Dynamics of Annular Bright Field Scanning Transmission Electron Microscopy Imaging

S.D. Findlay¹, N. Shibata¹², H. Sawada³, E. Okunishi³, Y. Kondo³, Y. Ikuhara¹⁴⁵

¹Institute of Engineering Innovation, The University of Tokyo, Tokyo, 116-0013, Japan
²PRESTO, Japan Science and Technology Agency, Saitama, 332-0012, Japan
³JEOL Ltd., Tokyo, 196-8558, Japan
⁴Nanostructures Research Laboratory, Japan Fine Ceramics Center, Nagoya, 456-8587, Japan
⁵WPI Advanced Institute for Materials Research, Tohoku University, Sendai, 980-8577, Japan

An annular detector within the bright field region in atomic resolution scanning transmission electron microscopy (STEM) has recently been shown to produce images showing both light and heavy element columns simultaneously [1,2]. We call this annular bright field (ABF) imaging, by analogy to annular dark field imaging. The use of bright field annular detectors in STEM has precedent [3], but the earlier work, prior to aberration correction, did not predict the robustness with respect to thickness of the simultaneous imaging of light and heavy columns at atomic resolution. Fig. 1 shows a defocus-thickness map of ABF images of SrTiO₃ [011], giving some indication of the form of the images (dark contrast at the column sites), and the robust, reliable interpretation over a wide thickness range.

Ref. [2] presented a simple s-state channeling model to explain the form and robustness of the ABF images. But the s-state model is approximate, only providing a guide to the imaging dynamics. Systematic simulations are needed to explore the imaging dynamics more fully, including issues like optimum aperture sizes and the effect of intercolumn spacing and structural distortion.

Figs. 2(a) and (b) plot the on-column signal as a function of thickness in a fictitious single-column structure assuming 22 mrad and 32 mrad probe-forming apertures respectively. The signals for different elements overlap a little, suggesting that ABF contrast is not a completely reliable guide to column constituency. However, there is more discrimination between the elements for the larger probe-forming aperture. Averaging over the oscillations in this latter case produces a monotonic relationship between signal and atomic number. The “signal”, the zero thickness limit minus this average value, is plotted as a function of atomic number in Fig. 2(c). The scaling is roughly Z⁻¹/³, though an exponential fit is better. Fig. 3 shows the effect of intercolumn spacing. As columns move closer together, there is some displacement of the apparent column location, though the existence of the columns remains clear.

References

[4] S.D.F. was supported for part of this work as a Japan Society for the Promotion of Science (JSPS) fellow. N.S. acknowledges support from Industrial Technology Research Grant program in 2007 from New Energy and Industrial Technology Development Organization (NEDO) of Japan.

FIG. 2. ABF signal as a function of thickness with the probe on top of the column in a fictitious single-column structure for a probe forming aperture of: (a) 22 mrad and (b) 32 mrad, for the detector ranges and elements as labeled on the figure. (c) Zero-thickness limit less the averaged ABF signal over 300–600 Å as a function of atomic number, compared with some approximate analytic forms.

FIG. 3. ABF line scan as a function of specimen thickness for a fictitious two column (Ca and O) structure for the intercolumn spacing given above each panel. A 200 keV, aberration free probe with 22 mrad probe-forming aperture semiangle and a detector collection range of 11–22 mrad are assumed.