Ultramicroscopy 118 (2012) 35–43

Contents lists available at SciVerse ScienceDirect

Ultramicroscopy

journal homepage: www.elsevier.com/locate/ultramic

Using a monochromator to improve the resolution in TEM to below 0.5 Å. Part II: Application to focal series reconstruction

P.C. Tiemeijer [a,*], M. Bischoff [a], B. Freitag [a], C. Kisielowski [b]

[a] FEI Company, PO Box 80066, 5600 KA Eindhoven, The Netherlands
[b] National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 7 August 2008
Received in revised form
29 March 2012
Accepted 30 March 2012
Available online 27 April 2012

Keywords:
TEM
Monochromator
Brightness
Focal-series reconstruction

ABSTRACT

We apply monochromated illumination to improve the information transfer in focal series reconstruction to 0.5 Å at 300 kV. Contrary to single images, which can be taken arbitrarily close to Gaussian focus in a C_S-corrected microscope, images in a focal series are taken at a certain defocus. This defocus poses limits on the spatial coherence of the illumination, and through this, limits on the brightness of the monochromated illumination. We derive an estimate for the minimum spatial coherence and the minimal brightness needed for a certain resolution at a certain defocus and apply this estimate to our focal series experiments. We find that the 0.5 Å information transfer would have been difficult and probably impossible to obtain without the exceptionally high brightness of the monochromated illumination.

1. Introduction

In a preceding paper [1], we demonstrated how monochromation can improve the resolution in single TEM images from 0.7 Å to 0.5 Å. There we discussed that TEM illumination of high spatial coherence and high brightness can be created if the image of the energy-dispersed source is focused on the specimen. With this so-called 'Nelsonian' illumination, the coherence angles have circular symmetry even though the beam is not free of dispersion at the exit of the monochromator. In this companion article we put the brightness and the spatial coherence of this illumination further to the test by applying it to focal series reconstruction, in order to improve also the information in the reconstructed exit wave to 0.5 Å. Focal series reconstruction is a desirable technique since the artifacts in the image caused by non-linear imaging [2] are minimized by this technique [3–5], and since it allows using numerical phase plates to correct *a posteriori* possible remaining aberrations [6]. It is equally important that the reconstruction provides the full complex information about the scattering process in the sample itself.

Resolution improvement in focal series reconstruction is more challenging than in single imaging, because of the required stability and especially because of the defocus inherently involved in the images of the focal series. In a C_S-corrected microscope, a single image can be taken at a focus which is almost arbitrarily close to Gaussian focus. In the out-of-focus images of the focal series, however, phase aberrations can become significant and can limit the resolution unless the coherence angle of the illumination is made sufficiently small. In principle, the spatial coherence required in the out-of-focus images can be obtained by sufficiently de-magnifying the beam cross-over in front of the specimen, but this goes at the expense of the beam current. The relation between improvement of spatial coherence and loss of beam current is governed by the brightness of the illumination. We will discuss that, for a given defocus and for a given current per pixel of the camera, the required brightness scales inversely with the fourth power of the targeted resolution. Compared to single imaging, focal series reconstructions benefit from the increased signal-to-noise ratio that naturally comes from combining the multiple images of the focal series, and this increased signal-to-noise ratio reduces the brightness required for a focal series compared to that required for single imaging. However, this holds only as long as radiation damage, specimen drift or other instabilities do not limit the total exposure time.

This paper is structured as follows. In Section 2 we investigate the theoretical relation between defocus, spatial coherence and brightness. In Section 3 we present our experimental results. These results were obtained during the final acceptance tests of the TEAM0.5 microscope at the factory in August 2007 and they were already briefly presented in [7]. The results support the theory developed in Section 2. The paper ends with some concluding remarks.

* Corresponding author. Tel.: +31 6 1208 9765; fax: +31 40 2356655.
E-mail address: p.tiemeijer@fei.com (P.C. Tiemeijer).

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http://dx.doi.org/10.1016/j.ultramic.2012.03.019

2. Brightness and resolution

2.1. Qualitative discussion on defocus and spatial coherence

As discussed in our preceding paper [1], the information limit can be used as an estimate for the resolution when the dampening due to partial spatial coherence is minimal. Let us now investigate in more detail for what optical settings this condition is met. We start with a qualitative discussion using Fig. 1. The figure illustrates for some typical HR-TEM settings how the spatial coherence reduces the contrast transfer function (CTF). Fig. 1(a) shows a typical set-up for an uncorrected TEM. The defocus is set to $F = -500$ nm. This defocus balances the spherical aberration near the information limit. Fig. 1(a) shows the dampening envelope E_S and the CTF for three different values of coherence angle α. As illustrated by this figure, the coherence angle should not increase much above ~0.1 mrad in order to maintain sufficient contrast at intermediate frequencies. Fig. 1(b) shows the curves for the same uncorrected TEM near Scherzer focus, $F = -60$ nm. The defocus does not balance the spherical aberration near the information limit, and the transfer near the information limit is already significantly reduced for coherence angles as small as ~0.03 mrad. Fig. 1(c) shows the graphs for a C_S-corrected TEM at the same defocus $F = -60$ nm. Such a defocus may be encountered in a focal series. The dampening due to the spherical aberration C_S is no longer present and this increases the allowed coherence angle by an order of magnitude compared to the uncorrected TEM. Significant reduction of the transfer starts for angles above ~0.3 mrad. Finally, Fig. 1(d) shows the curves for a C_S-corrected TEM where the defocus has been brought back to only $F = -3$ nm. At this small value, the first zero-crossing of the CTF is near the information

