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Towards Quantification of the In-Distribution in InGaAs Quantum Dots

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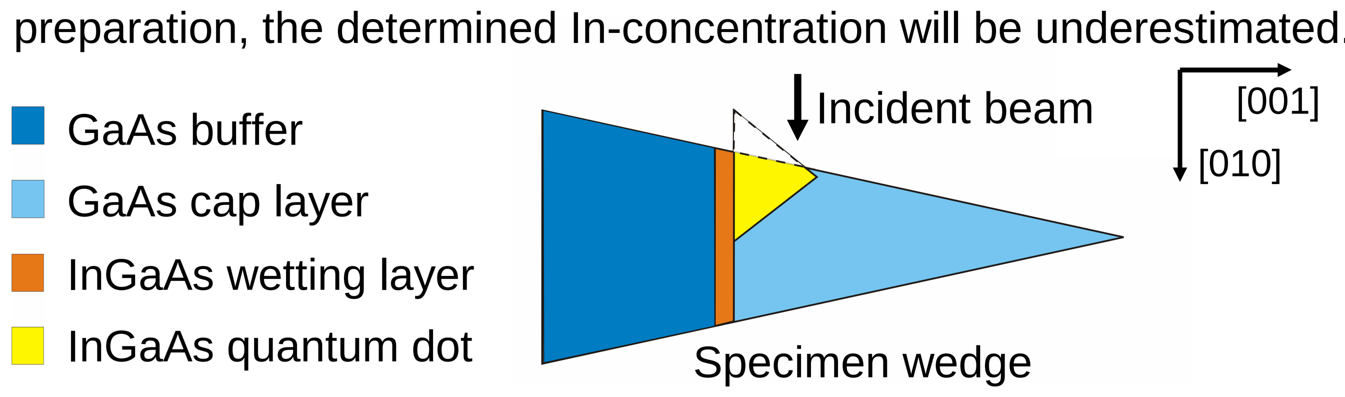
Motivation

Composition evaluation by lattice fringe analysis (CELFA) [1] in transmission electron microscopy (TEM) is a well suited technique to quantify the In-concentration, e.g. in $In_xGa_{1-x}As$ quantum-well structures.

Problem: Applied to quantum dots (QDs) this method cannot account for the three-dimensional shape of QDs buried within a TEM sample. Since embedded QDs are surrounded by a GaAs cap layer and might become cut (see figure) during TEM sample preparation, the determined In-concentration will be underestimated.



Task: Determination of the local extent of the QD with respect to the sample thickness along the incident beam direction to correct the CELFA result.

Specimen

Growth by molecular beam epitaxy on GaAs(001) substrates:
- Substrate temperature: 500 °C
- Buffer: 720 nm GaAs
- Wetting layer: 2.4 monolayers (ML) InAs (nominal) at a deposition rate of 0.0057 ML/s → formation of InGaAs QDs in the self-organized Stranski-Krastanov growth mode
- Growth interruption between deposition of wetting layer and cap layer: 10 s
- Cap layer: 28 nm GaAs

TEM cross-section and plan-view sample preparation using standard methods (grinding, polishing, Ar^+-etching and wet-chemical etching, respectively).

Methods

Quantification of the In-concentration with CELFA
- Cross-section HRTEM images with lattice fringes perpendicular ((002) reflection) and parallel ((200) reflection) to the [001] growth direction (Fig. 1a,b)
- Artifacts in CELFA due to strong bending of the (002) planes
- Strain contrast and thus artifacts minimal in the center of the QDs along the growth direction in micrographs using the (200) reflection (Fig. 1b) → **only area and imaging condition for reliable evaluation**
- Evaluation without consideration of the QD's three-dimensional shape and surrounding GaAs material yields a maximal In-concentration of x=0.46 (Fig. 1c)

