CEOS SEMCOR Cs/Cc aberration corrector for low voltage CD-SEM and its application in mask metrology

White Paper

CEOS

Corrected Electron Optical
Systems GmbH

CEOS SEMCOR Cs/Cc aberration corrector for low voltage CD-SEM and its application in mask metrology

Dr. Nicole Frindt, Dr. Joachim Zach

CEOS GmbH, Englerstr. 28, 69126 Heidelberg, Germany

info@ceos-gmbh.de

www.ceos-gmbh.de

Tel.: +49 6221 89467-0

Fax: +49 6221 89467-29

1 Application

Metrology applications and industrial quality assurance with critical dimension scanning electron microscopes (CD-SEMs) for feature sizes below the 7 nm and 5 nm technology node.

2 Introduction

In the semiconductor industry the fabrication of defect free lithographic masks is an essential procedure step in the production process of solid state electronic components. Mask defects lead to high reject rates and to high production costs. Therefore the quality control with CD-SEMs is indispensable. With rapidly shrinking minimal structure sizes in semiconductor industry from 7 nm toward 5 nm, the demand for high resolution CD-SEMs with resolution capabilities below 2 nm is growing.

Current uncorrected low voltage CD-SEMs reach an image resolution between 4 nm and 8 nm for acceleration voltages between 300 V and 1000 V depending on the beam current. The resolution of such microscopes is normally limited by the lens aberrations of the electron lenses used in the CD-SEM. To enhance the microscope resolution the limiting spherical aberration (Cs) and chromatic aberration (Cc) must be compensated. The CEOS SEMCOR Cs/Cc corrector which is integrated into the SEM corrects electron optical aberrations up to 3rd order. This means the spherical and chromatic aberration as well as other aberrations are corrected. Thereby, the diameter of the electron beam is reduced up to a factor of three for most SEM column designs. This enables to resolve structures on lithographic masks with feature size below 2.0 nm. Additionally the CEOS SEMCOR Cs/Cc corrector offers the possibility to enhance the beam current up to a factor of ten for an unchanged electron probe diameter.

3 Mechanism of aberration correction and its benefits

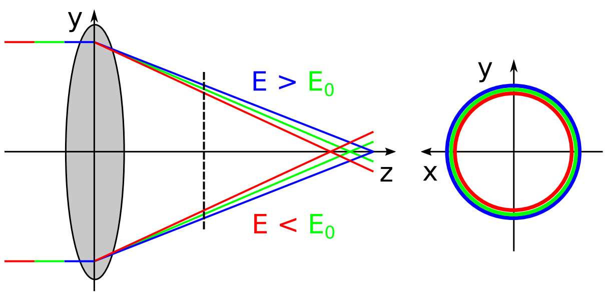
3.1 Reasons for aberrations in electron optical lenses and definition of spherical and chromatic aberration

Rotational symmetric electron lenses used in electron microscopes have always intrinsic aberrations which limit the resolution of the microscope. Already in 1936, Otto Scherzer [1] proved that chromatic aberration (Cc) and spherical aberration (Cs) for rotational symmetric, charge free and static lenses are always positive and that they cannot be compensated completely. This means that it is not possible to build aberration free electron optical rotational symmetric lenses. Their aberrations coefficients can only be minimized.

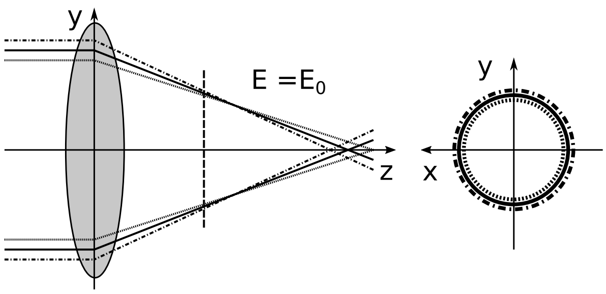
Chromatic aberration of a focusing electron lens means that electrons with higher energy are less deflected and thus less focused than electrons with lower energy (cf. figure 1a).

Spherical aberration of a focusing electron lens means that electrons that are propagating parallel to the optical axis and have a smaller radial distance to the optical axis are focused less than electrons with a larger radial distance (cf. figure 1b).

