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— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*
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[Continued on next page]

(54) Title: PROJECTION OBJECTIVE FOR MICROLITHOGRAPHY, MICROLITHOGRAPHY PROJECTION EXPOSURE APPARATUS WITH SAID PROJECTION OBJECTIVE, MICROLITHOGRAPHIC MANUFACTURING METHOD FOR COMPONENTS, AS WELL AS A COMPONENT MANUFACTURED WITH SAID METHOD

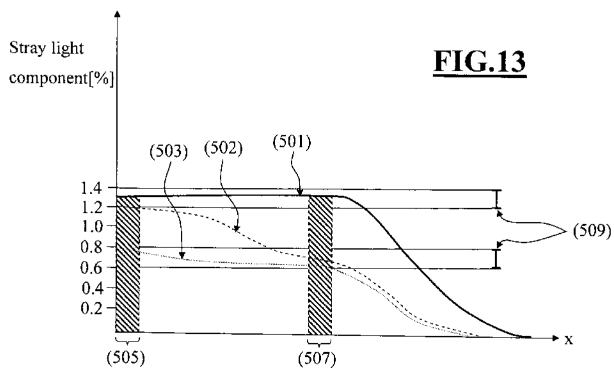

FIG.13

(57) Abstract: Projection objectives of current designs for use in microlithography have a stray light component (503) which varies over the exposure field. The variation of the stray light component over the field can be reduced by introducing additional stray light. This is accomplished advantageously by pre-adapting or altering the surface roughness of a field- proximate surface. In this, the invention makes use of the observation that the variation of the stray light component over the field presents greater problems to the manufacturers of semiconductor components than the stray light component itself. Particularly in projection objectives for immersion lithography where a strongly scattering polycrystalline material is used, the invention provides a way to compensate for the increased variation of the stray light component (502) of these projection objectives over the field and to thereby arrive at a stray light component (501) that is constant over the entire field.

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Description

PROJECTION OBJECTIVE FOR MICROLITHOGRAPHY, MICROLITHOGRAPHY PROJECTION EXPOSURE APPARATUS WITH SAID PROJECTION OBJECTIVE, MICROLITHOGRAPHIC MANUFACTURING METHOD FOR COMPONENTS, AS WELL AS A COMPONENT MANUFACTURED WITH SAID METHOD

The invention relates to a projection objective for applications in microlithography. Further, the invention also extends to a microlithography projection exposure apparatus with a projection objective according to the invention. The scope of the invention further includes a microlithographic manufacturing method for microstructured components. Lastly, the invention relates to a component manufactured under said manufacturing method.

The performance of projection exposure apparatus for the microlithographic production of semiconductor elements and other finely structured components is determined in essence 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 cannot use lenses as optical components, see US 2004/0051857 A1.

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.

The stray light component of an objective has different reasons, which are described in: Heinz Haferkorn, „Optik; Physikalisch-technische Grundlagen und 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 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 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 is 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.

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:

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

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.

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.

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.

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.

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.

Within the scope of this application, in order 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, wherein 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 of such importance also 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.

It should also be noted here that as an alternative to the measurement of the stray light by means of 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 required 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 required for an over-exposure of quadratic structures of different sizes, so that their image in the photoresist completely disappears. 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.

Current projection objectives 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 state of the art, a further reduction of the stray light component can only be achieved through a large development effort in regard to the material and the surface finish of mirrors and lenses. It needs to be noted, however, that projection objectives using the aforementioned new kinds of optical materials will according to all predictions have a larger stray light component and a higher variation of the stray light component.

It is therefore an object of the invention to ensure a good contrast over the image or over the exposure field in projection objectives with at least one optical element of polycrystalline material.

This task is solved according to the invention by a projection objective with the features named in claim 1, which consists of a multitude of optical elements and has at least one optical element of polycrystalline material, and wherein 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%, in particular less than 0.2%, in relation to the useful light and, accordingly, the projection objective has a constant stray light component in the sense of the present application.

A constant stray light component as understood herein 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%, in particular less than 0.2%, preferably less than 0.1%, and with still higher preference less than 0.05%, or for which said difference in relation to the maximum value in the exposure field is less than 60%, in particular less than 25%, preferably less than 12.5%, and with still higher preference less than 6.75%.

The invention makes use of the observation that the variation of the stray light component of a projection objective over the exposure field causes greater problems to 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 presently used projection objectives.

This result of an increased variation of the stray light component over the exposure field in comparison to present projection objectives is more pronounced if the last optical element consists of polycrystalline material. According to the invention it makes 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, as set forth in claim 2.

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, as set forth in claim 3, 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 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 acceptable to the manufacturers of semiconductor elements.

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, as set forth in claim 4, represents an acceptable upper limit.

The inventive concept of the present invention 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, as set forth in claim 5.

The inventive 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, as set forth in claim 6.

The inventive concept of introducing additional stray light in projection objectives with at least one optical element of a polycrystalline material, so that the result in accordance with claim 7 is a constant stray light component in the sense of this application over the entire exposure field, wherein 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.

The inventive concept of introducing additional stray light in projection objectives with at least one optical element of a polycrystalline material, so that the result in accordance with claim 8 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.

In order to increase the resolution of future projection objectives used for immersion lithography, it may become necessary 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 requirements imposed on the imaging performance of such future systems, and likewise the requirements imposed on the variation of the stray light component over the exposure field, will probably be higher than for present systems. The concept according to the invention to introduce additional stray light in projection objectives of this kind, so that the result according to claim 9 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 invention also provides the capability to meet increased future requirements on the constancy of the stray light component over the exposure field.

Applying a finishing treatment to at least one surface of at least one field-proximate optical element as set forth in claim 10 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 required 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.

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, as set forth in claim

11, 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. According to the invention, 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.

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, as set forth in claim 12, 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 stated in claim 12 for said 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 invention, 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 required if a strongly diffusing material is used for the last lens.

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, as set forth in claim 13, 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. Claims 14 and 15 state the simplest and fastest 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.

The local range of undulation wavelengths between 1 mm and 10 µm as set forth in claim 16 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 as set forth in claim 17 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.

The field aperture stop set forth in claim 18 has the task of preventing 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.

The dimensional allowance between the field aperture stop and the optically used area in the plane of the field aperture stop as set forth in claim 19 represents an advantageous compromise between an overly tight allowance which leads to a high cost due to the high precision required in the manufacturing process and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

The upper side referred to in claim 20, 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 means of surface roughness, as this surface is on the one hand located so close to the exposure field that by means of 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 require very large values for the surface roughness which are difficult to achieve in practice.

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 as set forth in claim 21 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.

The masking is realized cost-effectively by a coating as set forth in claim 22.

The dimensional allowance between the masking and the optically used area in the plane of the field aperture stop as set forth in claim 23 represents an advantageous compromise between an overly tight dimensional allowance which leads to a high cost due to the high manufacturing precision required in particular for coating tools and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

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 according to the invention 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 according to claim 24, which have a last lens of polycrystalline material with positive refractive power.

Using a planar-parallel plate as the last optical element, as set forth in claim 25, 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.

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 according to the invention, if large variations of the stray light component over the exposure field have to be corrected, to use for this purpose a mirror surface, as set forth in claim 26, 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.

It is a further object of the invention to reduce the variation of the stray light component over the image or over the exposure field.

The invention 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.

According to the invention, this task is solved by a projection objective with the features named, respectively, in claim 27 or claim 28, in that an additional stray light component is introduced with a non-constant profile over the exposure field, or that means are 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 $\geq 0.02\%$ in the additional stray light component in relation to the useful light portion. Thus according to claim 27 and/or claim 28, 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 means 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.

According to the invention, 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, as stated in claim 29, 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.

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) as set forth in claim 30 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.

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), as set forth in claim 31, 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. According to the invention, an additional stray light component is thereby produced which complements the otherwise existing stray light component of the projection objective in an ideal way.

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, as set forth in claim 32, 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 stated in claim 32 for said 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 invention.

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.

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, as set forth in claim 33, 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. Claims 34 and 35 state the simplest and fastest functions in this category, 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.

The range of wavelengths of the local undulation between 1 mm and 10 µm as set forth in claim 36 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 as set forth in claim 37 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.

The field aperture stop set forth in claim 38 has the task of preventing the additionally introduced stray light from getting into areas outside of the exposure field and leading to undesirable exposures of those areas.

The dimensional allowance between the field aperture stop and the optically used area in the plane of the field aperture stop as set forth in claim 39 represents an advantageous compromise between an overly tight allowance which leads to a high cost due to the high precision required in the manufacturing process and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

The upper side referred to in claim 40, i.e. the object-facing surface of the last optical element, is advantageously suited for introducing the stray light by means of surface roughness, because this surface is on the one hand located so close to the exposure field that by means of 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.

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 as set forth in claim 41 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.

The masking is realized cost-effectively by a coating as set forth in claim 42.

The dimensional allowance between the masking and the optically used area in the plane of the field aperture stop as set forth in claim 43 represents an advantageous compromise between an overly tight dimensional allowance which leads to a high cost due to the high manufacturing precision required in particular for coating tools and an overly large allowance which leads to too much undesirable stray light outside of the exposure field.

The inventive concept of introducing additional stray light is especially advantageous in projection objectives with optical elements of polycrystalline material as set forth in claim 44, 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.

The inventive 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, as set forth in claim 45, 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.

The inventive concept of introducing additional stray light in projection objectives with optical elements of a polycrystalline material consisting of many crystals that are birefringent as set forth in claim 46 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.

The inventive 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, as set forth in claim 47, 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.

The inventive 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, as set forth in claim 48, 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.

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, as set forth in claim 49, 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 invention, 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.

In order to increase the resolution of future projection objectives used for immersion lithography, it will probably be necessary 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 requirements imposed on the imaging performance of such future systems, and likewise the requirements imposed on the variation of the stray light component over the exposure field, will probably be higher than for present systems. The concept according to the invention to introduce additional stray light in projection objectives of this kind, as set forth in claim 50, takes this anticipated development into account, as the invention also provides the capability to meet increased future requirements on the variation of the stray light component over the exposure field.

