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Hybridization of Off-Axis and In-line High-Resolution Electron Holography

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Reconstruction of the complex-valued wave function that gives rise to the probability density of fast electrons in transmission electron microscopy (TEM) seems, at first glance, to be a solved problem. However, it is still challenging when considered more closely. In conventional TEM experiments, only the intensity *(i.e.,* the square of the amplitude) of the wave function can be measured. Direct information about the phase of the wave, which carries information about electrostatic and magnetic fields that the electron has passed through, is lost during detection. In order to recover the phase information, it is necessary to interfere the electron wave function with a reference wave, in order to create an interference pattern. Denis Gabor introduced an approach that could be used to solve this problem 66 years ago [1]. In Gabor's original setup, which is the pioneering scheme for in-line holography, the wave that has been scattered by the specimen (the object wave) interferes with a reference wave propagated along the same axis. Using laser light, Leith and Upatnieks [2] showed that separation of the axes of propagation of the reference and object waves could be used to solve the twin-image problem. Möllenstedt later translated this idea back to electron microscopy, creating the field of off-axis electron holography [3,4].

In-line electron holography, or focal series reconstruction, is now a common method in high-resolution TEM. Although it is very efficient for recovering high spatial frequecny variations in phase, it is inefficient for recovering phase information at low spatial frequencies. In contrast, high-resolution studies are very challenging for off-axis electron holography because the interference fringes must be at least twice as fine as the finest feature of interest in the object to be resolved in the reconstructed wave function. Decreasing the fringe spacing typically increases the noise level for a fixed source brightness, illumination ellipticity and exposure time.

Here, we present a new approach that combines off-axis and in-line holography and allows reliable phase information to be recovered for all spatial frequencies up to a resolution that is approximately twice as high as that obtained in a traditional off-axis electron holography experiment. For a desired signal-to-noise ratio, the required total exposure time is lower than that for traditional high-resolution off-axis electron holography.

Figure 1 shows preliminary results obtained using an FEI Titan TEM operated at 300 kV. All holographic data was acquired using round illumination. For off-axis electron holography, the biprism voltage was set to 97.4 V.

Figures 1a, b and c show phase images of a gold particle obtained using in-line electron holography, off-axis electron holography and a combination of the two signals, respectively, for a total exposure time of 16 s. In Figure 1d, power spectrum analysis reveals the increased resolution of the hybrid approach. The power spectrum is consistent with off-axis electron holography (Fig. 1b) for low spatial frequencies and with in-line electron holography (Fig. 1a) for high spatial frequencies. Although the noise level in the vacuum region is slightly higher than for in-line electron holography (0.055π vs. 0.046π), the recovery of low spatial frequencies is far better than for in-line holography alone. Such noise levels are difficult to achieve using off-axis holography for the exposure time utilized here.

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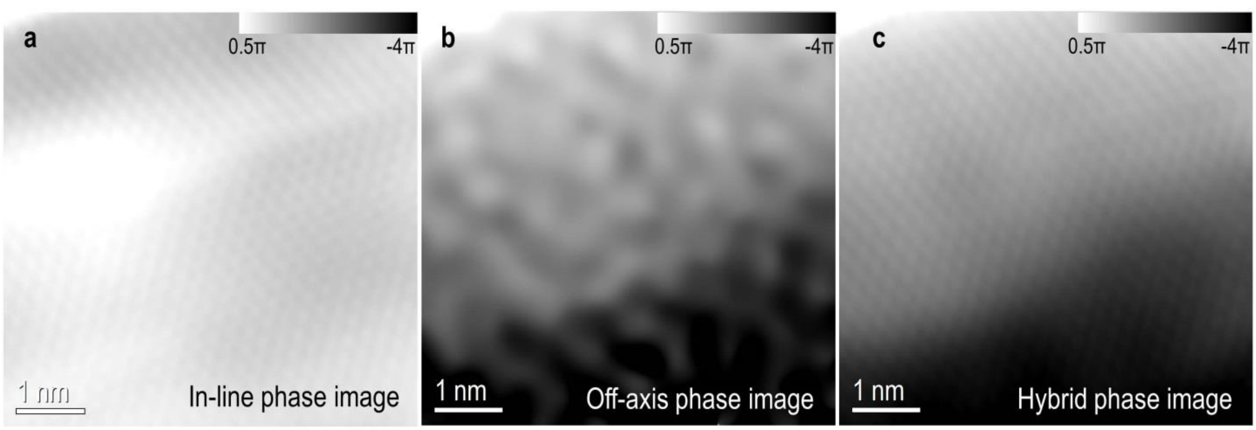

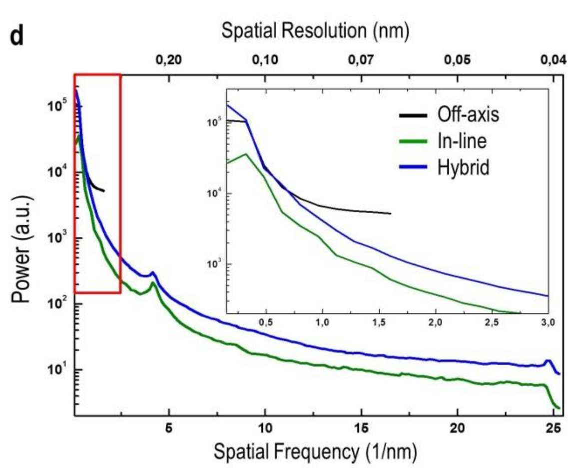

Figure 1. a)-c) Reconstructed phase from in-line, off-axis and hybrid methods, respectively. d) Power spectrum of the phase reconstructed using each method. The low frequency region marked by the red box is enlarged in the inset to show that with the hybrid method (blue) recovers both the low frequencies from the off-axis method and the high frequencies from the in-line method.

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