Chromatic Confocal Electron Microscopy with a Finite Pinhole Size

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Chromatic Confocal Electron Microscopy with a Finite Pinhole Size

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Abstract. Scanning confocal electron microscopy (SCEM) is a new imaging mode in electron microscopy. Spherical aberration corrected electron microscope instruments fitted with two aberration correctors can be used in this mode which provides improved depth resolution and selectivity compared to optical sectioning in a conventional scanning transmission geometry. In this article, we consider the depth resolution and energy resolution in the confocal optical configuration for SCEM using inelastically scattered electrons with a finite pinhole size. We experimentally demonstrate energy-filtered optical sectioning in a double aberration-corrected instrument with uncorrected chromatic aberration without using a dedicated energy filter.

1. Introduction
In a state-of-art aberration corrected transmission electron microscope (TEM), the depth of field can be reduced to a few nanometres [1] due to an enlarged numerical aperture. This offers the capability of depth sectioning in the TEM in a similar fashion to confocal scanning optical microscopy [2]. In contrast to widefield microscopy, the confocal geometry provides controllable depth discrimination and reduction of background signal away from the focal plane, as the scattering from points away from the confocal point are detected less strongly than the in-focus scattering, as shown in Fig. 1 a). The confocal mode detecting elastically scattered electrons, which is referred to as bright-field [3] SCEM (or coherent SCEM), was theoretically calculated by Cosgriff et al. [3] and experimentally demonstrated by Nellist et al. [4] on a double aberration corrected TEM/STEM instrument and further investigated by Mitsuishi et al. [5] and Wang et al.[6]. With an addition of an energy filter, Wang et al.[7, 8] have reported an incoherent confocal mode by filtering electrons that have been inelastically scattered with a specific energy-loss in the sample leading to energy-filtered (EF-) SCEM. They experimentally showed that this incoherent confocal geometry preserves depth resolution for a laterally extended object, unlike convention scanning TEM (STEM) imaging. This has been illustrated by considering the 3-D optical transfer function (OTF) [2] where the incoherent confocal mode does not have “missing cone”.

The calculation by Wang et al.[7, 8] further showed that on an instrument with chromatic aberration (Cc) in the post-specimen lenses the confocal geometry with an infinitesimal point-like pinhole possesses a capability of energy selecting with a resolution of ~2 eV even without a physical energy filter present. This makes it possible to carry out EF-SCEM for 3D elemental distribution on instruments that are not fitted with a physical energy filter. In practice, a finite-size pinhole has to be
used to obtain a sufficient signal to noise ratio, as the inelastically scattered electrons often suffer low counts. The extended pinhole size can affect the depth and energy discrimination.

In this paper, we will calculate the effect of the pinhole size on not only the depth resolution, but also the energy resolution in particular. We also experimentally illustrate the depth and energy discrimination in the confocal mode without an energy-filter using a through focal series of probe images recorded at the pinhole plane.

2. Energy filtered SCEM

To quantitatively examine the effective depth and energy resolution in EFSCEM, the plane-spread function or z−response of the SCEM for scattering by a planar film needs to be calculated. For a completely incoherent scattering object function \( V(R) \) located at a height, \( z=0 \) and in the confocal condition, the three-dimensional SCEM image intensity [4] can be written as:

\[
I(R, z) = \int V(R) \left| P_1(R - R, z) \right|^2 \left| P_2(R, -R, -z) \right|^2 dR
\]

where we have used the notation given in Reference[4]. Therefore, the point spread function (PSF) for incoherent confocal imaging is:

\[
PSF(R, z) = \left| P_1(R, z) \right|^2 \left| P_2(-R, -z) \right|^2
\]

Using the reciprocity principle and the symmetry of the confocal configuration, the probe function \( P_2 \) can be considered as a virtual probe that would be formed by the post-specimen optics from a hypothetical source at the pinhole [4]. In this incoherent confocal mode, the pinhole can be treated as an incoherent virtual source in the same way as the finite source size. Therefore the PSF with the finite-size pinhole can be calculated as:

\[
PSF(R, z) = \left| P_1(R, z) \right|^2 \left| P_2(-R, -z) \right|^2 \otimes D(R)
\]

where \( D \) is the circular pinhole function or top-hat function and \( \otimes \) is the notation for convolution of the coordinate \( R \). To setup a confocal condition for an energy loss of interest \( \Delta E_{\text{loss}} \), an increment of \( k\Delta E_{\text{loss}} \) in the accelerating voltage \( E_0 \) needs to be introduced, where \( k = Cc_2 / (Cc_1 + Cc_2) \) (\( Cc_1 \) and \( Cc_2 \) are the chromatic coefficients of the pre- and post-specimen optics, respectively) [7]. The SCEM PSF can be further written [8] as:

\[
PSF(R, \varepsilon) = \left| P_1(R, z) \right|^2 \left| P_2[-R, -(z + \frac{\varepsilon}{E_0} Cc_2)] \right|^2 \otimes D(R)
\]

where a parameter, \( \varepsilon \), which gives the deviation in the energy of scattered electrons from the desired energy loss \( \Delta E_{\text{loss}} \). The additional term of \( \frac{\varepsilon}{E_0} Cc_2 \) is included to take into account of focal spread at the pinhole plane due to the \( Cc_2 \) in the post-specimen lenses as shown in Fig. 1 b).

