

MICROLITHOGRAPHY PROJECTION OPTICAL SYSTEM, METHOD FOR MANUFACTURING A DEVICE
AND METHOD TO DESIGN AN OPTICAL SURFACE

5 This disclosure relates to a microlithography projection optical system, in particular to a projection objective, a microlithographic tool comprising such an optical system, a method for microlithographic production of microstructured components using such a microlithographic tool, a microstructured component being produced by such a method and a method to design an optical surface in
10 such an optical system.

Projection objectives are widely used in microlithography to transfer a pattern from a reticle to a substrate by forming an image of the reticle on a layer of a photosensitive material disposed on the substrate. In general, projection objectives fall into three different classes: dioptric objectives; catoptric objectives;
15 and catadioptric objectives. Dioptric objectives use refractive elements (e.g., lens elements) to image light from an object plane to an image plane. Catoptric objectives use reflective elements (e.g., mirror elements) to image light from an object plane to an image plane. Catadioptric objectives use both refractive and reflective elements to image light from an object plane to an image plane.
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Objectives, in particular for use in projection systems, are known from T. Jewell: "Optical system design issues in development of projection camera
25 for EUV lithography", Proc. SPIE 2437 (1995). Other objectives are known from EP 0 730 169 A, EP 0 730 179 A, EP 0 730 180 A, EP 0 790 513 A, US 5 063 586 A, US 6 577 443 A, US 6 660 552 A and US 6 710 917 A.

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It is an object of the present invention, to improve an optical system which can in particular be used as projection objective in a microlithography projection exposure apparatus with respect to its resolution with a given illumination wavelength. Further, the optical systems according to the present invention
5 should have a high light throughput with respect to illumination light.

This object is met by an optical system having the features of claim 1.

In the following specification, a rotationally asymmetric surface according to
10 the invention also is referred to as a freeform surface. Unlike spherical or aspherical mirrors, freeform surfaces do not have an axis of rotational symmetry. Freeform surfaces according to the present invention differ from known aspheric rotational symmetric mirror surfaces for EUV projection objectives in that such known aspheric mirror surfaces are described via a mathematical
15 Taylor expansion, i.e. having a sag being given by a rotational symmetric polynomial of grade n . The center point of this Taylor expansion for all these polynomial terms is defined by a common optical axis. Known mirror surfaces are described by such an expansion, because the Taylor expansion is easy to calculate, easy to optimize and there exists a lot of experience in manufactur-
20 ing such mirror surfaces. However, it was realized by the inventors that the known Taylor expansion with common center leads to an unwanted distortion which cannot be lowered below a certain level. This distortion limitation being inherent to rotational symmetric optical surfaces is avoided, when according to the invention one of the optical surfaces is embodied as freeform or
25 rotationally asymmetric surface. Using freeform surfaces it is possible to overcome limitations with respect to numerical aperture and distortion being inherent to rotational symmetric surfaces which in particular is advantageous in the field of EUV microlithography protection. In a special embodiment, a freeform surface may be a surface being mirror symmetric to a meridional
30 plane of the optical system. A meridional plane is a plane being defined by the

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normal of the object plane and the center points of the object field and the apertures of the optical components of the optical system. Advantageously, the projection objective according to the present invention is a catoptric projection objective. In general, the image plane of the optical system is parallel to the

5 object plane. The optical system may have a field at the image plane having a minimum radius of curvature of 300 mm. In the optical system, the chief rays may be at an angle of about 3° , 5° , 7° or more with respect to the object plane normal at the object plane. The optical system may have an entrance pupil which is located more than 2.8 m, in particular more than 10 m from the ob-

10 ject plane. In general, in an optical system with freeform surfaces, an exactly defined pupil plane does not exist. In a pupil plane of the optical system, the chief rays corresponding to different field points meet. In the pupil plane, the ray bundles from each field point superpose. The term pupil plane is used to characterize a region perpendicular to the light beam guided in the optical sys-

15 tem where an intensity distribution corresponds to an illumination angle distribution in the object plane. The imaged radiation may be reflected from an object positioned at the object plane. The object positioned at the object plane may be a reticle that is imaged by the plurality of elements to the image plane. The optical system may have a demagnification of 4X. The optical system

20 according to the present invention may comprise four or more reflective elements. In particular, the optical system may comprise six or more reflective elements. A plurality of elements may be arranged to image the radiation to an intermediate image plane between the object plane and the image plane. In this case, a field stop may be positioned at or near the intermediate image

25 plane. In particular, the plurality of elements may comprise five elements and the intermediate image plane may be located between a fourth element and a fifth element along the path of the radiation from the object plane to the image plane. The object and image planes may be separated by a distance L being about 1 m or more. The optical path length of the radiation from the object

30 plane to the image plane may be about $2L$, $3L$, $4L$ or more. The plurality of

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elements may comprise at least one pair of adjacent elements in the path of the radiation, where the pair of adjacent elements is separated by about 0,5 L or more. Advantageously, none of the plurality of elements causes an obscuration of the exit pupil. The plurality of elements may comprise a first mirror and a
5 second mirror, the first and second mirrors having a minimum distance from the object plane of d_1 and d_2 , respectively, where d_1/d_2 is about 2 or more. Alternatively, d_1/d_2 may be smaller than 2. In that case, the optical system as a rule has a large working distance at the object side. The plurality of elements may include a first element in the path of the radiation from the object plane to
10 the image plane, where the first element has positive optical power. The optical system may comprise an aperture stop positioned between the object plane and the image plane. The plurality of elements of the optical system may comprise three elements and the aperture stop may be positioned between the second and third elements in the path of the radiation from the object plane to
15 the image plane. Alternatively, the aperture stop may be positioned at the second or at the third element. The radiation may pass through the aperture stop once or twice. A radiation source which is used with the optical system according to the invention may be a laser radiation source having a wavelength of about 300 nm or less, 200 nm or less, 100 nm or less.

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A mathematical expansion of the freeform surface according to claim 2 gives a good and reproducible manufacturing of the reflective surfaces. In this expansion, α may be 66. Further, m may consist of even integers. Further, $m + n$ may be equal to or bigger than 10.

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A deviation according to claim 3 or 4 provides for a proper reduction of the objective's distortion below the limit which is reachable using rotationally symmetric optical surfaces. The rotationally asymmetric surface may deviate from the best-fit rotationally symmetric surface by about 100λ or more at the
30 one or more locations. The rotationally asymmetric surface may deviate from

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the best-fit rotationally symmetric surface by about 50 nm or more, by about 100 nm or more, by about 500 nm or more or by about 1000 nm or more at the one or more locations.

- 5 A mirror symmetric freeform optical surface according to claim 5 lowers the requirements for production of the freeform optical surface.

Two reflective elements with freeform optical surfaces according to claim 6 lead to the possibility of a better aberration minimization on the one hand and
10 give the possibility to meet certain aberration minimization requirements with less complicated to manufactured freeforms. The optical system also may have three, four, five or six freeform elements.

An optical system having no more than two reflective elements with a positive
15 chief ray angle magnification according to claim 7 exhibits relatively low incident ray angles on the mirrors, thus causing lower aberrations at the outset. This holds in particular using an optical system including only one reflective element having a positive chief ray angle magnification according to claim 8.

20 A numerical aperture of the optical system according to claim 9 allows a high resolution. The image-side numerical aperture may be as high as 0.25, 0.28, 0.3, 0.35, 0.4 or more.

An image field dimension according to claim 10 enables an efficient use of the
25 optical system in a microlithography projection apparatus. As an aberration correction is improved with freeform surfaces, now designs with rectangular image fields are possible which by use of rotationally symmetric surfaces would exhibit aberrations being too high to meet demanding requirements.

The rectangular field may have a minimum dimension of about 2 mm and may
30 have a first dimension of about 1 mm or more and a second dimension of

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about 1 mm or more where the first and second dimension are orthogonal.
This second dimension may be about 10 mm or about 20 mm or more.

A distortion according to claim 11 and a wavefront error according to claim 12
5 lead to a projection quality which only may be limited by diffraction, i.e. by
the wavelength of the projection light. An optical system with such low distortion in particular is optimized for use with EUV light sources in the range between 10 and 30 nm.

10 The optical system may have chief rays which are non-parallel to the object plane normal at the object plane. A chief ray angle according to claim 13 gives the possibility to control the distribution of illumination angles in the image plane by controlling an intensity distribution in the illumination optics in front of the projection objective with a low number of optical components. This is
15 not possible using an optical system with a convergent set of chief ray angles as this would result in the requirement of additional components to give access to a manipulation plane to control the distribution of illumination angles via an intensity distribution in this manipulation plane. In an optical system with diverging chief rays according to claim 13, the object plane is positioned
20 between the plurality of elements and an entrance pupil of the optical system.

Maximum angles of incidence according to claim 14 help to avoid high aberrations at the outset. The maximum angle of incidence on a surface of each of the elements may be less than 18° or less than 15°.

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A telecentric optical system according to claim 15 tolerates height variations of a substrate arranged in the image plane.

An optical system according to claim 16 leads to a very high resolution. The
30 ratio θ/NA may be about 60 or less or 50 or less.

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5 An optical system with an object-image shift of about 75 mm or less according to claim 17 leads to a slim optical design of the optical system. The object-image shift may be about 50 mm or less or about 25 mm or less. In case of zero object-image shift, the optical system can be rotated about the axis intersecting the center field points in the object and image fields without the central field point translating. This is in particular advantageous where metrology and testing tools are used requiring rotation of the optical system.

10 Freeboards of the elements according to claim 18 give a compact design with small incidence angles of the chief rays. Four or more elements of the optical system may have freeboards of about 5 mm or more. This lowers the requirements regarding holder and substrate design of the optical elements of the optical system.

15 An optical system having a radiation source according to claim 19 exploits advantageously the aberration minimization by use of the at least one freeform surface, as aberrations and distortions in the range of the wavelength of such a radiation source are possible. Preferably, the wavelength is in a range from
20 about 10 nm to about 15 nm.

The advantages of an optical system according to claim 20 and a microlithographic tool according to claim 21 correspond to those mentioned above with respect to the optical system according to claims 1 to 19. The same holds with
25 respect to the manufacturing method according to claim 22 and with respect to the component according to claim 23.

A design method according to claim 24 gives a reproducible design instruction to create freeform surfaces which can be produced in a controllable manner.

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Furthermore, embodiments can include one or more of the following advantages. For example, embodiments include catoptric projection objectives that are telecentric at the image plane. This can provide for constant or nearly constant image magnification over a range of image-side working distances.

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In certain embodiments, catoptric projection objectives have extremely high resolution. For example, projection objectives can have the capability of resolving structures smaller than about 50 nm. High resolution can be achieved in projection objectives that have a high image-side numerical aperture that are designed for operation at short wavelengths (e.g., about 10 nm to about 30 nm).

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Projection objectives can provide images with low aberrations. In certain embodiments, projection objectives are corrected for wavefront error of about 30 mλ or less. In certain embodiments, projection objectives are corrected for distortion below values of about 2 nm or less.

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Embodiments include catoptric objectives that have a high numerical aperture and provide imaging with low image distortion, low wavefront error, and telecentricity at the image plane over a relatively large image field. These features can be achieved by use of one or more freeform mirrors.

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In some embodiments, projection objective metrology can be easily implemented despite rotations of the projection objective about a rotation axis. For example, embodiments of projection objectives (e.g., high NA projection objectives) may have relatively small or zero object-image shift which result in little or no translation of an on-axis field point when the projection objective rotates about the axis. Thus, when the projection objective is subject to rotation, metrology can be repeatably performed in the same field position without having to relocate that field position.

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Embodiments also include catoptric projection objectives that have no field dependent pupil obscuration or no central pupil obscuration at all.

- 5 Embodiments of projection objectives can be adapted for operation at a variety of different wavelengths, including visible and ultraviolet (UV) wavelengths. Embodiments can be adapted for operation at Extreme UV (EUV) wavelengths. Furthermore, embodiments can be adapted for use at more than one wavelength, or over a range of wavelengths.

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Embodiments of catoptric projection objectives can be used in lithography tools (e.g., lithography scanners) and can provide relatively low overscan. Low overscan is accomplished, for example, by using projection objectives with rectangular image fields. In such embodiments, the image can be aligned
15 so that an edge of the rectangular field is parallel to the leading edge of the die sites, avoiding the need to scan the leading edge of the die sites beyond the edge of the image field in order to scan the site corners, as is typically the case when rectangular or square die sites are scanned relative to arcuate fields.

- 20 Embodiments include lithography tools with relatively high throughput. For example, embodiments having relatively low overscan are more efficient than comparable systems that have larger overscan. Accordingly, these low overscan systems can provide higher wafer throughput than the comparable systems.

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In some embodiments, catoptric projection objectives are provided that have low or no field dependence of shading effects. For example, catoptric projection objectives can have their entrance pupil located far from the object plane (e.g., at infinity) providing uniform illumination angles of the chief rays
30 on the object field. This can reduce or avoid field dependent shading effects

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that occurs where chief ray angles vary across the object field. Alternatively, or additionally, projection objectives can have relatively small values chief ray incident angles and/or small variations of incident angles for rays in the meridional section for each mirror in the projection objective, resulting in an increased average reflectivity of each mirror, given a respective multi layer reflecting stack being optimized for such incident angles.

In certain embodiments, projection objective can include features that allow a reduction in the complexity of the illumination system. For example, the location of the entrance pupil of projection objectives may be in front of the object plane. In other words, chief rays starting at different field points are divergent with respect to each other. This can make the entrance pupil of the projection objective/exit pupil of the illumination system accessible without using a telescope in the illumination system to relay the illumination system's exit pupil to the location of the projection objective's entrance pupil.

Other features and advantages will be apparent from the description, the drawings, and the claims.

FIG. 1 is a schematic view of an embodiment of a microlithography tool.

FIG. 2A is a schematic view showing a portion of the microlithography tool shown in FIG. 1.

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FIG. 2B is a cross-sectional view of a rotationally asymmetric surface and a corresponding rotationally symmetric reference surface.

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- FIG. 3 is a cross-sectional view of an embodiment of a projection objective shown in meridional section.
- FIG. 4 is a cross-sectional view of a portion of a mirror from a projection objective shown in meridional section.
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- FIG. 5A is a schematic view of a ray path at a mirror having a positive chief ray angle magnification.
- 10 FIG. 5B is a schematic view of a ray path at a mirror having a negative chief ray angle magnification.
- FIG. 6A is a view of a mirror's footprint.
- 15 FIG. 6B is a cross-section view of the mirror shown in FIG. 6A.
- FIG. 7A is a plan view of an embodiment of a ring segment field.
- FIG. 7B is a plan view of a ring segment field relative to a pair of wafer die sites.
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- FIG. 7C is a plan view of a rectangular field relative to a pair of wafer die sites.
- 25 FIG. 8 is a schematic view of the projection objective of the embodiment of microlithography tool shown in FIG. 1.
- FIG. 9 is a cross-sectional view of a projection objective shown in meridional section.
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- FIG. 10 is a cross-sectional view of a portion of a projection objective shown in meridional section.
- FIG. 11 is a cross-sectional view of a projection objective shown in meridional section.
- FIG. 12 is a cross-sectional view of a projection objective shown in meridional section.
- FIG. 13 is a cross-sectional view of a projection objective shown in meridional section.
- FIG. 14A is a cross-sectional view of a projection objective shown in meridional section.
- FIG. 14B is a cross-sectional view of an optical system that includes the projection objective shown in FIG. 14A and of an illumination system.
- FIG. 15 is a cross-sectional view of a projection objective shown in meridional section.
- FIG. 16A is an x-y vector plot showing calculated distortion as a function of position in the image field for the projection objective shown in FIG. 15.
- FIG. 16B is an x-y vector plot showing calculated chief ray angle as a function of position in the image field for the projection objective shown in FIG. 15.

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- FIG. 17 is a cross-sectional view of a projection objective shown in meridional section.
- FIGS. 18 to 20 are plots showing lateral aberrations as a function of position in the image field for the projection objective shown in Fig. 17.
- FIG. 21 is a cross-sectional view of a projection objective shown in meridional section.
- FIGS. 22 to 24 are plots showing aberrations as a function of position in the image field for the projection objective shown in Fig. 21.
- FIG. 25 is a cross-sectional view of a projection objective shown in meridional section.
- FIGS. 26 to 28 are plots showing aberrations as a function of position in the image field for the projection objective shown in Fig. 25.
- FIG. 29 is a cross-sectional view of a projection objective shown in meridional section.
- FIGS. 30 to 32 are plots showing aberrations as a function of position in the image field for the projection objective shown in Fig. 29.
- FIG. 33 is a cross-sectional view of a projection objective shown in meridional section.

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- FIGS. 34 to 36 are plots showing aberrations as a function of position in the image field for the projection objective shown in Fig. 33.
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FIG. 37 is a cross-sectional view of a projection objective shown in meridional section.
- FIGS. 38 to 40 are plots showing aberrations as a function of position in the image field for the projection objective shown in Fig. 37.
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- FIG. 41 is a cross-sectional view of a projection objective shown in meridional section.
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- FIGS. 42 to 44 are plots showing aberrations as a function of position in the image field for the projection objective shown in Fig. 41.
- 20 FIG. 45 is a cross-sectional view of a projection objective shown in meridional section.
- FIGS. 46 to 48 are plots showing aberrations as a function of position in the image field for the projection objective shown in Fig. 45.
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- FIG. 49 is a cross-sectional view of a projection objective shown in meridional section.

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FIG. 50 is a plot showing aberrations as a function of position in the image field for the projection objective shown in Fig. 49.

5 FIG. 51 is a cross-sectional view of a projection objective shown in meridional section.

FIG. 52 is a cross-sectional view of a projection objective shown in meridional section.

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FIG. 53 is a flowchart showing steps in the manufacture of a semiconductor device.

FIG. 54 is a flowchart showing steps in a wafer process.

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In one aspect, the disclosure relates to catoptric projection objectives that have one or more mirrors having a freeform mirror surface (referred to as freeform mirrors). Catoptric projection objectives with freeform mirrors can be used in microlithography tools. Referring to FIG. 1, a microlithography tool 100

20 generally includes a light source 110, an illumination system 120, a projection objective 101, and a stage 130. A Cartesian co-ordinate system is shown for reference. Light source 110 produces radiation at a wavelength λ and directs a beam 112 of the radiation to illumination system 120. Illumination system 120 interacts with (e.g., expands and homogenizes) the radiation and directs a beam 122 of the radiation to a reticle 140 positioned at an object plane 103.

25 Projection objective 101 images radiation 142 reflected from reticle 140 onto a surface of a substrate 150 positioned at an image plane 102. The radiation on the image-side of projection objective 101 is depicted as rays 152. As shown in FIG. 1, the rays are illustrative only and not intended to be accurately depict the path of the radiation with respect to reticle 140, for example. Substrate 150

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is supported by stage 130, which moves substrate 150 relative to projection objective 101 so that projection objective 101 images reticle 140 to different portions of substrate 150.

- 5 Projection objective 101 includes a reference axis 105. In embodiments where projection objective is symmetric with respect to a meridional section, reference axis 105 is perpendicular to object plane 103 and lies inside the meridional section.
- 10 Light source 110 is selected to provide radiation at a desired operational wavelength, λ , of tool 100. In some embodiments, light source 110 is a laser light source, such as a KrF laser (e.g., having a wavelength of about 248 nm) or an ArF laser (e.g., having a wavelength of about 193 nm). Non-laser light sources that can be used include light-emitting diodes (LEDs), such as LEDs
- 15 that emit radiation in the blue or UV portions of the electromagnetic spectrum, e.g., about 365 nm, about 280 nm or about 227 nm.

- Typically, for projection objectives designed for operation in lithography tools, wavelength λ is in the ultraviolet portion, the deep ultraviolet portion or
- 20 the extreme ultraviolet portion of the electromagnetic spectrum. For example, λ can be about 400 nm or less (e.g., about 300 nm or less, about 200 nm or less, about 100 nm or less, about 50 nm or less, about 30 nm or less). λ can be more than about 2 nm (e.g., about 5 nm or more, about 10 nm or more). In embodiments, λ can be about 193 nm, about 157 nm, about 13 nm, or about
- 25 11 nm. Using a relatively short wavelength may be desirable because, in general, the resolution of a projection objective is approximately proportional to the wavelength. Therefore shorter wavelengths can allow a projection objective to resolve smaller features in an image than equivalent projection objectives that use longer wavelengths. In certain embodiments, however, λ

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can be in non-UV portions of the electromagnetic spectrum (e.g., the visible portion).

5 Illumination system 120 includes optical components arranged to form a collimated radiation beam with a homogeneous intensity profile. Illumination system 120 typically also includes beam steering optics to direct beam 122 to reticle 140. In some embodiments, illumination system 120 also include components to provide a desired polarization profile for the radiation beam.

10 Typically object plane 103 is parallel to image plane 102. However, in certain embodiments, image plane 102 is tilted with respect to object plane 103. For example, image plane 102 can be tilted by an angle being about 1° or more (e.g. about 2° or more, about 3° or more, about 4° or more, about 5° or more).

15 Object plane 103 is separated from image plane 102 by a distance L, which is also referred to as the lengthwise dimension, or tracklength, of projection objective 101. The tracklength is defined by the distance between two parallel planes. The first plane is the object plane, the second is defined as the plane parallel and closest to the object plane such that the object field, the image
20 field and the optical components are located between these two parallel planes. In general, this distance depends on the specific design of projection objective 101 and the wavelength of operation of tool 100. In some embodiments, such as in tools designed for EUV lithography, L is in a range from about 1 m to about 3 m (e.g., in a range from about 1.5 m to about 2.5
25 m). In certain embodiments, L is less than 2 m, such as about 1.9 m or less (e.g., about 1.8 m or less, about 1.7 m or less, about 1.6 m or less, about 1.5 m or less). L can be more than about 0.2 m or more (e.g., about 0.3 m or more, about 0.4 m or more, about 0.5 m or more, about 0.6 m or more, about 0.7 m or more, about 0.8 m or more, about 0.9 m or more, about 1 m or more).

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The ratio of the optical path length of imaged radiation to the tracklength varies depending on the specific design of projection objective 101. In some embodiments, the ratio of this optical path length to tracklength can be relatively high. For example, the ratio of this optical path length to tracklength
 5 can be about two or more (e.g., about 2.5 or more, about three or more, about 3.5 or more, about four or more, about 4.5 or more, about five or more).

Projection objective 101 has a magnification ratio, which refers to the ratio of the dimensions of the field at object plane 103 to the corresponding
 10 dimensions of the field at image plane 102. Typically, projection objectives used in lithography tools are reduction projection objectives, meaning they reduce the dimensions of, or demagnify, the image. In some embodiments, therefore, projection objective 101 can produce a field at image plane 102 whose dimensions are reduced by about 2X or more (e.g., about 3X or more,
 15 about 4X or more, about 5X or more, about 6X or more, about 7X or more, about 8X or more, about 9X or more, about 10X or more) compared to the dimensions at object plane 103. In other words, projection objective 101 can have a demagnification of about 2X or more, (e.g., about 3X or more, about 4X or more, about 5X or more, about 6X or more, about 7X or more, about
 20 8X or more, about 9X or more, about 10X or more). More generally, however, projection objectives can be designed to provide a magnified image or an image the same size as the object.

Referring also to FIG. 2A, rays 152 define a cone of light paths that form the
 25 reticle image at image plane 102. The angle of the cone of rays is related to the image-side numerical aperture (NA) of projection objective 101. Image-side NA can be expressed as

$$NA = n_o \sin \theta_{\max} ,$$

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where n_0 refers to the refractive index of the immersing medium adjacent the surface of substrate 150 (e.g., air, nitrogen, water, or evacuated environment), and $\theta_{\max}$ is the half-angle of the maximum cone of image forming rays from projection objective 101.

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In general, projection objective 101 can have an image side NA of about 0.1 or more (e.g., about 0.15 or more, about 0.2 or more, about 0.25 or more, about 0.28 or more, about 0.3 or more, about 0.35 or more). In some embodiments, projection objective 101 has a relatively high image-side NA.

10 For example, in some embodiments, projection objective 101 may have an image-side NA of more than 0.4 (e.g., about 0.45 or more, about 0.5 or more, about 0.55 or more, about 0.6 or more). In general, the resolution of projection objective 101 varies depending on wavelength λ and the image-side NA.

Without wishing to be bound by theory, the resolution of a projection

15 objective can be determined based on the wavelength and image-side NA based on the formula,

$$R = k \frac{\lambda}{NA},$$

20 where R is the minimum dimension that can be printed and k is a dimensionless constant called the process factor. k varies depending on various factors associated with the radiation (e.g., the polarization properties), the illumination properties (e.g., partial coherence, annular illumination, dipole settings, quadrupole settings, etc.) and the resist material. Typically, k is

25 in a range from about 0.4 to about 0.8, but can also be below 0.4 and higher than 0.8 for certain applications.

Projection objective 101 is also nominally telecentric at the image plane. For example, the chief rays can deviate by about 0.5° or less (e.g., about 0.4° or

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- less, about 0.3° or less, about 0.2° or less, about 0.1° or less, about 0.05° or less, 0.01° or less, 0.001° or less) from being parallel to each other at the image plane over the exposed field. Thus, projection objective 101 can provide substantially constant magnification over a range of image-size
- 5 working distances. In some embodiments, the chief rays are nominally orthogonal to image plane 102. Thus, a non flat topography of the wafer surface or a defocusing of the image plane does not lead to distortion or shading effects in the image plane.
- 10 In certain embodiments, projection objective 101 has a relatively high resolution (i.e., the value of R can be relatively small). For example, R can be about 150 nm or less (e.g., about 130 nm or less, about 100 nm or less, about 75 nm or less, about 50 nm or less, about 40 nm or less, about 35 nm or less, about 32 nm or less, about 30 nm or less, about 28 nm or less, about 25 nm or
- 15 less, about 22 nm or less, about 20 nm or less, about 18 nm or less, about 17 nm or less, about 16 nm or less, about 15 nm or less, about 14 nm or less, about 13 nm or less, about 12 nm or less, about 11 nm or less, such as about 10 nm).
- 20 The quality of images formed by projection objective 101 can be quantified in a variety of different ways. For example, images can be characterized based on the measured or calculated departures of the image from idealized conditions associated with Gaussian optics. These departures are generally known as aberrations. One metric used to quantify the deviation of a
- 25 wavefront from the ideal or desired shape is the root-mean-square wavefront error (W_{rms}). W_{rms} is defined in the "Handbook of Optics," Vol. I, 2nd Ed., edited by Michael Bass (McGraw-Hill, Inc., 1995), at page 35.3, which is incorporated herein by reference. In general, the lower the W_{rms} value for an objective, the less the wavefront deviates from its desired or ideal shape, and
- 30 the better the quality of the image. In certain embodiments, projection

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objective 101 can have a relatively small W_{rms} for images at image plane 102. For example, projection objective 101 can have a W_{rms} of about 0.1λ or less (e.g., about 0.07λ or less, about 0.06λ or less, about 0.05λ or less, about 0.045λ or less, about 0.04λ or less, about 0.035λ or less, about 0.03λ or less, about 0.025λ or less, about 0.02λ or less, about 0.015λ or less, about 0.01λ or less, such as about 0.005λ).

