An Approach toward Phase Electron Microscopy

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Many samples in electron microscopy are phase objects as in the case of optical microscopy, for which Zernike has introduced a phase plate. However, it has been difficult to realize a phase plate in electron microscopy. Thus, Scherzer proposed a simple technique to realize a phase plate approximately by adjusting the defocus against to a spherical aberration. Recently, a Cs-corrected HRTEM becomes commercially available. However, a phase object cannot be observed ideally at the Scherzer defocus using a Cs-corrected machine, since an information transfer determined by the phase contrast transfer function is not uniform.

On the other hand there are some algorithms to reconstruct a wave front (complex wave function) from a series of through-focus images. The maximum likelihood method [1] and the Wiener filter method [2] usually use about twenty images, while the Gerchberg-Saxton type iteration method [3] requires normally five images. All of these techniques use a series of images taken at a wide defocus range, and thus recover also low frequency components that will not be recorded in the image taken at the Scherzer defocus. After or during a wave front reconstruction, we can correct any aberrations including spherical aberration, and use information beyond the Scherzer limit. However, using these techniques it is difficult to obtain phase information in real time, since they require a series of images taken at a wide defocus range.

Contrary to these techniques Teague [4] showed that the phase might be determined by measuring only the intensity by using a so-called Transport of Intensity Equation (TIE):

$$\frac{2\pi}{\lambda}\frac{\partial}{\partial z} I(xyz) = -\nabla_{xy} \bullet \left(I(xyz)\nabla_{xy}\phi(xyz)\right) \qquad (1)$$

This corresponds to an imaginary part of the Schrödinger equation under the small angle (paraxial) approximation. This equation says that a phase distribution on a specific plane may be estimated from an intensity distribution and its derivative along the wave propagation direction on the plane. Using three images taken with a fixed defocus step the intensity derivative at the middle image plane can be estimated from two images at both sides. It was shown recently this procedure could be applicable to evaluate a phase distribution at atomic resolution [5].

In this report we will show that a good qualitative result can be obtained by using only two images. In this case we estimate a derivative at the mid plane from a difference between observed two images, and an image intensity at the mid plane from a mean between two images. Here, we use a set of twenty-five images (#1 to #25) of Au obtained with a focus step of 2.4 nm using a Philips CM300 with FEG at NCEM. FIG. 1 shows an example that compares the phase distributions that were obtained from three images, namely #1, #3 and #5, and two images (#1 and #5) only. As you may note there is no significant visual difference. These phase distributions were calculated by using the software, QPt for DigitalMicrograph [6], which was developed based on the algorithm proposed by Paganin and Nugent [7]. FIG. 2 shows a result obtained from another two images (#12 and #16). The difference between the two phase-distributions will reflect structure changes during an observation period. Provided that we have an enough computing power, we can obtain a phase image at each image acquisition, if we measure image intensity at two image planes back and forth [8]. By simply pressing the button a more quantitative phase distribution may be obtained by using three images within a similar computing time. We may note that we can correct a spherical aberration in real time, and use information more evenly than using a Cs-corrected machine.

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[9] The author greatly acknowledges Dr. Christian Kisielowski for providing the Au data.

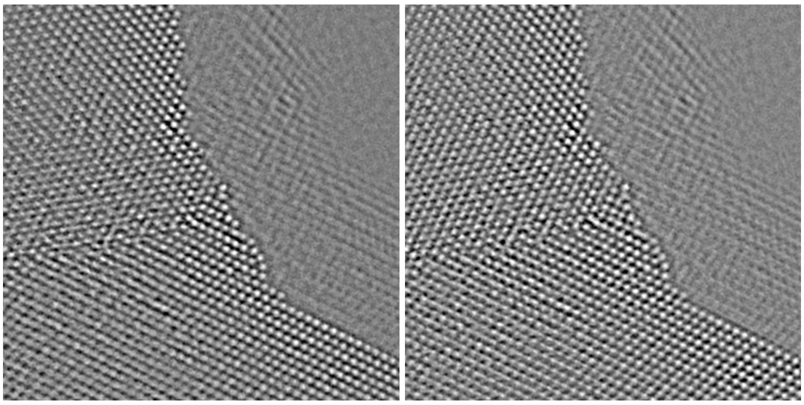

FIG. 1. Phase distributions obtained using three images (left) and two images.

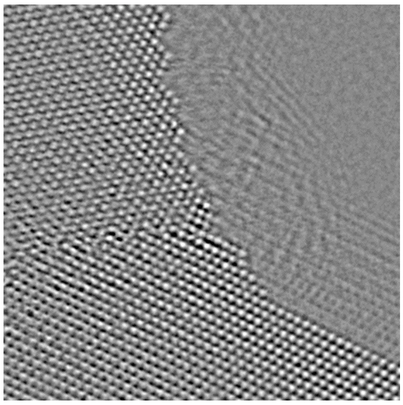

FIG. 2. Another phase distribution.