# Development of advanced scanning transmission electron microscopy for materials science research

Naoya Shibata

*Institute of Engineering Innovation, School of Engineering, The University of Tokyo*

Understanding the atomic-scale structures of surfaces and interfaces is essential to control the functional properties of many materials and devices. Recent advances in aberration-corrected scanning transmission electron microscopy (STEM) have made possible the direct characterization of localized atomic structures in materials, especially at interfaces. In STEM, a finely focused electron probe is scanned across the specimen and the transmitted and/or scattered electrons from a localized volume of the material are detected by the post-specimen detector(s) as a function of raster position. By controlling the detector geometry, we gain flexibility in determining the contrast characteristics of the STEM images and the formation mechanisms involved. Thus, it may be possible to obtain further useful information of materials by exploring new detector geometries in atomic-resolution STEM.

By elaborating special detector geometries, we can now not only image atomic structures of materials, but also can image local electromagnetic fields inside materials through differential phase contrast (DPC) imaging techniques [1]. We have been continuously developing area detectors that are capable of atomic-resolution STEM imaging. These area detectors can obtain 16 simultaneous atomic-resolution STEM images which are sensitive to the spatial distribution of scattered electrons on the detector plane. By applying these area detectors, atomic-resolution DPC STEM imaging has been realized [2,3]. We can now visualize electric field distribution within a single atom: the electric field between positive atomic nucleus and negative electron clouds. Now, atomic-resolution STEM opens the new stage of microscopy that enables directly visualization of electronic structures within individual atoms! We also found that DPC STEM imaging is very powerful to directly characterize many interesting internal electromagnetic structures such as pn junctions in semiconductor devices, polar oxide interfaces and magnetic Skyrmions which cannot be observed by normal STEM imaging techniques using annular type detectors.

[1] N. Shibata et al., *Acc. Chem. Res.*, **50**, 1502-1512 (2017).

[2] N. Shibata et al., *Nature Phys.*, **8**, 611-615 (2012).

[3] N. Shibata et al., *Nature Comm.* **8**, 15631 (2017).

KEYWORDS: Electron microscopy, Electromagnetic field, Interface science