To compensate for these aberrations in an electron microscope (for example a CD-SEM) and thus to enhance the attainable resolution, non-rotational symmetric electron optical elements are required. They are generally called multipoles.



(a) Chromatic aberration shown in 2D profiles in the y-z-plane and x-y-plane for a beam with the shape of a hollow cylinder. The dotted line in the y-z-plane image marks the position of the image in the x-y-plane.



(b) Spherical aberration shown in 2D profiles in the y-z-plane and x-y-plane for a beam with the shape of a hollow cylinder. The vertical dotted line in the y-z-plane image marks the position of the image in the x-y-plane.

Figure 1: Chromatic and spherical aberration

3.2 When does Cs or Cc dominate?

Depending on the kind of the microscope (low voltage SEM, TEM or STEM) and depending on the used acceleration voltage, the optical design of the corrector may vary. The following formulas [2] can be used to estimate the resolution limit r as a function of spherical or chromatic aberration at a given acceleration voltage and electron wavelength.

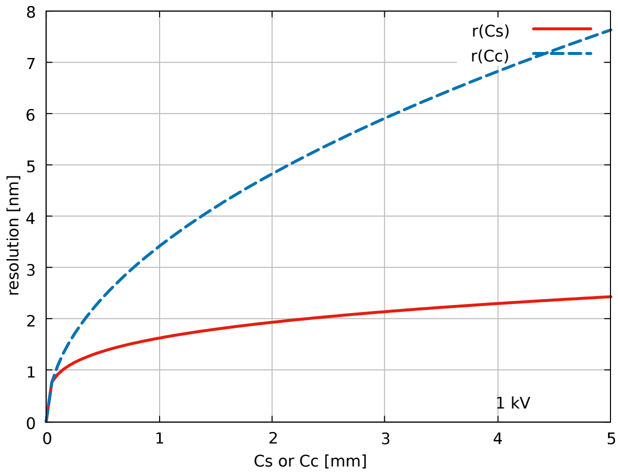
$$r(C_c) = \sqrt{1.2\lambda \frac{\Delta E}{E} C_c} \tag{1}$$

$$r(C_s) = \sqrt[4]{0.12\lambda^3 C_s} \tag{2}$$

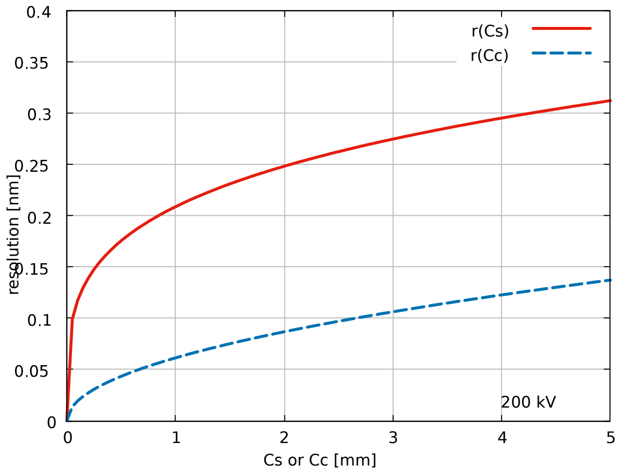
Here, C_c is the chromatic aberration, C_s is the spherical aberration, λ is the electron wavelength, $\Delta E/E$ is the relative energy width of the beam. Figure 2 shows the results for 1 kV and 200 kV. At high acceleration voltages, the spherical aberration dominates the resolution limit. This can be corrected by a hexapole corrector based on [3] as for example with our series of correctors for (S)TEM applications: CETCOR, CESCOR, DCOR, ASCOR, and BCOR. At lower acceleration voltages as used for CD-SEM applications, the situation is reversed and the chromatic aberration dominates the resolution limit down to a resolution of 1 nm. For high resolution CD-SEMs with resolution capabilities below 2 nm, both Cs and Cc have to be corrected. This can be done by implementing our CEOS SEMCOR Cs/Cc corrector.