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 according to the invention of introducing additional stray light in such projection objectives, as set forth in claim 51, 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.

Using a planar-parallel plate as the last optical element, as set forth in claim 52, 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.

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 according to the invention, if large variations of the stray light component over the exposure field have to be corrected, to use for this purpose a mirror surface, as set forth in claim 53.

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

According to the invention, this task is solved by a method according to claim 54, wherein 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.

It was recognized in the invention 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.

A method according to claim 55, wherein 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 required surface roughness profile over the at least one field-proximate surface in a way that is very specifically targeted and to realize the required profile in an equally target-oriented way by pre-adapting or altering the surface roughness.

The method according to claim 56 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 required surface roughness can be preset or adapted in advance already during the production of the optical elements of the projection objective.

A method according to claim 57 or 65 has 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 according to the invention 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.

If no measurements according to claim 57 or 65 are performed on the optical components in regard to the stray light component to be expected, the method according to claim 58 or 66 offers 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 require 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.

The method according to claim 59 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 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 require 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 invention.

In comparison to the method according to claim 59 it is advantageous to use the method of claim 60, 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 according to the invention 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 a method according to claim 60 to perform a random sample examination within the scope of a quality assurance program, wherein for the determination of the required 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.

A method is presented in claim 61 wherein 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.

It is a further object of this invention to provide a method of introducing additional stray light in accordance with claim 62 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.

It was recognized in the invention 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.

A method according to claim 63, wherein 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 required surface roughness profile over the at least one field-proximate surface in a way that is very specifically targeted and to realize the required 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.

The method according to claim 64 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 required 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.

The method according to claim 67 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 require 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 invention in order to achieve a constant stray light component of the projection objective in the sense of this application over the entire exposure field.

In comparison to the method according to claim 67 it is advantageous to use the method of claim 68, 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 according to the invention 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 a method according to claim 70 to perform a random sample examination within the scope of a quality assurance program, wherein for the determination of the required 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.

A method is presented in claim 69 wherein 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.

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

This task is solved according to the invention by a projection exposure apparatus according to one of the claims 70, 71 or 72, a manufacturing method according to claim 73, as well as a component according to claim 74.

Examples of embodiments of the invention are hereinafter presented in more detail with references to the drawing, wherein

Figure 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);

Figure 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;

Figure 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;

Figure 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;

Figure 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;

Figure 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;

Figure 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;

Figure 8 schematically represents the optical components of a projection exposure apparatus for immersion lithography;

Figure 9 represents a plan view of a polycrystalline material with it microscopic structures;

Figure 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;

Figure 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;

Figure 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;

Figure 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;

Figure 14 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;

Figure 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;

Figure 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;

Figure 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;

Figure 18 schematically illustrates the last lens element before the field plane of the two-mirror design of Figure 17;

Figure 19 represents a sectional view of the optical components of a so-called six-mirror design of a projection objective for EUV lithography;

Figure 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;

Figure 21 represents a flowchart diagram of several possible process steps for producing in a projection objective a corrected stray light component according to the invention;

Figure 22 represents a flowchart diagram for a method of producing microstructured semiconductor elements by means of a projection exposure apparatus with a projection objective in accordance with the present patent application.

Figure 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 Figure 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 Figure 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 means of 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 Figure 1. The border areas (also referred to herein as marginal areas) 7 and 9 of the exposure field, which are likewise shaded in Figure 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 Figure 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.

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 Figure 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.

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 Figure 1.

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.

Figure 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 Figure 2 which are analogous to those in Figure 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 Figures 14, 16 and 17 of the present patent application. What has been said above in the context of Figure 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.

Figure 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 Figure 3 which are analogous to those in Figure 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 said above in the context of Figure 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 Figure 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 Figure 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.

Figure 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 Figure 4 which are analogous to those in Figure 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 requires that the projection objective provides 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 Figure 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.

Figure 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 Figure 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.

The lower part of Figure 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 Figure 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 Figure 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 Figure 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.

Figure 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 Figure 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 Figure 6, but a representation like the one in Figure 6 facilitates the explanation of the optical concepts of field and pupil. The pupil plane 133 according to Figure 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 Figure 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 G20 (see Figure 16) is their optical axis. Based on this criterion, it is clear that the two lenses 129 in Figure 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.

By means of 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 requirements 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.

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.

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.

In the context of Figures 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 Figure 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.

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.

Figure 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.

Figure 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 means 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.

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.

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

Figure 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.

Figure 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 I_{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 Figure 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 Figure 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.

Based on the stray light models in WO 2006/061255, or in Figures 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, Figures 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.

Figure 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 Figure 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 Figure 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 Figure 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.

Figure 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 invention, 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 Figure 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 Figure 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 Figure 13 represents the stray light component of a projection objective that has been corrected in accordance with the invention, with a last lens of polycrystalline material. This stray light component 501 of the projection objective which has been corrected according to the invention 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.

The invention 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.

Figure 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 Figure 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 Figure 38 of US 2005/0190435 A1. The design 2100 is drawn in Figure 14a 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 according to the invention 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 Figure 14b. Further indicated by the shaded bars in Figure 14b 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 Figure 14b, 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 Figure 14b.

However, in the representation of the design in Figures 14a and 14b 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 Figures 14a and 14b insofar indicate only the field-proximate surfaces which can be considered for an adaptation of the surface roughness according to the invention, and on the other hand only illustrate the principle according to the invention 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.

Figure 15 shows a so-called four-mirror design PL1 of a projection objective for immersion lithography with an image-side numerical aperture of 1.2. The design PL1 has been borrowed from Figure 9 of US 2007/0024960 A1, keeping the same reference symbols. Only the reference symbol for the field plane W1 is newly added in comparison to Figure 9 of US 2007/0024960 A1. The mask plane R1 is projected onto an intermediate image plane Q by the first catadioptric objective group G1 consisting of the purely refractive subgroup G11 with the lenses L1 to L4 and the catadioptric subgroup consisting of the lens 5 and mirrors M1 and M2. The intermediate image plane Q is projected into the field plane W1 immediately after the lens 18 by the second catadioptric objective group G2 consisting of the two mirrors M3 and M4, the refractive subgroup G21 with the lenses L6 and L7, the refractive subgroup G22 with the lenses L8 to L12, and the refractive subgroup G23 with the lenses L13 to L18. A pupil plane or aperture plane AS1 is located between the subgroups G22 and G23. The broken lines extending the mirror surfaces M2 and M3 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 PL1 shown in Figure 15 has to be rotated about the optical axis AX1. After this rotation, all optical elements possess rotational symmetry relative to the optical axis AX1, and the optical axis AX1 is now also the optical axis of all optical elements within the design PL1.

The field-proximate surface areas near the field plane W1, or near the intermediate image plane Q, in the direction of the light path from the mask plane R1 to the field plane W1, which according to the invention are suitable for correcting the variation of the stray light component over the exposure field by increasing the surface roughness are in this design PL1 all of the mirror surfaces M1 to M4 and the surfaces of the lenses L5, L6 and L18.

Figure 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 Figure 19 of US 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 W1 for the field plane, the reference symbol M10 for the first direction-changing mirror, and the reference symbol M20 for the second direction-changing mirror have been newly added in comparison to Figure 19 of US 2004/019128 A2. The first refractive objective group G10 with the lenses L110 to L1100 projects the mask plane R1 into a first extended intermediate image area after the first direction-changing mirror M10. The catadioptric group G20 consisting of the lenses L210, L220 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 M20. The second intermediate image plane is projected into the field plane W1 immediately below the lens L3150 by the second refractive objective group G30 with the lenses L310 to L3150. 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 G20, 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 M10 and before the second direction-changing mirror M20, 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 W1, or near the intermediate image plane Q, in the direction of the light path from the mask plane R1 to the field plane W1, which according to the invention 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 mirror surfaces M10 and M20 as well as the surfaces of the lenses L100, L310 and L3150.

Figure 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 Figure 8 of US 2006/133801 A1, wherein the reference symbols have to the largest extent been maintained. Only the reference symbols of the objective groups G100 to G900 have been expanded in comparison to Figure 8 of US 2006/133801 A1 by adding double zeroes. The first refractive objective group ROP1 projects the mask plane OP into an extended intermediate image plane IMI1. The first refractive group has a pupil plane or aperture plane identified as AS. The extended intermediate image plane IMI1 is projected into a further extended intermediate image plane IMI2 by the mirror group COP2 with the mirrors CM1 and CM2. The second refractive objective group ROP3 projects the extended intermediate image plane IMI2 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 LOE1 and LOE2 with an immersion liquid IL between the partial lenses (see description of Figure 18).

The field-proximate surfaces near the field plane IP, or near the extended intermediate image planes IMI1 and IMI2, in the direction of the light path from the mask plane OP to the field plane IP, which according to the invention 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 CM1 and CM2 as well as the surfaces of the lenses B800, LOE and the lens before CM1 in the direction of the light rays from the mask plane OP to the image plane IP.

Figure 18 shows as a detail of the design 800 of Figure 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 LOE1 and sapphire for the partial lens LOE2, wherein the crystallographic axis in the latter is oriented in the direction CA parallel to the optical axis AX. Between the two partial lenses LOE1 and LOE2 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 LOE2, 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_2O_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 requirement 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 LOE2 in Figure 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.

Figure 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 Figure 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 G15 projects the mask plane OB5 into the intermediate image IMI5 by means of the mirrors M15 and M25. Said objective group includes the pupil plane or aperture plane APE5. The second catoptric objective group G25 projects the intermediate image IMI5 into the field plane IM5 by means of the mirrors M35, M45, M55, and M65. 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 invention, 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 IMI5, in the direction of the light path from the mask plane OB5 to the field plane IM5, which according to the invention 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 M25, M35 and M45.

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 OA5 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 said normal vector, the optical element is referred to as pupil-proximate, otherwise it will be referred to as field-proximate.

