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Abstract

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Atomically Accurate 3D Measurements on Nanometer-size Structures by HR-SEM and Modeling

The best high-resolution scanning electron microscopes (HR-SEMs) today can focus the electron beam into a sub-0.5 nm spot that – in principle - allows for measurements with atomic resolution. Special stages permit taking images from as many angles as needed for the reconstruction of the three-dimensional (3D) shape of the sample. Nevertheless, the accurate determination of the 3D shape at the nm-scale is not trivial: the signals of the SEM are the results of complex interactions and the luminance values of its images do not represent sample dimensions directly. A 1 nm diameter Si sphere has only 26 atoms in a volume of about 0.4 nm^3. Because the smallest nanometer-scale features consist of a small number of atoms, which can generate only weak signals, atomic level SEM measurements must be fully optimized for the measurand, i.e., the information sought.

Recently, cryogenic transmission electron microscopy (TEM) has achieved unprecedented, atomic resolution in 3D measurements of protein molecules and other biological structures [1]. Other TEM measurement techniques are also available for nanoparticle 3D reconstruction [2]. Due to the nature of the transmitted electron signal, TEM images show inner structures of the sample chiefly, while the SEM shows mainly the surface, therefore the various SW methods for 3D TEM measurements are not directly applicable to SEM imagery.

The SEM secondary electron signal contains 3D information that – with suitable software – can be used for shape reconstruction. Even a single top-down image can be sufficient for simple structures. Some of the best, model-based size and shape SEM measurements of 10 nm size objects have achieved measurement uncertainty of 0.1 nm, i.e., only a few atoms [3]. These SEM measurement results match that of TEM and x-ray scatterometry. For complex samples, images taken from more than one vantage point are necessary.

As the signal generation in the SEM is fairly complex, accurate, physics-based simulation methods, like NIST JMONSEL are necessary to deduce the 3D shape of the sample. A great deal of improvement is possible both in the determination of the best measurement conditions (see Figure 1 as illustration) and in the analysis and interpretation of the measured raw data. For very accurate atomic scale measurements, high-throughput, high-resolution laser interferometry is indispensable to compensate for the nm-scale unwanted motions of the sample.

This contribution will present our progress in nm-scale 3D SEM measurements and identify the needs and possibilities for an international cooperation to usher in the widespread use of computational scanning electron microscopy along with fully optimized, significantly improved, atomic-resolution 3D measurements and new, higher performance SEMs.

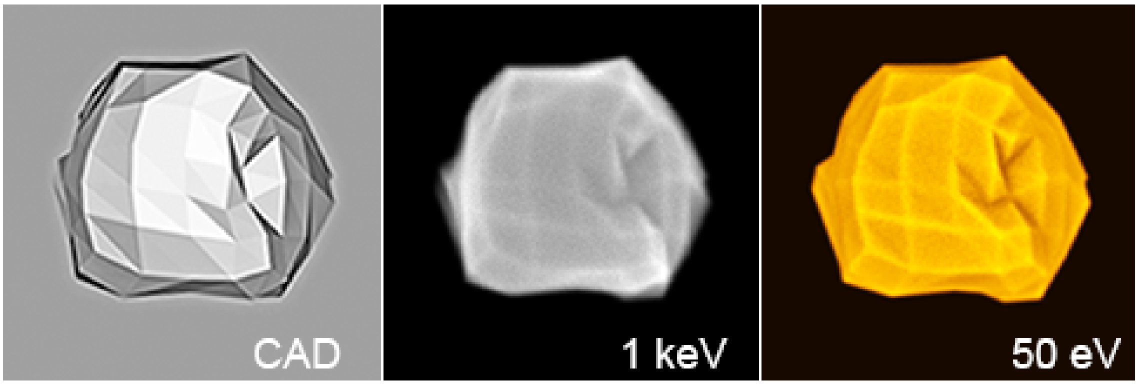

Figure 1: Monte-Carlo-simulated 3D secondary electron images of a 60-nm size Au nanoparticle: computer-assisted design (CAD) model, and 1 keV and 50 eV landing energy images. The lower landing energy electron beam generates images that are more suitable for atomic-resolution 3D reconstruction.

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References

[1] `https://doi.org/10.1038/nature.2017.22738`

[2] `https://doi.org/10.1016/j.micron.2016.09.010`

[3] `https://doi.org/10.1117/12.2045977`