# Imaging the Properties of Atoms and Fields at the Picometer Scale inside Materials and Devices

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Electron microscopes use electrons with wavelengths of a few picometers, and are potentially capable of imaging individual atoms in solids at a resolution ultimately set by the intrinsic size of an atom. Even with the rapid advances in aberration-corrector technology, both residual aberrations in the electron lenses and multiple scattering of the incident beam inside the sample, the best resolution possible was an order of magnitude worse than this limit. However, with recent advances in detector technology [1] and ptychographic algorithms to unscramble multiple scattering, the resolution of the electron microscope is now limited only by the dose to the sample, and thermal vibrations of the atoms themselves [2]. At high doses, these approaches have allowed us to image the detailed vibrational envelopes of individual atom columns as well as locating individual interstitial atoms that would be hidden by scattering of the probe with conventional imaging modes. The three-dimensional nature of the reconstruction means surface relaxations can be distinguished from the bulk structure, and interface roughness and step edges inside devices can be resolved – including gate-all-around transistors and Josephson junctions. Even the location of all atoms in thin amorphous films now seems within reach. These approaches have also allowed us to image the internal structures of both magnetic and ferroelectric vortices, skyrmions and merons, including their singular points that are critical for accurately describing the topological properties of these field textures.

[1] M. W. Tate, P. Purohit, D. Chamberlain, K. X. Nguyen, R. Hovden, C. S. Chang, P. Deb, E. Turgut, J. T. Heron, D. G. Schlom, D. C. Ralph, G. D. Fuchs, K. S. Shanks, H. T. Philipp, D. A. Muller, and S. M. Gruner. "High Dynamic Range Pixel Array Detector for Scanning Transmission Electron Microscopy" *Microscopy and Microanalysis* **22**, (2016): 237–249.

[2] Z. Chen, Y. Jiang, Y.-T. Shao, M. E. Holtz, M. Odstrčil, M. Guizar-Sicairos, I. Hanke, S. Ganschow, D. G. Schlom, and D. A. Muller. "Electron Ptychography Achieves Atomic-Resolution Limits Set by Lattice Vibrations" *Science* **372**, (2021): 826–831