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(54) **PROJECTION OBJECTIVE FOR MICROLITHOGRAPHY**

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(57) **ABSTRACT**

A projection objective for use in microlithography, a microlithography projection exposure apparatus with a projection objective, a microlithographic manufacturing method for microstructured components, and a component manufactured under the manufacturing method are disclosed.

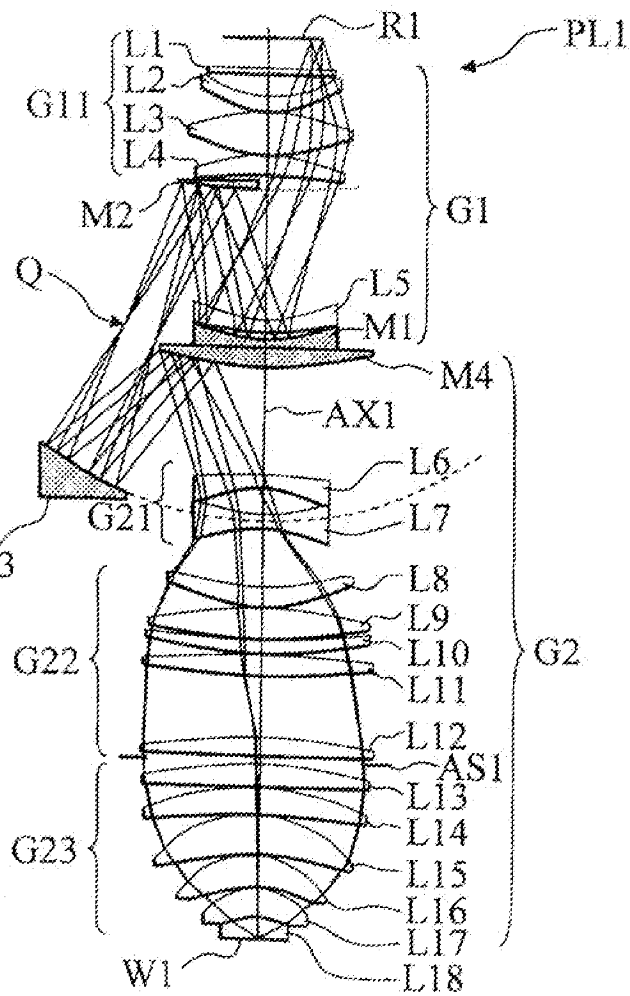


FIG.1

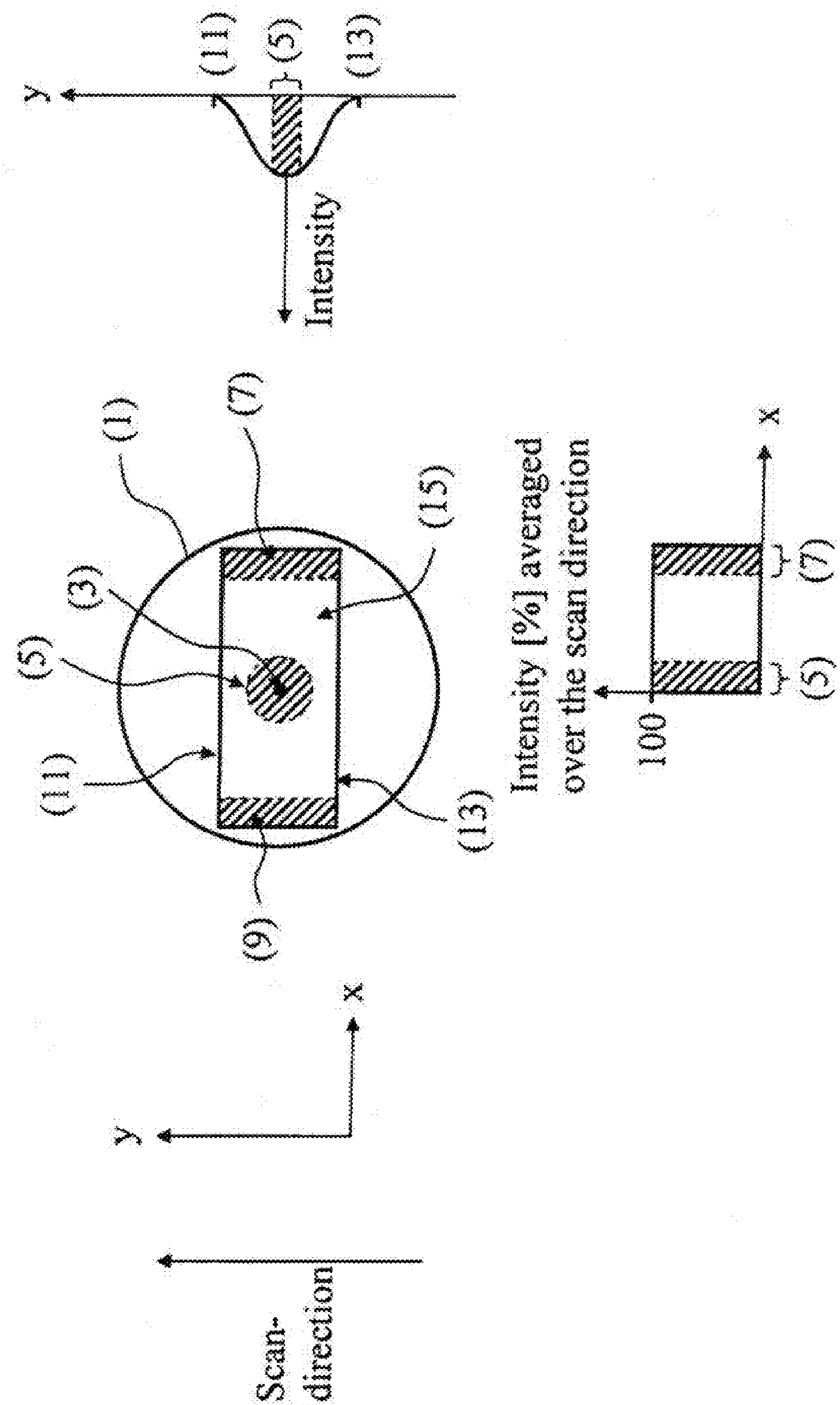

y
(11)
(5)
(13)
Intensity
(1)
(7)
(15)
(3)
(5)
(11)
(13)
(9)
Intensity [%] averaged
over the scan direction
100
(5)
(7)
x
y
x
Scan-
direction

FIG.4

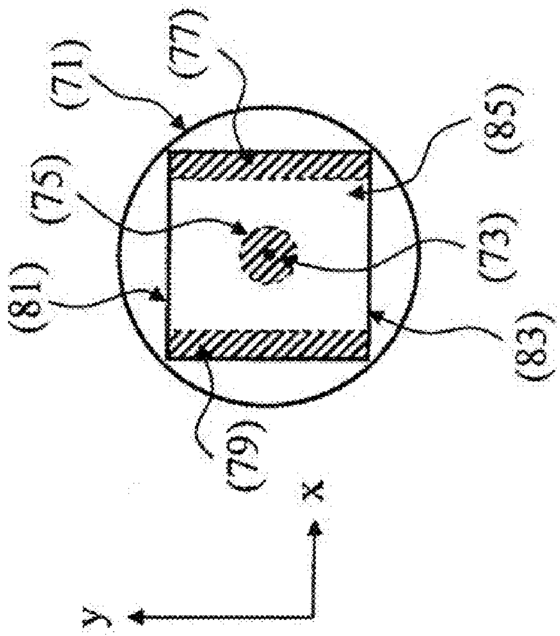


FIG.2

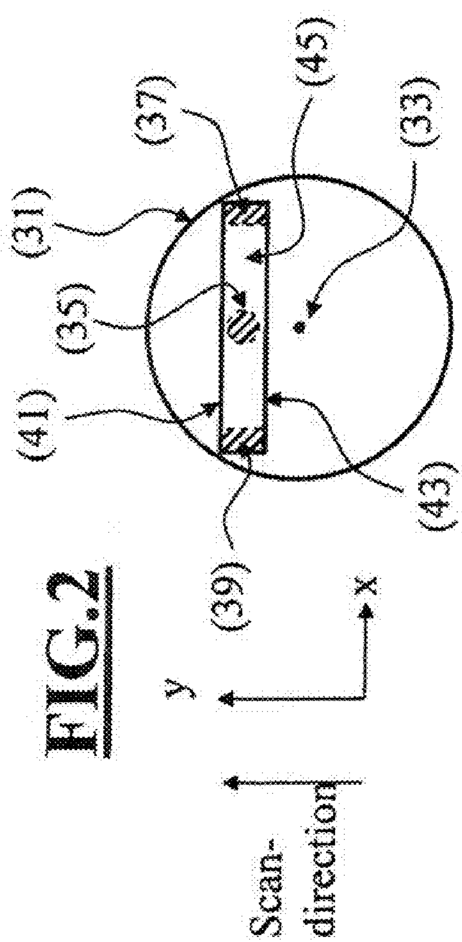


FIG.3

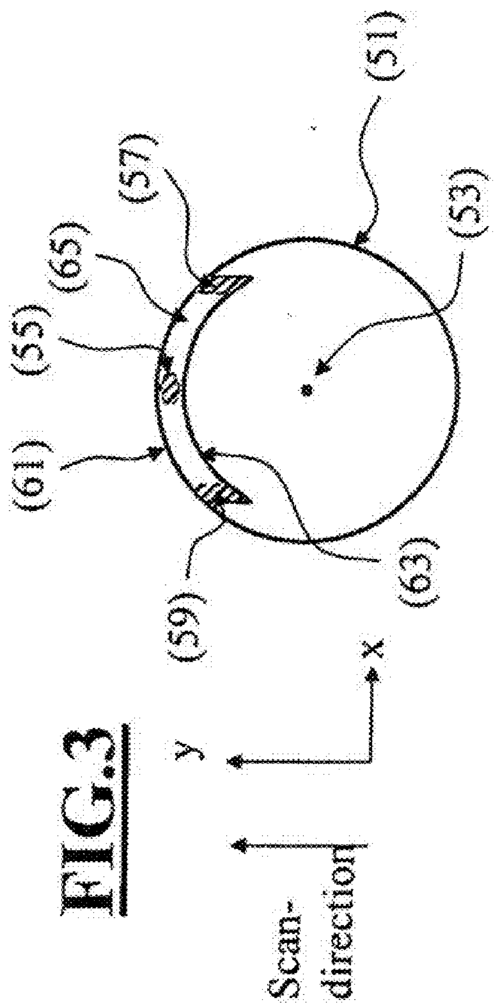


FIG.5

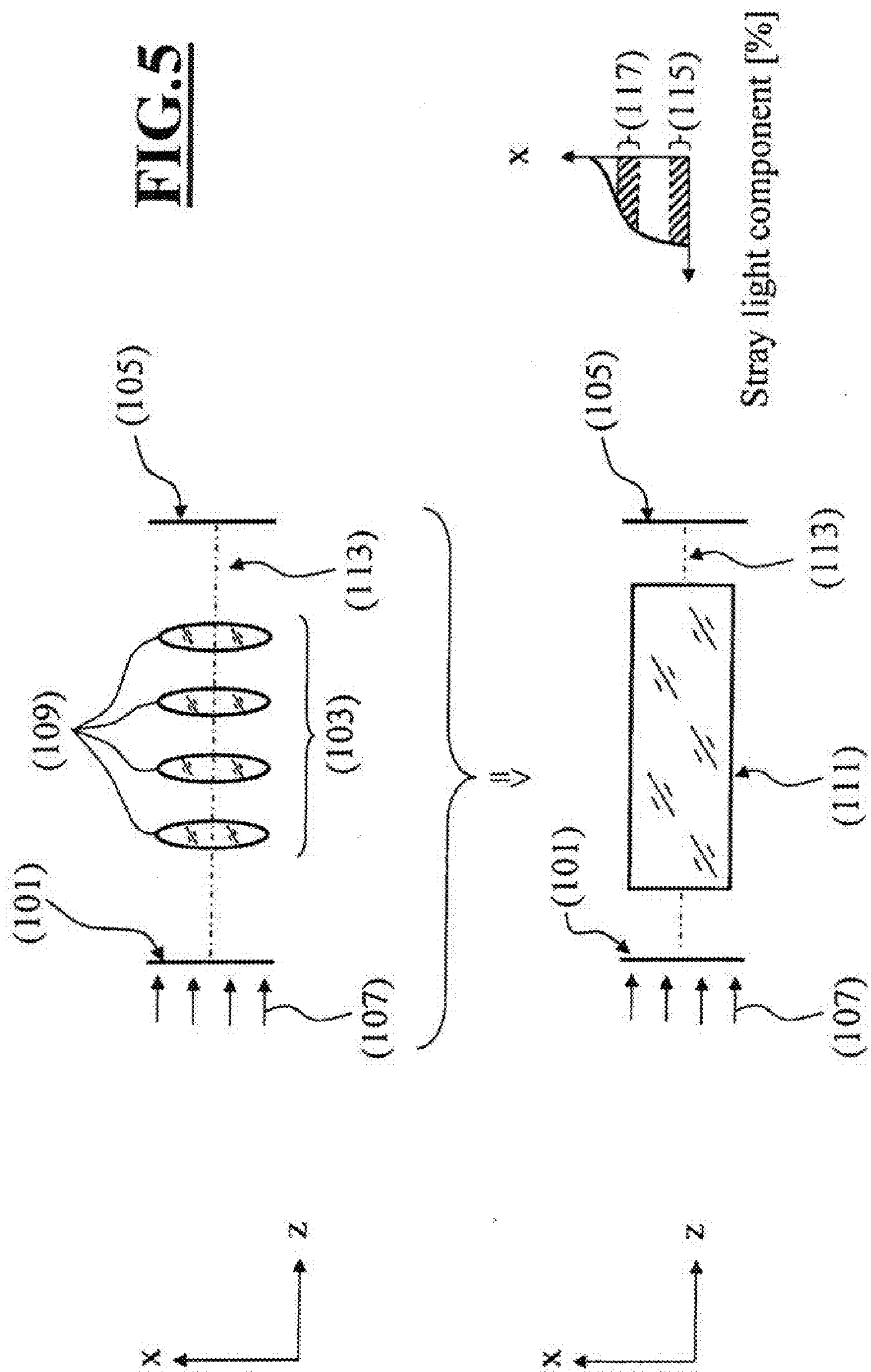


FIG.6

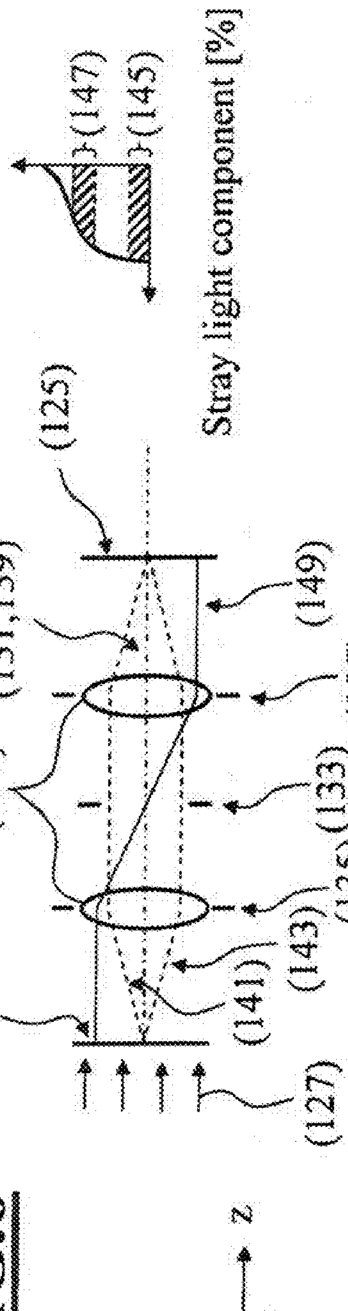

x
z
(127)
(121)
(141)
(143)
(135)
(129)
(133)
(137)
(123)
(131,139)
(149)
(125)
(145)
(147)
Stray light component [%]

