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Aberration-Corrected STEM by Means of Diffraction Gratings

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For a long time, the resolution in electron microscopy was limited by the spherical aberration of the objective lens [1], i.e. the imaging lens in transmission electron microscopy (TEM) and the probe forming lens in scanning transmission electron microscopy (STEM). However, after aberration correction by means of multipole optics became feasible [2, 3], modern electron microscopes routinely allow sub-Ångstrøm image resolution. Nevertheless, aberration correctors are quite complicated and can be quite expensive. Here, we demonstrate the correction of spherical aberration in STEM by means of a simple diffraction grating that can easily be incorporated to most uncorrected STEMs.

The microscopy community became aware of electron diffraction gratings in the context of vortex beams [4, 5], where the phase structure of a vortex, i.e. an azimuthal phase shift, had been superimposed to the “empty” phase shift in a line grating. The phase shift of a vortex state was then found in the diffracted beams in the far field of the grating.

This kind of wave-front engineering can also be used in a different way: In the case of the spherical aberration of the objective lens that blurs the STEM probe, the diffraction grating requires a radially dependent phase shift ($\sim R^4$) that compensates for the lens aberration. Such a grating is shown in Fig. 1. According to Fig. 2, this kind of diffraction grating in the condenser aperture yields three STEM probes on the object. The transmitted beam (0th order) is not affected by the phase shift of the grating, hence it is a conventional aberrated STEM probe. The first order diffracted beam however, gains the imprinted phase shift of the grating for the order beam and loses the phase shift for the beam of order Consequently, in the “+1”-beam the spherical aberration of the objective lens is reduced, whereas in the “-1”-beam the spherical aberration increases.

In our experiment, the diffraction grating was designed to correct a spherical aberration of C_3 = 1.25 mm at 300 kV (wave length λ = 1.97 pm). For a common condenser lens setting in the uncorrected FEI Titan at University of Oregon in Eugene, a condenser aperture radius of R_{max} = 35 µm corresponds to an illumination half angle of θ_{max} = 17.5 mrad. For the phase shift χ_g of the diffraction grating to cancel out the spherical aberration of the objective lens, χ_{OL} the grating parameter C_g has to fulfill the condition

$$\chi_{OL} = \frac{2\pi}{\lambda}\frac{C_3}{4}\theta_{max}^4 \stackrel{!}{=} -C_g \cdot R_{max}^4 = -\chi_g$$

The desired grating structure has been imprinted with a line spacing of 80 nm on a commercially-available Silicon Nitride membrane and then positioned in the C2-condenser aperture of the microscope. The three resulting STEM probes are spatially separated by ~50 nm on the specimen and can be isolated with a small selected area aperture in an intermediate image plane. This allows inspecting them individually in the diffraction plane, i.e. the Ronchigram (compare Fig. 2). For STEM imaging, either the sample can be positioned in such a way that the unnecessary “0” and “-1” diffraction orders pass through vacuum (suitable for HAADF and all secondary signals such as EDX) or an additional aperture above the sample has to be used to let pass only the “+1”probe (suitable for all STEM signals). [6]

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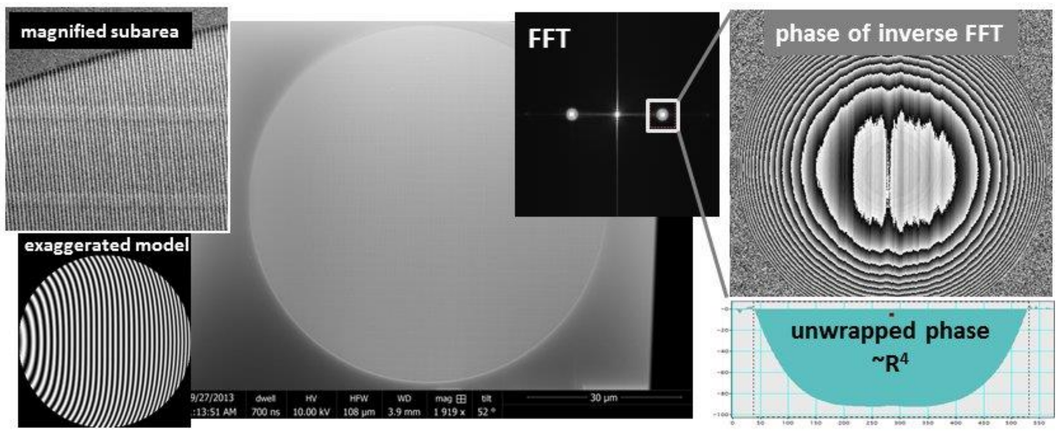

Figure 1. SEM image of the Cs-correction grating - The grating lines in the Silicon Nitride membrane have a radially dependent phase shift that mimics the aberration function of the objective lens. Here, geometric phase analysis of the grating lines reveals the C_j-typical radial power-of-four phase shift.

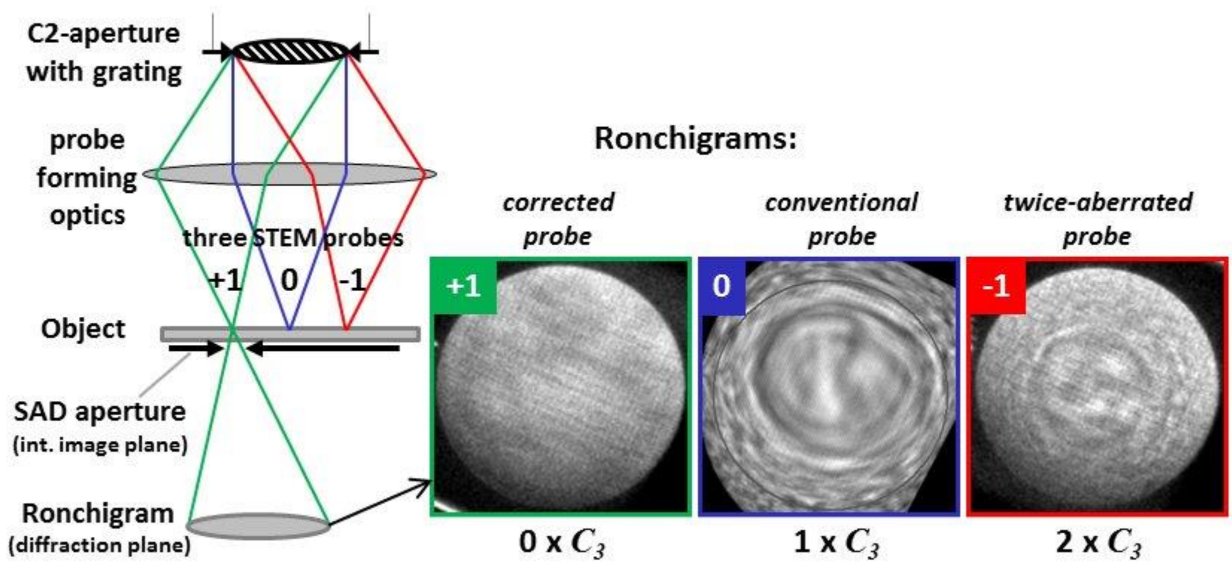

Figure 2. Demonstration of spherical aberration correction - The grating in the condenser aperture creates three STEM probes on the object. For alignment purpose the Ronchigrams of the individual probes can be separated with a selected area aperture. Evidently, the Ronchigram of the corrected probe is completely flat over the whole grating area (full C_3-compensation) whereas the flat areas of the aberrated "0"-order and "-1"-order probes are much smaller due to C_3 and $2C_3$, respectively.

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