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Chromatic Aberration Correction by Combination Concave Lens

H. Sawada[*,**], F. Hosokawa[**], T. Sasaki[*,**], S. Yuasa[**], M. Kawazoe[**], M. Terao[**], T. Kaneyama[*,**], Y. Kondo[**], K. Kimoto[*,***] K. Suenaga[*,****]

[*]Japan Science and Technology Agency, CREST, 5, Sanbancho, Chiyoda-ku, Tokyo, 102-0075, Japan
[**] JEOL Ltd., 3-1-2 Musashino, Akishima, Tokyo, 196-8558, Japan
[***]National Institute for Materials Science (NIMS), 1-1 Namiki, Tsukukba, Ibaraki 305-0044, Japan
[****]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, 305-8565, Japan

A lens for an electron microscopy has imperfections [1]. By development of spherical aberration correctors, geometrical limitation of resolution has been overcome. The correctors operated at acceleration voltage of 60–300 kV in electron microscopes have been widely used and allow us to perform high-resolution structural and analytical studies [3-6]. The performances at these middle acceleration voltages had been improve enough to resolve an atomic position in a specimen. However, when we operate an electron microscope at a lower acceleration voltage, the reduction of resolution is much severer than that at a higher-voltage microscope, since the blur from the chromatic aberration d_{Cc} define as $d_{Cc} = Cc \cdot dU / U \cdot \alpha$, where Cc is a coefficient of chromatic aberration, U is an acceleration voltage, and α is semi-angle. Operation at low acceleration voltage has an advantage for observation of soft matter made of light elements, due to small electron-related irradiation damage and high contrast on account of the larger scattering cross-section [6]. It is an interesting challenge to maintain the resolution at the atomic level by using a Cc corrector for low-voltage electron microscopy. Therefore, we are developing a Cc corrector for image-forming system at acceleration voltage less than 30 kV.

Our Cc corrector system employs combination concave lens [7] caused by quadrupole (two-fold astigmatism) field. For the Cc correction, it is required two conditions. First requirement is that the system introduces a concave lens, and second is that refractive index of the concave lens for an electron is different from that of an objective lens. Equation 1 shows a slope r' of an electron trajectory in the long quadrupole field using complex geometrical notation,

$$r' = -\sum_{n=1} \frac{\overline{\omega_0}}{(4n-3)!\, f^{4n-3}} \widetilde{A}_2 \cdot |\widetilde{A}_2|^{2(n-1)}\, z^{4n-3} + \sum_{n=1} \frac{\omega_0}{(4n-1)!\, f^{4n-1}} |\widetilde{A}_2|^{2n}\, z^{4n-1}, \text{---Eq.1}$$

where ω_0 represents the complex angle of the incident ray, f is the focal length of the objective lens, z is the length of the multipole, and m and n denote integers. The force on the electron to make two-fold astigmatism A_2 per unit length is denoted by $|\widetilde{A}_2|$. Long quadrupole field produces two-fold astigmatism (first term in Eq.1) and an effect of combination concave lens (second term in Eq.1). Using the optical system consisting of two quadrupole fields (Fig.1) connected with transfer lenses, it is possible to cancel out the two-fold astigmatism and to obtain a concave lens. (Eq.2).

$$r' = -2\sum_{n=1} \frac{\omega_0}{(4n-1)!\, f^{4n-1}} |\widetilde{A}_2|^{2n}\, z^{4n-1} + \sum_{n=1} \sum_{m=1} \left\{\frac{16mn-4n-4m}{(4n)!(4m)!}\right\} \frac{\omega_0}{f^{4n+4m-1}} |\widetilde{A}_2|^{2n+2m}\, z^{4n+4m-1}$$
$$+\sum_{n=1} \sum_{m=1} \left\{\frac{-16mn+12n+12m-8}{(4n-2)!(4m-2)!}\right\} \frac{\omega_0}{f^{4n+4m-5}} \cdot |\widetilde{A}_2|^{2n+2m-2}\, z^{4n+4m-5} \quad \text{---Eq.2}$$

For this study, we use a dodecapole to make static magnetic $|\widetilde{A}_{2M}|$ and electronic $|\widetilde{A}_{2E}|$ two-fold astigmatism field (Fig.2). Relationships between forces of two fields and the acceleration voltage are shown in Eqs.3a and 3b,

$$|\widetilde{A}_{2M}| \propto \frac{1}{\sqrt{U}} \quad \text{---Eq.3a,} \qquad |\widetilde{A}_{2E}| \propto \frac{1}{U}, \text{---Eq3b}$$

whereas that of objective lens is $1/f \propto 1/U$. The static magnetic and electronic two-fold astigmatism fields oppositely deflect the electron to avoid a trajectory changing largely in the dodecapole. With this system, the system needs no line-focus condition, as shows in Eq.4.

$$\frac{2f^2}{z^2} \geq |\widetilde{A}_{E2} - \widetilde{A}_{E2}| \text{---Eq4}$$

In the combination concave lens term in Eq.2, there are several powers of $|\widetilde{A}_2|$, which cause the term of $1/\sqrt{U}^N$ (N: integer), resulting in that the refractive index for an electron is different from that of an objective lens (Eqs.3). Thus, the effect of the combination concave lens is applicable to compensate Cc (Fig.3).

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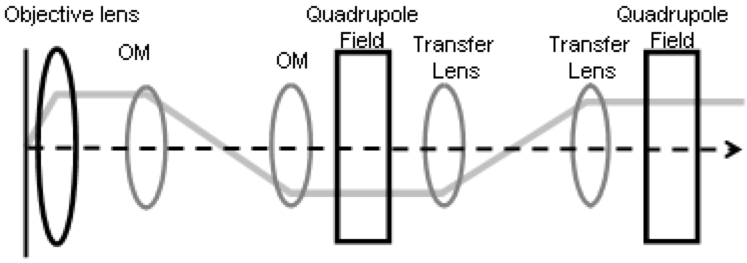

Figure 1 Configuration of combination concave lens system for chromatic aberration correction. OM denotes an objective mini lens.

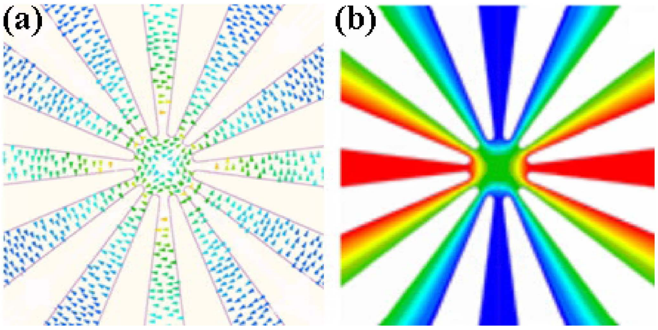

Figure 2 (a) Magnetic and (b) Electronic qadrupole field (Red: 5kV. Bule: -5kV).

Figure 3 Developed Cc Corrector.