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Off-axis Electron Holography on 2D Materials with Small Coherent and Incoherent Aberrations

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The reduced dimensionality in two-dimensional materials (2DMs) leads to a wealth of unusual properties, which are currently explored for both fundamental and applied sciences. In order to study the crystal structure, edge states, the formation of defects and grain boundaries, or the impact of adsorbates, high-resolution microscopy techniques, such as Transmission Electron Microscopy, adapted to the specifics of 2DMs (weak scatterer, radiation damage sensitivity), are indispensable.

Most 2DMs behave as weak phase objects (WPOs) in the TEM, i.e., they only slightly modulate the phase of the electron wave transmitting the sample. Therefore, conventional TEM (CTEM) and high resolution TEM (HRTEM) typically employ large defoci to generate sufficient phase contrast, which, however, has an unavoidable large transfer gap for low spatial frequencies (Fig. 1) that can impede the quantitative evaluation of the recorded data (e.g., in terms of large-scale morphology changes).

Off-axis holography in principle resolves that problem by a reconstruction of amplitude and phase of the electron wave with a gap-free contrast transfer [1]. Reconstructing the whole wave also facilitates the *a posteriori* correction of residual aberrations [1] and a quantitative analysis of the electrostatic potentials with sub-nm resolution, which might be used to reconstruct the atomic charge density distribution. Widespread exploitation of these advantages currently depends on a robust *a posteriori* aberration correction and high signal to noise ratio of reconstructed phases, where the latter depends on brightness, aberrations and detector MTF and DQE.

Here, we tackle these critical points by combining electron holography with high-brightness cold field emission electron sources, spherical and chromatic aberration correction, low-noise CMOS detectors, and automatic a-posteriori residual aberration correction exploiting the WPO property and other Fourier space symmetries [2]. We use the technique to reconstruct potentials in multilayered hexagonal Boron Nitride (Fig. 2), Graphene and several Dichalgogenides, such as WSe_2. We reconstruct the average electrostatic potential as a function of layer thickness in these materials, delocalized edge states affected by edge reconstructions and defect potentials.

We conclude that off-axis electron holography adapted to specifics of 2DMs represents a powerful tool for multiscale potential analysis of 2DMs with no need for *a priori* knowledge about the sample or additional aberration assessment damaging the sample.

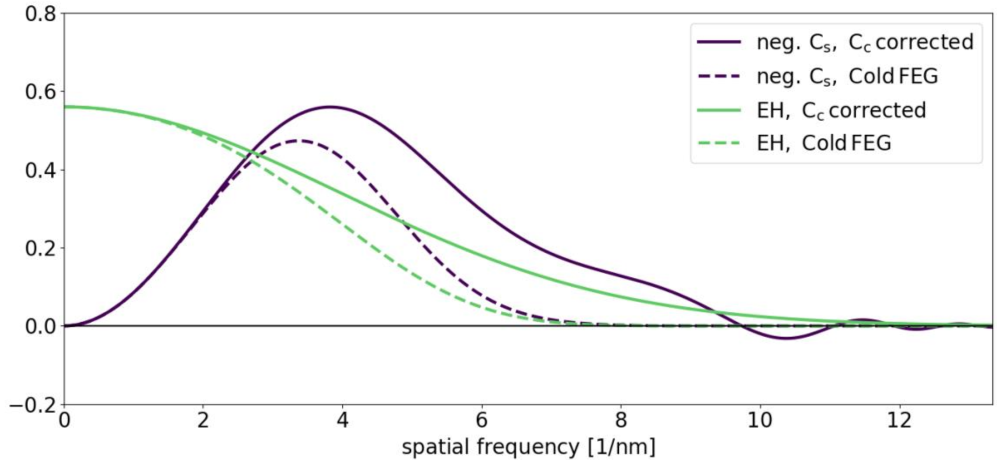

Figure 1. Signal-to-noise (SNR) transfer functions for HRTEM in negative Cs conditions (−Cs) and Electron Holography (EH) for two cases: Cc corrected with a Schottky FEG, residual linear Cc = 39 µm, energy spread = 0.7 eV (C1 = 6.7 nm, C3 = -8.1 µm) and without Cc correction and a Cold FEG, linear Cc = 1.3 mm, energy spread = 0.3 eV (C1 = 13.6 nm, C3 = -33.1 µm). Both transfer functions are given for an acceleration voltage of 80 kV, a semi convergence angle of 0.15 mrad and image spread envelope of 40 pm.

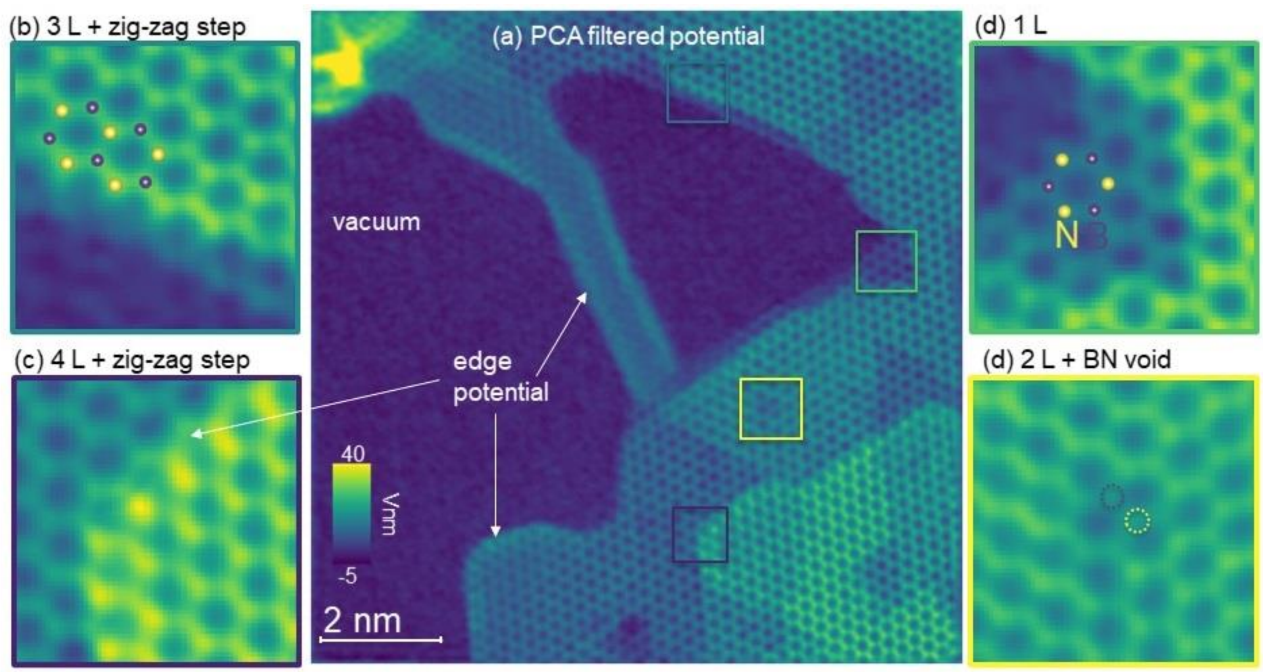

Figure 2. (a) High-resolution potential analysis in h-BN. Insets: Zig-zag steps comprising two atomic layers (b), (c), a monolayer region (d), and a BN void defect (d). Image adapted from [2].

References
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