As a possible example, Figure 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 Figures 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 required value for the surface roughness is obtained by normalizing the diagram of Figure 20 accordingly. The profile of the surface roughness value in the diagram of Figure 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 Figure 20. It is for example not possible for polishing machines to realize the break at height 0 in the diagram curve of Figure 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 Figure 12.

Figure 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.

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 said 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.

Figure 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 Figure 22 or is directed to the starting point of another process in another apparatus.

Even though the invention 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 invention and that the scope of the invention is limited only by the attached patent claims and their equivalents.

Patent Claims:

1. Projection objective for the field of microlithography, serving to project an image of a mask plane into a field plane, with a large number of optical elements and with at least one optical element of polycrystalline material, characterized in that in an exposure field in the field plane 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%, relative to the useful light.

2. Projection objective for the field of microlithography according to claim 1, with a large number of optical elements along a light ray path from the mask plane to the field plane and with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, characterized in that the last optical element consists of polycrystalline material.

3. Projection objective for the field of microlithography according to claim 1 or 2, characterized in that the exposure field has a maximum stray light component of the projection objective, averaged over the scan direction, amounting to less than 2% relative to the useful light.

4. Projection objective for the field of microlithography according to one of the claims 1 to 3, characterized in that the field plane outside of the exposure field has a maximum stray light component of the projection objective, averaged over the scan direction, amounting to less than 2% relative to the useful light.

5. Projection objective for the field of microlithography according to one of the claims 1 to 4, wherein the polycrystalline material consists of a fluoride, an oxide of group II, an oxide of group III, an oxide of the rare earths, garnet or spinel.

6. Projection objective for the field of microlithography according to one of the claims 1 to 5, wherein the polycrystalline material consists of many individual crystals that are birefringent.

7. Projection objective for the field of microlithography according to claim 6, wherein the optical element of polycrystalline material overall has a lesser degree of birefringence than each of the individual crystals.

8. Projection objective for the field of microlithography according to one of the claims 1 to 7, wherein the optical element of polycrystalline material has a stray light component which varies over the field by more than 0.1%, in particular more than 0.2%, relative to the useful light in the exposure field.

9. Projection objective for the field of microlithography according to one of the claims 1 to 7, characterized in that the last optical element consists of material with a refractive index larger than 1.7 at the operating wavelength.

10. Projection objective for the field of microlithography according to one of the claims 1 to 8, characterized in that at least one surface of at least one field-proximate optical element has a surface roughness which generates a stray light component complementing the stray light

component of the rest of the projection objective in such a way that in an exposure field in the field plane 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%, relative to the useful light.

11. Projection objective for the field of microlithography according to claim 10, wherein the at least one surface comprises an optically used area with a center and a border, and wherein 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.

12. Projection objective for the field of microlithography according to claim 11 with a difference in surface roughness of the at least one surface from the border to the center, wherein said difference is larger than 0.5 nm RMS, preferably larger than 1.0 nm RMS, and with even higher preference larger than 2 nm RMS.

13. Projection objective for the field of microlithography according to claim 11 or 12, wherein the profile of the surface roughness of the at least one surface as a function of a lateral distance from the center corresponds to a root function of a general polynomial function wherein the lateral distance represents the variable quantity.

14. Projection objective for the field of microlithography according to claim 13, wherein the surface roughness of the at least one surface increases quadratically with the lateral distance from the center.

15. Projection objective for the field of microlithography according to claim 13, wherein the surface roughness of the at least one surface increases linearly with the lateral distance from the center.

16. Projection objective for the field of microlithography according to one of the claims 10 to 15, wherein the surface roughness of the at least one surface has a wavelength range of local undulation and said wavelength range of local undulation of the surface roughness lies between 1 mm and 10 µm.

17. Projection objective for the field of microlithography according to one of the claims 10 to 15, wherein the surface roughness of the at least one surface has a wavelength range of local undulation and said wavelength range of local undulation of the surface roughness lies between 10 mm and 1 mm.

18. Projection objective for the field of microlithography according to one of the claims 1 to 17, with a large number of optical elements along a light ray path from the mask plane to the field plane, with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, characterized in that a field aperture stop is present between the last optical element and the field plane.

19. Projection objective for the field of microlithography according to claim 18, wherein an optically used area extends in a plane of the field aperture stop, and wherein the field aperture stop has an allowance for the lateral dimension of less than 1 mm, in particular less than

0.2 mm added to the optically used area in the plane of the field aperture stop.

20. Projection objective for the field of microlithography according to one of the claims 10 to 19, with a large number of optical elements along a light ray path from the mask plane to the field plane, with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, wherein the last optical element has an upper side and an underside and wherein, relative to the light ray direction from the mask plane to the field plane, said upper side occupies a place ahead of the underside and said underside occupies a place ahead of the field plane, and wherein said surface is the upper side of the last optical element.

21. Projection objective for the field of microlithography according to one of the claims 18 to 20, with a large number of optical elements along a light ray path from the mask plane to the field plane, with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, wherein the last optical element has an upper side and an underside and wherein, relative to the light ray direction from the mask plane to the field plane, said upper side occupies a place ahead of the underside and said underside occupies a place ahead of the field plane, and wherein the field aperture stop is realized by masking off parts of the underside of the last optical element.

22. Projection objective for the field of microlithography according to claim 21, wherein said masking-off is

achieved through a coating with an absorbent or reflective layer.

23. Projection objective for the field of microlithography according to claim 22, wherein an optically used area extends on the underside of the last optical element, and wherein the masking-off includes an allowance for the lateral dimension of less than 0.5 mm, in particular less than 0.1 mm, added to the optically used area.

24. Projection objective for the field of microlithography according to one of the claims 1 to 23, wherein the at least one optical element of polycrystalline material is a lens.

25. Projection objective for the field of microlithography according to one of the claims 1 to 23, wherein the at least one optical element of polycrystalline material is a planar-parallel plate.

26. Projection objective for the field of microlithography according to one of the claims 10 to 17, wherein the at least one surface of the at least one field-proximate optical element is the surface of a mirror.

27. Projection objective for the field of microlithography, serving to project an image of a mask plane into a field plane, with an exposure field in the field plane, characterized in that an additional stray light component with a non-constant profile over the exposure field is introduced into the exposure field in the field plane.

28. Projection objective for the field of microlithography, serving to project an image of a mask plane into a field

plane, with an exposure field in the field plane, characterized in that the projection objective comprises means for introducing into the exposure field in the field plane an additional stray light component with a non-constant profile over the exposure field.

29. Projection objective for the field of microlithography according to claim 27 or 28, wherein the exposure field in the field plane comprises a central area and a border area and the additional stray light component is lower in the central area of the field than in the border area of the field.

30. Projection objective for the field of microlithography according to one of the claims 27 to 29, with a large number of optical elements along a light ray path from the mask plane to the field plane, with at least one field-proximate optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, or which in the ray direction from the mask plane to the field plane is arranged immediately before or after an intermediate image plane that is conjugate to said field plane, characterized in that 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.

31. Projection objective for the field of microlithography according to claim 30, wherein said surface comprises an optically used area with a center and a border, and wherein the surface roughness of said surface increases from the center of the optically used area to the border of the optically used area.

32. Projection objective for the field of microlithography according to claim 31 with a difference in surface roughness from the border to the center, wherein said difference is larger than 0.5 nm RMS, preferably larger than 1.0 nm RMS, and with even higher preference larger than 2 nm RMS.

33. Projection objective for the field of microlithography according to claim 31 or 32, wherein the surface roughness as a function of a lateral distance from the center corresponds to a root function of a general polynomial function wherein the lateral distance represents the variable quantity.

34. Projection objective for the field of microlithography according to claim 33, wherein the surface roughness increases quadratically with the lateral distance from the center.

35. Projection objective for the field of microlithography according to claim 33, wherein the surface roughness increases linearly with the lateral distance from the center.

36. Projection objective for the field of microlithography according to one of the claims 30 to 35, wherein the surface roughness has a wavelength range of local undulation and said wavelength range of local undulation of the surface roughness lies between 1 mm and 10 μm.

37. Projection objective for the field of microlithography according to one of the claims 30 to 35, wherein the surface roughness has a wavelength range of local

undulation and said wavelength range of local undulation of the surface roughness lies between 10 mm and 1 mm.

38. Projection objective for the field of microlithography according to one of the claims 27 to 37, with a large number of optical elements along a light ray path from the mask plane to the field plane, with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, characterized in that a field aperture stop is present between the last optical element and the field plane.

39. Projection objective for the field of microlithography according to claim 38, wherein an optically used area extends in a plane of the field aperture stop, and wherein the field aperture stop has an added allowance for the lateral dimension of less than 1 mm, in particular less than 0.2 mm.

40. Projection objective for the field of microlithography according to one of the claims 30 to 39, with a large number of optical elements along a light ray path from the mask plane to the field plane, with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, wherein the last optical element has an upper side and an underside and wherein, relative to the light ray direction from the mask plane to the field plane, said upper side occupies a place ahead of the underside and said underside occupies a place ahead of the field plane, and wherein said surface is the upper side of the last optical element.

41. Projection objective for the field of microlithography according to claim 40, wherein a field aperture stop is located between the last optical element and the field plane and the field aperture stop is realized by masking off parts of the underside of the last optical element.

42. Projection objective for the field of microlithography according to claim 41, wherein said masking-off is achieved through a coating with an absorbent or reflective layer.

43. Projection objective for the field of microlithography according to claim 42, wherein an optically used area extends on the underside of the last optical element, and wherein the masking-off includes an allowance for the lateral dimension of less than 0.5 mm, in particular less than 0.1 mm added to the optically used area.

44. Projection objective for the field of microlithography according to one of the claims 27 to 43, with a large number of optical elements, characterized in that at least one optical element consists of polycrystalline material.

45. Projection objective for the field of microlithography according to claim 44, wherein the polycrystalline material consists of a fluoride, an oxide of group II, an oxide of group III, an oxide of the rare earths, garnet or spinel.

