Object wave reconstruction by carbon-film-based Zernike- and Hilbert-phase plates

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Recently several types of physical phase plates (PP) were applied to enhance the contrast of weak-phase objects in a transmission electron microscope. However any image in transmission electron microscopy (TEM) represents the absolute square of the aberrated object wave function, while phase information is lost. Besides electron holography and through-focal series reconstruction a new technique was proposed to recover the amplitude and phase information of an arbitrary object wave function by the use of a PP [1]. This new 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 an axially symmetrical, matter-free phase shifting device. While some electrostatic approaches [2] are close to realize such an idealized PP, images taken by the use of amorphous carbon (a-C) film-based PPs are always affected by scattering in the a-C film. The corresponding reduction of the amplitude of the electrons coherently scattered in the sample, denoted as damping in the following, thus needs to be corrected before object wave reconstruction.

Zernike-PPs can be realized by an a-C film which causes a phase shift and a damping of the diffracted electrons with respect to the undiffracted beam that passes through a hole in the film [3]. In the weak-phase object approximation the damping of the diffracted electrons can be corrected by dividing all spatial frequencies except for the undiffracted beam of the Fourier transformed image by the damping coefficient of the a-C film. However this correction is inappropriate for objects where nonlinear image formation becomes significant. For nonlinear image formation it has to be considered that the nonlinear image contributions are damped twice with respect to the linear terms. This results in a system of equations that can be solved using three damped images at different arbitrary phase shifts and the damping coefficients of the a-C film Zernike-PPs. Other parameters like defocus, spherical aberration and exposure time have to be identical in all three images. The solution of the equations yields three corrected undamped images at different phase shifts that can be used for object wave reconstruction.

Hilbert-PPs can be realized by an a-C film which covers half of the reciprocal space. Images that are taken using a Hilbert-PP have to be corrected with respect to the special geometrical properties and damping before object wave reconstruction is possible. Recently proposed correction methods using two images only hold in the weak-phase object approximation [4]. For nonlinear image formation four “half-plane” images and one conventional image are needed. To obtain the “half-plane” images one half of the reciprocal space is alternately covered by the Hilbert-phase plate or blanked out. Again all other parameters have to be identical in the five images. Using the damping coefficient of the a-C film the appropriate system of equations can be solved for three images at different phase

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shifts that correspond to those of an axially symmetrical, matter-free PP and can be used for object wave reconstruction.

Moreover the special case of an anamorphotic Hilbert-PP [5] will be discussed, where only four images are needed to correct the geometrical properties.

The validity of the proposed correction methods is demonstrated for simulated high resolution TEM images of crystalline Si in a [100]-zone axis orientation for different sample thicknesses between 1.09 nm and 10.9 nm. All simulations were performed using a nonlinear image formation formalism. Besides the three damped images needed for correction in the case of an a-C film-based Zernike-PP, one conventional and four “half-plane” images were calculated to perform the proposed correction method in the case of an a-C film-based Hilbert-PP. The corrected images were compared to appropriate ones simulated for an idealized, axially symmetrical, matter-free PP. Fig.1(a) shows the mean deviation in percent between images that were corrected by the methods proposed in the weak-phase object approximation and images simulated for an idealized PP as a function of the sample thickness. The deviation increases rapidly with increasing specimen thickness and increasing significance of nonlinear image formation. Images that were corrected by the presented methods agree well with the appropriate ones simulated for an idealized PP (Fig.1(b)) and thus can be used for object wave reconstruction.

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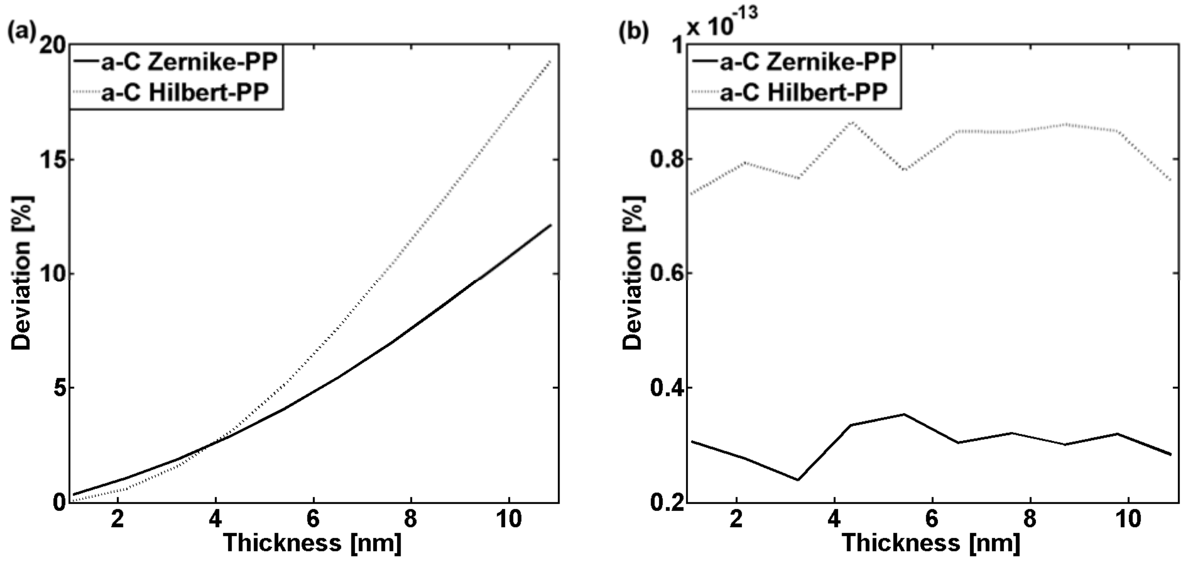

Figure 1. Deviation in percent between corrected images simulated for an a-C film-based Zernike-PP (a-C film-based Hilbert-PP) and appropriate images simulated for an idealized axially symmetrical, matter-free PP as a function of the sample thickness for Si in [100]-zone axis orientation.
(a) Correction by the methods proposed on the basis of the weak-phase object approximation. The deviation increases with increasing significance of nonlinear image formation.
(b) Correction by the presented methods with negligible deviation due to numerical issues.

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