3.3 Setup of the CEOS SEMCOR Cs/Cc corrector

Our CEOS SEMCOR Cs/Cc corrector is based on [4]. It consists of four multipole elements, in the following referred to as multipole I, II, III and IV. These multipoles, are either electric or electromagnetic elements that for instance can be driven as a dipole, quadrupole, hexapole or octupoles. A schematic presentation of the multipole arrangement inside the CEOS SEMCOR Cs/Cc corrector together with the Gaussian ray path and the fundamental ray paths X_α and Y_β within the corrector is shown in figure 3. A round electron beam entering the corrector is deformed towards an astigmatic or line shaped electron beam. Following electrical and magnetic quadrupoles and octupoles correct for the chromatic and spherical aberration. Afterwards the electron beam is reformed to a round bundle before



(a) Estimation of the resolution limit at 1 kV.



(b) Estimation of the resolution limit at 200 kV.

Figure 2: Estimation of the resolution limit according to (1) and (2) at (a) 1 kV and (b) 200 kV acceleration voltage with an energy width of 0.5 eV and as a function of spherical and chromatic aberration, respectively.

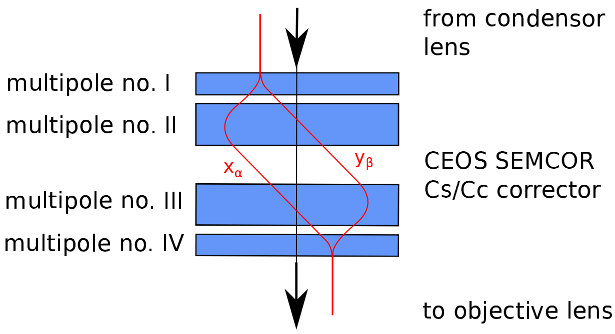


Figure 3: Schematic design of the corrector with four multipole elements and the Gaussian ray path. The fundamental ray paths X_α and Y_β start in the center of the electron source and intersect the center of the scanning spot with unit inclination.

leaving the corrector. The structure of a typical SEM together with a CEOS SEMCOR Cs/Cc aberration corrector is shown in figure 4.

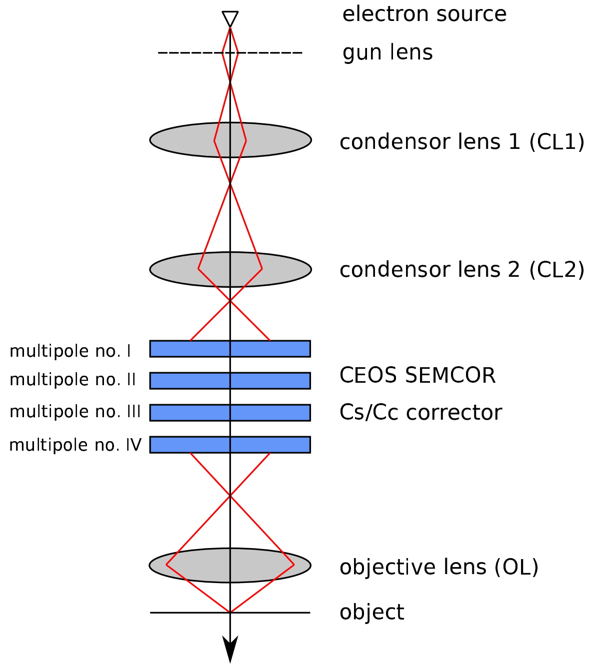


Figure 4: Schematic illustration of the CEOS SEMCOR Cs/Cc corrector inside an SEM column.

3.4 Operating mode for chromatic aberration correction

As already mentioned, chromatic aberration means that electrons with higher energy ($E > E_0$) are focused less than electrons with lower energy ($E < E_0$), where E_0 is the nominal energy. A beam with the shape of a hollow cylinder would be imaged by a chromatic lens as shown in figure 1a. The left side shows the splitting of the ray path for energies $E > E_0$, $E = E_0$ and $E < E_0$ in the y-z-section. The right side shows this splitting in the x-y-section.

