

## Which atoms are where? Which fields are around?

### Nanoquestions answered by Quantitative Electron Holography.

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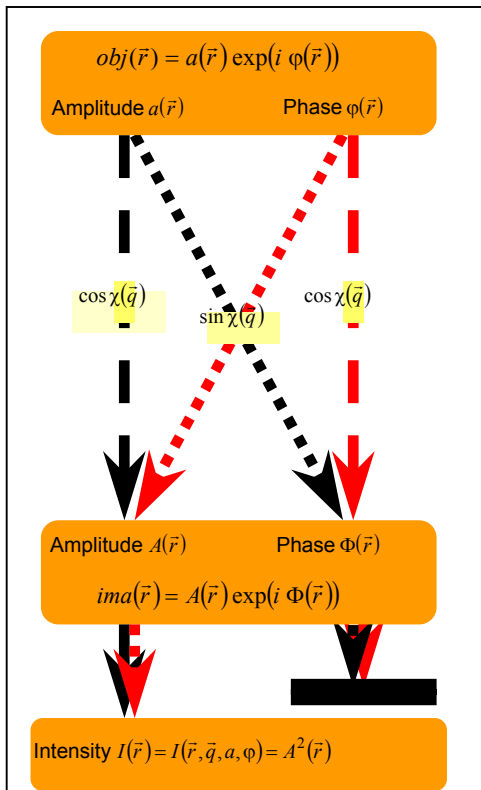
In Transmission Electron Microscopy, electrons are waves, which exhibit the typical wave phenomena: They are diffracted at the object structure, and they form the image by means of interference. Waves consists of two quantities, i.e. amplitude and phase. However, the detectable intensity of a wave only shows the amplitude squared, whereas the phase is not visible.

**Transmission Electron microscopy** (TEM) is wave optics. The plane incident wave is modulated by the object in amplitude  $a(x, y)$  and phase  $\varphi(x, y)$  such that the object wave is given as  $obj(x, y) = a(x, y) \exp(i\varphi(x, y))$ . In fact, the phase carries most of the information about the object structure, i.e. the electromagnetic fields such as the atomic Coulomb field characteristic to an atom. The imaging process is described wave optically: By means of the lenses, the object wave is transferred into the image plane, where one finds the image wave  $ima(x, y) = A(x, y) \exp(i\Phi(x, y))$ . Image amplitude  $A(x, y)$  and phase  $\Phi(x, y)$  are related to the object wave by the transfer functions (defined in Fourier space) of the optics, as sketched in fig.1. In the image intensity, contrast stemming from the object amplitude arises according to the Amplitude Contrast Transfer Function  $ACTF = \cos(\chi(\vec{q}))$ , the contrast from the object phase is given by the Phase Contrast Transfer Function  $PCTF = -\sin(\chi(\vec{q}))$ .  $\chi(\vec{q})$  is the wave aberration of the lens in dependence of the Fourier coordinate  $\vec{q}$ , which contains defocus, spherical aberration, astigmatism and axial coma. In the recorded intensity image, amplitude contrast and phase contrast are indiscernibly mixed up hence difficult to interpret. The main problems stem from the fact that the phase channel is blocked hence a lot of object information is lost in a conventional electron micrograph. This reduces resolution and interpretability.