46. Projection objective for the field of microlithography according to claim 44 or 45, wherein the polycrystalline material consists of many individual crystals that are birefringent.

47. Projection objective for the field of microlithography according to claim 46, wherein the optical element of polycrystalline material overall has a lesser degree of birefringence than each of the individual crystals.

48. Projection objective for the field of microlithography according to one of the claims 44 to 46, wherein the optical element of polycrystalline material has a stray light component which varies over the field by more than 0.1%, in particular more than 0.2%, relative to the useful light in the exposure field.

49. Projection objective for the field of microlithography according to one of the claims 44 to 48, with a large number of optical elements along a light ray path from the mask plane to the field plane and with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, characterized in that at least the last optical element consists of polycrystalline material.

50. Projection objective for the field of microlithography according to one of the claims 27 to 49, with a large number of optical elements along a light ray path from the mask plane to the field plane and with a last optical element which in the ray direction from the mask plane to the field plane is arranged before the field plane, characterized in that the last optical element consists of material with a refractive index larger than 1.7 at the operating wavelength.

51. Projection objective for the field of microlithography according to one of the claims 38 to 50, wherein the last optical element is a lens.

52. Projection objective for the field of microlithography according to one of the claims 38 to 50, wherein the last optical element is a planar-parallel plate.

53. Projection objective for the field of microlithography according to claim 30, wherein the at least one field-proximate optical element is a mirror and the at least one surface is a mirror surface.

54. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to one of the claims 27 to 53, with at least one field-proximate surface having a surface roughness, characterized in that the surface roughness of the at least one field-proximate surface is adapted in advance or is altered in such a way that the additional stray light component of the projection objective with a non-constant profile over the exposure field is obtained.

55. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to claim 54, comprising the following steps:

- simulating or measuring the stray light component within the exposure field of the entire projection objective;
- adapting in advance or altering the surface roughness of the at least one field-proximate surface in such a way that the additional stray light component of the projection objective with a non-constant profile over the exposure field is obtained.

56. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to claim 55, 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.

57. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to claim 55, in a projection objective with a large number of optical components, wherein the required surface roughness of the at least one field-proximate surface is determined from measurements taken on the optical components and the stray light component of the projection objective is determined from the measurement results of the optical components.

58. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to claim 57, wherein the large number of optical components comprises several lenses that are manufactured from blanks and wherein the measurement results for the lenses are determined from the measurement results of the respective blanks.

59. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to claim 54, comprising the following steps:

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

- adapting in advance or altering the surface roughness of the at least one field-proximate surface in such a way that the additional stray light component of the projection objective with a non-constant profile over the exposure field is obtained.

60. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to claim 59, wherein the required surface roughness of the at least one field-proximate surface is determined from measurements taken on a second lens that is equal in design to the first lens, and wherein the measurement results of the second lens are carried over to the first lens.

61. Method of introducing an additional stray light component of a projection objective for the field of microlithography according to claim 59, wherein the lens is manufactured from a blank, and wherein the measurement results for the lens are determined from the measurement results of the respective blank.

62. Method of generating a stray light component of a projection objective for the field of microlithography according to one of the claims 1 to 26, with at least one field-proximate surface having a surface roughness, characterized in that the surface roughness of the at least one field-proximate surface is adapted in advance or altered in such a way that an exposure field in the field plane receives a stray light component of the projection objective, averaged over the scan direction, which varies over the exposure field by less than 0.5%, in particular less than 0.2%, relative to the useful light.

63. Method of generating a stray light component of a projection objective for the field of microlithography according to claim 62, comprising the following steps:

- simulating or measuring the stray light component within the exposure field of the entire projection objective;
- adapting in advance or altering the surface roughness of the at least one field-proximate surface in such a way that an exposure field in the field plane receives a stray light component of the projection objective, averaged over the scan direction, which varies over the exposure field by less than 0.5%, in particular less than 0.2%, relative to the useful light.

64. Method of generating a stray light component of a projection objective for the field of microlithography according to claim 63, 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.

65. Method of generating a stray light component of a projection objective for the field of microlithography according to claim 63, in a projection objective with a large number of optical components, wherein the required surface roughness of the at least one field-proximate surface is determined from measurements taken on the optical components and the stray light component of the projection objective is determined from the measurement results of the optical components.

66. Method of generating a stray light component of a projection objective for the field of microlithography according to claim 65, wherein the large number of optical components comprises several lenses that are manufactured from blanks and wherein the measurement results for the lenses are determined from the measurement results of the respective blanks.

67. Method of generating a stray light component of a projection objective for the field of microlithography according to claim 62, comprising the following steps:

- simulating or measuring the stray light component of at least one lens;
- adapting in advance or altering the surface roughness of the at least one field-proximate surface in such a way that an exposure field in the field plane receives a stray light component of the projection objective, averaged over the scan direction, which varies over the exposure field by less than 0.5%, in particular less than 0.2%, relative to the useful light.

68. Method of generating a stray light component of a projection objective for the field of microlithography according to claim 67, wherein the required surface roughness of the at least one field-proximate surface is determined from measurements taken on a second lens that is equal in design to the first lens, and wherein the measurement results of the second lens are carried over to the first lens.

69. Method of generating a stray light component of a projection objective for the field of microlithography according to claim 67, wherein the lens is manufactured from a blank, and wherein the measurement results for the

lens are determined from the measurement results of the respective blank.

70. Projection exposure apparatus with a projection objective according to one of the claims 1 to 53.

71. Projection exposure apparatus with a projection objective which has an additional stray light component that is generated through a method according to one of the claims 54 to 61.

72. Projection exposure apparatus with a projection objective which has a stray light component that is generated through a method according to one of the claims 62 to 69.

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

- providing a substrate on which a coating of a light-sensitive material is deposited at least over sections of the substrate surface;
- providing a mask comprising structures of which an image is to be produced;
- providing a projection exposure apparatus according to one of the claims 70 to 72;
- projecting at least a section of the mask onto an area of the light-sensitive coating of the substrate by means of the projection exposure apparatus.

74. Structured component, which is produced through a method according to claim 73.

FIG.1

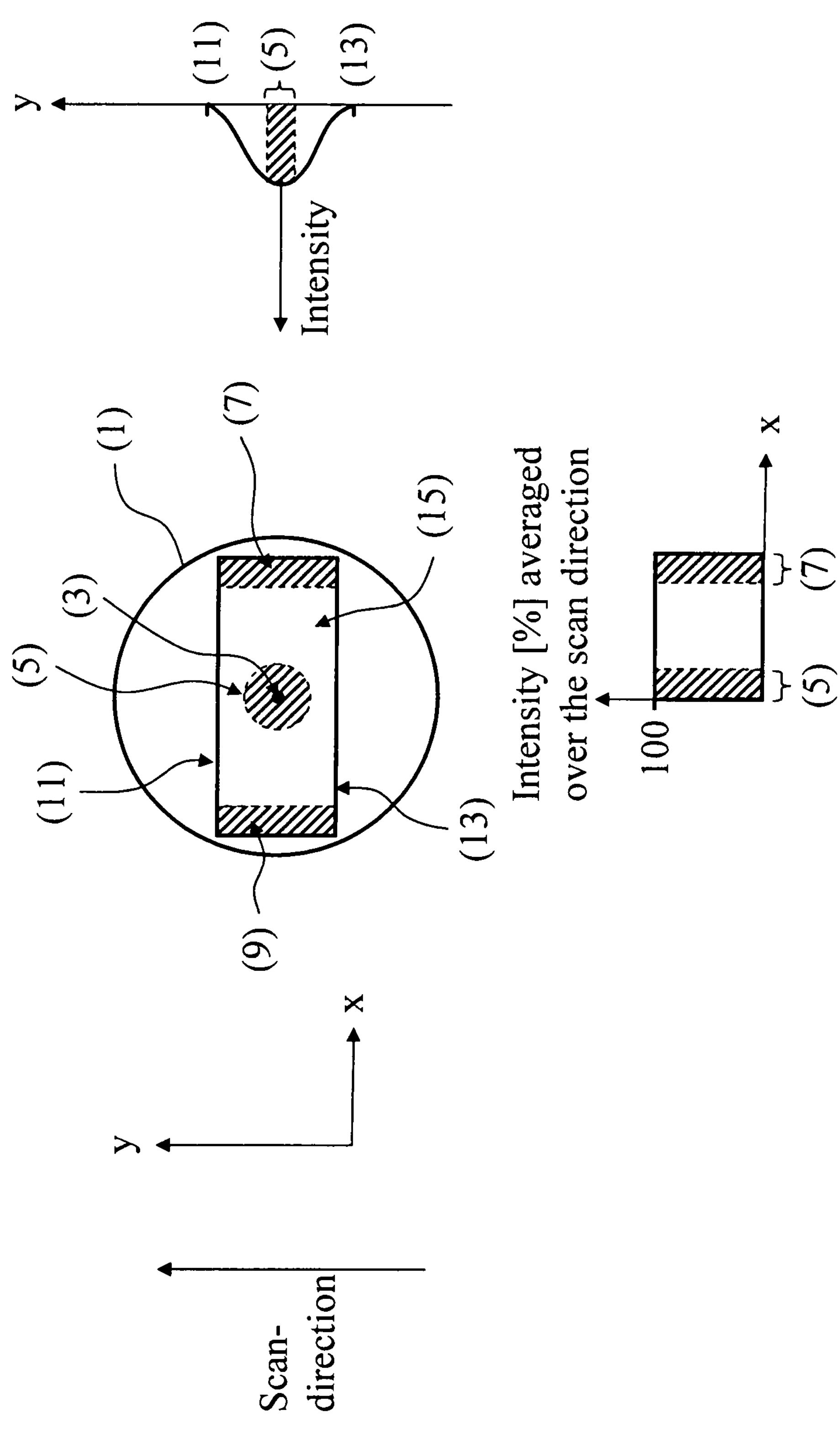

y
(11)
(5)
(13)
Intensity
(1)
(7)
(3)
(5)
(15)
(11)
(13)
(9)
Intensity [%] averaged
over the scan direction
x
100
(7)
(5)
x
y
Scan-
direction

