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Low-Voltage Atomic-Resolution Off-Axis Holography on Hexagonal Boron Nitride

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Off-axis electron holography is a powerful method that can access the phase shift of the electron wave from only one single electron micrograph [1]. Its capabilities have been proven in numerous applications [e.g. 2]. After hardware C_S-correction has found to be very beneficial for holography to improve the signal resolution in the reconstructed phase shift [3], the chromatic aberration C_C remains the limiting factor for low-voltage high-resolution holography. Recently, off-axis holography had been set up in the TEAM I microscope to allow recording holograms in a C_C-C_S-corrected TEM [4]. Since no monochromator is required to reduce the resolution-limiting focus spread due to chromatic aberration, the full beam current is available and high-quality holograms with atomic resolution can be recorded at low voltages such as 80 kV.

In general, low-voltage imaging capabilities have attained a lot of attention since the lower electron energy avoids knock-on damage, which is especially important for light elements. Here, we exemplify the capabilities of C_C-corrected low-voltage off-axis holography on hexagonal boron nitride (h-BN).

Figure 1a shows an 80 kV high-resolution hologram of h-BN, which is only one single member of a time series of 31 frames. Since the underlying phase shifts are so extremely small, virtually no bending in the interference fringes can be observed. Due to the great instrumental stability, exposure times of eight seconds can reliably be used without significant concessions to hologram fringe contrast and lateral resolution. Consequently, the image wave can be reconstructed with very little noise. Figure 1c shows the reconstructed image wave, which is still affected by residual aberrations. After numerical correction of defocus, two- and three-fold astigmatism, second order coma and residual spherical aberration, the pure object phase shift (figure 1d) can be observed to investigate such details as defects and the phase shift behavior at the edge of individual layers. Since the material only degrades slowly under the electron beam, holographic time series can easily be used to cover a decent amount of time. In this particular time series, the same h-BN area was observed for about 20 minutes.

The TEAM I microscope is part of a user facility. Therefore, the holographic setup is available to the electron microscopy community and a wide range of researchers can benefit from this instrumentation to solve materials science problems. [5]

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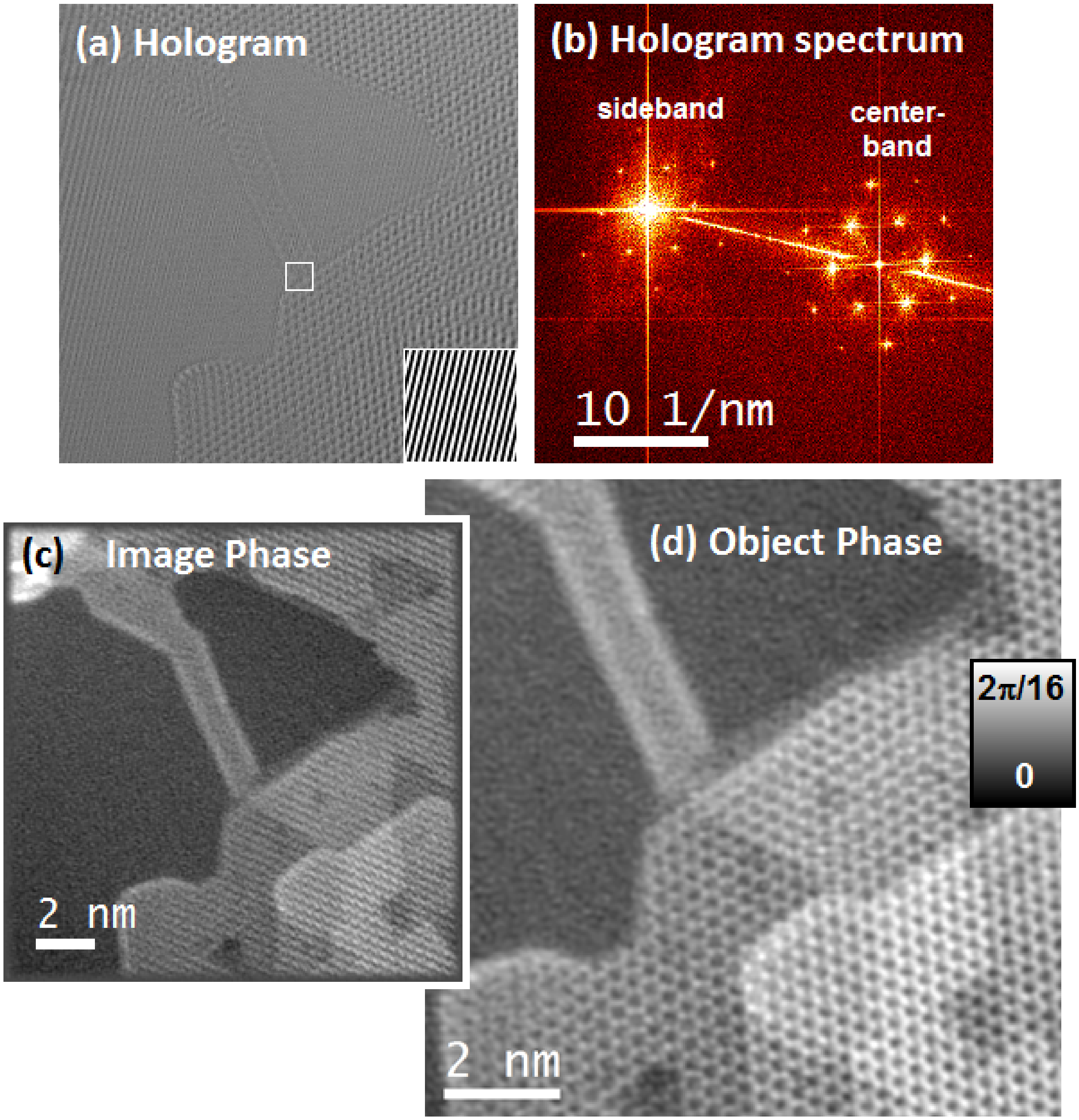

Figure 1. (a) The hologram of h-BN is a single frame of a 20 minute time series. Each hologram was recorded with an acquisition time of eight seconds and constantly provided a high hologram quality with 30% interference fringe contrast and about 8,000 CCD counts/pix. (b) The hologram FFT –here a subimage of the centerband and one sideband– indicates sufficient information transfer for atomic resolution. (c) The image wave is still affected by some residual aberrations, mainly defocus and two-fold astigmatism. (d) After numerical aberration correction, the aberration-free object phase provides pure, quantitative phase contrast. Note the magnitude of the object phase shift: the grey-levels, which are usually scaled from 0 to 2π, had to be amplified by a factor of 16 in order to show the phase values that are present in the image with reasonable contrast.

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