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Magneto-Photoluminescence Spectroscopy of Single InAs/AlAs Quantum Dots

D Sarkar[1,*], H P van der Meulen[1], J M Calleja[1], J M Meyer[2], R J Haug[2] and K Pierz[3]

[1] Departamento de Física de Materiales, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
[*] present address: Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, United Kingdom
[2] Institut für Festkörperphysik, Leibniz Universität Hannover, D-30167 Hannover, Germany
[3] Physikalisch-Technische Bundesanstalt Braunschweig, D-38116 Braunschweig, Germany

Email: D.Sarkar@sheffield.ac.uk

Abstract. We present non-resonant, polarization-resolved magneto-photoluminescence measurements up to 12 T on single InAs/AlAs quantum dots. We observe typical *g*-factors between 1 and 2, very low diamagnetic shifts due to strong exciton localization and low-energy sidebands, which are attributed to the piezoelectric exciton-acoustic phonon interaction.

1. Introduction

Single self-assembled semiconductor quantum dots (QDs) [1-9] are of great interest for their possible use in quantum information processing. For qubit operations using spin degrees of freedom the knowledge of electron and hole *g*-factors and their control are important.

In this work we study the fine structure of the electronic states of single InAs quantum dots by magneto-photoluminescence (magneto-PL). The high AlAs barrier strongly localizes the wavefunction, thereby giving rise to very low diamagnetic shifts. Low-energy sidebands which have been investigated previously are now studied in magnetic field [7]. Their energy shifts with increasing field support the proposed mechanism of piezoelectric exciton-acoustic phonon interaction.

2. Experimental

The sample is grown by molecular beam epitaxy and consists of a single layer of self-assembled InAs QDs embedded in a 40-nm wide AlAs matrix. Magneto-PL spectroscopy on single QDs is performed in a helium-4 bath cryostat with a superconducting magnet (0-12 T) at a temperature of about 2 K. The sample is mounted on a three axis piezo-stage, which allows selection and alignment of single QDs. The piezoscanner together with the sample and an aspherical lens are immersed in the helium bath and centered in the bore of the magnet. The magnetic field is aligned normal with respect to the sample surface, i.e. parallel to growth direction. The polarization of the luminescence was analyzed by a quarter-wave retarder and a linear polarizer. A scrambler was placed in front of the spectrometer's entrance slit, in order to get rid of the polarization sensibility of the gratings. The dots were excited non-resonantly above the wetting layer with the 514 nm line of an argon ion laser.

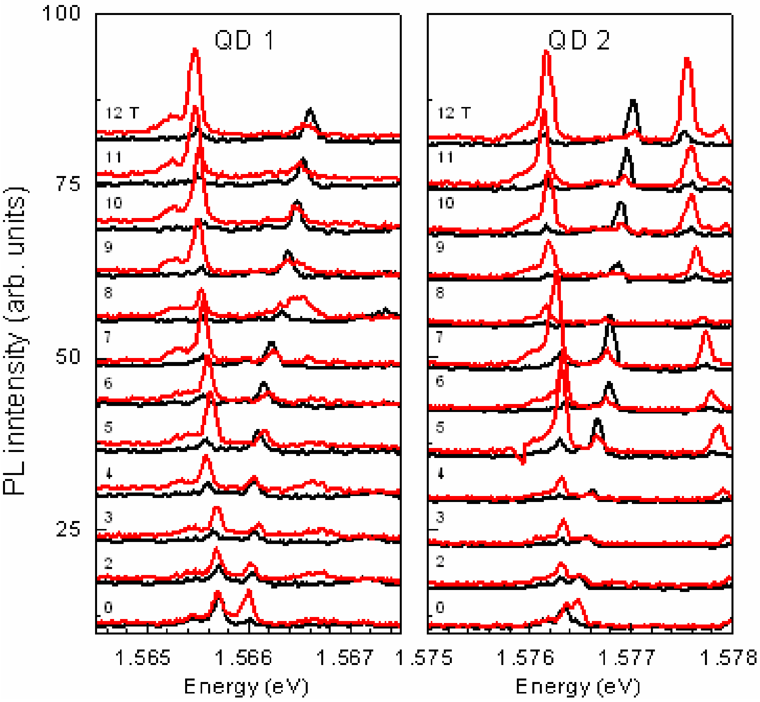

Figure 1. Polarized PL spectra of the exciton doublet for a series of magnetic fields up to 12 T. Red and black curves show right and left circularly polarized emission, respectively. The exciton emission of two individual quantum dots QD1 and QD2 is observed. Low-energy sidebands accompany the zero-phonon lines doublets up to 12 T. Already for low magnetic fields (> 4 T), the magnetic field restores the D_{2d} symmetry and the emission is transformed from linear to almost fully circularly polarized. Spectra are taken at 2 K.