FIG.4

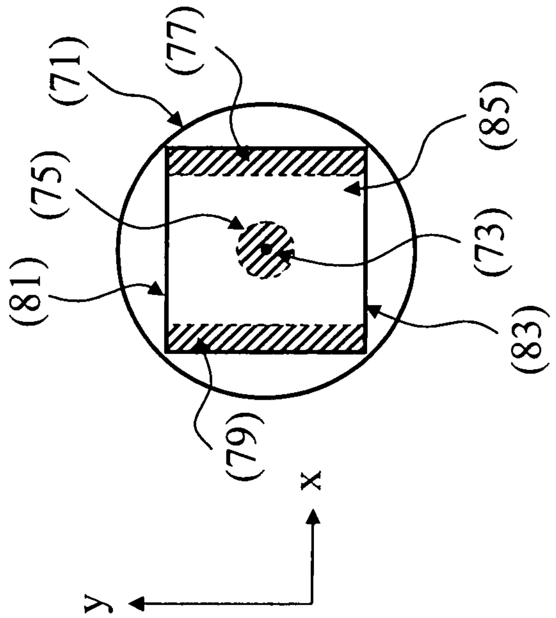


FIG.2

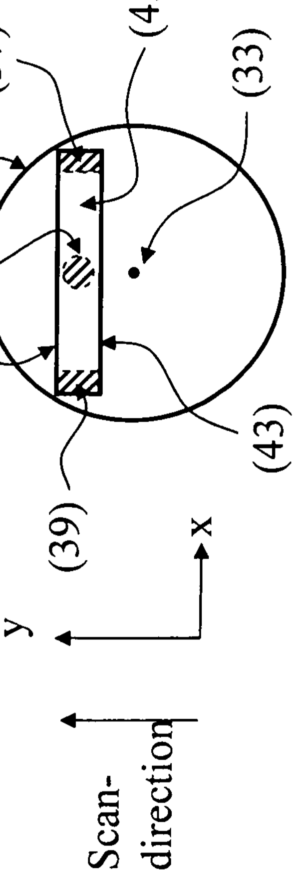


FIG.3

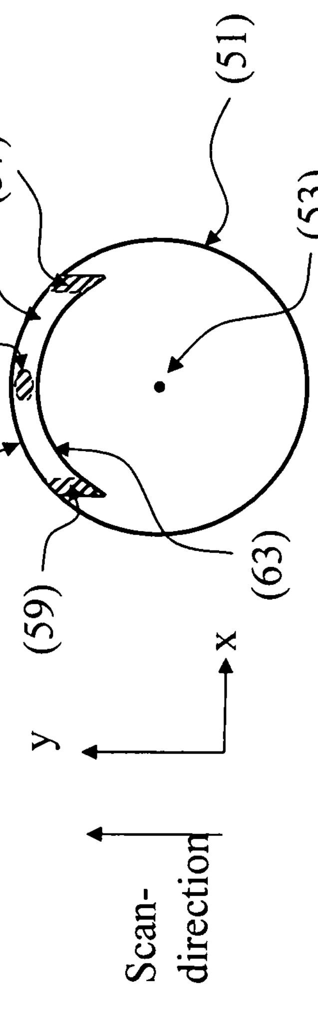
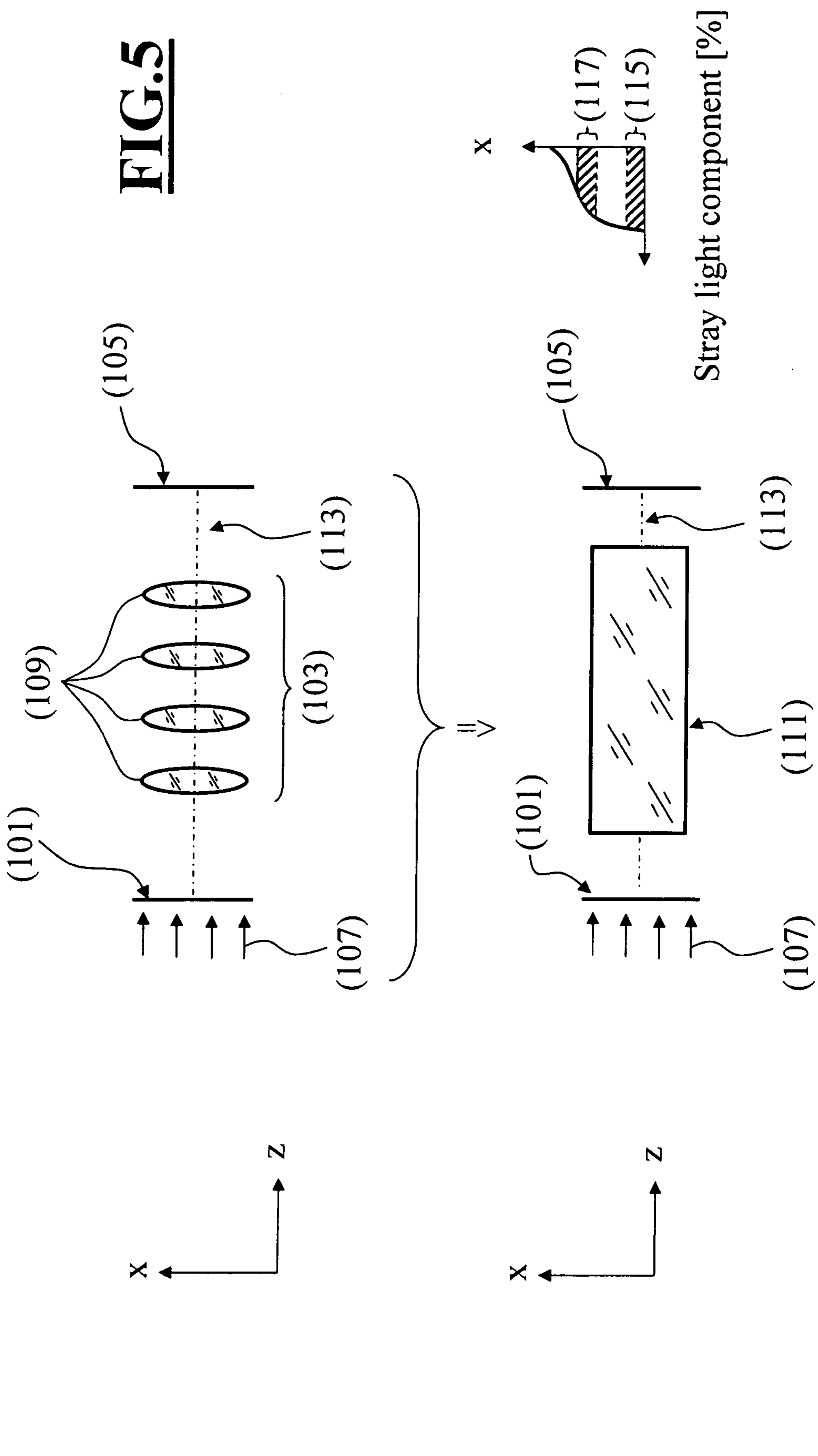


FIG.5



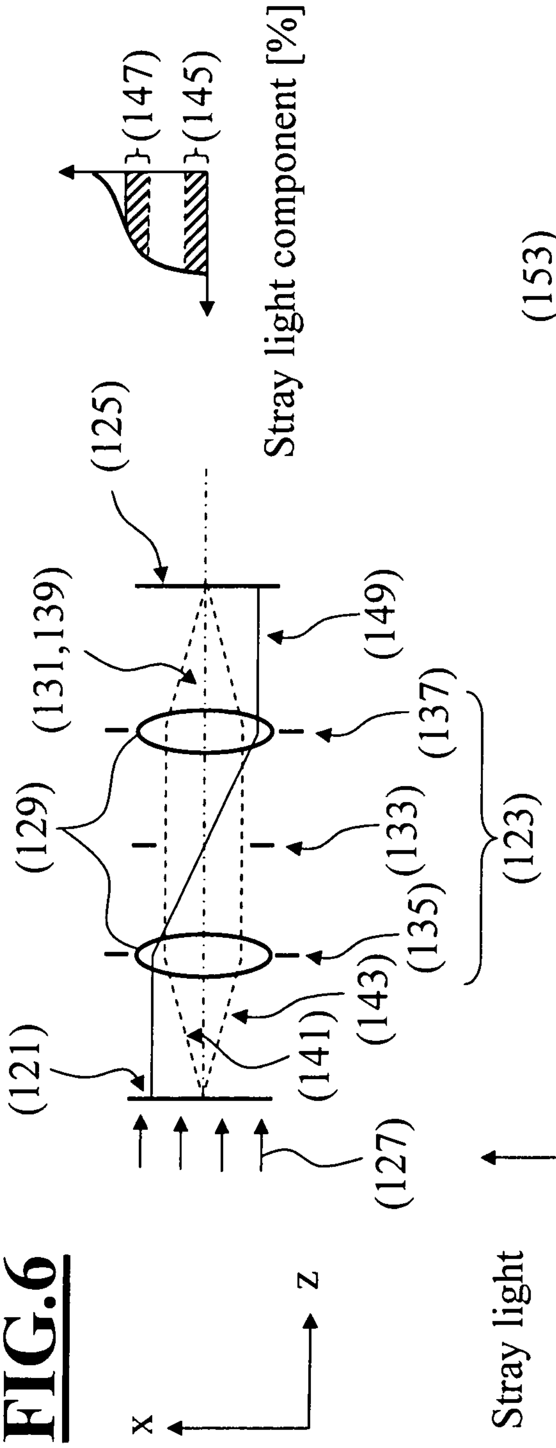

(121)
(125)
(127)
(129)
(131,139)
(133)
(135)
(137)
(123)
(141)
(143)
(149)
(147)
(145)
Stray light component [%]
x
z