The challenge is to create an optical element, which deflects electrons with higher energy more than electrons with lower energy. With a single magnetic or electric field this is not possible. But following the principle of Wien-Filters with mutually perpendicular electric and magnetic fields and a proper choice of the field strength can yield such an effect. This is possible, because the deflection effect of the electric force is proportional to the particle energy whereas the magnetic one is proportional to the particle velocity, which is roughly the square root of the energy for non-relativistic particles.

To act as a focusing element like a round lens, the deflecting force has to be proportional to the distance from the optical axis. The only other field, which shows this behaviour, is a quadrupole field. Using a Wien-Filter-like arrangement of quadrupoles as described in [5] and as shown in figure 5 generates a spectral distribution within a hollow cylindrical beam.

The electromagnetic quadrupole has the opposite effect of a round lens with chromatic aberration in y-direction. However, in the x-direction the effect has the same direction, so the chromatic aberration is even increased. In figure 6 these effects are illustrated in y- and x-direction for a beam path through a focusing lens with chromatic aberration and an electromagnetic quadrupole.

To avoid this unwanted behaviour in x-direction, the beam is squeezed together to a vertical line such that only the intended effect in y-direction re-

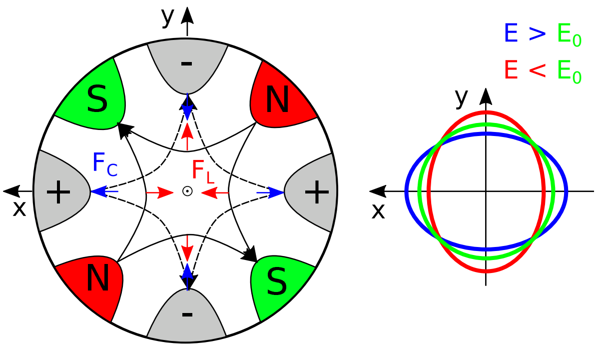
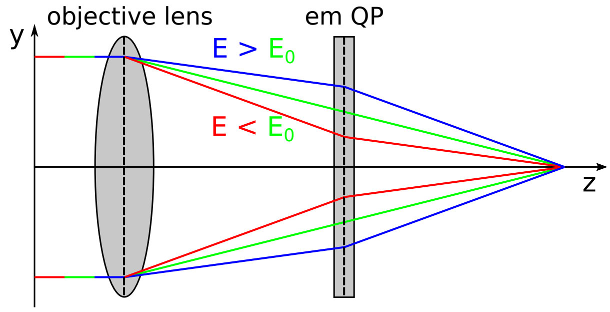
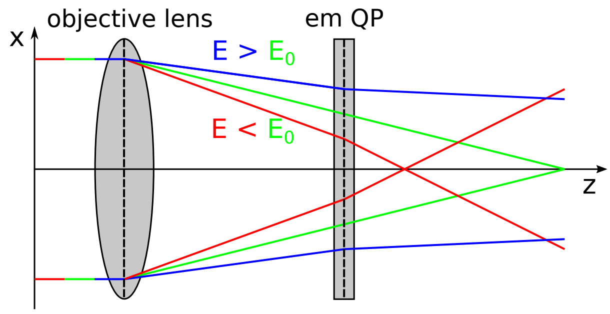


Figure 5: Left: Cross section of an electromagnetic quadrupole (em QP) forming a first order Wien-Filter. Magnetic force and electric force are indexed with F_L and F_C. Right: 2D profile of a hollow cylindrical beam after passing through an electromagnetic quadrupole. Electrons with $E < E_0$ are focused less than electrons with $E > E_0$ in the y direction. This compensates chromatic aberration in the y direction. In x direction chromatic aberration is increased.

mains, as shown in figure 7. This is done because the forces in the x-direction vanish for $x = 0$ in a quadrupole. As a result the chromatic aberration is compensated only in y-direction. To compensated chromatic aberration in x-direction, the procedure has to be repeated but the beam has now to be squeezed together to a horizontal line passing an electromagnetic quadrupole, which is rotated by 90°. To produce this squeezed beam and to relax it again towards a round electron beam, an electric quadrupole is placed at multipole position I (figure 3) in front of the first Wien-Filter (multipole position II) and one is placed at multipole position IV behind the second Wien-Filter (multipole position III). The combined beam path is shown in figure 8. The CEOS SEMCOR Cs/Cc corrector is based on the described correction principle and implements this beam path.



