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Electron Holography: Possibilities and Limits

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The carrier of information in electron microscopy is the electron wave. By interaction with the object, the electron wave is modulated both in amplitude and phase. The “object exit wave” leaving the sample is transferred to the final image delivering the image wave to the detector plane. Since the transfer of the wave through the optical system is understood in detail, the image wave can be related back to the object exit plane. However, the detector only sees the intensity of the image wave, and hence loses the phase information in the image plane. This phase loss is one of the major problems in that it hinders electron microscopy from utilizing the abilities of structure analysis completely from intensity images: All information stemming from electromagnetic fields in solids is lost, except for the highly-localized nuclear Coulomb fields shielded by the electron shell; these give also a considerable contribution to the conventional atomic contrast as shown by transfer theory. Since for a comprehensive characterization of solids one needs not only the geometric arrangement of the atoms, but also the electromagnetic fields generated by them, in order to understand the structure-property relation, one has to apply interference techniques to detect also the phases. Electron Holography is a way of doing this [1].

Amongst the 20 forms of electron holography identified by Cowley [2], the most successful method so far is off-axis electron holography, which uses the Moellenstedt electron biprism [3] as a beam splitter. It superposes a reference wave to the image wave hence gives rise to an interference pattern (“hologram”), which contains both amplitude and phase in the contrast and position of the interference fringes. By means of a reconstruction procedure, the distributions of amplitude and phase in the field of view are determined quantitatively, i.e. the image wave is revived completely. Details are given in the review [4].

The uniqueness of holography lies in the fact that, in addition to the amplitude (intensity), it provides the phase distribution from the object. Therefore, most applications of holography evaluate only the reconstructed phase images.

At medium resolution with details larger than 2 nm, the aberrations of the lens 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. This is the basis for studying

- Mean Inner Potentials in solids
- Soft Matter: Phase contrast in focus without staining
- Functional potentials: pn-junctions in semiconductors
- Electric Fields controlling growth in biominerals
- Ferroelectric polarization
- Electric potential distribution in charge-modulated structures
- Magnetic fields in and around magnetic structures down to a nanoscale

Examples of such applications are described in detail in [5].

At atomic resolution, amplitude and phase of image wave differ considerably from the object wave and hence cannot be interpreted directly. First, the aberrations have to be corrected by appropriate processing. Then, both in amplitude and phase, lateral resolution can be achieved as high as determined by the information limit (close to 0.1nm) offered by the TEM used for recording the hologram. Then, phase images allow details of the atomic structure to be revealed, such as

- difference of atomic numbers of different constituents
- number of atoms in an atomic column
- interatomic electric potentials
- potentials across interfaces

Examples and further references are given in [4].

Performance Limits

The performance of electron holography mainly depends on the TEM used for recording the hologram. The optimal reachable lateral resolution is given by the information limit of the microscope. We have reached about $0.1nm$ so far using a Philips CM30 TEM. Besides lateral resolution, the signal resolution, i.e. the discernibility of details of the phase image, is often more essential to see the very weak object details. The two aspects, i.e. lateral and signal resolution, can be combined in one figure of merit, which we call the Information Content $InfoCont = n_{\varphi} n_{rec}$ [6]. It is the product of the number n_{φ} of phase values distinguishable in the range $(0,2\pi)$, and the number n_{rec} of pixels reconstructed across the field of view, as shown in Fig.1. It turns out that $InfoCont$ depends on the brightness of the electron emitter, stability of the TEM, and the quality of the electron detector used. In our case, $InfoCont = 7100$ is achievable. This means for example that in order to see details of $2\pi/50$ such as fields of single atoms, corresponding to $n_{\varphi} = 50$, the number of reconstructed pixels is limited to $n_{rec} = 140$. Reachable lateral resolution and field of view are related accordingly: aiming at a lateral resolution of $0.1nm$, the reachable field of view is limited to $7nm$, because one resolution element is made up by two pixels (Nyquist sampling theorem).

In summary, one can say that, after 40 years of development, electron holography is an established method for comprehensive characterization of solids including their intrinsic electromagnetic fields. The performance, essentially restricted by quantum noise, 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 of this unrivalled method for nanocharacterization.

References

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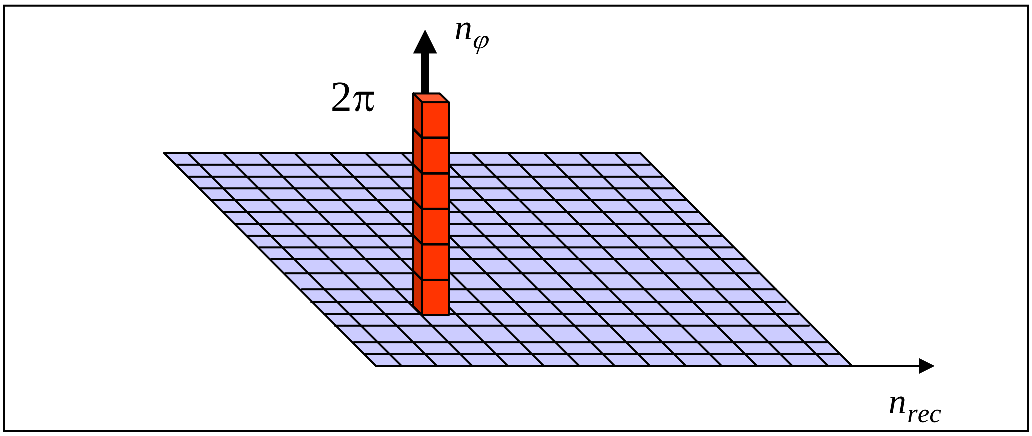

FIG. 1. Definition of number of reconstructed pixels n_{rec} and number of discernible phase values n_{φ}. The squared hologram width gives the pixelated field of view.