Effect of a Physical Phase Plate on Contrast Transfer in an Aberration-Corrected Transmission Electron Microscope

B. Gamm1, K. Schultheiss1, D. Gerthsen1, R.R. Schröder2
1 Laboratorium für Elektronenmikroskopie, Universität Karlsruhe, D-76128 Karlsruhe, Germany
2 CellNetworks, BioQuant, Universität Heidelberg, D-69120 Heidelberg, Germany
Contact: gamm@lem.uni-karlsruhe.de

Motivation
- Novel TEM imaging techniques by realization of “physical” phase plates (PP) [1]
- Cs-corrector [2,3] allows in principle full correction of aberrations up to the fifth order, but contrast vanishes for weak-phase objects without aberrations
- Combining Cs-correction and an ideal phase plate yields optimal contrast with full correction of aberrations
- We apply the weak-phase object approximation to explore ranges for defocus Z and Cs-values resulting in optimal imaging conditions, for both phase plate imaging and conventional Cs-corrected imaging

Phase Contrast Transfer
- Imaging of weak-phase objects is commonly described by the phase contrast transfer function (PCTF)
- The object wave function is Fourier transformed and multiplied by the PCTF given as
  \[ PCTF(u) = \sqrt{2} \lambda \sin(\chi) \]
- Optimal phase contrast in TEM without Cs-corrector at Scherzer defocus with corresponding Scherzer resolution:
  \[ Z_{\text{Scherzer}} = \sqrt{\frac{8}{3} C_s U_{\text{PP}}} \]
- Phase distortion function \( \chi \) with a phase plate in the back focal plane of the microscope:
  \[ Z_{\text{phase plate}} = \frac{0.73}{\sqrt{\lambda}} U_{\text{PP}} \]
- Optimal phase contrast conditions for uncorrected phase plate imaging are given according to [4] by
  \[ Z_{\text{Scherzer}} = \sqrt{\frac{8}{3} C_s U_{\text{PP}}} \]

Cs-Correction & Phase Plates
- Optimal parameters for imaging without a phase plate but with Cs-correction described by Lentzen et al. [5]
- Scherzer resolution is not extended far beyond the information limit of the microscope, as well as delocalization is minimized
- Optimal defocus and Cs-value are given as
  \[ C_{\text{Lentzen}} = \frac{64}{27} \frac{1}{U_{\text{PP}}} \quad Z_{\text{Lentzen}} = \frac{16}{1} \frac{1}{U_{\text{PP}}} \]

Quantification of Phase Contrast
- Influence of defocus and Cs-values on phase contrast (PC) quantified by integrating the PCTF
  \[ PC = \frac{1}{E} |E| \sin \left( \frac{\chi}{2} \right) du \]
- Comparison with optimal phase contrast
  \[ PC_{\text{opt}} = \frac{1}{E} |E| du \]
- Fig. 4: PC for a 200 keV phase plate microscope and a normal 200 keV microscope; black lines denote 5% (10%) reduction with respect to PC_{opt}
  \[ PC_{\text{red}} = 0.05 (0.1) \]
- Consideration of Delocalization R:
  - White lines in Fig. 4 denote delocalization corresponding to Lentzen parameters
  - Phase contrast microscopes (gray lines) show wider defocus ranges, i.e. permitting a rougher sample-surface topography at same resolution and eventually a larger sample region to be imaged.
- 300 keV microscopes show a slight advantage compared to 200keV microscopes.

Real Phase Plates
- Real Boersch phase plates show an electrode ring completely obstructing information for a certain region of low frequencies (object features larger than approx. 5.5 nm for a typical 200keV microscope)
- Calculations for Fig. 4 and Fig. 5 have been done with Boersch geometry considered and it was found that the loss of information sums up to approx. 8% for a 200keV microscope (3% for a 300keV with 0.05 nm information limit)

Summary
- Almost perfect coincidence of the phase contrast transfer function with the envelope function for partial temporal coherence even for future microscopes with next-generation correctors possible
- In-focus phase contrast with a Boersch phase plate will provide strong and localized object contrast over the entire resolution range in one single image
- Effective interpretable field of view increases for in-focus phase contrast imaging, due to reduced delocalization

References

Acknowledgements
The project is funded by the German Research Foundation (Deutsche Forschungsgemeinschaft) under Ge 841/16 and Sch 424/11.