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Statistics of quantum dot exciton fine structure splittings and their polarization orientations

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Abstract

The fine structure splitting of neutral excitons in InGaAs quantum dots is investigated using polarization sensitive photoluminescence. The QDs were grown with an in situ annealing step to shift the emission wavelength to ~950 nm. Statistics of the fine structure reveal a large spread in magnitude and little preferential orientation of the polarization axis. We speculate that these findings are due to the redistribution of QD material during the annealing step.

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Keywords: Quantum dots; Fine structure; Isotropic dipole orientation

Self-assembled semiconductor QDs can be considered as artificial atoms. In contrast to real atoms QDs have the advantage of being embedded in a host material so that no intricate traps are needed to study a single one. However, the solid-state host material can also introduce deviations from perfect symmetry. The lack of symmetry in the QD lifts the natural degeneracy of the ground state, creating the fine structure splitting (FSS). Elimination of the FSS allows for the generation of entangled photon pairs from the bi-exciton to exciton to vacuum state cascade [1,2]. Therefore, a detailed characterization of the FSS is essential. We present FSS measurements performed on 161 single QDs grown using the partially capped island (PCI) method [3]. In our sample, the InAs island was covered by 1 nm of GaAs and then annealed for 30 s at the QD growth temperature of 530 °C before complete QD capping. The annealing step is performed in order to shift the center of the QD photoluminescence emission wavelength to ~950 nm and causes an anisotropic redistribution of the island material and In–Ga inter-diffusion. The resulting structure has an In-rich center thinner than at the edges and is elongated along the [1 1 0] direction, as known from STM studies on cleaved samples grown by the same technique [4].

In order to investigate the FSSs of the described QDs and to see if the FSS is aligned along the [1 1 0] direction, PL spectra of single QDs are recorded and analyzed with a linear polarizer rotated in steps of 10° from 0° to 600°. The individual spectra are fitted by Lorentzians as shown in Fig. 1(a) and the center positions of these fits (as function of polarization angle) are fitted by a sinusoid to obtain the magnitude and the polarization of the FSS, as shown in Fig. 1(b). This allows us to determine the FSS with an accuracy of $\leqslant 5\,\mu$eV [5]. Hence the polarization-resolved PL allows us to study the magnitude and orientation of the FSS with high precision, also the FSS for most QDs is much smaller than the spectral resolution of the setup (45 μeV).

The experiment is performed on a sample with a high QD density, so that spectra of 10–20 QDs are recorded

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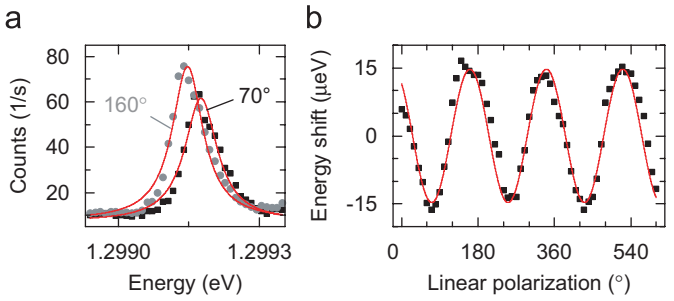

Fig. 1. Two PL spectra of the same QD recorded for linear polarizations of 70° and 160° relative to the [1 1 0] direction of the GaAs substrate are fitted by Lorentzians and shown in (a). The relative shift of the center energy of the emitted PL as a function of the linear polarization orientation is shown in (b). The data points are obtained from the fits and the line shows a sinusoidal fit, corresponding to an FSS of 29 μeV.

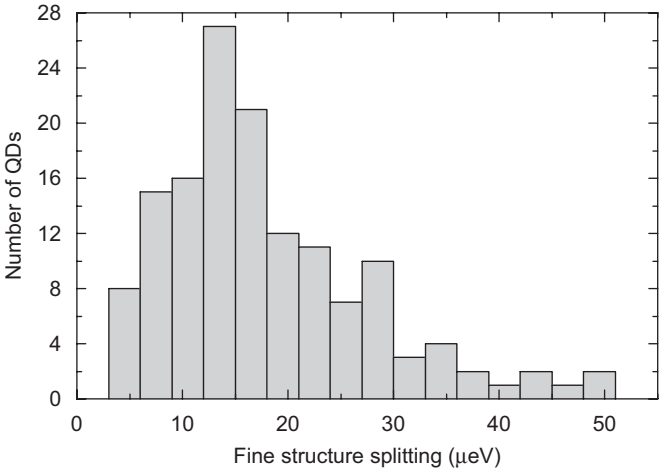

Fig. 2. Histogram of the FSS of the 142 QDs showing oscillations in PL energy as function of the polarization angle.

