Mesoscale Priority Research Direction

3D Imaging of Mesoscale Architectures with Nanoscale Resolution

Opportunity

a wide range of phenomena in energy-related materials science urgently demands 3D imaging, from studies of water and oil percolation in rocks, to porous polymers, and the need to "see inside" the three-dimensional organisation of everything from composite materials to new battery electrode designs or semiconductor devices.

Approach

Coherent X-ray sources enable "lensless" X-ray imaging with resolution beneath the diffraction limit

Meso Challenge

The attainment of three-dimensional imaging in the mesoscale window between 10 nm and 10 microns , preferably with chemical sensitivity, has proven surprisingly difficult.

Impact

We confidently expect wide application of this exciting new mesoscopic imaging mode to a wide range of problems, wherever scientists need to "look inside" their newly-designed (or naturally occuring) material structures.

References: see attached *Imaging at the nanoscale - seeing inside*

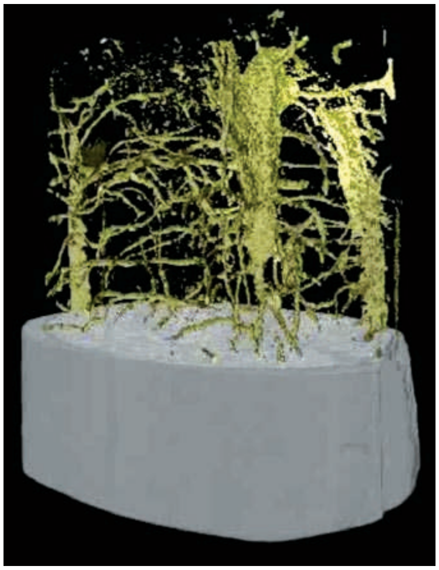
Contact: John Spence (ASU)

Imaging at the nanoscale - seeing inside. Draft for DOE Meso Report.
JCHS Nov 18 2011

Atomic-resolution imaging techniques have developed rapidly in recent decades, from the field-ionization atom-probe (AP), with its atom-by-atom identification capability, to the scanning tunnelling microscope, so powerful for imaging surfaces, and, most recently, the aberration-corrected transmission electron microscope (TEM), with its associated inner-shell spectroscopic mapping on a sub-nanometer scale. Of these, the AP provides three-dimensional views (with destructive readout), while 3D imaging by TEM in materials science is in its infancy, usually limited to nanometer rather than atomic resolution. At the opposite end of the scale, X-ray tomography provides vivid three-dimensional reconstructions both in medicine and materials science, with resolutions usually at the many-micron level. These instruments have recently become available in lab-scale machines, in addition to synchrotron-based instruments.

The attainment of three-dimensional imaging in the mesoscale window between 10nm and 10 microns , preferably with chemical sensitivity, has proven surprisingly difficult. Only X-rays have sufficient penetrating power, combined with adequate source brightness and particle lifetime, to be useful. Yet zone-plate lenses for X-rays have only recently been developed, and have serious limitations. Yet a wide range of phenomena in energy-related materials science urgently demands such a capability, from studies of water and oil percolation in rocks, to porous polymers, and the need to "see inside" the three-dimensional organisation of everything from composite materials to new battery electrode designs or semiconductor devices.

A quiet revolution has occured in imaging science over the last decade, following the realisation that, if coherent X-ray sources are available, "lensless" X-ray imaging is possible, where lenses can be replaced by a computer, giving an aberration-free image reconstruction, whose resolution is limited only by the X-ray wavelength. Iterative solutions to the non-crystallographic phase problem have improved greatly in performance over the past decade, with the method of Ptychography currently showing greatest promise. This method, proposed in the nineteen sixties for electron diffraction, has been extensively developed recently by Rodenburg and colleagues for use with X-rays. A large number of microdiffraction patterns from ovelapping regions of the sample are used, and iterations between them constrained for consistency. Many views (or projections) of a rotating sample are needed for three-dimensional reconstuction. The figure shows a striking example of this lensless hard X-ray imaging of a mouse femur bone, clearly revealing the porous internal structure of bone in this quantitative three-dimensional reconstruction. Note that the phase-shift of the X-rays in passing through the sample is measured, rather than their absorption, allowing less damaging harder X-ray radiation to be used, and resulting in a truly quantitative method which gives a direct reading of local bone density in this case. This early application of the method provided about 100nm resolution - improvements to better than 10 nm are expected soon. The addition of chemical sensitivity to this method has already been demonstrated more recently for two-dimensional imaging. We confidently expect applications of this exciting new mesoscopic imaging mode to a wide range of problems, wherever scientists need to "look inside" their newly-designed (or naturally occuring) material structures.



Mouse femur, imaged in three dimensions at 100nm resolution, by quantitative hard X-ray phase-contrast tomography (Ptychography). From Diefolf et al . Nature p. 436, 467 (2010).