2.8: Aberrations

For designing advanced optical systems Gaussian geometrical optics is not sufficient. Instead nonparaxial rays, and among them also non-meridional rays, must be traced using software based on Snell's Law with the sine of the angles of incidence and refraction. Often many thousands of rays are traced to evaluate the quality of an image. It is then found that in general the non-paraxial rays do not intersect at the ideal Gaussian image point. Instead of a single spot, a spot diagram is found which is more or less confined. The deviation from an ideal point image is quantified in terms of **aberrations**. One distinguishes between monochromatic and chromatic aberrations. The latter are caused by the fact that the refractive index depends on wavelength. Recall that in paraxial geometrical optics Snell's Law (2.3.7) is replaced by: $n_i\theta_i = n_t\theta_t$, i.e. sin θ_i and sin θ_t are replaced by the linear terms. If instead one retains the first two terms of the Taylor series of the sine, the errors in the image can be quantified by five monochromatic aberrations, the so-called **primary** or **Seidel aberrations**. The best known is **spherical aberration**, which is caused by the fact that for a convergent spherical lens, the rays that makes a large angle with the optical axis are focused closer to the lens than the paraxial rays (see Figure $2.8.1$). **Distortion** is one of the five primary aberrations. It causes deformation of images due to the fact that the magnification depends on the distance of the object point to the optical axis.

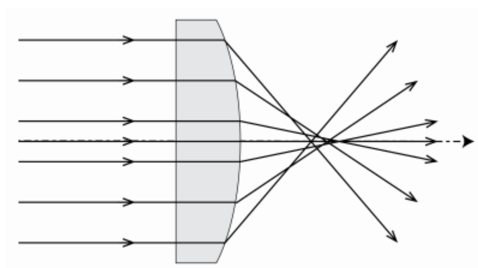

Figure $2.8.1$: Spherical aberration of a planar-convex lens.

For high-quality imaging the aberrations have to be reduced by adding more lenses and optimising the curvatures of the surfaces, the thicknesses of the lenses and the distances between them. For high quality systems, a lens with an aspherical surface is sometimes used. Systems with very small aberrations are extremely expensive, in particular if the field of view is large, as is the case in lithographic imaging systems used in the manufacturing of integrated circuits.

2.7.1 Diffraction Optics

Aberrations can be quantified by analysing the spot diagram or, alternatively, by considering the shape of the actual wavefront in image space, which in Gaussian geemotrical optics would converge to the Gaussian image point. Aberrations cause the wavefront to deviate from a perfect sphere. According to a generally accepted criterion formulated first by Rayleigh, aberrations start to deteriorate images considerably if the wavefront aberrations cause path length differences of more than a quarter of the wavelength. When the aberrations are less than this, the system is called **diffraction limited**. A very comprehensive treatment of aberration theory can be found in the book by Braat et al. Even if the wave transmitted by the exit pupil would be perfectly spherical, the wave front consists of only a circular section of a sphere since the field is limited by the aperture. An aperture causes **diffraction**, i.e. bending and spreading of the light. When one images a point object on the optical axis, diffraction causes the light distribution called the Airy spot, as shown in Figure $2.8.3$. The Airy spot has full-width at half maximum:

$$FWHM = 0.6\frac{\lambda}{NA},$$

with NA= arcsin(a/si) is the numerical aperture (i.e. 0<NA<1) with a the radius of the exit pupil and si the image distance as predicted by Gaussian geometrical optics. Diffraction depends on the wavelength and hence it cannot be described by geometrical optics, which applies in the limit of vanishing wavelength. We will treat diffraction by apertures in Chapter 6.

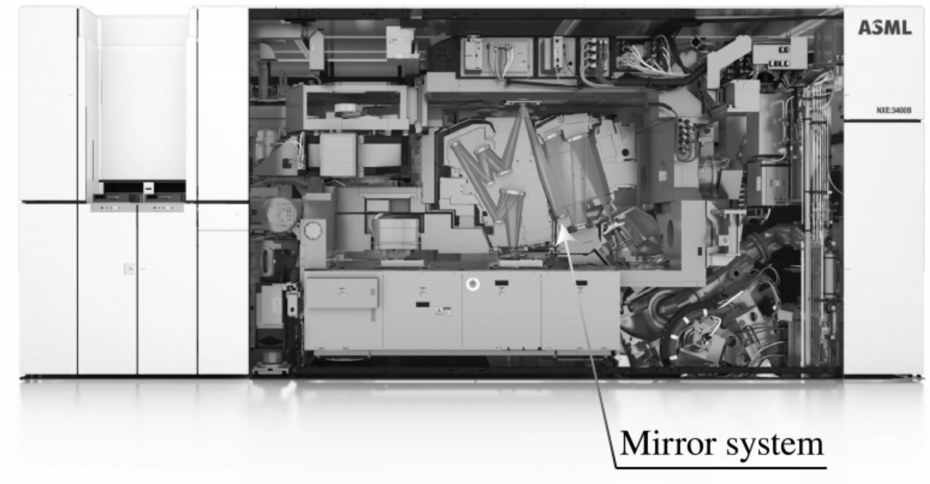

Figure 2.8.2: The EUV stepper TWINSCAN NXE:3400B.Lithographic lens system for DUV (192 nm), costing more than € 500.000. Ray paths are shown in purple. The optical system consists of mirrors because there are no suitable lenses for this wavelength (Courtesy of ASML).

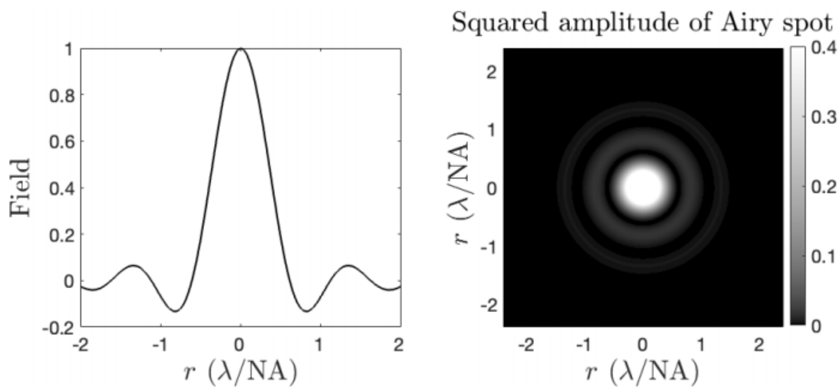

Figure 2.8.3: Left: cross section of the field of the Airy pattern. Right: intensity pattern of the Airy pattern.