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Imaging Nucleation, Growth and Disorder at the Single-atom Level by Atomic Electron Tomography (AET)

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It is rare to find perfect crystals in nature. Defects such as grain boundaries, interfaces, point defects and dislocations have important effects on the structural and electrical properties of most materials. [1] However, probing the structure, arrangement and interactions of such defects is difficult as this requires determination of atomic coordinates in three-dimensions with high precision. Aberration-corrected scanning transmission electron microscopy (STEM) is able to resolve most atomic distances although the images produced are only two-dimensional projections of the 3D atomic arrangements. Further, electron tomography can determine three-dimensional density maps of objects [2] but achievement of atomic resolution required several further developments in the field of atomic electron tomography (AET) from acquisition techniques, advanced reconstruction algorithms and atom tracing methods [3]. Recent achievements of AET include ~20 pm precision of atomic coordinates in three-dimensions [4], chemical sensitivity based on atomic number (Z) contrast [5], and no assumption of crystallinity leading to measurements of point defects, disorder, phase nucleation and growth (Figure 1) [6].

This talk will present recent progress in the field of AET in determining chemical order/disorder, nucleation and growth of ordered phases as well as the prospects for solving amorphous structures. We will show the imaging of grain boundaries, chemical species swap defects and point defects. We will also show nucleation, growth, merging and dissolution of the $L1_0$ phase of FePt from an initially disordered A1 phase. Finally, the presentation will look forward to more advanced phase contrast methods utilizing the recent capabilities of scanning nano-diffraction (also known as 4D-STEM) such as differential phase contrast and ptychography beyond ADF-STEM. Such methods will enable imaging of low-Z atoms simultaneously with high-Z atoms and at lower doses. We expect AET to be an important method in materials science to solve the atomic structure of complex materials without the assumption of crystallinity.

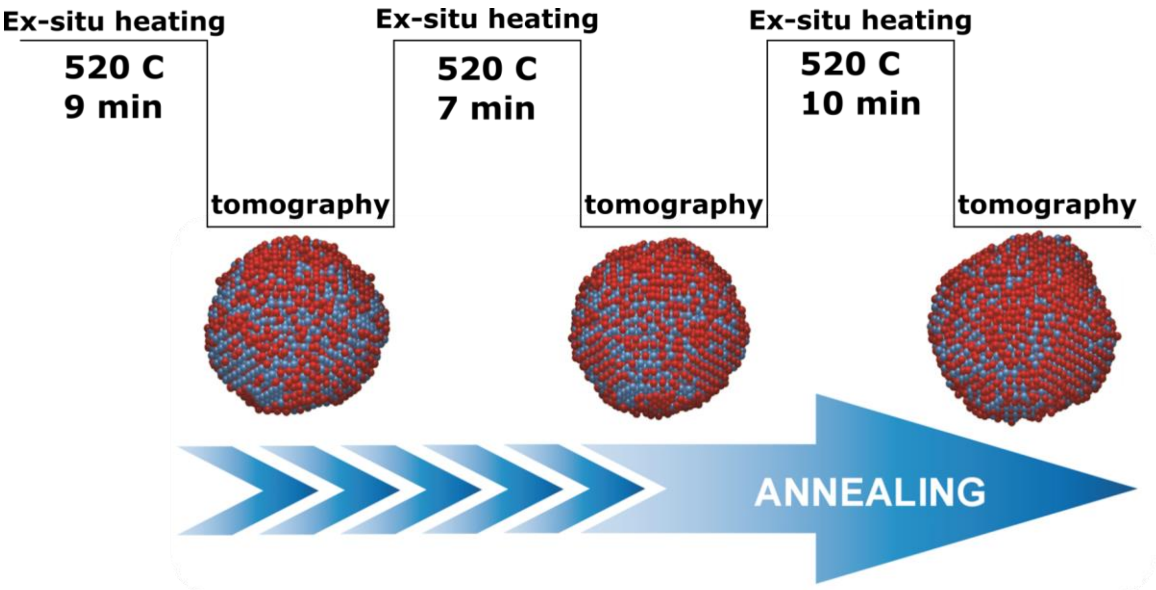

Figure 1. Atomic electron tomography heating experiment where a FePt nanoparticle was heated in three different stages with tomographic tilt series acquired between each heating step. The resulting 4D AET (3D + time) results show nucleation and growth (heterogeneous) of the magnetic L10 phase of iron on the surface.

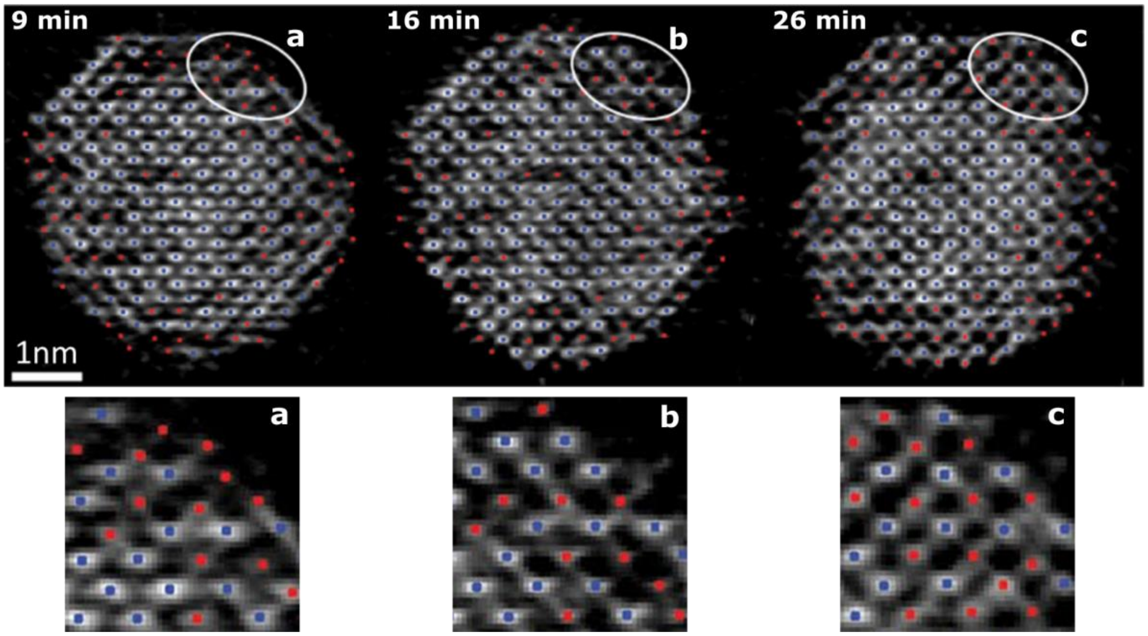

Figure 2. The same internal plane of atoms through a nanoparticle along the [010] direction at the three annealing times of 9, 16 and 26 minutes. The raw reconstructed intensity (grayscale) has Fe atom (red) and Pt atom (blue) overlaid to show the rearrangement of an initially compositionally disordered region into the L10 phases. Zoomed in images (below) of the circled regions are shown to highlight the structural ordering.

References

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