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doi:10.1017/S1431927614002943
Microsc. Microanal. 20 (Suppl 3), 2014

Electron holography: state and prospects

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The phase loss encountered in conventional (S)TEM means a substantial loss of object information, because essential structure components, e.g. electric and magnetic fields, mainly modulate the image phase hence are virtually invisible in a conventional micrograph. This presents a huge obstacle for a thorough understanding of modern functional materials e.g. in semiconductors and nano-magnetism. Phases can only be determined by interference of the image wave with a reference wave. Gabor's bright idea of holography was to use the interference pattern (hologram) as a diffraction grating, where one of the diffracted waves turns out a replica of the image wave. This replica wave is reconstructed from the hologram allowing subsequent quantitative evaluation of both amplitude and phase separately.

Holography needs coherence between the image wave and the reference wave for recording the hologram. In electron holography, alas, the coherent current given by the brightness of the electron beam is severely restricted, and hence the intensity in a coherently illuminated area gives rise to signal/noise-problems. Furthermore, the hologram should be recorded in the object plane or a conjugate image plane, because otherwise the waves diffracted into larger angles hence carrying the information about fine details, end outside the coherent area, and hence are missing in the reconstructed wave. Up to now, *Image Plane off-axis Electron Holography* is the most powerful holographic method in electron microscopy.

After improving the method´s performance, an increasing spectrum of applications has been reported from an increasing number of groups. The high quality allows investigating subtle details of the solid state such as the magnetization in nanoparticles, basics of superconductivity, electric fields and dopant distribution in semiconductors as well as the behavior of the charge carriers; at atomic resolution including a-posteriori aberration correction and fine-tuning, using an aberration-corrected TEM allows measuring atomic fields of single atoms, enabling to identify different atom species.

Resolution comprises both lateral resolution and signal resolution; signal resolution means the smallest phase difference distinguishable between two adjacent reconstructed pixels. Both parts of resolution are in principle limited by the Quantum Noise found at certain degree of coherence, i.e., at the corresponding contrast of the hologram fringes. It turns out that lateral resolution and signal resolution are concatenated by means of the figure of merit *InfoCont* given by the quality of the TEM and the disturbance level in the lab. Concatenation is simply given as $n_{rec}\eta_{\varphi} = InfoCont$, with n_{rec} the number of reconstructed pixels across the width w of the wave; by $n_{rec} = 2q_{res}w$, it links field of view w with lateral resolution q_{res}. n_{φ} is the number of phase steps distinguishable in the phase range of 2π; the phase detection limit follows as $\delta\varphi_{lim} = 2\pi/n_{\varphi}$. For example, at our FEI Tecnai F20 Cs-corr TEM operated in the Triebenberg-Lab, *InfoCont* ≈ 18,000 can be reached, and hence a wave reconstructed with $n_{rec} = 180$ pixels allows measuring phase differences down to $2\pi/100$ between adjacent pixels. This would allow seeing single light atoms such as carbon or oxygen with $2\pi/60$ ... $2\pi/50$, or recognizing single electron charges with $2\pi/100$ .... $2\pi/30$, however, by far not single Bohr Magnetons with $2\pi/10^5$.

Holographic Tomography: Although holography in principle allows 3D-imaging, as seen from beautiful examples in light holography, with electrons the diffraction angles subtended at the object are so small that the image wave virtually represents a 2D-projection. Therefore, to allow the analysis of 3D - distributions of fields in solids, holographic tomography has been developed opening up the angular width. A series of about 70 holograms taken at small tilt increment of the object allows reconstructing a corresponding tilt series of 2D-phase projections. Using the techniques of tomography, these projections are combined for building up a 3D-phase distribution. Arbitrary slices through such a 3D-phase distribution allow uniquely measuring the 3D-arrangement of interior fields in solids, e.g. across pn-junctions, without falsification from surface and projection effects.

Dark field holography: The reflections in Fourier space carry the geometrical phases indicating the positions of the respective Fourier components in real space making up the object. Therefore, discrepancies from a perfect lattice lead to local variations of these phases. For analysis of imperfections of a crystal such as defects, Hanszen recorded dark field holograms in the light of single reflections of a disturbed crystal area selecting an undisturbed crystal area as reference. For this, one only needs diffraction at the crystal but no atomic resolution in the hologram plane thus avoiding the problems e.g. stemming from aberrations. Martin Hÿtch advanced this method in particular for strain measurements in the diffracted waves and applications in semiconductor technology.

Inelastic holography: The phase modulation by the object evaluated so far stems from elastic interaction, i.e. there is no residual transfer of energy between the beam electrons and the object. However, there are additionally inelastic interactions, such as excitations of phonons and plasmons. From the point of view of understanding the basics of electron waves, also these inelastic interactions are very interesting. Since an inelastic event is suitable for detecting the position of the electron, quantum mechanics suggests the collapse of the wave function, i.e. decoherence. For investigation of the measurement of coherence (Energy-Filtered) EFTEM-holography is performed. The results show that e.g. exciting bulk or surface plasmons in Si, there remain coherence areas in the object at the respective energy losses, which have an extension of several 10nm. This shows that also Energy-Filtered Microscopy (EFTEM) has to be understood as wave optics, however, incoherent with elastic imaging.

Outlook: Even if we have solved all present shortcomings of the hitherto available holographic methods and succeed in reconstructing a perfect wave, the most severe task will be the unique interpretation of the findings in term of the object. The difficulty is that very many different properties of an object are added together in the phase, and it is a huge challenge to identify, extract and evaluate each of them separately:

- Mean Inner Potentials (MIP), local variations of MIP at defects, boundaries, e.g. due to strain
- doping, intended or unintended (impurities)
- surface states trapping charges; surface reconstruction and adsorption
- electric polarization, e.g. in ferroelectrics or in polarized nanostructures such as $LaAlO_3$
- interface segregation and outdiffusion; interdiffusion in heterogeneous stacking layers
- mobile charges compensating inner fields
- thickness variations, e.g. by preferential etching
- contact potentials, Schottky effect
- Electron beam induced currents and voltage drops; charging under the beam

Besides, the more accurate the reconstructed data are, the more one also has to understand the contributions from residual phase shifting effects stemming from dynamic interaction. Therefore, we have to strengthen in-situ experiments where only the parameter of interest is varied; furthermore, a better insight into solid state science has to be gained and used for a more detailed and accurate modeling of the substance under investigation.

More details and rich references may be found, e.g., in the various companion chapters on Wave Optics and Holography in the textbook *Transmission Electron Microscopy* published by Carter and Williams.

https://doi.org/10.1017/S1431927614002943 Published online by Cambridge University Press