

Towards Quantification of the In-Distribution in InGaAs Quantum Dots

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To determine quantitatively the In-concentration, e.g. in InGaAs quantum-well structures, composition evaluation by lattice fringe analysis (CELFA) [1] in transmission electron microscopy (TEM) is a well suited technique. However, applied to quantum dots (QDs) this method cannot account for the three-dimensional shape of QDs buried within a TEM sample. If the QDs are surrounded by a GaAs cap layer and are only contained partially in the TEM sample, the measured In-concentration will be lower than the real one. We suggest here a procedure for the quantification of the In-concentration in InGaAs QDs which accounts for shape and position of a QD within the TEM specimen.

The investigated samples were grown by molecular beam epitaxy on GaAs(001) substrates. The GaAs buffer was deposited at a substrate temperature of 500°C, followed by deposition of 2.4 monolayers (ML) InAs at a deposition rate of 0.0057 ML/s. After a growth interruption of 10 s a 28 nm GaAs capping layer was deposited. During the growth process InGaAs QDs with a base length of about 20 nm are formed in the self-organized Stranski-Krastanow growth mode.

The relative positions of the QDs within the cross-section sample and the local sample thickness is determined by recording a tilt series of TEM dark-field images. The images are taken by exciting the chemically sensitive (200) beam. The sample is tilted around an axis parallel to the [100] direction in steps of 5° beginning close to the [010]-zone axis. With increasing tilt angle the projection of the thin wetting layer broadens (Figure 1). The relative position of the QD within the specimen can then be derived from its relative position with respect to the projected wetting layer. The local sample thickness is estimated by measuring the width of the projected wetting layer at a given tilt angle and applying simple trigonometry. For the QD shown in Figure 1 we obtain an averaged local sample thickness of 32 nm and with its position within the boundaries of the projected wetting layer it can be concluded that the QD is contained completely within the TEM sample.

To determine the QD shape, in addition to the dark-field TEM images, we used plan-view bright-field TEM images which are compared with image simulations [2] and cross-section high angle annular dark-field scanning transmission microscopy (STEM) images. The shape of the QDs was determined to be pyramids with {101} facets - in some cases with truncated tops.

For the CELFA analysis cross-section HRTEM lattice fringe images with lattice fringes parallel and perpendicular to the [001]-growth direction were recorded. Artifacts in the CELFA analysis are induced due to the strong bending of the (002) planes. For this reason, only the images taken with the (200) reflection were further analyzed. For the QD in Figure 1 we obtain a maximum In-concentration of 46%.

For the post-processing we calculate a function which - applied to the CELFA data - multiplies values of the local In-concentration by the quotient of the local thickness of the sample and the local thickness of the QD. Parameters other than the sample thickness and the QDs shape are the onset of the pyramids base and the base length. For the QD in Figure 1 we thus obtain a shape-corrected maximum In-concentration close to 100 % (Figure 2) which is in agreement with the expectation for QDs grown under the applied MBE conditions. A refinement of the post-processing procedure can be achieved by the application of electron holography to get a thickness profile of the sample [3].

- [1] A. Rosenauer and D. Gerthsen, *Advances in Imaging and Electron Physics* 107, 121 (1999), and A. Rosenauer, *Transmission Electron Microscopy of Semiconductor Nanostructures - An Analysis of Composition and Strain* (Heidelberg, Springer) Springer Tracts in Modern Physics (2003), 182 p.
 [2] K. Scheerschmidt, Max-Planck-Institut für Mikrostrukturphysik, Halle/Saale, in progress
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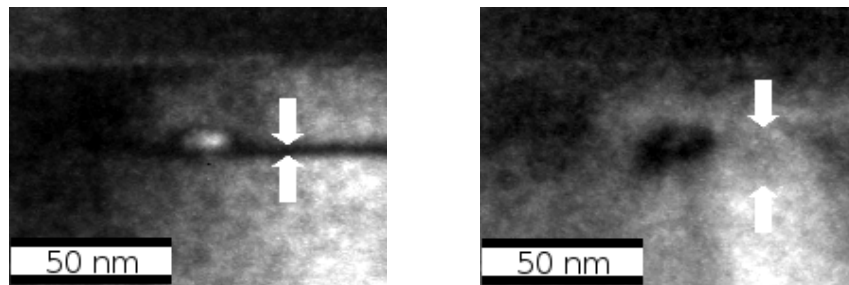


Figure 1: (200) dark-field TEM images of the QD at a tilt of 5° (left) and 35° (right). Broadening of the contrast of wetting layer with increasing tilt angle can be seen.

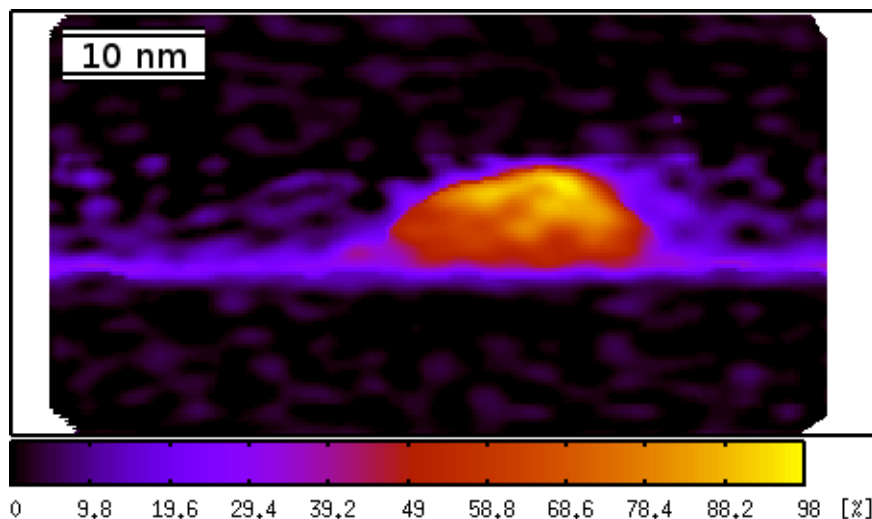


Figure 2: Color-coded In-concentration map after post processing of the CELFA data. A high In-concentration at the top of the QD can be seen.