The EFSCEM z−response for a planar object for an energy loss with a deviation of \( \varepsilon \) from \( \Delta E_{\text{loss}} \) can be written as:

\[
Z_{\text{SCEM}}(z, \varepsilon) = \int \left| P_1(R, z) \right|^2 \left| P_2[-R, -(z + \frac{\varepsilon}{E_0} Cc_2)] \right|^2 \otimes D(R) dR
\]

By integrating over all possible energy deviations (\( \varepsilon \)) or all possible heights (\( z \)) of a scattering plane in Eq. 4, we obtain the z−responses or the energy filtering response, as shown in Fig. 1 c) and d), respectively, as a function of the pinhole size. Both the z−response and the energy-response are deteriorated with the increase of the pinhole size. Without a pinhole (or when the pinhole size is \( \infty \)), Eq. 4 is degraded to

\[
Z_{\text{STEM}}(z) = \int \left| P_1(R, z) \right|^2 dR
\]
which is the z-response for the STEM imaging [8]. Due to the total intensity of the beam propagating through the plane for each value of \( z \) being constant, \( Z \) is constant and hence the depth discrimination for a planar object completely disappears, as shown as the dotted black curve (···) in Fig. 1 c) . As a result, Eq. 6 is no longer a function of the energy deviation (\( \varepsilon \)), so that there is no energy response as shown as the dotted black curve (···) in Fig. 1 d).

\[
\Delta z = \frac{k \Delta E_{\text{loss}} \cdot C_{c2} / E_0}{E}\n\]

**Figure 1** shows schematic diagrams of confocal trajectory illustrating the depth a) and energy loss b) discriminations given by a pinhole. It not only can reject the out-of-focus ray (----) in a) to improve depth resolution, but also can select the beam (—) with an energy loss \( \Delta E \) of interest and excludes the beams (---) and (···) with an energy deviation of \( \pm \varepsilon \) in b) due to \( C_c \) in the post-specimen optics. c) and d) show the z- and energy-response for different values of the pinhole size in diameter, respectively.

### 3. Experimental optical sectioning without an energy filter

To experimentally examine the z- and energy-response without an energy filter, we used a 2-D carbon thin film as a sample and setup a confocal condition for an energy loss of the carbon K-edge using the approach described in Ref [7, 8]. Fig. 1 b) shows that the post-specimen optics images the incident probe on the sample to form a probe image on the pinhole plane. Due to the absence of an energy filter and the residue \( C_{c2} \) in the post-specimen optics, the probe image was formed by all the electrons experiencing elastic and (or) inelastic scattering. By replacing the pinhole with a Gatan CCD camera, Fig. 2 show the probe images at the pinhole plane, with the 2-D carbon film at the confocal point a), 93nm b) and 106 nm away from the confocal point along the z direction, respectively. It is clear to see that the electrons which suffered the energy loss of carbon K-edge formed the bright and sharp central peak labeled with a red arrow, as shown in Fig 2 a), whereas the zero-loss beam was largely under-focused by \( \Delta z = k \Delta E_{\text{loss}} \cdot C_{c2} / E_0 \) and formed the majority intensity of the background disc. This experimentally illustrates that the electrons that undergo different energy loss with the energy deviations (c) from \( \Delta E_{\text{loss}} \) (here \( \Delta E_{\text{loss}} \) is the carbon K-edge), became out-of-focus at the collection plane, as shown in Fig. 1 b). By inserting the pinhole, it is feasible to reject or detect less strongly the electrons with other energy loss to give energy discrimination. As predicted in Fig. 1 d), the pinhole size determines the energy resolution.

Fig. 2 d) shows line-profiles across the central peaks in the probe images as shown in Fig. 2 a), b) and c), respectively. As the specimen was moved away the confocal point, only the signal at the central peak in the probe image dropped off, whereas the intensities of the background disc remained relatively unchanged. This is because the electrons which contributed to the background had been largely defocused at the pinhole plane. Therefore, the variations of the sample heights only gave small and local fluctuations in the background, as shown in Fig. 2 a), b) and c). However, the sharp central peak, which was formed by the electrons with the energy loss in the confocal condition, was sensitive to the height variations. As the sample was moved away from the confocal point, the scattered
electrons became out-of-focus at the collection plane, which gave the apparent signal drop-off, as shown in Fig. 2 d). Virtual pinholes with diameters of 0.03 (single pixel of the CCD) and 0.5 nm were applied to a through focal series of the probe images by integrating the intensities within a circular region centred at each central peak. Fig. 2 e) shows that the larger the pinhole is used, the worse the depth resolution is. In an extreme case where the virtual pinhole is infinitely large, all the intensities of the probe images are integrated as shown as the dotted black curve (⋯) in Fig. 2 e). As predicted by Eq. 6, the system was revert to the conventional STEM imaging case and no z-response exists, which consists with the dotted black curve (⋯) as shown in Fig. 1 c). Because of the integration of all the electrons, the energy response also disappears, as predicted in the dotted black curve (⋯) as shown in Fig. 1 d).

**Figure 2** a) shows experimental probe images formed through a carbon film in the EFSCEM mode for the carbon K-edge without an energy filter, when the film is just at the confocal point a), 93 b) and 106 nm c) away from it, respectively. d) line-profiles across the centre peaks, labelled with a red arrow, in a), b) and c), respectively. e) shows an optical sectioning z line scan with the virtual pinhole with diameters of 0.03, 0.5, 2 and ∞ nm, respectively.

4. Conclusion
We showed the mechanisms of the depth and energy discriminations in EFSCEM on a chromatic electron microscope without an energy filter. We theoretically calculated that the depth and energy resolution can be controlled by the pinhole size, allowing the operator to trade image and energy resolution versus signal to noise ratio, which are further proved by the experimental optical sectioning using a through focal series of the probe images recorded on the CCD without an energy filter.

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