3. Results and Discussion

Figure 1 shows circularly polarized micro-PL spectra for a varying magnetic field up to 12 T of two individual QD excitons emitting approximately at 1.566 eV (QD1) and 1.576 eV (QD2) at zero-field, respectively. Spectra are vertically shifted for clarity. Red and black curves show $\sigma+$ and $\sigma-$ polarized spectra, respectively. For increasing magnetic fields, the energy separation of the zero-field split exciton doublets increases due to the Zeeman interaction. For both excitons the $\sigma+$ polarized low-energy component first shifts slightly to lower energies and is nearly constant for higher magnetic fields, since the diamagnetic shift to higher energies compensates for the Zeeman shift to lower energies. In contrast, the $\sigma-$ polarized high-energy emission peaks experience a strong shift to higher energies, as both contributions have the same sign. Furthermore, both exciton doublets exhibit narrow sidebands, which remain close to the Zeeman-split exciton peaks for all magnetic fields.

For low magnetic fields, both components of the exciton doublets are observed in both circular polarizations, since both are linearly cross-polarized. For increasing fields the emission gradually becomes circularly polarized. In-plane isotropy can be restored by comparatively small magnetic fields of B > 4 T, indicating only small geometric in-plane anisotropy. Interestingly, a very large zero-field fine-structure splitting of about 0.28 meV is observed, while our magneto-PL results indicate only a small lateral asymmetry. This suggests that the large fine-structure splitting is not originated by geometrical asymmetry, but due to larger confinement due to higher AlAs barriers compared to GaAs barriers and to increased piezoelectric effects [2].

Figure 2 (a) shows the energy positions of the main exciton transitions, (which will be called zero-phonon-lines (ZPLs)) and the sidebands of QD1 as a function of the magnetic field. The energy difference of the bright exciton doublet (black curve) is shown in Figure 2 (b). For fields up to 5 T, the splitting deviates significantly from the linear Zeeman trend due to the large fine-structure splitting. For fields above 5 T, the splitting increases linearly with increasing magnetic field. At 12 T it amounts to 1.2 meV corresponding to an absolute exciton *g*-factor of 1.7. For QD2 a value of 1.4 is found. These are comparable to values typically observed for self assembled QDs [3, 4]. A study on dots with AlGaAs barriers [6] gives a g-factor of 2.25. Since the dark exciton is not observed in the spectra, the electron and hole g-factors cannot be determined separately.