(a) y-z-section of a beam path through an objective lens and an electromagnetic quadrupole (em QP). As a result the chromatic aberration is reduced.



(b) x-z-section of a beam path through an objective lens and an electromagnetic quadrupole (em QP). As a result the chromatic aberration is increased.

Figure 6: Objective lens followed by an electromagnetic quadrupol and its influence on chromatic aberration.

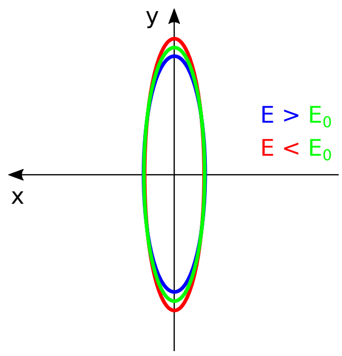


Figure 7: Profile in x-y-section of a beam, if it is squeezed to a line when passing through the quadrupole.

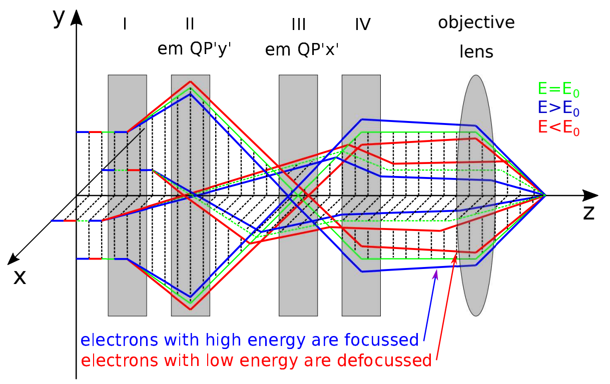
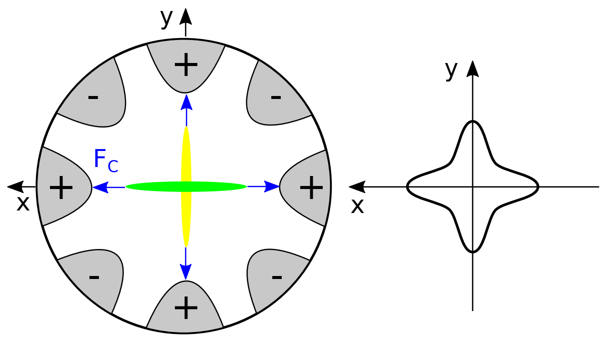


Figure 8: Schematic 3D ray path presentation for correction of chromatic aberration of an objective lens with an CEOS SEMCOR Cs/Cc corrector.

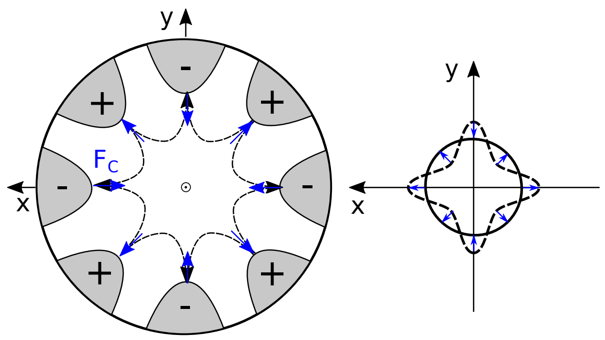
3.5 Operating mode for spherical aberration correction

As mentioned in section 3.1 spherical aberration means that electrons with larger radial distance from the optical axis are focused more than electrons with a smaller radial distance (see figure 1b). This additional focusing force is proportional to the third power of the radial distance r to the optical axis ($C_S \sim r^3$), as Cs is the third order spherical aberration. To compensate for this aberration an optical element is needed which deflects or rather defocuses electrons with larger radial distance to the optical axis more than electrons with a smaller radial distance. For compensating spherical aberration, combinations of hexapoles or a combination of octupoles can be used. For octupoles the effective force is proportional to the third power of the radial distance r to the optical axis ($F \sim r^3$). For extended hexapoles the mechanism is more complicated. It is not discussed here, because in the CEOS SEMCOR Cs/Cc corrector octupoles are used.