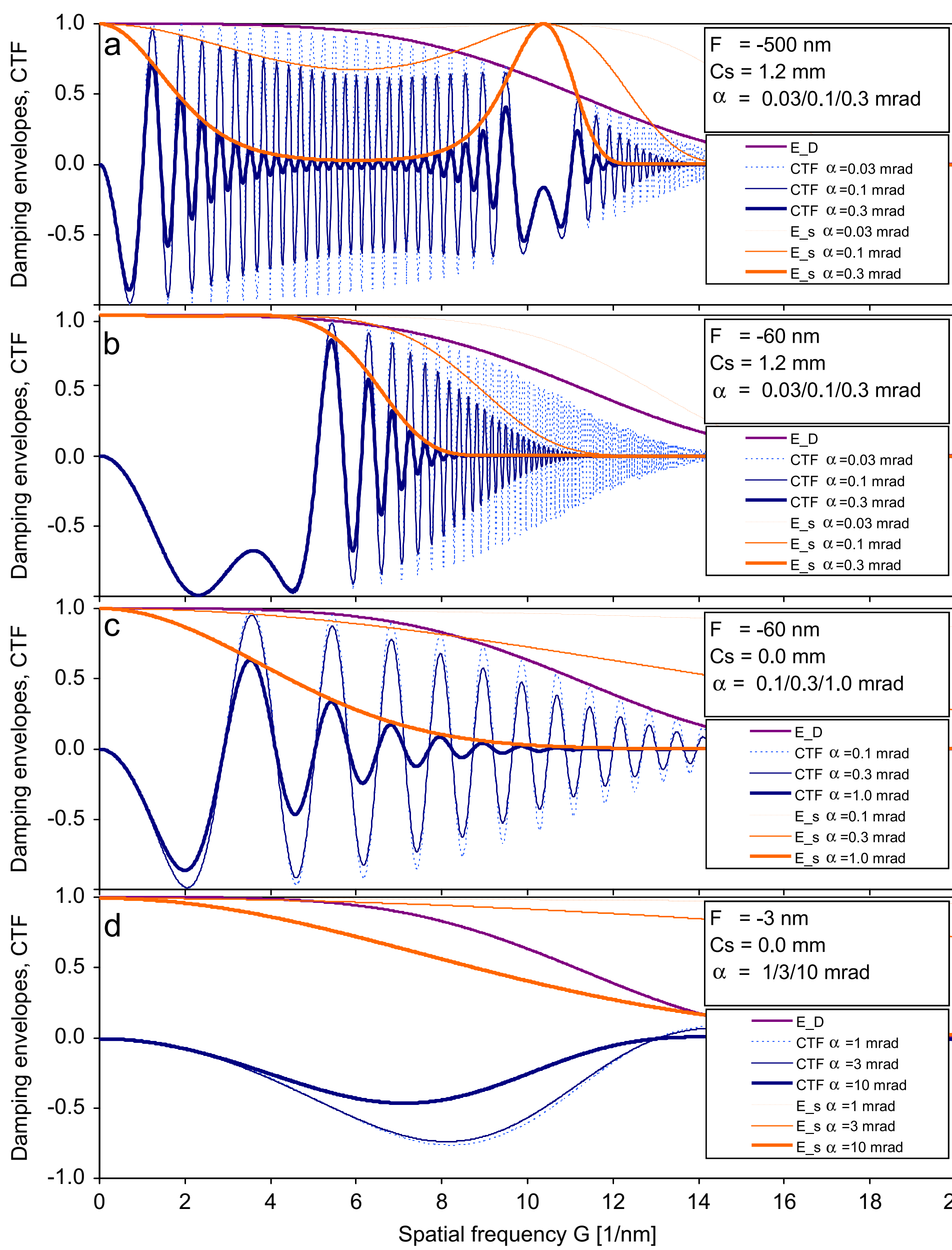

Fig. 1. These graphs show how the coherence angle impacts on the spatial coherence damping envelopes $E_s(G)$ and on the phase contrast transfer function for four typical settings in HR-TEM: (a) uncorrected TEM near the Lichte defocus, (b) uncorrected TEM at the Scherzer focus, (c) corrected TEM at -60 nm defocus, as may be used in a focal series, and (d) corrected TEM close to the Gaussian focus. All graphs are calculated for an information limit of 0.7 Å. Thin broken lines: smallest coherence angle; thin solid lines: medium coherence angle; thick lines: largest coherence angle.