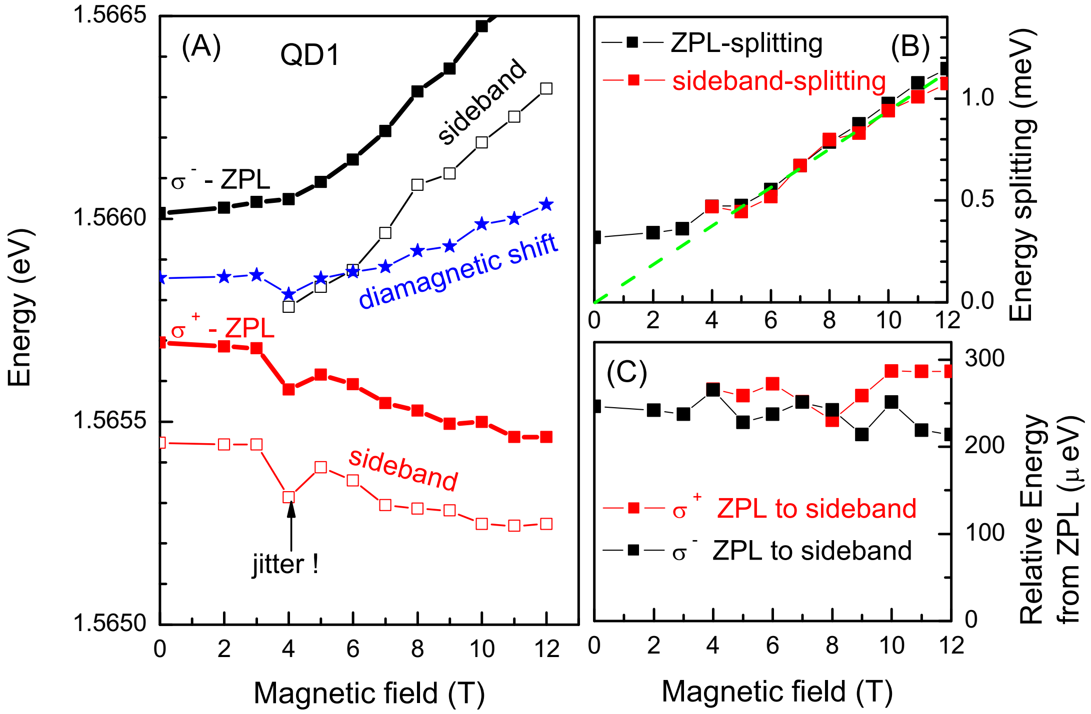

Figure 2. Magnetic field dependence of peak positions and splittings of QD1: (a) The energy position of the zero-phonon lines and their narrow sidebands are shown in black (σ−) and red (σ+) curves. The blue curve is the center of the ZPL doublet, i.e. it shows the diamagnetic shift. (b) The black and red curves show the splittings between the ZPLs and sidebands, respectively. (c) The red (black) curve shows the energy separations between for the σ+ (σ−) -sideband and the corresponding ZPL.

The center of the Zeeman split doublet (the blue curve of Figure 2 (a)) shows the diamagnetic shift of the exciton level. The diamagnetic coefficient of the quadratic shift to higher energies is extremely small with γ_2 = 1.38 μeV/T^2 and well below the typically reported values cited above for the commonly studied In(Ga)As/GaAs QDs [5]. This indicates the strong localization due to the high AlAs barriers. In accordance with this, a likewise small value of 3.5 μeV/T^2 [6] was reported for InAs QDs in InAs/Al$_{0.6}$Ga$_{0.4}$As barriers. The shift is quadratic with the field up to 12 T. This shows that, due to the strong confinement, the system does not approach the linear Landau-level behavior in the available magnetic field range.

We discuss now the narrow sidebands appearing at 0.25 meV below the exciton ZPLs. Since similar splittings were reported for the bright-dark exciton splitting in self-assembled QDs, one might tentatively attribute the sidebands to the emission of the dark exciton states. For InAs dots embedded in AlAs barriers a much larger bright-dark exciton splitting (in the meV-range) was estimated [8,9]. The magneto-PL measurements contradict the dark-exciton hypothesis. The red curve in Figure 2 (b) shows that the splitting between the two narrow sidebands is essentially the same as the bright exciton Zeeman splitting. Figure 2 (c) demonstrates that the separation between the ZPLs and their sidebands is fairly constant for magnetic fields up to 12 T. Only in the unlikely case where either the electron or the hole *g*-factor is zero will both bright and dark exciton Zeeman splittings be the same, which would lead to the behavior observed in panels (b) and (c). This excludes the possibility that the sidebands are due to dark exciton states, but rather would seem to indicate that they are a feature of the ZPLs themselves. In reference 7 is shown that the narrow sidebands are due to the interaction of the QD exciton with acoustic phonons. Besides, the line-shape evolution at low excitation power cannot be explained by dark excitons but is well described by piezoelectric coupling and screening [8].

4. Conclusions

In summary, at high magnetic fields the Zeeman splitting of InAs/AlAs QD excitons corresponds to a bright exciton g-factor of 1.7, which is close to the widely reported value of around 2. An extremely small diamagnetic shift of 1.4 $\mu eV/T^2$ points to strong localization due to the high AlAs barriers. Circular polarization is restored for small fields, indicating only a small structural dot asymmetry. The magneto-PL measurements reveal that the narrow sidebands below the ZPLs are not due to dark exciton emission. Instead they are attributed to exciton-acoustic phonon coupling.

Acknowledgements

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