Another metric that can be used to evaluate the quality of the image is referred to as field curvature. Field curvature refers to the peak-to-valley distance for the field point dependent position of the focal plane. In some embodiments, projection objective 101 can have a relatively small field curvature for images at image plane 102. For example, projection objective 101 can have an image-side field curvature of about 50 nm or less (e.g., about 30 nm or less, about 20 nm or less, about 15 nm or less, about 12 nm or less, 10 nm or less).

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A further metric that can be used to evaluate the optical performance is referred to as distortion. Distortion refers to the maximum absolute value of the field point dependent deviation from the ideal image point position in the image plane. In some embodiments, projection objective 101 can have a relatively small maximum distortion. For example, projection objective 101 can have a maximum distortion of about 50 nm or less, (e.g. about 40 nm or less, about 30 nm or less, about 20 nm or less, about 15 nm or less, about 12 nm or less, 10 nm or less, 9 nm or less, 8 nm or less, 7 nm or less, 6 nm or less, 5 nm or less, 4 nm or less, 3 nm or less, 2 nm or less, such as 1 nm).

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Further, in certain embodiments, distortion can vary by a relatively small amount across the image field. For example, distortion can vary by about 5 nm or less (e.g., about 4 nm or less, about 3 nm or less, about 2 nm or less, about 1 nm or less) across the image field.

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Being a catoptric system, projection objective 101 includes a number of mirrors arranged to direct radiation reflected from reticle 140 to substrate 150 in a way that forms an image of reticle 140 on the surface of substrate 150.

- 5 Specific designs of projection objectives are described below. More generally, however, the number, size, and structure of the mirrors generally depends on the desired optical properties of projection objective 101 and the physical constraints of tool 100.
- 10 In general, the number of mirrors in projection objective 101 may vary. Typically, the number of mirrors is related to various performance trade-offs associated with the optical performance characteristics of the objective, such as the desired throughput (e.g., the intensity of radiation from the object that forms the image at image plane 102), the desired image-side NA and related
- 15 image resolution, and the desired maximum pupil obscuration.
- In general, projection objective 101 has at least four mirrors (e.g., five or more mirrors, six or more mirrors, seven or more mirrors, eight or more mirrors, nine or more mirrors, ten or more mirrors, eleven or more mirrors, twelve or
- 20 more mirrors). In embodiments where it is desirable that all the mirrors of the objective are positioned between the object plane and the image plane, objective 101 will typically have an even number of mirrors (e.g., four mirrors, six mirrors, eight mirrors, ten mirrors). In certain embodiments, an odd number of mirrors can be used where all the mirrors of the projection
- 25 objective are positioned between the object plane and image plane. For example, where one or more mirrors are tilted at relatively large angles, a projection objective can include an odd number of mirrors where all the mirrors are positioned between the object plane and image plane.

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In general, at least one of the mirrors in projection objective 101 has a rotationally asymmetric or freeform surface. Unlike spherical or aspherical mirrors, freeform mirror surfaces do not have an axis of rotational symmetry. Generally, a freeform surface deviates from a rotationally symmetric reference surface (e.g., a spherical or aspherical rotationally symmetric reference surface), which refers to the rotationally symmetric surface that most closely matches the rotationally asymmetric surface.

Rotationally-symmetric reference surfaces can be determined for a freeform mirror surface as follows. First, one obtains information that characterizes the freeform mirror surface under consideration. In embodiments where optical data of the mirror is known, this information includes determining the basic radius of the mirror (e.g. $1/c$, where c is the vertex curvature), a conic constant of the mirror, k , and polynomial coefficients characterizing the mirror. Alternatively, or additionally, the information characterizing the mirror can be obtained from a surface figure measurement of the mirror surface (e.g. obtained using an interferometer). A surface figure measurement can provide a function $z'(x', y')$ describing the mirror's surface, where z' is the sag of the mirror surface along the z' -axis for different (x', y') coordinates, as illustrated in Fig. 2B. The initial step also includes determining the footprint for the mirror, which refers to an area of the mirror surface that is actually used to reflect image-forming radiation in the objective. The footprint can be determined by tracing rays through the objective using a ray tracing program and extracting the mirror area contacted by the rays.

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After obtaining the information characterizing the rotationally asymmetric surface, a local coordinate system for the surface is established for which decentration and tilt of the surface is zero. Setting the tilt and decentration of the surface gives a well defined starting point for an optimization algorithm to determine the reference surface and also define an axis, z' , along which the

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sag differences between the mirror surface and the reference surface can be determined. Where optical data for the mirror surface is known, the z' -axis is determined based on the conic constant, k , and basic radius, $1/c$. For the rotationally symmetric portion of the optical data, the z' -axis is the symmetry axis for the rotationally symmetric part of the rotationally asymmetric surface.

5 In embodiments where the mirror surface is characterized from a surface figure measurement, the z' -axis corresponds to the metrology axis (e.g. the interferometers optical axis). Fig. 2B illustrates this for a two-dimensional section of a rotationally asymmetric mirror 201, where the local coordinate

10 system is denoted by the x' , y' and z' axes. The boundaries for the footprint of the rotationally asymmetric mirror 201 are shown as $x_{\min}$ and $x_{\max}$ for the cross-section shown in Fig. 2B.

An initial reference surface is then established with respect to the coordinate

15 system. The initial reference surface has zero tilt and zero decentration. The initial reference surface is either a spherical surface or a rotationally symmetric aspherical surface. The initial reference surface is established by one designating a rotationally symmetric surface that approximates the rotationally asymmetric mirror surface. The initial reference surface represents

20 a starting point for an optimization algorithm. Once the initial reference surface is established, a local distance, b_i ($i = 1 \dots N$) between a number of points of the initial reference surface and points on the surface of the rotationally asymmetric surface footprint measured along the z' -axis of the local coordinate system are determined. Next, the rotationally symmetric

25 reference surface (surface 211 in Fig. 2B) is established by determining a minimal value for the local distances (d_i) using a number fitting parameters and a fitting algorithm. In the event that the rotationally symmetric reference surface is a spherical surface, the parameters include the location of the center of the sphere within the local coordinate system, the radius, of the reference

30 surface. In Fig. 2B, decentering of the sphere center from the coordinate

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system origin is shown by coordinates x_c and z_c (decentration along the y' -axis by an amount y_c is not shown in Fig. 2B). The radius of the spherical surface is designated as R . The parameters R , x_c , y_c and z_c are optimized to provide a minimal value for the local distances, d_i , based on the equation:

5

$$z' = (R^2 - (x' - x_c)^2 - (y' - y_c)^2)^{1/2} - z_c,$$

which is the equation for a spherical surface of radius R , centered at coordinate (x_c, y_c, z_c) .

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Where the rotationally symmetric reference surface is an aspherical surface, the parameters can include decentration and tilt of the reference surface, base radius, conical constant and aspherical coefficients. These parameters can be determined based on the equation

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$$z' = \frac{c'h^2}{1 + \sqrt{1 - (1 + k')c'^2 h^2}} + \sum_j A'_j h^{2j},$$

which is an equation describing conic and aspheric surfaces. Here, $h^2 = x'^2 + y'^2$, and A'_j are coefficients characterizing the deviation of the rotationally-symmetric reference surface from a conic surface. Generally, the number of aspherical coefficients, A'_j , used to fit the reference surface to the mirror surface can vary depending on the computational power of the system being used to calculate the surface, the time available, and the desired level of accuracy. In some embodiments, the reference surface can be calculated using aspherical coefficients up to third order. In certain embodiments, coefficients higher than third order (e.g., fourth order, sixth order) are used. For additional discussion on parameterization of conic and aspheric surfaces see, for

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example, the product manual for Code V, available from Optical Research Associates (Pasadena, CA).

In general, fitting can be performed using a variety of optimization algorithms.

- 5 For example, in some embodiments, a least squares fitting algorithm, such as a damped least squares fitting algorithm, can be used. Damped least squares fitting algorithms may be performed using commercially-available optical design software, such as Code V or ZEMAX (available from Optima Research, Ltd., Stansted, United Kingdom) for example.

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After the rotationally-symmetric reference surface is determined, the local distance between additional points on the mirror surface can be determined and visualized. Additional characteristics of the rotationally-symmetric reference surface can be determined. For example, a maximum deviation of

- 15 the rotationally-symmetric reference surface from the rotationally-asymmetric mirror surface can be determined.

A freeform surface can, for example, have a maximum deviation from a best fit sphere or a rotationally symmetric reference surface of about λ or more

- 20 (e.g., about 10λ or more, about 20λ or more, about 50λ or more, about 100λ or more, about 150λ or more, about 200λ or more, about 500λ or more, about $1,000\lambda$ or more, about $10,000\lambda$ or more, about $50,000\lambda$ or more). A freeform surface can have a maximum deviation from a best fit rotationally symmetric asphere of about λ or more (e.g., about 5λ or more, about 10λ or more, about 20λ or more, about 50λ or more, about 100λ or more, about 200λ or more, about 500λ or more, about $1,000\lambda$ or more, about $10,000\lambda$ or more). In some embodiments, a freeform surface can have a maximum deviation from a best fit rotationally symmetric asphere of about $1,000\lambda$ or

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less (e.g., about 900λ or less, about 800λ or less, about 700λ or less, about 600λ or less, about 500λ or less).

In certain embodiments, freeform surfaces have a maximum deviation from a best fit sphere by 10 nm or more (e.g., about 100 nm or more, about 500 nm or more, about $1 \mu\text{m}$ or more, about $5 \mu\text{m}$ or more, about $10 \mu\text{m}$ or more, about $50 \mu\text{m}$ or more, about $100 \mu\text{m}$ or more, about $200 \mu\text{m}$ or more, about $500 \mu\text{m}$ or more, about $1,000 \mu\text{m}$, about $2,000 \mu\text{m}$ or more, about $3,000 \mu\text{m}$ or more). Freeform surfaces can have a maximum deviation from a best fit sphere by about 10 mm or less (e.g., about 5 mm or less, about 3 mm or less, about 2 mm or less, about 1 mm or less, about $500 \mu\text{m}$ or less).

Freeform surfaces can have a maximum deviation from a best fit rotationally symmetric asphere by 10 nm or more (e.g., about 100 nm or more, about 500 nm or more, about $1 \mu\text{m}$ or more, about $5 \mu\text{m}$ or more, about $10 \mu\text{m}$ or more, about $50 \mu\text{m}$ or more, about $100 \mu\text{m}$ or more, about $200 \mu\text{m}$ or more, about $500 \mu\text{m}$ or more, about $1,000 \mu\text{m}$). Freeform surfaces can have a maximum deviation from a best fit rotationally symmetric asphere by about 10 mm or less (e.g., about 5 mm or less, about 3 mm or less, about 2 mm or less, about 1 mm or less, about $500 \mu\text{m}$ or less).

The curvature of the mirror surfaces is characterized by a first and second mean principal curvature, which are determined at the point on each mirror surface that reflects the chief ray of the central field point. First and second principal curvatures are calculated as described in Handbook of Mathematics by I. N. Bronstein, et al., 4th Ed. (Springer, 2004), p. 567. In general, the first principal curvature for a mirror can be different from the second principal curvature for that mirror. In some embodiments, the absolute value of the difference between the first and second principal curvatures can be about 10^{-8}

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or more (e.g., 10^{-7} or more, 5×10^{-7} or more, about 10^{-6} or more, about 5×10^{-6} or more, about 10^{-5} or more, about 5×10^{-5} or more, about 10^{-4} or more, about 5×10^{-4} or more, about 10^{-3} or more).

- 5 In general, the first and/or second principal curvatures can be positive or negative. The first and/or second principal curvatures for a mirror surface can be relatively small. For example, in some embodiments, the absolute value of the first principal curvature for one or more mirrors in projection objective 101 is about 10^{-2} or less (e.g., about 5×10^{-3} or less, about 3×10^{-3} or less, about 2×10^{-3} or less, about 10^{-3} or less). The absolute value of the sum of the first principal curvatures for the mirrors in projective objective 101 can be about 10^{-3} or less (e.g., about 5×10^{-4} or less, about 3×10^{-4} , about 2×10^{-4} or less, about 10^{-4} or less, 5×10^{-5} or less, 10^{-5} or less).
- 15 In certain embodiments, the absolute value of the second principal curvature for one or more mirrors in projection objective 101 is about 10^{-2} or less (e.g., about 5×10^{-3} or less, about 3×10^{-3} or less, about 2×10^{-3} or less, about 10^{-3} or less). The absolute value of the sum of the second principal curvatures for the mirrors in projective objective 101 can be about 10^{-3} or less (e.g., about 5×10^{-4} or less, about 3×10^{-4} , about 2×10^{-4} or less, about 10^{-4} or less, 5×10^{-5} or less, 10^{-5} or less).
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- The sum of the first and second principal curvatures of the mirrors in projection objective 101, i.e. the sum of the first principal curvatures of all mirrors in projection objective 101, the sum of the second principal curvatures of all mirrors in projection objective 101 or the sum of all first and second principle curvatures of all mirrors in projection objective 101, can be relatively small. For example, the absolute value of the sum of the first and second principal curvatures of the mirrors can be about 10^{-3} or less (e.g., about
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5×10^{-4} or less, about 3×10^{-4} , about 2×10^{-4} or less, about 10^{-4} or less, 5×10^{-5} or less, 10^{-5} or less).

In certain embodiments, freeform mirror surfaces can be described

5 mathematically by the equation:

$$Z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{j=2}^{66} C_j X^m Y^n$$

where

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$$j = \frac{(m+n)^2 + m + 3n}{2} + 1$$

and Z is the sag of the surface parallel to a Z -axis (which may or may not be parallel to the z -axis in projection objective 101, i.e. in general is decentered

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and tilted to the z -axis in projection objective 101), c is a constant

corresponding to the vertex curvature, k is a conic constant, and C_j is the coefficient of the monomial $X^m Y^n$. Typically, the values of c , k , and C_j are determined based on the desired optical properties of the mirror with respect to projection objective 101. Further, the order of the monomial, $m + n$, can

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vary as desired. Generally, a higher order monomial can provide a projection objective design with a higher level of aberration correction, however, higher order monomials are typically more computationally expensive to determine.

In some embodiments, $m + n$ is 10 or more (e.g., 15 or more, 20 or more). As discussed below, the parameters for the freeform mirror equation can be

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determined using commercially-available optical design software. In some embodiments, $m + n$ is less than 10 (e.g., 9 or less, 8 or less, 7 or less, 6 or less, 5 or less, 4 or less, 3 or less).

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- In general, freeform surfaces can be described mathematically using equations other than those presented above. For example, in some embodiments, freeform surfaces can be described mathematically using Zernike polynomials (such as presented in the manual for CODE V[®], commercially available from
- 5 Optical Research Associates, Pasadena, CA) or using two-dimensional spline surfaces. Examples of two-dimensional spline surfaces are Bezier splines or non-uniform rational Bezier splines (NURBS). Two-dimensional spline surfaces can be described, for example, by a grid of points in an x-y plane and corresponding z-values or slopes and these points. Depending on the specific
- 10 type of spline surface, the complete surface is obtained by a specific interpolation between the grid points using, e.g., polynomials or functions that have certain properties with respect to continuity or differentiability (e.g., analytical functions).
- 15 In general, the number and position of freeform mirrors in projection objective 101 can vary. Embodiments include projection objectives with two or more freeform mirrors (e.g., three or more freeform mirrors, four or more freeform mirrors, five or more freeform mirrors, six or more freeform mirrors).
- 20 Projection objective 101 generally includes one or more mirrors with positive optical power. In other words, the reflective portion of the mirror has a concave surface and is referred to as a concave mirror. Projection objective 101 can include two or more (e.g., three or more, four or more, five or more, six or more) concave mirrors. Projection objective 101 can also include one or
- 25 more mirrors that have negative optical power. This means that one or more of the mirrors has a reflective portion with a convex surface (referred to as a convex mirror). In some embodiments, projection objective 101 includes two or more (e.g., three or more, four or more, five or more, six or more) convex mirrors.

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An embodiment of a projection objective that includes six mirrors is shown in FIG. 3. Specifically, projection objective 300 includes six freeform mirrors 310, 320, 330, 340, 350, and 360. Data for projection objective 300 is presented in Table 1A and Table 1B below. Table 1A presents optical data, while Table 1B presents freeform constants for each of the mirror surfaces. For the purposes of Table 1A and Table 1B, the mirror designations correlate as follows: mirror 1 (M1) corresponds to mirror 310; mirror 2 (M2) corresponds to mirror 320; mirror 3 (M3) corresponds to mirror 330; mirror 4 (M4) corresponds to mirror 340; mirror 5 (M5) corresponds to mirror 350; and mirror 6 (M6) corresponds to mirror 360. "Thickness" in Table 1A and subsequent tables refers to the distance between adjacent elements in the radiation path. The monomial coefficients, C_j , for the freeform mirrors, along with the amount the mirror is decentered and rotated (or tilted) from an initial projection objective design, are provided in Table 1B. R, the radius, is the inverse of the vertex curvature, c . Decenter is given in mm and rotation is given in degrees. Units for the monomial coefficients are mm^{j+1} . Nradius is a unitless scaling factor (see, for example, the manual for CODE V[®]).

In FIG. 3, projection objective 300 is shown in meridional section. The meridional plane is a symmetry plane for projection objective 300. Symmetry about the meridional plane is as the mirrors are decentered only with respect to the y -axis and tilted about the x -axis. Further, the coefficients for the freeform mirrors having an odd degree in the x -coordinate (e.g., x , x^3 , x^5 , etc.) are zero.

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Projection objective 300 is configured for operation with 13.5 nm radiation and has an image-side NA of 0.35 and a tracklength of 1,500 mm. The optical path length of imaged radiation is 3,833 mm. Accordingly, the ratio of optical path length to tracklength is approximately 2.56. Projection objective has a demagnification of 4X, a maximum distortion of less than 100 nm, W_{rms} of 0.035

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λ , and a field curvature of 28 nm. Additional characteristics of projection objective 300 are presented in the discussion of projection objective 101 that follows.

- 5 For example, the first mirror in the radiation path from object plane 103, mirror 310, has positive optical power. Mirrors 320, 340, and 360 are also P mirrors. Mirrors 330 and 350 have (N) negative optical power. The sequence of mirrors in the radiation path in projection objective 300 is thus PPNPNP.

Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	714.025	
Mirror 1	-1678.761	-414.025	REFL
Mirror 2	2754.233	564.025	REFL
Mirror 3	350.451	-316.293	REFL
Mirror 4	590.379	906.948	REFL
Mirror 5	433.060	-435.447	REFL
Mirror 6	521.283	480.767	REFL
Image	INFINITY	0.000	

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Table 1A

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Coefficient	M1	M2	M3	M4	M5	M6
K	-4.724690E+00	-9.830444E+01	-3.914225E-01	-8.227088E-01	7.162282E+00	9.391806E-02
Y	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ²	-1.641507E-04	-1.736185E-04	-2.373278E-04	2.451198E-05	-1.557674E-04	-6.667760E-06
Y ²	-1.752262E-04	-1.741103E-04	-9.708884E-04	-3.130199E-05	1.398839E-04	9.098616E-06
X ² Y	-2.463783E-08	-2.724028E-07	6.327587E-07	-9.301810E-08	9.519017E-07	-8.040311E-10
Y ³	-3.641831E-08	-1.681535E-07	-6.103587E-07	2.218271E-08	6.329282E-07	-4.521618E-10
X ⁴	-1.405718E-10	1.314594E-09	-1.671620E-08	4.569574E-10	7.852021E-10	-5.450396E-11
X ² Y ²	-3.301633E-10	1.799995E-09	9.953323E-09	-1.957005E-10	3.524719E-09	-5.846553E-11
Y ⁴	5.029041E-11	2.141266E-09	2.197236E-09	9.287687E-10	6.848802E-09	-6.829886E-12
X ⁴ Y	2.090103E-13	4.363226E-12	-5.435284E-11	1.915106E-13	-2.016721E-11	5.660569E-15
X ² Y ³	-4.188774E-13	4.826497E-12	3.808642E-11	-5.874603E-12	-1.600920E-11	-1.079542E-14
Y ⁵	-3.154238E-13	-4.239647E-12	-9.502949E-13	9.213338E-13	7.113886E-12	-1.553415E-14
X ⁶	1.150997E-16	-5.978561E-15	1.819755E-13	1.113227E-15	-7.841517E-14	-1.105247E-16
X ⁴ Y ²	-1.278596E-15	-1.564797E-14	-9.716106E-14	4.491475E-15	2.513948E-14	-2.683146E-16
X ² Y ⁴	4.862795E-15	2.347370E-14	-8.086932E-14	-1.357215E-14	7.550314E-13	-1.006466E-16
Y ⁶	-2.281966E-15	6.013241E-15	-9.790347E-15	9.777397E-16	5.013963E-13	2.221551E-17
X ⁶ Y	1.931804E-18	-3.973144E-17	1.435292E-15	2.420914E-18	1.092143E-15	2.493748E-20
X ⁴ Y ³	1.873466E-17	-2.704307E-16	6.491544E-16	1.627727E-18	4.414328E-15	-3.302939E-21
X ² Y ⁵	-1.108422E-17	-6.723973E-16	1.496578E-17	-1.880319E-17	8.552963E-15	-3.287503E-20
Y ⁷	1.208226E-17	-3.735956E-17	5.421342E-17	-8.994976E-19	4.894980E-15	-1.747517E-20
X ⁸	-6.860939E-22	3.733020E-20	-1.370615E-17	-3.978807E-21	-1.975913E-18	-3.966972E-22
X ⁶ Y ²	-2.665919E-20	-1.577571E-19	1.832427E-17	-2.552872E-21	-2.066761E-17	-1.153602E-21
X ⁴ Y ⁴	-1.606232E-19	9.112068E-19	3.422045E-18	-4.011070E-20	-4.034354E-17	-9.786532E-22
X ² Y ⁶	-7.104780E-20	4.547933E-18	3.897160E-19	8.558317E-21	3.324806E-17	-2.054121E-22
Y ⁸	-2.837115E-20	3.557864E-20	-5.077104E-20	8.825661E-22	3.460507E-17	4.049399E-23
X ⁸ Y	1.837688E-23	1.087991E-21	-7.892883E-20	-4.154231E-23	3.418177E-20	2.593417E-25
X ⁶ Y ³	1.326930E-22	6.381757E-21	8.816591E-20	-7.838712E-23	-1.567137E-20	3.310704E-25
X ⁴ Y ⁵	5.956987E-22	3.566833E-22	3.431915E-21	-1.727422E-22	-2.315754E-19	1.062541E-25
X ² Y ⁷	4.749865E-22	-1.305899E-20	-1.115108E-21	2.927898E-23	0.000000E+00	5.083980E-27
Y ⁹	2.880675E-23	3.134161E-21	4.687247E-23	-2.354646E-24	0.000000E+00	-4.697062E-26
X ¹⁰	3.263322E-27	-1.350621E-25	7.223418E-23	3.596439E-27	0.000000E+00	-1.214434E-27
X ⁸ Y ²	-7.476461E-26	-8.102951E-24	-1.439645E-22	-6.842489E-26	0.000000E+00	-7.139344E-27
X ⁶ Y ⁴	-2.162180E-25	-1.982986E-23	1.317953E-22	-1.079450E-25	0.000000E+00	-8.881170E-27
X ⁴ Y ⁶	-8.415305E-25	-1.821358E-26	-5.971700E-24	-1.561940E-25	0.000000E+00	-3.378805E-27
X ² Y ⁸	-8.228853E-25	3.745838E-24	-3.016526E-24	3.289669E-26	0.000000E+00	1.400401E-27
Y ¹⁰	2.644302E-26	-1.118733E-23	5.389015E-25	-3.012754E-27	0.000000E+00	9.011434E-28
Nradius	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Y-decenter	-100.000	-84.186	100.000	19.008	11.570	24.216
X-rotation	-7.020	-1.728	-11.272	-5.323	-2.295	-1.825

Table 1B

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For the mirrors in projection objective 300, the maximum deviation of the freeform surfaces from a best fit sphere for each mirror is as follows: 154 μm for mirror 310; 43 μm for mirror 320, 240 μm for mirror 330; 1,110 μm for mirror 340; 440 μm for mirror 350; and 712 μm for mirror 360. The maximum deviation of the freeform surfaces from a best fit rotationally symmetric asphere is 47 μm for mirror 310; 33 μm for mirror 320, 96 μm for mirror 330; 35 μm for mirror 340; 152 μm for mirror 350; and 180 μm for mirror 360.

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The first and second principal curvature for mirror 310 are 9.51×10^{-4} and 9.30×10^{-4} respectively. Respective first and second principal curvatures for the other mirrors in projection objective 300 are as follows: 2.76×10^{-5} and 1.56×10^{-5} for mirror 320; -2.38×10^{-3} and -2.17×10^{-3} for mirror 330; 1.79×10^{-3} and 1.75×10^{-3} for mirror 340; -2.64×10^{-3} and -2.10×10^{-3} for mirror 350; and 1.93×10^{-3} and 1.91×10^{-3} for mirror 360. The sum of the first principal curvature for projection objective 300 is -3.19×10^{-4} . The sum of the second principal curvature is 3.29×10^{-4} . The sum of the first and second principal curvatures is 9.97×10^{-6} and the inverse sum of the first and second principal curvatures is 1.00×10^5 .

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In certain embodiments, the arrangement of mirrors in projection objective 101 images radiation from object plane 103 to one or more intermediate-image planes. For example, projection objective 300 images radiation from object plane 103 to an intermediate image at a location 305 near mirror 360. Embodiments that have one or more intermediate images, also include two or more pupil planes. In some embodiments, at least one of these pupil planes is physically accessible for the purposes of placing an aperture stop substantially

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at that pupil plane. An aperture stop is used to define the size of the projection objective's aperture.

Coma at an intermediate image in projection objective 101 can be relatively
5 large. Coma can be quantified by the distance between the chief ray and the upper and lower rays at the point where the upper and lower rays cross. In some embodiments, this distance can be about 1 mm or more (e.g., about 2 mm or more, about 3 mm or more, about 4 mm or more, about 5 mm or more, about 6 mm or more, such as about 7 mm). Coma at an intermediate image in
10 projection objective can be relatively small. In some embodiments, the distance can be about 1 mm or less (e.g., about 0.1 mm or less, 0.01 mm or less).

In general, mirrors in projection objective 101 are formed so that they reflect a
15 substantial amount of radiation of wavelength λ normally-incident thereon or incident thereon over a certain range of incident angles. Mirrors can be formed, for example, so that they reflect about 50% or more (e.g., about 60% or more, about 70% or more, about 80% or more, about 90% or more, about 95% or more, 98% or more) of normally incident radiation at λ .