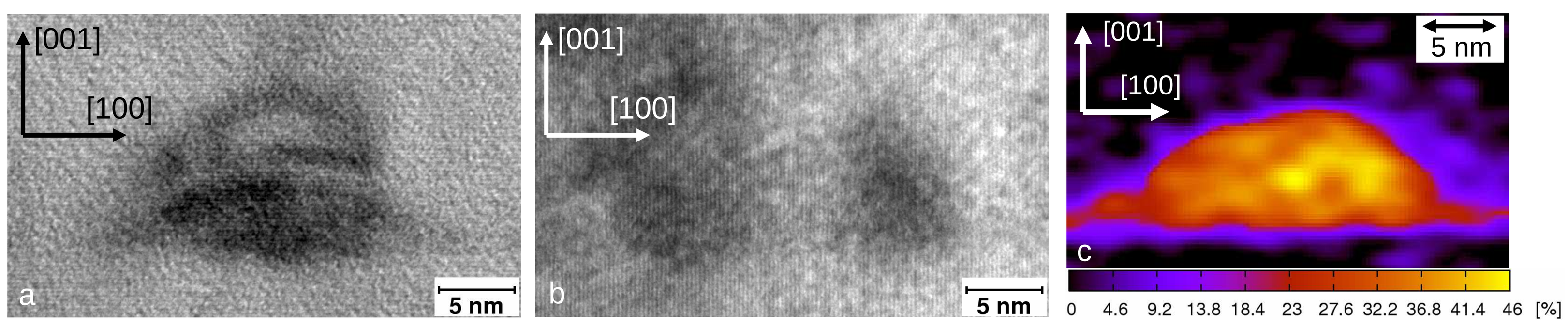


Fig. 1: Lattice fringe images using a) (002) reflection, b) (200) reflection; c) CELFA result

Determination of sample thickness and relative position of the QD

Idea: Tilt series of TEM dark-field images of the cross-section sample:
- Excitation of the chemically sensitive (200) reflection
- Sample tilting around an axis parallel to the [100] direction in steps of 5° beginning close to the [010] zone axis

→ Broadening of the projection of the wetting layer with increasing tilt (Fig. 2)

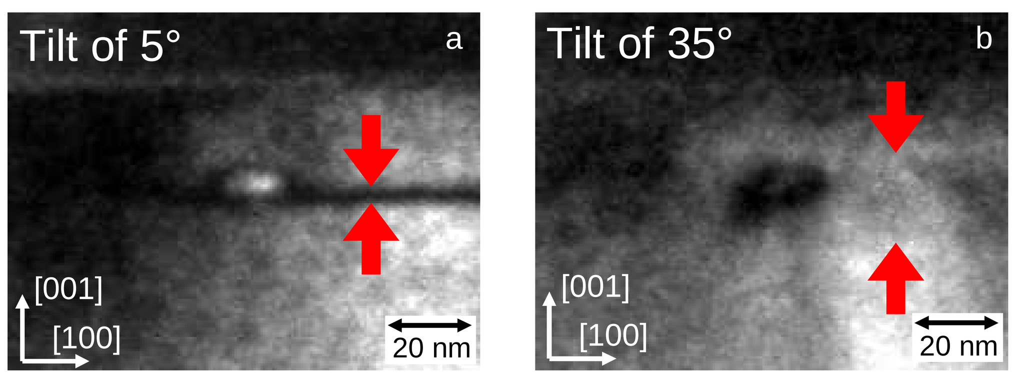


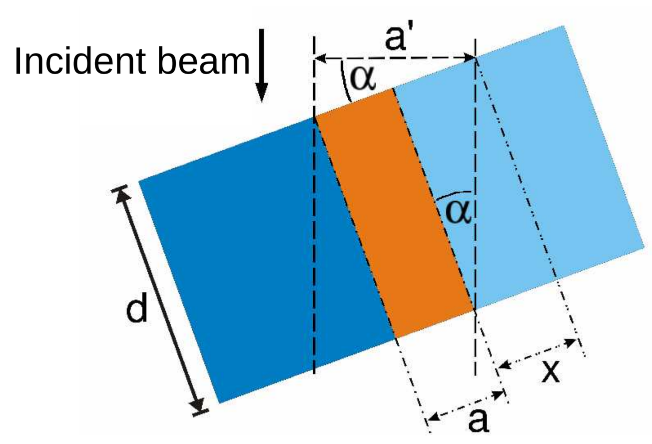
Fig. 2: Dark-field micrographs: extent of the projected wetting layer marked by arrows

