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Imaging with a hole-free phase plate

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Amongst the various ideas that have been brought forward during the latest revival of electron phase plate imaging [1,2], we have proposed the "hole-free phase plate" (HFPP) concept [3]. In this design, the phase shift between the low- and high-frequency parts of the object spectrum is achieved by the localized charging induced by the transmitted beam impinging on a continuous thin film placed in the back focal plane. The proposed design offers several advantages over conventional phase plates (PPs): i) the charged area, comparable in size with the central spot, is automatically centred; ii) charging, the primary obstacle preventing large scale implementation of PPs so far, is turned into an advantage; iii) any microscope can accommodate a HFPP; iv) replacing an exhausted HFPP is accomplished by moving the same film by a few microns. Similarly to most other PP designs, HFPP imaging provides in-focus phase contrast resulting in imaging dose reduction at constant resolution and SNR. Drawbacks of the HFPP are the difficulty in keeping the charge under control, resulting in lack of tunability, and the peculiar image intensity that appears to combine the clean Zernike phase contrast with fringes reminiscent of Fresnel imaging. The aim of this paper is to study more in detail image formation with a HFPP, and compare it with other imaging methods to illustrate the benefits and drawbacks just mentioned.

The HFPP functionality can be summarized as follows: i) the electron beam generates a positive charge distribution, most likely due to secondary electron emission, that is compensated by negative charges located nearby; ii) once the charge distribution reaches an equilibrium, subsequent electrons travel across regions where the electrostatic potential varies in space; iii) as a consequence, a Zernike-type phase shift arises between the low-*q* and high-*q* regions of the spectrum, resulting in phase contrast. Image formation with a HFPP can be treated conventionally by a transmission function $f(q)$ that becomes an extra term $\exp[if(q)]$ in the transfer function $\exp[i\chi(q)]$ since the HFPP is located in the focal plane. We consider two scenarios for the HFPP $f(q)$: in A, the positive beam-induced charge is compensated by remote charges, possibly located on the grid, electrical contacts, or inner walls of the column; in B, the positive charge accumulates at the surface of the film and is compensated by negative charges in the metal underneath. The transmission functions corresponding to scenarios A and B are, respectively,

$$f_A(q) = C_E V_A R\left[-\frac{q^2}{q_c^2}u(q_c - q) + \log\left(\frac{q_c}{q} - \frac{1}{2}\right)u(q - q_c)\right], \qquad f_B(q) = C_E V_B R\ \mathrm{Re}\left[\frac{2}{\pi}E\left(\frac{q^2}{q_c^2}\right) - 1\right], \qquad (1)$$

while $\chi(q)=0$. In equations (1), $V_{A,B}$ are the maximum potentials generated by the charge distribution (modelled as a constant charge density over a disk of radius R), $u(x)$ is a unit step function, and $E(x)$ is the complete elliptic integral of the second kind. HFPP image simulations will be compared to a conventional Zernike phase plate (ZPP), where $\chi(q)=0$ and $f(q)=\phi_Z u(q-q_c)$, with q_c the cut-on spatial frequency associated with the hole radius and ϕ_Z the Zernike phase shift, and with Fresnel images, where we have $\chi(q)=\pi\lambda Z q^2$ (Z is the defocus, λ is the electron wavelength) and $f(q)=0$.

Figure 1 shows two snapshots extracted from a movie that was recorded while the HFPP was settling. The initial bright field image in on the left shows a set of Au nanoparticles appearing as dark dots due to diffraction contrast. The corresponding diffractogram is consistent with a very small amount of defocus, or none at all. The image on the right, recorded after about 2 minutes, shows the Au particles as bright dots, while the corresponding diffractogram reveals that the transfer function has been modified by the build-up of charges on the HFPP, as Thon rings have appeared.

Figure 2 shows a set of image simulations where a 4 nm Au nanoparticle is visualized in various imaging modes. The bright field reference image (a) shows mainly amplitude contrast, and is representative of Fig. 1(a). If we used an ideal ZPP, the dark contrast of the particle would be reinforced, as shown in 2(b). On the other hand, a HFPP within scenario B (local compensating charges) would reverse the contrast and make the Au particle look bright over a darker background, as shown in 2(c). The expected appearance of the particle in HFPP mode within scenario A (remote compensating charges) is more complicated due to the long-range modifications to the transfer function that result in the appearance of intensity oscillations, as shown in 2(d). In conclusion, if the beam-induced charge is positive, compensating charges are not too far away, and the resulting potential peaks around 1-2 V, the HFPP behaves similarly as a $3\pi/2$ ZPP, providing a strong and localized bright peak in the image intensity associated with phase objects [4].