FIG.7

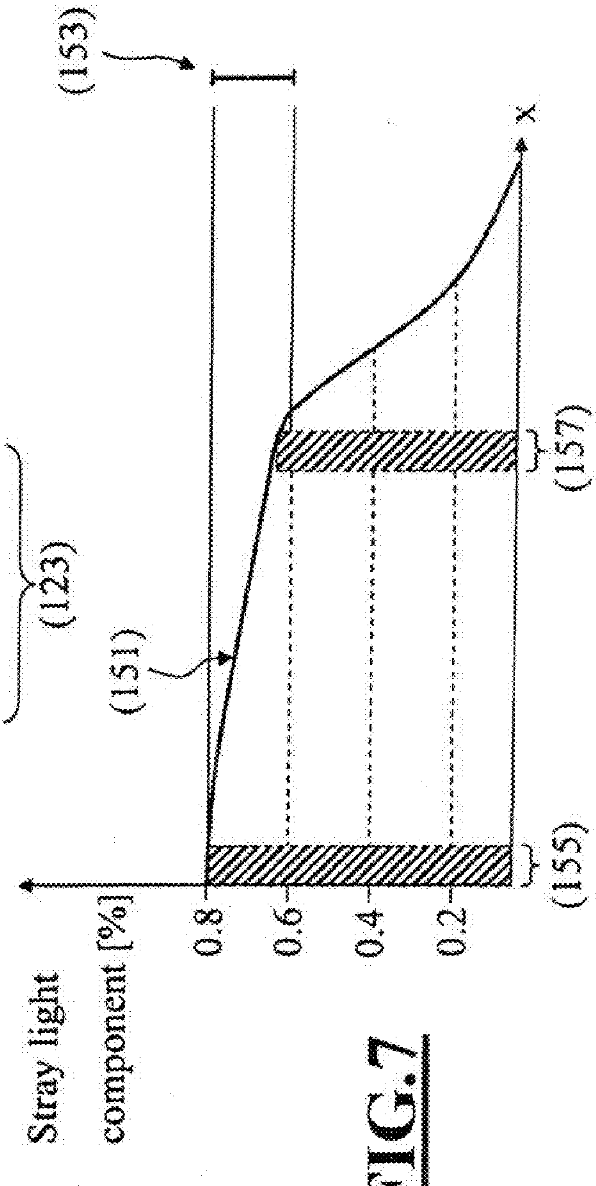

Stray light component [%]
0.8
0.6
0.4
0.2
(155)
(151)
(157)
(153)
x

FIG.8

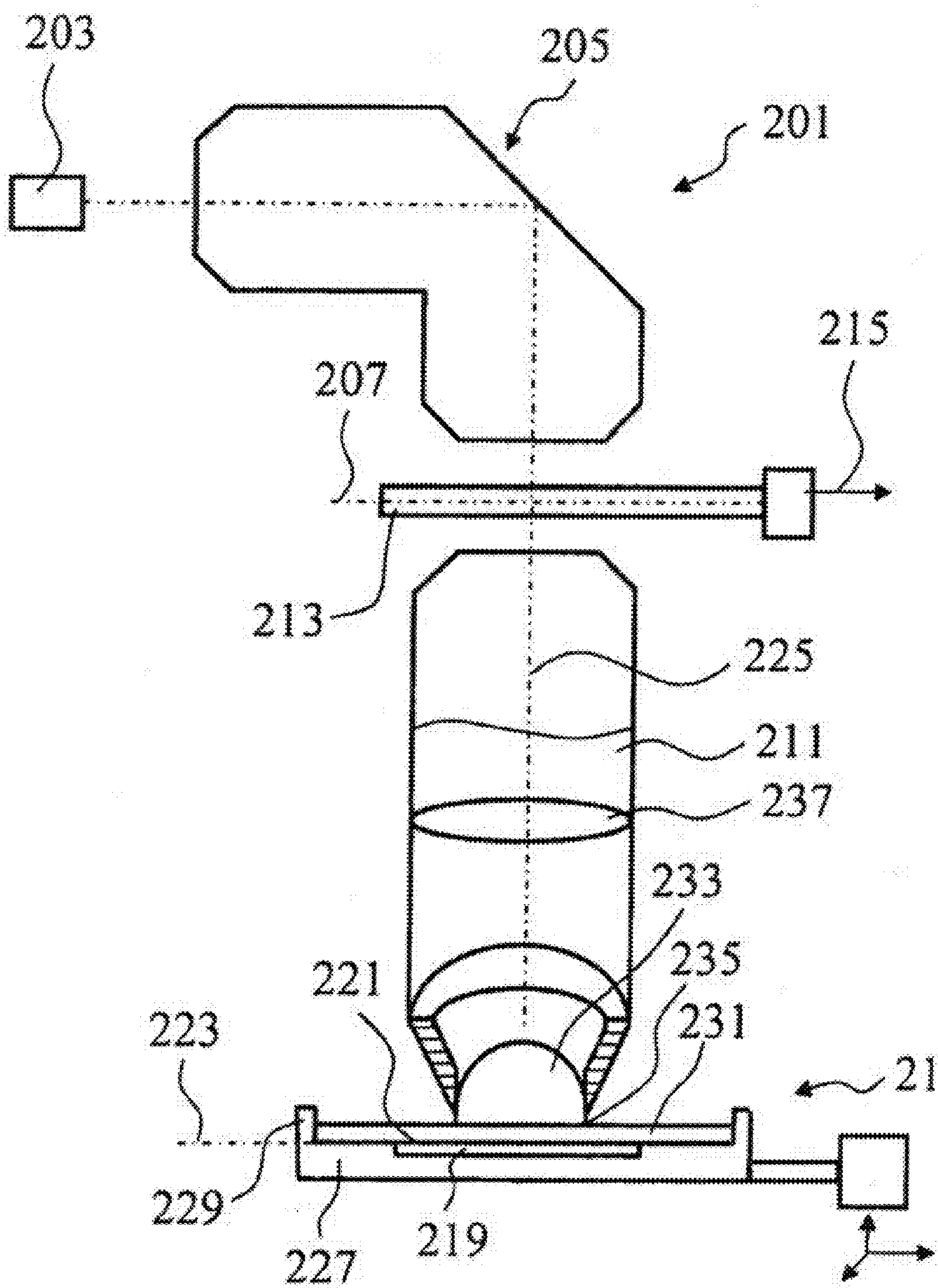

203
205
201
215
207
213
225
211
237
233
221
235
231
223
217
229
227
219

FIG.9

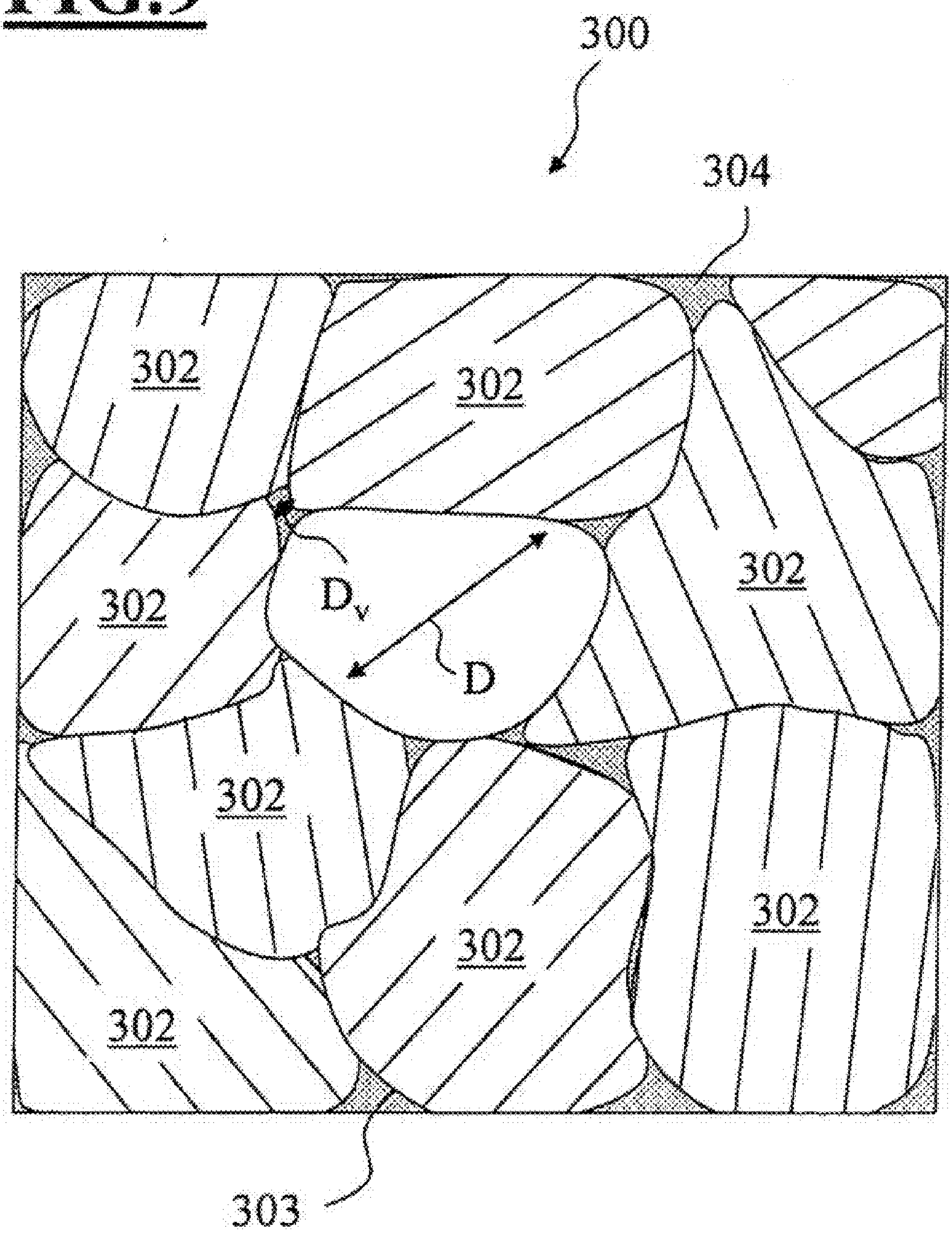


FIG.10

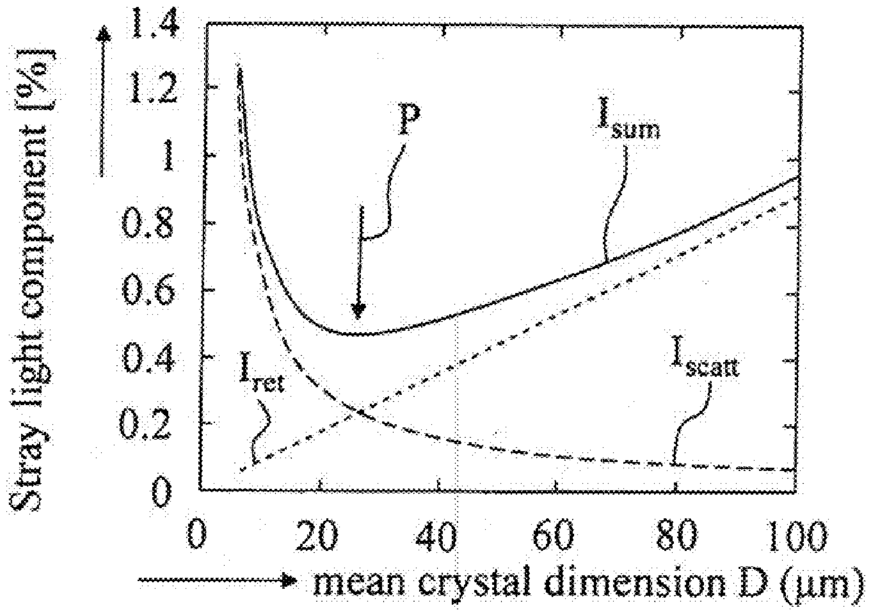

Stray light component [%]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
P
I_{sum}
I_{ret}
I_{scatt}
0
20
40
60
80
100
mean crystal dimension D (μm)

FIG11

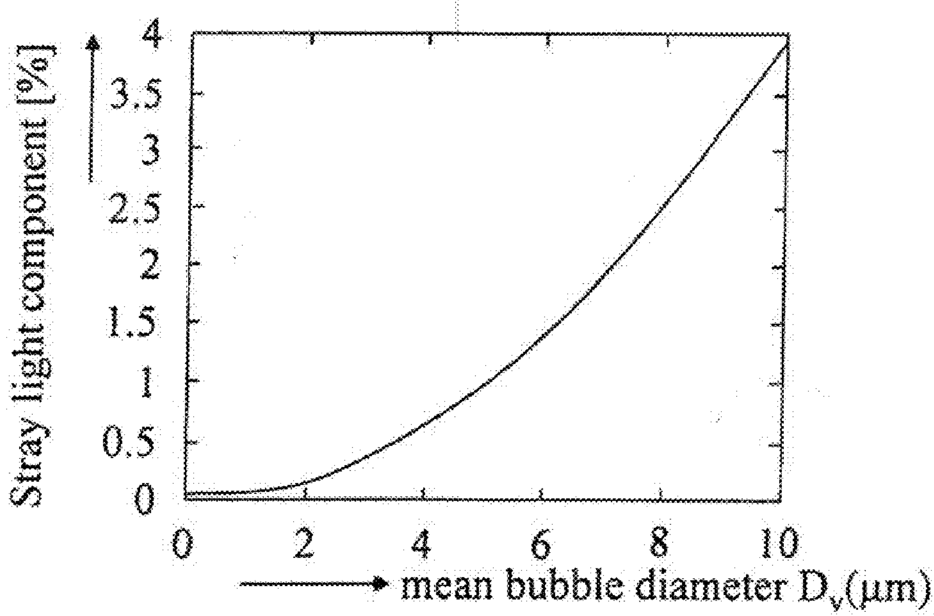

Stray light component [%]
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
mean bubble diameter D_v(μm)

FIG.12

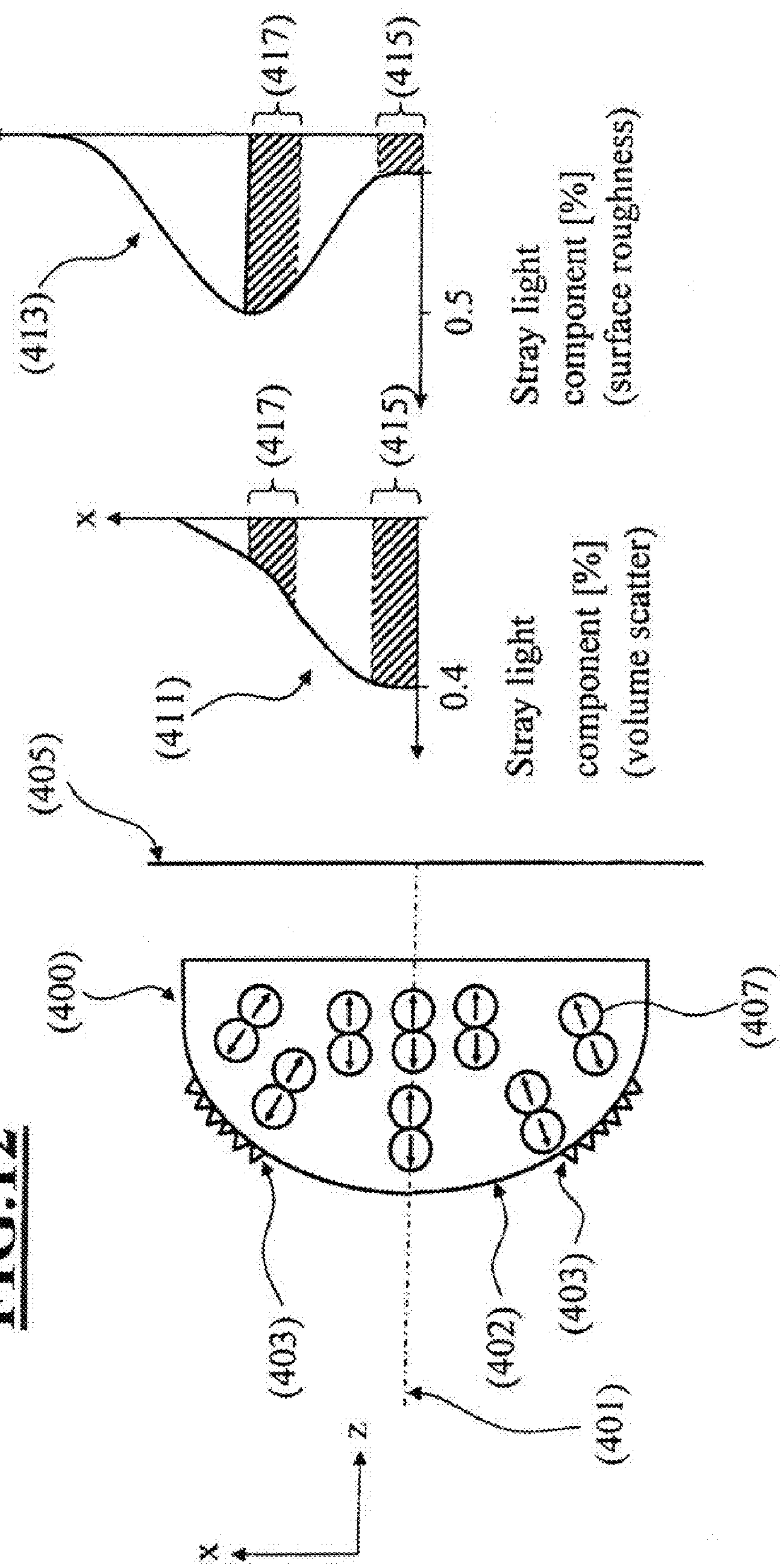

(400)
(401)
(402)
(403)
(403)
(405)
(407)
(411)
(413)
(415)
(417)
(415)
(417)
x
z
x
x
0.4
0.5
Stray light component [%] (volume scatter)
Stray light component [%] (surface roughness)

FIG.13

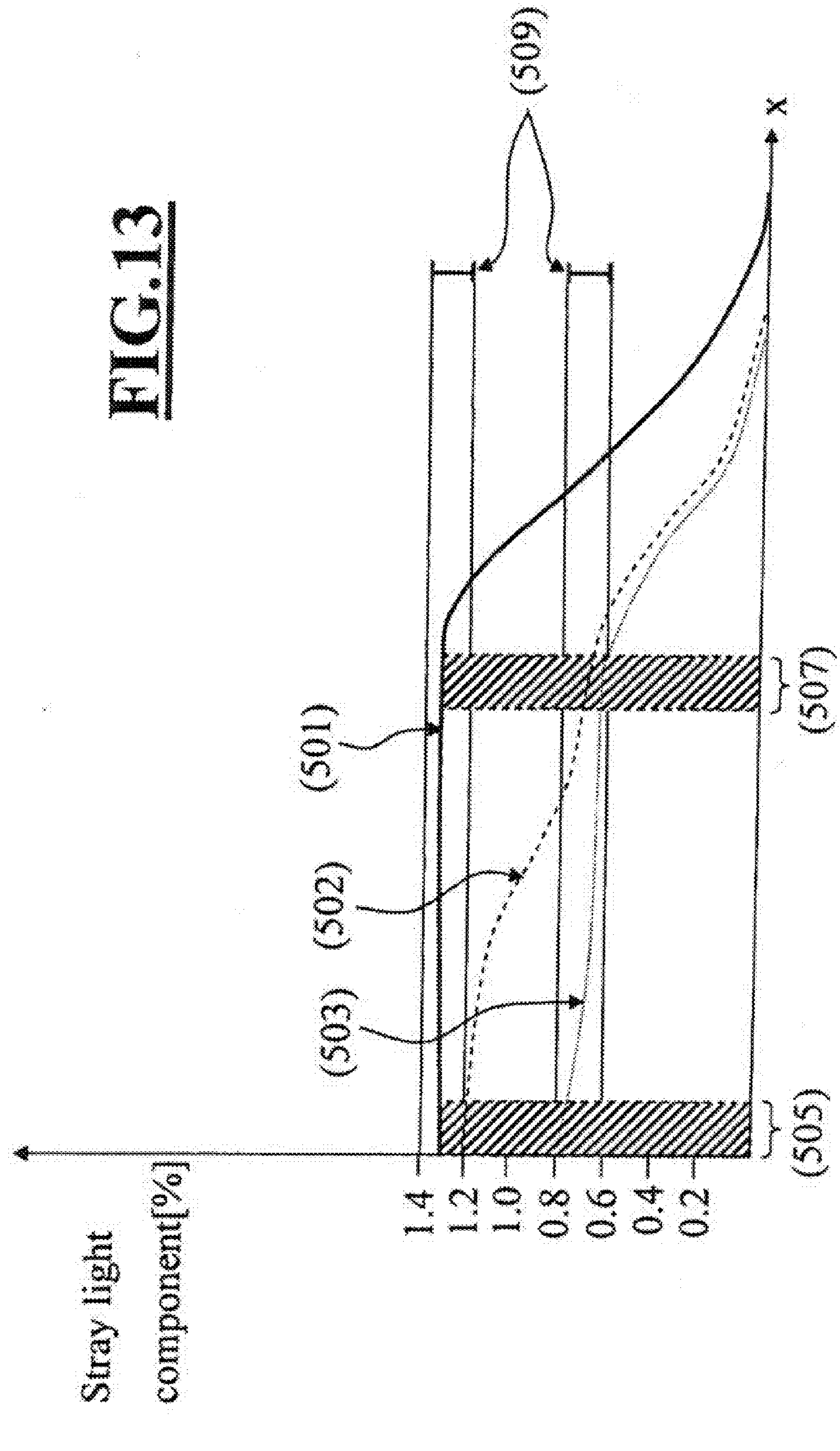

Stray light component[%]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
x
(501)
(502)
(503)
(505)
(507)
(509)