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In some embodiments, the mirrors include a multilayer stack of films of different materials arranged to substantially reflect normally incident radiation at λ . Each film in the stack can have an optical thickness of about $\lambda/4$.

Multilayer stacks can include about 20 or more (e.g., about 30 or more, about
25 40 or more, about 50 or more) films. In general, the materials used to form the multilayer stacks are selected based on operational wavelength λ . For example, multiple alternating films of molybdenum and silicon or molybdenum and beryllium can be used to form mirrors for reflecting radiation in the 10 nm to 30 nm range (e.g., for λ of about 13 nm or about 11

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nm, respectively). Generally, multiple alternating films of molybdenum and silicon are preferred for $\lambda = 11$ nm and multiple alternating films of molybdenum and beryllium are preferred for $\lambda = 13$ nm.

- 5 In certain embodiments, the mirrors are made of quartz glass coated with a single layer of aluminum and overcoated with one or more layers of dielectric materials, such as layers formed from MgF_2 , LaF_2 , or, Al_2O_3 . Mirrors formed from aluminum with dielectric coatings can be used, for example, for radiation having a wavelength of about 193 nm.

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In general, the percentage of radiation at λ reflected by a mirror varies as a function of the angle of incidence of the radiation on the mirror surface.

Because imaged radiation propagates through a catoptric projection objective along a number of different paths, the angle of incidence of the radiation on

- 15 each mirror can vary. This effect is illustrated with reference to FIG.4, which shows a portion of a mirror 400, in meridional section, that includes a concave reflective surface 401. Imaged radiation is incident on surface 401 along a number of different paths, including the paths shown by rays 410, 420, and 430. Rays 410, 420, and 430 are incident on portions of surface 401 where the
- 20 surface normal is different. The direction of surface normal at these portions is shown by lines 411, 421, and 431, corresponding to rays 410, 420, and 430, respectively. Rays 410, 420, and 430 are incident on surface 401 at angles θ_{410} , θ_{420} , and θ_{430} , respectively. In general, angles θ_{410} , θ_{420} , and θ_{430} may vary.

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For each mirror in projection objective 101, the incident angles of imaged radiation can be characterized in a variety of ways. One characterization is the maximum angle of incidence of meridional rays on each mirror in a meridional section of projection objective 101. Meridional rays refer to rays

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lying in the meridional section. In general, $\theta_{\max}$ can vary for different mirrors in projection objective 101.

In some embodiments, the maximum value of $\theta_{\max}$ for all the mirrors in
 5 projection objective 101 is about 75° or less (e.g., about 70° or less, about 65°
 or less, about 60° or less, about 55° or less, about 50° or less, about 45° or
 less). $\theta_{\max}$ can be more than about 5° (e.g., about 10° or more, about 20° or
 more). In some embodiments, the maximum value of $\theta_{\max}$ can be relatively
 low. For example, the maximum value of $\theta_{\max}$ can be about 40° or less (e.g.,
 10 about 35° or less, about 30° or less, about 25° or less, about 20° or less, about
 15° or less, about 13° or less, about 10° or less).

As an example, in projection objective 300, $\theta_{\max}$ for mirror 310 is 8.22° , $\theta_{\max}$
 for mirror 320 is 10.38° , $\theta_{\max}$ for mirror 330 is 22.35° , $\theta_{\max}$ for mirror 340 is
 15 7.49° , $\theta_{\max}$ for mirror 350 is 24.58° , and $\theta_{\max}$ for mirror 360 is 6.15° .

In some embodiments, the ratio of the maximum value of $\theta_{\max}$ (in degrees) to
 image-side NA can be about 100 or less (e.g., about 80 or less, about 70 or
 less, 68 or less, about 60 or less, about 50 or less, about 40 or less, about 30 or
 20 less).

Another characterization is the angle of incidence of the chief ray
 corresponding to the central field point on each mirror in a meridional section
 of projection objective 101. This angle is referred to as θ_{CR} . In general, θ_{CR}
 25 can vary. For projection objective 300, for example, mirror 310 has θ_{CR} of
 6.59° , mirror 320 has θ_{CR} of 7.93° , mirror 330 has θ_{CR} of 20.00° , mirror 340
 has θ_{CR} of 7.13° , mirror 350 has θ_{CR} of 13.06° , and mirror 360 has θ_{CR} of
 5.02° . In some embodiments the maximum value of θ_{CR} , $\theta_{\text{CR}}(\max)$, in
 projection objective 101 can be relatively low. For example, $\theta_{\text{CR}}(\max)$ can be

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about 35° or less (e.g., about 30° or less, about 25° or less, about 20° or less, about 15° or less, about 13° or less, about 10° or less, about 8° or less, about 5° or less). For projection objective 300, $\theta_{CR(max)}$, which is θ_{CR} for mirror 330, is 20.00°.

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In some embodiments, the ratio of the maximum value of $\theta_{CR(max)}$ (in degrees) to image-side NA can be about 100 or less (e.g., about 80 or less, about 70 or less, 68 or less, about 60 or less, about 50 or less, about 40 or less, about 30 or less).

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Each mirror in projection objective 101 can also be characterized by the range of angles of incidence, $\Delta\theta$, of rays for a meridional section of projection objective 101. For each mirror, $\Delta\theta$ corresponds to the difference between θ_{max} and θ_{min} , where θ_{min} is the minimum angle of incidence of rays on each mirror

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in a meridional section of projection objective 101. In general, $\Delta\theta$ may vary for each mirror in projection objective 101. For some mirrors, $\Delta\theta$ can be relatively small. For example, $\Delta\theta$ can be about 20° or less (e.g., about 15° or less, about 12° or less, about 10° or less, about 8° or less, about 5° or less, about 3° or less, 2° or less). Alternatively, for some mirrors in projection

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objective 101, $\Delta\theta$ can be relatively large. For example, $\Delta\theta$ for some mirrors can be about 20° or more (e.g., about 25° or more, about 30° or more, about 35° or more, about 40° or more). For projection objective 300, $\Delta\theta_{max}$ for mirror 310 is 3.34°, $\Delta\theta_{max}$ for mirror 320 is 4.92°, $\Delta\theta_{max}$ for mirror 330 is 5.18°, $\Delta\theta_{max}$ for mirror 340 is 0.98°, $\Delta\theta_{max}$ for mirror 350 is 24.07°, and $\Delta\theta_{max}$

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for mirror 360 is 2.77°.

In some embodiments, the maximum value for $\Delta\theta$, $\Delta\theta_{max}$, for all the mirrors in projection objective 101 can be relatively small. For example, $\Delta\theta_{max}$ can be about 25° or less (e.g., about 20° or less, about 15° or less, about 12° or less,

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about 10° or less, about 9° or less, about 8° or less, about 7° or less, about 6° or less, about 5° or less, such as 3°). For projection objective 300, $\Delta\theta_{\max}$ is 24.07°.

- 5 Another way to characterize the radiation path in projection objective 101 is by the chief ray magnification at each mirror, which refers to the quotient of the tangent of the angle between the chief ray (e.g. in the meridional section) and reference axis 105 before and after reflection from each mirror. For example, referring to FIG. 5A where a chief ray 501 diverges from reference
- 10 axis 105 prior to reflection from a mirror 510, and reflects from mirror 510 back towards reference axis 105, mirror 510 has a positive chief ray angle magnification. Referring to FIG. 5B, alternatively, where a chief ray 502 diverges from reference axis 105 both before and after reflection from a mirror 520, mirror 520 has a negative chief ray angle magnification. In both cases,
- 15 the chief ray magnification is given by $\tan(\alpha)/\tan(\beta)$. In certain embodiments, having multiple mirrors with positive chief ray angle magnification can correspond to relatively large incident angles on one or more mirrors in the projection objective. Accordingly, projection objectives having only one mirror with positive chief ray angle magnification can also exhibit relatively
- 20 low incident ray angles on the mirrors. For projection objective 300, mirrors 310, 320, 330 and 350 have negative chief ray angle magnifications, while mirror 340 has positive chief ray angle magnification.

- The relative spacing of mirrors in projection objective 101 can vary depending
- 25 on the specific design of the projection objective. Relatively large distances between adjacent mirrors (with respect to the path of the radiation) can correspond to relatively low incident ray angles on the mirrors. In certain embodiments, projection objective 101 can include at least one pair of adjacent mirrors that separated by more than 50% of the projection objective

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tracklength. For example, in projection objective 300, mirrors 340 and 350 are separated by more than 50% of the projection objective's track length.

In certain embodiments, having a large relative distance, d_{op-1} , between the
 5 object plane and the first mirror in the radiation path compared to the distance, d_{op-2} , between the object plane and the second mirror in the radiation path can also correspond to relatively low incident ray angles on the mirrors. For example, embodiments where d_{op-1}/d_{op-2} is about 2 or more (e.g., about 2.5 or more, about 3 or more, about 3.5 or more, about 4 or more, about 4.5 or more,
 10 about 5 or more) can also have relatively low incident ray angles. In projection objective 300, d_{op-1}/d_{op-2} is 2.38.

In general, the footprint size and shape of the mirrors in projection objective
 101 can vary. The footprint shape refers to the shape of the mirror projected
 15 onto the x - y plane. The footprint of the mirrors can be circular, oval, polygonal (e.g., rectangular, square, hexagonal), or irregular in shape. In embodiments, the footprint is symmetric with respect to the meridional plane of projection objective 101.

20 In certain embodiments, mirrors can have a footprint with a maximum dimension that is about 1,500 mm or less (e.g., about 1,400 mm or less, about 1,300 mm or less, about 1,200 mm or less, about 1,100 mm or less, about 1,000 mm or less, about 900 mm or less, about 800 mm or less, about 700 mm or less, about 600 mm or less, about 500 mm or less, about 400 mm or less,
 25 about 300 mm or less, about 200 mm or less, about 100 mm or less.) Mirrors may have footprint that has a maximum dimension that is more than about 10 mm (e.g., about 20 mm or more, about 50 mm or more).

An example of a mirror 600 with an oval footprint is shown in FIG. 6A. .

30 Mirror 600 has a maximum dimension in the x -direction given by M_x . In

embodiments, M_x can be about 1,500 mm or less (e.g., about 1,400 mm or less, about 1,300 mm or less, about 1,200 mm or less, about 1,100 mm or less, about 1,000 mm or less, about 900 mm or less, about 800 mm or less, about 700 mm or less, about 600 mm or less, about 500 mm or less, about 400 mm or less, about 300 mm or less, about 200 mm or less, about 100 mm or less). M_x can be more than about 10 mm (e.g., about 20 mm or more, about 50 mm or more).

Mirror 600 is symmetric with respect to meridian 601. Mirror 600 has a dimension M_y along meridian 601. For mirror 600 M_y is smaller than M_x , however, more generally, M_y can be smaller, the same size, or larger than M_x . In some embodiments, M_y is in a range from about 0.1 M_x to about M_x (e.g., about 0.2 M_x or more, about 0.3 M_x or more, about 0.4 M_x or more, about 0.5 M_x or more, about 0.6 M_x or more, about 0.7 M_x or more about 0.8 M_x or more, about 0.9 M_x or more). Alternatively, in certain embodiments, M_y can be about 1.1 M_x or more (e.g., about 1.5 M_x or more), such as in a range from about 2 M_x to about 10 M_x . M_y can be about 1,000 mm or less (e.g., about 900 mm or less, about 800 mm or less, about 700 mm or less, about 600 mm or less, about 500 mm or less, about 400 mm or less, about 300 mm or less, about 200 mm or less, about 100 mm or less). M_y can be more than about 10 mm (e.g., about 20 mm or more, about 50 mm or more).

In projection objective 300, M_x and M_y for mirror 310 are 303 mm and 139 mm, respectively; M_x and M_y for mirror 320 are 187 mm and 105 mm, respectively; M_x and M_y for mirror 330 are 114 mm and 62 mm, respectively; M_x and M_y for mirror 340 are 299 mm and 118 mm, respectively; M_x and M_y for mirror 350 are 99 mm and 71 mm, respectively; and M_x and M_y for mirror 360 are 358 mm and 332 mm, respectively.

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- In some embodiments, the base of the mirrors may extend beyond the mirror surface (i.e., the portion of the mirror that reflects imaged radiation) in one or more directions. For example, a mirror's base can extend about 10 mm or more (e.g., about 20 mm or more, about 30 mm or more, about 40 mm or more, about 50 mm or more) beyond the optically active surface in the *x*- and/or *y*-directions. Mirror base extension can facilitate mounting the mirror in projection objective 101 by providing surfaces that are not optically active that can be attached to mounting apparatus.
- 10 Preferably, mirror base extensions should not be in a direction that occludes the radiation path in projection objective 101. The distance between the edge of a mirror and the radiation path as it passes the mirror is related to a parameter referred to as the "freeboard," which is the minimum distance between the rays closest to a mirror's edge and the rays nearest the mirror's
- 15 edge that are reflected by the mirror. In some embodiments, projection objective 101 can include one or more mirrors with freeboards of about 20 mm or more (e.g., about 25 mm or more, about 30 mm or more, about 35 mm or more, about 40 mm or more, about 45 mm or more, about 50 mm or more). Large freeboards provide flexibility in mirror fabrication as the projection
- 20 objective can accommodate an extended mirror base without occlusion of the imaged radiation. However, relatively small freeboards can correspond to low incident ray angles on the mirrors in the projection objective. In some embodiments, projection objective 101 can include one or more mirrors with freeboards of about 15 mm or less (e.g., about 12 mm or less, about 10 mm or less, about 8 mm or less, about 5 mm or less). In certain embodiments,
- 25 projection objective 101 includes one or more mirrors having a freeboard between 5 mm and 25 mm. For example, in projection objective 300, mirrors 310, 320, 330, 350, and 360 have freeboards between 5 mm and 25 mm.

- In general, the thickness of the mirrors in projection objective 101 may vary. Mirror thickness refers to the dimension of the mirror normal to its optical surface. Mirrors should generally have sufficient thickness to facilitate mounting within the projection objective. Referring to FIG. 6B, the thickness of mirror 600 can be characterized by a maximum thickness, $T_{\max}$, and a minimum thickness, $T_{\min}$. Typically, the difference between $T_{\max}$ and $T_{\min}$ will depend on the curvature of the mirror surface and the structure of the mirror's base. In some embodiments, $T_{\max}$ is about 200 mm or less (e.g., about 150 mm or less, about 100 mm or less, about 80 mm or less, about 60 mm or less, about 50 mm or less, about 40 mm or less, about 30 mm or less, about 20 mm or less). In certain embodiments, $T_{\min}$ is about 1 mm or more (e.g., about 2 mm or more, about 5 mm or more, about 10 mm or more, about 20 mm or more, about 50 mm or more, about 100 mm or more).
- 15 In some embodiments, the maximum dimension of any mirror in projection objective is about 1,500 mm or less (e.g., about 1,400 mm or less, about 1,300 mm or less, about 1,200 mm or less, about 1,100 mm or less, about 1,000 mm or less, about 900 mm or less, about 800 mm or less, about 700 mm or less, about 600 mm or less, about 500 mm or less, such as about 300 mm). In
- 20 certain embodiments, the maximum dimension of any mirror in projection objective is about 10 mm or more (e.g., about 20 mm or more, about 30 mm or more, about 40 mm or more, about 50 mm or more, about 75 mm or more, about 100 mm or more).
- 25 In general, the shape of the field of projection objective 101 can vary. In some embodiments, the field has an arcuate shape, such as the shape of a segment of a ring. Referring to FIG. 7A, a ring-segment field 700 can be characterized by an x -dimension, d_x , a y -dimension, d_y , and a radial dimension, d_r . d_x and d_y correspond to the dimension of the field along the x -direction and y -direction, respectively. d_r corresponds to the ring radius, as measured from an axis 705
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to the inner boundary of field 700. Ring-segment field 700 is symmetric with respect to a plane parallel to the y-z plane and indicated by line 710. In general, the sizes of d_x , d_y , and d_r vary depending on the design of projection objective 101. Typically d_y is smaller than d_x . The relative sizes of field dimensions d_x , d_y , and d_r at object plane 103 and image plane 102 vary depending on the magnification or demagnification of projection objective 101.

In some embodiments, d_x is relatively large at image plane 102. For example, d_x at image plane 102 can be more than 1 mm (e.g., about 3 mm or more, about 4 mm or more, about 5 mm or more, about 6 mm or more, about 7 mm or more, about 8 mm or more, about 9 mm or more, about 10 mm or more, about 11 mm or more, about 12 mm or more, about 13 mm or more, about 14 mm or more, about 15 mm or more, about 18 mm or more, about 20 mm or more, about 25 mm or more). d_x can be about 100 mm or less (e.g., about 50 mm or less, about 30 mm or less). d_y at image plane 102 can be in a range from about 0.5 mm to about 5 mm (e.g., about 1 mm, about 2 mm, about 3 mm, about 4 mm).

Typically, d_r at image plane 102 is about 10 mm or more. d_r can be, for example, about 15 mm or more (e.g., about 20 mm or more, about 25 mm or more, about 30 mm or more) at image plane 102. In some embodiments, d_r can be extremely large (e.g., about 1 m or more, about 5 m or more, about 10 m or more). In certain embodiments, the field is rectangular in shape and d_r is infinite. Projection objective 300, for example, has a rectangular field. Specifically, projection objective 300 has a rectangular field with a y-dimension of 2 mm and an x-dimension of 26 mm, measured in the image plane.

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More generally, for other field shapes, projection objective 101 can have a maximum field dimension of more than 1 mm (e.g., about 3 mm or more, about 4 mm or more, about 5 mm or more, about 6 mm or more, about 7 mm or more, about 8 mm or more, about 9 mm or more, about 10 mm or more, about 11 mm or more, about 12 mm or more, about 13 mm or more, about 14 mm or more, about 15 mm or more, about 18 mm or more, about 20 mm or more, about 25 mm or more) at image plane 102. In certain embodiments, projection objective has a maximum field dimension of no more than about 100 mm (e.g., about 50 mm or less, about 30 mm or less).

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In some embodiments, the image field shape can correspond (e.g., in one or more dimensions) to the shape of die sites on a wafer that is exposed using projection objective 101. For example, the image field can be shaped to reduce overscan when exposing the wafer. Overscan refers to the need to scan the image field beyond the edge of a die site to expose the entire site. Generally, this occurs where the shape of the image field does not conform to the shape of die site.

Overscan can be characterized by the ratio (e.g., expressed as a percentage) of the maximum distance between the leading edge of the image field and the trailing edge of the die site at the position where the corners at the trailing edge of the die site are exposed. Referring to FIG. 7B, overscan corresponds to the ratio of d_{os} to d_y , where d_{os} is the distance between the leading edge of image field 700 and the trailing edge of die sites 720 at the position where corners 721 and 722 are exposed. In certain embodiments, projection objective can have relatively low overscan. For example, projection objective can have an overscan of about 5% or less (e.g., about 4% or less, about 3% or less, about 2% or less, about 1% or less, about 0.5% or less, 0.1% or less).

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In certain embodiments, projection objective 101 can be used with zero overscan. For example, referring to FIG. 7C, in embodiments where an image field 730 is used to expose square die sites 740, scanning can be achieved with zero overscan.

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Referring to FIG. 8, in general, projection objective 101 introduces an object-image shift, d_{ois} , that varies depending on the specific design of the projection objective. The object-image shift refers to the distance of a point in the image field from the corresponding point in the object field, as measured in the x - y plane. For projection objectives that have an optical axis (a common axis of rotational symmetry for each mirror in the projection objective) the object-image shift can be calculated using the formula:

$$d_{ois} = h_o(1 - M)$$

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where h_o refers to the distance in the x - y plane of the central field point in the object field from the optical axis and M is the projection objective magnification ratio. For example, for a projection objective have a demagnification of 4X (i.e., $M = 0.25$) and where the central field point is 120 mm from the optical axis, d_{ois} is 90 mm.

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In some embodiments, projection objective 101 can have a relatively small object-image shift. For example, projection objective has zero object-image shift. Projection objectives having relatively small object image shifts can be have a relatively slim optical design. Furthermore, in embodiments that have zero object-image shift, projection objective 101 can be rotated about the axis intersecting the central field points in the object and image fields without the central field point translating with respect to, e.g., stage 130. This can be advantageous where, for example, metrology tools (e.g., detection optical systems, such as those disclosed in U.S. 6,240,158 B1) for inspecting and

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aligning wafers with respect to projection objective 101 are placed at a nominal position of the central field point because the central field point is not translated with respect to this position when the projection objective rotates. Accordingly, zero object-image shift can facilitate easier metrology and testing of projective objective 101 where the projection objective is subject to rotations during the course of operation. This is illustrated in Fig. 8 showing a testing or metrology tool 150a located with its detection surface, e.g. a two-dimensional CCD array, within the image plane 150. The testing and metrology tool 150a is arranged such that a reference axis coinciding with axis 105 intersects a central point of the detection surface. The lateral extension of the detection surface of the testing and metrology tool 150a is larger than the object-image shift d_{ois} . Due to the small object-image shift d_{ois} , the metrology and testing tool 150a is able to measure the projection quality of projection objective 101 irrespective of a rotation of the projection objective 101 around the reference axis 105.

In some embodiments, projection objective 101 has a d_{ois} of about 80 mm or less (e.g., about 60 mm or less, about 50 mm or less, about 40 mm or less, about 30 mm or less, about 20 mm or less, about 15 mm or less, about 12 mm or less, about 10 mm or less, about 8 mm or less, about 5 mm or less, about 4 mm or less, about 3 mm or less, about 2 mm or less, about 1 mm or less). Projection objective 300, for example, has a d_{ois} of 57 mm.

Embodiments of projection objective 101 can have a relatively large image-side free working distance. The image-side free working distance refers to the shortest distance between image plane 102 and the mirror surface of the mirror closest to image plane 102 that reflects imaged radiation. This definition of a free working distance differs from that in conventional optical systems having rotationally symmetric surfaces where the free working distance is always measured in the optical axis. The free working distance

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with respect to the definition according to the present application is illustrated in FIG. 9, which shows a mirror 810 as the closest mirror to image plane 102. Radiation reflects from surface 811 of mirror 810. The image-side free working distance is denoted d_w . In some embodiments, d_w is about 25 mm or more (e.g., about 30 mm or more, about 35 mm or more, about 40 mm or more, about 45 mm or more, about 50 mm or more, about 55 mm or more, about 60 mm or more, about 65 mm or more). In certain embodiments, d_w is about 200 mm or less (e.g., about 150 mm or less, about 100 mm or less, about 50 mm or less). Projection objective 300, for example, has an image-side free working distance of approximately 45 mm. A relatively large working distance may be desirable because it can allow the surface of substrate 150 to be positioned at image plane 102 without contacting the side of mirror 810 facing image plane 102.

Analogously, the object-side free working distance refers to the shortest distance between object plane 103 and the mirror surface of the reflective side of the mirror in projection objective 101 closest to object plane 103 that reflects imaged radiation. In some embodiments, projection objective 101 has a relatively large object-side free working distance. For example, projection objective 101 can have an object-side free working distance of about 50 mm or more (e.g., about 100 mm or more, about 150 mm or more, about 200 mm or more, about 250 mm or more, about 300 mm or more, about 350 mm or more, about 400 mm or more, about 450 mm or more, about 500 mm or more, about 550 mm or more, about 600 mm or more, about 650 mm or more, about 700 mm or more, about 750 mm or more, about 800 mm or more, about 850 mm or more, about 900 mm or more, about 950 mm or more, about 1,000 mm or more). In certain embodiments, the object-side free working distance is no more than about 2,000 mm (e.g., about 1,500 mm or less, about 1,200 mm or less, about 1,000 mm or less). Projection objective 300, for example, has an object-side free working distance of approximately 300 mm. A relatively large

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object-side free working distance may be advantageous in embodiments where access to the space between projection objective 101 and object plane 103 is desired. For example, in embodiments where reticle 140 is a reflective reticle, it is necessary to illuminate the reticle from the side that faces objective 101.

- 5 Therefore, there should be sufficient space between projection objective 101 and object plane 103 to allow the reticle to be illuminated by illumination system 120 at a desired illumination angle. Furthermore, in general, a larger object-side free working distance allows flexibility in design of the rest of tool, for example, by providing sufficient space to mount other components
- 10 (e.g. an uniformity filter) between projection objective 101 and the support structure for reticle 140.

In general, projection objective 101 can be designed so that chief rays either converge, diverge, or are substantially parallel to each other at reticle 140.

- 15 Correspondingly, the location of the entrance pupil of projection objective 101 with respect to object plane 103 can vary. For example, where chief rays converge at reticle 140, the entrance pupil is located on the image plane side of object plane 103. Conversely, where the chief rays diverge at reticle 140, object plane 103 is located between the entrance pupil and image plane 102.
- 20 Furthermore, the distance between object plane 103 and the entrance pupil can vary. In some embodiments, the entrance pupil is located about 1 m or more (e.g., about 2 m or more, about 3 m or more, about 4 m or more, about 5 m or more, about 8 m or more, about 10 m or more) from object plane 103 (measured along an axis perpendicular to object plane 103). In some
- 25 embodiments, the entrance pupil is located at infinity with respect to object plane 103. This corresponds to where the chief rays are parallel to each other at reticle 140. For projection objective 300, the incident angle of the chief ray at the central field point at object plane 103 is 7° and the maximum variation of the chief ray angle from the central field point chief ray is 0.82° . The

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entrance pupil is located 1,000 mm from object plane 103 on the opposite side of object plane 103 from image plane 102.

Illumination system 120 may be arranged so that the exit pupil of the
5 illumination system is positioned substantially at the entrance pupil of projection objective 101. In certain embodiments, illumination system 120 includes a telescope subsystem which projects the illumination system's exit pupil to the location of the entrance pupil of projection objective 101. However, in some embodiments, the exit pupil of illumination system 120 is
10 positioned at the entrance pupil of projection objective 101 without using a telescope in the illumination system. For example, when the object plane 103 is between projection objective 101 and the entrance pupil of the projection objective, the exit pupil of illumination system 120 may coincide with the projection objective's entrance pupil without using a telescope in the
15 illumination system.

In general, projection objective 101 can be designed using commercially available optical design software like ZEMAX, OSLO, or Code V. Typically, a
20 design is started by specifying an initial projection objective design (e.g., arrangement of mirrors) along with parameters such as the radiation wavelength, field size and numerical aperture, for example. The code then optimizes the design for specified optical performance criteria, such as, for example, wavefront error, distortion, telecentricity, and field curvature.

