Differential Phase Contrast Imaging of Domain Structure in Ferroelectric $BaTiO_3$

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The electron scattering distribution in the scanning transmission electron microscope (STEM) contains more information than is used in the standard modes of annular dark-field and bright field imaging. To take advantage of this, we developed a segmented detector comprising four nested rings divided into quadrants–16 individually addressable detectors in total (Fig. 1)–for use in an atomic-resolution STEM [1].

The signals from individual detector segments can be combined arithmetically. Adding images from segments in the same ring (e.g., segments 5, 6, 7 and 8 in Fig. 1(a) constitute "ring 2") at suitable camera length gives simultaneous atomic resolution annular bright field, low angle annular dark field and high angle annular dark field images. We may also take the difference between images. Differential phase contrast imaging, used previously to explore magnetic structure at low magnification [2], is based on this approach. We will apply it to exploring domain structure in a ferroelectric, taking $BaTiO_3$ (Fig. 2(a)), as our case study.

Our low magnification STEM images are still formed using an atomically fine probe, and thus constitute the average over many unit cells of the atomic resolution signal. Position-averaged STEM diffraction patterns have recently been investigated [3]. Fig. 2(c) shows a simulated position-averaged diffraction pattern for $BaTiO_3$ [010] assuming a 200 keV probe and 23 mrad probe-forming aperture angle. Though containing some weak structure, it does not differ greatly from the specimen-free image in Fig. 2(b). The polarization field is neglected in Fig. 2(c) but is included in Fig. 2(d). To first order, the field produces a deflection of the diffraction pattern, by an amount dependent on the polarization field and specimen thickness. This is evident in Fig. 2(e), the difference between Figs. 2(c) and 2(d), and Figs. 2(g) and (h), which show the electron density falling on particular detector segments.

The difference signals thus change as we scan across polarization domains in $BaTiO_3$ [4]. This is seen in Fig. 3. Consideration of the numeric signal strength allows us to assign the direction of the polarization field within each domain. Further work on characterizing the detector is needed to separate the effect of specimen thickness and directly measure the polarization field strength.

References

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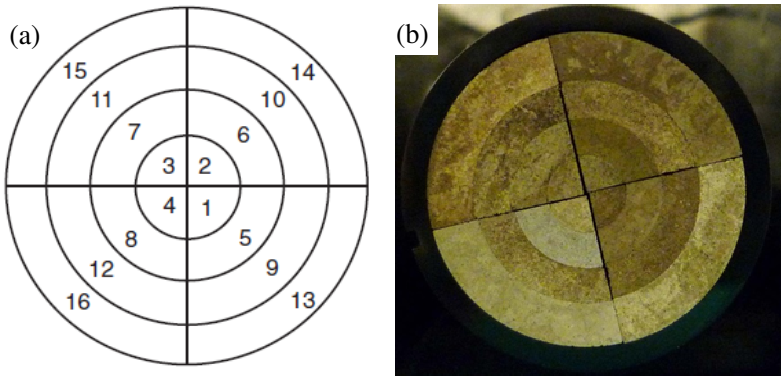

FIG. 1. (a) Schematic and (b) photograph of the new detector showing the 16 individually addressable segments.

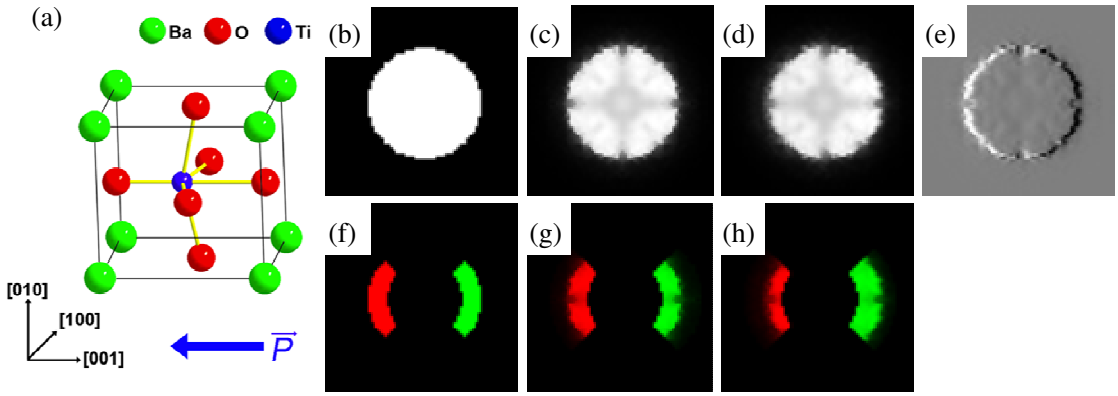

FIG. 2. (a) $BaTiO_3$ structure showing the polarization field. (b-d) Simulated position-averaged diffraction patterns from: (b) no specimen; (c) 300 Å of $BaTiO_3$ [010], neglecting the polarization field; and (d) 300 Å of $BaTiO_3$ [010], including the polarization field. (e) The difference between patterns (c) and (d). (f-h) For the diffraction patterns in (b-d) respectively, the intensity falling into two diametrically opposed segments of the detector at suitable camera length. In (h), the signals on the two detector segments are clearly no longer equal.

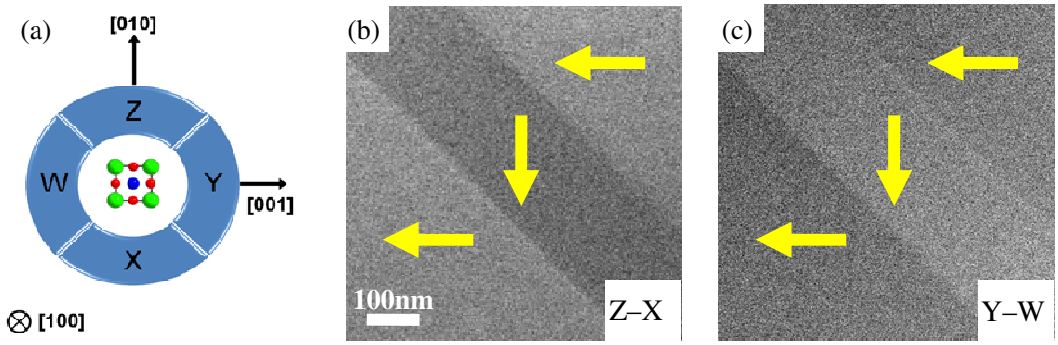

FIG. 3. For the detector orientation relative to $BaTiO_3$ crystal shown in (a) (ring 2 only shown), experimental low magnification differential phase contrast images are shown in (b) and (c). The domain structure is clear. Yellow arrows mark the polarization directions.