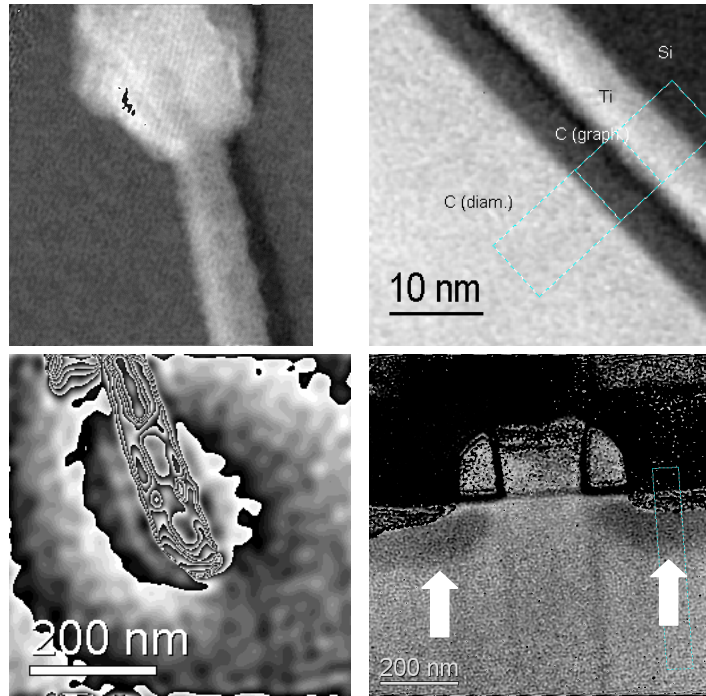
**Electron holography** in a TEM opens the phase channel in that it records the complete image wave by interference with a well-known reference wave. Since from a hologram the image wave is reconstructed completely, it can be corrected from aberrations, and hence amplitude  $a(x, y)$  and phase  $\varphi(x, y)$  of the object wave can be determined and evaluated quantitatively. In particular the phase is most interesting because it represents quantitative data about the electromagnetic field in solids, and it is better suitable to direct interpretation of materials properties. This is shown in fig.2 by means of examples at medium resolution for largely extended phase structures like electric and magnetic micro-fields. Fig.3 presents a phase image at atomic resolution, which shows the feasibility of “holographic materials analysis”, i.e. to analyze the atomic species from the specific atomic phase shift.

Further reading:

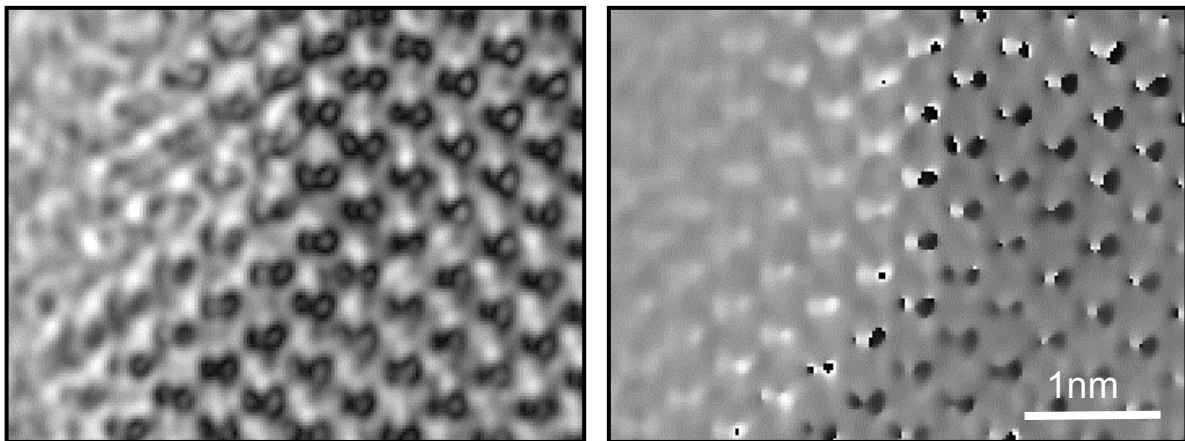
M. Lehmann and H. Lichte, *Tutorial on Off-axis Electron Holography*  
Microscopy and Microanalysis 8 (2002) 447 - 466



**Fig.1** Transfer scheme of the wave in a TEM with wave aberration  $\chi(\vec{q})$ . At conventional imaging the phase channel is blocked, only the intensity is recorded. Holography opens the phase channel hence allows to evaluate the object structure completely.



**Fig. 2** Phase images reconstructed from medium resolution holograms. Top left: T5-bacteriophage unstained. Top right: a strong contrast arises between graphitic and diamond-like carbon. Bottom left: Magnetic stray field around Ni encapsulated in a nanotube. Bottom right: Negative potential (arrows) provoked by p-doping in a Field Effect Transistor.



**Fig.3** Amplitude (left) and phase (right) of the aberration-corrected object wave of (110)-GaAs. Dumbbells of Ga and As atoms are well resolved both in amplitude and phase. The phase shift from the right atom in each dumbbell is always a little stronger than from the left one: the right one is As ( $Z = 33$ ), the left one is Ga ( $Z = 31$ ). Contrast reversal occurs at the extinction thickness of the wedge-shaped crystal with thickness increasing from left to right.