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 \( \sim 950 \) 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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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 \( \sim 950 \) 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 \( \leq 5 \) µeV [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...
simultaneously in a spectral window of $\sim 10 \text{ meV}$. 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 $\mu$eV and the distribution is shown as a histogram in Fig. 2. The FSS mean value is 18 $\mu$eV and the distribution has a standard deviation of 9.7 $\mu$eV. The maximum of the distribution is around 14 $\mu$eV.

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 $\mu$eV 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 $\mu$eV 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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References