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Benefits of Chromatic Aberration Correction for Off-axis Electron Holography

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Off-axis electron holography is an interferometric phase retrieval method that has become a powerful tool for analysis of electric potentials and magnetic fields [1, 2]. On the atomic scale, off-axis holography allows accessing the complete object exit-wave full-quantitatively with very direct reconstruction techniques. For a long time, high-resolution holography was hampered by the very limited signal resolution. However, recent instrumental developments such as spherical aberration correctors and high brightness electron emitters have enabled holographic atomic resolution measurements with very high signal resolution [3, 4].

Recently, the TEAM I microscope at the National Center for Electron Microscopy in Berkeley, CA has been equipped with a biprism for off-axis electron holography [5]. This combination for the first time allows recording off-axis holograms in an environment that is not only corrected for spherical aberration but also for chromatic aberration. It turns out that the C_C-corrector is extremely beneficial for high-resolution holography at low accelerating voltages U_A:
In an electron microscope that is corrected for spherical aberration only, the resolution limit is dominated by the chromatic information limit $d_{Cc} = \sqrt{\pi / 2 \cdot \lambda \cdot \sigma_z}$ with the wave length λ and the chromatic focus spread $\sigma_z = \sqrt{\left(C_C \cdot \sigma_E / eU_A\right)^2 + \left(C_C \cdot \sigma_{U_A} / U_A\right)^2 + \left(C_C^* \cdot 2\sigma_I / I\right)^2}$. The variances σ_E, σ_{UA} and σ_I describe the emitter's energy spread, high-voltage ripple and instability of the objective lens current I, respectively. The relativistically corrected chromatic aberration coefficient $C_C = f \cdot C_C{}^*$ is given by the nominal chromatic aberration coefficient $C_C{}^*$ and a relativistic correction factor f [6].

In order to achieve a better information limit without chromatic aberration correction, a monochromator has to be used. For a Gaussian distributed beam energy, the resulting beam current for a certain monochromator slit width ΔE can be estimated by the Error function $Erf(\Delta E)$ (see figure 1b). This yields a significant reduction of intensity: reducing a Gaussian distribution of 0.7 eV FWHM to 0.1 eV causes a drop by a factor of four. Consequently, the signal resolution of the holographically reconstructed phase signal $\sigma_\varphi = \sqrt{2 / V^2 N}$, which depends on basic fringe contrast V and electron dose N, deteriorates as well.
If the chromatic information limit is improved by C_C-correction instead, the holographic signal resolution becomes independent of accelerating voltage. Figure 1a shows the required energy spread σ_E to achieve a certain chromatic information limit depending on accelerating voltage. Here, the desired resolution $d = \lambda / \alpha$ is defined by an aperture half angle $\alpha = 50$ mrad, which corresponds to 172 pm at 20 kV, 120 pm at 40 kV, 83.6 pm at 80 kV and 50.2 pm at 200 kV. Figure 1b shows the remaining beam current that results from the desired energy width ΔE to be cut-out by the monochromator slit. In figure 2, the behavior of holographic signal resolution is plotted depending on high voltage. Evidently, already at large voltage U_A, the σ_φ-value is less than half of the C_C-corrected case $\sigma_{\varphi Cc}$. Towards low accelerating voltages below 80 kV, σ_φ drops dramatically compared to $\sigma_{\varphi Cc}$.

In summary, off-axis electron holography in a C_C-corrected TEM is capable of atomic resolution phase contrast imaging at low accelerating voltages such as 80 kV and below. Since no monochromator is required to reduce the effects of chromatic aberration, the full beam current can be used to shape the highly elliptic illumination. Consequently, the special requirements for spatial coherence can be met with a reasonably high dose for recording high-quality off-axis holograms. With the freedom to work at low beam energies to avoid the knock-on damage of light elements, high-resolution off-axis electron holography is now able to inspect materials which had been out of reach before. [7]

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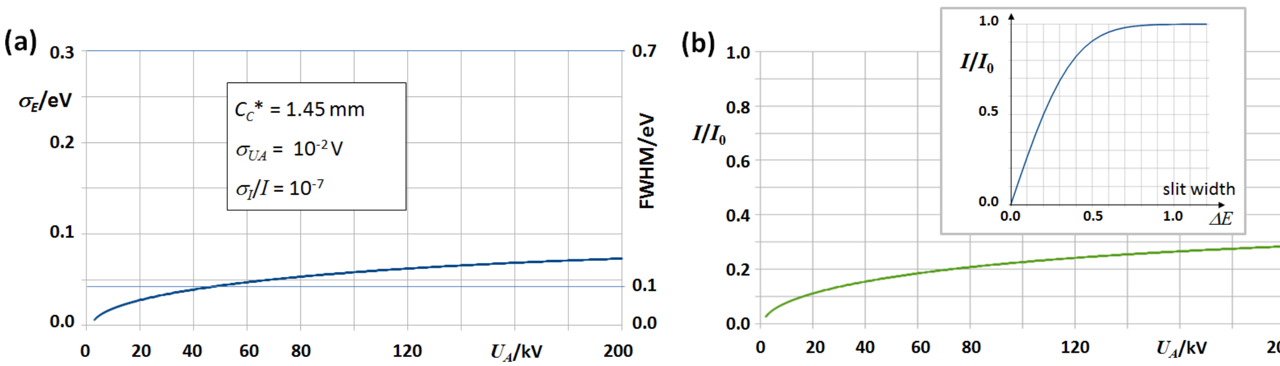

Figure 1. (a) Required energy spread σ_E to achieve a resolution that corresponds to an objective aperture of 50 mrad radius, (b) Relative remaining beam current I/I_0, if a monochromator slit of size ΔE realizes the required energy spread from (a); the inlay indicates how the beam current drops with ΔE.

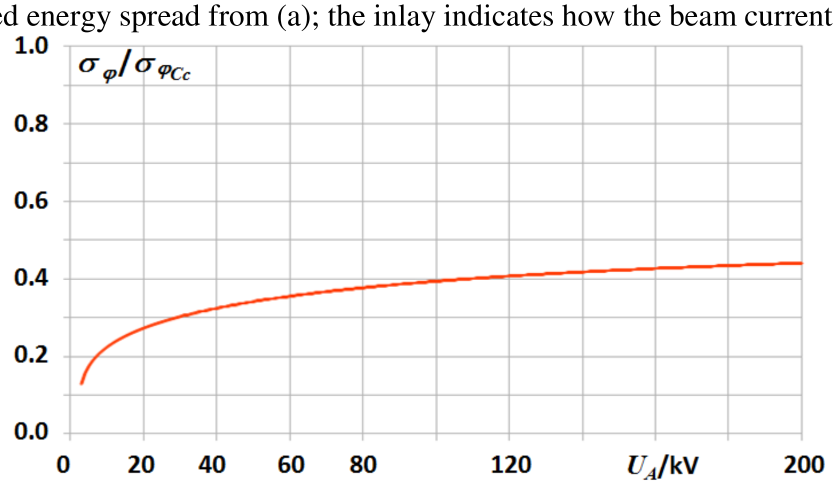

Figure 2. The holographic signal resolution σ_φ decreases strongly compared to the C_C-corrected case $\sigma_{\varphi Cc}$ due to the reduced beam current. Thus, C_C-correction is prerequisite for low-voltage holography.

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