FIG.14a

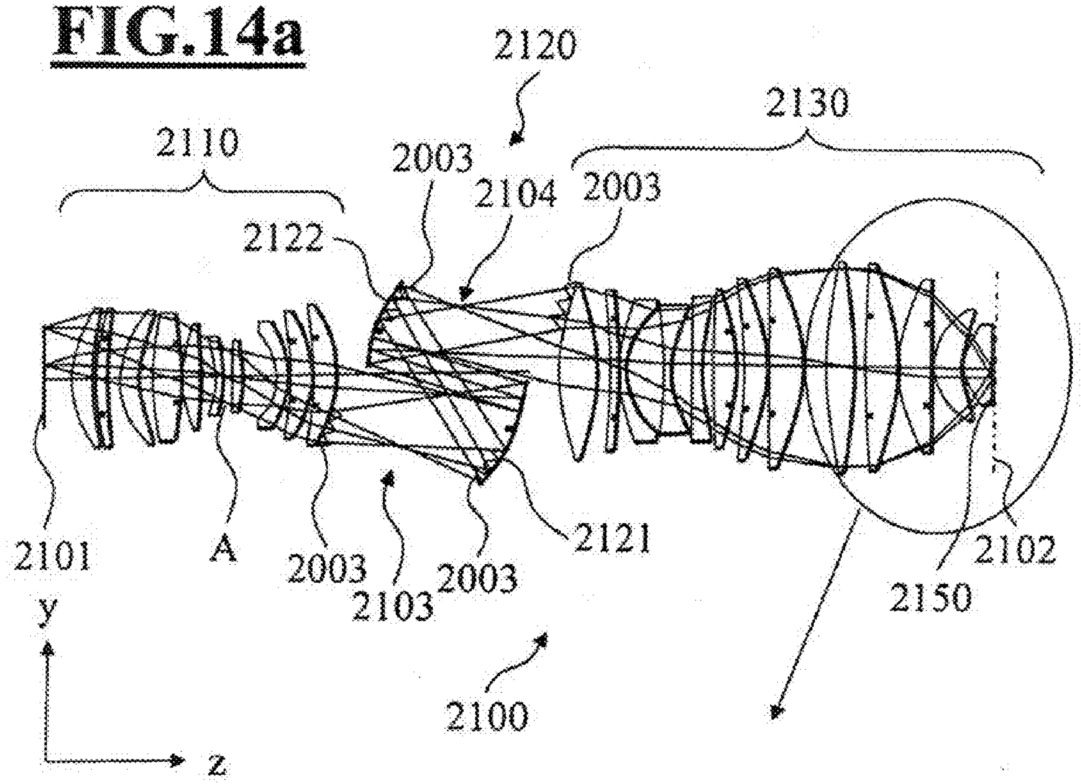
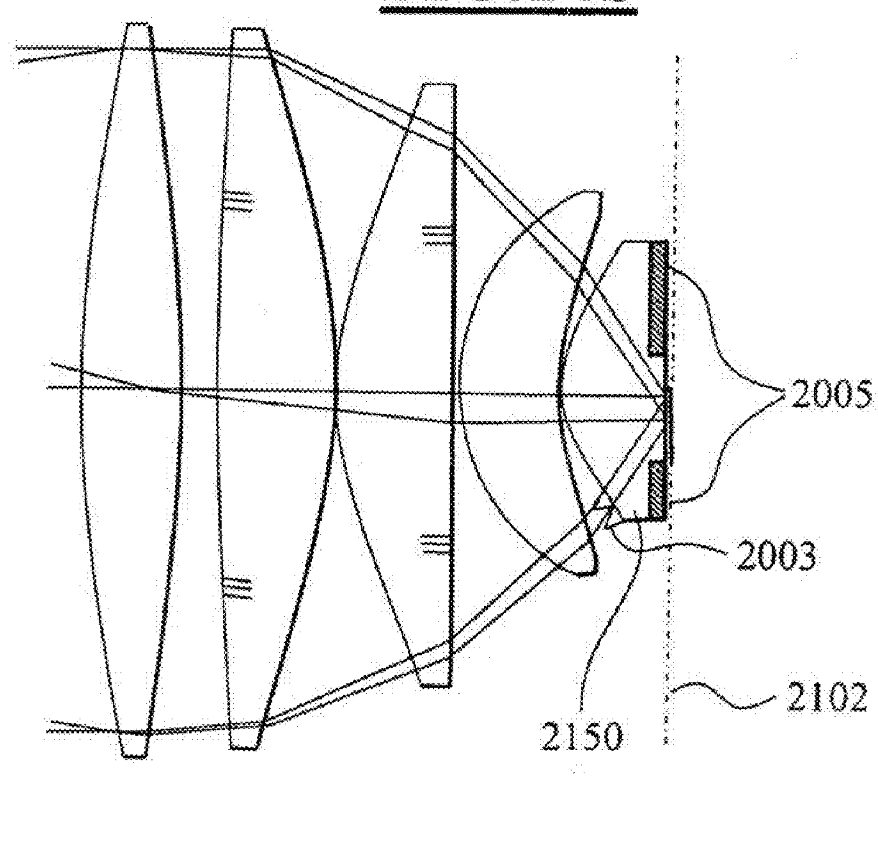


FIG.14b



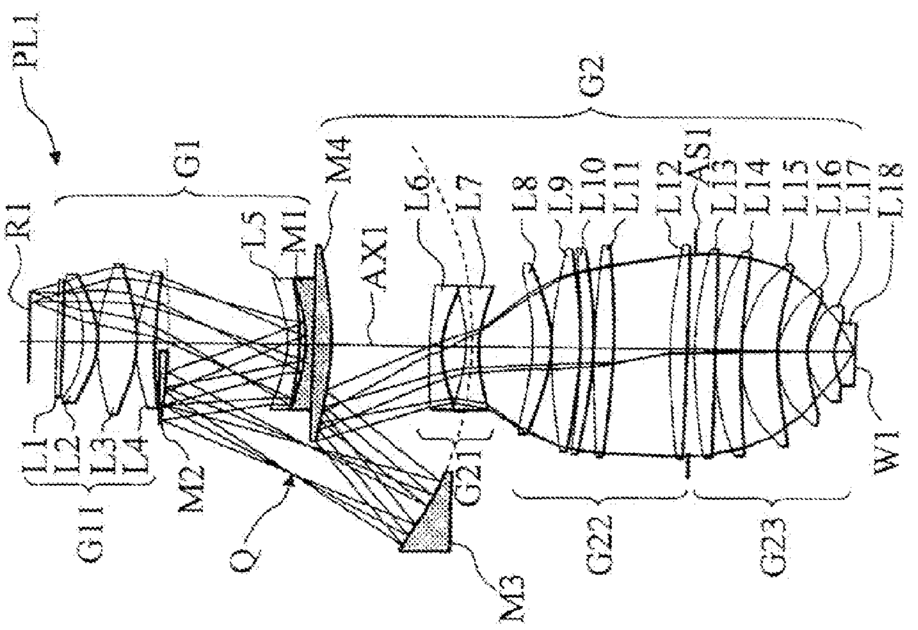

PL1
R1
G1
G11
L1
L2
L3
L4
L5
M1
M2
M3
M4
Q
AX1
L6
L7
L8
L9
L10
L11
L12
AS1
L13
L14
L15
L16
L17
L18
G2
G21
G22
G23
W1

FIG.15

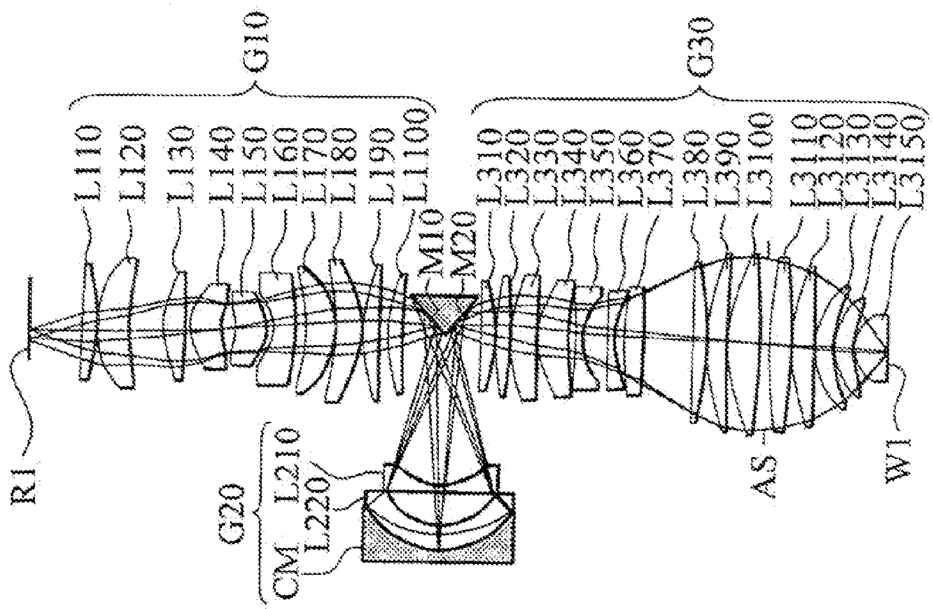

R1
G10
L110
L120
L130
L140
L150
L160
L170
L180
L190
L1100
M10
M20
G20
CM
L210
L220
G30
L310
L320
L330
L340
L350
L360
L370
L380
L390
L3100
L3110
L3120
L3130
L3140
L3150
AS
W1

FIG.16

FIG.17

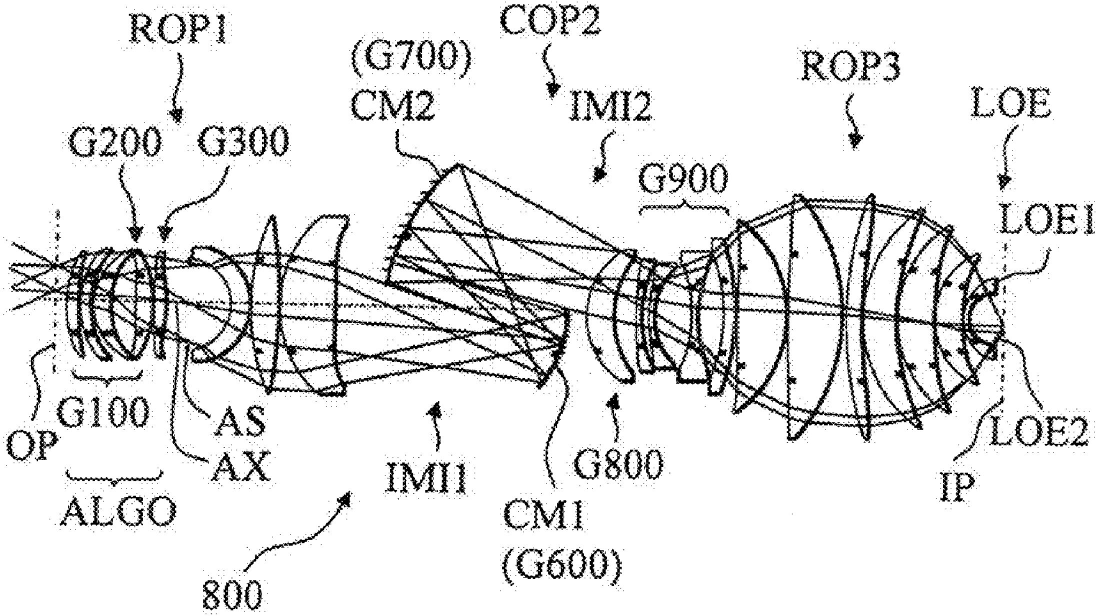

ROP1
(G700)
CM2
COP2
IMI2
ROP3
LOE
G200
G300
G900
LOE1
G100
OP
AS
AX
ALGO
IMI1
800
CM1
(G600)
G800
LOE2
IP

FIG.18

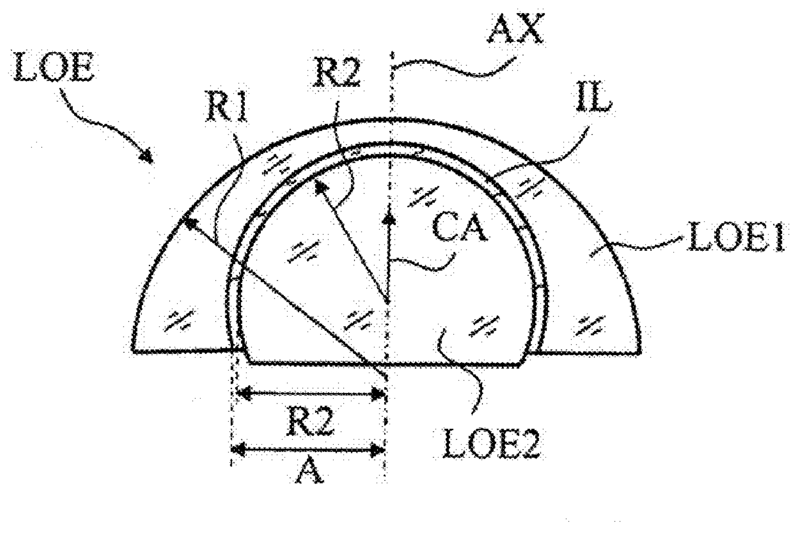

LOE
R1
R2
AX
IL
CA
LOE1
R2
A
LOE2

FIG.19

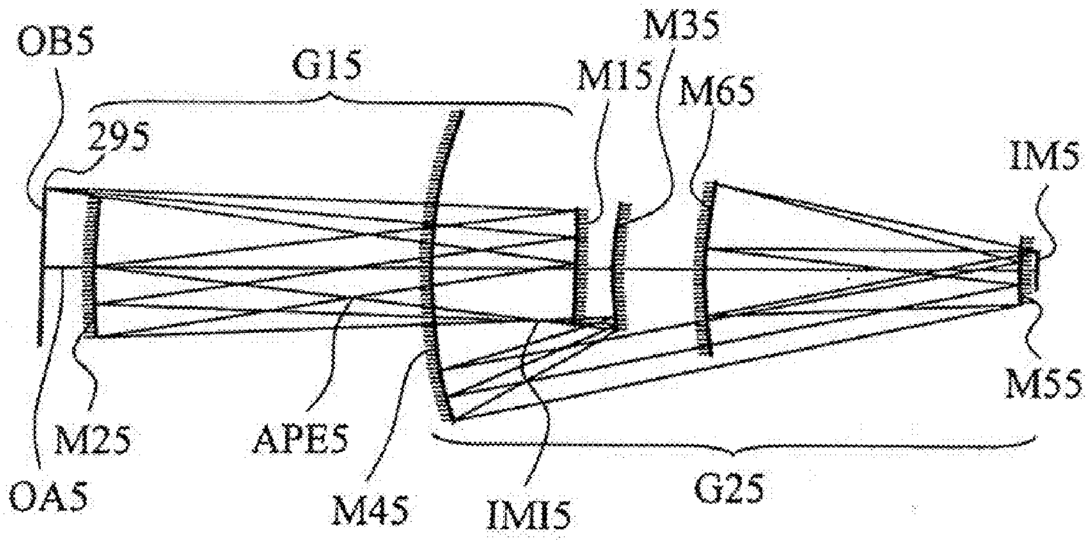


FIG.20

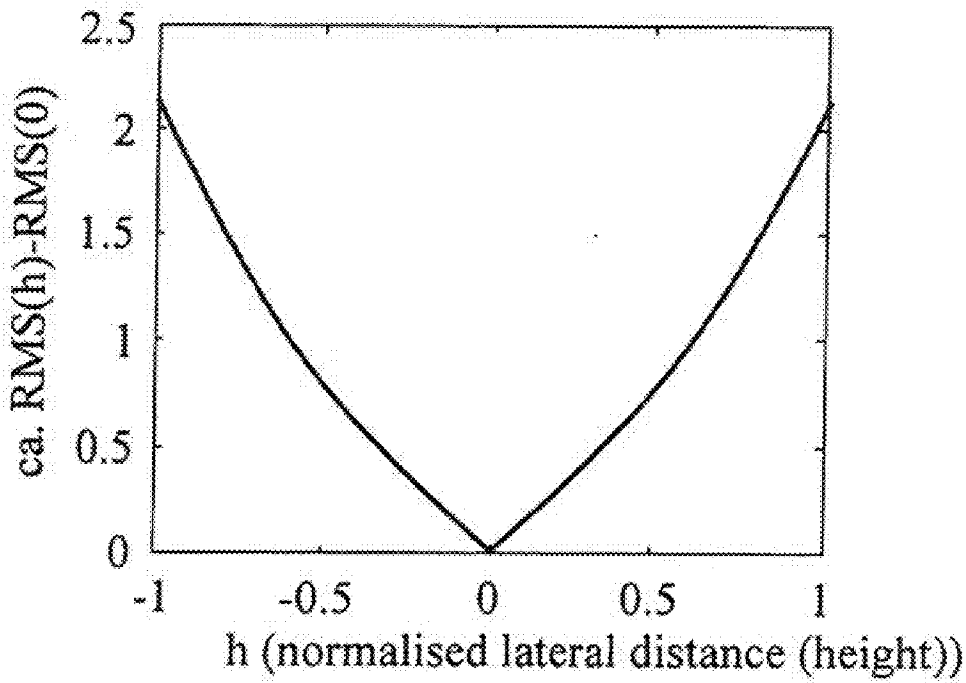

2.5
2
1.5
1
0.5
0
ca. RMS(h)-RMS(0)
-1
-0.5
0
0.5
1
h (normalised lateral distance (height))

FIG.21

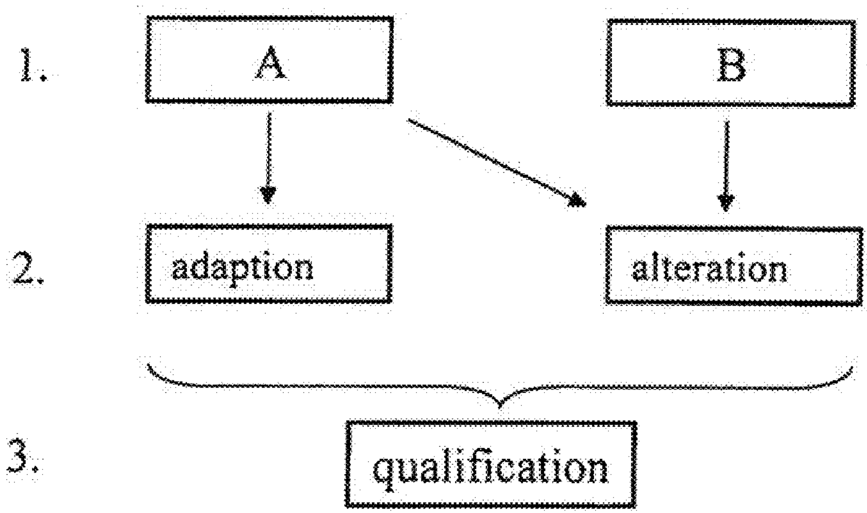
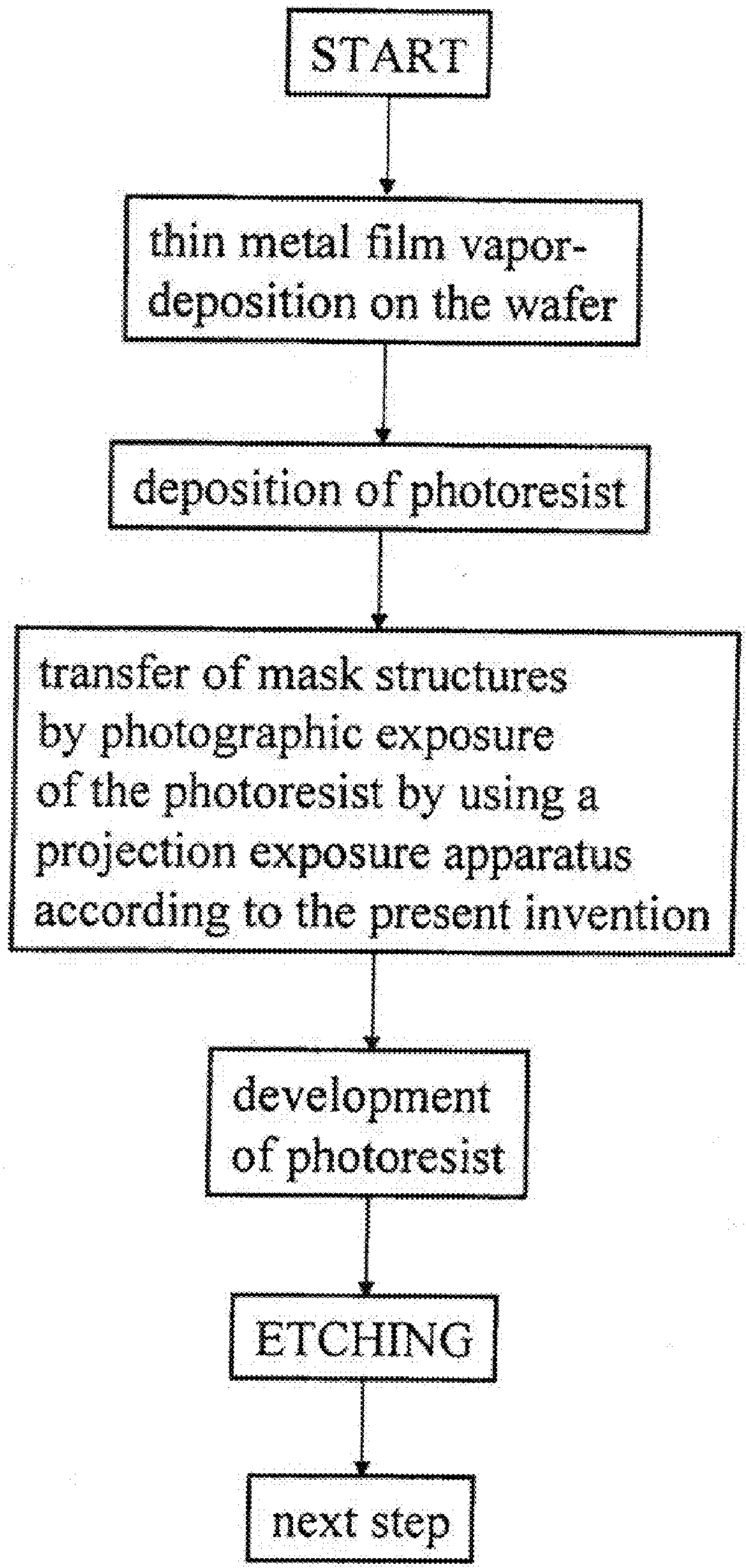

1.
A
B
2.
adaption
alteration
3.
qualification

FIG.22


START
thin metal film vapor-deposition on the wafer
deposition of photoresist
transfer of mask structures by photographic exposure of the photoresist by using a projection exposure apparatus according to the present invention
development of photoresist
ETCHING
next step

PROJECTION OBJECTIVE FOR MICROLITHOGRAPHY

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of, and claims benefit under 35 USC 120 to, international application PCT/EP2008/004081, filed May 21, 2008, which claims benefit of German Application No. 10 2007 024 685.6, filed May 25, 2007 and U.S. Ser. No. 60/940,117, filed May 25, 2007. International application PCT/EP2008/004081 is hereby incorporated by reference in its entirety.