To compensate the round lens aberration with octupoles in the horizontal (x-direction) and vertical direction (y-direction), the beam has to be squeezed to a horizontal line in a first octupole and to a vertical line in a following octupole. This is the same procedure as for compensation of chromatic aberration. In figure 9a on the left side an octupole and the position of a vertical and a horizontal beam line are shown together with the effective components of the electrical octupole forces. As the force is proportional to the third power of the radial distance r, the shape of a hollow electron beam after passing through two octupoles as a squeezed beam and being desqueezed again would look like the image in 9a on the right side, when imaged far away from the octupoles. Since the octupoles have a fourfold symmetry, a fourfold astigmatism is visible. Now we have also to care about the 45° rotated direction to compensate for this remaining fourfold astigmatism. This is done with additional octupoles at the position of the outer quadrupoles (multipole position I and IV), which are used to squeeze and desqueeze the beam for the chromatic correction (cf. figure 9b). These octupoles have a reverse polarity compared to the two central octupoles at multipole position II and III. Again, when imaged far away from the octupoles, the fourfold astigmatism is corrected and a round, Cs corrected hollow electron beam is visible.



(a) Left side: Octupole element as used in multipole II to compensate spherical aberration in y-direction and in multipole III to compensate the remaining spherical aberration in x-direction. In octupole II the beam is squeezed to a vertical line (yellow). In octupole III the beam is squeezed in horizontal direction (green). Right side: 2D profiles of a hollow beam after after passing through the two octupoles (II and III) as a squeezed beam and being desqueezed again, when imaged far away from the octupoles.



(b) Left: Octupole element as used in multipole I and II to compensate the remaining fourfold astigmatism in 45° rotated direction. Right: 2D profiles of the beam with remaining fourfold astigmatism (dotted line) and the vectorial forces of an octupole, needed to correct the fourfold astigmatism in 45° rotated direction towards a round and spherical aberration free hollow beam (continuous line).

Figure 9: Octupole elements to compensate spherical aberration.

4 Capabilities of HOLON ZX CD-SEM with integrated CEOS SEMCOR Cs/Cc Corrector

Due to the aberration compensation and the reduction of the electron beam diameter up to a factor of three, structures on lithographic masks with feature sizes below 2.0 nm can be resolved. In the following chapter we show the resolution improvement in low-voltage CD-SEM imaging.

4.1 Experimental setup

For the experimental verification of the correction of chromatic and spherical aberrations a CD-SEM Z-System from HOLON was used with an integrated CEOS SEMCOR Cs/Cc corrector. The CD-SEM was operated at 1.5 kV acceleration voltage. The beam current was 20 pA, the aperture angle was 30 mrad for the corrected beam and 9 mrad for the uncorrected case. An EUV mask, a phase shift mask and gold particles on carbon were used as samples (images kindly provided by HOLON Co., Ltd., Japan). The image resolution was evaluated according to edge sharpness with a 24% - 76% rise criterion. This threshold criterion originates from the derivative (DR) method shown in [6].

4.2 Experimental results

The impact of spherical and chromatic aberration correction on image resolution for low voltage CD-SEM is demonstrated first using EUV masks. Figure 10 shows an EUV mask with a hole pattern imaged with and without aberration correction at 1.5 keV landing energy. The edge sharpness improved from 4.98 nm to 1.94 nm, which is an improvement in resolution by a factor of 2.57. Figure 11 shows a second EUV mask with a line and space (L&S) pattern also imaged with and without aberration correction at 1.5 keV landing energy. The edge sharpness improved from 4.48 nm to 1.94 nm, which is an improvement in resolution by a factor of 2.31. The reached resolution for the uncorrected and the corrected images are in good agreement with the estimated resolution shown in figure 2 for 1.0 kV acceleration voltage and an uncorrected system with Cc = 2.0 mm and Cs = 2.0 mm which is the case for an uncorrected HOLON Z-System.

