Measurement of focal spread, beam divergence and vibration in HREM images

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For the quantitative comparison of high-resolution electron microscope image intensities with simulations, it is important to be able to determine imaging parameters accurately, especially when approaching image resolutions of 0.1 nm using C_S-corrected microscopes. Aberrations such as defocus and astigmatism can be measured from diffractograms calculated from defocus series of images of amorphous specimens [1]. However, the measurement of focal spread, beam divergence and specimen vibration is more difficult, as these parameters have similar effects on axial images. Here, we show that images acquired using tilted illumination can be used to determine these parameters independently.

Focal spread, beam divergence and vibration all attenuate high spatial frequencies in images. The contributions to this attenuation from focal spread and vibration are independent of defocus. Interestingly, when using tilted illumination, there exist 'achromatic rings' in diffractograms, whose radii depend on beam tilt. Focal spread causes no attenuation around these rings, as shown in FIG. 1 [2-3]. The width of each ring depends on the focal spread, allowing the determination of this parameter. For a particular defocus $\Delta f_c = -C_S\theta^2$ (where θ is the beam tilt), the achromatic rings are also unaffected by beam divergence, while at defoci away from Δf_c beam divergence increasingly attenuates transfer, as shown in FIG. 2. Specimen vibration is unaffected by both beam tilt and defocus, and thus still attenuates high spatial frequencies, as shown in FIG. 3.

As a result, focal spread can be determined from the widths of the achromatic rings recorded at defocus Δf_c, beam divergence can be determined from the change in the intensity around each ring measured as a function of defocus, and vibration can be determined from the intensity around each ring measured at defocus Δf_c. The width of each ring measured at Δf_c also changes with beam divergence, but in practice for a field emission gun the beam divergence is much smaller than that shown here. FIG. 4 shows a diffractogram acquired at 300 kV from an amorphous carbon film with tilted illumination, using a microscope with C_S = 0.65 mm. Parts of the achromatic rings are visible, as marked, although these rings are not of equal intensity owing to specimen vibration being asymmetric in the side-entry holder used. The width of each ring is consistent with an energy spread of 1 eV, as shown in FIG. 1b, while the absence of any change in ring intensity with defocus shows that the beam divergence is small, as expected for a field emission gun [4].

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[2] Parsons J.R. and Hoelke C.W. *Phil. Mag.* **30** (1974) 135-143.
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[4] We acknowledge useful discussions with Dr C Hetherington.

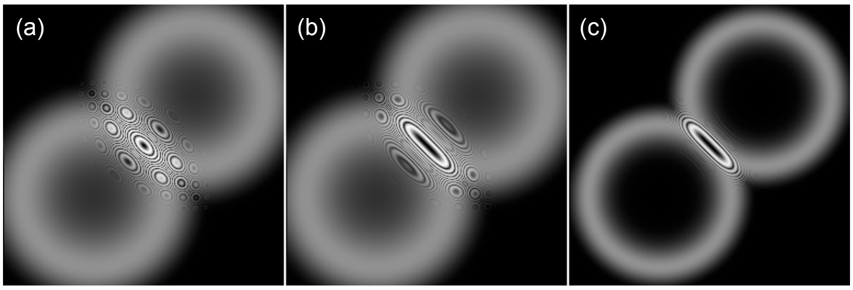

FIG. 1. 300 kV diffractograms simulated for a beam tilt of 20 mrad with C_S = 0.65 mm and no beam divergence.
a) Defocus $\Delta f = -100$ nm, focal spread $\Delta = 2.45$ nm (1 eV energy spread),
b) $\Delta f = -260$ nm, $\Delta = 2.45$ nm,
c) $\Delta f = -260$ nm, $\Delta = 4.9$ nm.

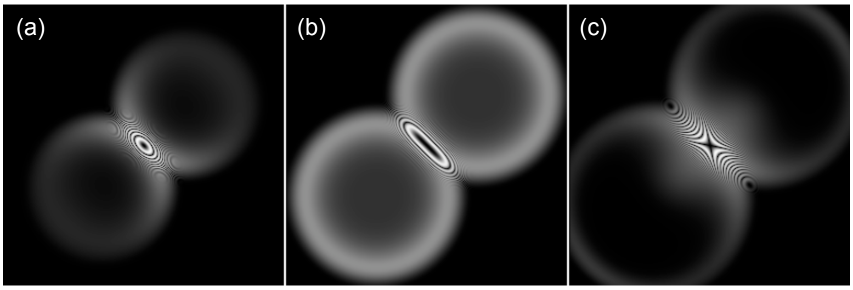

FIG. 2. As for FIG. 1 but for a beam divergence of 0.2mrad.
a) $\Delta f = -100$ nm,
b) $\Delta f = -260$ nm,
c) $\Delta f = -420$ nm.

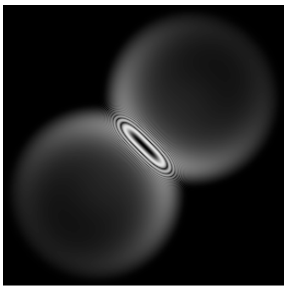

FIG. 3. As for FIG. 2b but for a specimen vibration of 0.015 nm.

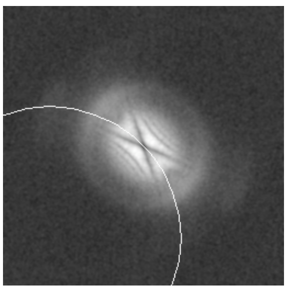

FIG. 4. Experimental tilted beam diffractogram acquired from an amorphous C film, with an achromatic ring marked. Two graphite diffraction rings are also visible.