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Electron Holography for nano-measurements

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The uniqueness of holography lies in the fact that, in addition to the amplitude (intensity), it provides the phase distribution from the object. The phase represents additional object information, for example about electric and magnetic fields down to an atomic scale, which are invisible in conventional intensity images. Therefore, most applications of holography evaluate mainly the reconstructed phase images.

Electron holography using an aberration corrected TEM

In fact, nearly two decades ago, holography was shown capable of a-posteriori correction of the coherent aberrations of the TEM during reconstruction of the electron wave [1]. Therefore, at first glance, these aberrations of the TEM do not play a decisive role for lateral resolution in holography. However, they do for signal resolution, because each point in the image wave is smeared out by the comparably large point-spread function, even at optimum focus for holography. Therefore, an accordingly wide hologram has to be recorded and hence the coherent current density drops. This gives rise to considerable quantum noise burying small phase modulations. With an aberration corrector [2], the quality of holograms is much improved in that the point-spread function and hence the noise level is substantially decreased. In our Tecnai F20 Cs-corr TEM, together with the signal enhancement resulting from opening up the imaging aperture, the signal/noise properties are found improved by a factor ≈4 [3]. Furthermore, the capabilities of a-posteriori correction are very favorable for a-posteriori fine-tuning of aberrations in the reconstructed wave. Finally, the performance allows atomic resolution both laterally and in signal. Any improvement of electron microscopy, such as of lateral resolution and of brightness of the electron gun, will enhance the capabilities also of electron holography. A further big step forward is achieved by recording holograms with the improved brightness of a “X-FEG” gun in a FEI-Titan TEM. Here, the best atomic holograms ever taken [4,5] show signal/noise improved by annother factor of about 5 (fig.1). Presently, the most severe challenge is to understand and distinguish the phase shifts arising at atomic dimensions, such as from atoms, fields, boundaries and defects, as well as from mistilt and thickness variations of the object.

Holographic Tomography

At medium resolution with details larger than 2 nm, the aberration of the optics can be neglected, and hence the image wave agrees with the object wave. Thus, the reconstructed phase distribution can directly be interpreted in terms of the object. However, even in the simplest case (“phase grating approximation”) of an object representing a 3D electric potential $V_{obj}(x,y,z)$, the reconstructed phase $\varphi(x,y) = \sigma V_{proj}(x,y)$ with interaction constant σ represents only the “projected potential”

$$V_{proj}(x,y) = \int_{object} V_{obj}(x,y,z)dz\,.$$

Consequently, if the object is not homogenous in z-direction along the electron beam, such as in layered systems, this projection from 3D into 2D gives severe interpretation problems. Whereas light optical holography is famous for 3D-imaging allowing resolution also in z-direction, alas, in electron holography the scattering angles at the object are so narrow that a 3D-effect can hardly be exploited. This became evident at the investigation of FIB-prepared pn-junctions: Due to amorphization and doping of the surface layers by the FIB-ions, the measured projected potentials were substantially discrepant from the ones expected across a mere pn-junction. This can only be improved, if the angular width is opened up by recording tilt series, i.e. by combining holography and tomography [6,7].

We developed a fully-computerized method (“THOMAS” software package) for recording holographic tilt series and reconstructing the 3D-phase distribution represented by the object [8]. By means of corresponding algorithms, one can visualize the outer habit e.g. of growth, or the interior phase distribution, for example in the nanorod shown in fig.2. Arbitrary slices can be cut through this data set representing, without any projection effect, the actual local phase distribution hence the true potential distribution in the selected layer. In fact, these potentials agree very accurately with the literature data.

References

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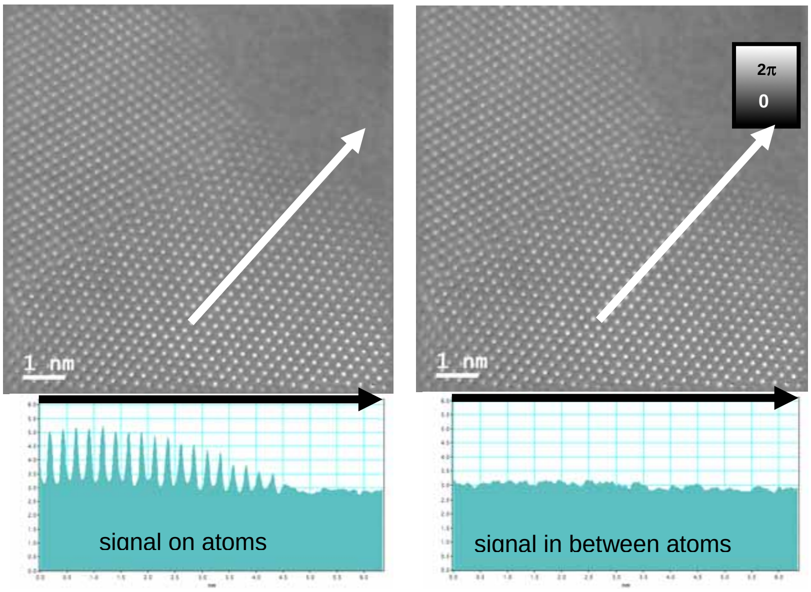

Fig. 1 Phase image of a gold crystal reconstructed from a XFEG-hologram.
Due to the improvement in brightness and the correction of aberrations, both lateral and signal resolution are truly atomic:(left) Profile across the atoms; the two smallest peaks at the crystal edge correspond to single gold atoms.(Right) The profile between the atoms does hardly show atomic information: between the atoms are only vacuum and possibly small electric fields between the atoms.

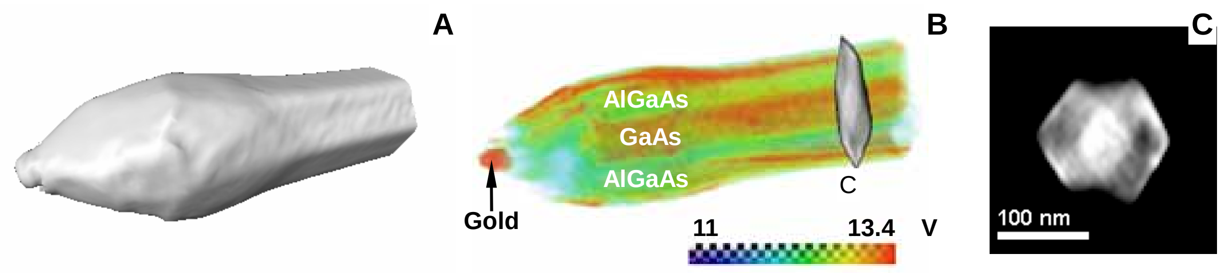

Fig. 2 3D Potential of a GaAs/AlGaAs nanorod reconstructed from holographic tilt series.
A: growth habit represented by the 9V-isopotential surface.
B: Volume texture allowing visualizing the interior structure revealing the GaAs core and the AlGaAs shell, as well as the gold particle used as catalyst for growing the nanorod by MOVPE.
C: cross-section shows the hexagonal shape according to [111]-growth direction of nanorod.
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