission line. Therefore, the X3 line cannot be identified as multiexcitonic emission line related to the X1. The X2 line emerges with increasing power in both excitation modes. If it were a biexcitonic emission line, it would appear either in one (as a biexciton with the X1 final state) or the other spectrum (as a biexciton with the X3 final state). Its presence in both spectra must be due to its configuration, different from those of X1 and X3. The nearly linear power dependence of all three lines suggests their attribution to single excitons.

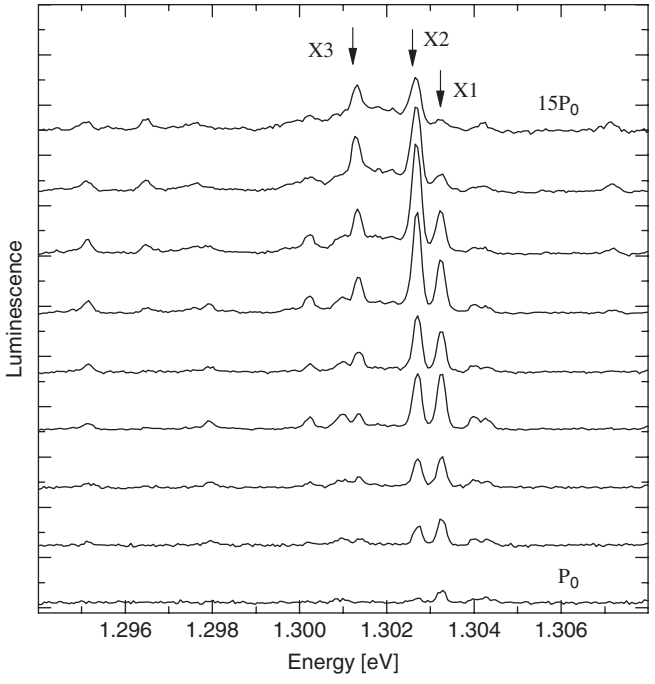

Fig. 1. Power dependence of the spectrum obtained with $\lambda = 514.5$ nm excitation at $T = 4.2$ K.

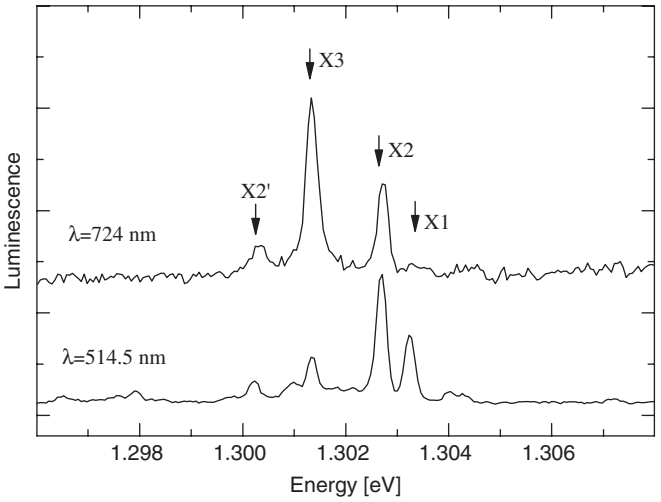

Fig. 2. The spectra obtained with $\lambda = 724$ and $\lambda = 514.5$ nm excitation in magnetic field $B = 0$.

The absence (presence) of particular excitonic features in both spectra shown in Fig. 2 allows us to relate them to different charge states of a single QD. The subsequent appearance of the X1, X2, X3 lines (green-light excitation) and the X3 and X2 lines (the red-light excitation) suggests their attribution to charge states with the excess carrier occupation changing by one.

As the QDs are grown on the n^+-doped substrate, it is reasonable to propose that the X1, X2 and X3 lines are due to the recombination of different multicharged excitons: X^{-n}, $X^{-(n+1)}$, $X^{-(n+2)}$. Simultaneous observation of all three lines suggests that the number of excess electrons in the dot considerably fluctuates within the timescale of experiment (usually 120 s). Similar effect has been observed previously [7,8]. The attribution of the X*i* lines to the actual number of excess electrons can be done using the results of measurements in magnetic field. The spectra obtained with both excitation modes were investigated in magnetic field perpendicular to the sample surface (Faraday configuration).

The *s*-shell related spectra collected with the green-light excitation in magnetic field up to 2 T are presented in Fig. 3. No significant shift of the X1 and X2 emission lines can be observed in magnetic field up to 2 T (the parabolic dependence of the X1 and X2 emission lines on magnetic field, which results from their diamagnetic shift can be appreciated in higher fields). Such behavior is characteristic for a neutral exciton X_0, as well as for the singly and doubly charged excitons X^{-1}, X^{-2} [9].

On the contrary, a clear anticrossing in energy region of the X3 line can be observed around 1 T. The anticrossing is similar to previously observed for the triply charged exciton X^{-3}. No effect of anticrossing can be expected for excitons in a dot with less than three excess electrons [3]. The attribution of the X3 line to the triply charged exciton X^{-3} also points out to the X1 and X2 features as emission lines due to recombination of a singly charged exciton X^{-1} and a doubly charged exciton X^{-2},