FIELD

[0002] The disclosure relates to a projection objective for use in microlithography, a microlithography projection exposure apparatus with a projection objective, a microlithographic manufacturing method for microstructured components, and a component manufactured under the manufacturing method.

BACKGROUND

[0003] The performance of projection exposure apparatus for the microlithographic production of semiconductor elements and other finely structured components is largely determined by the imaging properties of the projection objectives. Examples for designs of projection objectives of a projection exposure apparatus which project an image of a mask into an exposure field can be found in WO 2004/019128 A2, US 2005/0190435 A1, WO 2006/133801 A1 and US 2007/0024960. These references relate primarily to designs of projection objectives for immersion lithography, as the technique is called, wherein an immersion liquid is present between the last optical element and the wafer which is located in the field plane of the exposure field. The subject of WO 2004/019128 A2, US 2005/0190435 A1, WO 2006/133801 A1 and US 2007/0024960 in its entirety, including the claims, is hereby incorporated by reference in the content of the present application. Furthermore, there are also designs of projection objectives of a projection exposure apparatus for applications in so-called EUV (extreme ultraviolet) lithography, which operate with an operating wavelength of less than 100 nm and therefore generally cannot use lenses as optical components, see US 2004/0051857 A1.

SUMMARY

[0004] The term "imaging properties" as commonly understood encompasses besides the point-to-point imaging properties also other kinds of imaging properties such as for example the amount of stray light (hereinafter referred to as the stray light component) contributed by the projection objective, because the contrast of the image is affected by it.

[0005] The stray light component of an objective has different reasons, which are described in: Heinz Haferkorn, "Optik; Physikalisch-technische Grundlagen and Anwendungen" (*Optics, Physical and Technical Theory and Applications*), Fourth Revised and Expanded Edition; Verlag WileY-VCH, Weinheim; pages 690-694. On the one hand, there is the kind of stray light which is caused by the scattering of light at inhomogeneities within a transparent optical material, and on the other hand the kind of stray light which is caused by the scattering of light at irregularities of the surfaces of the optical elements. Besides these two primary causes of stray light, there are also secondary causes such as for example double reflections, scattering which takes place at parts of mounting devices, at borders of aperture stops and at walls, or scattering caused by undesirable dust particles. The foregoing secondary causes of stray light are treated in the specialized literature also under the term "false light". The secondary causes of stray light can be reduced considerably through a careful layout of the design, the mounts and aperture stops, as well as through increased cleanness, blackening of the mount, and the development of effective so-called anti-reflex coatings. In classic glass melts, a term which herein is meant to also include the quartz glass for the projection objectives used in microlithography, the inhomogeneities inside a transparent optical material can be small enclosed particles, minor variations of the refractive index, bubbles and striations. New kinds of optical materials, in particular for projection objectives used in immersion lithography, are polycrystalline materials composed of a multitude of individual crystals of different sizes with hollow spaces of different sizes lying between them, which will hereinafter also be referred to as bubbles (see WO 2006/061225 A1). The subject of WO 2006/061225 A1 in its entirety, including the claims, is hereby incorporated by reference in the content of the present patent application. In the polycrystalline materials, not only the inhomogeneities in the form of bubbles are the reason for the stray light, but the base material itself in the form of individual small crystals causes stray light. This distinguishes the new materials from the classic materials, since the basic material of the latter by itself generally causes no stray light except for small variations of the refractive index. This and the fact that significantly more bubbles are present in the new materials than in the classic materials is the reason why optical elements made of the new kinds of materials can generate much more stray light than would be generated by analogous elements made of conventional material. In addition, many of the new materials consist of crystals that are birefringent, and a light ray traversing the material therefore sees many changes of the refractive index due to the different crystallographic orientations, whereby stray light can be produced again due to the refractive index variations themselves, as mentioned above. The many refractive index variations themselves, in turn, have the effect that the new kind of material itself hardly has a birefringent effect despite the fact that it consists of many small crystals of birefringent material.

[0006] The elastic scattering of light of the wavelength λ at the inhomogeneities inside a transparent optical material can be treated according to three different cases based on the diameter D of the scattering centers:

- [0007] cases where D is small in comparison to λ are referred to as Rayleigh scattering;
- [0008] if D is about as large as λ, one speaks of Mie scattering, and
- [0009] if D is significantly larger than λ, this is called geometric scattering.

[0010] In each of these three cases different models are used in order to describe the elastic scattering of light. In classic materials the Mie scattering and the geometric scattering occur with predominance. In the new kinds of materials, none of the aforementioned kinds of scattering can be disregarded because a sufficient number of bubbles between the crystals can be very small and a sufficient number of individual crystals may be very large as a source of scattering.

[0011] The elastic scattering of light of the wavelength λ which takes place at irregularities of surfaces is described through the theory of diffraction at gratings based on the assumption of a grating whose height equals the quadratic mean value of the height variation by which the irregularities deviate from the ideal surface and whose grid period corresponds to the mean local undulation wavelength of the irregularities. The quadratic mean value of the height variation of the irregularity from the ideal surface is also referred to as RMS value (root mean square value) of the surface roughness.

[0012] When characterizing the measurable qualities of a projection objective, an analysis as to which cause a measured stray light component of the projection objective should be attributed to is a priori impossible. However, a measurable property through which stray light can be characterized is based on different lateral penetrations into a shadow range (see WO 2005/015313 and the references cited therein). Within the scope of conventional measurement methods, this property is tested by using appropriate test masks which have dark areas of different lateral diameters. In images of such masks which are produced by the projection objective, it is examined how large a portion of stray light is found in the field of the projection objective at the center of the shadow range of the respective images of the individual dark areas. The diameters on the image side for the images of the individual dark areas as measured in the field plane of the projection objective are typically 10 μm, 30 μm, 60 μm, 200 μm, 400 μm, 1 mm, and 2 mm. Such measurements are performed at different field points in order to obtain the distribution of the stray light component over the exposure field of the projection objective.

[0013] Stray light which is still able to reach the center of a shadow range of more than 400 μm diameter has a range of more than 200 μm and is called long-range stray light, while stray light which reaches the center of a shadow range of less than 200 μm is referred to as short-range or medium-range stray light. However, the transition between the terms is fluid so that an amount of 500 μm for the diameter of the shadow range can serve equally well as borderline between the terms of long-range or short/medium-range stray light.

[0014] The stray light stemming from secondary causes for stray light is normally not very localized or focused in the field plane, so that at a corresponding field point it normally extends uniformly over a lateral range larger than for example 0.5 mm. This stray light belongs accordingly to the long-range stray light and is thus represented equally in each measurement regardless of the diameters of the dark areas. This means that the long-range stray light is always present as a background in a measurement of the short-range or medium range stray light.

[0015] To quantify the proportion of the stray light which is due to primary causes through a measure that is not falsified by a stray light component that is due to secondary causes, the term “stray light component” as used herein is understood to mean only that part of the stray light which is obtained as the cumulative result of the individual measurements of the short-range portion up to a test diameter of 400 μm, where in each of the individual measurements of the short-range portion of the stray light the measurement result is reduced by the value of the stray light portion from the 1 mm measurement or an equivalent stray light measurement of the long-range portion. By setting this rule for the stray light component within the bounds of this application, the short-range portion of the stray light due to primary causes is thus set apart from the background of the long-range portion of the stray light. This clear delineation of the stray light portion due to primary causes is relevant because the long-range portion of the stray light due to secondary causes contains the double reflections which, in turn, depend on the way in which the mask that is to be projected is illuminated.

[0016] It should also be noted here that as an alternative to the measurement of the stray light via sensors, the stray light can also be measured through an exposure method for photoresists, the so-called Kirk test. In a first step of this test, one determines the dose desired for the complete exposure of the photoresist, the so-called clearing dose D_c, and in a second step one determines the dose D_s involved in an over-exposure of quadratic structures of different sizes, so that their image in the photoresist completely disappears.

[0017] The ratio between D_c and D_s now represents a measure for the relative stray light component of the square-shaped structure being examined.

[0018] Current projection objectives generally have a stray light component, according to the rule used herein, of about 1% in relation to the useful portion of the light, wherein the stray light component varies by about 0.2% over the image or over the exposure field. Starting from this, a further reduction of the stray light component can be achieved through a large development effort in regard to the material and the surface finish of mirrors and lenses. It should be noted, however, that projection objectives using the aforementioned new kinds of optical materials will according to predictions have a larger stray light component and a higher variation of the stray light component.

[0019] In some embodiments, the disclosure ensures a good contrast over the image or over the exposure field in projection objectives with at least one optical element of polycrystalline material.

[0020] In certain embodiments, the disclosure provides a projection objective that includes a multitude of optical elements and has at least one optical element of polycrystalline material. The stray light component of the projection objective, averaged over the scan direction, has a variation over the exposure field of less than 0.5%, such as less than 0.2%, in relation to the useful light. Accordingly, the projection objective has a constant stray light component in the sense of the present application.

[0021] As used herein, a constant stray light component in the exposure field, averaged over the scan direction, means a stray light component for which the difference between the maximum value in the exposure field and the minimum value in the exposure field in relation to the useful light is less than 0.5% (e.g., less than 0.2%, less than 0.1%, less than 0.05%), or for which the difference in relation to the maximum value in the exposure field is less than 60% (e.g., less than 25%, less than 12.5%, less than 6.75%).

[0022] The disclosure makes use of the observation that the variation of the stray light component of a projection objective over the exposure field often causes greater problems for the manufacturers of semiconductor components than a somewhat greater stray light component of the projection objective would cause by itself, and that the variation of the stray light component over the exposure field in a projection objective with at least one optical element of polycrystalline material exceeds the variation of the stray light component of many currently used projection objectives.

[0023] This result of an increased variation of the stray light component over the exposure field in comparison to many currently used projection objectives is more pronounced if the last optical element consists of polycrystalline material. It can make sense especially in this case to generate a constant stray light component of the projection objective over the exposure field in the sense of this application.

[0024] Setting an upper limit for the stray light component of a projection objective over the exposure field of 2% in relation to the useful light, takes into account that unrestrictedly large constant stray light components of a projection objective in the sense of this application are not compatible with the fabrication processes used by the manufacturers of semiconductor elements. Large stray light components can still lead to loss of contrast, and only small constant stray light components of a projection objective in the sense of this application, representing a low percentage of the useful light, are typically acceptable to the manufacturers of semiconductor elements.

[0025] Of comparable importance is the stray light component of a projection objective outside of the exposure field, because if it is too large it leads to undesirable exposures outside of the exposure field. Setting a maximum of 2% for the stray light component of a projection objective outside of the exposure field can represent an acceptable upper limit.

[0026] The concept to introduce additional stray light in projection objectives with optical elements made of a fluoride, an oxide of group II, an oxide of group III, rare earth oxides, garnet or spinel leads to a compensation of the additional profile portion which the crystals and the bubbles between the crystals contribute to the profile of the stray light component in the exposure field, so that the result is a constant stray light component of the projection objective in the sense of this application over the entire exposure field.

[0027] The concept of introducing additional stray light in projection objectives with optical elements of a polycrystalline material consisting of many crystals that are birefringent leads to a compensation of the additional profile portion which the many refractive index fluctuations that occur as a result of the different orientations of the crystals contribute to the profile of the stray light component in the exposure field, so that the result is a constant stray light component of the projection objective in the sense of this application over the exposure field.

[0028] The concept of introducing additional stray light in projection objectives with at least one optical element of a polycrystalline material, so that the result is a constant stray light component in the sense of this application over the entire exposure field, where the polycrystalline material exhibits a lesser degree of birefringence than each of the individual crystals, is especially important in projection objectives used for immersion lithography, because in these projection objectives a material that is nearly free of birefringence is used with preference especially for the last optical element before the exposure field.

[0029] The concept of introducing additional stray light in projection objectives with at least one optical element of a polycrystalline material, so that the result is a constant stray light component in the sense of this application over the entire exposure field, is of particular importance in cases where the optical element itself already has a stray light component with a profile variation of more than 0.1% over the exposure field, because in this case the individual optical element itself exhibits a variation of the stray light component over the exposure field which equals about one-half the variation of the stray light component over the exposure field that is seen in currently used projection objectives.

[0030] In order to increase the resolution of future projection objectives used for immersion lithography, it may become desirable to further increase the numerical aperture NA, i.e. the aperture angle. However, in order to accomplish this, materials with a refractive index greater than 1.7 are needed for the last optical element if the operating wavelength is for example 193 nm. In this regard, the reader is referred to the discussion of the refractive index of the last lens element in WO 2006/133,801. With other operating wavelengths, too, such as for example 157 or 248 nm, it is sensible to use a material with a high refractive index at the respective operating wavelength for the last lens element in projection objectives with a high aperture. The desired properties for the imaging performance of such future systems, and likewise the desired properties for the variation of the stray light component over the exposure field, will probably be higher than for present systems. The concept to introduce additional stray light in projection objectives of this kind, so that the result is a constant stray light component in the sense of this application over the entire exposure field, takes this anticipated development into account, as the disclosure also provides the capability to meet increased future desired properties regarding the constancy of the stray light component over the exposure field.

[0031] Applying a finishing treatment to at least one surface of at least one field-proximate optical element represents a simple and cost-effective way to introduce in a projection objective an additional stray light component, so that the result is a constant stray light component of the projection objective in the sense of this application over the entire exposure field. The finishing treatment can also be applied to several field-proximate surfaces, so that the total additional stray light component comes out as the sum of the stray light contributed by the individual surfaces. This distribution of the desired surface roughness over several surfaces can be advantageous if it results for the individual surface in a roughness value which can be realized simply by omitting the last polishing step on this surface or on parts of it. Field-proximate in this context means that surfaces close to an intermediate image rather than to the exposure field can also be selected for the finishing treatment. This is particularly advantageous if these surfaces are easier to work on in regard to their geometry, or if based on their optical sensitivity in regard to image errors, they are easier to install or uninstall than the last optical element immediately before the exposure field. In particular a planar-parallel plate is favored as an optical element under this point of view, because the mechanical position tolerances that can be allowed for a planar-parallel plate are much larger than for lenses or mirrors. A planar-parallel plate has the additional advantage that it can also be designed as an easily interchangeable element and thus offers the possibility that this element can be exchanged or reworked or altered according to customer specifications at a later time when the system is in operation.

[0032] Increasing the roughness of a field-proximate surface at the margin of the optically used area as compared to the center of the optically used area of a surface is the simplest way of producing in the exposure field an additional stray light component which has a profile over the exposure field and is stronger in the border area than in the central area of the exposure field, so that the overall result is a constant stray light component in the sense of this application over the entire exposure field for the projection objective as a whole. An additional stray light component is thereby produced which complements the otherwise existing stray light component of the projection objective in an ideal way, so that the result is a constant stray light component of the projection objective in the sense of this application over the entire exposure field.

[0033] The difference of more than 0.5 nm between the respective RMS values for the surface roughness at the margin of the optically used area of a field-proximate surface and the surface roughness at the center of the optically used area corresponds to an additional stray light component of about 0.02% in proportion to the useful light in the exposure field at an operating wavelength of e.g. 193 nm. The difference of 0.5 nm represents about the lower limit for a value for which it makes sense to correct the stray light component in the exposure field. The RMS value larger than 2 nm for the difference in the surface roughness from the border to the center fills the task of correcting projection objectives currently used for microlithography with their variation of the stray light component over the exposure field of 0.2% relative to the useful light at a wavelength of e.g. 193 by introducing an additional stray light component with a non-constant profile over the exposure field in accordance with the disclosure, so that the result is a constant stray light component of the projection objective in the sense of this application over the entire exposure field. Particularly in immersion objectives used for immersion lithography, where the last lens immediately before the field is strongly positive, an additional variation of the stray light component over the exposure area from the border area to the central area occurs, and to compensate for this variation it makes sense to use a stronger differentiation of the RMS values of the surface roughness from the border to the central area. Additionally increased values for the difference in the RMS values of the surface roughness are involved if a strongly diffusing material is used for the last lens.

[0034] A surface roughness profile as a function of a lateral distance from the center, expressed through a root function of a general polynomial function in which the lateral distance represents the independent variable offers the advantage of making it easier to program the polishing machines, in particular the polishing robots, because a system of functions is used which is indigenous or familiar to the machines. Disclosed herein are relatively simple and fast functions in this category, which allow an increase of the RMS roughness value at the margin of a surface to be accomplished in the simplest and fastest possible manner.

[0035] The local range of undulation wavelengths between 1 mm and 10 μm has the advantage that it keeps the amount of so-called out-of-field stray light small. The out-of-field stray light is stray light which gets outside the exposure field into areas where it can cause undesirable exposures. The local range of wavelengths between 1 mm and 10 mm has the advantage that it not only has an effect on the stray light but also influences the image-forming wave front of a field point, so that it is possible with this local wavelength range to make a simultaneous correction of the wave front of an arbitrary field point.

[0036] A field aperture stop can help prevent the additional stray light, which was introduced to achieve the result of a constant stray light component of the projection objective in the sense of this application over the entire exposure field, from getting into areas outside of the exposure field and leading to undesirable exposures of those areas.

[0037] The dimensional allowance between the field aperture stop and the optically used area in the plane of the field aperture stop represents an advantageous compromise between an overly tight allowance which leads to a high cost due to the high precision desired in the manufacturing process and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

[0038] An upper side, i.e. the object-facing surface of the last optical element before the field plane, as seen in the direction of the light rays from the mask plane to the field plane, is advantageously suited for introducing the stray light by surface roughness, as this surface is on the one hand located so close to the exposure field that by a profile of the surface roughness over the upper side a profile of the stray light component in the exposure field can be produced, and that on the other hand the sub-apertures of the individual field points on the upper side are still wide enough that small irregularities in the finish of the upper side have no effect on the image of the respective field points. Particularly in projection objectives used for immersion lithography, it is especially advantageous to finish the upper side of the last optical element because, due to the small difference in the refractive indices of the lens and the immersion liquid, finishing or reworking of the underside would involve very large values for the surface roughness which are difficult to achieve in practice.

[0039] In projection objectives used for immersion lithography, the design space between the last optical element and the wafer is too narrow to allow the use of mechanical aperture stops. The concept of masking therefore represents the best possible way of realizing a field aperture stop in immersion systems, which prevents the additional stray light, which was introduced to achieve the result of a constant stray light component of the projection objective in the sense of this application over the entire exposure field, from getting into areas outside of the exposure field and leading to undesirable exposures of those areas.

[0040] The masking is realized cost-effectively by a.

[0041] The dimensional allowance between the masking and the optically used area in the plane of the field aperture stop represents an advantageous compromise between an overly tight dimensional allowance which leads to a high cost due to the high manufacturing precision desired in particular for coating tools and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

[0042] Particularly in immersion objectives for use in immersion lithography, where the refractive power of the last lens immediately before the field is strongly positive, this strongly curved lens alone has the effect that the path lengths traveled by the light rays through the material differ by a few percent for rays traversing the border area in comparison to rays passing through the central area, which results in an additional variation of the stray light component over the exposure field. This effect is further increased if strongly diffusing material is used for the last lens. The concept of introducing additional stray light, so that the overall result is a constant stray light component of the projection objective in the sense of this application over the entire exposure field, is therefore advantageous to reduce the variation of the stray light component over the exposure field in projection objectives, which have a last lens of polycrystalline material with positive refractive power.

[0043] Using a planar-parallel plate as the last optical element has the advantage that the planar-parallel plate allows for large mechanical position tolerances in comparison to lenses or mirrors and that it is thus optically insensitive. This kind of optical element is therefore advantageous in regard to reworking operations, as it can be uninstalled from and reinstalled in the projection objective without major problems. A refinishing operation at the customer's location is thereby also made possible, so that an adjustment of the stray light profile according to a customer's wish becomes feasible. This customer request could be connected for example with a specific illumination of the mask.