References

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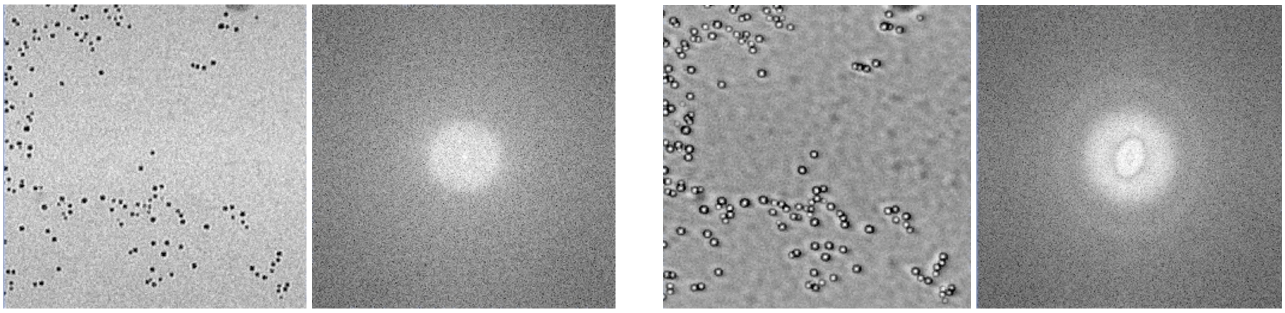

Figure 1. *Representative experimental images without (left) and with (right) HFPP Au nanoparticles. The modification of the transfer function induced by the HFPP (which in this case was made of Germanium) is visible from the diffractogram on the right hand side of each micrograph.*

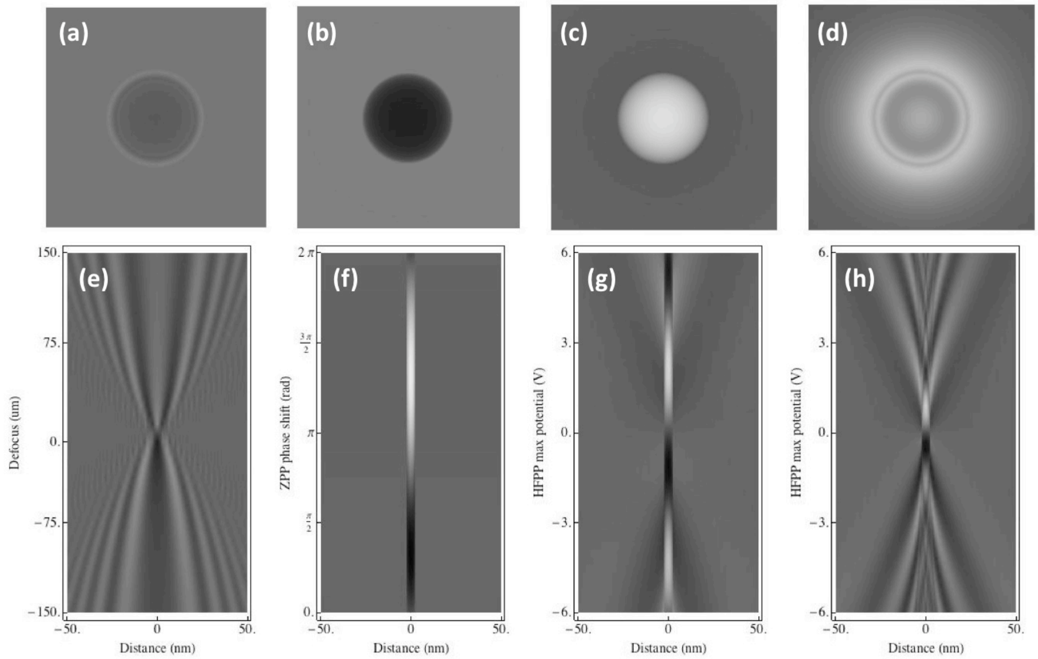

Figure 2. *Top row (a-d): image simulations for a 4 nm diameter Au nanoparticle (20 V mean inner potential) as visualized in bright field (a, Z=50 nm, amplitude variation 20%), ZPP mode (b, $\phi_Z=\pi/2$), HFPP mode scenario B (c, V_B=1.4 V), HFPP mode scenario A (d, V_A=1.4 V). Bottom row (e-h): tableaus of image intensity profiles for varying parameters defocus (e), Zernike phase shift (f), V_B (g), V_A (h).*