FIG.6

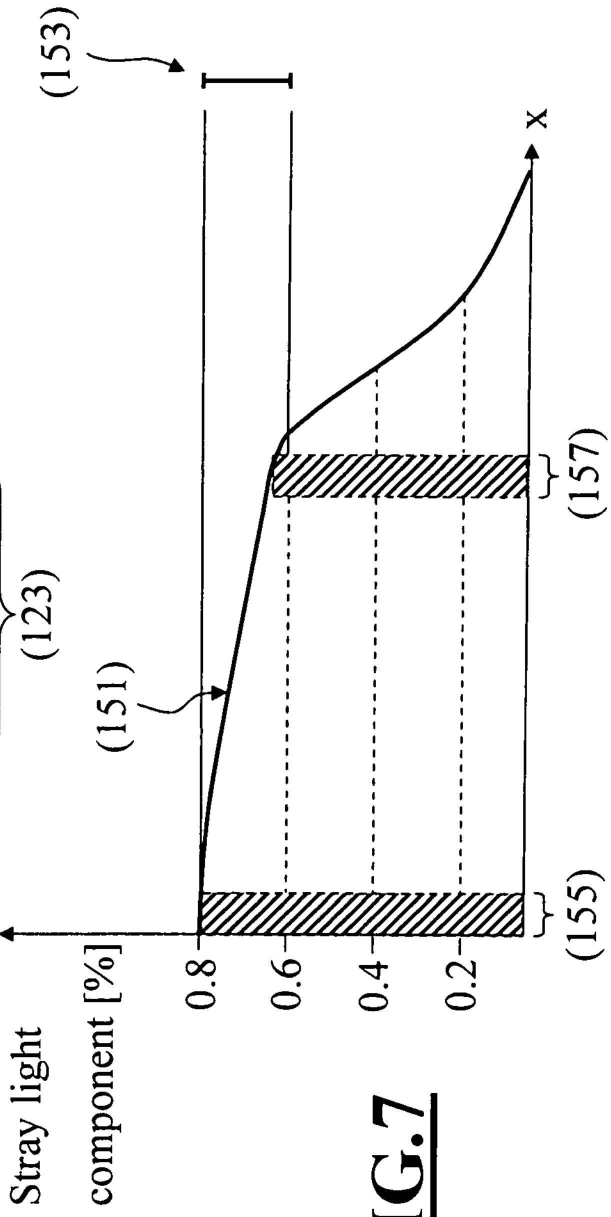

(151)
(153)
(155)
(157)
Stray light component [%]
0.8
0.6
0.4
0.2
x

FIG.7

FIG.8

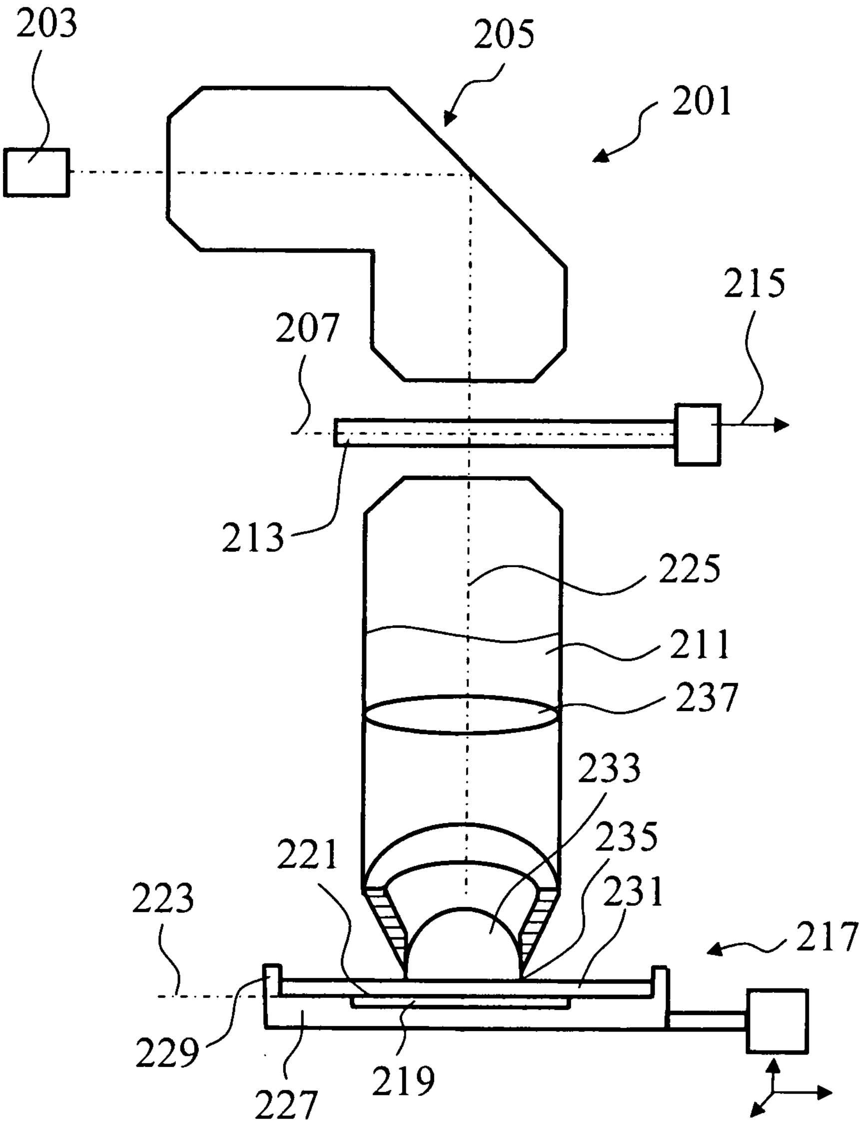

203
205
201
215
207
213
225
211
237
233
235
221
231
223
217
229
219
227

FIG.9

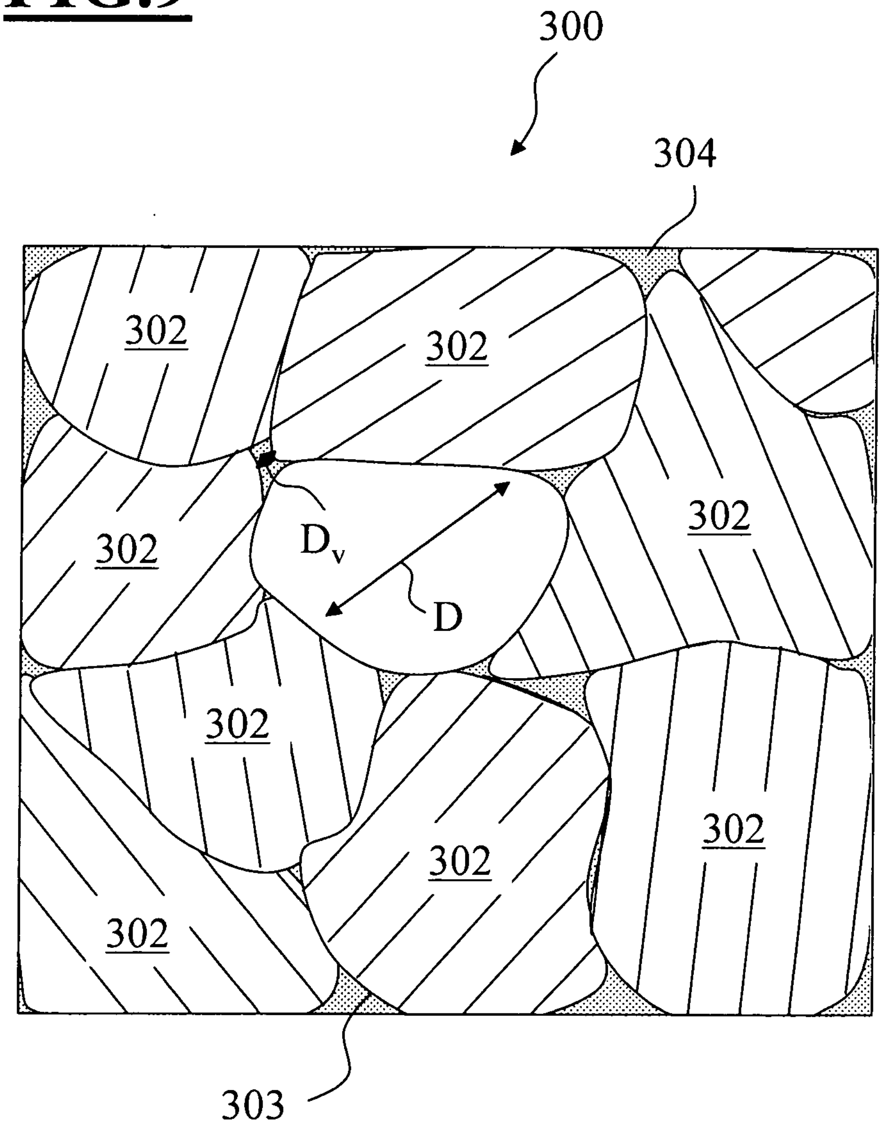


FIG.10

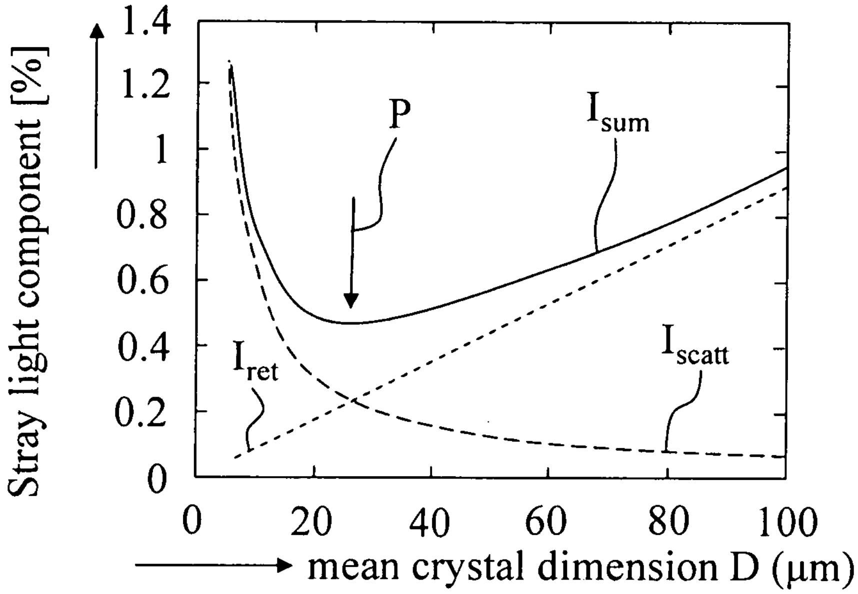

Stray light component [%]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
P
I_{sum}
I_{ret}
I_{scatt}
0
20
40
60
80
100
mean crystal dimension D (μm)