Additionally, we evaluated the increase in image sharpness for low voltage CD-SEM analysis of a conventional phase shift mask with a line and space pattern (L&S) and of gold particles on carbon. Figure 12 shows a phase shift mask with a L&S pattern, imaged with and without aberration corrector at 1.5 keV landing energy. As the edge rise in the images is not compatible to the regulations for 24% - 76% edge sharpness evaluation, no image resolution in therms of 24% - 76% edge sharpness is specified. However, the fine granular structure of the mask material on the lines patterns is clearly resolved and the edges of the lines are imaged clearly sharper in the aberration corrected image. Figure 13 shows gold particles on a carbon layer, imaged at 1.5 keV landing energy. The edge sharpness improved from 4.73 nm to 2.09 nm, which is an improvement in resolution by a factor of 2.27. Beside an improvement in edge sharpness of the large gold particles, very small gold particle that were not resolvable in the uncorrected image can clearly be seen and distinguished from the nearby large gold particles.

Both the EUV mask samples as well as the gold on carbon sample imaged with and without aberration correction show that the Z-System from HOLON in combination with the CEOS SEMCOR Cs/Cc corrector is the ideal choice for metrology applications for the emerging EUV technology in semiconductor industry and the 5 nm logic node. For detailed technical specifications regarding the CD-SEM Z-System from HOLON please contact the manufacturer HOLON Co., Ltd., Japan.

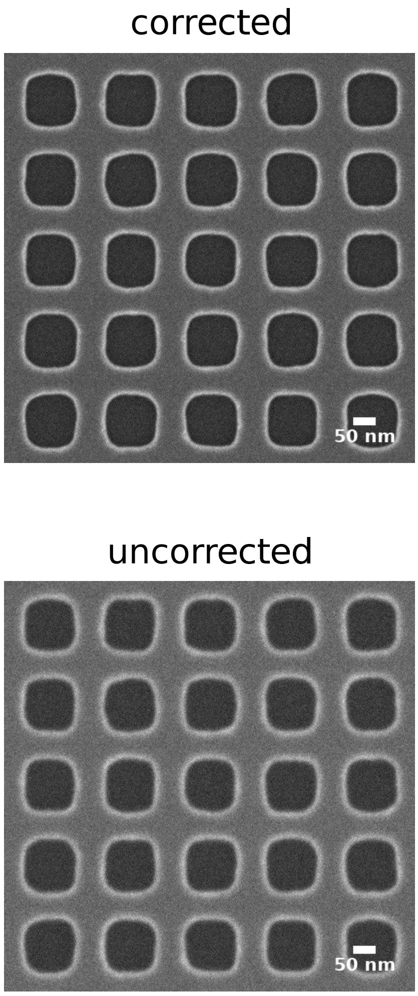


Figure 10: Comparison of CD-SEM images of a EUV mask with a hole pattern, with and without aberration correction at 1.5 keV landing energy.

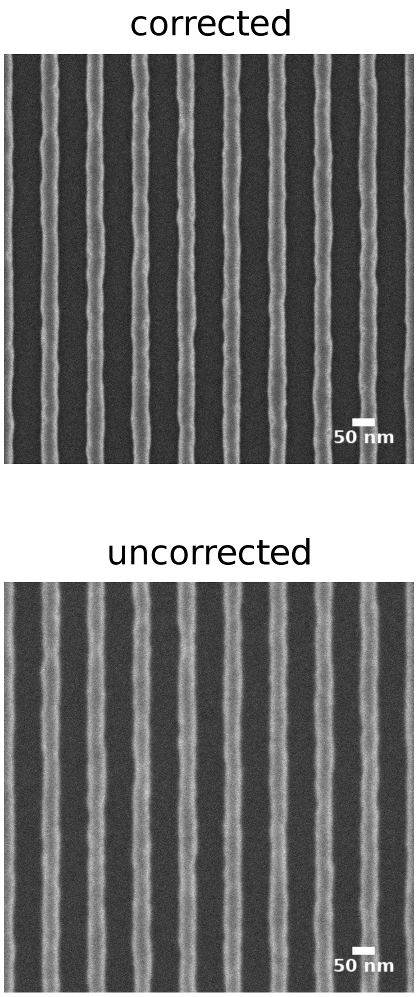


Figure 11: Comparison of CD-SEM images of an EUV mask with a line and space pattern, with and without aberration correction at 1.5 keV landing energy.

