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Charged magneto-exciton states in semiconductor quantum dots

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Abstract

By embedding a layer of self-assembled quantum dots into a field-effect structure, we are able to control the exciton charge in a single dot. We present the results of photoluminescence experiments as a function of both charge and magnetic field. The results demonstrate a hierarchy of energy scales determined by quantization, the direct Coulomb interaction, the electron–electron exchange interaction, and the electron–hole exchange interaction. For excitons up to the triply charged exciton, the behavior can be understood from a model assuming discrete levels within the quantum dot. For the triply charged exciton, this is no longer the case. In a magnetic field, we discover a coherent interaction with the continuum states, the Landau levels associated with the wetting layer.

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A self-assembled quantum dot has electronic levels separated by tens of meV as a result of the electronic quantization on a nanometer length scale [1]. The Coulomb energy between two electrons in such a quantum dot is also large, typically around 20 meV [1]. As a result, a self-assembled quantum dot exhibits a very pronounced Coulomb blockade [1]. This has been demonstrated even on an ensemble of self-assembled quantum dots as the inhomogeneous broadening can be sufficiently small that the Coulomb blockade is not smeared out [1,2]. In addition to the electronic Coulomb blockade, we have observed an excitonic Coulomb blockade by

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measuring the photoluminescence (PL) from a single self-assembled quantum dot in a vertical tunneling structure [3]. At one voltage, the emission is completely dominated by one excitonic charge, with abrupt shifts in PL energy at special values of the voltage as the exciton charge changes by one quantum unit. We have recently extended these experiments to resonant excitation, detecting exciton formation in the transmission coefficient [4,5]. We present here a summary of the properties of charged excitons in a single self-assembled quantum dot.

The quantum dots for these experiments are produced by MBE in the Stranski–Krastanow growth mode of InAs on GaAs, increasing the ground state PL energy from 1.05 eV to about 1.3 eV with an annealing step during the overgrowth [6]. The dots are incorporated into a vertical tunneling structure; a back contact is connected to earth and the electric potential of the dots is changed via a voltage applied to a Schottky barrier on the surface. Details of the exact heterostructure can be found elsewhere [3,7]. Optical experiments are performed on a processed piece of wafer material using fiber-based confocal microscopes with the sample at 4.2 K. A magnetic field can be applied perpendicular to the quantum dot layer.

Fig. 1 shows the PL from a single quantum dot as a function of gate voltage, V_g, representing the PL intensity with a color scale. The exciton responsible for each emission line is marked. X^0 is the neutral exciton, X^{1-} the singly charged exciton, and so on. There is a large red-shift of the PL when the X exciton is transformed into X^{1-}. The origin of this is the Coulomb energy: the presence of the additional electron in the X^{1-} complex increases the renormalization of the emission energy. The ultimate origin of the red-shift is the smaller spatial extent of the hole wave function relative to the electron wave function [8]. While the red-shift of the ground state excitons in the PL is typically about 4 meV, the shifts of the excited state excitons can be much larger, ~20 meV, as in this case, the cancellation between the electron–electron and electron–hole interactions is less complete [7].

The X^{1-} extends over a larger region of voltage than the X^0 as a result of shell filling which is very

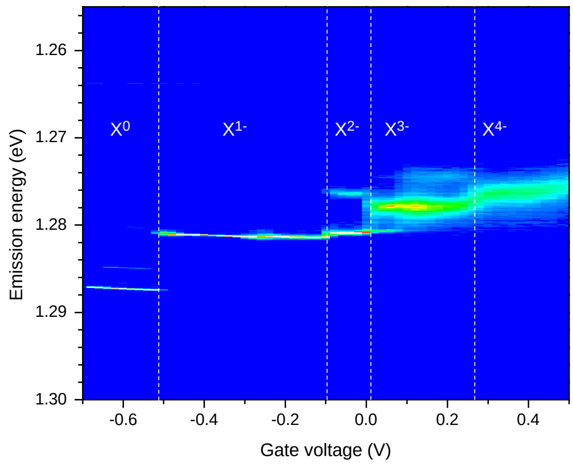

Fig. 1. Photoluminescence (PL) from a single quantum dot in a vertical tunneling structure as a function of voltage applied to the Schottky barrier on the sample surface. The PL intensity is represented with a color scale, with blue representing zero signal, with the signal rising as the color changes from green to yellow to red. The sample temperature was 4.2 K. The exciton state is labelled: X^0 denotes the neutral exciton, X^{1-} the singly charged exciton, and so on. The wetting layer loads with electrons around 0 V as revealed by the capacitance–voltage trace of the sample (not shown).

pronounced in self-assembled quantum dots. To form the X^{2-} electronic excited state, the p shell, must be occupied. As shown in Fig. 1, the X^{2-} is red-shifted with respect to the X^{1-}, again as a consequence of the Coulomb renormalization to the exciton energy, but in addition, the X^{2-} has a satellite at lower energy, as shown also in the PL spectrum in Fig. 2. The origin of the splitting is electron–electron exchange. After photon emission from the initial state with electron spin $S=\frac{1}{2}$, there are two possible final states, a triplet with $S=1$ and a singlet with $S=0$. These two states are split by $2X_{sp}$ where X_{sp} is the exchange energy between an s and a p electron, in complete analogy to the excited states of the He atom. The configuration diagrams for these states are shown in Fig. 3. The splitting for the dot in Fig. 2 is 4.2 meV, implying an exchange energy of $X_{sp}=$ 2.1 meV. A noticeable feature is that emission into the triplet is sharp with a line width below the resolution limit of our detection system (80 μeV), but the emission into the triplet is broad with a linewidth of typically 0.6 meV [3]. In both cases,