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Differential Phase Contrast Imaging by Magnetic-field-free Atomic Resolution Scanning Transmission Electron Microscope

Naoya Shibata[1,2,3]

[1.] Institute of Engineering Innovation, The University of Tokyo, Tokyo, Japan
[2.] Nanostructures Research Laboratory, Japan Fine Ceramic Center, Nagoya, Japan
[3.] Quantum-Phase Electronics Center (QPEC), The University of Tokyo, Tokyo, Japan.
* Corresponding author: shibata@sigma.t.u-tokyo.ac.jp

Aberration-corrected scanning transmission electron microscopy (STEM) is a powerful technique for directly observing atomic-scale local structures inside materials and devices. In the state-of-the-art aberration-corrected STEM, a probe size of less than 0.5Å in diameter has been realized, and almost all the constituent atoms in materials can now be imaged in real space. However, in ordinary STEM, atomic-resolution observation of magnetic materials is essentially difficult, since high magnetic fields are inevitably exerted on samples inside the magnetic objective lens. In recent years, we have succeeded in developing a new magnetic objective lens system that realizes a magnetic field free environment at the sample position. Using this new objective lens system combined with the state-of-the-art higher order aberration corrector, direct atom-resolved imaging of magnetic materials such as silicon steels is realized in STEM [1]. This novel electron microscope (Magnetic-field-free Atomic Resolution STEM: MARS) is expected to be used for research and development of advanced magnetic materials and devices.

On the other hand, in recent years, new imaging possibilities in STEM has been widely explored owing to the rapid development of segmented and pixelated detectors which are capable of atomic-resolution STEM imaging. Differential phase contrast (DPC) imaging is considered to be one of the most useful imaging techniques because electromagnetic field distribution inside materials and devices can be directly imaged in real space. Applying DPC imaging for atomic-resolution STEM [2], it has been shown that the electric field distribution within single atoms can be imaged [3,4], i.e. the electric field between the positively charged atomic nucleus and the negatively charged electron cloud. Moreover, the total charge density distribution inside the atoms can be also visualized [5].

By combining the magnetic-field-free STEM with DPC imaging technique, it is tempting to observe atomic-scale magnetic fields, which strongly correlate with the properties of magnetic materials and devices. However, there are remaining major difficulties for visualizing magnetic fields at very high resolution even after magnetic-field-free atomic-resolution STEM imaging becomes possible. One difficulty is that both the specimen's electric and magnetic fields contribute to the phase shift of the incident electron probe. To visualize magnetic fields, we must differentiate between electric and magnetic phase shift components in the atomic-resolution DPC images. The other difficulty is that the phase shift induced by the atomic-scale magnetic field is predicted to be extremely small. Therefore, very high signal-to-noise ratio imaging conditions are needed. We have shown that, by combining kernel filtering and unit-cell averaging techniques to solve the difficulties of differentiating between electric and magnetic phase shift components and extremely small magnetic phase shifts, real-space visualization of intrinsic magnetic fields of an antiferromagnetic is possible [6]. Figure 1 shows thus obtained magnetic field image of a hematite (α-Fe_2O_3) crystal. The details of atomic-resolution DPC STEM for magnetic field imaging using MARS will be presented in the talk [7].

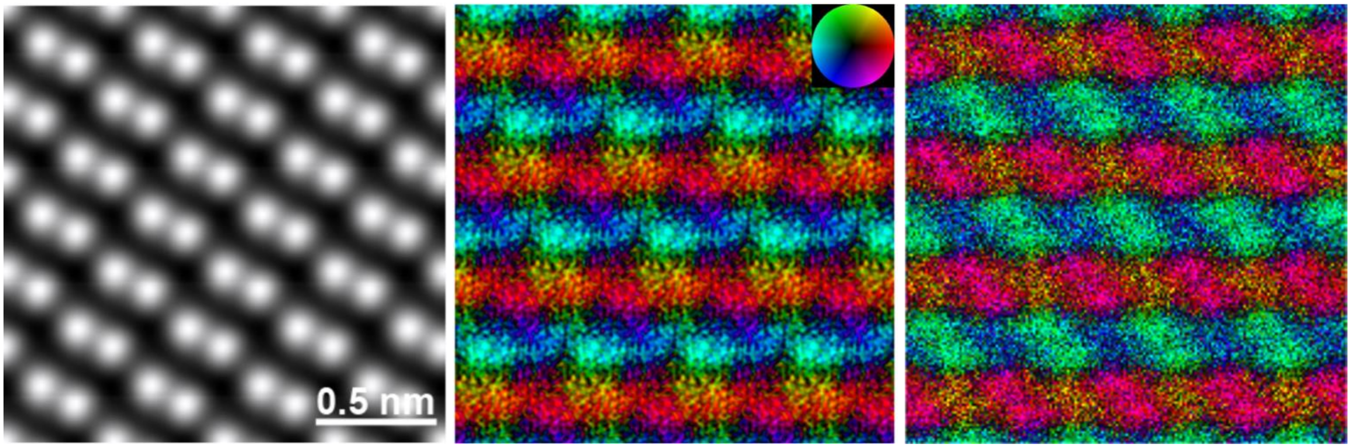

Figure 1. (left) Unit cell averaged and tiled ADF image of α-Fe_2O_3 observed along the [$\bar{1}\bar{1}20$] direction. (center) The corresponding projected magnetic field vector color map. (right) The simulated image assuming room temperature antiferromagnetic structure of α-Fe_2O_3. The antiparallel magnetic field component on the adjacent Fe-Fe double atomic layers is clearly observed, visualizing antiferromagnetic order in this crystal [6].

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