Applied wave optics on the atomic scale: Electron holography materials characterization in a Titan TEM

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Electron microscopy offers excellent possibilities for materials research down to atomic scale. Unfortunately, recording intensity images in a TEM suffers from the loss of the phase shift of the electron wave, which contains valuable information about the object. Off-axis electron holography has opened the possibilities 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.

To obtain reliable results, both lateral and signal resolution should be as high as possible [2]. Therefore of course, the combination of off-axis electron holography with state-of-the-art instrumentation is of special interest. In this work, high-resolution electron holograms have been recorded by means of the Titan TEM operated at 300 kV. The microscope is equipped with an image aberration corrector to provide sub-Angstrom resolution and a high-brightness Schottky field emission electron source ("X-FEG"), which increases the brightness by a factor of five with respect to the conventional Schottky emitter. In order to separate the sidebands from the centerband, the holographic acquisition requires a biprism voltage of at least 900 V. Consequently for image acquisition, the CCD camera of the post-column energy filter has to be used to resolve all holographic features with accurate sampling. All in all, this setup allows recording holograms with an information content, which to the best knowledge has never been reached before [3]. As an example, figure 1 shows the holographically reconstructed object exit wave after correction of residual aberrations using the Triebenberg Holography Reconstruction Software [4]. The object is a thin foil of gold in [110] orientation with a large angle grain boundary close to the specimen edge. In real space, the data give access to atomic positions and column weight, while at the same time crystallographic properties can be evaluated in reciprocal space. The Fourier transforms of sub-areas allow obtaining local nano-diffraction patterns, while the single reflection analysis gives access to precise crystal orientation and thickness as well as the geometric phases of the partial waves.

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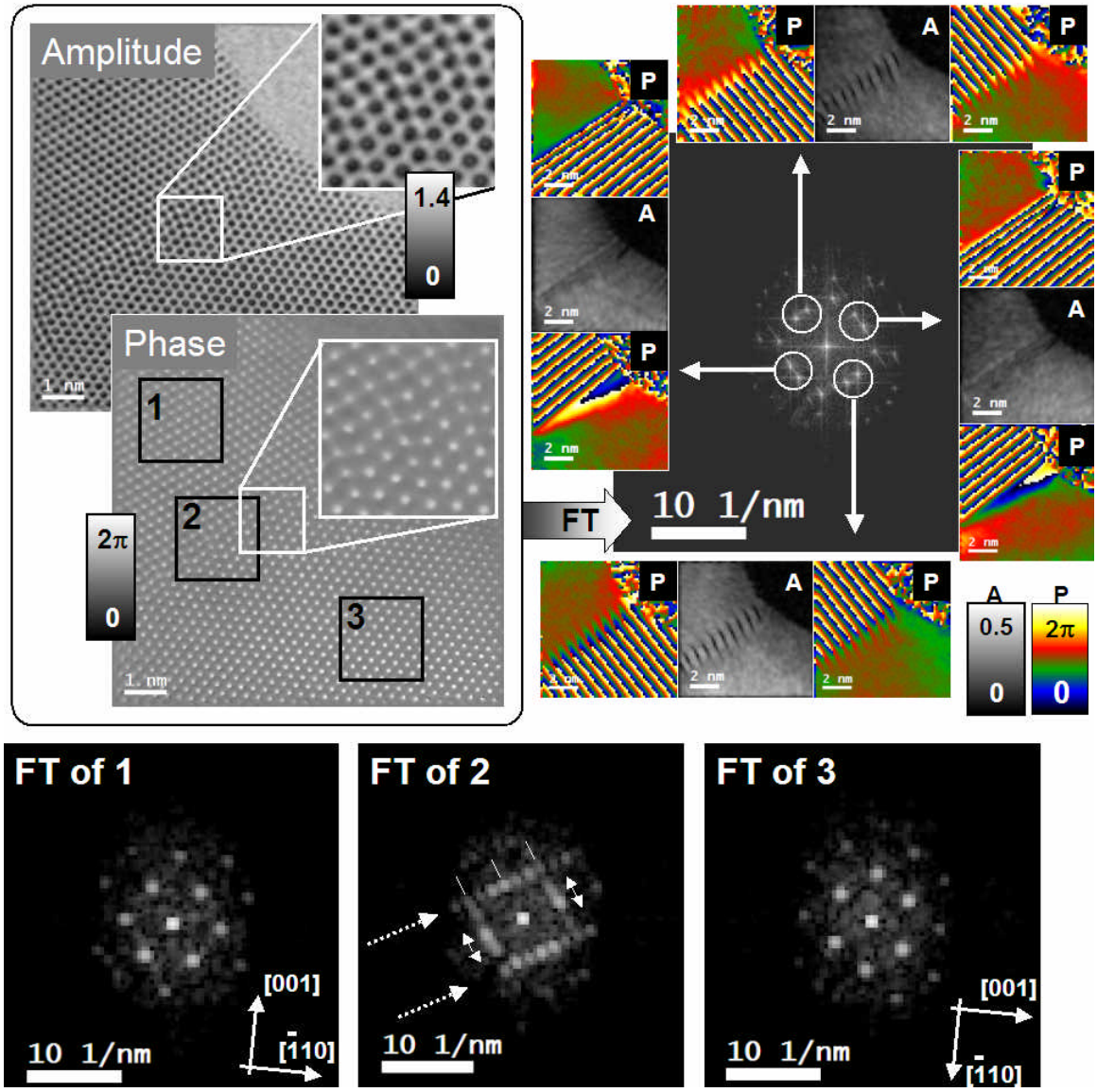

Figure 1. After reconstruction of the complex object exit wave and correction of residual aberrations, all atomic details in a large angle grain boundary of a gold film in [110] orientation are clearly resolved in amplitude and phase (top left). The Fourier transforms from the three numbered sub-areas (bottom) correspond to real diffraction patterns from areas of only 2x2 nm^2. These allow evaluating local crystallographic properties from areas normally too small to be recorded by means of selected area diffraction. As an example, the nano-diffraction pattern #2 directly at the grain boundary reveals additional "triple" reflections that correspond to periodic dislocations occurring after three monolayers each. Furthermore, the lattice plane bending causes a rotational smearing of some of the reflections (small arrows). Additionally, the complex wave can be analyzed in the light of single reflections (top left). The partial wave reconstruction allows analyzing the beam amplitudes (A) in terms of thickness and – by comparing the amplitudes of opposite reflections – determining the residual miss-orientation. Here, the uniform excitation of opposite Bragg spots indicates a perfect crystal orientation with respect to the electron beam. At the same time, the phase shifts (P) of the partial waves can be evaluated in terms of strain, stacking faults and lattice plane bending. Here, the phase shifts of the two regions have been evaluated separately by centering to each of the two Bragg spots independently. From these data, a strong surface relaxation towards the specimen edge is found at the lower side of the grain boundary.

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