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Prospects for Off-Axis Electron Holography in the TEAM I Microscope

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Electron microscopy offers excellent possibilities for materials research with true atomic resolution. Unfortunately, intensity images that are recorded in a TEM always suffer from the loss of the phase shift, which contains valuable information about the object. Off-axis electron holography has opened the possibility to analyze the complete complex electron wave in both amplitude and phase hence gives additional access to the object information encoded in the phase [1]. At atomic resolution, electron holography exhibits its strengths in allowing sophisticated wave optical analysis: Single reflection analysis and nano-diffraction, i.e. diffraction patterns from areas of a few unit cells only, are powerful numerical tools for a comprehensive analysis of crystalline specimen.
However, especially at very high lateral resolution, the signal resolution in the holographically reconstructed wave is strictly limited. Often, the signal resolution was not sufficient to apply holography to materials science questions until the C_S-corrector pushed the atomic resolution holography performance beyond previous limits [2]. Nowadays, off-axis holography in a state-of-the-art aberration-corrected TEM offers remarkable signal resolution at atomic-level lateral resolution: Recently, from a single 300 keV atomic resolution hologram a phase signal resolution of the order of a single hydrogen atom phase shift has been reported [3].
It is of great interest to utilize off-axis electron holography in NCEM's TEAM I microscope, which incorporates a number of technological advances, including a high brightness gun, a piezoceramic stage, a C_C/C_S corrector and a direct electron detector. There are several areas where electron holography will benefit substantially from these advances in instrumentation.

1. High-resolution holography at low accelerating voltages:
Currently, many materials science questions, especially on carbon based materials, require a low accelerating voltage such as 80 kV or even less. To overcome the increasing influence of chromatic aberration, often a monochromator is used, which is detrimental for holography since it dramatically reduces the signal resolution. The TEAM I instrument, however, is equipped with a corrector for chromatic aberration [4]; hence –low voltage electron holography" can be performed without any drawbacks on signal resolution.

2. Direct electron detection with the TEAM detector:
Off-axis electron holography is a form of image-plane interferometry in the TEM, which requires recording very fine high quality interference fringes i.e. three times smaller than the smallest desirable object detail and of high fringe contrast with a high number of electron counts. Therefore, the modulation transfer function (MTF) and the detection quantum efficiency (DQE) of the recording device are some of the most severe limitations for electron holography. The TEAM I instrument, however, is equipped with a direct electron detector [5], which overcomes the drawbacks of the commonly used CCDs that are fiber-optically coupled to a scintillator. On the one hand, electron holography will benefit from the better signal resolution due to better MTF and DQE. On the other hand, it will be possible to achieve the same signal resolution as before with shorter exposure time.

Moreover, the new detector allows image acquisition with a very high number of frames per second (currently about 50 fps for $1k^2$ images with much room for improvements). This will open up brand new opportunities for electron holography such as hologram time series to observe dynamic phenomena with a time resolution that has so far been out of reach. Alternatively, the hologram series can be evaluated to improve lateral resolution and signal resolution by averaging the object waves after numerical correction of biprism drift, object drift and even aberration drift.

3. Ultra-stable piezo-driven object stage:
To achieve the ambitious project goals of the TEAM project, a special piezo-driven object stage was built [6]. The TEAM stage is a tilt-rotation-stage that allows extremely high tilt angles. At the same time, it is possible to access object positions with high accuracy and precision. These properties are essential for time-consuming experiments such as holographic tomography, which require a high degree of automation [7].
Additionally, the stage is capable of flipping over the specimen, i.e. 180 degree tilt. This is very useful for holographic investigations on magnetic objects: In order to separate the phase shift contributions of the electric potential and the magnetic field usually two holograms of the same object flipped by 180 degrees are required. With the TEAM stage, these two data sets can be acquired very easily. Previously, the object usually had to be removed from the TEM column and be flipped over by hand.

4. Chromatic aberration correction with the Lorentz lens:
The technique of electron holography is particularly interesting for magnetic materials since there is no other method that is capable of imaging the magnetic field in the object with nanometer resolution. To image magnetic objects, however, the high-resolution lens is not suitable because it often magnetizes the object along the beam direction (out of plane). Therefore, the so-called Lorentz Lens is commonly used to image magnetic materials without an outer magnetic field at the object. Unfortunately, the lateral resolution of the Lorentz lens is strictly limited by huge spherical and chromatic aberration ($C_S = 8000$ mm and $C_C = 42$ mm) yielding an information limit of 3 nm in general and about 1 nm, if corrected for spherical aberration. The combination of Lorentz Lens and C_C-corrector is expected to significantly enhance the lateral resolution.

This talk will highlight some of the opportunities provided by these new technologies and illustrate them with experimental results from different materials [8].

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