25 In certain embodiments, the initial projection objective is designated by rotationally symmetric mirrors (e.g., spherical or aspherical mirrors) that are centered on an optical axis. Each mirror is then decentered from the optical axis to a position where the mirror satisfies some pre-established criterion. For example, each mirror can be decentered from the optical axis by an amount
30 which minimizes the chief ray angle of incidence across the mirror for

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particular field. In embodiments, mirrors can be decentered by about 5 mm or more (e.g., about 10 mm or more, about 20 mm or more, about 30 mm or more, about 50 mm or more). In certain embodiments, mirrors are decentered by about 200 mm or less (e.g., about 180 mm or less, about 150 mm or less, 5 about 120 mm or less, about 100 mm or less).

Alternatively, or additionally, each mirror can be tilted to a position where the mirror satisfies some pre-established criterion. The tilt refers to the orientation of each mirrors symmetry axis with respect to the optical axis of the initial 10 configuration of the projection objective. Mirrors can be titled by about 1° or more (e.g., about 2° or more, about 3° or more, about 4° or more, about 5° or more). In some embodiments, mirrors are tilted by about 20° or less (e.g., about 15° or less, about 12° or less, about 10° or less).

15 After decentering and/or tilting, a freeform shape for each mirror can be determined to optimize the projection objective design for specified optical performance criteria.

In addition to mirrors, projection objective 101 can include one or more other 20 components, such as one or more aperture stops. In general, the shape of the aperture stop can vary. Examples of aperture stops include circular aperture stops, elliptical aperture stops, and/or polygonal aperture stops. Apertures stops can also be positioned so that the image radiation makes a double pass or a single pass through the aperture stop. Aperture stops can be interchanged 25 in projection objective 101 and/or may have an adjustable aperture.

In some embodiments, projection objective 101 includes a field stop. For example, in embodiments where projective objective includes an intermediate image, the field stop can be positioned at or near the intermediate image.

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Embodiments can include baffles (e.g., to shield the wafer from stray radiation). In some embodiments, projection objective 101 can include components (e.g., interferometers) for monitoring changes in the position of mirrors within the projection objective. This information can be used to adjust
5 the mirrors to correct for any relative movement between the mirrors. Mirror adjustment can be automated. Examples of systems for monitoring/adjusting mirror position are disclosed in U.S. 6,549,270 B1.

Referring to FIG. 10, an embodiment of a projection objective 1000 includes
10 six mirrors 1010, 1020, 1030, 1040, 1050, and 1060, and has an image-side numerical aperture of 0.35 and an operating wavelength of 13.5 nm. Mirrors 1010, 1020, 1030, 1040, 1050, and 1060 are all freeform mirrors. Projection objective 1000 images radiation from object plane 103 to image plane 102 with a demagnification ratio of 4X. The tracklength of projection objective
15 1000 is 1497 mm and the optical path length of imaged radiation is 4760 mm. Accordingly, the ratio of the optical path length to tracklength is approximately 3.18.

The entrance pupil of projection objective 1000 is located 1,000 mm from
20 object plane 103 with object plane positioned between the entrance pupil and the mirrors. Due to the reflective reticle positioned at object plane 103, illumination optics can be positioned at location 1070, corresponding to the entrance pupil. The chief ray angle of the central field point at object plane 103 is 7°. The maximum variation of chief ray angles at object plane 103 is 0.82°.

25

Projection objective 1000 has a rectangular field. The image-side field width, d_x , is 26 mm. The image-side field length, d_y , is 2 mm. Projection objective 1000 has an object-image shift of 13 mm.

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The performance of projection objective 1000 includes an image-side W_{rms} of 0.021 λ . Distortion is less than 10 nm, and image-side field curvature is 19 nm. Projection objective 1000 provides an intermediate image between mirrors 1040 and 1050. Coma at the intermediate image is relatively large. In particular, the distance between the chief ray and the upper and lower rays at the location where the upper and lower rays cross is 7 mm.

The optical power of the mirrors in the order of the radiation path from object plane 103 to image plane 102 is as follows: mirror 1010 has positive optical power; mirror 1020 has negative optical power; mirror 1030 has positive optical power; mirror 1040 has positive optical power; mirror 1050 has negative optical power; and mirror 1060 has positive optical power.

The dimension of the footprint of each mirror, given as $M_x \times M_y$, is as follows: 323 mm x 152 mm for mirror 1010; 107 mm x 59 mm for mirror 1020; 297 mm x 261 mm for mirror 1030; 277 mm x 194 mm for mirror 1040; 99 mm x 72 mm for mirror 1050; and 268 mm x 243 mm for mirror 1060.

The maximum deviation of mirror 1010 from a best fit sphere is 475 μm . Maximum deviation from best fit spheres of mirrors 1020, 1030, 1040, 1050, and 1060 are 1,234 μm , 995 μm , 1,414 μm , 170 μm , and 416 μm , respectively. The maximum deviation of each mirror from a best fit asphere is 236 μm , 102 μm , 102 μm , 148 μm , 54 μm , and 372 μm for mirrors 1010, 1020, 1030, 1040, 1050, and 1060, respectively.

The first and second principal curvature for mirror 1010 are 1.16×10^{-3} and 1.05×10^{-3} respectively. Respective first and second principal curvatures for the other mirrors in projection objective 1000 are as follows: -3.02×10^{-3} and -1.13×10^{-3} for mirror 1020; 5.97×10^{-4} and 4.96×10^{-4} for mirror 1030; $5.50 \times$

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10⁻⁴ and 3.63 x 10⁻⁴ for mirror 1040; -2.24 x 10⁻³ and -2.04 x 10⁻³ for mirror 1050; and 2.57 x 10⁻³ and 2.48 x 10⁻³ for mirror 1060. The sum of the first principal curvature for projection objective 1000 is -3.78 x 10⁻⁴. The sum of the second principal curvature is 1.22 x 10⁻³. The sum of the first and second principal curvatures is 8.45 x 10⁻⁴ and the inverse sum of the first and second principal curvatures is 1.18 x 10³.

The chief ray angle of incidence for the central field point is 3.40°, 9.86°, 6.48°, 10.13°, 13.66°, and 7.00° for mirrors 1010, 1020, 1030, 1040, 1050, and 1060, respectively. The maximum angle of incidence, $\theta_{\max}$, on each mirror for the meridional section is 3.94°, 10.42°, 7.45°, 14.34°, 24.28°, and 8.61° for mirrors 1010, 1020, 1030, 1040, 1050, and 1060, respectively. $\Delta\theta$ for mirrors 1010, 1020, 1030, 1040, 1050, and 1060 are 1.13°, 2.74°, 3.42°, 9.96°, 23.69°, and 3.95°, respectively.

15

Mirrors 1010, 1020, 1030, 1050, and 1060 have freeboards that are more than 5 mm and less than 25 mm. Mirror 1030 has positive chief ray angle magnification while mirrors 1040 and 1050 have negative chief ray angle magnification.

20

The image-side free working distance of projection objective 1000 is 45 mm. The object-side free working distance is 252 mm.

In projection objective 1000, $d_{\text{op-1}}/d_{\text{op-2}}$ is 3.14. Furthermore, adjacent mirror pairs 1020 and 1030, 1030 and 1040, and 1040 and 1050 are separated by more than 50% of the projection objective's tracklength. Further, the distance between mirror 1010 and object plane 103 is more than 50% of the projection objective's tracklength.

25

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Data for projection objective 1000 is presented in Table 2A and Table 2B below. The parameters and units for the parameters for Table 2A and 2B and subsequent tables are the same as the corresponding parameters and units presented in Table 1A and 1B above. Table 2A presents optical data, while Table
5 2B presents freeform constants for each of the mirror surfaces. For the purposes of Table 2A and Table 2B, the mirror designations correlate as follows: mirror 1 (M1) corresponds to mirror 1010; mirror 2 (M2) corresponds to mirror 1020; mirror 3 (M3) corresponds to mirror 1030; mirror 4 (M4) corresponds to mirror 1040; mirror 5 (M5) corresponds to mirror 1050; and mirror
10 6 (M6) corresponds to mirror 1060.

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Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	788.884	
Mirror 1	-651.356	-537.372	REFL
Mirror 2	-463.216	952.014	REFL
Mirror 3	-1710.243	-783.854	REFL
Mirror 4	1821.345	1032.444	REFL
Mirror 5	309.420	-306.504	REFL
Mirror 6	405.847	351.549	REFL
Image	INFINITY	0.000	

Table 2A

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Coefficient	M1	M2	M3	M4	M5	M6
K	-5.925412E-01	1.525505E+00	-1.851822E+00	3.314097E+00	1.983829E+00	2.009323E-01
Y	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ²	2.471303E-04	6.505963E-04	7.593410E-05	2.922157E-05	-4.716078E-04	1.426720E-05
Y ²	1.863347E-04	6.677442E-05	-2.868206E-05	-7.428048E-05	-3.446472E-04	5.312976E-05
X ² Y	-3.545294E-08	-2.891983E-06	1.048420E-07	9.891278E-08	2.877558E-06	-2.714955E-08
Y ³	-1.873281E-08	-3.078489E-06	-7.296056E-08	-3.920160E-08	1.288669E-06	-9.898583E-09
X ⁴	1.180642E-11	3.342373E-10	-3.287877E-11	-8.971583E-11	3.862440E-10	-8.982825E-11
X ² Y ²	3.437144E-11	5.937123E-09	-2.687658E-11	-7.769409E-11	1.693138E-08	2.462964E-11
Y ⁴	9.863178E-11	-2.340521E-08	-1.605207E-10	-1.806038E-10	-2.208217E-09	-3.099379E-11
X ⁴ Y	-4.051355E-14	1.381955E-13	-2.895532E-14	5.170900E-14	4.797213E-11	-4.214964E-14
X ² Y ³	-2.144219E-13	-2.531232E-10	-1.637831E-13	2.916068E-13	1.961281E-10	-3.785260E-14
Y ⁵	-2.415401E-14	1.279499E-10	-7.226386E-14	1.273503E-13	2.976407E-11	4.394992E-14
X ⁶	-2.920211E-17	1.949737E-14	-1.774795E-17	-2.785422E-16	8.466233E-14	-5.281246E-16
X ⁴ Y ²	7.135583E-17	-6.187267E-13	-2.447653E-16	-1.867205E-16	3.921385E-13	-5.767253E-16
X ² Y ⁴	5.606882E-16	4.378172E-13	-4.812153E-16	4.588123E-16	7.309790E-13	-7.534000E-17
Y ⁶	-7.879310E-16	-6.710705E-13	6.992795E-19	3.331795E-16	-3.185164E-13	-9.186437E-17
X ⁶ Y	2.435160E-20	-3.445743E-16	-3.254844E-19	-4.053237E-18	1.681642E-15	-7.144774E-20
X ⁴ Y ³	-1.325499E-18	2.205904E-15	-4.637731E-19	-1.132243E-18	6.530207E-15	-1.155827E-19
X ² Y ⁵	2.538976E-18	7.780251E-15	-5.473994E-19	9.042940E-19	5.583512E-15	1.826925E-19
Y ⁷	6.001333E-18	7.757557E-15	-8.424804E-21	7.805993E-20	-2.390583E-15	3.562442E-19
X ⁸	-2.140710E-22	-1.536511E-18	-5.293518E-23	-7.757919E-22	1.098261E-18	-2.871286E-21
X ⁶ Y ²	-2.383343E-21	-3.017606E-17	-2.564847E-21	-2.918509E-20	-1.382527E-17	-5.946767E-21
X ⁴ Y ⁴	4.328735E-21	-3.407893E-17	-3.923348E-22	-6.995732E-21	2.738740E-17	-2.968388E-21
X ² Y ⁶	-4.831336E-20	-1.206126E-16	-1.673186E-22	5.920827E-22	4.911090E-17	8.147751E-22
Y ⁸	-3.800647E-20	-6.246834E-17	-5.575611E-23	-7.691743E-22	-4.049646E-18	-1.438562E-21
X ⁸ Y	2.973276E-24	6.697817E-20	-9.383994E-25	-1.349984E-23	8.777395E-22	-9.763800E-25
X ⁶ Y ³	1.179538E-23	5.201215E-19	-6.639018E-24	-8.645373E-23	-3.199889E-19	-4.878981E-24
X ⁴ Y ⁵	-1.203834E-23	-4.705218E-20	-1.462557E-25	-1.508808E-23	8.645921E-20	-3.908340E-24
X ² Y ⁷	2.304206E-22	1.208243E-19	2.562699E-25	1.368282E-24	4.649092E-19	2.276452E-24
Y ⁹	1.418250E-22	-1.077428E-19	7.645118E-27	-3.895996E-25	1.402632E-20	5.582547E-24
X ¹⁰	4.021654E-28	2.141815E-23	-3.668876E-27	-1.991462E-26	1.059359E-22	-2.694594E-26
X ⁸ Y ²	-1.314266E-26	-8.696134E-22	-1.671744E-27	-3.158518E-26	-2.330392E-22	-7.617267E-26
X ⁶ Y ⁴	-7.356431E-27	-3.656759E-21	-5.748164E-27	-9.269087E-26	-2.103517E-21	-6.065950E-26
X ⁴ Y ⁶	1.059736E-26	3.564328E-22	-1.527905E-28	-1.292503E-26	-3.644105E-22	1.700246E-26
X ² Y ⁸	-3.817918E-25	2.574506E-21	1.902672E-28	1.728267E-27	1.530993E-21	1.267011E-26
Y ¹⁰	-2.256936E-25	1.804566E-21	1.126083E-29	-2.712119E-28	-1.135939E-22	-1.049025E-26
Nradius	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Y-decenter	-141.222	-91.036	45.162	-4.535	-0.554	-8.496
X-rotation	-9.184	-15.081	1.443	-3.391	-6.975	-1.780

Table 2B

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Referring to FIG. 11, an embodiment of a projection objective 1000 includes six mirrors 1110, 1120, 1130, 1140, 1150, and 1160, and has an image-side numerical aperture of 0.35 and an operating wavelength of 13.5 nm. Mirrors
5 1110, 1120, 1130, 1140, 1150, and 1160 are all freeform mirrors. Projection objective 1100 images radiation from object plane 103 to image plane 102 with a demagnification ratio of 4X. The tracklength of projection objective 1100 is 2000 mm and the optical path length of imaged radiation is 5337 mm. Accordingly, the ratio of the optical path length to tracklength is approxi-
10 mately 2,67. Projection objective 1100 has an aperture stop 1106 positioned at mirror 1120.

The entrance pupil of projection objective 1100 is located at infinity. The chief ray angle of the central field point at object plane 103 is 7°. The maxi-
15 mum variation of chief ray angles at object plane 103 is less than 0.06°.

Projection objective 1100 has a rectangular field. The image-side field width, d_x , is 26 mm. The image-side field length, d_y , is 2 mm. Projection objective 1100 has an object-image shift of 31 mm.

20

The performance of projection objective 1100 includes an image-side W_{rms} of 0.025 λ . Image-side field curvature is 10 nm. Projection objective 1100 provides an intermediate image between mirrors 1140 and 1150.

25 The optical power of the mirrors in the order of the radiation path from object plane 103 to image plane 102 is as follows: mirror 1110 has positive optical power; mirror 1120 has positive optical power; mirror 1130 has negative optical power; mirror 1140 has positive optical power; mirror 1150 has negative optical power; and mirror 1160 has positive optical power.

30

The dimension of the footprint of each mirror, given as $M_x \times M_y$, is as follows: 291 mm x 195 mm for mirror 1110; 159 mm x 152 mm for mirror 1120; 157 mm x 53 mm for mirror 1130; 295 mm x 66 mm for mirror 1140; 105 mm x 86 mm for mirror 1150; and 345 mm x 318 mm for mirror 1160.

5

The chief ray angle of incidence for the central field point is 4.38° , 4.03° , 18.37° , 7.74° , 12.64° , and 5.17° for mirrors 1110, 1120, 1130, 1140, 1150, and 1160, respectively. The maximum angle of incidence, $\theta_{\max}$, on each mirror for the meridional section is 6.48° , 6.44° , 20.05° , 9.12° , 21.76° , and 7.22° for
10 mirrors 1110, 1120, 1130, 1140, 1150, and 1160, respectively. $\Delta\theta$ for mirrors 1110, 1120, 1130, 1140, 1150, and 1160 are 4.27° , 4.92° , 4.09° , 3.12° , 19.37° , and 4.61° , respectively.

Mirrors 1110, 1150, and 1160 have freeboards that are more than 5 mm and
15 less than 25 mm. Mirror 1140 has positive chief ray angle magnification while mirrors 1110, 1120, 1130, and 1150 have negative chief ray angle magnification.

The image-side free working distance of projection objective 1100 is 25 mm.
20 The object-side free working distance is 163 mm.

In projection objective 1100, $d_{\text{op-1}}/d_{\text{op-2}}$ is 6.57. Furthermore, adjacent mirror pair 1040 and 1050 are separated by more than 50% of the projection objective's tracklength. Further, the distance between mirror 1110 and object plane
25 103 is more than 50% of the projection objective's tracklength.

Data for projection objective 1100 is presented in Table 3A and Table 3B below. Table 3A presents optical data, while Table 3B presents aspherical constants for each of the mirror surfaces. For the purposes of Table 3A and Table
30 3B, the mirror designations correlate as follows: mirror 1 (M1) corresponds to

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mirror 1110; mirror 2 (M2) corresponds to mirror 1120; mirror 3 (M3) corresponds to mirror 1130; mirror 4 (M4) corresponds to mirror 1140; mirror 5 (M5) corresponds to mirror 1150; and mirror 6 (M6) corresponds to mirror 1160.

5

Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	1070.002	
Mirror 1	-2069.710	-907.121	REFL
Mirror 2	1710.596	0.000	REFL
STOP	INFINITY	907.500	
Mirror 3	414.111	-319.107	REFL
Mirror 4	618.022	1223.709	REFL
Mirror 5	406.139	-436.552	REFL
Mirror 6	522.609	461.570	REFL
Image	INFINITY	0.000	

Table 3A

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Coefficient	M1	M2	M3	M4	M5	M6
K	-2.012543E+00	-7.790981E+00	-9.061196E-01	-4.714699E-01	5.253415E+00	1.051556E-01
Y	-1.801229E-01	-2.676895E-01	6.249715E-03	2.914352E-02	3.699848E-02	6.762162E-04
X ²	-3.718177E-05	-1.568640E-04	-4.213586E-04	-1.680785E-04	-6.132874E-05	2.479745E-06
Y ²	-5.757281E-05	-1.359112E-04	-3.015850E-04	-9.908817E-05	-6.383717E-05	1.909227E-06
X ² Y	-3.283304E-08	-1.421641E-07	-4.802304E-08	-4.234719E-08	5.460366E-07	-5.398408E-09
Y ³	-7.289267E-08	-9.447144E-08	3.714670E-07	1.405667E-07	2.644773E-08	-4.741511E-09
X ⁴	-3.792148E-11	2.173390E-10	-8.723035E-10	-2.377992E-11	1.030821E-09	-1.926536E-11
X ² Y ²	-1.087876E-10	5.689855E-10	-5.959943E-10	-4.401654E-10	2.045233E-09	-4.586698E-11
Y ⁴	-1.237594E-10	2.990476E-10	8.549602E-10	-4.022663E-11	5.551510E-11	-2.632066E-11
X ⁴ Y	-3.587007E-14	-1.028868E-12	-8.033093E-12	1.716353E-13	5.551826E-12	-2.577816E-14
X ² Y ³	8.925822E-14	4.492952E-13	-1.186636E-12	-7.545064E-13	-4.309344E-12	-1.775797E-14
Y ⁵	-7.423435E-14	5.791519E-13	8.705928E-14	-2.700779E-13	-7.302230E-12	-9.309635E-15
X ⁶	1.876383E-17	2.916278E-16	-2.307341E-14	-1.670466E-15	8.878140E-15	-3.351380E-17
X ⁴ Y ²	-3.009967E-16	-3.620666E-16	-2.232847E-14	1.589023E-15	4.463758E-14	-1.408427E-16
X ² Y ⁴	1.992400E-16	3.916129E-16	1.756497E-15	3.477633E-16	1.478648E-13	-1.372823E-16
Y ⁶	8.315953E-18	-6.580116E-16	8.232062E-16	1.253553E-16	3.691569E-14	-3.799352E-17
X ⁶ Y	-2.621825E-20	-1.237101E-17	-3.125465E-16	-7.682746E-18	3.293829E-16	-1.214309E-19
X ⁴ Y ³	-1.344388E-18	3.730815E-17	1.376670E-16	5.918289E-18	8.409538E-16	5.369262E-20
X ² Y ⁵	-6.157858E-19	3.202677E-17	4.387074E-19	2.707480E-18	4.875870E-16	-1.363873E-20
Y ⁷	2.770009E-20	8.487049E-18	2.518948E-18	1.820744E-19	1.274511E-16	2.776746E-21
X ⁸	2.265356E-23	-1.881878E-20	6.916970E-19	3.815768E-20	-1.030207E-19	-2.085793E-23
X ⁶ Y ²	-1.848041E-22	-1.667898E-19	-1.070800E-18	1.947584E-20	-6.071205E-19	-1.191227E-22
X ⁴ Y ⁴	-1.617091E-21	-4.471313E-20	-2.039154E-19	-1.469302E-21	8.581801E-18	-2.848570E-22
X ² Y ⁶	-1.152811E-21	-1.417078E-19	-4.885470E-20	8.329380E-22	2.867618E-18	8.073429E-24
Y ⁸	5.021474E-23	-1.270497E-20	-2.834042E-20	-1.011971E-21	1.813992E-18	-6.757839E-23
X ⁸ Y	0.000000E+00	0.000000E+00	7.973679E-21	2.492982E-22	0.000000E+00	-2.465296E-25
X ⁶ Y ³	0.000000E+00	0.000000E+00	7.629111E-22	1.401277E-22	0.000000E+00	2.930653E-25
X ⁴ Y ⁵	0.000000E+00	0.000000E+00	-7.196032E-21	-4.219890E-23	0.000000E+00	1.194933E-25
X ² Y ⁷	0.000000E+00	0.000000E+00	-1.090375E-22	-3.791571E-24	0.000000E+00	5.412579E-25
Y ⁹	0.000000E+00	0.000000E+00	-5.080252E-23	1.076602E-24	0.000000E+00	3.891280E-26
X ¹⁰	0.000000E+00	0.000000E+00	-6.129418E-25	-1.289913E-27	0.000000E+00	0.000000E+00
X ⁸ Y ²	0.000000E+00	0.000000E+00	2.295090E-23	4.078311E-25	0.000000E+00	0.000000E+00
X ⁶ Y ⁴	0.000000E+00	0.000000E+00	5.951785E-24	1.728297E-25	0.000000E+00	0.000000E+00
X ⁴ Y ⁶	0.000000E+00	0.000000E+00	-1.732732E-23	-5.280557E-26	0.000000E+00	0.000000E+00
X ² Y ⁸	0.000000E+00	0.000000E+00	0.000000E+00	-1.410994E-27	0.000000E+00	0.000000E+00
Y ¹⁰	0.000000E+00	0.000000E+00	0.000000E+00	3.484416E-27	0.000000E+00	0.000000E+00
Nradius	1.000000E+00	1.000000E+00	1.000000E+00	1.000000E+00	1.000000E+00	1.000000E+00
Y-decenter	194.936	-49.734	36.609	9.442	30.019	40.956
X-rotation	-5.944	-17.277	-5.569	-0.579	0.301	-0.924

Table 3B

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Referring to FIG. 12, an embodiment of a projection objective 1200 includes six mirrors 1210, 1220, 1230, 1240, 1250, and 1260, and has an image-side numerical aperture of 0.35 and an operating wavelength of 13.5 nm. Mirrors
5 1210, 1220, 1230, 1240, 1250, and 1260 are all freeform mirrors. Projection objective 1200 images radiation from object plane 103 to image plane 102 with a demagnification ratio of 4X. A reference axis 1205, orthogonal to object plane 103 and image plane 102 intersects corresponding field points in the object and image fields. The tracklength of projection objective 1200 is 1385
10 mm and the optical path length of imaged radiation is 4162 mm. Accordingly, the ratio of the optical path length to tracklength is approximately 3,01. Projection objective 1200 has an aperture stop positioned at mirror 1220.

The entrance pupil of projection objective 1200 is at infinity with object plane
15 positioned between the entrance pupil and the mirrors. The chief ray angle of the central field point at object plane 103 is 7°. The maximum variation of chief ray angles at object plane 103 is less than 0.06°.

Projection objective 1200 has a rectangular field. The image-side field width,
20 d_x , is 26 mm. The image-side field length, d_y , is 2 mm. Projection objective 1200 has zero object-image shift.

Projection objective 1200 provides an intermediate image between mirrors
25 1240 and 1250.

The optical power of the mirrors in the order of the radiation path from object plane 103 to image plane 102 is as follows: mirror 1210 has positive optical power; mirror 1220 has negative optical power; mirror 1230 has positive optical power; mirror 1240 has positive optical power; mirror 1250 has negative
30 optical power; and mirror 1260 has positive optical power.

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The dimension of the footprint of each mirror, given as $M_x \times M_y$, is as follows:
 250 mm x 153 mm for mirror 1210; 70 mm x 69 mm for mirror 1020; 328
 mm x 153 mm for mirror 1230; 325 mm x 112 mm for mirror 1240; 87 mm x
 5 75 mm for mirror 1250; and 269 mm x 238 mm for mirror 1260.

The chief ray angle of incidence for the central field point is 6.13° , 10.61° ,
 8.65° , 8.26° , 14.22° , and 5.23° for mirrors 1210, 1220, 1230, 1240, 1250, and
 10 1260, respectively. The maximum angle of incidence, $\theta_{\max}$, on each mirror for
 the meridional section is 6.53° , 11.63° , 8.91° , 11.39° , 24.26° , and 7.44° for
 mirrors 1210, 1220, 1230, 1240, 1250, and 1260, respectively. $\Delta\theta$ for mirrors
 1210, 1220, 1230, 1240, 1250, and 1260 are 1.07° , 3.64° , 1.74° , 7.44° , 21.70° ,
 and 4.51° , respectively.

15 Mirrors 1210, 1220, 1250, and 1260 have freeboards that are more than 5 mm
 and less than 25 mm. Mirror 1240 has positive chief ray angle magnification
 while mirrors 1210, 1220, 1230, and 1250 have negative chief ray angle mag-
 nification.

20 The image-side free working distance of projection objective 1200 is 40 mm.
 The object-side free working distance is 439 mm.

In projection objective 1200, $d_{\text{op-1}}/d_{\text{op-2}}$ is 1.91. Furthermore, adjacent mirror
 pair 1240 and 1250 are separated by more than 50% of the projection objec-
 25 tive's tracklength. Further, the distance between mirror 1210 and object plane
 103 is more than 50% of the projection objective's tracklength.

Data for projection objective 1200 is presented in Table 4A and Table 4B be-
 low. Table 4A presents optical data, while Table 4B presents aspherical con-
 30 stants for each of the mirror surfaces. For the purposes of Table 4A and Table

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4B, the mirror designations correlate as follows: mirror 1 (M1) corresponds to mirror 1210; mirror 2 (M2) corresponds to mirror 1220; mirror 3 (M3) corresponds to mirror 1230; mirror 4 (M4) corresponds to mirror 1240; mirror 5 (M5) corresponds to mirror 1250; and mirror 6 (M6) corresponds to mirror 5 1260.

Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	836.375	
Mirror 1	-614.878	-397.397	REFL
Mirror 2	-383.358	0.000	REFL
STOP	INFINITY	655.992	
Mirror 3	-1204.989	-659.631	REFL
Mirror 4	1885.915	909.840	REFL
Mirror 5	302.954	-308.805	REFL
Mirror 6	403.492	348.850	REFL
Image	INFINITY	0.000	

Table 4A

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Coefficient	M1	M2	M3	M4	M5	M6
K	-6.673329E-01	-2.825442E-01	-1.843864E+00	2.076932E+00	3.340547E+00	1.990979E-01
Y	-5.045837E-02	2.263660E-01	-1.277806E-01	-3.310548E-02	-1.935522E-01	1.783092E-02
X ²	1.827144E-04	1.686990E-04	9.963384E-05	5.203052E-05	-3.849892E-04	3.792405E-05
Y ²	1.737812E-04	2.093994E-04	-1.747764E-05	-7.184095E-05	-3.329705E-04	1.662759E-05
X ² Y	4.765150E-08	-1.595967E-06	-5.515151E-08	-8.752119E-10	1.213426E-06	5.552151E-08
Y ³	5.091508E-08	-1.231538E-06	-1.294839E-07	-1.939381E-07	1.502735E-06	9.165146E-08
X ⁴	-4.718889E-11	-6.941238E-09	-7.002011E-11	-5.996832E-11	-2.342602E-09	9.552648E-12
X ² Y ²	-4.340357E-11	-7.827867E-09	-1.801185E-10	-7.139217E-11	-1.234047E-08	-1.611525E-10
Y ⁴	1.234053E-10	-3.130174E-09	-7.281275E-11	-1.598859E-10	-1.206604E-08	-1.662004E-10
X ⁴ Y	1.205203E-13	-6.495768E-11	-3.614883E-14	-4.344276E-14	2.268270E-11	2.930397E-13
X ² Y ³	2.259661E-13	-4.304439E-11	-1.048629E-13	-7.811421E-16	2.977954E-11	8.493936E-13
Y ⁵	-5.198478E-13	-1.485266E-11	5.022687E-15	-1.422459E-14	-1.556209E-11	4.051187E-13
X ⁶	-1.306395E-16	-4.159695E-14	0.000000E+00	-3.767576E-17	1.374773E-14	-9.890588E-17
X ⁴ Y ²	8.838986E-17	1.462867E-14	0.000000E+00	-1.369883E-16	-3.320990E-13	-1.312584E-15
X ² Y ⁴	-1.745854E-16	4.353978E-13	0.000000E+00	-7.920443E-17	-1.008910E-13	-2.069868E-15
Y ⁶	1.020155E-15	-1.927189E-13	0.000000E+00	-3.431888E-17	-9.148646E-14	-6.650861E-16
X ⁶ Y	1.090627E-19	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	1.607288E-18
X ⁴ Y ³	-4.158749E-19	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.652411E-18
X ² Y ⁵	-1.758731E-18	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	4.087290E-18
Y ⁷	-3.081679E-18	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	9.802736E-19
X ⁸	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁶ Y ²	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁴ Y ⁴	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ² Y ⁶	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
Y ⁸	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁸ Y	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁶ Y ³	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁴ Y ⁵	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ² Y ⁷	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
Y ⁹	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ¹⁰	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁸ Y ²	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁶ Y ⁴	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁴ Y ⁶	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ² Y ⁸	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
Y ¹⁰	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
Nradius	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Y-decenter	-118.847	-100.000	100.000	24.472	-11.760	-37.772
X-rotation	-7.782	7.388	1.406	-2.140	-8.177	6.989

Table 4B

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Referring to FIG. 13, an embodiment of a projection objective 1300 includes six mirrors 1310, 1320, 1330, 1340, 1350, and 1360, and has an image-side numerical aperture of 0.35 and an operating wavelength of 13.5 nm. Mirrors
5 1310, 1320, 1330, 1340, 1350, and 1360 are all freeform mirrors. Projection objective 1300 images radiation from object plane 103 to image plane 102 with a demagnification ratio of 4X. The tracklength of projection objective 1300 is 1500 mm and the optical path length of imaged radiation is 4093 mm. Accordingly, the ratio of the optical path length to tracklength is approxi-
10 mately 2,73. Projection objective 1300 has an aperture stop positioned at mirror 1320.

The entrance pupil of projection objective 1300 is at infinity. The chief ray angle of the central field point at object plane 103 is 7°. The maximum varia-
15 tion of chief ray angles at object plane 103 is less than 0.1°.

Projection objective 1300 has a rectangular field. The image-side field width, d_x , is 26 mm. The image-side field length, d_y , is 2 mm. Projection objective 1000 has an object-image shift of 119 mm.

20

Projection objective 1300 provides an intermediate image between mirrors 1340 and 1350.

The optical power of the mirrors in the order of the radiation path from object
25 plane 103 to image plane 102 is as follows: mirror 1310 has positive optical power; mirror 1320 has negative optical power; mirror 1330 has positive optical power; mirror 1340 has positive optical power; mirror 1350 has negative optical power; and mirror 1360 has positive optical power.

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The dimension of the footprint of each mirror, given as $M_x \times M_y$, is as follows: 271 mm x 173 mm for mirror 1310; 69 mm x 65 mm for mirror 1320; 290 mm x 115 mm for mirror 1330; 272 mm x 66 mm for mirror 1340; 81 mm x 67 mm for mirror 1350; and 274 mm x 243 mm for mirror 1360.

5

The chief ray angle of incidence for the central field point is 9.66° , 12.15° , 9.10° , 5.45° , 13.31° , and 4.60° for mirrors 1310, 1320, 1330, 1340, 1350, and 1360, respectively. The maximum angle of incidence, $\theta_{\max}$, on each mirror for the meridional section is 11.20° , 15.46° , 9.63° , 8.64° , 23.31° , and 6.17° for
10 mirrors 1310, 1320, 1330, 1340, 1350, and 1360, respectively. $\Delta\theta$ for mirrors 1310, 1320, 1330, 1340, 1350, and 1360 are 3.25° , 7.32° , 1.57° , 6.92° , 21.18° , and 3.63° , respectively.

Mirror 1340 has positive chief ray angle magnification while mirrors 1310,
15 1320, 1330, and 1350 have negative chief ray angle magnification.

The image-side free working distance of projection objective 1300 is 40 mm. The object-side free working distance is 582 mm. This large object-side free working distance allows insertion of additional components, in particular of the illumination system, e.g. an additional grazing incidence folding mirror or
20 a uniformity filter.

In projection objective 1300, d_{op-1}/d_{op-2} is 1.63. Furthermore, adjacent mirror pairs 1340 and 1350 is separated by more than 50% of the projection objective's tracklength. Further, the distance between mirror 1310 and object plane
25 103 is more than 50% of the projection objective's tracklength.

Data for projection objective 1300 is presented in Table 5A and Table 5B below. Table 5A presents optical data, while Table 5B presents aspherical constants for each of the mirror surfaces. For the purposes of Table 5A and Table
30 5B, the mirror designations correlate as follows: mirror 1 (M1) corresponds to

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mirror 1310; mirror 2 (M2) corresponds to mirror 1320; mirror 3 (M3) corresponds to mirror 1330; mirror 4 (M4) corresponds to mirror 1340; mirror 5 (M5) corresponds to mirror 1350; and mirror 6 (M6) corresponds to mirror 1360.

5

Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	946.404	
Mirror 1	-605.890	-364.901	REFL
Mirror 2	-368.417	0.000	REFL
STOP	INFINITY	626.468	
Mirror 3	-1202.217	-556.441	REFL
Mirror 4	1949.768	808.432	REFL
Mirror 5	276.499	-313.562	REFL
Mirror 6	401.291	353.600	REFL
Image	INFINITY	0.000	

Table 5A

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Coefficient	M1	M2	M3	M4	M5	M6
K	-5.95606E-01	-1.82166E+00	-5.82444E-01	-2.38948E+00	3.35329E+00	1.67263E-01
Y	1.96214E-02	1.05243E-01	-1.91165E-01	-6.23536E-02	-4.99892E-02	1.30034E-02
X ²	1.71425E-04	1.61788E-04	8.52106E-05	7.49004E-05	-2.48914E-04	3.88103E-05
Y ²	1.59322E-04	1.15506E-04	-1.78602E-05	-9.20778E-05	-2.00659E-04	4.01025E-05
X ² Y	3.03035E-08	-8.08249E-07	-6.98999E-08	-6.74632E-08	7.56105E-07	5.29501E-09
Y ³	2.86899E-08	-3.26183E-07	-9.54345E-08	-1.51650E-07	2.54367E-07	8.86827E-09
X ⁴	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ² Y ²	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Y ⁴	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁴ Y	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ² Y ³	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Y ⁵	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁶	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁴ Y ²	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ² Y ⁴	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Y ⁶	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁶ Y	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁴ Y ³	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ² Y ⁵	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Y ⁷	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁸	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁶ Y ²	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁴ Y ⁴	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ² Y ⁶	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Y ⁸	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁸ Y	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁶ Y ³	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁴ Y ⁵	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ² Y ⁷	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Y ⁹	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ¹⁰	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁸ Y ²	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁶ Y ⁴	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ⁴ Y ⁶	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
X ² Y ⁸	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Y ¹⁰	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Nradius	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Y-decenter	-200.000	-82.208	200.000	44.996	-23.759	-73.032
X-rotation	-11.492	6.153	4.904	-0.617	-3.814	7.081

Table 5B

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Referring to FIG. 14A, an embodiment of a projection objective 1400 includes six mirrors 1410, 1420, 1430, 1440, 1450, and 1460, and has an image-side numerical aperture of 0.40 and an operating wavelength of 13.5 nm. Mirrors
5 1410, 1420, 1430, 1440, 1450, and 1460 are all freeform mirrors. Projection objective 1400 images radiation from object plane 103 to image plane 102 with a demagnification ratio of 4X. The tracklength of projection objective 1400 is 1498 mm and the optical path length of imaged radiation is 3931 mm. Accordingly, the ratio of the optical path length to tracklength is approxi-
10 mately 2,62. Projection objective 1400 has a pupil plane positioned between mirrors 1420 and 1430.

The entrance pupil of projection objective 1400 is located 1,000 mm from object plane 103 with object plane positioned between the entrance pupil and
15 the mirrors. The chief ray angle of the central field point at object plane 103 is 7°. The maximum variation of chief ray angles at object plane 103 is 0.82°.

Projection objective 1400 has a rectangular field. The image-side field width, d_x , is 26 mm. The image-side field length, d_y , is 2 mm. Projection objective
20 1000 has an object-image shift of 38 mm.

The performance of projection objective 1000 includes an image-side W_{rms} of 0.083 λ . Distortion is approximately 100 nm, and image-side field curvature is 36 nm. Projection objective 1400 provides an intermediate image between
25 mirrors 1440 and 1450.

The optical power of the mirrors in the order of the radiation path from object plane 103 to image plane 102 is as follows: mirror 1410 has positive optical power; mirror 1420 has positive optical power; mirror 1430 has negative opti-

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cal power; mirror 1440 has positive optical power; mirror 1050 has negative optical power; and mirror 1460 has positive optical power.

The dimension of the footprint of each mirror, given as $M_x \times M_y$, is as follows:

- 5 326 mm x 159 mm for mirror 1410; 210 mm x 123 mm for mirror 1420; 120 mm x 66 mm for mirror 1430; 312 mm x 119 mm for mirror 1440; 112 mm x 83 mm for mirror 1450; and 405 mm x 379 mm for mirror 1460.

- The chief ray angle of incidence for the central field point is 6.70° , 8.08° ,
 10 20.41° , 6.68° , 14.52° , and 5.67° for mirrors 1410, 1420, 1430, 1440, 1450, and 1460, respectively. The maximum angle of incidence, $\theta_{\max}$, on each mirror for the meridional section is 8.61° , 10.91° , 21.98° , 7.41° , 27.19° , and 6.86° for mirrors 1410, 1420, 1430, 1440, 1450, and 1460, respectively. $\Delta\theta$ for mirrors 1410, 1420, 1430, 1440, 1450, and 1460 are 3.92° , 5.69° , 3.82° , 1.79° , 26.83° ,
 15 and 3.20° , respectively.

- Mirrors 1410, 1420, 1430, 1450, and 1460 have freeboards that are more than 5 mm and less than 25 mm. Mirror 1440 has positive chief ray angle magnification while mirrors 1410, 1420, 1430, and 1450 have negative chief ray angle
 20 magnification.

The image-side free working distance of projection objective 1400 is 45 mm. The object-side free working distance is 291 mm.

- 25 In projection objective 1400, $d_{\text{op-1}}/d_{\text{op-2}}$ is 2.47. Furthermore, adjacent mirror pair 1440 and 1450 is separated by more than 50% of the projection objective's tracklength.

- Data for projection objective 1400 is presented in Table 6A and Table 6B below. Table 6A presents optical data, while Table 6B presents aspherical con-
 30

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stands for each of the mirror surfaces. For the purposes of Table 6A and Table 6B, the mirror designations correlate as follows: mirror 1 (M1) corresponds to mirror 1010; mirror 2 (M2) corresponds to mirror 1020; mirror 3 (M3) corresponds to mirror 1030; mirror 4 (M4) corresponds to mirror 1040; mirror 5 (M5) corresponds to mirror 1050; and mirror 6 (M6) corresponds to mirror 1060.

Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	719.154	
Mirror 1	-1768.086	-427.871	REFL
Mirror 2	2334.525	575.634	REFL
Mirror 3	352.553	-347.888	REFL
Mirror 4	610.853	933.638	REFL
Mirror 5	431.588	-434.965	REFL
Mirror 6	521.464	479.940	REFL
Image	INFINITY	0.000	

Table 6A

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Coefficient	M1	M2	M3	M4	M5	M6
K	-7.735395E+00	-6.005799E+01	-3.751432E-01	-8.758413E-01	6.604547E+00	8.612526E-02
Y	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ²	-1.485069E-04	-1.263679E-04	-2.624294E-04	1.347923E-05	-1.388138E-04	-6.931036E-06
Y ²	-1.726040E-04	-1.711814E-04	-1.005287E-03	-3.665045E-05	1.295215E-04	8.615161E-06
X ² Y	-5.200823E-08	-4.156617E-07	7.669496E-07	-5.478449E-08	9.580682E-07	-4.043887E-09
Y ³	-3.734392E-08	-4.637041E-08	-5.212076E-07	4.563436E-08	1.158899E-07	-6.370253E-09
X ⁴	-1.602036E-10	1.080674E-09	-1.784900E-08	3.290440E-10	2.227159E-09	-4.223672E-11
X ² Y ²	-5.655636E-10	1.150736E-09	9.356049E-09	-1.772824E-10	7.086270E-09	-3.649540E-11
Y ⁴	7.840007E-11	1.816509E-09	1.947612E-09	9.043201E-10	3.962050E-09	5.321857E-12
X ⁴ Y	-9.204024E-14	2.366905E-12	-2.677935E-11	-8.314955E-13	-1.528996E-11	2.788263E-15
X ² Y ³	1.079182E-12	3.100338E-12	3.708016E-11	-5.930044E-12	-2.181691E-11	-3.366047E-14
Y ⁵	-4.579479E-13	-6.879640E-12	-4.466462E-13	9.529833E-13	-2.295402E-11	-2.906642E-14
X ⁶	6.241273E-17	-3.829664E-15	1.521283E-13	1.097127E-15	-3.501249E-14	-6.862154E-17
X ⁴ Y ²	1.666766E-15	1.243647E-14	5.320614E-14	7.533431E-16	8.652054E-14	-1.407857E-16
X ² Y ⁴	-2.345440E-15	2.162639E-15	-5.453363E-14	-1.396841E-14	4.036247E-13	1.131588E-17
Y ⁶	-3.012261E-15	-1.224080E-14	-1.034267E-14	9.519542E-16	1.105527E-13	3.923271E-17
X ⁶ Y	3.484859E-18	-9.656525E-18	-6.882044E-16	7.124323E-18	8.790794E-16	2.032080E-20
X ⁴ Y ³	-2.997302E-18	-1.020453E-16	-4.147278E-16	1.059357E-17	9.581262E-16	-8.784820E-20
X ² Y ⁵	3.436846E-18	2.303857E-17	-1.104525E-16	-1.635704E-17	-1.619074E-15	-2.001426E-19
Y ⁷	1.247042E-17	1.643841E-16	4.675424E-17	-7.809506E-19	-3.824576E-15	-5.405817E-20
X ⁸	6.566049E-22	4.616940E-20	-8.583253E-18	1.135128E-21	-4.651481E-19	-3.090479E-22
X ⁶ Y ²	-1.894284E-20	-2.084017E-19	-4.140672E-18	3.271179E-20	-2.096068E-17	-7.650033E-22
X ⁴ Y ⁴	-4.216883E-21	-3.239553E-19	-3.670866E-18	4.460462E-20	-8.776559E-17	-1.201625E-22
X ² Y ⁶	-2.826171E-21	-3.920562E-19	3.151001E-20	7.969094E-21	-5.615799E-17	3.016401E-22
Y ⁸	-1.315593E-20	-3.058425E-19	2.416437E-20	8.284460E-22	-1.006196E-17	1.721317E-22
X ⁸ Y	-9.935149E-25	-5.168771E-24	-2.316832E-20	-2.523681E-24	1.540486E-20	-3.155606E-26
X ⁶ Y ³	3.001708E-23	1.226818E-21	-2.812819E-21	3.078069E-23	-1.510545E-19	-4.150182E-25
X ⁴ Y ⁵	7.941504E-24	1.371322E-21	-5.440197E-21	3.362723E-23	-6.912241E-19	-2.930215E-25
X ² Y ⁷	-9.194045E-25	7.101398E-22	4.152263E-22	1.093452E-23	-4.418575E-19	3.377883E-25
Y ⁹	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ¹⁰	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁸ Y ²	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁶ Y ⁴	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ⁴ Y ⁶	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ² Y ⁸	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
Y ¹⁰	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
Nradius	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Y-decenter	-182.329	-165.907	121.386	20.437	21.141	28.282
X-rotation	-10.857	-0.974	-13.061	-5.217	-2.314	-0.850

Table 6B

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- Referring to FIG. 14B, projection objective 1400 can be used in an optical system 1401 that includes a light source 1405 and illumination optics including a collector unit 1415, a spectral purity filter 1425, a field facet mirror 1435 and a pupil facet mirror 1445. Light source 1405 is an EUV light source configured to provide radiation at 13.5 nm to the projection objective. Collector unit 1415 gathers radiation from source 1405 and directs the radiation towards spectral purity filter 1415 which filters incident radiation at wavelengths other than 13.5 nm and directs the radiation at 13.5 nm towards field facet mirror 1435. Together with pupil facet mirror 1445, field facet mirror illuminates a reflective reticle positioned at object plane 103 with radiation at 13.5 nm. The radiation is provided so that the chief rays diverge from the reticle. The radiation is provided to the reticle in this way without the use of additional components, such as a grazing incidence mirror.
- Referring to FIG. 15, an embodiment of a projection objective 1500 includes six mirrors 1510, 1520, 1530, 1540, 1550, and 1560, and has an image-side numerical aperture of 0.40 and an operating wavelength of 13.5 nm. Mirrors 1510, 1520, 1530, 1540, 1550, and 1460 are all freeform mirrors. Projection objective 1500 images radiation from object plane 103 to image plane 102 with a demagnification ratio of 4X. The tracklength of projection objective 1500 is 1499 mm and the optical path length of imaged radiation is 4762 mm. Accordingly, the ratio of the optical path length to tracklength is approximately 3,18.
- The entrance pupil of projection objective 1500 is located 1000 mm from object plane 103 with object plane positioned between the entrance pupil and the mirrors. Due to the reflective reticle positioned at object plane 103, illumination optics, in particular a mirror having pupil facets, can be positioned at location 1501, corresponding to the entrance pupil. The chief ray angle of the

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central field point at object plane 103 is 7° . The maximum variation of chief ray angles at object plane 103 is 0.82° .

Projection objective 1500 has a rectangular field. The image-side field width, d_x , is 26 mm. The image-side field length, d_y , is 2 mm. Projection objective 1500 has an object-image shift of 7 mm.

The performance of projection objective 1500 includes an image-side W_{rms} of 0.040λ . Referring also to FIG. 16A, distortion is less than about 3 nm across the image field. Image-side field curvature is 35 nm. Projection objective 1500 provides an intermediate image between mirrors 1540 and 1550. Referring to FIG. 16B, the chief rays are orthogonal to image plane 102 to within about 0.001 rad (0.06°) at the image field.

- 15 The optical power of the mirrors in the order of the radiation path from object plane 103 to image plane 102 is as follows: mirror 1510 has positive optical power; mirror 1520 has negative optical power; mirror 1530 has positive optical power; mirror 1540 has positive optical power; mirror 1550 has negative optical power; and mirror 1560 has positive optical power.
- 20 The dimension of the footprint of each mirror, given as $M_x \times M_y$, is as follows: 253 mm x 162 mm for mirror 1510; 105 mm x 66 mm for mirror 1520; 227 mm x 301 mm for mirror 1530; 182 mm x 220 mm for mirror 1540; 111 mm x 85 mm for mirror 1550; and 289 mm x 275 mm for mirror 1560.
- 25 The chief ray angle of incidence for the central field point is 3.96° , 12.21° , 7.51° , 11.98° , 15.82° , and 8.08° for mirrors 1510, 1520, 1530, 1540, 1550, and 1560, respectively. The maximum angle of incidence, θ_{max} , on each mirror for the meridional section is 4.47° , 12.81° , 8.55° , 16.91° , 27.68° , and 9.96° for mirrors 1510, 1520, 1530, 1540, 1550, and 1560, respectively. $\Delta\theta$ for mirrors

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1510, 1520, 1530, 1540, 1550, and 1560 are 1.10° , 3.61° , 4.19° , 12.12° , 27.17° , and 4.79° , respectively.

Mirrors 1510, 1520, 1540, 1550, and 1560 have freeboards that are more than
5 5 mm and less than 25 mm. Mirror 1530 has positive chief ray angle magnification while mirrors 1510, 1520, 1540, and 1550 have negative chief ray angle magnification.

The image-side free working distance of projection objective 1500 is 45 mm.
10 The object-side free working distance is 260 mm.

In projection objective 1500, d_{op-1}/d_{op-2} is 3.05. Furthermore, adjacent mirror
pairs 1520 and 1530, 1530 and 1540, and 1540 and 1550 are separated by
more than 50% of the projection objective's tracklength. Further, the distance
15 between mirror 1510 and object plane 103 is more than 50% of the projection
objective's tracklength.

Data for projection objective 1500 is presented in Table 7A and Table 7B be-
low. Table 7A presents optical data, while Table 7B presents aspherical con-
20 stants for each of the mirror surfaces. For the purposes of Table 7A and Table
7B, the mirror designations correlate as follows: mirror 1 (M1) corresponds to
mirror 1510; mirror 2 (M2) corresponds to mirror 1520; mirror 3 (M3) corre-
sponds to mirror 1530; mirror 4 (M4) corresponds to mirror 1540; mirror 5
(M5) corresponds to mirror 1550; and mirror 6 (M6) corresponds to mirror
25 1560.

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Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	793.452	
Mirror 1	-652.351	-533.717	REFL
Mirror 2	-459.234	946.263	REFL
Mirror 3	-1711.458	-789.999	REFL
Mirror 4	1814.404	1037.812	REFL
Mirror 5	310.131	-304.837	REFL
Mirror 6	407.712	349.882	REFL
Image	INFINITY	0.000	

Table 7A

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Coefficient	M1	M2	M3	M4	M5	M6
K	-5.917992E-01	1.401977E+00	-1.852312E+00	3.134672E+00	1.276852E+00	2.162747E-01
Y	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
X ²	2.486175E-04	6.462590E-04	8.097144E-05	3.683589E-05	-5.694587E-04	1.127522E-05
Y ²	1.796052E-04	-1.218131E-05	-3.272168E-05	-7.479058E-05	-3.798909E-04	5.142215E-05
X ² Y	-3.704365E-08	-3.061838E-06	1.166808E-07	1.073313E-07	3.054784E-06	-1.901527E-08
Y ³	-8.473076E-09	-4.336504E-06	-6.831514E-08	-2.680850E-08	1.944165E-06	2.077407E-09
X ⁴	1.525482E-11	2.440415E-10	-2.839993E-11	-8.352784E-11	1.477727E-09	-1.231925E-10
X ² Y ²	4.909383E-11	1.819997E-09	-2.639958E-11	-7.953809E-11	1.884598E-08	-4.030921E-11
Y ⁴	7.241758E-11	-1.924132E-08	-1.611187E-10	-1.805904E-10	2.829058E-09	-6.788132E-11
X ⁴ Y	-3.944773E-14	-3.384346E-12	4.634420E-14	1.089774E-13	4.746215E-11	7.092901E-15
X ² Y ³	-2.485019E-13	-1.985647E-10	-1.749321E-13	2.706968E-13	1.878106E-10	7.623271E-14
Y ⁶	-6.222758E-14	1.546404E-10	-7.306272E-14	1.121470E-13	2.713089E-11	1.059625E-13
X ⁶	-2.853060E-17	1.499373E-14	-3.327224E-16	-3.396117E-16	1.122966E-13	-7.141998E-16
X ⁴ Y ²	5.428060E-17	-4.560639E-13	-2.729510E-17	1.958645E-17	4.975385E-13	-1.157245E-15
X ² Y ⁴	9.034205E-16	4.633694E-13	-4.803414E-16	4.337124E-16	9.650331E-13	-6.079561E-16
Y ⁶	9.726812E-16	-1.567936E-12	-9.119915E-19	3.224937E-16	-4.013641E-13	-1.910957E-16
X ⁶ Y	7.541120E-20	-5.491590E-16	-3.248735E-18	-4.999870E-18	1.809992E-15	1.533677E-19
X ⁴ Y ³	-7.407407E-19	1.626025E-15	-4.175176E-19	-1.121906E-18	4.277794E-15	7.709209E-19
X ² Y ⁵	-3.053897E-18	-1.459850E-15	-5.190383E-19	9.702383E-19	5.157566E-15	9.414679E-19
Y ⁷	-1.167661E-17	1.377526E-14	-3.283791E-21	9.398678E-20	-3.053184E-15	3.954522E-19
X ⁸	-1.128385E-22	-2.091289E-19	-1.560172E-21	-2.941200E-21	2.054965E-18	-3.788563E-21
X ⁶ Y ²	-2.424101E-21	-5.485841E-18	-1.205060E-20	-3.188366E-20	8.911569E-18	-9.560288E-21
X ⁴ Y ⁴	4.347588E-22	-3.722786E-17	-1.249304E-21	-8.368608E-21	1.007777E-17	-8.789392E-21
X ² Y ⁶	2.577199E-21	-2.687589E-17	-2.354061E-22	8.597809E-22	1.143993E-17	-3.545101E-21
Y ⁸	5.215288E-20	-7.369037E-17	-4.229309E-23	-6.689468E-22	-7.499429E-18	-1.703637E-21
X ⁸ Y	7.792174E-25	0.000000E+00	-7.813621E-24	-2.516130E-23	0.000000E+00	8.396981E-25
X ⁶ Y ³	8.992421E-24	0.000000E+00	-1.921637E-23	-8.262460E-23	0.000000E+00	4.664369E-24
X ⁴ Y ⁵	-4.714974E-25	0.000000E+00	-1.610571E-24	-1.778199E-23	0.000000E+00	9.398752E-24
X ² Y ⁷	6.059892E-24	0.000000E+00	3.848059E-26	1.222213E-24	0.000000E+00	1.042278E-23
Y ⁹	-8.700880E-23	0.000000E+00	6.368781E-27	-2.288415E-25	0.000000E+00	7.789109E-24
X ¹⁰	0.000000E+00	0.000000E+00	-5.411923E-27	-1.603639E-26	0.000000E+00	-3.929816E-26
X ⁸ Y ²	0.000000E+00	0.000000E+00	-8.609679E-27	-4.538477E-26	0.000000E+00	-1.453997E-25
X ⁶ Y ⁴	0.000000E+00	0.000000E+00	-1.127835E-26	-7.710579E-26	0.000000E+00	-1.839705E-25
X ⁴ Y ⁶	0.000000E+00	0.000000E+00	-8.495275E-28	-1.413945E-26	0.000000E+00	-8.230974E-26
X ² Y ⁸	0.000000E+00	0.000000E+00	4.740792E-29	1.022008E-27	0.000000E+00	-8.755646E-27
Y ¹⁰	0.000000E+00	0.000000E+00	1.728076E-29	1.964912E-28	0.000000E+00	-7.204080E-27
Nradius	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Y-decenter	-144.660	-98.223	42.173	-14.449	2.986	-10.929
X-rotation	-8.868	-16.235	1.500	-3.658	-7.600	-1.635

Table 7B

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FIGS. 17 to 20 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors

5 S1 to S4 as M1 to M4. For the embodiment according to FIGS. 17 to 20, the following data are given:

Numerical aperture: 0.26

Imaging factor: 1:4

10 Form of object fields: rectangular

Width of scanning field on the object side: 100 mm

Height of scanning field on the object side: 8 mm

Length: 2360 mm

Tilt of image plane: - 3,084°.