[0044] A surface roughness of a mirror surface has an approximately 16 times stronger effect than an equivalent surface roughness of a lens in air with a refractive index of about 1.5. It is insofar advantageous, if large variations of the stray light component over the exposure field have to be corrected, to use for this purpose a mirror surface so that the overall result is a constant stray light component of the projection objective in the sense of this application over the entire exposure field.

[0045] It is a further object of the disclosure to reduce the variation of the stray light component over the image or over the exposure field.

[0046] The disclosure makes use of the observation that the variation of the stray light component over the exposure field causes greater problems to the manufacturers of semiconductor components than the stray light component itself.

[0047] This task can be solved by a projection objective with the features in which an additional stray light component is introduced with a non-constant profile over the exposure field, or that a mechanism is provided in the projection objective for introducing into the exposure field in the field plane an additional stray light component with a non-constant profile over the exposure field. The property of an additional stray light component as having a non-constant profile over the exposure field in this context is understood to mean a profile of the additional stray light component wherein for at least two arbitrary field points within the exposure field there is a difference of $\geqq 0.02\%$ in the additional stray light component in relation to the useful light portion. Thus, a projection objective is made available for use in microlithography, serving to project an image of a mask plane into a field plane and having an exposure field in the field plane, which is characterized by the fact that besides the existing stray light component of the projection objective an additional stray light component is introduced with a non-constant profile over the exposure field, and/or that the projection objective includes a mechanism whereby besides the existing stray light component of the projection objective an additional stray light component with a non-constant profile over the exposure field is introduced into the exposure field, so that the variation of the stray light component over the exposure field is reduced.

[0048] It was further recognized that it makes sense for any optical body if the stray light component in the border area of the exposure field is increased in comparison to the central area of the exposure field in order to equalize over the exposure field the profile of the stray light component which stems from a homogeneous light flow of the useful light even if the latter takes place only in part of the optical body. This entails the precondition that the optical body consists of a homogeneous material and has homogeneously finished surfaces, as for example a lens or a plurality of lenses of a projection objective. Particularly in immersion objectives for use in immersion lithography, where the refractive power of the last lens immediately before the field is strongly positive, this strongly curved lens alone has the effect that the path lengths traveled by the light rays through the material differ by a few percent for rays traversing the border area in comparison to rays passing through the central area, which results in an additional variation of the stray light component, with an increased proportion in the central area and a lower proportion in the border area of the exposure field. This effect is further increased if strongly diffusing material is used.

[0049] The finishing treatment of at least one surface of at least one optical element close to the field (also referred to herein as a field-proximate element) represents a simple and cost-effective way to introduce in a projection objective an additional stray light component with a non-constant profile over the exposure field. The finishing treatment can also be applied to several field-proximate surfaces, so that the total additional stray light component comes out as the sum of the stray light contributed by the individual surfaces. This distribution of the additional surface roughness over several surfaces can be advantageous if it results for the individual surface in a roughness value which can be realized simply by omitting the last polishing step on this surface or on parts of it. Close to a field (or field-proximate) means in this context that surfaces close to an intermediate image instead of close to the exposure field can also be selected for the finishing treatment. This is particularly advantageous if these surfaces are easier to work on in regard to their geometry, or if based on their optical sensitivity in regard to image errors, they are easier to install or uninstall than the last optical element immediately before the exposure field. In particular a planar-parallel plate is favored as an optical element under this point of view, because the mechanical position tolerances that can be allowed for a planar-parallel plate are much larger than for lenses or mirrors. A planar-parallel plate has the additional advantage that it can also be designed as an easily interchangeable element and thus offers the possibility that this element can be exchanged or reworked or altered according to customer specifications at a later time when the system is in operation.

[0050] Increasing the surface roughness at the margin of the optically used area as compared to the center of the optically used area of a surface near a field (also referred to herein as a field-proximate surface) is the simplest way of producing in the exposure field an additional stray light component which has a profile over the exposure field and is stronger in the border area than in the central area of the exposure field. An additional stray light component is thereby produced which complements the otherwise existing stray light component of the projection objective in an ideal way.

[0051] The difference of more than 0.5 nm between the respective RMS values for the surface roughness at the margin of the optically used area of a field-proximate surface and the surface roughness at the center of the optically used area corresponds to an additional stray light component of about 0.02% in proportion to the useful light in the exposure field at an operating wavelength of e.g. 193 nm. The difference of 0.5 nm represents about the lower limit for a value for which it makes sense to correct the stray light component in the exposure field. The RMS value larger than 2 nm for the difference in the surface roughness from the border to the center fills the task of correcting projection objectives currently used for microlithography with their variation of the stray light component over the exposure field of 0.2% relative to the useful light at a wavelength of e.g. 193 by introducing an additional stray light component with a non-constant profile over the exposure field in accordance with the disclosure.

[0052] Particularly in immersion objectives for use in immersion lithography, where the refractive power of the last lens immediately ahead of the field is strongly positive, a stronger variation of the stray light component over the exposure field from the border area to the central area occurs, as mentioned previously, where it makes sense to compensate for the variation by using larger values for the difference in RMS surface roughness from the border to the center. Additionally increased values for the difference in the RMS surface roughness are needed if strongly diffusive material is used for a last lens in this kind of arrangement.

[0053] The profile of the surface roughness as a function of a lateral distance from the center according to a function represented by the root of a general polynomial function in which the lateral distance is the independent variable offers the advantage of making it easier to program the polishing machines, in particular the polishing robots, because a system of functions is used which is indigenous or familiar to the machines. Relatively simple and fast functions in this category are disclosed, which allow an increase of the RMS roughness value at the border of a surface to be accomplished in the simplest and fastest possible manner.

[0054] The range of wavelengths of the local undulation between 1 mm and 10 μm has the advantage that it keeps the amount of so-called out-of-field stray light small. The out-of-field stray light is stray light which gets outside the exposure field into areas where it may cause undesirable exposure to light. The local range of undulation wavelengths between 1 mm and 10 mm has the advantage that it not only has an effect on the stray light but also influences the image-forming wave front of a field point, so that it is possible with this local wavelength range to make a simultaneous correction of the wave front of an arbitrary field point. As mentioned above, the local wave length range of a surface roughness or irregularity is understood within the bounds of this application to mean the range of the lateral grid periods of the irregularities along the surface of an optical element.

[0055] A field aperture stop can help prevent the additionally introduced stray light from getting into areas outside of the exposure field and leading to undesirable exposures of those areas.

[0056] The dimensional allowance between the field aperture stop and the optically used area in the plane of the field aperture stop represents an advantageous compromise between an overly tight allowance which leads to a high cost due to the high precision desired in the manufacturing process and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

[0057] An upper side, i.e. the object-facing surface of the last optical element, is advantageously suited for introducing the stray light by surface roughness, because this surface is on the one hand located so close to the exposure field that by a profile of the surface roughness over the upper side a profile of the stray light component in the exposure field can be produced, and because on the other hand the sub-apertures of the individual field points on the upper side are still wide enough that small irregularities in the finish of the upper side have no effect on the image of the respective field point. Particularly in projection objectives used for immersion lithography, the finish of the upper side of the last optical element is especially important because, due to the small difference in the refractive indices of the lens and the immersion liquid, finishing or reworking of the underside would lead to large values for the surface roughness, which would have a negative effect on the imaging properties of the projection objective or on the dynamics of the immersion liquid during the scanning process.

[0058] In projection objectives used for immersion lithography, the design space between the last optical element and the wafer is too narrow to allow the use of mechanical aperture stops. The concept of masking is therefore almost the only possible way in immersion systems to realize a field aperture stop which prevents the additionally introduced stray light from getting into areas outside of the exposure field and leading to undesirable exposures of those areas.

[0059] The masking is realized cost-effectively by a coating

[0060] The dimensional allowance between the masking and the optically used area in the plane of the field aperture stop represents an advantageous compromise between an overly tight dimensional allowance which leads to a high cost due to the high manufacturing precision desired in particular for coating tools and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

[0061] The concept of introducing additional stray light is especially advantageous in projection objectives with optical elements of polycrystalline material as the polycrystalline material in these projection objectives causes a stronger variation of the stray light component over the field than would be the case in currently used projection objectives.

[0062] The concept of introducing additional stray light in projection objectives with optical elements made of a fluoride, an oxide of group II, an oxide of group III, rare earth oxides, garnet or spinel leads to a compensation of the additional profile portion which the crystals and the bubbles between the crystals contribute to the profile of the stray light component in the exposure field.

[0063] The concept of introducing additional stray light in projection objectives with optical elements of a polycrystalline material consisting of many crystals that are birefringent leads to a compensation of the additional profile portion which the many refractive index fluctuations that occur as a result of the different orientations of the crystals contribute to the profile of the stray light component in the exposure field.

[0064] The concept of introducing additional stray light in projection objectives with at least one optical element of a polycrystalline material which exhibits a lesser degree of birefringence than each of the individual crystals is especially important for projection objectives used for immersion lithography, because in these projection objectives a material that is nearly free of birefringence is used with preference especially for the last optical element before the exposure field.

[0065] The concept of introducing additional stray light in projection objectives with at least one optical element of a polycrystalline material represents a sensible approach in particular if the optical element itself already has a stray light component with a profile variation of more than 0.1% over the exposure field because in this case the individual optical element itself exhibits a variation of the stray light component over the exposure field which equals about one-half the variation of the stray light component over the exposure field that is seen in currently used projection objectives.

[0066] In particular a last optical element of polycrystalline material located before the field plane, in reference to the direction of a light ray from the mask plane to the field plane leads to a stronger variation of the stray light component of a projection objective over the exposure field, which needs to be compensated in accordance with the disclosure, because downstream of such a field-proximate optical element there is no further possibility to place aperture stops immediately ahead of the field plane with the exposure field in order to prevent the stray light generated by this element from reaching the exposure field.

[0067] In order to increase the resolution of future projection objectives used for immersion lithography, it will probably be desirable to further increase the numerical aperture NA, i.e. the aperture angle. However, in order to accomplish this, materials with a refractive index greater than 1.7 are needed for the last optical element if the operating wavelength is for example 193 nm. In this regard, the reader is referred to the discussion of the refractive index of the last lens element in WO 2006/133,801 A1. With other operating wavelengths, too, such as for example 157 or 248 nm, it is sensible to use a material with a high refractive index at the respective operating wavelength for the last lens element in projection objectives with a high aperture. The desired properties for the imaging performance of such future systems, and likewise the desired properties for the variation of the stray light component over the exposure field, will probably be higher than for present systems. The concept to introduce additional stray light in projection objectives of this kind takes this anticipated development into account, as the disclosure also provides the capability to meet increased future desired properties for the variation of the stray light component over the exposure field.

[0068] Particularly in immersion objectives for use in immersion lithography, where the refractive power of the last lens immediately before the field is strongly positive, this strongly curved lens alone has the effect that the path lengths traveled by the light rays through the material differ by a few percent for rays traversing the border area in comparison to rays passing through the central area, which results in an additional variation of the stray light component. This effect is further increased if strongly diffusing material is used for the last lens. The concept of introducing additional stray light in such projection objectives is thus helpful in reducing the variation of the stray light component over the exposure field in projection objectives with a last lens of positive refractive power.

[0069] Using a planar-parallel plate as the last optical element has the advantage that the planar-parallel plate allows for large mechanical position tolerances in comparison to lenses or mirrors and that it is thus optically insensitive. This kind of optical element is therefore advantageous in regard to reworking operations, as it can be uninstalled from and reinstalled in the projection objective or exchanged for another planar-parallel plate without major problems. A refinishing operation at the customer's location is thereby also made possible, so that an adjustment of the stray light profile according to a customer's wish becomes feasible. This customer request could be connected for example with a specific illumination of the mask.

[0070] A surface roughness of a mirror surface has an approximately 16 times stronger effect than an equivalent surface roughness of a lens in air with a refractive index of about 1.5. It is insofar advantageous, if large variations of the stray light component over the exposure field have to be corrected, to use for this purpose a mirror surface.

[0071] A further object of the disclosure is to provide a method of reducing the variation of the stray light component of a projection objective in the exposure field.

[0072] This task can be solved by a method in which additional stray light with a non-constant profile over the exposure field is introduced by an advance adaptation or an alteration of the surface roughness of at least one field-proximate surface.

[0073] It was recognized in the disclosure that a method in which the surface roughness of at least one field-proximate surface is adapted in advance according to a specified profile over the surface or altered in a way that is targeted to achieve the specified profile represents a suitable way to produce an additional stray light component which results in an overall reduction of the variation of the stray light component over the exposure field.

[0074] A method in which a simulation or a measurement is used to determine the stray light component that is to be expected or is present within the exposure field of the entire projection objective, offers the possibility to determine the desired surface roughness profile over the at least one field-proximate surface in a way that is very specifically targeted and to realize the desired profile in an equally target-oriented way by pre-adapting or altering the surface roughness.

[0075] A method can offer the advantage of taking the measurements on another projection objective of the same design, for example on a prototype, instead of measuring the projection objective itself, and to transfer the results to the projection objective for making the correction. This saves expensive and risky corrective steps in the manufacturing process, where the already completed projection objective has to be disassembled again, i.e. the steps of measuring the projection objective, uninstalling the surface that needs to be changed, reworking the surface, and reinstalling the reworked surface. By transferring the measurement results for example from a prototype, the desired surface roughness can be preset or adapted in advance already during the production of the optical elements of the projection objective.

[0076] A method can have the advantage that measurements which were already made in the production of the individual optical components can be used for determining the stray light component to be expected for the entire projection objective, so that the surface roughness of the at least one field-proximate surface can be adapted in advance already in the production of the respective optical element, without having to disassemble the projection objective again at a later stage of the production process.

[0077] If no measurements are performed on the optical components in regard to the stray light component to be expected, the method can offer the advantageous possibility to take such measurements on the blanks of the lenses. The blanks can all be measured with one and the same measurement setup, while lenses may in some cases involve different measurement setups, depending on the geometry of the lens. Performing a measurement regarding the existing stray light component on the blanks offers insofar a significant cost advantage over a measurement of the stray light component that is performed in any of the subsequent production steps.

[0078] A method can be very cost-effective, because for the determination of the stray light component of the projection objective only at least one lens is measured or simulated for the advance adaptation or subsequent alteration of the surface roughness of the at least one field-proximate optical surface, rather than making measurements on an entire projection objective which would involve a more extensive measuring apparatus. This is of particular interest for projection objectives used for immersion lithography with a last lens of polycrystalline material, where this individual lens alone already contributes a large portion of the stray light component of the projection objective and where the attention is focused on correcting this particular contribution to the stray light component in accordance with the disclosure.

[0079] In comparison to certain methods it is advantageous to use some methods because only a single measurement needs to be made, e.g. on a lens prototype consisting, e.g., of polycrystalline material, in order to make the correction in all projection objectives that contain such a lens without the need to measure each of the individual lenses by itself. It is also possible with certain methods to perform a random sample examination within the scope of a quality assurance program, wherein for the determination of the desired surface roughness of the at least one field-proximate surface a second lens is measured which is of identical design as the first lens of the projection objective and the results of the measurements from the second lens are applied to the first lens.

[0080] A method is disclosed in which instead of measuring a lens, the measurements are made on the blank from which the lens will be made, in order to obtain from the measurement results of the blank the data for the advance adaptation or subsequent alteration of the surface roughness of the at least one field-proximate surface, so that one obtains as a result the additional stray light component with the non-constant profile over the exposure field of the projection objective. This method is simple and cost-effective because a suitable measurement setup for a blank can be realized in a simpler and more cost-effective way than a corresponding measurement setup for a completed lens or an entire objective.

[0081] It is a further object of this disclosure to provide a method of introducing additional stray light by a preemptive adaptation or subsequent alteration of the surface roughness of at least one field-proximate surface, so that as a result the stray light component of the projection objective, averaged over the scan direction, varies over the exposure field by less than 0.5%, in particular less than 0.2%, in relation to the useful light, and accordingly a constant stray light component of the projection objective in the sense of this application is achieved.

[0082] It was recognized in the disclosure that a method in which the surface roughness of at least one field-proximate surface is adapted in advance according to a specified profile over the surface or changed in a way that is targeted to achieve the specified profile represents a suitable way to produce an additional stray light component which results in an overall reduction of the variation of the stray light component over the exposure field, so that a constant stray light component of the projection objective in the sense of this application is achieved.

[0083] A method is disclosed in which a simulation or a measurement is used to determine the stray light component that is to be expected or is present within the exposure field of the entire projection objective, offers the possibility to determine the desired surface roughness profile over the at least one field-proximate surface in a way that is very specifically targeted and to realize the desired profile in an equally target-oriented way by adapting it in advance or changing it, so that a constant stray light component of the projection objective in the sense of this application is achieved.

[0084] A method is disclosed that offers the advantage of taking the measurements on another projection objective of the same design, for example on a prototype, instead of measuring the projection objective itself, and to transfer the results to the projection objective for making the correction. This saves expensive and risky corrective steps in the manufacturing process, where the already completed projection objective has to be disassembled again, i.e. the steps of measuring the projection objective, uninstalling the surface that needs to be changed, reworking the surface, and reinstalling the reworked surface. By transferring the measurement results for example from a prototype, the desired surface roughness can be preset or adapted in advance already during the production of the optical elements of the projection objective, so that a constant stray light component of the projection objective in the sense of this application is achieved.

[0085] A method is disclosed that is very cost-effective, because for the determination of the stray light component of the projection objective only at least one lens is measured or simulated for the advance adaptation or the alteration of the surface roughness of the at least one field-proximate optical surface in order to achieve a constant stray light component of the projection objective in the sense of this application, rather than making measurements on an entire projection objective which would involve a more extensive measuring apparatus. This is of particular interest for projection objectives used for immersion lithography with a last lens of polycrystalline material, where this individual lens alone already contributes a large portion of the stray light component of the projection objective and where the attention is focused on correcting this particular contribution to the stray light component in accordance with the disclosure in order to achieve a constant stray light component of the projection objective in the sense of this application over the entire exposure field.

[0086] In comparison to the method according to some methods it is advantageous to use certain methods because only a single measurement needs to be made, e.g. on a lens prototype consisting, e.g., of polycrystalline material, in order to make the correction in all projection objectives that contain such a lens so that a constant stray light component of the projection objective in the sense of this application is achieved without the need to measure each of the individual lenses by itself. It is also possible with certain methods to perform a random sample examination within the scope of a quality assurance program, wherein for the determination of the desired surface roughness of the at least one field-proximate surface a second lens is measured which is of identical design as the first lens of the projection objective and the results of the measurements taken from the second lens are applied to the first lens, so that a constant stray light component of the projection objective in the sense of this application is achieved.

[0087] A method is disclosed in which instead of measuring a lens, the measurements are made on the blank from which the lens will be made, in order to obtain from the measurement results of the blank the data for the advance adaptation or the alteration of the surface roughness of the at least one field-proximate surface, so that one obtains as a result the additional stray light component with the non-constant profile over the exposure field of the projection objective. This method is simple and cost-effective because a suitable measurement setup for a blank can be realized in a simpler and more cost-effective way than a corresponding measurement setup for a completed lens or an entire objective.

[0088] It is a further object of the disclosure to provide a projection exposure apparatus with a projection objective, also to provide a microlithographic manufacturing method which can be performed with the projection exposure apparatus, and further to describe a component which can be manufactured with the apparatus and method.

[0089] The disclosure provides a projection exposure apparatus, a manufacturing method, and a component.