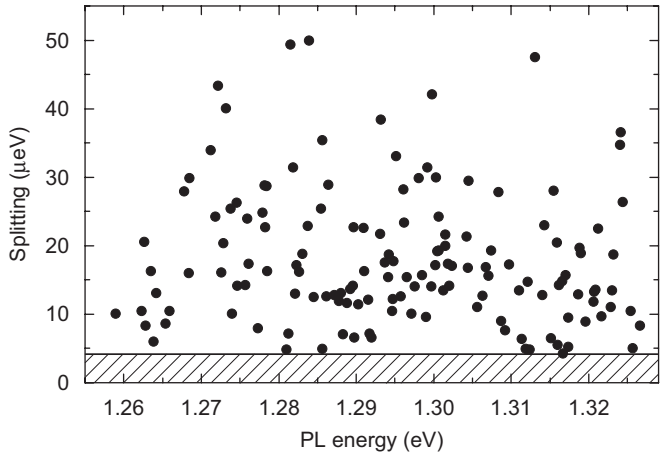

Fig. 3. The fine structure splitting of 142 QDs is plotted as function of their emission energy. The splitting shows no energy dependence. The hatched area is not accessible by the system's resolution and the FSS of 19 further QDs is not resolved.

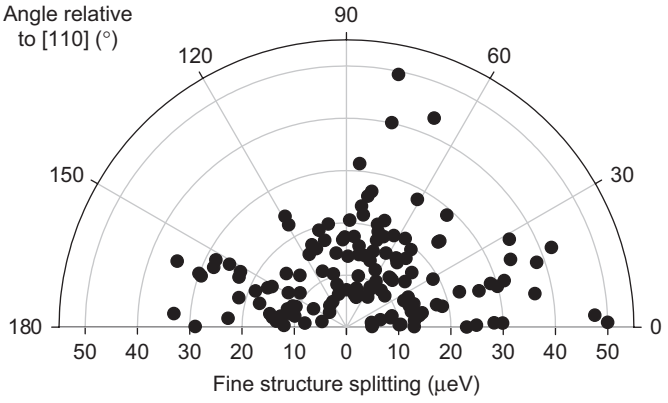

Fig. 4. The polar plot shows the direction of the linear polarized emission with the lower energy relative to the [1 1 0] direction of the GaAs. The sample shows no alignment of the QDs fine structure splitting.

simultaneously in a spectral window of ~10 meV. Nineteen of the 161 investigated QDs do not show energy oscillations, which means the FSS is too small to resolve with the applied technique. That the QDs are charged can be excluded as the dots are embedded in a charge tunable device [6,7].

The magnitude of the observed FSS varies between 4.2 and 50.0 μeV and the distribution is shown as a histogram in Fig. 2. The FSS mean value is 18 μeV and the distribution has a standard deviation of 9.7 μeV. The maximum of the distribution is around 14 μeV.

In Fig. 3 the FSS is plotted as function of the emission energy. No emission energy dependence can be seen. This is in contrast to other publications where a reduction of the FSS is observed with increasing PL energy [8,9]. They further report an alignment of the FSS polarization along the crystal axis.

Fig. 4 shows the splitting as a function of the dipole direction in a polar plot. The angle is measured between the lower energy linear polarization and the [1 1 0] direction. The uncertainty of the angle is less than 3°. Very little dipole alignment is observed. For QDs with a large FSS there is a trend for alignment along [1 1 0]. All QDs with a splitting larger than 30 μeV are either in the angle range 60°–90° or −30° (corresponds to 150°) to 30°. Random dipole directions have been observed in QDs based on II–VI materials [10–12].

We therefore conclude that QDs grown in the PCI-mode with an FSS below 30 μeV do not show a dipole alignment. In addition, a large variation in the FSS, which is independent of emission wavelength, exists for these QDs. Hence, there is always the availability of a QD with small FSS and suitable orientation to choose for active manipulation [13–16] to restore the symmetry of the QD.

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