FIG11

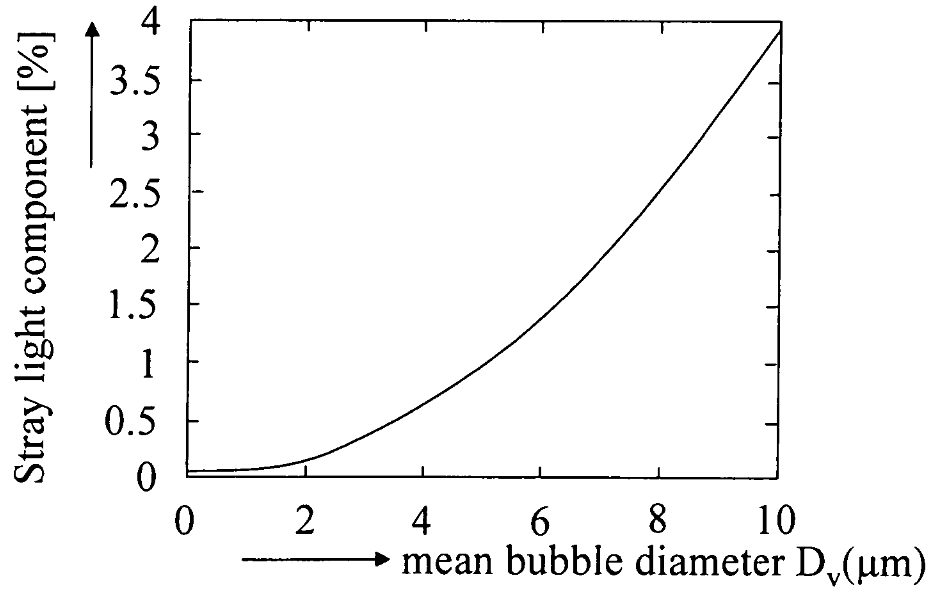

Stray light component [%]
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
mean bubble diameter D_v(μm)

FIG.12

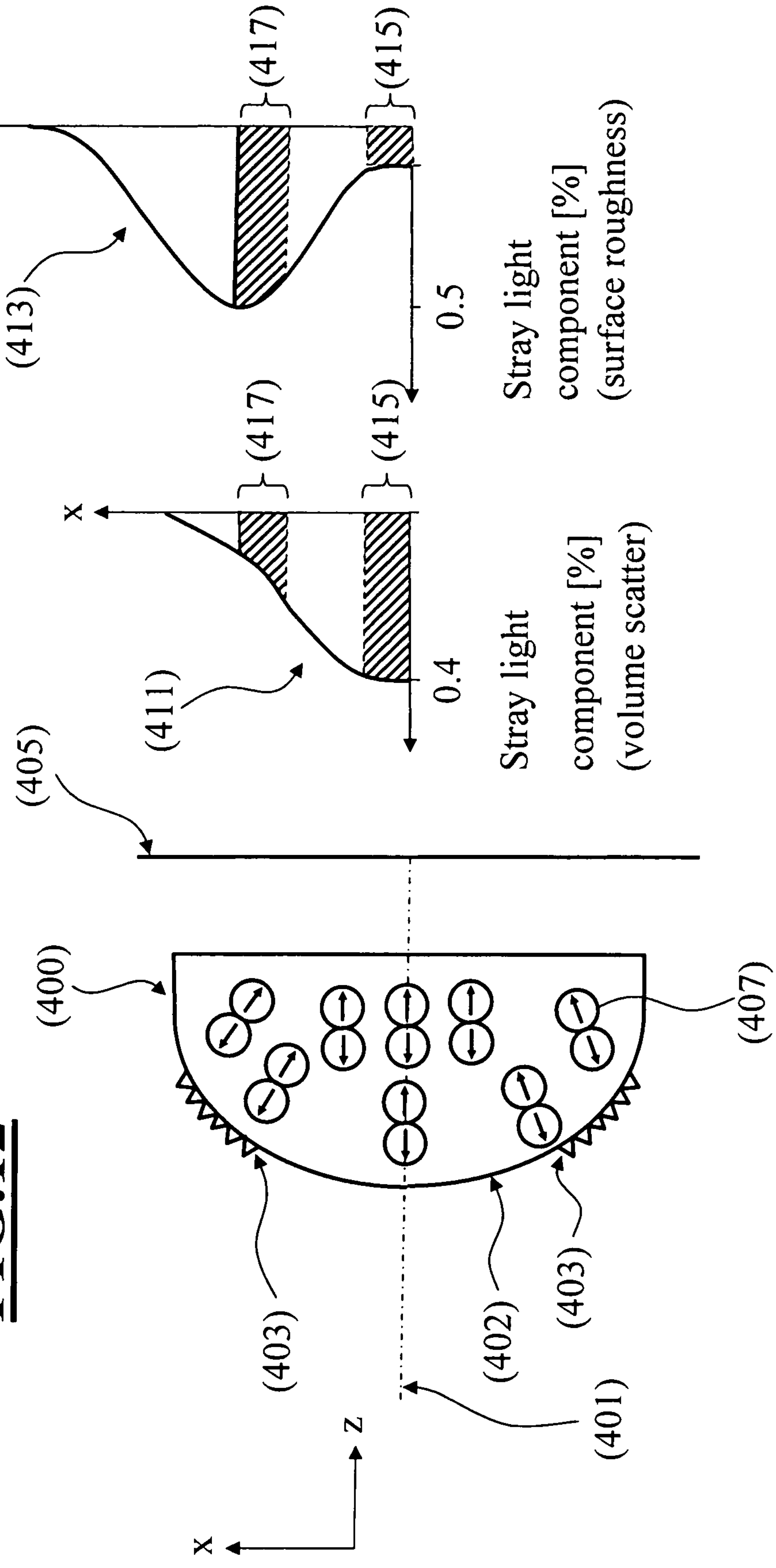

x
(417)
(415)
(413)
0.5
Stray light
component [%]
(surface roughness)
x
(417)
(415)
(411)
0.4
Stray light
component [%]
(volume scatter)
(405)
(400)
(407)
(403)
(402)
(403)
(401)
z
x

FIG.13

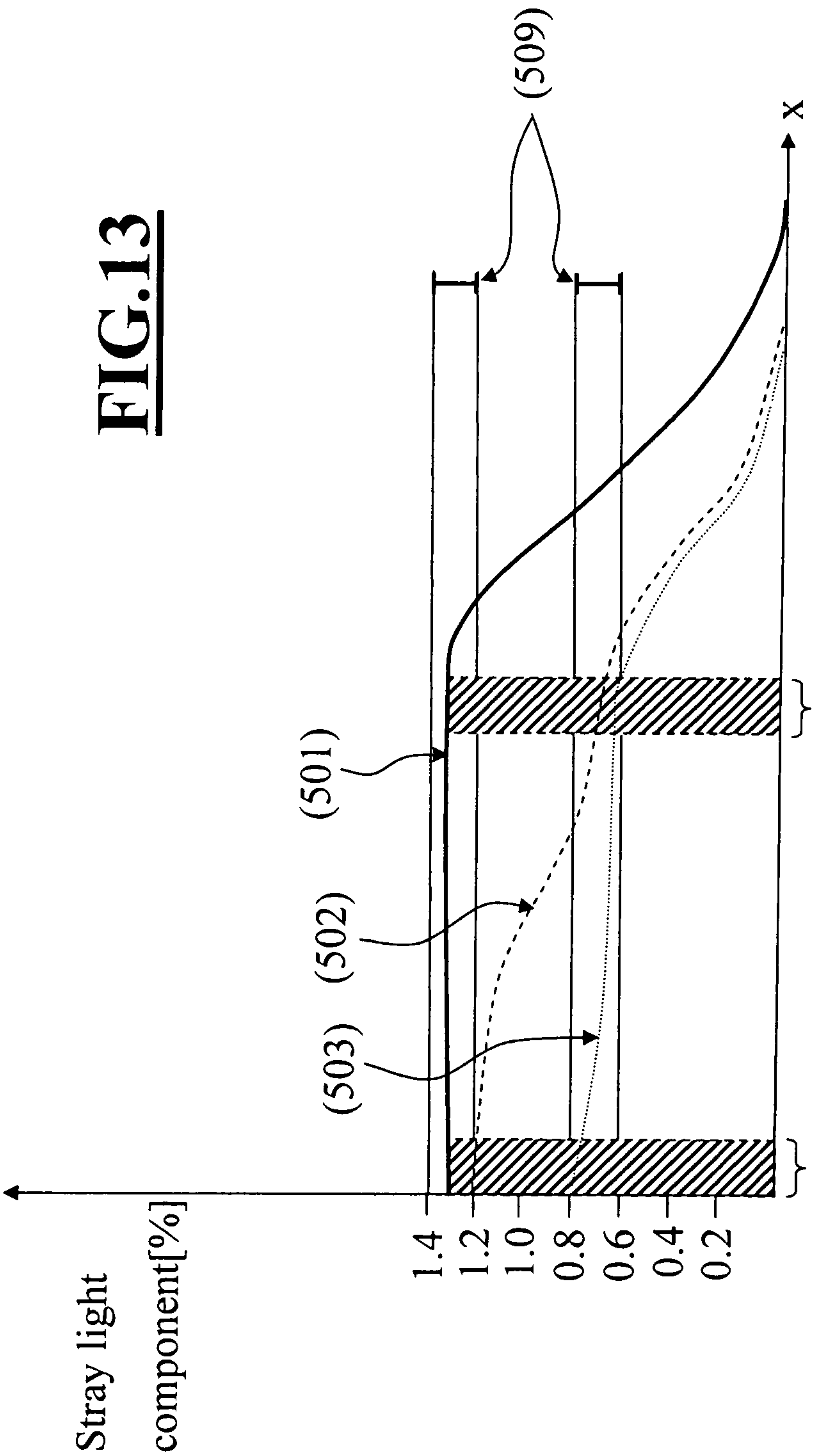

Stray light component[%]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
x
(501)
(502)
(503)
(505)
(507)
(509)