BRIEF DESCRIPTION OF THE DRAWINGS

[0090] Examples of embodiments of the disclosure are hereinafter presented in more detail with references to the drawing, wherein

[0091] FIG. **1** is a schematic representation of an exposure field in the field plane of a projection objective for microlithography applications which is used as a scanner, including the distribution of the useful light relative to two orthogonal axes (X- and Y-axis);

[0092] FIG. **2** is a schematic representation of an exposure field in the field plane of a projection objective for microlithography applications which is used as a scanner and has a so-called off-axis field of rectangular shape;

[0093] FIG. **3** is a schematic representation of an exposure field in the field plane of a projection objective for microlithography applications which is used as a scanner and has a so-called ring field;

[0094] FIG. **4** is a schematic representation of an exposure field in the field plane of a projection objective for microlithography applications which is used as a stepper and has a square field;

[0095] FIG. **5** shows a schematically simplified sectional view of a projection objective and a substitute model for the projection objective in the form of a homogeneous glass cylinder serving to explain the resultant natural stray light distribution;

[0096] FIG. **6** shows a schematic representation of an image-forming light ray pattern of a projection objective according to geometric optics to illustrate the concepts of field and pupil;

[0097] FIG. **7** represents a graph of the profile of the stray light component in percent in relation to the useful light of a projection objective for microlithography applications, averaged over the scan direction Y, along the field in the X-direction;

[0098] FIG. **8** schematically represents the optical components of a projection exposure apparatus for immersion lithography;

[0099] FIG. **9** represents a plan view of a polycrystalline material with it microscopic structures;

[0100] FIG. **10** represents a graph of a model-dependent stray light component, expressed in percent relative to the useful light, of a polycrystalline material as a function of the average crystal size;

[0101] FIG. **11** represents a graph of a model-dependent stray light component, expressed in percent relative to the useful light, of a polycrystalline material as a function of the average bubble size;

[0102] FIG. **12** represents a sketch to illustrate principal concepts in a lens and graphs to explain, respectively, the scattering at inhomogeneities in a polycrystalline material of a last lens and the concept of adapting the surface roughness of a last lens as well as the resultant distribution of stray light over the field;

[0103] FIG. **13** represent a graph of a corrected profile of the stray light component, expressed in percent relative to the useful light, of a projection objective for microlithography applications, averaged over the scan direction Y along the field in the X-direction;

[0104] FIG. **14***a*-*b* represents a sectional view in the Y-Z plane of the optical components of a so-called two-mirror design of a projection objective for immersion lithography with a numerical aperture larger than 1;

[0105] FIG. **15** represents a sectional view in the Y-Z plane of the optical components of a so-called four-mirror design of a projection objective for immersion lithography with a numerical aperture of 1.2;

[0106] FIG. **16** represents a sectional view in the Y-Z plane of the optical components of a so-called RCR design of a projection objective for immersion lithography with a numerical aperture of 1.25;

[0107] FIG. **17** represents a sectional view in the Y-Z plane of the optical components of a further two-mirror design of a projection objective for immersion lithography with a numerical aperture of 1.75;

[0108] FIG. **18** schematically illustrates the last lens element before the field plane of the two-mirror design of FIG. **17**;

[0109] FIG. **19** represents a sectional view of the optical components of a so-called six-mirror design of a projection objective for EUV lithography;

[0110] FIG. **20** represents a graph of a possible distribution of the surface roughness over the optically used area of a surface of a field-proximate optical element;

[0111] FIG. **21** represents a flowchart diagram of several possible process steps for producing in a projection objective a corrected stray light component;

[0112] FIG. **22** represents a flowchart diagram for a method of producing microstructured semiconductor elements by a projection exposure apparatus with a projection objective in accordance with the present patent application.

DETAILED DESCRIPTION

[0113] FIG. **1** shows the exposure field **15** in the field plane of a projection objective for microlithography applications which is used as scanner, including the distribution of the useful light along the X- and Y-axes. In FIG. **1**, the field plane in which the exposure field **15** is located is seen in plan view, meaning that the plane of the paper coincides with the field plane. Further in FIG. **1**, a coordinate system is defined in the field plane in accordance with the rule that for so-called scanners the scan direction should be oriented in the Y-direction. In so-called scanners, the mask structure of a microstructured component is not transferred in its entirety in one exposure step by the projection objective onto a so-called wafer, because the image of the entire mask structure is too large for the maximum image field **1** of a projection objective. Instead, the mask structure is gradually moved through the object- or mask plane of the projection objective in a scanning process, while the wafer is moved at the same time in a synchronized movement through the image- or field plane. In conventional rotationally symmetric projection systems, which have refractive elements exclusively, the maximum image field **1** in the field plane is a circle whose center is defined by the optical axis **3** of the projection system. By field aperture stops which are located in the illumination system, the so-called REMA (reticle-masking) blades, the maximum image field **1** is trimmed back to the rectangular exposure field **15** whose center is defined by the optical axis **3** of the objective. The REMA blades have the additional function at the beginning and end of a scanning process, respectively, to retract and deploy themselves over the exposure field **15**. The center of the exposure field **15** is formed by a central area **5** which is shaded in FIG. **1**. The border areas (also referred to herein as marginal areas) **7** and **9** of the exposure field, which are likewise shaded in FIG. **1**, are those border areas **7** and **9** of the rectangular exposure field which form the left and right margins of the exposure field in the direction perpendicular to the scan direction. In the scan direction, the front edge **11** and the rear edge **13** of the exposure field **15** are the lines between which the exposure field **15** is located and between which the light projected by the objective has an intensity larger than zero. The respective intensity distribution profiles of the useful light in the scan direction and perpendicular to the scan direction are different from each other, as shown in the two diagrams in FIG. **1**. In the scan direction, the intensity distribution profile of the useful light is adjusted so that it takes on a value of zero at the front edge **11** and the rear edge **13** and has its maximum within the central area **5**. The exact intensity distribution between these two points is selected so that in the scanning process every partial area of a microstructured component receives a nearly equal portion of the light. This would be impossible to achieve with a so-called top hat profile, i.e. a rectangular distribution profile in the scan direction, because a pulsed laser is typically used as a light source and it could not be ruled out in this case that one partial area of the microstructured component would receive light from one more laser pulse than another partial area, with 5 to 7 laser pulses per partial area or per exposure field being typical. With an intensity distribution in the scan direction which continuously increases towards the central area **5** from a value of zero at the front edge **11** and at the rear edge **13**, such intensity effects on the microstructured components are suppressed.

[0114] In contrast, the intensity distribution perpendicular to the scan direction is a so-called top hat distribution or rectangular distribution over the exposure field **15**, with the same intensity value for the central area **5**, the border areas **7** and **9** and all field points lying in between along a line that is perpendicular to the scan direction. Insofar, the shape of this intensity distribution also does not change if it is averaged over the scan direction. This intensity distribution, averaged over the scan direction and expressed in percent relative to the useful light is represented by the diagram in the bottom part of FIG. **1**. This averaged intensity distribution has the same value of 100% relative to the useful light for the central area **5** as for the border area **7**.

[0115] The stray light component defined according to the measuring rule stated above is understood herein as a stray light component that is averaged over the scan direction and expressed as a relative amount in proportion to the useful light or, in other words, as a relative amount in proportion to the 100% value of the intensity distribution in the scan direction as illustrated in FIG. **1**.

[0116] The exposure field **15** of a scanner typically measures 20 to 30 mm perpendicular to the scan direction and 5 to 10 mm in the scan direction. Together with these dimensions, the central area **5** of the exposure field **15** should not exceed a diameter of 4 mm, and the border areas **7** and **9** of the exposure field **15** should not exceed a width of 2 mm perpendicular to the scan direction, as these areas should only occupy small surface portions immediately at the center and at the border of the exposure field **15** without spreading out over major portions of the exposure field **15**.

[0117] FIG. **2** shows the exposure field **45** in the field plane of a projection objective for microlithography applications which is used as a scanner and has a so-called off-axis field **45** of rectangular shape as exposure field **45**. The elements in FIG. **2** which are analogous to those in FIG. **1** have the same reference numerals raised by 30. Such rectangular off-axis fields **45** as exposure fields **45** of a projection objective are typical in projection objectives which have at least one catadioptric partial objective. The attribute "catadioptric" means here that besides refractive elements such as for example lenses, there are also reflective elements such as for example mirrors being used as elements which contribute to the formation of the image and thus carry refractive power. Due to the folded ray path of these systems, the exposure field **45** is offset relative to the optical axis **33** and the maximum image field **31** of these systems. When referring to the optical axis **33** and the maximum image field **31** in this context, this does not imply that the optical axis **33** as well as the entire maximum image field **31** can be covered in the projected image of these catadioptric projection objectives. It only indicates that many of these catadioptric projection objectives can still be described in terms of rotational symmetry in regard to their design, even though the ray propagation pattern used in the completed objective is not folded with rotational symmetry relative to the optical axis **31** and the physical shapes of some of the optical elements are no longer rotationally symmetric relative to the optical axis **31**. Examples for the design of a catadioptric projection objective with a rectangular off-axis field **45** as exposure field **45** are presented in US 2005/0190435 A1, WO 2004/019128 A2 and WO 2006/133801 A1, as well as in FIGS. **14**, **16** and **17** of the present patent application. What has been the above in the context of FIG. **1** about the intensity distribution in the scan direction and perpendicular to it is also directly applicable to the rectangular off-axis field **45** and therefore needs no further explanation. Rectangular off-axis fields **45** of catadioptric projection objectives have about the same size as exposure fields **15** of purely refractive projection objectives. Catadioptric projection objectives are used primarily for immersion lithography because even with the large numerical aperture values (NA) of more than 1 of an immersion objective, catadioptric projection objectives allow the lens- and mirror diameters to be kept relatively small in comparison to a purely refractive design.

[0118] FIG. **3** shows the exposure field **65** in the field plane of a projection objective for microlithography applications which is used as a scanner and has a so-called ring field **65** as exposure field **65**. The elements in FIG. **3** which are analogous to those in FIG. **1** have the same reference numerals raised by 50. Such ring fields **65** are typical for catadioptric objectives of a design that does not allow for a folded light ray path that would lead to a rectangular field. What has been the above in the context of FIG. **1** about the intensity distribution in the scan direction and perpendicular to it is also directly applicable to the ring field **65** and therefore needs no further explanation. The intensity distribution in the scan direction can differ from the intensity distribution shown in FIG. **1** insofar as with different heights in the X-direction the resultant distribution is not the same for all intensity distributions in the scan direction. However, this is of no consequence, and it would also be of no consequence if it occurred in a system with a rectangular field **15**, **45**, as all scanner systems are always designed so that regardless of the shape of the intensity distribution along the scan direction, one always obtains an intensity distribution perpendicular to the scan direction which, when averaged over the scan direction, conforms to a top-hat profile or rectangular profile of the type illustrated in the lower part of FIG. **1**. Ring fields **65** of catadioptric projection objectives have about the same dimension perpendicular to the scan direction as the dimension perpendicular to the scan direction of exposure fields **15** of purely refractive projection objectives.

[0119] FIG. **4** shows the exposure field **85** in the field plane of a projection objective for microlithography applications which is used as a stepper and has a square-shaped field **85** as exposure field **85**. The elements in FIG. **4** which are analogous to those in FIG. **1** have the same reference numerals raised by 70. In contrast to a scanner, a stepper functions in such a way that the mask structure for the semiconductor element to be produced, which is located in the object- or mask plane of the projection objective, is projected in its entirety, i.e. without a scanning process, into the exposure field **85** in the field plane. However, this involves the projection objective providing larger exposure fields **85** than in the case of scanners. As an alternative for the large exposure fields **85** in the case of steppers, the semiconductor element can be exposed sequentially in a stepper in individual portions, using a so-called stitching technique. In this case, it is also possible to use smaller exposure fields **85** than in the case of scanners. The exposure field **85** in steppers can arbitrarily be made larger and smaller in the X-direction as well as the Y-direction by the REMA blades in the illumination system. The intensity distribution over the exposure field **85** in steppers is completely homogeneous, so that the resultant distribution has a top-hat- or rectangular profile in the X-direction as well as in the Y-direction. To ensure that the steppers can be compared to the scanners within the scope of this patent application, border areas **77** and **79**, located to the right and left at the borders of the stepper field perpendicular to the Y-direction. Furthermore, analogous to the scanners described herein, the intensity distribution in the X-direction is averaged over the Y-direction, which results in a top-hat distribution of the kind shown in the lower part of FIG. **1**, with the same intensity value of 100% of the useful light for the central areas **5** and **75**, respectively, as for the border areas **7** and **77**, respectively. To maintain the comparability with scanners, the stray light component of steppers is likewise defined as being averaged along the Y-direction.

[0120] FIG. **5** presents a schematic illustration of a projection objective **103** and also a substitute model of a projection objective as a homogeneous glass cylinder **111** serving to explain the natural stray light distribution which occurs as a result in the field plane **105**. In the upper part of FIG. **5**, a schematic representation of a projection objective **103** is indicated by four lenses **109** along an optical axis **113**. This projection objective **103** has the function of projecting an image of a mask **101** which is located in a mask plane into a field plane **105**. The mask to be projected is homogeneously illuminated for this purpose by light **107** from an illumination system which is not shown in the drawing. The illumination system is capable of changing the angular distribution of the incident light rays **107** falling homogeneously on the mask **101**, without thereby changing the intensity distribution over the mask. This makes it possible to have different so-called settings available for the semiconductor manufacturer, which can be described in terms of the theory of partially coherent images and which have the purpose that certain structures on the mask **101** can be projected into the smallest possible image size.

[0121] The lower part of FIG. **5** represents, as a substitute model for the projection objective **103**, a homogeneous glass cylinder **111** which is homogeneously illuminated by the light rays **107** which fall homogeneously on the mask **101**. A glass cylinder **111** of this kind, which is homogeneously illuminated over its cross-sectional area, will generate equal amounts of stray light within equal-sized surface elements of the cross-sectional area. If the glass cylinder **111** from the mask **101** to the field plane **105** along the optical axis **113** is looked at as a series of many such homogeneously illuminated cross-sectional areas wherein the overall intensity of the illumination decreases along the optical axis **113** from the mask **101** to the field plane **105** due to absorption and scattering, one obtains a stray light component in the field plane **105**, averaged over the scan direction Y, which conforms to the diagram at the lower right of FIG. **5**. Due to the fact that each of the equal-sized surface elements of each cross-sectional area generates an equal amount of stray light, the proportion of stray light is higher in the central area **115** of the exposure field of the field plane **105** than in the border area **117** of the exposure field (as illustrated in the diagram at the lower right of FIG. **5**), because the central area **115** receives the stray light of more mutually adjacent surface elements of each cross-sectional area than does the border area **117**. This profile of the stray light component over the exposure field as illustrated in the lower right-hand part of FIG. **5**, which results from the homogeneous illumination of a cylindrical glass body, will be referred to hereinafter as the natural profile of the stray light component.

[0122] FIG. **6** shows the image-forming light ray pattern of a projection objective according to the principles of geometric optics to illustrate the concepts of field and pupil. The projection objective **123** in FIG. **6** is shown as a so-called 4f system consisting in this schematically simplified representation of two lenses **129**, between the latter a pupil plane **133**, and two field-proximate planes **135**, **137** in which the lenses **129** are located. The projection objective projects an image of the mask **121**, which is homogeneously illuminated by the light rays **127**, along the optical axis **131** into the field plane **125**. To explain the image-projecting light ray pattern, three specific ray paths are shown for the axis point of the mask **121**, i.e., the principal ray **139** along the optical axis **131**, the upper aperture ray or coma ray **141**, and the lower aperture ray or coma ray **143**. These aperture rays or coma rays are those rays which leave the axis point at the maximum possible angle at which they can still be projected into an image by the projection objective. Also shown is the path of the principal ray **149** for the outermost field point to be projected by the projection objective. The pupil is defined as the area at whose center the principal rays **139**, **149** of all field points intersect each other and whose size is determined by the aperture rays **141**, **143**. Thus, the pupil does not necessarily always have to be in a pupil plane **133** as shown in FIG. **6**, but a representation like the one in FIG. **6** facilitates the explanation of the optical concepts of field and pupil. The pupil plane **133** according to FIG. **6** is therefore the location relative to the light propagation direction or Z-direction where the principal rays **139**, **149** of the field points meet each other. Since a principal ray **139** coincides with the optical axis, the pupil in FIG. **6** also is the location where all principal rays **139**, **149** of the field points intersect the optical axis. The principal rays

139, **149** of the field points thus have no height, or distance from the optical axis, in the pupil. The aperture rays **141**, **143**, on the other hand, define the border of the pupil and thus have the maximum height, or maximum distance from the optical axis, of all possible rays in the pupil. The height, or distance from the optical axis, of the rays thus represents a suitable criterion as to whether an optical element in an objective can be referred to as being near a pupil (pupil-proximate) or near a field (field-proximate). If the height or distance of an aperture ray **141**, **143** of the axis point, or central field point, at a surface of an optical element is more than six times the height of the principal ray of the outermost projectable field point on the same surface, then the optical element will be referred to herein as being near a pupil (or pupil-proximate), otherwise it will be referred to herein as being near a field (or field-proximate), wherein in so-called RCR designs (refractive-catadioptric-refractive designs) the reference for the distance of the rays in the elements of the Schupmann group G**20** (see FIG. **16**) is their optical axis. Based on this criterion, it is clear that the two lenses **129** in FIG. **6** are located, respectively, in field-proximate planes **135** and **137**. Furthermore, field and pupil are related to each other through a spatial Fourier transform wherein the height, or distance from the optical axis **131**, of an image-forming ray **139**, **141**, **143**, **149** in the field corresponds to the angle between the image-forming ray **139**, **141**, **143**, **149** and the optical axis in the pupil. At the same time, the inverse relationship also holds, i.e., the angle between the image-forming ray **139**, **141**, **143**, **149** and the optical axis in the field corresponds to the height, or distance from the optical axis **131**, of the image-forming ray **139**, **141**, **143**, **149** in the field. In other words, the path of the principal ray **149** of the outermost field point that can be projected has its maximum height, or greatest distance from the optical axis **131**, in the image plane of the mask **121**, with an angle of zero relative to the optical axis **131**. The same ray path **149** crosses the optical axis **131** at the center of the pupil plane **133** with the maximum angle of intersection, i.e. the height of the ray from the optical axis **131** is minimal at this point, while the angle relative to the optical axis **131** is maximal. Conversely, the aperture rays have their smallest heights and largest angles relative to the optical axis **131** in the image plane of the mask **121** and the field plane **125**, while their greatest heights and smallest angles relative to the optical axis **131** occur in the pupil plane **133**. Based on this special relationship between field and pupil, it is possible to perform interventions into the light distribution in the pupil which have a uniform effect on every field point of the field. The simplest possibility is for example to constrict the pupil with an aperture stop, so that all field points are lacking rays whose angle in the field is larger than the maximum possible aperture angle allowed by the constricted pupil.

[0123] By an illumination system, the light rays **127** which are falling homogenously on the mask **121** are adapted in regard to their angular distribution relative to the optical axis in order to meet customer's desired properties that specify so-called illumination settings, so that different areas with different intensities are formed in the pupil of the projection objective, whereby lenses near a pupil of the projection objective are illuminated differently depending on the illumination setting. For example, an annular setting in combination with a suitable mask structure has the consequence that lenses near a pupil are receiving light only in border areas of the optically usable part of the lens. For an explanation of the working principle of the illumination settings in combination with the mask structures, the reader is referred to the pertinent literature concerning the theory of partially coherent images of objects that are not self-luminous.

[0124] In the relationship between pupil, specifically lenses near a pupil, and stray light it is important that due to the three causes of Rayleigh scattering, Mie scattering and geometric scattering, the elastic scattering of light of the wavelength λ which occurs at the inhomogeneities of the glass material always produces an angular distribution that is symmetric around the direction of the useful light ray. This means that for field points at the border of the field, whose principal rays are strongly angled in the pupil, and for a conventional setting with a small sigma value (which is a setting in which only the central area of the pupil, i.e. the area traversed by the principal rays, is being used), the resultant angular distributions of the stray light in pupil-proximate lenses are oriented outwards to the housing of the objective and away from the optical axis, so that on the way from the pupil to the field, stray light is absorbed by the housing of the objective and by the lens mounts. The result of this is a stray light component profile over the field which, due to the stray light absorption, has a lower value in the border area **147** of the exposure field than in the rest of the exposure field. For an annular setting on the other hand, which uses the border area of the pupil and thus the area traversed by the aperture rays, there is overall only an insignificant difference in the angles of inclination of the aperture rays between field points of the border area and field points of the central area, but due to the proximity of the border area of the pupil to the housing of the objective, the part of the stray light that is scattered in the pupil under a large angle is absorbed most strongly. Since large angles in the pupil translate according to the Fourier transform into large heights in the field, the stray light that is scattered in the pupil under a large angle is subject to absorption in the housing of the objective and therefore lacking in the border area **147** in comparison to the central area **145** of the exposure field. Accordingly, an annular illumination setting in particular (i.e. a setting where the light rays **127** fall on the mask **121** with rotational symmetry at angles of incidence within a narrowly defined angular range) does not lead to a profile of the stray light component that is qualitatively different from the profile obtained with a conventional setting. Consequently, that part of the variation of the stray light component averaged in the scan direction which occurs as a result of different settings can overall be considered negligible in relation to the amount by which the stray light component, averaged in the scan direction, according to the measurement rule used herein varies over the field.

