552
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Object-Wave Reconstruction by Carbon Film-Based Zernike- and Hilbert-Phase Plate Microscopy: A Theoretical Study not Restricted to Weak-Phase Objects

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Recent advances in the application of physical phase plates (PP) have opened up novel imaging possibilities in transmission electron microscopy (TEM). However, any image in TEM corresponds to the absolute square of the aberrated object-wave function, which causes a complete loss of phase information. Besides electron holography and through-focal series reconstruction a novel technique was proposed to recover the object-wave function by the use of a PP [1]. This technique, which is not restricted to weak-phase objects and linear image formation, requires three images to be taken at different arbitrary phase shifts induced by a centrosymmetric, matter-free, ideal PP. Nonlinear image contributions are effectively eliminated in the differences of two images obtained at different phase shifts. Taking into account the contrast transfer function, the object-wave function can be derived from analytical expressions. While some electrostatic approaches [2] aim at the realization of an ideal PP, amorphous carbon (a-C) film-based PPs are always affected by the scattering of electrons within the a-C film. This causes a reduction of the amplitude of the electrons coherently scattered in the sample, denoted as damping in the following. Moreover, characteristic image artefacts are produced by noncentrosymmetric approaches such as the Hilbert-PP. Phase-contrast images taken by noncentrosymmetric and/or a-C film-based PPs therefore have to be corrected with respect to undesired effects induced by the PP, before object-wave reconstruction is possible.

Zernike-PPs are realized by an a-C film located in the back focal plane of the objective lens [3]. Depending on the a-C film thickness, Zernike-PPs induce a damping and phase shift of the scattered electrons with respect to the zero-order beam, which passes through a central hole in the film. Within the weak-phase object approximation (WPOA), the damping of the scattered electrons can be corrected quite intuitively by dividing all spatial frequencies except for the zero-order beam in the Fourier-transformed phase-contrast image by the damping coefficient of the a-C film. However, this procedure is inappropriate if nonlinear image formation becomes significant. The consideration of nonlinear image contributions, which are damped twice with respect to the linear terms, results in a system of equations that can be solved using three phase-contrast images at different phase shifts induced by Zernike-PPs with different a-C film thickness. Other imaging parameters like defocus, spherical aberration coefficient and exposure time have to be identical in all images. The solution of the equations yields three corrected images corresponding to those taken by an ideal PP and suitable for object-wave reconstruction.

Hilbert-PPs are realized by an a-C film, which covers half of the reciprocal space. The damping induced by the a-C film occurs in combination with characteristic image artefacts due to the noncentrosymmetric PP design. Recently proposed correction methods using two images of the specimen are restricted to the WPOA [4]. Taking into account nonlinear image formation, one conventional bright-field and four “half-plane” images are required to correct phase-contrast images taken by an a-C Hilbert-PP. To obtain the “half-plane” images one half of the reciprocal space is alternately covered by the Hilbert-PP or totally obstructed. Again the solution of the corresponding system of equations provides three corrected images at different phase shifts suitable to recover the object-wave function. Moreover, the special case of an anamorphotic Hilbert-PP [5] will be discussed, where only four images of the specimen are required for object-wave reconstruction.

The validity of the presented correction methods is demonstrated for simulated high-resolution TEM images of crystalline Si in a [100]-zone axis orientation. All simulations were performed using a nonlinear image formation formalism. Since there are no restrictions to weak-phase objects and linear image formation, the correction process is carried out for different specimen thicknesses from 1.1 nm to 21.7 nm. For each step in specimen thickness, three phase-contrast images are simulated assuming three Zernike-PPs with different a-C film thickness. Moreover, one conventional bright-field and four “half-plane” images are calculated to correct phase-contrast images taken by an a-C Hilbert-PP. The corrected images are compared to reference images simulated for an ideal PP. FIG. 1(a) shows the mean deviation in percent between the reference images and phase-contrast images corrected by the presented novel methods as a function of the specimen thickness. Negligible deviations demonstrate the suitability of the corrected phase-contrast images for object-wave reconstruction. To illustrate the limitations of the WPOA, the phase-contrast images are for comparison corrected by the correction methods proposed for weak-phase objects (FIG. 1(b)). The deviation increases rapidly as soon as nonlinear image formation becomes significant.

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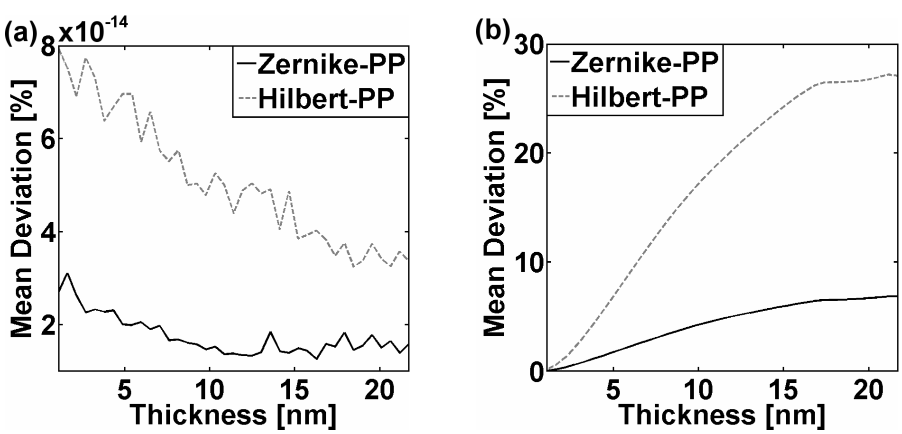

FIG. 1. Mean deviation in percent between corrected phase-contrast images simulated for an a-C Zernike-PP (Hilbert-PP) and reference images calculated assuming an ideal PP as a function of the specimen thickness for Si in [100]-zone axis orientation.
(a) Correction by presented methods, (b) correction by methods proposed for weak-phase objects [4].