Electron Microscopy with Atomic Resolution: Recent Advances and Applications

Ferdinand Hofer

Institute for Electron Microscopy and Nanoanalysis and Graz Centre for Electron Microscopy
Graz University of Technology
Steyrergasse 17, 8010 Graz

Atomic resolution imaging with a scanning transmission electron microscope (STEM) equipped with a spherical aberration-corrector is now an indispensable method for studying complex materials. This is owed to the flexibility of the STEM by using advanced detectors such as the high-angle annular dark field (HAADF) and the annular bright field (ABF) detectors and recently also by using differential phase contrast (DPC) detectors. An aberration corrected STEM also enables atomic-resolution mapping of the chemical elements in a material thus allowing a unique correlation of structural and chemical information by means of electron energy-loss spectrometry (EELS) and energy dispersive X-ray spectrometry (EDS).

Quantification of elemental maps at atomic resolution remains a challenge. This situation changed with the novel simultaneous acquisition of EELS and X-ray signals thus enabling elemental quantification in terms of volumetric densities [1]. Here we will discuss recent developments and how quantification can be extended to the third dimension by combining electron tomography methods with simultaneous EELS and EDX spectroscopies finally revealing voxel spectroscopy data at the nanoscale [2].

Around 15 years ago we saw the hype with the monochromated STEM-EELS instruments of the first generation, which allowed to acquire EELS spectra with an energy-resolution of 150 meV. This development was extremely important for studying surface plasmons on noble metal nanoparticles and nanostructures by taking advantage of the TEM's unbeaten high spatial resolution. In the meanwhile, STEM-EELS is the most important method for direct imaging of surface plasmons on nano-objects [3]. In the meanwhile, a new generation of monochromated STEMs deliver an energy resolution in the sub-20 meV regime. It gives access to a range of new experiments hitherto impossible on any other TEM: vibrational spectroscopy with a nm-sized probe or even smaller [4].

Finally, we will describe a few application examples such as the analysis of interstitial Sr atom colums in silicon by combining STEM and DFT simulations [5], then the diffusion defining atomic-scale spinodal decomposition within precipitates in an Al-alloy [6] and finally the imaging of atoms and molecules in porous materials.

[1] G. Kothleitner et al., Phys. Rev. Lett. 112 (2014) 085501
[2] G. Haberfehlner et al., Nature Comm. 6 (2015) 8779
[3] B. Schaffer et al., Physical Review B 79(4) (2009) 041401
[4] O.L. Krivanek et al., Nature 514 (2014) 209
[5] M. Albu et al., Sci. Rep. 6 (2016) 31635
[6] A. Orthacker, Nat. Materials 17 (2018) 1101.