Microsc. Microanal. 8 (Suppl. 2), 2002
DOI 10.1017.S1431927602101498

Benefits and Possibilities of C_C–Correction for TEM / STEM

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During the last decade aberration correction became possible for several types of electron optical instruments. Correctors for the spherical aberration of TEM / STEM objective lenses are now commercially available [1,2]. In case of the SEM [3] and the LEEM / PEEM [4] the correction of both the spherical and the chromatic aberration has been demonstrated in experiments. In spite of these great advancements aberration correction for TEM / STEM is still restricted to the spherical aberration. An improvement of the information limit by C_c–correction for the TEM / STEM has not yet been demonstrated.

For a C_s–corrected 200kV FEG–TEM equipped with a hexapole corrector an information limit of $d = 0.12$ nm has been measured. For such an instrument the information limit is determined both by the chromatic aberration of the objective lens and that of the hexapole corrector. In order to reach this limit a very accurate alignment and a sufficient mechanical and electrical stability of the microscope are necessary. For a thin phase object the chromatic information limit can be quantified by a visibility criterion based on the chromatic envelope of the contrast transfer function

$$H_c(\theta) = \exp\left(-\frac{\pi^2 \sigma_E^2 C_c^2 \theta^4}{2\lambda^2 E_0^2}\right) \overset{!}{>} 0.3 \; ,$$

where $\Delta E_{1/2} = \sqrt{8\ln(2)}\,\sigma_E$ denotes the FWHM of the energy width. The influence of the lateral incoherence on the information limit is strongly suppressed for a C_s–corrected microscope. A further improvement of the information limit is only possible either by reducing the energy width or by chromatic correction. Different types of gun monochromators have been proposed to reduce $\Delta E_{1/2}$ below 0.3 eV [5]. A TEM equipped with a gun monochromator and a high–resolution pole piece optimized for a minimum C_c should be able to approach an information limit of about 0.08 nm. Unfortunately, a high–resolution pole piece with a very narrow magnetic gap is inadequate for many applications, especially for in-situ electron microscopy. In order to improve the resolution of an electron microscope equipped with a pole piece with a sufficiently large gap C_c–correction is the only possibility, if we refuse to accept a dramatic loss in beam current by monochromatization down to $\Delta E_{1/2} < 0.1$ eV.

Several methods for correcting the chromatic aberration have been proposed. While a mirror corrector [4] or a purely electro-static corrector [6] are not feasible for a high–voltage TEM / STEM an electric–magnetic quadrupole $\mathrm{C}_c/\mathrm{C}_s$–corrector is a possible choice. Unlike a hexapole C_s–corrector a quadrupole corrector strongly alters the path of the paraxial rays. If we use the linear combinations $u_\alpha = \frac{1}{2}\,(x_\alpha + y_\beta)$ and $u_{\overline{\alpha}} = \frac{1}{2}\,(x_\alpha - y_\beta)$ for the axial fundamental rays x_α and y_β the contribution of the quadrupoles to the chromatic aberration C_c and to the chromatic two–fold astigmatism $\overline{\mathrm{C}}_c$ adopts the simple form

$$\mathrm{C}_c = \int_{z_O}^{z_I} 2\,(\Psi_{2s} - \Phi_{2c})\, u_\alpha u_{\overline{\alpha}}\; dz \; , \quad \overline{\mathrm{C}}_c = \int_{z_O}^{z_I} (\Psi_{2s} - \Phi_{2c})\left(u_\alpha^2 + u_{\overline{\alpha}}^2\right)\, dz \; .$$

The normalized multipole strengths are chosen imaginary $\Psi_2 = i\Psi_{2s}$ for the magnetic and real $\Phi_2 = \Phi_{2c}$ for the electrostatic quadrupoles in order to separate the paraxial ray equations. We find that the path of rays inside the corrector must be astigmatic ($u_{\overline{\alpha}} \not\equiv 0$). The "minimum" quadrupole C$_c$–corrector requires two magnetic and two combined electric–magnetic quadrupoles arranged anti–symmetrically with respect to the mid-plane of the system in order to avoid a two–fold chromatic astigmatism $\overline{\mathrm{C}}_c$. The correction of the spherical aberration can be achieved by additional octupole elements which act symmetrically on the path of rays. The path of the fundamental rays for each section is determined by the sum of the focussing and defocussing strength of the magnetic and electric quadrupoles. Hence, for each element a negative chromatic aberration is introduced in one section. The dependence of the refraction power on the beam energy is different for electric and magnetic quadrupoles, since only magnetic interaction depends on the velocity of the electron. For small energy deviations the change of the refraction power of a magnetic quadrupole is only half as large as in the case of an electric one.

Unfortunately, the minimum quadrupole corrector described above introduces strong off-axial aberrations. Therefore, it can be applied only in a low–voltage SEM [3]. For the TEM more advanced designs with reduced off–axial aberration have been proposed. All these correctors are symmetrically arranged with respect to their mid-plane. Recently, we have seized a suggestion by Rose [7] and investigated a new class of correctors based on a double–symmetric arrangement of electric–magnetic quadrupoles. For these highly symmetric systems the geometrical aberrations of third order can be controlled completely.

A second, even more critical property of all C$_c$/C$_s$–correctors based on the superposition of electric–magnetic quadrupole fields is the stability requirement for the power supplies of the combined electric–magnetic elements. In order to produce a sufficiently large negative chromatic aberration they must be rather strong. Their electric and magnetic refraction powers compensate each other to a large extent. However, this is not true for small uncorrelated instabilities of voltage and current. For a perfectly designed and aligned corrector instabilities result in a variation of defocus σ_{C_1} and two–fold astigmatism σ_{A_1} avoiding image displacement. These incoherent perturbations decrease the information limit, which can be approximated by an additional damping envelope of the contrast transfer function. Just like in the case of the chromatic aberration the tolerable variation of defocus and two–fold astigmatism can be estimated by a visibility criterion

$$H_D(\theta) = \exp\left(-\frac{\pi^2|\sigma_D|^2\theta^4}{2\lambda^2 E_0^2}\right) \overset{!}{>} 0.3\ , \quad D \in \{A_1, C_1\}\ .$$

This shows that any C$_c$–corrector is useful for a maximum aperure θ_A only if the stability condition $|\sigma_D| < 0.5\,\frac{\lambda}{\theta^2}$, with $D \in \{A_1, C_1\}$ can be fulfilled.

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