Monochromator with Double Wien-filter for Aberration-Corrected STEM

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In material science, it is important to measure electronic structures at atomic scale to study characters of materials. With an aberration-corrected scanning transmission electron microscope (STEM), an elemental analysis at atomic scale has been realized in combination with an electron energy-loss spectroscopy (EELS). [1] To perform the atomic scale analysis of electronic structures with a high energy resolution, we developed a monochromator for an aberration-corrected STEM. [2]

The developed monochromator consists of two Wien-filters and an energy selection slit inserted between the two filters. Since the electron trajectories inside of the monochromator are set to be symmetric to the slit plane so that the energy-dispersion arisen at the slit plane is cancel out at an exit plane, resulting in an achromatic electron probe at the specimen plane. Therefore, the energy spread of the electron probe is controllable independently on the probe sizes by choosing the slit width. Figure 1 shows the intensity profiles of the zero-loss peaks for several widths of the slits with a 0.1 seconds acquisition at 200 kV. These profiles are normalized based on an amplifying factor to compare intensities and energy spreads with different slit widths. The ultimate energy resolution was 36 meV with a slit of 0.25 μm.

Figures 2 (a) and (b) show raw HAADF-STEM images of Si [110] with different slit widths at 200 kV and their Fourier transforms. Figure 2 (a) was obtained with an energy spread of 294 meV using a 4 μm slit, showing clear separations of dumbbells of 136 pm, and the spots appeared at positions smaller than 100 pm^{-1} spacing in the Fourier transform. Figure 2 (b) was obtained with an energy spread of 36 meV using a 0.25 μm slit. In order to compensate the reduced probe current due to narrower slit, the scanning speed of this image was set to be 100 μs/pix. The Fourier transforms of these two images in insets of Figs. 2 (a) and (b) showed the isotropic resolution, even when the monochromated probes formed after the slits. Thus, the developed monochromator with the double Wien-filter system enables us to obtain a round monochromated electron probe with atomic resolution at any energy resolution.

In order to investigate both of the high energy resolution and the high spatial resolution in the analytical works, we tried the atomic resolution EELS mapping of $SrTiO_3$ [100] with an electron probe with energy spread of 146 meV at 200 kV by spectrum imaging technique. The area for the elemental mapping was chosen at the framed area shown in the HAADF-STEM image of Fig. 3(a). Figure 3(b) shows an atomic resolution Ti map, whose intensity in each pixel was integrated over multiply acquired maps after subtracting the background from original spectrum shown in Fig. 3(c). Thus, the atomic columns of Ti in a $SrTiO_3$ have been successfully visualized using the monochromated electrons with 146 meV energy spread.

References:

[1] E. Okunishi et al.: *Microsc. Microanal. (suppl.2)* **13** (2006) 1150-1151
[2] M. Mukai et al.: *Microsc. Microanal. (suppl.2)* **19** (2013) 1126-1127

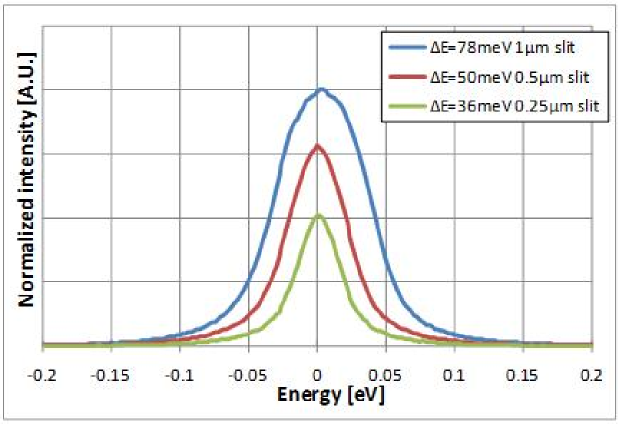

FIG. 1. Intensity profiles of zero-loss peaks for the slit of 1 μm, 0.5 μm and 0.25 μm obtained with 0.1 seconds acquisition at 200 kV.

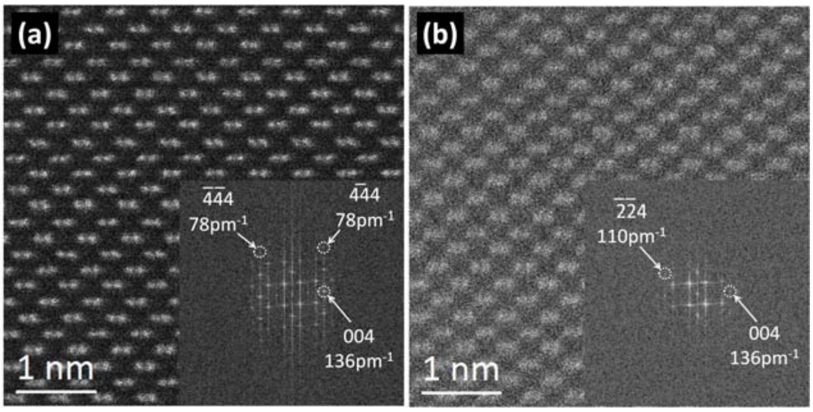

FIG. 2. Raw HAADF-STEM images of Si [110] with different setting of monochromator at 200 kVand their Fourier transforms. (a) Energy spread of 294 meV using 4 μm slit with 12 pA probe current and 38 μs/pixel scan speed, (b) Energy spread of 36 meV using 0.25 μm slit with 0.8 pA probe current and 100 μs/pixel scan speed.

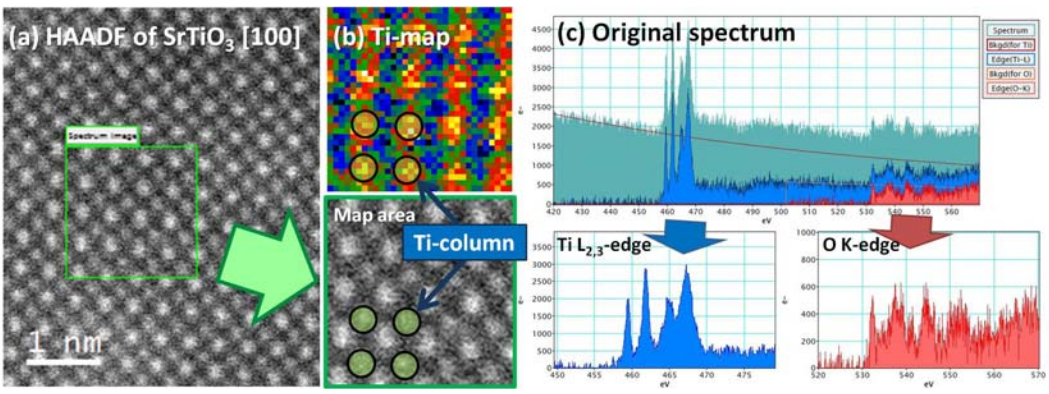

FIG. 3. (a) Raw HAADF-STEM image of $SrTiO_3$ [100] obtained with 112 pA probe current and 146 meV energy resolution at 200 kV, (b) Ti map of $SrTiO_3$ [100], (c) Original spectrum with 0.05 sec. acquisition time and background-subtracted spectra of Ti $L_{2,3}$- and O K-edges.