UNDERSTANDING AND CONTROLLING ENERGY-RELATED NANOMATERIALS BY USING ELECTRON MICROSCOPY

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Electron microscopy is helping to bring new scientific and technological insights that are advancing progress in areas such as health, transport, security, energy and the environment. Energy is perhaps the most pervasive of these topics, since the conversion, storage, transport, efficiency and use of energy impacts heavily on the rest. As scientists and technologists work towards both developing and discovering clean, sustainable sources of energy, as well as more efficient processing, handling and consumption, how can electron microscopy contribute to these vitally important efforts? In particular, how are the tools and techniques advancing to meet the challenges of such global issues? Well, in fact, the requirements go hand-in-hand as we strive to better understand, control and optimise the relevant materials and processes.

For example, among the new generation of energy-efficient and environmentally-friendly systems is the solid oxide fuel cell (SOFC), which can be used in electrocatalytic reactions, as a conductor of oxygen and to produce hydrogen directly from methanol. For catalytic reactions, a large surface area with plenty of active sites is a must, and one way to achieve this is by the formation of tiny nanocrystalline particles. The nature of the exposed crystal facets at the surface determines the degree of catalytic action, but in order to precisely characterise these facets in the electron microscope, it is crucial to be able to clearly observe the positions of atoms at the edges of the nanocrystals (see Figure 1). The aberration-corrected (scanning) transmission electron microscope (S/TEM) gives the ability to make these observations with great accuracy, allowing individual atoms to be identified along with any atomic-scale kinks or steps in the material, without the limitations of contrast delocalisation associated with standard electron optics, which previously made image interpretation much more complicated or even impossible.

Electron microscopy is also helping to bring new knowledge at the nanoscale and atomic level for materials being used for bright, highly efficient light emitting diodes (LEDs). LEDs offer great potential for saving electricity and fuel as well as for reducing greenhouse gas emissions by replacing conventional light bulbs. In addition to using the TEM for observing such materials, techniques such as monochromated SEM and STEM-in-SEM are capable of revealing closely-spaced spaced quantum wells, as shown in Figure 2. We can expect to see further progress being made in this area and many others, such as increased understanding of materials for solar cells and technology for carbon dioxide separation and zero emission power plants, with the help of next-generation high-resolution electron microscopy and associated spectroscopic chemical analysis. In particular, electron and ion tomographic techniques hold great promise for three dimensional visualization and quantification of heterogeneous nanostructures (see Figure 3, for example).

Finally, *in situ* observation of processes such as catalytic reactions and the synthesis of new nanomaterials and structures can be carried out dynamically. For some time the environmental SEM (ESEM) has enabled such *in situ* experiments and now, with the advent of commercially-available aberration-corrected TEMs that can operate over a wide temperature range and in the presence of gases, the ability to watch as individual atoms interact with each other has become a reality, suggesting that electron microscopy has a yet more significant role to play in tackling global issues in the future.

In summary, with global energy resources under increasing pressure, great efforts are being made to develop new nanomaterials that will lead to renewable energy sources and increased efficiency, to sustain energy supplies into the long term future whilst helping to preserve and protect the Earth’s environment. To get there, we are being taken into the realms of atomic interfaces and quantum wells such that, to tailor new nanomaterials for specific functions, there is an essential requirement to precisely understand, accurately control and truly visualize structure-property relations at an unprecedented level. The atomic structure of nanomaterials and the energy needed for their function can be optimized by the fundamental understanding of catalytic behavior of nanoparticles and by a better understanding of the physical properties on the atomic level of solar cells, fuel cells and light sources (LEDs). Ultimately, this requires advanced tools that allow us to see down to the individual atoms and sense their chemical environment. It means having the ability to perform experiments *in situ*, across various lengthscales, to follow specific chemical reactions and physical processes, and there is a need to be able to do these things in multi-dimensions, spatial and temporal.

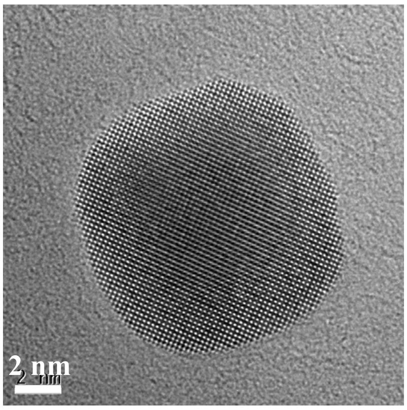

Figure 1: A gold nanoparticle imaged using aberration-corrected TEM, with atomic resolution and clearly defined edges. Courtesy of Bert Freitag, FEI.

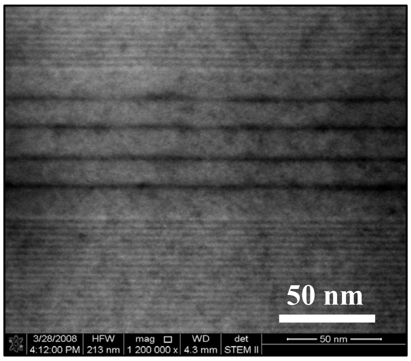

Figure 2: Indium phosphide multilayer quantum wells imaged using STEM-in-SEM. Courtesy of David Wall, FEI NanoPort Acht, sample courtesy of Uni of Wurzburg, Germany.

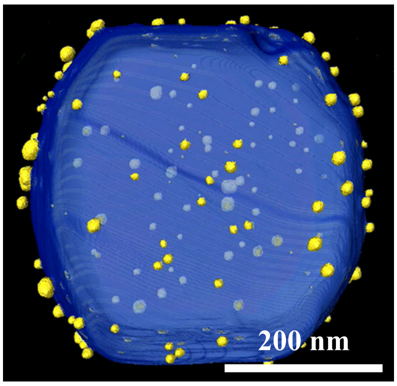

Figure 3: 3D TEM tomographic visualization of a mesoporous silica support and catalyst particles. Courtesy of Christian Kuebel and co-workers, Forschungcentrum Karlsruhe, Germany