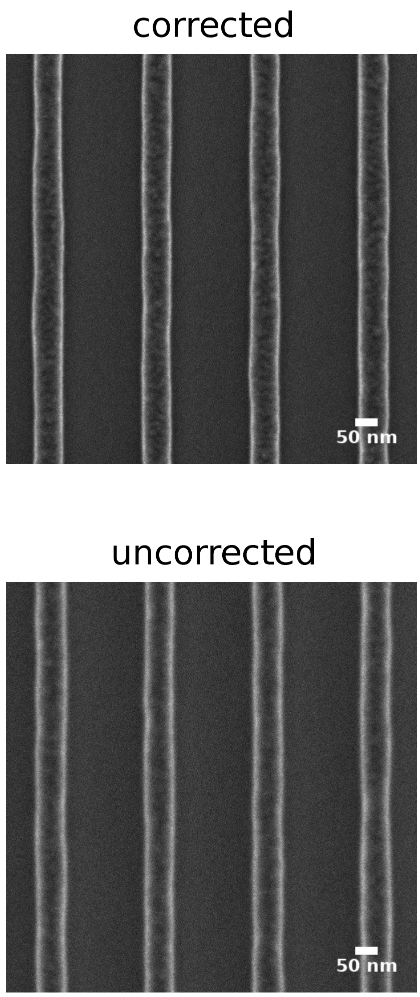


Figure 12: CD-SEM images of a phase shift mask with a line and stripes pattern, imaged at 1.5 keV landing energy.

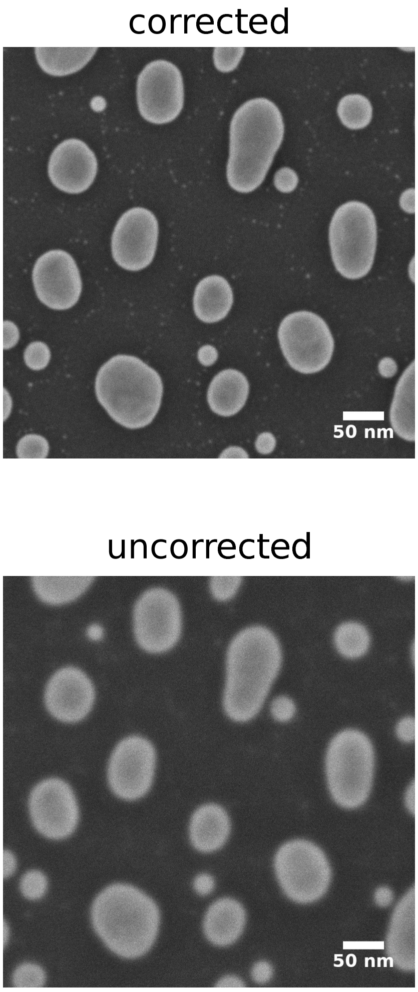


Figure 13: CD-SEM images of gold particles on a carbon layer, imaged at 1.5 keV landing energy.

5 Contributors

We thank HOLON Co., Ltd., Japan for the collaboration, for providing samples and for the permission to use their image data.

References

[1] O. Scherzer. Über einige fehler von elektronenlinsen. *Zeitschrift für Physik*, 101(9-10):593–603, 1936.

[2] J. Zach and M. Haider. Aberration correction in a low voltage sem by a multipole corrector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 363(1-2):316–325, 1995.

[3] H. Rose. Outline of a spherically corrected semiaplanatic medium-voltage transmission electron microscope. *Optik*, 85:19–24, 1990.

[4] H Rose. Abbildungseigenschaften spharisch korrigierter elektronenoptischer achromate. *Optik*, 33:1–24, 1971.

[5] J Zach and H Rose. Efficient detection of secondary electrons in low-voltage scanning electron microscopy. *Scanning*, 8(6):285–293, 1986.

[6] ISO/TS 24597. Methods of evaluating image sharpness. 2011.