Recent progress in chromatic aberration corrected transmission electron microscopy of nanomaterials

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Whereas the instrumental resolution of a transmission electron microscope (TEM) is now well known to improve appreciably as a result of coherent aberration (C_S) correction, it is also important to minimise incoherent disturbances that can affect image resolution in order to improve the information limit further. Chromatic aberration (C_C) correction promises to improve the spatial resolution and interpretability of images when compared with C_S correction alone. The primary characteristic of a C_C corrected TEM is that the defocus f of an image stays almost constant when the electron energy is changed over a large range. The axial chromatic defocus is given by the expression

$$\Delta f(\Delta E) = C_C \frac{\Delta E}{E_0} \quad (1)$$

where ΔE is energy loss, E_0 is the primary electron energy and Cc is the chromatic aberration coefficient of the objective lens.

For energy-filtered TEM, C_C correction allows large energy windows and large objective aperture sizes to be used without compromising spatial resolution. An important advantage of using large energy windows is that it permits dose-efficient imaging when substantial inelastic scattering is present, in particular for tilt-series tomography if the projected specimen thickness at high tilt angles exceeds the inelastic mean free path. The improved signal-to-noise ratio provided by the use of large energy windows and large objective aperture sizes also facilitates the recording of EFTEM chemical maps on the atomic scale. Figure 1 shows the instrumental resolution plotted as a function of collection angle for EFTEM in both a C_S corrected and a C_S/C_C corrected instrument. C_C correction reduces chromatic broadening by more than two orders of magnitude and provides sub-Ångstrom resolution for the largest energy-selecting slit width and objective aperture size, which are required for good signal-to-noise in thick samples and for high-resolution EFTEM images, especially when the maximum tolerable dose is limited. The fact that the use of small objective apertures and small energy-selecting slit widths to minimise chromatic broadening in energy-filtered images is no longer required in a C_S/C_C corrected microscope is illustrated in Fig. 2, which shows that the resolution in C_S/C_C corrected EFTEM images of CdSe nanoparticles is hardly affected by the choice of energy-selecting slit width.

Furthermore, C_C correction of the Lorentz lens of a TEM allows ferromagnetic materials to be imaged in magnetic-field-free conditions with a spatial resolution of better than 0.5 nm with the conventional TEM objective lens switched off, suggesting that it may be possible to image magnetic fields in selected materials with close to atomic spatial resolution. It also promises to allow large objective lens pole-piece gaps to be used for *in situ* experiments without compromising spatial resolution significantly.

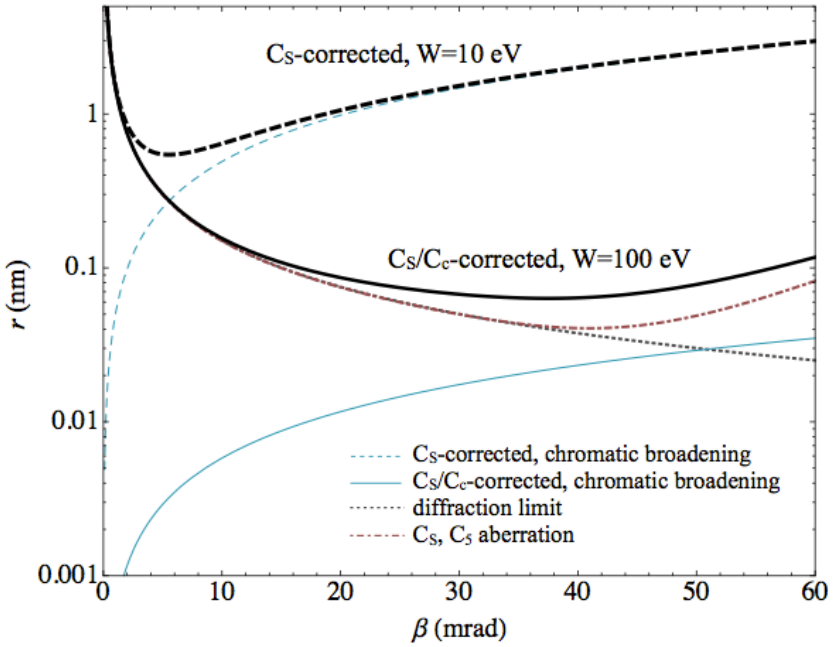

Figure 1. EFTEM resolution r plotted as a function of semi-collection angle β for a C_S corrected instrument and a C_S/C_C corrected FEGTEM at 200 kV (left). The thick dashed line shows the total resolution for the C_S corrected microscope for an energy-selecting slit width of 10 eV, the thick solid line the total resolution of the C_S/C_C corrected microscope for a slit width of 100 eV. Thin blue lines display the contribution of chromatic broadening, the grey dotted line the diffraction limit and the red dot-dashed line the residual delocalisation due to spherical aberration. C_S balances a higher-order spherical aberration C_5 of 4 mm for optimum phase contrast. The total resolution is the sum of the residual delocalisation and the chromatic broadening.

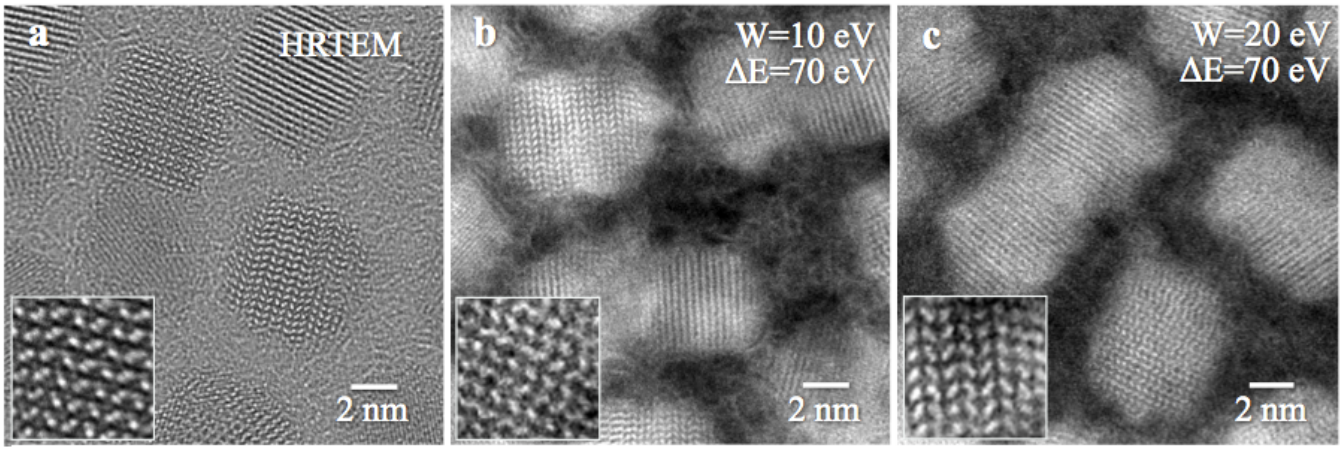

Figure 2. (a) High-resolution image and (b, c) EFTEM images of CdSe nanoparticles on a C support taken at 80 kV in the C_S/C_C corrected PICO instrument in Jülich. The EFTEM images were acquired using energy-selecting slit widths of 10 and 20 eV with an exposure time of 20 s at an energy loss of 70 eV, which includes plasmon losses and the Se $M_{4,5}$ core loss. No objective aperture was used.