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Resolution Enhancement at Low-Accelerating-Voltage by Improvements of Diffraction Limit and Chromatic Aberration

H. Sawada[1], T. Sasaki[1], F. Hosokawa[1], and K. Suenaga[2]

[1]JEOL Ltd., 3-1-2 Musashino, Akishima, Tokyo, 196-8558, Japan

[2]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, 305-8565, Japan

An atomic-resolution microscope operating at a lower voltage is increasingly requested because the lower accelerating voltage provides less specimen damage and larger scattering cross-section that results in a high signal for analysis [1-3]. However, a resolution reduction by a diffraction limit becomes severe with an increase in the wavelength of an electron as an accelerating voltage decreases. Another resolution reduction is caused by a chromatic aberration due to an energy spread of the electron source. For maintaining atomic resolution at low accelerating voltage, a larger convergence angle realized with an aberration corrector and a narrower energy spread of the source are required. The developed microscope by us achieved atomic resolution at the accelerating voltage lower than 60 kV, using a higher-order aberration corrector [4]. The atomic-resolution imaging showing 136 pm resolution using a Si [110] has been demonstrated at 30 and 60 kV [5]. This paper reports the realization of sub-angstrom imaging at 60 kV using a Ge [112] specimen which shows 82-pm dumbbells [6].

The developed microscope was equipped with a CFEG. The electron source for the gun was chosen to be a tungsten [310] tip to obtain a narrow energy spread. In our observation, the energy spread was measured to be 0.36 eV in full width of half maximum (FWHM), after setting of an extracting voltage to provide a proper emission current used for a high resolution imaging. A demagnification factor of probe on a specimen refer to the source in probe forming lens system was set so as to obtain a Gaussian probe size of 14 pm on a specimen. Figure 1(a) shows the calculated probe profiles at convergence semi-angles of 30 mrad, 35 mrad, 40 mrad, and 45 mrad. The probe profiles show sharper peaks with an increase in the convergence semi-angle. The probe profile at 45 mrad shows diameters of 57.8 pm in FWHM, 91.4 pm in D50 and 120.4 pm in D59, where D50 and D59 denote the diameter of the electron beam that include 50% and 59% of the total beam current, respectively. The probe diameter at 45 mrad expected to realize sub-angstrom STEM imaging at low accelerating voltages. Figure 2 shows a set of simulated STEM images of Ge [112] at 60 kV at several convergence semi-angles [7]. The dips between the atomic dumbbells become deeper with an increase of convergence angle. The large diffraction limit, due to a longer wavelength at a low accelerating voltage, worsens the resolution in the sub-angstrom imaging. Judging from the simulations, at a convergence semi-angle larger than 40 mrad, the 82-pm dumbbell is expected to be resolved because of the small diffraction limit.

For experimental evaluation for the sub-angstrom resolution, a Ge [112] crystalline specimen was observed at 60 kV, as shown in Fig. 3. The current and convergent semi-angle for the probe were measured to be 6 pA and 45 mrad. The simulated image at 45 mrad is displayed at the upper left of Fig. 3(a). Figure 3(b) shows a Fourier transform of the STEM image shown in Fig. 3(a). The Ge-Ge dumbbells are resolved in Fig. 2(a), and the $44\overline{4}$ spot (corresponding to $(82\ \text{pm})^{-1}$) is clearly visible in Fig. 3(b).

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We achieved a resolution of 82 pm using the Ge-Ge dumbbell structure by high angle annular dark-field imaging. We also experimentally confirmed that resolution at a low accelerating voltage is severely affected by a convergence angle and a energy spread of the probe [8]. This work was supported by JST under the Research Acceleration Program (2012–2016).

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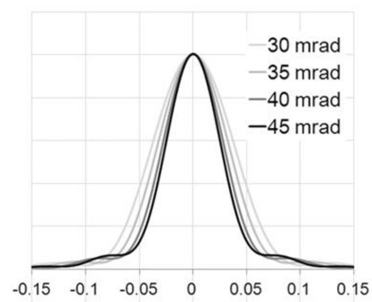

Figure 1. (a) Calculated probe shapes at convergence semi-angles of 30 mrad, 35 mrad, 40 mrad, and 45 mrad.

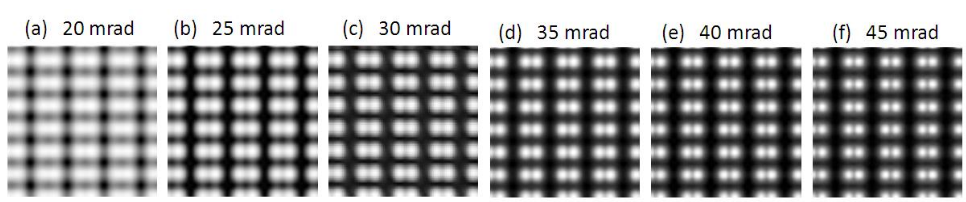

Figure 2. Simulated dark-field images of the Ge [112] specimen at convergence semi-angles of (a) 20 mrad, (b) 25 mrad, (c) 30 mrad, (d) 35 mrad, (e) 40 mrad, and (f) 45 mrad at 60 kV [7] by the multi-slice method.

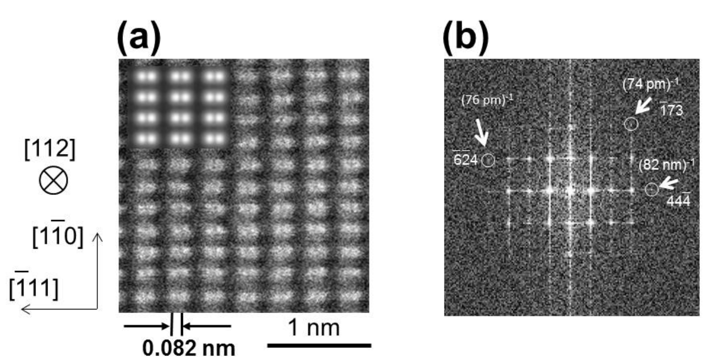

Figure 3. (a) The Ge [112] dark-field image at 60 kV. (b) The power spectrum of Fourier transform for the STEM image in (a). The pattern clearly shows spots of (82 pm)$^{-1}$.

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