Karlsruhe Institute of Technology

Laboratory for Electron Microscopy

Application of a Zach Phase Plate in High-Resolution Transmission Electron Microscopy

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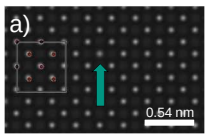
Introduction

- Physical phase plates (PP) enhance the contrast of weak-phase objects (WPO) in transmission electron microscopy (TEM):
  - **Zach-PP**[1]: An electrode, surrounded by insulating and metallic shielding layers, generates an electrostatic field close to the zero-order beam. Depending on the applied voltage, a relative phase shift between unscattered and scattered electrons is induced.
- Weak-phase objects and resolution:
  - **Typical WPO**: Biological samples or nanoparticles at low magnifications weakly change the mean phase of electrons over larger areas.
  - **Single Atoms**: Even for heavy atoms, the potential is smeared by the point spread function across an area. Introduced mean phase shift can be small.

➡ Crystalline specimens in HRTEM typically **NOT** weak-phase objects

Motivation

- Crystalline objects and phase-plates:
  - **Contrast**: Contrast in conjunction with high doses typically strong
  - **Interpetation**: Can be difficult due to thickness and delocalisation effects
  - **Non-perodic information**: Contrast of point defects like oxygen vacancies can behave like weak phase objects.
- Image simulation of crystalline wave-function with point defects
  - ➡ Vacancy of 50% Si-atoms in projection missing (Fig. 1)



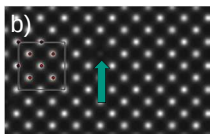


Fig.1: Simulated images of Si specimen with vacancies (marked by arrow). 300 kV, C_S= 1 µm, Z= -2 nm
(a) φ_{PP}= 0 π
(b) φ_{PP}= -0.5 π

Application of Zach Phase Plate

- InGaAs quantum dot images with different induced phase shifts (Fig. 2)

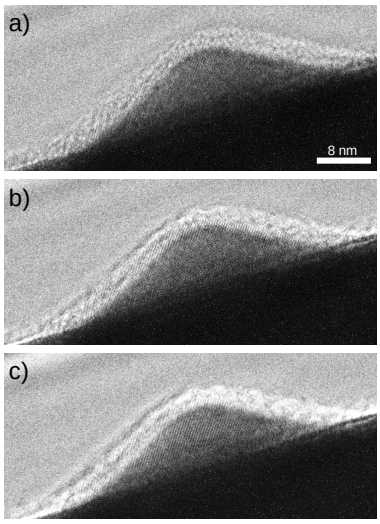


Fig.1: Images of InGaAs quantum dots acquired with a Zeiss 923 Omega FEG microscope (C_S= 2.2 mm) equiped with a Zach phase plate. Different voltages applied to phase plate result in differnt lattice fringe contrast. Voltages are:

(a) U_{PP} = -0.8V
(b) U_{PP} = 0 V
(c) U_{PP} = 0.8 V

Defocus remained contant during acquisition of phase shift series. Fresnel fringe contrast at the edge does not change in form, but only in intensity.

Resolution and signal-to-noise ratio limited by allowable dose due to charging effects of the phase plate.

References

[1] K. Schultheiss et al., Microsc. Microanal. 16 (2010) 785-794
[2] Gamm et al., Ultramicroscopy 110 (2010) 807-814
[3] A. Rosenauer and D. Gerthsen, Ultramicroscopy 76 (1999) 49-60

Acknowledgement

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Analysis of HRTEM contrast

- Contrast change of reflections
  - ➡ Intensity of a reflection depends on structure factor, orientation, defocus, phase plate phase shift and spatial frequency
  - ➡ Varying phase shift changes intensity of reflections defocus remained constant (Fig. 3)

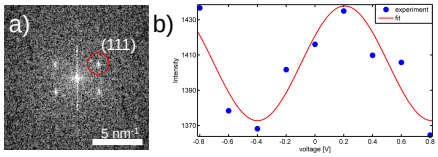

Fig.3: Intensity of the (111)-reflection in dependence of applied voltage to the phase plate.

(a) Diffractogram of QD in Fig. 2 a
(b) Experimental intensity values (blue dots) and sine-type fit (red line)

- Contrast change of lattice fringes
  - ➡ Fringe contrast changes with applied voltage similar to defocus changes
  - ➡ Line profiles perpendicular to fringes across the quantum dot demonstrate the phase shift dependence of contrast (Fig. 4)

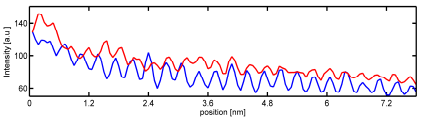

Fig.4: Line profiles across the quantum dot, perpendicular to fringes. Fringes are also shifted towards the edge of the dot (left side).
Red line: Fig. 2 a (-0.8V)
Blue line: Fig. 2 c (+0.8V)

Application of HRTEM techniques with phase plates

- Use of phase plates in HRTEM can add to existing methods:
  - ➡ Inline holography possible with phase plates [2]
  - ➡ CELFA [3] can be done with phase shift series
- Phase shift series offer advantage of easy handling non-linear image contribution compared to defocus series
  - ➡ Non-linear intensity described by transmission cross coefficient remains constant during variation of phase shift

Challenges of HRTEM phase plates

- Positioning and characterisation of phase plate
  - ➡ Positioning phase plate by beam tilt changes orientation of specimen, best practice using PP-holder requires very precise piezo holder
  - ➡ Characterisation requires amorphous specimen, optimally near to area of interest
- Signal-to-noise ratio main problem of PP-HRTEM
  - ➡ Charging of PP requires low dose
  - ➡ Phase plate does not significantly decrease coherence
- Reduced charging expected for electrostatic phase-plates by
  - ➡ Heating the phase-plate chip with a micro-heating.
  - ➡ Use of bonded contacts for optimal grounding.

cf. IM1.P101 & 102

Summary

- HRTEM done with electrostatic phase plates
- Fringe contrast changes in dependence of induced phase plate phase shift
- Adaption of phase plates to HRTEM methods like wave-function reconstruction
- SNR main difficulty in conjunction with charging; coherence not an issue