[0125] In projection objectives for immersion lithography, the last lens with its strongly positive refractive power has the result that the path lengths in the optical material are different for different field points. The relative path length difference of all image-forming rays of a field point in the border area of the exposure field in comparison to all image-forming rays of the central field point of the exposure field for such a lens alone can amount to a few percent. Consequently, since the stray light component due to inhomogeneities in the glass material depends directly on the path length traveled in the glass material by the useful light, this leads particularly in strongly scattering material to a resultant stray light component profile over the field with a lower value in the border area **147** of the exposure field than in the central area **145**.

[0126] In the context of FIGS. **5** and **6**, a total of three different effects have been discussed, all of which lead to a stray light component, averaged over the scan direction, wherein the profile over the exposure field has a stronger stray light component in the central area **145** than in the border area **147** of the exposure field, as illustrated in the right-hand part of FIG. **6**. All of these three effects result from the primary stray light due to elastic scattering of light at inhomogeneities in the glass material and are, respectively, the natural stray light profile of a homogenously illuminated glass body, the stray light profile of the lenses near a pupil, and the stray light profile due to the differences in path length in strongly positive field lenses.

[0127] In addition to the effects just mentioned, which are due to the primary cause of stray light, i.e. the elastic scattering of light at inhomogeneities in the glass material, there is the superimposed stray light which is due to the scattering of light at surface irregularities which, as mentioned above, represents a second primary cause of stray light. The lenses are usually polished to a uniform finish quality on all parts of the surface and consequently, the above train of reasoning that the image-forming ray paths of field points from the border area of the field are overall more strongly inclined relative to the optical axis and relative to the refractive surfaces than the image-forming ray paths of field points from the central area, in combination with the fact that the angular distribution of the stray light is rotationally symmetric to the direction of the useful light also in the case of surface scattering, leads to the conclusion that the scattering at the surface irregularities likewise results in an average stray light component over the scan direction which is stronger in the central area of the field than in the border area of the field and is characterized by a profile over the field.

[0128] FIG. **7** shows a typical stray light component **151**, averaged over the scan direction, for a microlithography projection objective of a current design as a profile graph along the X-direction over the exposure field in accordance with the measurement rule observed herein. As is evident, the stray light component **151** is higher in the central area **155** of the field with a value of 0.8% relative to the useful light than it is in the border area **157** with a value of 0.6% relative to the useful light.

[0129] FIG. **8** schematically illustrates the optical part of a projection exposure apparatus **201** for immersion lithography. The projection exposure apparatus **201** has an excimer laser **203** as its light source with a wavelength of 193 nm. As an alternative, it is also possible to use other wavelengths such as 248 nm or 157 nm. An illumination system **205** arranged in the light path downstream of the light source produces a sharply delimited homogeneous illumination field in its image plane **207** which is at the same time the object plane **207** of the projection objective **211** which follows in the light path. Normally in this arrangement the ray geometry at the output side of the illumination system **205** is adapted to the ray geometry at the input side of the projection system **211**. As mentioned above, the illumination system **205** includes a mechanism for structuring the angular distribution of the light rays **207** falling on the object plane **207** and for controlling the state of polarization of the incident light rays. A so-called reticle stage holds the mask **213** in the object plane of the illumination system and in accordance with the scanning process moves the mask along the scan direction **215**. After the object plane **207** which at the same time represents the mask plane **207**, the projection objective **211** follows next in the light path, projecting a reduced image of the mask **213** onto a wafer **219**. The wafer **219** carries a light-sensitive so-called photoresist **221** and is positioned so that the planar surface of the wafer **219** with the photoresist **221** is located in the image plane **223**, or field plane **223**, of the projection objective **211**. The wafer **219** is held by a so-called wafer stage **217** and advanced at a rate that is synchronized with the movement of the mask **213**. The wafer stage **217** also has manipulators which can move the wafer **219** along the optical axis **225** or perpendicular to it. Likewise incorporated in the wafer stage **217** is a tilting manipulator which can tilt the wafer **219** about an axis perpendicular to the optical axis **225**. The wafer stage **217** is designed specifically for immersion lithography and includes a holder element **227** with a shallow recess for the substrate **219** as well as a rim **229** to contain the immersion liquid **231**.

[0130] The projection objective **211** for immersion lithography applications has an image-side numerical aperture NA that is larger than 1.0, preferably larger than 1.2, and with even higher preference larger than 1.5. The projection objective **211** has as its last optical element before the field plane **223** a planar-convex lens **233** whose underside **235** is the last optical surface of the projection objective **211** in the light path as seen in the direction of the light rays propagating from the mask plane to the field plane. This underside **235** is totally immersed in an immersion liquid **231**.

[0131] The hemispherical planar-convex lens **233** consists preferably of polycrystalline material whose microscopic structure is illustrated in FIG. **9**. Conceivably, further lenses **237** of a projection objective could also consist of polycrystalline material.

[0132] FIG. **9** shows the microscopic structure of a polycrystalline material schematically and not true to scale. The material **300** shown here is polycrystalline magnesium spinel ($MgAl_2O_4$) and has a large number of differently oriented crystals **302** delimited by respective crystal boundaries **303**. The mean crystal dimension in this example is around 25 μm. Interspersed between the crystals **302** are hollow spaces, or bubbles **304**, whose mean dimension in this example is about 1 μm. Other polycrystalline materials are likewise conceivable for use as an optical material, for example other polycrystalline spinels, polycrystalline YAG [yttrium aluminum garnet ($Y_3Al_5O_{12}$)], polycrystalline LuAG [lutetium aluminum garnet ($Lu_3Al_5O_{12}$)], polycrystalline magnesium oxide (MgO), polycrystalline beryllium oxide (BeO), polycrystalline aluminum oxide (Al_2O_3), polycrystalline yttrium oxide (Y_2O_3) or polycrystalline fluorides with a high refractive index, such as for example $BaLiF_3$ or LaF_3.

[0133] FIG. **10** shows the stray light component in percent relative to the useful light of a homogeneous polycrystalline material of spinel with 40 mm thickness as a function of the mean crystal dimension D according to the corresponding stray light model presented in WO 2006/061225. This stray light model, besides taking the stray light L_{ret} into account which results from the refractive index fluctuations due to the different orientations of the crystals along a light path, also includes a stray light component I_{scat} which results from the total reflection taking place at the crystal boundaries **303**. This adds up to a total stray light component for the stray light, which is represented as I_{sum} in FIG. **10** and has its minimum for the crystal size marked by the arrow P. Furthermore, a model-dependent stray light component of a polycrystalline material of spinel of 40 mm thickness is represented in FIG. **11**, expressed in percent relative to the useful light as a function of the mean bubble diameter according to the corresponding stray light model in WO 2006/061255.

[0134] Based on the stray light models in WO 2006/061255, or in FIGS. **10** and **11**, only specific parameter ranges for the mean crystal size and the mean bubble diameter in polycrystalline material are feasible for using this kind of material in projection objectives for microlithography applications, as the stray light component of the projection objective will otherwise become too large. However, FIGS. **10** and **11** lead to the conclusion that even if the parameter ranges that are optimal in regard to stray light are adhered to in the production of the polycrystalline spinel material, an optical element of spinel with a thickness of 40 mm will still produce a stray light component of about 0.4% relative to the useful light. By also considering the aforementioned natural stray light distribution of a body carrying a homogeneous flow of light, one arrives at the result that for a last, field-proximate lens of polycrystalline material immediately before the field plane, the profile of the stray light component, averaged over the scan direction, has a variation over the entire field plane of 0.4% relative to the useful light. The exact amount of variation over the exposure field in the field plane for the stray light component of such a field-proximate lens, averaged over the scan direction, depends on the exact geometry of the lens and the exposure field as well as on the distance of the lens from the field plane, and it is entirely possible for the variation to be only half as large as the aforementioned value. Insofar, a strongly positive single lens of spinel, used as the last lens of the objective, has a variation of the stray light over the exposure field that is about half as large as the variation of an entire projection objective of current design.

[0135] FIG. **12** represents a sketch to illustrate principal concepts regarding the scattering at inhomogeneities **407** in the polycrystalline material of a last lens **400** and regarding the concept of adapting the surface roughness **403** of a last lens, as well as the resultant stray light distributions **411**, **413** over the field. In FIG. **12** a last lens **400** of a projection objective is located before the field plane **405** which extends perpendicular to the optical axis **401** immediately after the last lens **400**. The inhomogeneities of the glass material are symbolically indicated in the lens **400** as scatter lobes **407** which represent the angular distribution of the stray light. The stray light component **411** of the lens **400** due to the inhomogeneities of the glass material (volume scatter), averaged over the scan direction and expressed as a percentage relative to the useful light is shown in the mid-portion of FIG. **12** as a profile graph over the field along the X-direction. Current Monte Carlo simulations concerning the stray light component **411** due to the volume scatter of a lens consisting of polycrystalline material and arranged in last position before the field plane in the ray direction from the mask plane to the field plane lead to the result that the stray light component averaged over the scan direction and expressed as a percentage of the useful light is about 0.4% in the central area **415** of the exposure field and about 0.2% in the border area **417** of the exposure field, thus confirming the stray light values of WO 2006/061225 which have been discussed above. To compensate for the stray light component **411** due to the volume scatter of the last lens which consists of spinel, the surface roughness of the upper side **402**, i.e. the side of the last lens that faces away from the field plane **405**, is increased in the border zones **403**, which produces the result of an added stray light component **413**. The change of the surface roughness of the upper side **402** is selected so that it results in an additional stray light component **413** whose profile over the exposure field complements the stray light component **411** due to the volume scatter, so as to add up to an overall stray light component that is nearly constant. The added stray light component **413** due to the surface roughness, expressed as a percentage of the useful light and averaged over the scan direction, is shown in the right hand portion of FIG. **12** as a profile graph over the field along the X-direction. By changing the surface roughness on the upper side **402** of the last lens, only a very small amount of additional stray light **413** is introduced in the central area of the exposure field **415**, in contrast to the border area **417** of the exposure field where the added amount of stray light is about 0.5%, which compensates for the stray light **411** which comes from the volume scatter of the last lens. The surface roughness of the upper side **402** does not necessarily have to be produced in a reworking operation; it can also be adapted in advance during the production process of the lens.

[0136] FIG. **13** shows the stray light component, expressed as a percentage relative to the useful light, of a projection objective for microlithography applications, which has been corrected in accordance with the disclosure, averaged over the scan direction y and represented as a profile graph **501** in the X-direction along the field. The finely dotted line in FIG. **13** represents the stray light component, averaged over the scan direction, of a projection objective in which the last lens element does not consist of polycrystalline material, in the form of a profile graph **503** along the X-direction over the exposure field with a central area **505** and a border area **507**. The variation over the field is smaller than 0.2% for this stray light component, and the latter is therefore considered a constant stray light component within the bounds of this application. The horizontal grid lines and the bands **509** with a height of 0.2% serve as a graphic background to indicate the range within which a stray light component is considered constant within this application. The stray light component of a comparable projection objective in which the last lens consist of polycrystalline material is represented by a broken line with the reference symbol **502** in FIG. **13**. The stray light component **502** exhibits a stronger variation over the field than would be permissible for a constant stray light component **509**. A solid and heavier line **501** in FIG. **13** represents the stray light component of a projection objective that has been corrected in accordance with the disclosure, with a last lens of polycrystalline material. This stray light component **501** of the projection objective which has been corrected has a stray light component which in the central area **505** and in the border area **507** as well as in all field points in between amounts to about 1.3% relative to the useful light. Accordingly, this represents a very constant stray light component, averaged over the scan direction, with a variation over the exposure field far below 0.2% relative to the useful light.

[0137] The disclosure is suited insofar not only for the correction of projection objectives with a last lens of polycrystalline material, but also for the improvement of current projection objectives so that they will have a constant stray light component with less than 0.2% variation over the exposure field.

[0138] FIG. **14** shows a so-called two-mirror design **2100** of a projection objective for immersion lithography with an image-side numerical aperture larger than 1. The design **2100** has been borrowed from FIG. 38 of US 2005/0190435 A1, keeping the same reference symbols. Only the reference symbols for the areas **2003** of increased surface roughness are newly added in comparison to FIG. 38 of US 2005/0190435 A1. The design **2100** is drawn in FIG. **14***a* in an X-Y sectional view and thus in a plane that is defined by the scan direction y and the direction of the optical Z-axis, because the folded configuration of the ray path could not be visualized otherwise. The same form of representation is also used in all of the catadioptric design discussed hereinafter. The mask plane **2101** is projected by the first refractive objective group **2110** onto an extended intermediate image plane **2103**. The first refractive group has a pupil- or aperture plane A. The mirror group **2120** with the mirrors **2121** and **2122** projects the extended intermediate image plane **2103** into a further extended intermediate image plane **2104**. The second refractive objective group **2130** projects the extended intermediate image plane **2104** into the field plane **2102**. The last lens before the field plane **2102** in the direction of the light rays from the mask plane **2101** to the field plane **2102** carries the reference symbol **2150**. The surface areas of field-proximate optical elements near the exposure field **2102** or near the intermediate field planes **2103** and **2104**, which are suitable for correcting the variation of the stray light component over the exposure field by increasing the surface roughness are indicated by a heavier sawtooth line **2003**. For better clarity, the lower part of the second refractive group **2130** is shown in an enlarged view in FIG. **14***b*. Further indicated by the shaded bars in FIG. **14***b* is the area **2005** of the surface of the last optical element **2150** before the field plane **2102** in the direction of the light rays from the mask plane **2101** to the field plane **2102**, where an aperture stop could be suitably arranged to reduce stray light, in particular out-of-field stray light. This aperture stop can be realized with mechanical field aperture stops between the last optical element **2150** and the field plane **2102**. However, it is more advantageous to realize the aperture stop by masking the surface parts **2005** of the last optical element which are indicated by the shaded bars in FIG. **14***b*, because this creates no spatial interferences and has no detrimental influence on the flow dynamics of the immersion liquid. This masking can be accomplished cost-effectively by placing an absorbent or reflective coating on the areas **2005** that are shaded in FIG. **14***b*.

[0139] However, in the representation of the design in FIGS. **14***a* and **14***b* it should be noted that the design is shown in a Y-Z sectional view and thus in the scanning direction, because the structural concept of the design could not be represented in an X-Z section, i.e. perpendicular to the scanning direction. The heavier sawtooth lines **2003** in FIGS. **14***a* and **14***b* insofar indicate only the field-proximate surfaces which can be considered for an adaptation of the surface roughness, and on the other hand only illustrate the principle that those areas **2003** of the field-proximate surfaces which are met or traversed by rays of an outer field point of the exposure field have a higher surface roughness. The areas **2003** of the field-proximate surfaces with an increased surface roughness that are suitable for reducing the amount by which a stray light component, averaged over the scanning direction, varies perpendicular to the scanning direction over the exposure field can be illustrated better in an X-Z section of the design. Seen in an X-Z sectional view, the areas **2003** with the increased surface roughness are arranged on the optical elements in such a way that they are located equally at the borders to the right and left (relative to the x-direction) of the center of the optically used area, so that they have an equal effect on the stray light component, averaged over the scanning direction, in the border areas to the right and left (relative to the x-direction) of the central area.

[0140] FIG. **15** shows a so-called four-mirror design PL**1** of a projection objective for immersion lithography with an image-side numerical aperture of 1.2. The design PL**1** has been borrowed from FIG. 9 of US 2007/0024960 A1, keeping the same reference symbols. Only the reference symbol for the field plane W**1** is newly added in comparison to FIG. 9 of US 2007/0024960 A1. The mask plane R**1** is projected onto an intermediate image plane Q by the first catadioptric objective group G**1** consisting of the purely refractive subgroup G**11** with the lenses L**1** to L**4** and the catadioptric subgroup consisting of the lens **5** and mirrors M**1** and M**2**. The intermediate image plane Q is projected into the field plane W**1** immediately after the lens **18** by the second catadioptric objective group G**2** consisting of the two mirrors M**3** and M**4**, the refractive subgroup G**21** with the lenses L**6** and L**7**, the refractive subgroup G**22** with the lenses L**8** to L**12**, and the refractive subgroup G**23** with the lenses L**13** to L**18**. A pupil plane or aperture plane AS**1** is located between the subgroups G**22** and G**23**. The broken lines extending the mirror surfaces M**2** and M**3** illustrate the statement made above that catadioptric designs can normally be described through the terminology of rotationally symmetric designs, even if the real ray path geometry or the real physical shapes of the optical elements of such a design no longer exhibit this rotational symmetry. In order to retrace this thought process, the design PL**1** shown in FIG. **15** has to be rotated about the optical axis AX**1**. After this rotation, all optical elements possess rotational symmetry relative to the optical axis AX**1**, and the optical axis AX**1** is now also the optical axis of all optical elements within the design PL**1**.

[0141] The field-proximate surface areas near the field plane W**1**, or near the intermediate image plane Q, in the direction of the light path from the mask plane R**1** to the field plane W**1**, which are suitable for correcting the variation of the stray light component over the exposure field by increasing the surface roughness are in this design PL**1** all of the mirror surfaces M**1** to M**4** and the surfaces of the lenses L**5**, L**6** and L**18**.

[0142] FIG. **16** shows a so-called RCR design (refractive-catadioptric-refractive design) of a projection objective for immersion lithography with an image-side numerical aperture of 1.25. The design has been borrowed from FIG. 19 of WO 2004/019128 A2, wherein the reference symbols have been maintained to the largest extent, except that each of the reference symbols of the groups and lenses has been expanded with an added zero, while the reference symbol W**1** for the field plane, the reference symbol M**10** for the first direction-changing mirror, and the reference symbol M**20** for the second direction-changing mirror have been newly added in comparison to FIG. 19 of WO 2004/019128 A2. The first refractive objective group G**10** with the lenses L**110** to L**1100** projects the mask plane R**1** into a first extended intermediate image area after the first direction-changing mirror M**10**. The catadioptric group G**20** consisting of the lenses L**210**, L**220** and a spherical mirror CM forms a so-called Schupmann achromat for the correction of the longitudinal chromatic aberration and projects the first extended intermediate image area into a second extended intermediate image area before the second direction-changing mirror M**20**. The second intermediate image plane is projected into the field plane W**1** immediately below the lens L**3150** by the second refractive objective group G**30** with the lenses L**310** to L**3150**. The second refractive objective group has a pupil plane or aperture plane identified as AS. As has already been mentioned above, the optical axis of the Schupmann achromat, or group G**20**, represents the reference axis for the definition of the concepts of field and pupil as used herein in regard to all elements after the first direction-changing mirror M**10** and before the second direction-changing mirror M**20**, because in contrast to all other designs presented herein, the rotational symmetry of the design about the optical axis is broken by these direction-changing mirrors. The field-proximate surfaces near the field plane W**1**, or near the intermediate image plane Q, in the direction of the light path from the mask plane R**1** to the field plane W**1**, which are suitable for correcting the variation of the stray light component over the exposure field by increasing the surface roughness are in this RCR design the direction-changing changing mirror surfaces M**10** and M**20** as well as the surfaces of the lenses L**100**, L**310** and L**3150**.

[0143] FIG. **17** shows a further two-mirror design **800** of a projection objective for immersion lithography with an image-side numerical aperture of 1.75. The design **800** has been borrowed from FIG. 8 of WO 2006/133801 A1, wherein the reference symbols have to the largest extent been maintained. Only the reference symbols of the objective groups G**100** to G**900** have been expanded in comparison to FIG. 8 of WO 2006/133801 A1 by adding double zeroes. The first refractive objective group ROP**1** projects the mask plane OP into an extended intermediate image plane IMI**1**. The first refractive group has a pupil plane or aperture plane identified as AS. The extended intermediate image plane IMI**1** is projected into a further extended intermediate image plane IMI**2** by the mirror group COP**2** with the mirrors CM**1** and CM**2**. The second refractive objective group ROP**3** projects the extended intermediate image plane IMI**2** into the field plane IP. The last lens before the field plane IP in the direction of the light rays from the mask plane OP to the field plane IP carries the reference symbol LOE and consists of two partial lenses LOE**1** and LOE**2** with an immersion liquid IL between the partial lenses (see description of FIG. **18**).