- *Criterion:* Contrast of QD situated between boundaries of the projected wetting layer (Fig. 2b) → **QD completely embedded in TEM sample**
- Sample thickness *d* determined assuming parallel surfaces (Tilt angle α, width *a* of projected wetting layer untilted, width *a'* of the projected wetting layer at α)

$$d = [a'/\cos(\alpha) - a]/\tan(\alpha)$$

Thin wetting layers ($a \rightarrow 0$):

$$\mathbf{d = a'/\sin(\alpha)}$$



Determination of the local extent and shape of QD:

Idea: Identification of QD shape analyzing bright-field images
→ **local extent of QD in TEM sample calculable**

1) Modeling of molecular-dynamically relaxed InAs-QDs with different shapes:

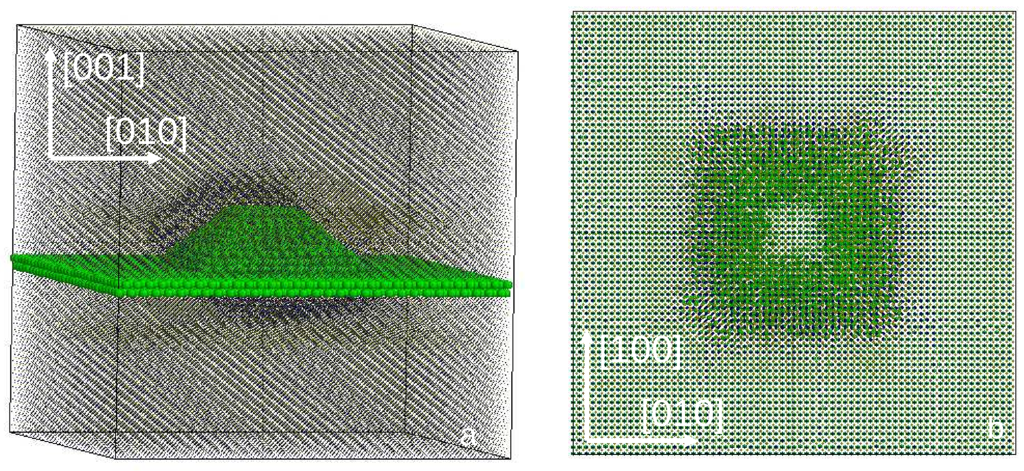


Fig. 3: a) three-dimensional view of a pyramidal QD with truncated top and {101} facets; b) plan-view sight of that model

2) Simulation of plan-view bright-field (BF) images using the modeled structures

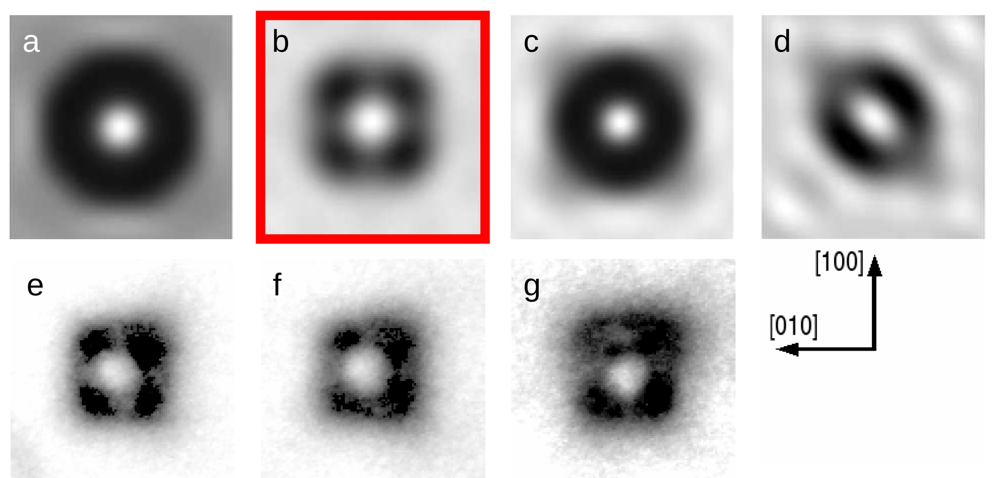


Fig. 4: simulated plan-view BF images of different QD shapes:
a) sphere,
b) pyramid {101},
c) pyramid {112},
d) pyramid {136} and
e-g) experimental data

