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Resolving 45 pm with 300 kV Aberration Corrected STEM

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Eternal challenge towards better resolution has been running by scientists who pursue to see smaller scale world, and countless efforts were spent since the microscope was invented. Within recent decades, Cs corrected microscope [1-3] realized sub-angstrom resolution [4,5]. And further resolution, sub-50-pm was demonstrated in dark-field STEM at 300 kV with an aberration corrected microscope using a Ge [114] specimen [6,7], which shows 47 pm spacing between Ge-Ge atomic columns. Our challenge to get better resolution over the 47 pm was successful with a developed 300 kV aberration corrected microscope equipped with a cold field emission gun (CFEG). This paper reports the results of our challenge, which showed 45 pm resolution using a Si [114] specimen [8].

The microscope we developed is equipped with an asymmetry type spherical aberration corrector [3] in the probe forming lens system. After the Cs correction, the next aberration to block the resolution limit is chromatic aberration. Therefore, the coefficient of chromatic aberration for the probe-forming system is optimized to be 1.35 mm with a developed objective lens pole piece. With $\Delta E = 0.4$ eV, simulated probe sizes as a function of Gaussian probe size on a specimen is shown in Fig. 1 (a). Figure 1 (a) indicates that Gaussian probe size, which is demagnified source size, is not negligible to pursue the sub-50 pm resolution. In the observation of Si [114], a probe current was set to be 3 pA. In this condition of probe forming system, the Gaussian probe size on a specimen was estimated to be 7 pm. Figure 1 (b) is a profile of the simulated probe with the experimental conditions, showing that Cs corrected STEM at 300 kV with a sufficiently small Gaussian probe size produces a sub-50-pm-sized probe. A full width of half maximum (FWHM) is calculated to be 32.2 pm, D50 is 38.6 pm and D59 is 45.9 pm. D50 and D59 denote the diameter of the electron beam that includes 50% and 59% of the total beam current, respectively.

Before testing the ultimate performance of the microscope by sub-50-pm imaging, we observed Si [110], Ge [112], Si [112], GaN [211] crystalline specimens, which show distances between atomic column dumbbells of 136 pm, 82 pm, 78 pm, and 63 pm, respectively in dark-field STEM mode. These atomic dumbbells are clearly resolved in raw images as shown in Figs. 2 (a-d). Ge [114] was also imaged to confirm sub-50 pm resolution as shown in Fig. 2 (e). Figure 2(f) shows experimentally obtained HAADF image of Si [114]. Since weaker scattering by Si atoms than Ge made a worse single-to-noise ratio in the raw image during the experiment, we doubly increased the dwell time per a pixel in the image acquisition for Si [114] relative to one for Ge[114].

Figure 3 (a) shows an experimentally obtained raw dark field image of Si [114], and Figure 3 (b) shows its low pass filtered image. Simulated images for a 20 nm thick sample were inserted at the lower right in both images. A spot corresponding with $(45\ \mathrm{pm})^{-1}$ is confirmed in a Fourier transform shown in Fig. 3 (c). An intensity profile in Fig. 3 (d) also shows 45 pm separation.

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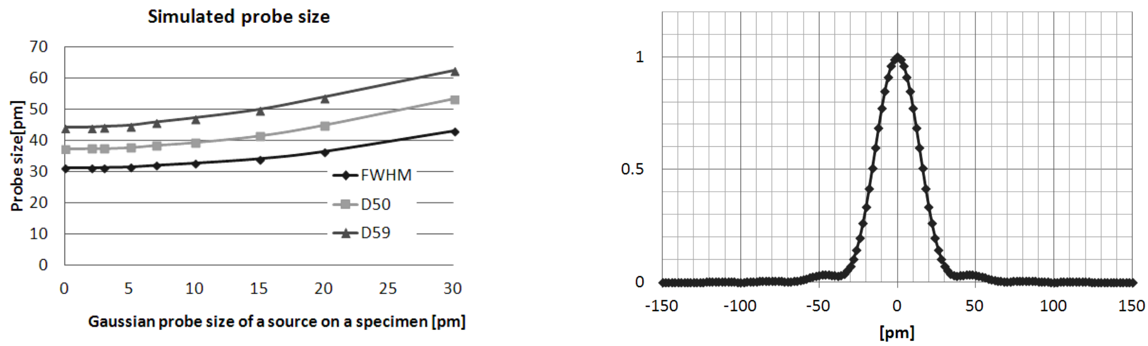

(a) (b)

Figure 1. (a) Simulated probe size including aberrations and Gaussian probe size, depending on Gaussian probe size at 300 kV. (b) Profile of the simulated probe with the experimental conditions: ΔE = 0.4eV, Cc= 1.35 mm.

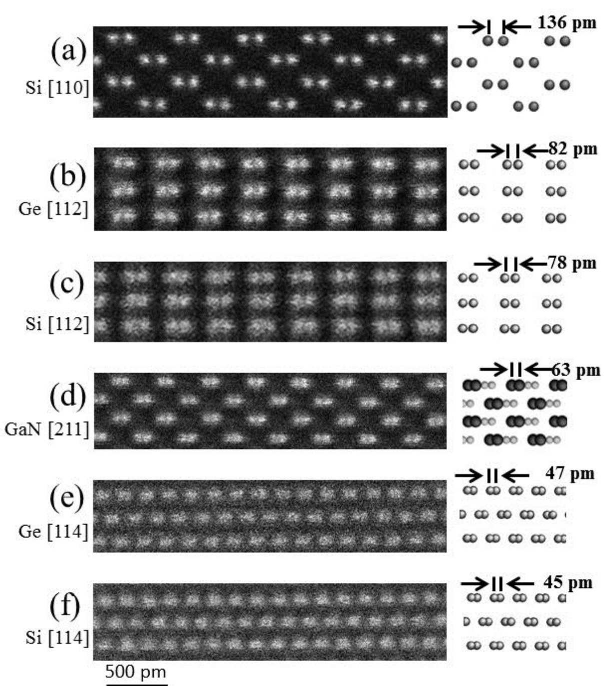

Figure 2. (a-f) Raw dark field STEM images and their structural models.

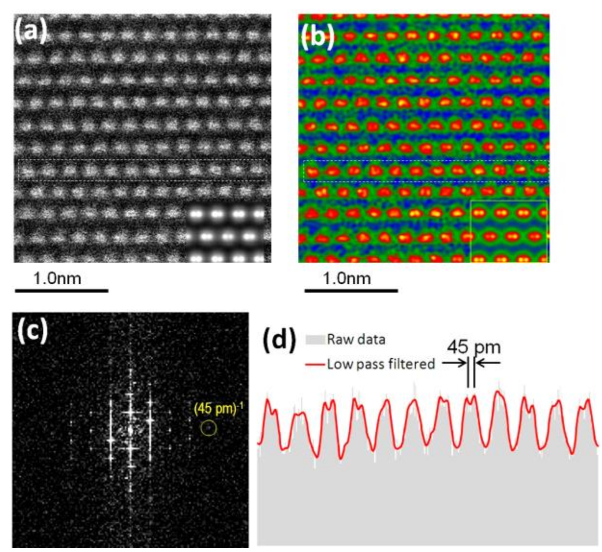

Figure 3. (a) Raw dark field STEM image of Si [114]. (b) Low pass filtered image of (a). Simulated images were inserted at the lower right in both images using the condition in Fig. 1 (b). (c) Power spectrum of (a). (d) Intensity profiles from the dotted rectangles in (a) and (b).

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