15

This embodiment shows a system having a balanced combination of numerical aperture, field size, system size, wavefront and distortion correction.

The optical data can be seen from the following tables:

20

Surface	Radius	Thickness	Mode
Object	INFINITY	2102,043	
Mirror 1	3004,821	-1812,311	REFL
Mirror 2	2545,365	1957,316	REFL
Mirror 3	706,710	0,000	REFL
STOP	INFINITY	-339,990	
Mirror 4	741,656	453,302	REFL
Image	INFINITY	0,000	

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Coefficient	M1	M2	M3	M4	Image
Y-decenter	-65,523	54,692	48,905	47,778	23,755
X-rotation	-2,620	-2,374	-2,706	-1,585	-3,084

Coefficient	M1	M2	M3	M4
K	-1,09E+00	5,80E-02	2,06E+00	6,72E-01
Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2	3,54E-04	9,93E-06	-5,35E-04	1,23E-04
Y2	1,97E-04	1,07E-05	1,23E-05	2,97E-04
X2Y	-6,42E-07	-2,47E-08	-4,37E-07	-2,44E-07
Y3	3,69E-07	1,89E-08	-1,34E-06	-4,72E-07
X4	2,63E-09	3,01E-12	-2,94E-08	-5,08E-09
X2Y2	-1,09E-10	2,13E-11	-3,33E-08	-5,07E-09
Y4	-6,07E-11	-1,88E-11	-1,42E-08	-1,36E-09
X4Y	-2,66E-11	-7,36E-14	4,84E-11	-4,80E-12
X2Y3	2,61E-11	3,55E-14	-5,06E-11	-1,05E-11
Y5	-1,67E-12	-6,53E-15	7,86E-11	-1,06E-11
X6	-8,14E-13	-2,93E-16	-7,71E-13	-1,04E-13
X4Y2	1,29E-13	6,33E-17	-1,53E-12	-4,13E-13
X2Y4	-4,50E-14	-7,40E-17	2,40E-13	-3,31E-13
Y6	1,04E-15	1,42E-17	-6,88E-13	1,99E-14
X6Y	1,96E-14	3,20E-18	-6,34E-15	-1,31E-15
X4Y3	-2,85E-16	2,38E-19	-1,30E-14	-5,72E-15
X2Y5	-1,60E-16	-4,36E-20	1,43E-14	-9,75E-16
Y7	1,93E-18	1,20E-20	1,61E-15	2,08E-15
X8	-1,62E-17	-1,41E-21	-8,44E-19	-7,70E-18
X6Y2	-1,69E-16	-1,19E-20	1,72E-16	-1,13E-16
X4Y4	3,10E-18	5,44E-22	2,91E-16	-1,26E-16
X2Y6	-2,80E-19	8,10E-22	9,83E-18	4,36E-17
Y8	8,73E-21	-4,31E-24	4,37E-17	3,31E-17
X8Y	1,79E-19	6,79E-24	1,76E-18	-4,84E-19
X6Y3	6,22E-19	1,62E-23	6,22E-18	-2,33E-18
X4Y5	-2,21E-20	-3,41E-24	-1,22E-19	-1,19E-18
X2Y7	4,10E-21	-2,28E-24	-2,47E-18	5,49E-19
Y9	9,75E-23	-5,21E-26	-5,68E-19	2,75E-19
X10	-3,29E-23	-8,73E-28	-5,00E-21	-4,71E-22
X8Y2	-4,75E-22	-7,40E-27	-6,76E-20	-6,64E-21
X6Y4	-8,19E-22	-6,01E-27	-1,52E-19	-1,46E-20
X4Y6	4,25E-23	3,34E-27	-4,79E-20	-4,03E-21
X2Y8	-6,29E-24	2,20E-27	5,65E-21	1,87E-21
Y10	-3,17E-25	9,18E-29	2,89E-21	8,49E-22
Nradius	3,00E+00	3,00E+00	3,00E+00	3,00E+00

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	x _{Object} /mm	y _{Object} /mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	600	0	-0.960073	0.960073	0.0196465	0.027195
	0	602	0	-1.46082	1.46082	0.0111602	0.019766
	0	604	0	-1.14157	1.14157	0.00258716	0.015522
	0	606	0	-0.708422	0.708422	0.00607316	0.01395
	0	608	0	-0.868087	0.868087	0.0148213	0.032279
10	12.5	600	-0.702813	-0.349919	0.785105	0.0226563	0.026075
	12.5	602	-0.506161	-0.815296	0.959639	0.0159931	0.018251
	12.5	604	-0.214821	-0.491402	0.536306	0.011916	0.01476
	12.5	606	0.161171	-0.084304	0.181888	0.0132822	0.014764
	12.5	608	0.611783	-0.300692	0.681685	0.0190686	0.032953
15	25	600	-0.828473	0.99838	1.29736	0.0299227	0.025603
	25	602	-0.613329	0.633853	0.882011	0.0254871	0.014924
	25	604	-0.210678	0.966257	0.988958	0.0234105	0.012561
	25	606	0.359349	1.28961	1.33874	0.0243974	0.016745
	25	608	1.07663	0.89729	1.40152	0.028208	0.035061
20	37.5	600	-0.079109	1.6231	1.62502	0.0391462	0.033551
	37.5	602	-0.207297	1.40928	1.42444	0.036144	0.015412
	37.5	604	-0.058849	1.73794	1.73893	0.035006	0.008795
	37.5	606	0.335888	1.90321	1.93262	0.0359723	0.018708
	37.5	608	0.946577	1.1986	1.5273	0.0389452	0.038658
25	50	600	1.28921	-0.96207	1.60861	0.0492443	0.056489
	50	602	0.261464	-1.00092	1.03450	0.0471902	0.03219
	50	604	-0.405953	-0.714664	0.821914	0.0466375	0.018965
	50	606	-0.753775	-0.809016	1.10575	0.0476858	0.02652
	50	608	-0.82272	-1.99027	2.15361	0.0502807	0.047096
30							

x_{Object}/mm and y_{Object}/mm denote the x- and y-coordinates in the object plane. The values Distortion(x)/nm and Distortion(y)/nm denote the distortion at the respective coordinate. Absolute Value of Distortion/nm denotes the absolute distortion value at the respective coordinate measured at the image plane.

- 35 Telecentricity/Degrees denotes the chief ray angle at the respective coordinate. Wavefront Error at 13,5 nm denotes the RMS wavefront error in units of the illumination wavelength $\lambda = 13,5$ nm. As the optical system is mirror symmetric with respect to the yz-plane it is sufficient to give data for fieldpoints having positive x-coordinates in the object plane.

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FIGS. 18 to 20 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 17. These aberration plots show the wavefront error for 15 fieldpoints, i.e. for five equidistant y-coordinates between $y_{\min}$ and $y_{\max}$ at the center of the object field at $x = 0$, at $x = x_{\max}/2$ and at $x = x_{\max}$.

FIGS. 21 to 24 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 21 to 24, the following data are given:

15	Numerical aperture:	0.3
	Imaging factor:	1:4
	Form of object fields:	rectangular
	Width of scanning field on the object side:	100 mm
	Height of scanning field on the object side:	8 mm
20	Length:	2354 mm
	Tilt of image plane:	- 3,798°.

This embodiment shows a system having an increased numerical aperture.

25 The optical data can be seen from the following tables:

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Surface	Radius	Thickness	Mode
Object	INFINITY	2102,043	
Mirror 1	3030,572	-1827,768	REFL
Mirror 2	2546,206	1949,851	REFL
Mirror 3	689,344	0,000	REFL
STOP	INFINITY	-322,728	
Mirror 4	734,331	452,552	REFL
Image	INFINITY	0,000	

Coefficient	M1	M2	M3	M4	Image
Y-decenter	-60,435	53,835	51,299	48,788	20,674
X-rotation	-2,524	-2,393	-2,965	-1,494	-3,798

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Coefficient	M1	M2	M3	M4
K	-1,64E+00	5,42E-02	2,28E+00	7,41E-01
Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2	3,01E-04	8,11E-06	-2,17E-04	3,12E-04
Y2	1,85E-04	9,90E-06	1,37E-05	3,77E-04
X2Y	-8,52E-07	-2,68E-08	-8,61E-07	-3,91E-07
Y3	3,22E-07	1,35E-08	-1,77E-06	-3,44E-07
X4	1,85E-09	-4,10E-12	-3,25E-08	-3,95E-09
X2Y2	1,66E-09	2,16E-11	-4,52E-08	-3,73E-09
Y4	-2,66E-10	-2,70E-11	-1,63E-08	1,07E-09
X4Y	-1,09E-11	-4,58E-14	2,88E-11	-5,23E-12
X2Y3	2,59E-11	1,36E-14	-5,03E-11	-3,04E-12
Y5	-2,08E-12	-8,16E-15	5,68E-11	9,47E-13
X6	-3,36E-13	-1,32E-16	-1,05E-12	-8,91E-14
X4Y2	4,77E-14	2,14E-18	-2,39E-12	-2,67E-13
X2Y4	-1,05E-13	-8,15E-17	-5,56E-13	-1,48E-13
Y6	2,44E-15	1,81E-17	-8,66E-13	-9,89E-14
X6Y	7,74E-15	1,24E-18	-2,94E-15	6,43E-17
X4Y3	-1,33E-16	3,33E-19	-7,65E-15	-1,59E-15
X2Y5	6,38E-17	1,05E-20	2,25E-15	-1,75E-15
Y7	1,78E-17	-9,61E-21	5,45E-15	-1,44E-15
X8	-5,84E-18	-6,31E-22	-2,12E-17	-2,74E-18
X6Y2	-6,51E-17	-4,73E-21	-2,21E-17	-2,49E-17
X4Y4	1,12E-18	-1,06E-21	1,03E-17	-4,22E-17
X2Y6	-1,87E-19	3,30E-23	-3,82E-17	-1,56E-17
Y8	-1,84E-20	-2,35E-23	4,83E-17	-2,21E-18
X8Y	6,56E-20	3,32E-24	5,90E-19	-1,29E-19
X6Y3	2,32E-19	6,89E-24	2,59E-18	-5,99E-19
X4Y5	-7,44E-21	1,27E-24	2,28E-19	-4,47E-19
X2Y7	2,48E-21	-3,15E-25	3,92E-19	-9,74E-20
Y9	4,79E-23	3,01E-26	-8,17E-20	7,95E-20
X10	-1,93E-23	-6,89E-28	-3,94E-21	-2,24E-22
X8Y2	-1,74E-22	-4,55E-27	-2,48E-20	-2,04E-21
X6Y4	-2,97E-22	-4,06E-27	-4,24E-20	-4,46E-21
X4Y6	1,36E-23	-1,24E-27	-3,93E-21	-1,90E-21
X2Y8	-4,52E-24	3,71E-28	9,91E-21	-3,41E-22
Y10	-2,43E-25	-8,40E-31	2,16E-21	3,64E-22
Nradius	3,00E+00	3,00E+00	3,00E+00	3,00E+00

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	X _{Object} /mm	Y _{Object} /mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	600	0	-2.20023	2.20023	0.0179382	0.046052
	0	602	0	-1.79021	1.79021	0.0109101	0.029756
	0	604	0	-1.28717	1.28717	0.00378722	0.023987
	0	606	0	-0.891336	0.891336	0.00343113	0.017834
	0	608	0	-0.799202	0.799202	0.0107455	0.043696
10	12.5	600	-1.08427	-1.27001	1.66991	0.0239704	0.043224
	12.5	602	-0.470847	-0.877877	0.996175	0.0193253	0.026959
	12.5	604	0.0397523	-0.421226	0.423098	0.0164496	0.024212
	12.5	606	0.437494	-0.10014	0.448809	0.016432	0.020337
	12.5	608	0.712381	-0.110954	0.72097	0.0193876	0.042811
15	25	600	-1.45171	0.861628	1.68815	0.0365032	0.04072
	25	602	-0.473724	1.1945	1.28501	0.0337094	0.021812
	25	604	0.296494	1.50628	1.53518	0.0322325	0.025914
	25	606	0.838851	1.59734	1.80421	0.0323169	0.027051
	25	608	1.13332	1.27182	1.70351	0.0340121	0.041958
20	37.5	600	-0.729082	2.21013	2.32728	0.0509314	0.052463
	37.5	602	0.112795	2.42562	2.42824	0.0490538	0.021672
	37.5	604	0.637771	2.47706	2.55785	0.0481478	0.026628
	37.5	606	0.815622	2.16558	2.31408	0.0483103	0.033809
	37.5	608	0.616222	1.29608	1.43512	0.0495729	0.044712
25	50	600	0.775128	-0.556886	0.954435	0.0660057	0.083092
	50	602	0.722695	-0.544482	0.904847	0.0646623	0.033187
	50	604	0.238001	-0.896861	0.927904	0.0640826	0.022442
	50	606	-0.719402	-1.81183	1.94942	0.0643192	0.040278
	50	608	-2.18984	-3.48339	4.11454	0.0653953	0.058456
30							

FIGS. 22 to 24 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 21.

FIGS. 25 to 28 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 25 to 28, the following data are given:

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- Numerical aperture: 0.25
 Imaging factor: 1:5
 Form of object fields: rectangular
- 5 Width of scanning field on the object side: 100 mm
 Height of scanning field on the object side: 8 mm
 Length: 3030mm
 Tilt of image plane: 0°.
- 10 This embodiment shows a system having parallel object and image planes.
 Further, this embodiment exhibits a different imaging factor of 1:5.

The optical data can be seen from the following tables:

Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	2802,724	
Mirror 1	3724,091	-2465,218	REFL
Mirror 2	3395,652	2585,049	REFL
Mirror 3	966,548	0,000	REFL
STOP	INFINITY	-489,055	
Mirror 4	977,692	596,613	REFL
Image	INFINITY	0,000	

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Coefficient	M1	M2	M3	M4	Image
Y-decenter	-100,324	68,520	71,277	70,971	11,261
X-rotation	-2,639	-2,442	-1,362	-1,500	0,000

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Coefficient	M1	M2	M3	M4
K	-1,16E+00	2,46E-02	1,91E+00	6,14E-01
Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2	7,57E-04	-5,51E-06	-1,67E-03	-7,26E-05
Y2	3,91E-04	1,41E-05	2,55E-04	5,59E-04
X2Y	3,33E-07	4,07E-08	7,06E-06	1,39E-06
Y3	7,43E-07	3,00E-08	-1,85E-06	-7,26E-07
X4	-3,29E-10	-1,40E-11	-3,83E-08	-9,63E-09
X2Y2	-5,31E-09	4,16E-11	-2,00E-08	-9,67E-09
Y4	-1,29E-10	3,16E-11	1,30E-09	-5,34E-10
X4Y	5,56E-11	-8,02E-16	2,62E-10	2,05E-11
X2Y3	9,40E-11	5,57E-14	1,95E-10	-4,65E-11
Y5	-4,49E-12	-1,18E-13	1,24E-10	-2,50E-11
X6	-1,02E-13	-2,32E-17	-7,28E-13	-2,01E-13
X4Y2	-6,56E-13	6,60E-16	3,35E-13	-7,74E-13
X2Y4	-2,69E-13	8,67E-16	3,48E-12	-1,39E-12
Y6	-1,18E-15	1,46E-16	4,55E-13	-6,59E-14
X6Y	1,01E-15	-3,25E-19	1,32E-14	-1,08E-15
X4Y3	3,51E-15	-1,59E-18	2,19E-14	-5,45E-15
X2Y5	-1,34E-16	-2,11E-18	2,46E-14	-1,09E-14
Y7	-2,06E-17	9,07E-21	1,98E-15	-1,21E-17
X8	6,20E-19	7,45E-23	-7,70E-18	-5,96E-18
X6Y2	-3,16E-18	1,52E-21	4,77E-17	-3,66E-17
X4Y4	-7,05E-18	2,84E-21	2,42E-16	-4,83E-17
X2Y6	1,15E-18	2,33E-21	-1,14E-17	-4,02E-17
Y8	8,47E-20	-8,82E-23	9,94E-17	6,83E-19
X8Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X6Y3	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X4Y5	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2Y7	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Y9	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X8Y2	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X6Y4	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X4Y6	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2Y8	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Y10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Nradius	4,00E+00	4,00E+00	4,00E+00	4,00E+00

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	X _{Object/m}	Y _{Object/mm}	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	800	0	-0.340392	0.340392	0.0258308	0.017169
	0	802	0	-0.548595	0.548595	0.0138699	0.019794
	0	804	0	-0.199318	0.199318	0.00186948	0.024128
	0	806	0	0.121535	0.121535	0.0101706	0.014148
	0	808	0	-0.173787	0.173787	0.0222505	0.035190
10	12.5	800	0.0450163	-0.176646	0.182292	0.0264815	0.018897
	12.5	802	-0.0866232	-0.387405	0.396971	0.0151773	0.020501
	12.5	804	-0.0707759	-0.0498264	0.0865557	0.00674106	0.024709
	12.5	806	0.0891365	0.250161	0.265567	0.0122229	0.015804
	12.5	808	0.389682	-0.0752142	0.396874	0.0233473	0.036331
15	25	800	0.164298	0.201778	0.260208	0.0283526	0.021433
	25	802	-0.143816	-0.0170961	0.144828	0.0185673	0.020512
	25	804	-0.157147	0.284935	0.325397	0.0131056	0.024535
	25	806	0.117459	0.521867	0.534922	0.0169632	0.017161
	25	808	0.673133	0.105856	0.681406	0.0263743	0.038085
20	37.5	800	0.382136	0.456584	0.595397	0.0312476	0.023030
	37.5	802	-0.192076	0.222698	0.294088	0.0231726	0.017658
	37.5	804	-0.324591	0.463967	0.566237	0.0195923	0.021537
	37.5	806	-0.025688	0.594265	0.59482	0.022802	0.014965
	37.5	808	0.694325	0.0256282	0.694798	0.0307906	0.038495
25	50	800	0.623063	0.0244512	0.623543	0.0349462	0.032248
	50	802	-0.351568	-0.233592	0.422096	0.0284496	0.023561
	50	804	-0.738167	-0.0805832	0.742553	0.0261558	0.025133
	50	806	-0.550452	-0.102823	0.559974	0.0291262	0.020735
	50	808	0.197816	-0.888445	0.910201	0.0361232	0.042244
30							

FIGS. 26 to 28 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 25.

FIGS. 29 to 32 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 29 to 32, the following data are given:

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- Numerical aperture: 0.24
 Imaging factor: 1:5
 Form of object fields: rectangular
 5 Width of scanning field on the object side: 100 mm
 Height of scanning field on the object side: 8 mm
 Length: 2273 mm
 Tilt of image plane: 0°.
- 10 Compared to the embodiment of FIG. 25, this embodiment has a somewhat lower numerical aperture and somewhat higher residual aberrations, but the length of the system according to FIG. 17.

The optical data can be seen from the following tables:

15

Surface	Radius (mm)	Thickness (mm)	Mode
Object	INFINITY	2102,043	
Mirror 1	2793,659	-1848,726	REFL
Mirror 2	2546,811	1938,769	REFL
Mirror 3	724,789	0,000	REFL
STOP	INFINITY	-366,800	
Mirror 4	733,040	447,458	REFL
Image	INFINITY	0,000	

Coefficient	M1	M2	M3	M4	Image
Y-decenter	-75,087	51,394	53,563	53,215	8,406
X-rotation	-2,635	-2,442	-1,373	-1,503	0,000

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Coefficient	M1	M2	M3	M4
K	-1,18E+00	2,43E-02	1,79E+00	6,25E-01
Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2	5,63E-04	-4,21E-06	-1,24E-03	-5,32E-05
Y2	2,93E-04	1,06E-05	1,91E-04	4,21E-04
X2Y	3,27E-07	3,31E-08	5,31E-06	1,03E-06
Y3	5,55E-07	2,25E-08	-1,34E-06	-5,45E-07
X4	-4,83E-11	-1,05E-11	-2,55E-08	-7,45E-09
X2Y2	-4,43E-09	2,08E-11	-8,22E-09	-8,28E-09
Y4	-1,07E-10	2,38E-11	5,97E-09	-1,14E-09
X4Y	2,99E-11	-1,99E-14	2,05E-10	1,41E-11
X2Y3	6,95E-11	5,53E-14	1,56E-10	-5,12E-11
Y5	-3,40E-12	-8,87E-14	1,05E-10	-2,19E-11
X6	-3,28E-14	6,98E-18	-3,80E-13	-1,62E-13
X4Y2	-3,27E-13	6,59E-16	6,90E-13	-6,77E-13
X2Y4	-1,84E-13	6,85E-16	3,09E-12	-1,35E-12
Y6	-8,30E-16	1,08E-16	3,25E-13	-5,27E-14
X6Y	2,31E-16	-3,71E-19	9,39E-15	-9,01E-16
X4Y3	1,75E-15	-1,64E-18	1,82E-14	-5,23E-15
X2Y5	-1,54E-16	-1,71E-18	2,00E-14	-1,08E-14
Y7	-1,38E-17	4,97E-21	1,64E-16	-8,50E-18
X8	4,46E-19	6,17E-23	2,58E-18	-4,70E-18
X6Y2	-8,01E-19	1,33E-21	8,08E-17	-2,87E-17
X4Y4	-3,59E-18	2,58E-21	2,26E-16	-4,48E-17
X2Y6	9,06E-19	1,87E-21	-2,45E-17	-4,08E-17
Y8	6,53E-20	-4,81E-23	8,45E-17	-2,43E-19
X8Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X6Y3	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X4Y5	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2Y7	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Y9	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X8Y2	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X6Y4	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X4Y6	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2Y8	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Y10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Nradius	3,00E+00	3,00E+00	3,00E+00	3,00E+00

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	XObject/mm	YObject/mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	600	0	-0.303712	0.303712	0.0350766	0.023748
	0	602	0	-0.943417	0.943417	0.0190794	0.022355
	0	604	0	-0.508069	0.508069	0.00301184	0.029861
	0	606	0	0.00377447	0.003775	0.0131266	0.017655
	0	608	0	-0.410098	0.410098	0.0293362	0.037546
10	12.5	600	-0.0976702	-0.0397139	0.105436	0.0359221	0.024194
	12.5	602	-0.336727	-0.658804	0.73987	0.0208196	0.021336
	12.5	604	-0.305426	-0.223582	0.378515	0.00938223	0.028592
	12.5	606	-0.0115266	0.267305	0.267554	0.0161529	0.016575
	12.5	608	0.537176	-0.188439	0.569269	0.0309678	0.038828
15	25	600	0.0740798	0.543069	0.548099	0.0383664	0.025529
	25	602	-0.488733	-0.0159655	0.488994	0.0253625	0.019218
	25	604	-0.511562	0.417058	0.660025	0.0180672	0.025576
	25	606	-0.00993471	0.843229	0.843287	0.0229845	0.014322
	25	608	1.00055	0.259991	1.03377	0.0354364	0.042367
20	37.5	600	0.635211	0.816881	1.03479	0.0421854	0.027832
	37.5	602	-0.420855	0.35196	0.548629	0.0315907	0.018948
	37.5	604	-0.668773	0.775246	1.02385	0.0269974	0.023314
	37.5	606	-0.131864	1.08739	1.09535	0.0312902	0.013747
	37.5	608	1.16644	0.285392	1.20085	0.0418989	0.047139
25	50	600	1.40779	-0.264954	1.43251	0.0471254	0.033617
	50	602	-0.396014	-0.610703	0.727863	0.0387971	0.027129
	50	604	-1.12571	-0.213831	1.14584	0.0360974	0.028277
	50	606	-0.812445	-0.0743145	0.815836	0.0402623	0.020092
	50	608	0.512487	-1.19576	1.30095	0.0496609	0.052034

30 FIGS. 30 to 32 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 29.

FIGS. 33 to 36 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the
35 image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 33 to 36, the following data are given:

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	Numerical aperture:	0.30
	Imaging factor:	1:5
	Form of object fields:	rectangular
	Width of scanning field on the object side:	100 mm
5	Height of scanning field on the object side:	8 mm
	Length:	2332 mm
	Tilt of image plane:	- 4,515°.

With this optical system, a very high numerical aperture without obscuration
 10 of the optical components is realized.

