Microsc. Microanal. 8 (Suppl. 2), 2002
DOI 10.1017.S1431927602101462

Correction of Aberrations—Past, Present and Future

H. Rose

Materials Science Division, Argonne National Laboratory, Argonne IL 60439, USA

The performance of static rotationally symmetric electron lenses is limited by unavoidable chromatic and spherical aberrations. In 1936, Scherzer demonstrated that the integrands of the integral expressions for the coefficients of these aberrations can be written as a sum of positive quadratic terms [1]. Hence these coefficients can never change sign. This important result is called the Scherzer theorem, the only theorem existing in electron optics. Employing variational methods, Tretner determined the field of magnetic and electrostatic round lenses, which yields the smallest spherical aberration coefficient for particular constraints [2]. Unfortunately, these coefficients are still too large for realistic boundaries to enable sub-Ångsrtöm resolution at medium voltages of about 200 to 300 kV. Therefore, the only possibility to directly reach this limit is the correction of the troublesome aberrations. It was again Scherzer who showed different procedures for cancelling these aberrations [3]. The most promising is the incorporation of a corrector consisting of multipole elements or of a tetrode mirror in the case of low voltages. Although the mirror is rotationally symmetric, a non-rotationally symmetric beam splitter is needed to separate the incident beam from the reflected beam.

The first corrector proposed by Scherzer consists of electrostatic elements, and was built and tested by Seeliger [4]. He first showed that spherical aberration could be eliminated by properly adjusting the octopoles. Since the resolution of his microscope was limited by instabilities, the correction did not improve the actual resolution. Nevertheless, his experiments clearly revealed that spherical aberration can be eliminated by means of a corrector. In order to demonstrate the effect of this correction, Moellenstedt increased the illumination angle to 0.02 rad, thereby enlarging the spherical aberration to such an extend that it blurred the image and limited the resolution. After adjusting the octopoles of the Seeliger corrector appropriately, the resolution was improved considerably accompanied by a striking increase in contrast [5]. The latter results from the reduction of delocalisation, because the correction of spherical aberration eliminates the extended base of the point-spread function. The importance of this behavior for artefact-free imaging of non-periodic objects, such as interfaces, has been recognized only recently [6].

The Seeliger corrector and the quadrupole-octopole corrector investigated later by Deltrap [7] are only applicable for probe-forming systems because they introduce large off-axial aberrations. The same holds true for the two Chicago correctors developed by Beck and Crewe, which were intended to reduce the probe-size in their STEM [8,9]. For imaging extended objects with high resolution in a TEM, an electron-optical aplanat has been designed, built and tested at Darmstadt over a period of almost 10 years starting in 1972. By increasing the number of multipole elements and employing symmetry conditions for their fields and the paths of the paraxial rays, it was possible to correct axial chromatic aberration, spherical aberration, chromatic distortion and coma [10]. It was shown by Koops [11] and Hely [12] in the course of the project that the chromatic and spherical correction worked perfectly. Nevertheless, an actual improvement in resolution could not be achieved because it was not possible to align the system with the required accuracy or to achieve the necessary electrical and mechanical stability at the time. Owing to a lack of adequate technology, all attempts have failed over a period of almost 45 years to improve the performance of electron microscopes by correcting the aberrations. As a result it was widely believed that a posteriori methods such as holography and digital image processing would provide more realistic and easier solutions.

This pessimistic view was proven wrong by Zach and Haider [13] who were the first to achieve an actual improvement in resolution with a multipole corrector in a dedicated low voltage SEM. Due to the rapid advancement in electronic technology and in computer-assisted alignment of systems consisting of many elements, the correction of aberrations can now routinely be performed in the TEM [14] and in the STEM [15]. Aplanatic systems have the further advantage to allow large tilt angles for the incident beam because tilting its axis introduces neither an appreciable image shift, nor defocus, astigmatism or axial coma. Aberration correction is also important to improve the performance of imaging energy filters. It has been demonstrated recently that a corrected 90-degree imaging energy filter is capable of filtering and transferring large-angle diffraction patterns without any appreciable distortion up to scattering angles of about 150 mrad.

At present the deleterious effect of chromatic aberration is best avoided by employing a monochromator, because it requires a significantly smaller expenditure than the correction of the chromatic lens defect by means of electric/magnetic quadrupoles. In this case it suffices to correct only for spherical aberration and off-axial coma by means of a hexapole corrector, because hexapoles do not affect the paraxial path of rays. However, the need for chromatic correction has recently been revived in the context of in situ high-resolution energy-filtering TEM and high-throughput electron projection lithography. The latter requires a system which is corrected for chromatic aberration and all third-order geometrical aberrations. A feasible system is proposed which consists of a demagnifying telescopic round lens doublet and a corrector composed of two identical symmetric quadupole-octopole septuplets. The realization and the alignment of this multi-element system is significantly facilitated by symmetry conditions imposed on the corrector as a whole and the two parts of it.

References:

[1] O. Scherzer, Z. Phys. 101 (1936) 593.
[2] W. Tretner, Optik 16 (1959) 155.
[3] O. Scherzer, Optik 2 (1947) 114.
[4] R. Seeliger, Optik 5 (1949) 490.
[5] G. Moellenstedt, Proc. Int. Conf. on EM, London (1954) 694.
[6] M. Haider et. al., J. Electr. Micr. 47(1998) 395.
[7] J.H.M. Deltrap. PhD Thesis, Univ. Cambridge,1964
[8] V. Beck and A. Crewe, EMSA 34 (1976) 578.
[9] V. Beck, Optik 53 (1979) 241.
[10] H. Rose, Optik 34 (1971) 285.
[11] H. Koops, G. Kuck, O. Scherzer, Optik 48 (1977) 225.
[12] H. Hely, Optik 60 (1982) 353.
[13] J. Zach and M. Haider, Nucl. Instr. and Meth. Phys. Res. A 363 (1995) 316.
[14] M. Haider, H. Rose, S. Uhlemann, E. Schwan, B. Kabius, K. Urban, Ultramicroscopy 75 (1998) 53.
[15] O.L. Krivanek, N. Dellby, A.R. Lupini, Ultramicroscopy 78 (1999) 1.

[16] Research supported by US Department of Energy under Contract W-31-109-Eng-38.