3) Comparison (Fig. 4) → Best match for a **{101} facetted pyramid**

4) Verification of the {101} facets by cross-section high angle annular dark-field scanning transmission electron microscopy

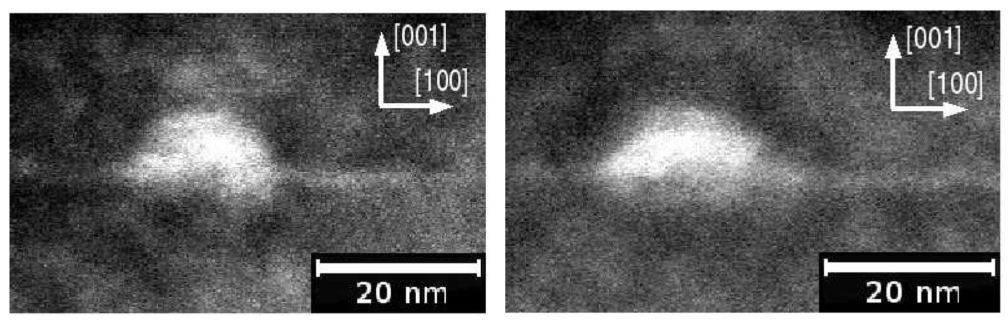


Fig. 5: Z-contrast shows angles around 45° between sides and base of the pyramids
→ Agreement with {101} facetted pyramids

Correction of the CELFA result
- Fitting of projection of {101} facetted pyramid on CELFA result (triangle in Fig. 6a)
- Determination of relevant parameters: distance d_S between {101} facets at vertical position z_S
- Ratio *V* between the sample thickness and the local thickness of the QD as a function of the vertical coordinate *z*: $V(z) = d/(d_S + 2\cdot(z_S - z))$
- Corrected In-concentration: $c_{corr}(x,z) = c_{CELFA}(x,z)\cdot V(z)$

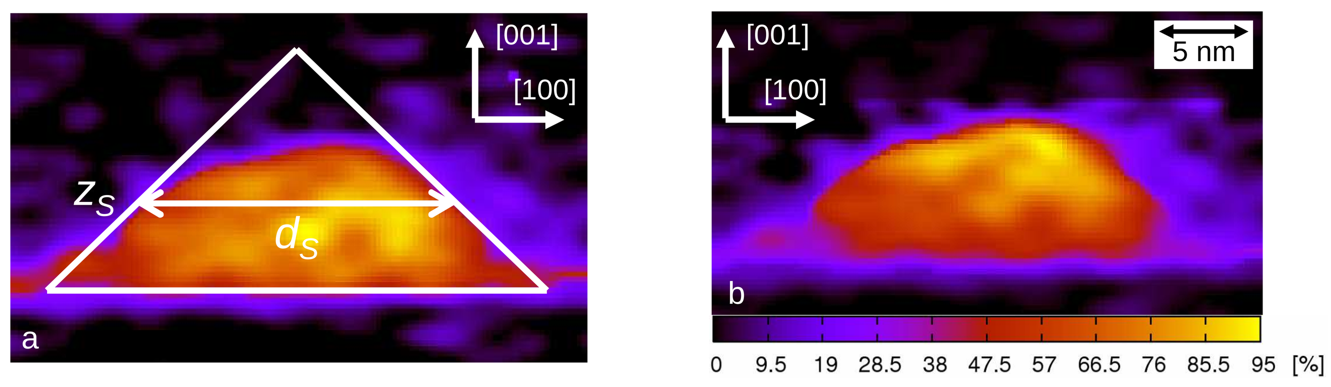


Fig. 6: a) Determination of the pyramid's parameters, b) shape corrected In-concentration

→ **Shape corrected CELFA result: Increasing In-concentration from bottom to top with a maximum of x=0.95 indium**

Summary

- Sample thickness obtained via tilt series
- Determination of QD shape (structural modeling, simulation of BF images, comparison) → local QD extent
- Correction of the CELFA result by considering the ratio between sample thickness and local thickness of the QD
- Corrected result in agreement with results obtained on similar samples with different experimental techniques [2,3]

Outlook and remaining problems

- Better results for the sample thickness by application of electron holography
- Errors due to deviations of the single QD's shape from the assumed ideal shape → more accurate information on the three-dimensional shape is needed

References

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