The optical data can be seen from the following tables:

Surface	Radius	Thickness	Mode
Object	INFINITY	2102,043	
Mirror 1	2806,084	-1838,550	REFL
Mirror 2	2547,909	1937,744	REFL
Mirror 3	678,009	0,000	REFL
STOP	INFINITY	-321,297	
Mirror 4	724,986	451,996	REFL
Image	INFINITY	0,000	

Coefficient	M1	M2	M3	M4	Image
Y-decenter	-60,550	48,435	58,618	51,407	8,786
X-rotation	-2,354	-2,502	-3,516	-1,667	-4,515

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Coefficient	M1	M2	M3	M4
K	-9,97E-01	3,10E-02	2,78E+00	8,33E-01
Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2	5,76E-04	3,29E-05	3,77E-04	7,34E-04
Y2	2,85E-04	8,60E-06	-2,80E-04	4,86E-04
X2Y	-1,58E-06	7,59E-11	2,37E-06	4,69E-08
Y3	5,91E-07	1,16E-08	-3,82E-07	-6,08E-07
X4	2,12E-09	2,57E-11	-2,39E-08	4,09E-10
X2Y2	1,66E-08	1,07E-10	-5,49E-08	-8,60E-10
Y4	-4,86E-11	3,13E-11	-4,63E-08	-1,53E-09
X4Y	-3,03E-11	-5,49E-14	1,73E-10	3,15E-12
X2Y3	-6,10E-11	-1,55E-13	1,88E-10	-7,52E-12
Y5	-4,20E-12	-4,44E-14	1,11E-10	-3,72E-12
X6	9,54E-15	3,01E-17	-7,68E-13	-2,46E-14
X4Y2	2,14E-13	4,63E-16	-2,74E-12	-1,59E-13
X2Y4	1,12E-14	3,89E-16	-3,32E-12	-1,92E-13
Y6	1,65E-15	2,47E-17	-1,30E-12	-7,78E-14
X6Y	-2,26E-16	-1,54E-19	8,48E-15	-1,53E-16
X4Y3	-5,47E-16	-7,87E-19	1,15E-14	-6,67E-16
X2Y5	5,78E-16	-3,98E-19	3,95E-15	-3,91E-16
Y7	1,29E-18	-6,38E-21	-3,30E-15	4,66E-16
X8	2,43E-19	3,50E-23	-1,57E-17	-1,17E-18
X6Y2	3,79E-19	4,92E-22	-9,74E-17	-7,71E-18
X4Y4	2,03E-21	1,04E-21	-1,74E-16	-1,21E-17
X2Y6	-1,22E-18	4,66E-22	-1,42E-16	-7,08E-18
Y8	1,73E-20	1,30E-23	-4,17E-17	1,05E-18
X8Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X6Y3	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X4Y5	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2Y7	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Y9	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X8Y2	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X6Y4	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X4Y6	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2Y8	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Y10	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Nradius	3,00E+00	3,00E+00	3,00E+00	3,00E+00

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	X _{Object} /mm	Y _{Object} /mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	600	0	-0.166318	0.166318	0.0148053	0.053501
	0	602	0	-0.731572	0.731572	0.00884521	0.019284
	0	604	0	-0.661487	0.661487	0.00282744	0.038268
	0	606	0	-0.504836	0.504836	0.0032483	0.021472
	0	608	0	-0.810627	0.810627	0.00938234	0.047628
10	12.5	600	-0.852921	0.132616	0.863169	0.0186158	0.052338
	12.5	602	-0.193958	-0.398416	0.44312	0.0145478	0.024553
	12.5	604	0.181685	-0.303572	0.353787	0.0121468	0.042437
	12.5	606	0.270096	-0.131573	0.300439	0.012504	0.02662
	12.5	608	0.0673771	-0.431381	0.436611	0.0154976	0.048115
15	25	600	-1.29433	0.754312	1.49809	0.0270423	0.048536
	25	602	-0.101019	0.323398	0.338808	0.0247903	0.031643
	25	604	0.524636	0.489914	0.717815	0.0238524	0.049015
	25	606	0.574789	0.705289	0.909844	0.0244236	0.033313
	25	608	0.0416169	0.420711	0.422764	0.0264463	0.04856
20	37.5	600	-1.11433	0.871449	1.41462	0.0371683	0.044918
	37.5	602	0.363273	0.598909	0.700471	0.0359881	0.032203
	37.5	604	0.986834	0.876191	1.31968	0.0357827	0.049123
	37.5	606	0.744538	1.15498	1.37416	0.0365972	0.031801
	37.5	608	-0.375406	0.886699	0.962894	0.0383944	0.049913
25	50	600	-0.505166	-0.901506	1.03339	0.0480691	0.060875
	50	602	0.879494	-0.970155	1.30947	0.0476135	0.036681
	50	604	1.12068	-0.556047	1.25104	0.0479137	0.044354
	50	606	0.202525	-0.20714	0.289695	0.0489775	0.03033

30 FIGS. 34 to 36 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 33.

FIGS. 37 to 40 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the
 35 image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 37 to 40, the following data are given:

- 95 -

- Numerical aperture: 0.20
 Imaging factor: 1:4
 Form of object fields: rectangular
- 5 Width of scanning field on the object side: 100 mm
 Height of scanning field on the object side: 8 mm
 Length: 2084 mm
 Tilt of image plane: + 6,890°.
- 10 This embodiment shows a mirror arrangement, giving high chief ray angles with respect to the normal of the object plane. This facilitates a separation of a not shown illumination ray path and the imaging ray path at a reflective mask or reticle. Further, the maximum angles of incidence on the mirror surfaces are somewhat lower in this embodiment, facilitating the manufacturing of multi-
- 15 layer reflective structures.

The optical data can be seen from the following tables:

Surface	Radius	Thickness	Mode
Object	INFINITY	1781,972	
Mirror 1	21581,586	-1639,081	REFL
Mirror 2	4053,640	1376,461	REFL
Mirror 3	1254,488	0,000	REFL
STOP	INFINITY	-1067,803	
Mirror 4	1733,205	1632,838	REFL
Image	INFINITY	0,000	

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Coefficient	M1	M2	M3	M4	Image
Y-decenter	-29,501	-2,134	-5,508	-0,487	5,838
X-rotation	-0,812	0,034	2,908	1,105	6,890

Coefficient	M1	M2	M3	M4
K	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Y	0,00E+00	0,00E+00	0,00E+00	0,00E+00
X2	2,80E-04	1,47E-05	-6,54E-04	-1,23E-04
Y2	1,13E-04	7,15E-05	-1,55E-04	-2,14E-05
X2Y	-8,62E-09	-9,59E-08	-2,20E-07	-1,32E-08
Y3	1,51E-07	5,42E-08	1,12E-07	3,86E-08
X4	2,07E-09	-1,04E-10	-6,16E-10	-7,05E-11
X2Y2	-3,64E-09	-1,00E-10	-4,18E-10	-3,95E-11
Y4	-2,70E-11	-3,46E-10	1,32E-09	5,30E-11
X4Y	-2,72E-11	-2,99E-13	1,86E-13	-6,90E-15
X2Y3	1,52E-11	2,29E-13	-1,45E-12	8,75E-14
Y5	-1,49E-12	4,09E-13	5,04E-12	2,35E-14
X6	-2,54E-14	-8,99E-17	-3,11E-16	-5,52E-17
X4Y2	7,40E-14	1,26E-15	-2,70E-15	-2,62E-17
X2Y4	-1,14E-14	-2,54E-15	1,21E-14	1,83E-16
Y6	1,69E-15	1,03E-16	-3,69E-15	6,00E-17
X6Y	-6,30E-17	4,44E-20	-8,25E-18	2,20E-20
X4Y3	6,36E-17	-1,53E-18	-3,51E-17	2,26E-19
X2Y5	-7,58E-17	4,16E-18	3,32E-17	-9,30E-20
Y7	-9,34E-19	-2,88E-19	3,35E-17	8,72E-20
X8	7,35E-18	3,66E-21	-3,46E-20	-7,26E-24
X6Y2	3,71E-18	1,22E-20	-3,57E-20	5,68E-22
X4Y4	3,71E-19	-4,74E-21	3,56E-19	-5,19E-22
X2Y6	1,26E-19	1,19E-21	4,63E-20	-8,91E-22
Y8	3,67E-21	-8,04E-22	3,00E-20	1,91E-22
X8Y	-6,70E-20	-8,52E-23	8,72E-23	1,96E-24
X6Y3	-1,92E-20	-1,06E-22	6,48E-22	2,15E-24
X4Y5	-4,59E-21	-2,85E-23	9,86E-22	-3,07E-24
X2Y7	7,55E-23	-1,72E-23	1,23E-21	-2,46E-24
Y9	3,46E-26	3,04E-24	-2,25E-22	3,35E-25
X10	5,05E-23	6,75E-26	1,03E-24	1,46E-27
X8Y2	1,43E-22	2,53E-25	4,57E-24	4,54E-27
X6Y4	2,81E-23	2,06E-25	2,76E-24	2,39E-27
X4Y6	7,66E-24	9,23E-26	-2,58E-24	-1,86E-27
X2Y8	-1,40E-25	2,75E-26	-6,32E-25	-2,02E-27
Y10	1,61E-27	-2,48E-27	6,81E-25	1,93E-28
Nradius	2,00E+00	2,00E+00	2,00E+00	2,00E+00

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	XObject/mm	YObject/mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	800	0	-0.366434	0.366434	0.0198854	0.093978
	0	802	0	-0.0892875	0.0892875	0.0104067	0.015958
	0	804	0	-0.0777646	0.0777646	0.0009187	0.032744
	0	806	0	0.0405964	0.0405964	0.0085785	0.042489
	0	808	0	0.661542	0.661542	0.018085	0.028159
10	12.5	800	0.0955838	-0.353342	0.366042	0.0306806	0.091554
	12.5	802	-0.0573173	-0.0687788	0.089531	0.0256084	0.020828
	12.5	804	-0.106637	-0.0760641	0.130985	0.0234513	0.03637
	12.5	806	-0.0613664	-0.00241775	0.061414	0.0249869	0.044044
	12.5	808	0.0696061	0.548237	0.552638	0.0296558	0.030805
15	25	800	0.115633	-0.279658	0.302621	0.0507857	0.08257
	25	802	-0.184329	0.0221776	0.185658	0.047943	0.024249
	25	804	-0.278855	-0.0466988	0.282738	0.0468785	0.040154
	25	806	-0.1860	-0.112547	0.2174	0.0477167	0.043512
	25	808	0.0763955	0.221706	0.234499	0.050368	0.032565
20	37.5	800	0.146594	-0.0521759	0.155602	0.072869	0.065923
	37.5	802	-0.292306	0.261705	0.392342	0.0709743	0.020204
	37.5	804	-0.42743	0.0728035	0.433586	0.0703175	0.037534
	37.5	806	-0.286029	-0.243519	0.375651	0.0709367	0.034303
	37.5	808	0.104968	-0.288511	0.307012	0.0728031	0.030384
25	50	800	0.555156	0.451152	0.715358	0.095576	0.062457
	50	802	-0.0193915	0.746217	0.746469	0.0941997	0.044595
	50	804	-0.197219	0.352291	0.403738	0.0937666	0.049527
	50	806	-0.0149766	-0.352951	0.353268	0.0942927	0.040292
	50	808	0.491125	-0.968364	1.08579	0.0957648	0.053486
30							

FIGS. 38 to 40 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 37.

FIGS. 41 to 44 show another embodiment of the invention having four mirrors
 35 being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 41 to 44, the following data are given:

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- Numerical aperture: 0.22
 Imaging factor: 1:4
 Form of object fields: rectangular
 5 Width of scanning field on the object side: 100 mm
 Height of scanning field on the object side: 6 mm
 Length: 1610 mm
 Tilt of image plane: - 3,269°.
- 10 This optical system has a full object field width of 100 mm combined with a high numerical aperture and a length being distinctly below 2 m.

The optical data can be seen from the following tables:

Surface	Radius	Thickness	Mode
Object	INFINITY	1401,362	
Mirror 1	2056,786	-1173,664	REFL
Mirror 2	1698,638	1307,130	REFL
Mirror 3	485,224	0,000	REFL
STOP	INFINITY	-242,471	
Mirror 4	500,544	317,875	REFL
Image	INFINITY	0,000	

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Coefficient	M1	M2	M3	M4	Image
Y-decenter	-39,335	41,119	28,409	29,500	20,214
X-rotation	-2,559	-2,218	-2,171	-1,946	-3,269

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Coefficient	M1	M2	M3	M4
K	1,99E-01	1,77E-02	-1,87E+00	4,88E-01
Y	2,81E-02	1,37E-02	3,55E-02	7,69E-03
X2	2,26E-04	3,48E-06	-4,91E-04	-4,94E-05
Y2	1,03E-04	5,88E-06	4,66E-05	1,24E-04
X2Y	-2,82E-07	-2,37E-09	6,97E-07	5,91E-08
Y3	2,75E-07	1,70E-08	1,19E-07	-2,41E-07
X4	9,82E-10	1,81E-11	4,96E-08	-2,57E-09
X2Y2	3,25E-10	7,65E-11	1,17E-07	-1,97E-09
Y4	3,00E-10	3,51E-11	5,55E-08	-1,12E-09
X4Y	1,63E-12	-5,37E-14	6,00E-11	-1,49E-12
X2Y3	7,72E-12	-1,83E-13	5,59E-11	-5,50E-12
Y5	-1,69E-12	-2,87E-14	1,06E-10	-7,08E-12
X6	-7,06E-13	-2,35E-16	7,97E-13	-3,51E-14
X4Y2	-1,89E-13	2,95E-16	2,92E-12	-2,27E-13
X2Y4	-2,95E-14	8,47E-16	3,43E-12	-8,71E-14
Y6	-6,58E-15	6,72E-17	1,51E-12	2,45E-13
X6Y	1,66E-14	2,27E-18	-5,35E-15	-1,05E-16
X4Y3	3,03E-16	-1,68E-18	-1,54E-14	-4,92E-15
X2Y5	3,34E-17	-1,58E-18	8,39E-15	-7,28E-18
Y7	6,29E-18	-9,72E-20	-1,58E-14	4,60E-15
X8	-8,43E-18	-5,58E-22	3,34E-17	-1,03E-18
X6Y2	-1,36E-16	-3,42E-21	2,48E-16	-4,99E-17
X4Y4	1,67E-17	1,04E-20	5,35E-16	-1,22E-16
X2Y6	-1,28E-19	2,47E-21	1,70E-16	1,96E-17
Y8	2,31E-20	2,12E-22	1,26E-17	2,70E-17
X8Y	6,81E-20	-6,83E-25	1,95E-18	-2,10E-19
X6Y3	4,40E-19	-1,21E-23	8,94E-18	-1,50E-18
X4Y5	-1,14E-19	-2,41E-23	2,11E-18	-1,40E-18
X2Y7	1,00E-21	-2,59E-24	-2,62E-18	2,58E-19
Y9	1,76E-22	-1,04E-25	4,55E-19	4,95E-20
X10	4,15E-23	1,40E-27	1,03E-21	-3,22E-22
X8Y2	-8,40E-23	8,23E-27	-2,65E-20	-3,81E-21
X6Y4	-4,40E-22	2,75E-26	-1,15E-19	-1,13E-20
X4Y6	2,15E-22	2,05E-26	-6,68E-20	-5,18E-21
X2Y8	-2,36E-24	2,35E-27	1,73E-20	1,16E-21
Y10	-4,82E-25	1,60E-28	7,05E-21	6,71E-23
Nradius	2,00E+00	2,00E+00	2,00E+00	2,00E+00

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	X _{Object} /mm	Y _{Object} /mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	400	0	-1.00949	1.00949	0.0229582	0.016806
	0	401.5	0	-1.95078	1.95078	0.0133671	0.014259
	0	403	0	-1.62222	1.62222	0.00369148	0.023621
	0	404.5	0	-1.10626	1.10626	0.00606921	0.019377
	0	406	0	-1.48681	1.48681	0.0159156	0.012538
10	12.5	400	-0.880918	-0.237177	0.912288	0.0242612	0.029659
	12.5	401.5	-0.966915	-1.11354	1.47475	0.0158373	0.024479
	12.5	403	-0.748886	-0.752973	1.06198	0.00983379	0.029615
	12.5	404.5	-0.234325	-0.238253	0.334175	0.0114533	0.0278
	12.5	406	0.569207	-0.653615	0.866723	0.0189539	0.028612
15	25	400	-0.712509	1.51156	1.67107	0.0278372	0.041582
	25	401.5	-1.05587	0.817705	1.33548	0.0216593	0.031971
	25	403	-0.794449	1.26023	1.48974	0.0186545	0.033731
	25	404.5	0.0563116	1.75538	1.75628	0.0204067	0.035112
	25	406	1.48083	1.21794	1.91735	0.0260668	0.043885
20	37.5	400	0.775815	2.32893	2.45475	0.0330354	0.035552
	37.5	401.5	-0.220665	1.89815	1.91094	0.0289732	0.019017
	37.5	403	-0.318211	2.43041	2.45116	0.0278179	0.018555
	37.5	404.5	0.458907	2.84034	2.87718	0.0299911	0.023281
	37.5	406	2.08622	2.04109	2.91862	0.0349482	0.041572
25	50	400	2.20545	-1.61745	2.73499	0.0393365	0.049861
	50	401.5	-0.163904	-1.76675	1.77434	0.0370418	0.045563
	50	403	-1.35027	-1.20714	1.81119	0.0372211	0.042817
	50	404.5	-1.38792	-1.02622	1.72611	0.0399036	0.036919
	50	406	-0.3114	-2.31311	2.33398	0.0446971	0.041068

30 FIGS. 42 to 44 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 41.

FIGS. 45 to 48 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the
35 image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 45 to 48, the following data are given:

- 101 -

Numerical aperture:	0.2
Imaging factor:	1:4
Form of object fields:	rectangular
Width of scanning field on the object side:	48 mm
5 Height of scanning field on the object side:	6 mm
Length:	805 mm
Tilt of image plane:	- 3,254

Having a somewhat smaller object field, this optical system is very compact.

10

The optical data can be seen from the following tables:

Surface	Radius	Thickness	Mode
Object	INFINITY	700,681	
Mirror 1	1028,806	-586,789	REFL
Mirror 2	849,319	653,594	REFL
Mirror 3	242,363	0,000	REFL
STOP	INFINITY	-121,170	
Mirror 4	250,164	158,873	REFL
Image	INFINITY	0,000	

Coefficient	M1	M2	M3	M4	Image
Y-decenter	-19,604	20,562	14,246	14,754	10,066
X-rotation	-2,555	-2,217	-2,176	-1,945	-3,254

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Coefficient	M1	M2	M3	M4
K	1,85E-01	1,74E-02	-1,85E+00	4,82E-01
Y	1,40E-02	6,82E-03	1,78E-02	3,82E-03
X2	1,12E-04	1,78E-06	-2,41E-04	-2,19E-05
Y2	5,11E-05	2,94E-06	2,25E-05	6,32E-05
X2Y	-1,50E-07	-2,03E-09	2,40E-07	6,62E-09
Y3	1,37E-07	8,46E-09	9,10E-08	-1,22E-07
X4	6,14E-10	1,05E-11	2,48E-08	-1,21E-09
X2Y2	1,18E-10	3,69E-11	5,87E-08	-8,27E-10
Y4	1,49E-10	1,75E-11	2,85E-08	-6,21E-10
X4Y	-4,96E-13	-4,03E-14	2,70E-11	-1,87E-12
X2Y3	3,75E-12	-9,18E-14	2,66E-11	-3,21E-12
Y5	-8,45E-13	-1,45E-14	5,11E-11	-3,08E-12
X6	-4,48E-13	-1,55E-16	4,07E-13	-1,32E-14
X4Y2	-9,93E-14	1,76E-16	1,48E-12	-1,34E-13
X2Y4	-1,45E-14	4,25E-16	1,72E-12	-4,41E-14
Y6	-3,27E-15	3,37E-17	5,96E-13	1,31E-13
X6Y	9,85E-15	1,26E-18	-4,00E-15	9,75E-18
X4Y3	2,03E-16	-8,24E-19	-7,92E-15	-2,79E-15
X2Y5	2,17E-17	-7,96E-19	4,39E-15	-2,79E-17
Y7	3,42E-18	-4,69E-20	-7,86E-15	2,14E-15
X8	-9,51E-18	-1,05E-21	2,00E-17	-1,48E-18
X6Y2	-7,13E-17	7,34E-23	1,55E-16	-3,11E-17
X4Y4	8,72E-18	5,00E-21	2,91E-16	-5,52E-17
X2Y6	-6,01E-20	1,22E-21	8,06E-17	1,21E-17
Y8	1,39E-20	1,11E-22	2,93E-17	1,34E-17
X8Y	8,76E-20	3,22E-24	1,62E-18	-1,88E-19
X6Y3	1,77E-19	-1,60E-23	6,77E-18	-9,63E-19
X4Y5	-6,03E-20	-1,18E-23	-5,88E-20	-5,35E-19
X2Y7	3,31E-22	-1,26E-24	-1,35E-18	1,61E-19
Y9	9,94E-23	-4,83E-26	9,84E-20	4,93E-20
X10	2,39E-23	5,19E-28	-1,04E-21	-2,67E-22
X8Y2	-1,62E-22	8,70E-28	-3,92E-20	-3,09E-21
X6Y4	-5,01E-23	2,68E-26	-9,03E-20	-7,21E-21
X4Y6	1,13E-22	1,01E-26	-3,00E-20	-1,55E-21
X2Y8	-8,02E-25	1,14E-27	9,53E-21	7,07E-22
Y10	-3,08E-25	6,63E-29	3,03E-21	1,68E-22
Nradius	1,00E+00	1,00E+00	1,00E+00	1,00E+00

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	XObject/mm	YObject/mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	200	0	0.448311	0.448311	0.0429146	0.030026
	0	201.5	0	-2.47405	2.47405	0.0235631	0.014465
	0	203	0	-0.967497	0.967497	0.00387066	0.028481
	0	204.5	0	0.932079	0.932079	0.0161673	0.017921
	0	206	0	-0.816331	0.816331	0.0365555	0.020854
10	6	200	-0.229332	0.72028	0.755908	0.0429896	0.031915
	6	201.5	-0.764827	-2.11395	2.24805	0.0241369	0.015911
	6	203	-0.727117	-0.578603	0.929236	0.00803243	0.028531
	6	204.5	-0.144224	1.28903	1.29708	0.018286	0.019129
	6	206	0.955191	-0.553491	1.10397	0.0378693	0.025583
15	12	200	0.0887838	1.34107	1.34401	0.0432387	0.034302
	12	201.5	-1.10902	-1.23729	1.66157	0.0258287	0.016652
	12	203	-1.16563	0.372291	1.22364	0.0146925	0.027176
	12	204.5	-0.139014	2.12835	2.13289	0.0235883	0.019707
	12	206	1.91157	-0.015856	1.91164	0.0416026	0.033254
20	18	200	1.27353	1.60761	2.05092	0.0437339	0.03238
	18	201.5	-0.903733	-0.573284	1.07023	0.0285705	0.014127
	18	203	-1.38256	1.11952	1.77898	0.0218489	0.02358
	18	204.5	-0.254443	2.63758	2.64983	0.0306063	0.015334
	18	206	2.38718	-0.072959	2.38829	0.0472927	0.036701
25	24	200	3.13573	-0.027319	3.13585	0.0445949	0.032197
	24	201.5	-0.646294	-1.71453	1.8323	0.0322942	0.028012
	24	203	-2.18957	0.0094815	2.18959	0.0293844	0.032097
	24	204.5	-1.62383	1.08662	1.95386	0.0386179	0.018853
	24	206	0.918622	-2.54687	2.70747	0.0544894	0.035386
30							

FIGS. 46 to 48 show lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 45.

All embodiments shown in FIGS. 17 to 52 show optical systems having a rectangular object field.

FIGS. 49 to 50 show another embodiment of the invention having four mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror S1, a second mirror S2, a third mirror S3, a

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fourth mirror S4. All subsequent tables with optical data refer to the mirrors S1 to S4 as M1 to M4. For the embodiment according to FIGS. 49 to 50, the following data are given:

- 5 Numerical aperture: 0.22
 Imaging factor: 1:4
 Form of object fields: ring segments having a radius of 600 mm and an azimuth angle of
- 10 $-4,8^\circ < \varphi < +4,8^\circ$
 Width of scanning field on the object side: 100 mm
 Height of scanning field on the object side: 8 mm
 Length: 2418 mm
 Tilt of image plane: $-3,284^\circ$.

15

This embodiment shows that the design advantages are transferable to optical systems with non-rectangular object fields.