[0144] The field-proximate surfaces near the field plane IP, or near the extended intermediate image planes IMI**1** and IMI**2**, in the direction of the light path from the mask plane OP to the field plane IP, which are suitable for correcting the variation of the stray light component over the exposure field by increasing the surface roughness are in this design **800** the mirror surfaces CM**1** and CM**2** as well as the surfaces of the lenses B**800**, LOE and the lens before CM**1** in the direction of the light rays from the mask plane OP to the image plane IP.

[0145] FIG. **18** shows as a detail of the design **800** of FIG. **17** the last lens element LOE before the field plane IP in the direction of the light rays from the mask plane OP to the image plane IP. This lens element consists of quartz glass for the partial lens LOE**1** and sapphire for the partial lens LOE**2**, wherein the crystallographic axis in the latter is oriented in the direction CA parallel to the optical axis AX. Between the two partial lenses LOE**1** and LOE**2** there is an immersion liquid. Other crystalline materials with a high index of refraction are also mentioned in WO 2005/133801 A1 for the second partial lens LOE**2**, such as for example spinel ($MgAl_2O_4$), YAG [yttrium aluminum garnet ($Y_3Al_5O_{12}$)], magnesium oxide (MgO), beryllium oxide (BeO), aluminum oxide (Al_20_3), yttrium oxide (Y_2O_3) or lanthanum fluoride (LaF_3). In the context of immersion lithography, it is important to note the teaching of WO 2006/133801 A1 that when a high image-side numerical aperture is specified as a desired property in a design, the value of the image-side numerical aperture should not exceed the refractive index of the last optical element before the exposure field. It is insofar important for designs with a numerical aperture larger than 1.7, as in the case of the design **800**, for the last lens element to have a refractive index larger than 1.7 at the applicable operating wavelength. Sapphire, which is used as the material of a second partial lens LOE**2** in FIG. **18**, has a refractive index of 1.92 at an operating wavelength of 193 nm and thus has according to the teachings of WO 2006/133801 A1 enough of a numerical distance from the image-side numerical aperture of 1.75 of the design **800**. However, it would also not involve a major task to adapt the design **800** to a design in which the last lens before the exposure field consists of polycrystalline material with a refractive index larger than 1.7 at an operating wavelength of e.g. 193 nm and to simultaneously realize high numerical aperture values around 1.7.

[0146] FIG. **19** shows a six-mirror design of a projection objective for applications in so-called EUV (extreme ultraviolet) lithography. The design has been borrowed from FIG. 1 of US 2004/0051857 A1, keeping to a large extent the same reference symbols to which only the numeral 5 has been added. The first catoptric objective group G**15** projects the mask plane OB**5** into the intermediate image IMI**5** by the mirrors M**15** and M**25**. The objective group includes the pupil plane or aperture plane APE**5**. The second catoptric objective group G**25** projects the intermediate image IMI**5** into the field plane IM**5** by the mirrors M**35**, M**45**, M**55**, and M**65**. Projection objectives for EUV lithography normally consist of mirrors, as there are no materials in existence that are sufficiently transparent for wavelengths below 100 nm. Insofar, the task of equalizing the profile over the exposure field for the portion of the stray light component that results from inhomogeneities in the glass material does not present itself in these projection objectives. However, mirrors with the same surface finish scatter the light about 16 times as strongly as lenses with a refractive index of about 1.5 in air. Consequently, EUV projection objectives are much more critical than conventional refractive systems in regard to stray light that is due to the surface properties of the optical elements. As an additional factor, not only the polish of the optical element itself but also the highly reflective coatings play a big part in EUV objectives as a source of stray light. Insofar, it is also of practical benefit in projection objectives used for EUV lithography to reduce the stray light component, averaged over the scan direction, in its profile over the exposure field in accordance with the disclosure, or to take measures to ensure in accordance with this patent application that the stray light component, averaged over the scan direction, has a constant profile over the exposure field. The field-proximate surfaces near the intermediate image plane IMI**5**, in the direction of the light path from the mask plane OB**5** to the field plane IM**5**, which are suitable for correcting the variation of the stray light component over the exposure field by increasing the surface roughness are in this design the mirror surfaces M**25**, M**35** and M**45**.

[0147] As the optically used areas on the mirrors of the projection objective are in many cases located at a considerable distance from the optical axis OA**5** of the projection objective, the optical axis can no longer serve as reference axis for the distance under the definition that was given above for distinguishing close-to-pupil and field-proximate elements in projection objectives for EUV lithography. Rather, the normal vector at the geometric center point of an optically used area of a surface is chosen to serve as new reference axis for the distance according to which pupil-proximate and field-proximate elements in projection objectives for EUV lithography are distinguished. If an aperture ray of the central field point of the exposure field on the surface of an optical element has a distance from the thus defined normal vector that is six times as large as the distance that the principal ray of a border point of the exposure field on the same surface of the optical element has from the normal vector, the optical element is referred to as pupil-proximate, otherwise it will be referred to as field-proximate.

[0148] As a possible example, FIG. **20** shows a distribution of the increase in surface roughness as an RMS value over the optically used area of the upper side of a last lens before the field plane in the direction of the light rays from the mask plane to the field plane, which correlates to the additional stray light component, averaged in the scan direction, in regard to its profile over the exposure field, with a smaller stray light component in the central area of the exposure field and a high stray light component in the border area of the exposure field, so that as a result the stray light component, averaged over the scan direction, will have a smaller variation over the exposure field of the projection objective, or more specifically, that a stray light component of the projection objective, averaged over the scan direction, is obtained which is constant in the sense of this patent application. The scale on the X-axis of the diagram is normalized so that the height of the border of the optically used area in the positive X-direction on the upper side of the last lens has a value of 1, and the height of the center of the optically used area has a value of zero. The maximum amount for the increase of the RMS value in this diagram of slightly more than 2 nm at the left and right borders of the optically used area in comparison to the RMS value at the center of the optically used area is sufficient at an operating wavelength of e.g. 193 nm in order to correct the variation of the stray light component of a projection objective, averaged over the scan direction, which amounts to about 0.2% over the exposure field. This is based on the assumption of typical geometric relationships of the last lens, distances between the last lens and the exposure field, aspect ratios of the exposure field, as well as the refractive indices of the last lens element according to the designs of FIGS. **14**, **15**, **16** and **17**. Depending on the different parameters, it is also possible that different values of about 0.1% to about 0.4% are obtained for the amount by which the stray light component, averaged over the scan direction, varies over the exposure field. If the amount by which the stray light component, averaged over the scan direction, varies over the exposure field is to be corrected by more than 0.2%, the desired value for the surface roughness is obtained by normalizing the diagram of FIG. **20** accordingly. The profile of the surface roughness value in the diagram of FIG. **20** can be described by a function in the form of a root of a general polynomial, wherein the lateral distance from the center represents the independent variable. This description has the advantage that the coefficients obtained from it are advantageously suited for the programming of polishing machines such as for example polishing robots. However, the profiles that can be realized with the polishing machines are not open to an arbitrary choice, as the polishing heads have a finite dimension which imposes limits on the curvatures of the curves that represent the profile of the surface roughness in the diagrams exemplified by FIG. **20**. It is for example not possible for polishing machines to realize the break at height **0** in the diagram curve of FIG. **20**, as the finite dimension of the polishing head will always have the consequence that a surface roughness value different from zero will remain at the height **0**. This would for example have the result of a residual value of the additional stray light component **413** in the central area **415**, as shown in FIG. **12**.

[0149] FIG. **21** schematically illustrates the different methods whereby it is possible to provide a projection objective for applications in the field of microlithography with an additional stray light component, averaged over the scan direction, whose profile over the exposure field is such that the stray light component of the projection objective, averaged in the scan direction, has a reduced variation over the exposure field or, more specifically, that a stray light component of a projection objective, averaged in the scan direction, is obtained which is constant in the sense of this patent application. In a first step A, the stray light component of the projection objective is either simulated or determined from data of the components or data of the respective blanks As an alternative first step B, it is possible to take measurements on the projection objective itself or on a projection objective of identical design and thereby determine the variation of the stray light component over the exposure field of the projection objective. In a second step, the surface roughness of a surface of a field-proximate optical element or the surface roughness properties of several surfaces of a plurality of field-proximate optical elements are either appropriately adapted in advance during production, prior to installation in the projection objective, or subsequently altered by the appropriate amount, so that the stray light component, averaged in the scan direction, has a reduced variation over the exposure field or, more specifically, that a stray light component of the projection objective, averaged in the scan direction, is obtained which in the sense of this patent application is constant over the exposure field. The success of the measures taken in the second step is verified in a third step by a measurement which is taken as part of a qualifying examination of the projection objective. Depending on the result of the third step, the projection objective is either accepted as having a sufficiently good correction, or the process loops back to the second step, wherein the surface roughness of the surface of the field-proximate element or of the surfaces of the field-proximate elements is changed from its previous value. These process steps two and three are repeated until the correction is found to be sufficient.

[0150] As an alternative to the foregoing method, it can be reasonable for projection objectives in which one individual lens contributes a major portion of the stray light component, to determine only the contribution of the individual lens in a first step of the method and to compensate the contribution in a second step by an advance adaptation or subsequent alteration of the surface roughness, so that the qualification test of the projection objective can be performed in a third step. Under this alternative procedure, the measurements can be performed on the lens itself in a first process step B, or the contribution of the lens is determined from measurements taken in a first process step B on a lens of the same design. As an alternative, the individual lens can be simulated as part of a first process step A, or the contribution from this lens can be determined from data that are obtained from the blank of the lens.

[0151] FIG. **22** schematically illustrates the process steps for producing microstructures on a wafer by using a projection exposure apparatus with a projection objective according to this patent application. In a first step, a thin metal film is vapor-deposited on the wafer. Next, in a second step, the wafer with the metal film is overlaid with a photosensitive coating, the so-called photoresist. In a third step, the projection exposure apparatus with a projection objective according to the present patent application transfers the structures of a mask in the mask plane in a scanning process to the currently addressed surface of a semiconductor element on the wafer by photographic exposure of the photoresist. This step is repeated until all surfaces of all semiconductor elements on the wafer have been exposed. Subsequently, the wafer with the exposed photoresist is developed, whereby the photoresist is removed from the wafer at those locations on the wafer that received a sufficient exposure. This makes it possible to remove the metal film at the locations where the photoresist was removed in the preceding process step. This process step is called etching. In a next step, the wafer is ready for further treatment for which the wafer returns to the starting point of the process of FIG. **22** or is directed to the starting point of another process in another apparatus.

[0152] Even though the disclosure has been described through the presentation of specific embodiments, those skilled in the pertinent art will recognize numerous possibilities for variations and alternative embodiments, for example by combining and/or exchanging features of individual embodiments. Accordingly, it will be understood by those skilled in the pertinent art that such variations and alternative embodiments are considered as being included in the present disclosure and that the scope of the disclosure is limited only by the attached patent claims and their equivalents.

What is claimed is:

1. A projection objective configured to project an image in an object plane into an exposure field in a field plane, the projection objective comprising:

a plurality of optical elements including at least one optical element of polycrystalline material,

wherein:

the exposure field extends along a scan direction in the field plane;

during use of the projection objective, light in the exposure filed includes useful light and a stray light component;

the stray light component in the exposure field, averaged over the scan direction, varies over the exposure field by less than 0.5% relative to the useful light; and

the projection objective is configured to be used in microlithography.

2. The projection objective according to claim **1**, wherein:

the plurality of optical elements are along a light ray path from the object plane to the field plane;

the optical element of polycrystalline material is a last optical element before the field plane in a ray direction of the light ray path from the object plane to the field plane;

the polycrystalline material comprises a material selected from the group consisting of a fluoride, an oxide of group II, an oxide of group III, an oxide of the rare earths, garnet and spinel; and

the optical element of polycrystalline material has a stray light component which varies over the exposure field by more than 0.2% relative to the useful light in the exposure field.

3. The projection objective according to claim **1**, wherein:

a maximum of the stray light component at the exposure field, averaged over the scan direction, is less than 2% relative to the useful light; and

a maximum of the stray light component outside the exposure field, averaged over the scan direction, is less than 2% relative to the useful light.

4. The projection objective according to claim **1**, wherein at least one surface of at least one field-proximate optical element has a surface roughness configured to generate a stray light component that complements the stray light component of the rest of the projection objective so that in the exposure field the stray light component of the projection objective, averaged over the scan direction, varies over the exposure field by less than 0.5% relative to the useful light.

5. The projection objective according to claim **4**, wherein the at least one surface includes an optically used area with a center and a border, the surface roughness of the at least one surface increases from the center of the optically used area to the border of the optically used area, and the profile of the surface roughness of the at least one surface as a function of a lateral distance from the center of the optically used area corresponds to a root function of a general polynomial function in which a lateral distance represents a variable quantity.

6. The projection objective according to claim **5**, wherein a difference in surface roughness of the at least one surface from the border of the optically used area to the center of the optically used are is larger than 0.5 nm RMS.

7. The projection objective according to claim **4**, wherein the surface roughness of the at least one surface has a wavelength range of local undulation between 10 mm and 10 μm.

8. The projection objective according to claim **1**, wherein:

the plurality of optical elements are along a light ray path from the object plane to the field plane, including a last optical element before the field plane in a ray direction of the light ray path from the object plane to the field plane;

a field aperture stop is between the last optical element and the field plane;

an optically used area extends in a plane of the field aperture stop; and

the field aperture stop has an allowance for a lateral dimension of less than 1 mm added to the optically used area in the plane of the field aperture stop.

9. The projection objective according to claim **4**, wherein:

the plurality of optical elements are along a light ray path from the object plane to the field plane, including a last optical element before the field plane in a ray direction of the light ray path from the object plane to the field plane;

the last optical element has an upper side and an underside;

relative to the light ray direction from the object plane to the field plane, the upper side is before the underside;

the underside is before the field plane in the light ray direction from the object plane to the field plane; and

the surface is the upper side of the last optical element.

10. The projection objective according to claim **1**, wherein:

the plurality of optical elements are along a light ray path from the mask plane to the field plane, including a last optical element before the field plane in a ray direction of the light ray path from the object plane to the field plane;

the last optical element has an upper side and an underside;

relative to the light ray direction from the object plane to the field plane, the upper side is before the underside;

the underside is before the field plane in the light ray direction from the object plane to the field plane;

a field aperture stop is formed of masked off parts of the underside of the last optical element;

the masking-off comprises a coating of an absorbent or reflective layer;

an optically used area extends on the underside of the last optical element; and

the masking-off includes an allowance for a lateral dimension of less than 0.5 mm added to the optically used area.

11. A projection objective configured to project an image in an object plane into an exposure field of a field plane,

wherein during use of the projection objective, an additional stray light component with a non-constant profile over the exposure field is present in the field plane, and

wherein the projection is configured to be used in microlithography.

12. A projection objective configured to project an image in an object plane into an exposure field of a field plane, the projection objective comprising:

a mechanism configured to introduce into the exposure field in the field plane an additional stray light component with a non-constant profile over the exposure field,

wherein the projection objective is configured to be used in microlithography.

13. The projection objective according to claim **12**, wherein the exposure field in the field plane includes a central area and a border area, and the additional stray light component is lower in the central area of the exposure field than in the border area of the exposure field.

14. The projection objective according to claim **12**, comprising a plurality of optical elements arranged along a light ray path from the object plane to the field plane, including at least one field-proximate optical element before the field plane in a ray direction along the light ray path from the object plane to the field plane, or which in the ray direction from the object plane to the field plane is arranged immediately before or after an intermediate object plane that is conjugate to the field plane,

wherein at least one surface of the at least one optical element has a surface roughness which produces the additional stray light component with the non-constant profile over the exposure field, the surface includes an optically used area with a center and a border, and the surface roughness of the surface increases from the center of the optically used area to the border of the optically used area.

15. The projection objective according to claim **14**, wherein:

a difference in surface roughness from the border of the optically used area to the center of the optically used area is larger than 0.5 nm RMS;

the surface roughness as a function of a lateral distance from the center corresponds to a root function of a general polynomial function in which a lateral distance represents a variable quantity; and

the surface roughness has a wavelength range of local undulation of between 10 mm and 10 μm.

16. The projection objective according to claim **12**, comprising a plurality of optical elements arranged along a light ray path from the object plane to the field plane, including a last optical element before the field plane in a ray direction along the ray path from the object plane to the field plane is arranged,

Wherein a field aperture stop is between the last optical element and the field plane, an optically used area extends in a plane of the field aperture stop, and the field aperture stop has an added allowance for a lateral dimension of less than 1 mm.

17. The projection objective according to claim **14**, comprising a plurality of optical elements arranged along a light ray path from the mask plane to the field plane, including a last optical element before the field plane in a ray direction along the light ray path from the mask plane to the field plane is arranged,

wherein:

the last optical element has an upper side and an underside;

relative to the light ray direction from the object plane to the field plane, the upper side is before the underside;

the underside is before the field plane in the light ray direction from the object plane to the field plane; and

the surface is the upper side of the last optical element.

18. The projection objective according to claim **17**, wherein the field aperture stop is formed of masked off parts of the underside of the last optical element, the masking-off comprises a coating with of absorbent or reflective layer, an optically used area extends on the underside of the last optical element, and the masking-off includes an allowance for a lateral dimension of less than 0.5 mm added to the optically used area.

19. The projection objective according to claim **12**, comprising a plurality of optical elements including at least one optical element comprising a polycrystalline material selected from the group consisting of a fluoride, an oxide of group II, an oxide of group III, an oxide of the rare earths, garnet or spinel,

wherein the optical element of polycrystalline material has a stray light component which varies over the field by more than 0.2% relative to useful light in the exposure field.

20. A method of introducing an additional stray light component of a projection objective configured to be used in microlithography, the projection objective configured to project an image in an object plane into an exposure field of a field plane, the projection objective comprising at least one field-proximate surface having a surface roughness, the method comprising:

prior to introducing the additional stray light component, adapting or altering the at least one field-proximate surface to obtain the additional stray light component of the projection objective so that the additional stray light component has a non-constant profile over the exposure field.

21. The method according to claim **20**, comprising:

simulating or measuring the stray light component within the exposure field of the entire projection objective; and

based on the simulation or measurement, adapting or altering the surface roughness of the at least one field-proximate surface to obtain the additional stray light component.

22. The method according to claim **21**, wherein the surface roughness of the at least one field-proximate surface is determined from measurements taken on a second projection objective that is equal in design to the first projection objective, and the measurement results of the second projection objective are carried over to the first projection objective.

23. A method of generating a stray light component of a projection objective configured to be used in microlithography according, the projection objective being configured to project an image in an object plane into an exposure field of a field plane, and the projection objective including at least one field-proximate surface having a surface roughness, the method comprising:

prior to generating the stray light component, adapting or alerting a surface roughness of at least one field-proximate surface so that an exposure field in the field plane receives the stray light component of the projection objective,

wherein:

the exposure field extends along a scan direction in the field plane; and

the stray light component, averaged over the scan direction, varies over the exposure field by less than 0.5% relative to the useful light.

24. The method according to claim **23**, comprising:

simulating or measuring the stray light component within the exposure field of the entire projection objective; and

based on the simulation or measurement, adapting or altering the surface roughness of the at least one field-proximate surface to obtain the stray light component.

25. The method according to claim **24**, wherein the required surface roughness of the at least one field-proximate surface is determined from measurements taken on a second projection objective that is equal in design to the first projection objective, and wherein the measurement results of the second projection objective are carried over to the first projection objective.

26. The method according to claim **23**, comprising:

simulating or measuring the stray light component of at least one lens; and

based on the simulation or measurement, adapting or altering the surface roughness of the at least one field-proximate surface so that an exposure field in the field plane receives the stray light component of the projection objective.

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