Automated Alignment Cs Correction System for STEM (I): Design and Verification of Automated Alignment System

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A sub-angstrom probe size has been achieved with a Cs corrector [1, 2] for a scanning transmission electron microscope (STEM). In general, in the alignment of the Cs corrector, a user needs to select the aberration that needs to be corrected on the basis of aberration measurements. Once wrong selection of aberrations to be corrected is executed, the number of measurements and corrections is increased. Therefore, an automated alignment system that does not require user operation is desired.

In addition to first-order astigmatisms (A1) corrected in conventional STEM, each aberration (second-order axial coma (B2), second-order astigmatisms (A2), third-order star aberrations (S3), and third-order astigmatisms (A3)) that is incidentally generated by the correction of third-order spherical aberrations (C3) should be corrected. However, the operation of a Cs corrector is difficult and stressful because it is necessary to correct many kinds of aberrations. In particular, the sequence and selection of aberration corrections depend on the user’s experience. Therefore, a method of automatic aberration correction (automated alignment system), which automatically evaluates the selection of the aberration to correct, is necessary.

Our objective is to develop an automated alignment system of a Cs corrector for STEM. Figure 1 shows a schematic diagram of the automated alignment system. We conducted an aberration correction experiment using a Hitachi dedicated 200 kV FE-STEM equipped with the produced Cs corrector. Our Cs corrector is controlled by a power supply which is adjusted by an automated alignment unit that selects and corrects the aberrations automatically according to aberration coefficients measured using the image from a CCD camera with the aid of the reinforcement learning method.

To evaluate the system performance, we first corrected the aberrations manually, i.e., a user selected and corrected the aberrations, before verifying the performance of the automated alignment system. Figure 2 shows the Ronchigram after the manual correction. The flat contrast area in the center circle is 38 mrad. A fifth-order astigmatism (six-fold) remains. Figure 3 shows a high angle annular dark field (HAADF) STEM image of Si(112) at 200 kV. It reveals that silicon dumbbells are separated at 78 pm corresponding to Si(444), and the silicon atoms are separated in the line profile of the image. Figure 4 is a HAADF STEM image of BaTiO3. It shows that the Ba and Ti/O columns are separated clearly. Moreover, we have verified the effectiveness of the automated alignment system and succeeded in achieving a flat contrast area of 32 mrad in the Ronchigram after auto-alignment. In conclusion, we demonstrated the fundamental performance of the automated alignment system.

References
Fig. 1 Cs corrector system of 200 kV STEM for auto-alignment.

Fig. 2 Ronchigram after manual correction of spherical aberration.

Fig. 3 HAADF STEM image of Si(112) at 200 kV.

Fig. 4 HAADF STEM image of BaTiO₃.