The optical data can be seen from the following tables:

20

Surface	Radius	Thickness	Mode
Object	INFINITY	2102,043	
Mirror 1	3086,275	-1760,111	REFL
Mirror 2	2547,993	1960,753	REFL
Mirror 3	727,984	0,000	REFL
STOP	INFINITY	-360,225	
Mirror 4	749,971	475,405	REFL
Image	INFINITY	0,000	

Coefficient	M1	M2	M3	M4	Image
Y-decenter	-59,076	61,644	42,310	44,405	30,452
X-rotation	-2,561	-2,218	-2,136	-1,933	-3,284

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Coefficient	M1	M2	M3	M4
K	2,00E-01	1,89E-02	-1,89E+00	4,80E-01
Y	4,23E-02	2,05E-02	5,14E-02	1,08E-02
X2	3,46E-04	6,56E-06	-7,12E-04	-6,02E-05
Y2	1,53E-04	8,72E-06	8,61E-05	1,95E-04
X2Y	-4,18E-07	4,24E-10	1,15E-06	1,02E-07
Y3	4,10E-07	2,56E-08	1,76E-07	-4,73E-07
X4	2,12E-09	2,92E-11	7,50E-08	-3,49E-09
X2Y2	5,90E-10	1,00E-10	1,77E-07	-2,72E-09
Y4	4,49E-10	5,40E-11	8,13E-08	-1,87E-09
X4Y	-3,35E-11	-1,41E-13	9,25E-11	-4,80E-12
X2Y3	1,08E-11	-2,57E-13	6,96E-11	-2,94E-11
Y5	-2,41E-12	-4,00E-14	1,39E-10	-5,57E-12
X6	-3,85E-13	-3,65E-17	1,18E-12	-4,06E-14
X4Y2	2,15E-13	8,00E-16	4,59E-12	-3,08E-13
X2Y4	-4,13E-14	1,38E-15	5,36E-12	-5,08E-13
Y6	-8,84E-15	1,00E-16	1,93E-12	4,48E-13
X6Y	7,18E-15	-4,72E-19	-7,85E-15	1,73E-15
X4Y3	-6,02E-16	-1,61E-18	-1,51E-14	2,44E-16
X2Y5	7,75E-17	-2,49E-18	1,58E-14	-2,98E-15
Y7	1,31E-17	-1,67E-19	-2,79E-14	6,45E-15
X8	-1,06E-17	-5,96E-22	5,82E-17	5,31E-18
X6Y2	-3,13E-17	1,16E-20	2,73E-16	2,65E-17
X4Y4	1,56E-18	3,02E-21	3,20E-16	6,02E-17
X2Y6	-2,21E-19	2,55E-21	-6,39E-18	3,59E-17
Y8	1,87E-20	3,05E-22	6,46E-17	2,87E-17
X8Y	7,61E-20	-2,02E-24	3,28E-18	-4,79E-20
X6Y3	-7,15E-20	-4,82E-23	1,05E-17	-4,21E-19
X4Y5	-2,92E-21	-1,16E-24	-3,75E-18	7,33E-19
X2Y7	1,11E-22	-5,59E-25	-4,58E-18	5,27E-19
Y9	3,34E-24	-4,27E-27	8,58E-19	1,71E-20
X10	1,71E-23	2,57E-28	-2,76E-21	-5,14E-22
X8Y2	-2,62E-23	1,39E-26	-1,87E-20	-3,15E-21
X6Y4	4,86E-22	5,94E-26	-2,67E-20	-6,00E-21
X4Y6	-9,99E-24	-5,21E-28	6,16E-20	3,68E-21
X2Y8	6,99E-25	7,71E-28	3,25E-20	2,02E-21
Y10	1,70E-26	1,19E-29	1,19E-20	9,56E-23
Nradius	3,00E+00	3,00E+00	3,00E+00	3,00E+00

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	X _{Object} /mm	Y _{Object} /mm	Distortion (x)/nm	Distortion (y)/nm	Absolute Value of Distortion/nm	Telecentricity/ Degrees	Wavefront Error at 13,5 nm
5	0	600	0	-0.892917	0.892917	0.0133679	0.012256
	0	602	0	-0.841667	0.841667	0.00534092	0.016933
	0	604	0	0.0201694	0.0201694	0.00275272	0.021805
	0	606	0	0.379474	0.379474	0.0109134	0.010404
	0	608	0	-1.08242	1.08242	0.0191416	0.02706
10	12.5655	599.868	-0.463563	-0.551102	0.720142	0.0164908	0.01867
	12.6073	601.868	-0.477332	-0.590644	0.759412	0.0108284	0.018161
	12.6492	603.868	-0.257454	0.245037	0.355423	0.0095748	0.022897
	12.6911	605.867	0.191813	0.643426	0.671409	0.0140875	0.014667
	12.733	607.867	0.866074	-0.713531	1.12215	0.0209974	0.029184
15	25.1254	599.474	-0.531595	0.291324	0.606187	0.0234981	0.028751
	25.2091	601.472	-0.737092	-0.0428674	0.738337	0.0195942	0.018248
	25.2929	603.47	-0.47659	0.691569	0.839884	0.0185603	0.0228
	25.3766	605.468	0.241321	1.18393	1.20828	0.0209057	0.018522
	25.4604	607.467	1.40777	0.117965	1.4127	0.0257861	0.030662
20	37.6743	598.816	0.166072	1.07231	1.08509	0.0319492	0.037305
	37.7999	600.812	-0.597255	0.172817	0.621755	0.0288103	0.012352
	37.9255	602.808	-0.665059	0.662666	0.938845	0.0277044	0.017593
	38.0511	604.804	-0.0504098	1.23414	1.23517	0.0289218	0.01636
	38.1766	606.8	1.23319	0.573939	1.36021	0.0322511	0.025322
25	50.2067	597.896	1.97056	0.813316	2.13181	0.0409886	0.048287
	50.3741	599.889	0.0758373	-1.03335	1.03613	0.0381837	0.020354
	50.5414	601.882	-0.898661	-1.045	1.37827	0.0369235	0.027327
	50.7088	603.875	-0.970685	-0.525246	1.10368	0.0374078	0.03097
	50.8761	605.868	-0.159467	-1.30833	1.31801	0.0398057	0.030446
30							

FIG. 50 shows lateral aberrations in the coordinate system of the exit pupil of the objective according to FIG. 49.

FIG. 51 shows another embodiment of the invention having six mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror M1, a second mirror M2, a third mirror M3, a fourth mirror M4, a fifth mirror M5 and a sixth mirror M6. This projection objective has an image side numerical aperture of 0,40. The field shape is rectangular with a width of 26 mm and a height of 2 mm. The operating wavelength is

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13,5 nm. The sequence of optical power of mirrors is PNPNNP. This optical system has one intermediate image between mirrors M4 and M5. The entrance pupil of this projection objective is located 1000 mm from object plane 3000, with the object plane 3000 positioned between the entrance pupil and the mirrors. The tracklength is 1736 mm. The object image shift is 65 mm. The optical path length is 4827 mm.

The performance of this projection objective includes an image-side W_{rms} of 0,037 λ . Distortion is smaller than 12 nm. Image-side field curvature is 25 nm.

10

The chief ray angle of the central field point at the object is 7°. The maximum variation of chief ray angles at object plane 3000 is 0,82.

The dimension of the footprint of each mirror, given as $M_x \times M_y$ is as follows:
 15 323 mm x 215 mm for mirror M1; 131 mm x 102 mm for mirror M2; 267 mm x 183 mm for mirror M3; 70 mm x 52 mm for mirror M4; 124 mm x 109 mm for mirror M5; 447 mm x 433 mm for mirror M6.

The chief ray angle of incidence for the central field point for the mirrors M1 to M6 is 4,06°; 11,34°; 12,20°; 31,60°; 12,27° and 7,64°. The maximum angles of incidence in meridional section for the mirrors M1 to M6 is 4,96°; 12,38°, 16,54°, 41,24°; 29,42° and 9,25°. The bandwidth of angle of incidence in meridional section for mirrors M1 to M6 is 1,08°; 2,71°; 9,83°; 22,72°; 29,13° and 4,28°. Mirrors M2 and M4 have freeboards that are more than
 25 5mm and less than 25 mm. Mirror M3 has positive chief ray angle magnification while mirrors M1, M2, M4 and M5 have negative chief ray angle magnification.

The image-side free working distance of this projection objective is 45 mm.

30 The object-side free working distance is 400 mm.

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In this projection objective, d_{OP-1}/d_{OP-2} is 2,67. Further, reticle and mirror M1 as well as mirrors M2 and M3 are separated by more than 50 % of the projection objective tracklength.

5

Data for the projection objective of FIG. 51 is presented in Tables 8A, 8B below. Table 8A presents optical data, while Table 8B presents aspherical constants for each of the mirror surfaces.

Surface	Radius	Thickness	Mode
Object	INFINITY	1067,761	
Mirror 1	-1219,687	-668,241	REFL
Mirror 2	-747,811	1291,054	REFL
Mirror 3	-969,893	-374,588	REFL
Mirror 4	-549,105	374,588	REFL
Mirror 5	470,063	-502,811	REFL
Mirror 6	618,025	547,811	REFL
Image	INFINITY	0.000	

10

Table 8A

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Coefficient	M1	M2	M3	M4	M5	M6
K	5,078166E-01	2,515234E+00	4,458912E-01	-5,135256E+00	3,709497E+00	1,305537E-01
Y	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
X2	-4,229616E-06	4,423002E-05	-1,137338E-04	6,243736E-04	-4,439433E-04	1,714681E-05
Y2	-2,042693E-05	-3,200090E-04	-1,490188E-04	4,230830E-05	-3,941063E-04	1,369711E-05
X2Y	-2,456512E-08	-1,681122E-06	1,278895E-08	1,439095E-06	1,109021E-07	-7,066857E-09
Y3	-1,017618E-08	-1,085440E-06	-9,040764E-08	-8,248306E-07	6,038369E-07	-8,198184E-09
X4	2,532498E-11	-4,655202E-10	-6,082020E-11	-7,879275E-09	-9,475896E-10	-9,236663E-12
X2Y2	2,917327E-11	-4,875362E-09	-7,951092E-11	-6,364830E-09	-2,626820E-09	-1,778520E-11
Y4	1,116055E-11	9,584332E-10	-1,259982E-10	2,921676E-09	-8,367567E-10	-1,348267E-11
X4Y	-7,018800E-15	-9,924549E-12	-5,700215E-14	-7,337153E-11	-3,015573E-13	-5,057127E-15
X2Y3	-2,588267E-14	-2,065300E-11	-1,623609E-13	-4,830483E-11	-3,421535E-12	-8,177430E-15
Y5	-5,631482E-14	1,175099E-13	-3,257076E-14	2,900148E-11	-5,156003E-12	-7,754740E-16
X6	2,507037E-17	7,181890E-15	-6,970398E-17	1,896541E-13	-2,402650E-14	-1,687447E-17
X4Y2	1,805398E-16	2,845435E-14	-1,726885E-16	-3,660328E-13	-3,460882E-14	-5,258270E-17
X2Y4	3,234883E-16	4,275982E-14	-3,443645E-16	-1,119940E-13	-2,515640E-14	-4,418332E-17
Y6	5,139221E-17	1,240058E-14	-4,807113E-19	2,665448E-14	-3,989968E-14	-9,729792E-18
X6Y	-1,655261E-20	2,112846E-16	-6,490967E-20	2,217817E-15	3,565159E-17	-2,533468E-21
X4Y3	6,406762E-19	7,287537E-16	-1,578781E-19	-1,022968E-15	-2,246920E-17	-9,556211E-21
X2Y5	1,095531E-18	4,084428E-16	-1,899934E-19	8,581644E-18	-4,609677E-16	-8,095822E-21
Y7	3,534107E-19	-1,119501E-16	-6,323108E-20	-1,566387E-16	-4,089822E-16	7,022063E-21
X8	-2,127854E-23	5,631762E-20	-1,645304E-22	-2,809082E-18	-2,426092E-19	-2,519698E-23
X6Y2	-2,911239E-22	1,595162E-18	1,240419E-22	8,883017E-18	-3,131391E-18	-1,169336E-22
X4Y4	2,052045E-21	3,313410E-18	-2,644748E-22	-1,246599E-18	-8,074234E-18	-1,413514E-22
X2Y6	2,303292E-21	8,331439E-19	-5,379641E-23	2,833584E-19	-6,891166E-18	-6,982184E-23
Y8	7,915735E-22	-4,495038E-19	-9,241853E-23	-3,000322E-19	-2,367176E-18	-1,361196E-23
X8Y	-3,633622E-25	-1,145501E-22	-8,423039E-26	-1,268652E-20	2,592347E-21	4,570116E-27
X6Y3	-1,500591E-24	1,545859E-21	6,330084E-25	1,171733E-20	1,459272E-21	1,168279E-26
X4Y5	2,954923E-24	3,997308E-21	1,050127E-26	-4,257185E-23	-1,756358E-22	1,479131E-26
X2Y7	1,472672E-24	3,951572E-22	8,889089E-29	-7,100170E-25	5,863402E-23	6,095900E-27
Y9	4,265712E-25	-3,958881E-23	-1,136961E-30	-9,034885E-27	7,298215E-25	4,531322E-28
X10	1,301003E-29	1,955419E-24	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
X8Y2	-6,199954E-28	-8,094414E-25	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
X6Y4	-1,564267E-27	-8,554437E-24	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
X4Y6	2,214569E-27	1,149257E-24	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
X2Y8	-6,083137E-29	6,386629E-26	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
Y10	1,486303E-30	1,060932E-26	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
Nradius	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00

Coefficient	M1	M2	M3	M4	M5	M6
Y-decenter	248,450	92,818	-2,826	26,446	-4,799	29,811
X-rotation	8,882	-0,938	1,151	-1,082	-3,174	-3,333

Table 8B

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The projection objective of FIG. 51 differs from the embodiments of FIGS. 3, 10, 11, 12, 13, 14 and 15 mainly in the shape of mirror M4. In contrast to these earlier described embodiments, mirror M4 of the embodiment of FIG. 51
5 is convex.

FIG. 52 shows another embodiment of the invention having six mirrors being all designed as freeform surfaces. Depicted is the object plane 3000, the image plane 3002, a first mirror M1, a second mirror M2, a third mirror M3, a fourth
10 mirror M4, a fifth mirror M5 and a sixth mirror M6. This projection objective has an image side numerical aperture of 0,35. The field shape is rectangular with a width of 26 mm and a height of 2 mm. The operating wavelength is 13,5 nm. The sequence of optical power of mirrors is PPNPNP. This optical system has one intermediate image between mirrors M4 and M5. The entrance
15 pupil of this projection objective is located on the image plane side of the object plane 3000 in a distance of 1749 mm. An aperture stop is positioned on mirror M2. The tracklength is 1700 mm. The object image shift is 41 mm. The optical path length is 4156 mm.

20 The performance of this projection objective includes an image-side W_{rms} of 0,020 λ . Distortion is smaller than 1,1 nm. Image-side field curvature is 17 nm.

The chief ray angle of the central field point at the object is 6°. The maximum
25 variation of chief ray angles at object plane 3000 is 0,58.

The dimension of the footprint of each mirror, given as $M_x \times M_y$ is as follows:
169 mm x 148 mm for mirror M1; 159 mm x 136 mm for mirror M2; 120 mm
x 61 mm for mirror M3; 265 mm x 118 mm for mirror M4; 101 mm x 77 mm
30 for mirror M5; 345 mm x 329 mm for mirror M6.

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The chief ray angle of incidence for the central field point for the mirrors M1 to M6 is 8,11°; 9,49°; 21,03°; 8,01°; 13,67°; 5,03°. The maximum angle of incidence in meridional section for the mirrors M1 to M6 is 10,31°; 12,06°; 21,56°; 8,45°; 24,59°; 6,36°. The bandwidth of angle of incidence in meridional section for mirrors M1 to M6 is 4,56°; 5,34°; 1,85°; 1,23°; 22,98°; 3,16°. Mirror M4 has positive chief ray angle magnification while mirrors M1, M2, M3 and M5 have negative chief ray angle magnification.

- 10 The image-side free working distance of this projection objective is 45 mm. The object-side free working distance is 441 mm.

In this projection objective, d_{OP-1}/d_{OP-2} is 1,89. Further, mirrors M4 and M5 are separated by more than 50 % of the projection objective tracklength.

15

Data for the projection objective of FIG. 52 is presented in Tables 9A, 9B below. Table 9A presents optical data, while table 9B presents aspherical constants for each of the mirror surfaces.

Surface	Radius	Thickness	Mode
Object	INFINITY	831,483	
Mirror 1	-2519,290	-390,700	REFL
Mirror 2	1736,318	0,000	REFL
STOP	INFINITY	510,700	
Mirror 3	353,216	-404,591	REFL
Mirror 4	691,089	1108,132	REFL
Mirror 5	454,789	-432,650	REFL
Mirror 6	522,649	477,625	REFL

20

Table 9A

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Coefficient	M1	M2	M3	M4	M5	M6
X	-5,620176E+01	-8,079329E+00	-8,913161E-01	-1,320517E+00	4,540035E+00	8,058603E-02
Y	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00	0,000000E+00
X2	-8,081674E-05	-2,443257E-05	-2,909041E-04	-5,514277E-05	-2,176416E-04	-1,481415E-05
Y2	-1,409006E-04	-8,853894E-05	-5,146801E-04	-2,593301E-05	1,796509E-04	7,215641E-06
X2Y	1,932586E-07	4,504714E-08	9,969292E-07	-1,801177E-07	1,153365E-06	5,683301E-09
Y3	-1,223280E-07	-1,884294E-08	-4,877028E-07	1,179942E-07	-2,117705E-07	-5,600182E-09
X4	-7,040228E-11	7,425419E-11	2,136430E-09	4,622733E-10	-1,333652E-09	-5,926598E-11
X2Y2	-1,318594E-10	1,067519E-10	9,622356E-09	-4,928633E-10	1,322772E-08	-2,894278E-11
Y4	6,586919E-11	1,598749E-10	9,675806E-10	8,019884E-10	3,924061E-09	1,500259E-11
X4Y	-1,333049E-12	9,551370E-14	4,142100E-11	7,245165E-13	-2,333334E-11	8,269178E-15
X2Y3	-7,486772E-12	-5,744418E-13	2,571945E-11	-5,121409E-12	-4,081436E-11	-1,142259E-14
Y5	-7,859762E-14	-1,146786E-12	1,015135E-12	7,149294E-13	-3,294173E-11	-6,514010E-14
X6	-1,349693E-17	-2,093126E-15	5,786287E-14	7,466543E-16	3,666869E-14	-1,312132E-16
X4Y2	-4,117907E-15	3,600153E-15	1,917870E-13	4,761724E-15	1,666994E-13	-1,600140E-16
X2Y4	2,686652E-14	2,433374E-14	1,452311E-14	-1,001928E-14	1,713311E-13	4,528614E-17
Y6	-6,985464E-16	-1,574024E-15	-4,040479E-15	1,285725E-15	3,233877E-13	1,795344E-16
X6Y	-6,324670E-18	1,672711E-17	6,549813E-16	7,589572E-18	1,109670E-15	7,389564E-20
X4Y3	1,633680E-16	-5,475446E-17	2,838607E-16	1,219368E-17	1,040774E-15	-3,901601E-20
X2Y5	2,578083E-17	-2,114042E-17	-8,191058E-17	-1,112382E-17	-4,281539E-15	-8,922758E-19
Y7	-5,352170E-18	-4,852332E-17	-8,778735E-18	1,658599E-18	-1,041652E-15	-5,361021E-19
X8	3,930907E-20	-3,041873E-20	1,620935E-18	3,142617E-21	-2,044671E-18	-3,471237E-22
X6Y2	2,642712E-19	1,926793E-19	2,461846E-18	4,103145E-20	9,496169E-18	-5,396836E-22
X4Y4	-1,209256E-18	7,815308E-19	2,461216E-20	2,400689E-20	2,006336E-17	4,153767E-23
X2Y6	-5,242330E-19	-2,345008E-19	-1,129636E-20	-4,573196E-22	-8,505126E-18	2,958769E-21
Y8	5,723961E-20	-4,523191E-19	2,359743E-20	2,441529E-21	2,039563E-17	1,076978E-21
X8Y	-5,843186E-22	4,059084E-22	1,256052E-20	1,926704E-23	-6,283441E-20	8,511910E-25
X6Y3	-1,725684E-21	-3,122858E-21	2,334258E-21	9,329420E-23	-1,729457E-19	2,027558E-25
X4Y5	4,331458E-21	-1,961697E-21	8,015847E-22	2,907419E-23	2,503951E-19	-5,006594E-24
X2Y7	1,628473E-21	-1,158132E-20	2,742066E-22	8,412546E-24	-3,164177E-19	-7,133872E-24
Y9	-2,174037E-22	-5,641899E-21	-6,405172E-23	1,117517E-24	1,693513E-19	-7,896547E-25
X10	3,942480E-26	-1,611794E-24	-3,181193E-25	1,249724E-27	-2,648224E-23	-6,952534E-28
X8Y2	2,026760E-24	2,715637E-24	2,416966E-23	3,491430E-26	-5,242301E-22	-5,078551E-27
X6Y4	3,177651E-24	1,517348E-23	-1,929381E-24	8,815740E-26	-7,406490E-22	-1,604907E-26
X4Y6	-6,089337E-24	-2,527074E-23	2,506522E-24	2,875808E-26	3,978023E-21	4,391294E-28
X2Y8	-1,609759E-24	-7,803424E-23	1,589355E-25	1,072608E-26	-2,716665E-21	4,653881E-27
Y10	2,665008E-25	-1,428174E-23	-2,253314E-25	5,234796E-28	1,510394E-21	-1,026184E-27
Nradius	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00

Coefficient	M1	M2	M3	M4	M5	M6
Y-decenter	-107,723	-48,244	142,711	9,140	15,331	1,453
X-rotation	-3,086	0,713	-20,000	-1,900	0,245	2,474

Table 9B

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The projection objective of FIG. 52 has chief rays converging to each other while starting from the object plane 3000.

5 Microlithography tools, such as microlithography tool 100 described above and shown in FIG. 1, can be used in the fabrication of semiconductor devices, such as semiconductor chips, liquid crystal display (LCD) panels, or arrays of charge coupled device (CCD) detectors, for example. Generally, the sequence of process steps used in the fabrication of semiconductor devices varies
10 depending on the specific device being fabricated. FIG. 53 is a flow chart that shows an example of a sequence of steps in the manufacture of a semiconductor device. Initially, in step 5310 the producer designs the integrated circuit to be manufactured for the semiconductor device. Subsequently, in step 5320 masks (i.e., reticles) are produced based on the
15 design of the integrated circuit. Prior to actually building the integrated circuit, wafers (e.g., silicon wafers) are prepared as indicated in step 5330. Next, the integrated circuit is formed on the wafer using the masks in a wafer processing step (step 5340). Details of wafer processing are discussed in greater detail below. After forming the integrated circuit in the wafer, the wafer is diced,
20 bonded, and packaged to produce individual microchips (step 5350). These assembly steps are often referred to as post-processing. After assembly, the chips are inspected (step 5360). For example, the chips' operability and/or durability may be tested. Those devices that pass inspection step 5360 are subsequently shipped to the customer (step 5370).

25

FIG. 54 is a flow chart showing details of the wafer processing step.

Generally, wafer processing involves forming a number of layers of various materials (e.g., conducting materials, semiconducting materials, and/or dielectric materials) on a wafer (Step 5410). One or more of these layers is
30 patterned using a lithographic process (Step 5420). The layers can be formed

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in a variety of ways. For example, forming the layer can involve oxidizing a surface of the wafer in an oxidation process step (Step 5411). In some embodiments, forming the layer involves depositing a material on a surface of the wafer, such as by chemical vapor deposition (CVD), for example (Step 5412). In certain embodiments, forming the layer involves an electrode forming process for forming electrodes on the wafer by vapor deposition, for example (Step 5412). Forming layers can involve an ion implanting process for implanting ions to the wafer (Step 5414).

After forming a layer of a material, the layer can be patterned using a lithographic process. This typically involves a resist process for applying a resist to the wafer (Step 5415). Step 5416 is an exposure process for printing, by exposure, the circuit pattern of the mask on the wafer using a lithography tool, such as lithography tool 100 described above. Step 5417 is a developing process in which the exposed resist is develop. After developing, portions of the wafer exposed by the developed resist are etched in an etching process (Step 5418). Finally, the remaining resist material is removed from the wafer in a resist separation process (Step 5419).

Steps 5410 and 5420 are repeated forming integrated circuits on the wafer. Embodiments can include additional process steps, such as wafer polishing, for example, before or after patterning a layer of material.

Other embodiments are in the claims.

Claims

1. Microlithography projection optical system, comprising:
 a plurality of elements arranged to image radiation at a wavelength λ from
 an object plane to an image plane, at least one of the elements being a re-
 flective element that has a rotationally asymmetric surface positioned in a
 path of the radiation,
 wherein the rotationally asymmetric surface deviates from a best-fit rota-
 tionally symmetric surface by at least λ at at least one location.

2. The optical system of claim 1, wherein the best-fit rotationally asymmet-
 ric surface deviates by about 0.1λ or less from a surface corresponding to
 the equation:

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{j=2}^{\alpha} C_j x^m y^n$$

- where

$$j = \frac{(m+n)^2 + m + 3n}{2} + 1,$$

z is the sag of the surface parallel to an axis, c is the vertex curvature and
 k is the conical constant, C_j is the coefficient of the monomial $x^m y^n$, and α
 is an integer.

3. The optical system of claim 1 wherein the rotationally asymmetric surface
 deviates from the best-fit rotationally symmetric surface by about 10λ or
 more at the one or more locations.
4. The optical system of claim 1 wherein the rotationally asymmetric surface
 deviates from the best-fit rotationally symmetric surface by about 20 nm
 or more at the one or more locations.

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5. The optical system of claim 1 wherein the plurality of elements define a meridional plane and the elements are mirror symmetric with respect to the meridional plane.
- 5
6. The optical system of claim 1 wherein the plurality of elements comprises two elements that are reflective elements that have rotationally asymmetric surfaces positioned in a path of the radiation.
- 10
7. The optical system of claim 1 wherein the plurality of elements includes no more than two reflective elements that have a positive chief ray angle magnification.
8. The optical system of claim 7 wherein the plurality of elements includes no more than one reflective element that has a positive chief ray angle magnification.
- 15
9. The optical system of claim 1 wherein the microlithography projection optical system has an image-side numerical aperture of about 0.2 or more.
- 20
10. The optical system of claim 1 wherein the optical system has a rectangular field at the image plane and wherein in each of the orthogonal directions the rectangular field has a minimum dimension of about 1 mm or more in both directions being orthogonal to each other.
- 25
11. The optical system of claim 1 wherein static distortion at the image field is about 10 nm or less.
12. The optical system of claim 1 wherein a wavefront error at the image field is about $\lambda/14$ or less.
- 30

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13. The optical system of claim 1 wherein the chief rays diverge from each other at the object plane.
- 5 14. The optical system of claim 13 wherein, for a meridional section of the optical system, the chief rays have a maximum angle of incidence on a surface of each of the elements of less than 20° .
15. The optical system of claim 1 being telecentric at the image plane.
- 10 16. The optical system of claim 1 wherein a path of the radiation through the optical system is characterized by chief rays and, for a meridional section of the optical system, the chief ray of a central field point has a maximum angle of incidence on a surface of each of the elements of θ degrees, the
- 15 optical system has an image side numeral aperture, NA, of more than 0.3, and the ratio θ/NA is less than 68.
17. The optical system of claim 1 wherein the optical system has an object-image shift of about 75 mm or less.
- 20 18. The optical system of claim 1 wherein the plurality of elements comprises four or more elements that have freeboards of about 25 mm or less.
19. The optical system of claim 1 further comprising a radiation source con-
- 25 figured to provide the radiation at λ to an object plane.
20. The optical system of claim 19 further comprising an illumination system comprising one or more elements arranged to direct radiation from the radiation source to an object positioned at the object plane, wherein the il-

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lumination system comprises an element positioned at a location corresponding to an entrance pupil of the optical system.

21. A microlithography tool, comprising:

- 5 the optical system of claim 20;
 a first moveable stage configured to position a reticle at the object plane so that the optical system images the reticle to the image plane; and
 a second moveable stage configured to position an article at the image plane so that the image of the reticle at a surface of the article.

10

22. Method for microlithographic production of microstructured components comprising the following steps:

- providing a substrate having at least a layer of radiation sensitive material,
- 15 - providing a mask having a structure which is to be projected,
- providing a microlithographic tool according to claim 21,
- projection at least a part of the mask on an area of the layer using the microlithographic tool.

20 23. Microstructured component being produced by a method according to claim 22.

24. Method to design a rotationally asymmetric surface in an optical system according to one of claims 1 to 20, comprising the following steps:

- 25 - start from a design being rotational symmetric with respect to the path of radiation;
- decenter the rotational symmetric design by translating the axis of rotational symmetry with respect to the axis defined by the path of radiation parallel to this path axis;

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- tilt the rotational symmetric design by tilting the axis of rotational symmetry with respect to the path axis;
- minimization of optical aberrations by implementing a freeform deviation from the decentered and tilted design.