FIG.14a

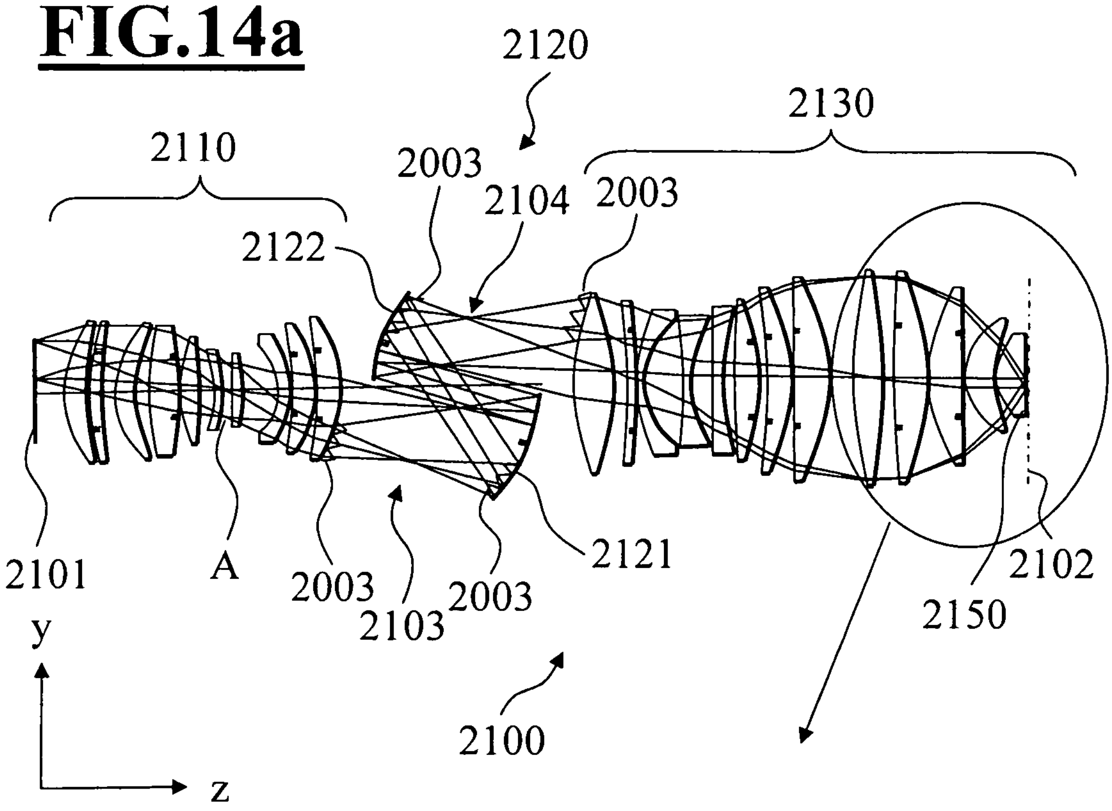


FIG.14b

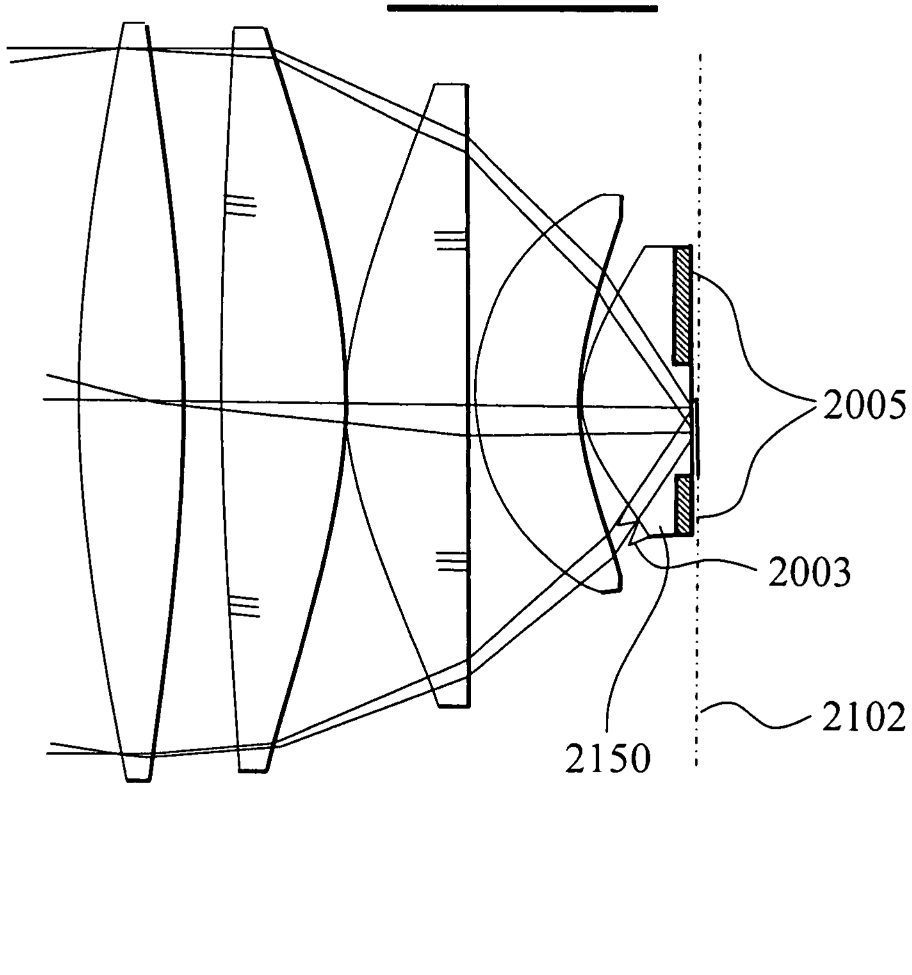


FIG.15

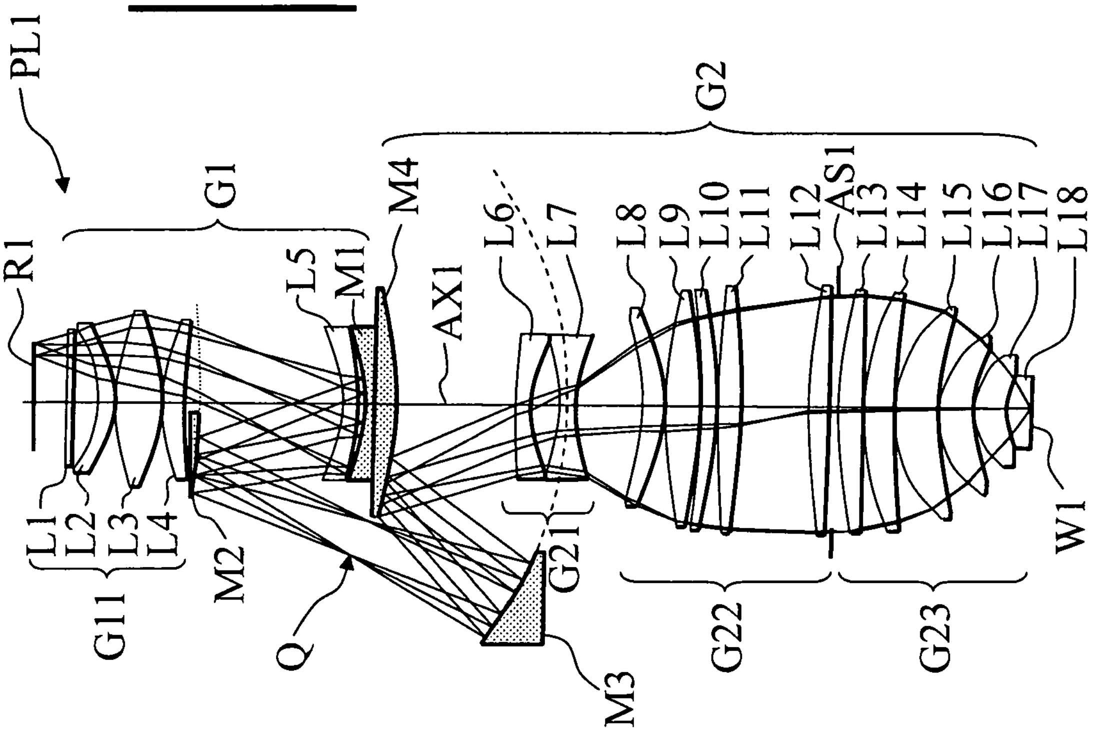

PL1
G1
G2
R1
L5
M1
M4
AX1
L6
L7
L8
L9
L10
L11
L12
AS1
L13
L14
L15
L16
L17
L18
L1
L2
L3
L4
M2
G11
Q
M3
G21
G22
G23
W1

FIG.16

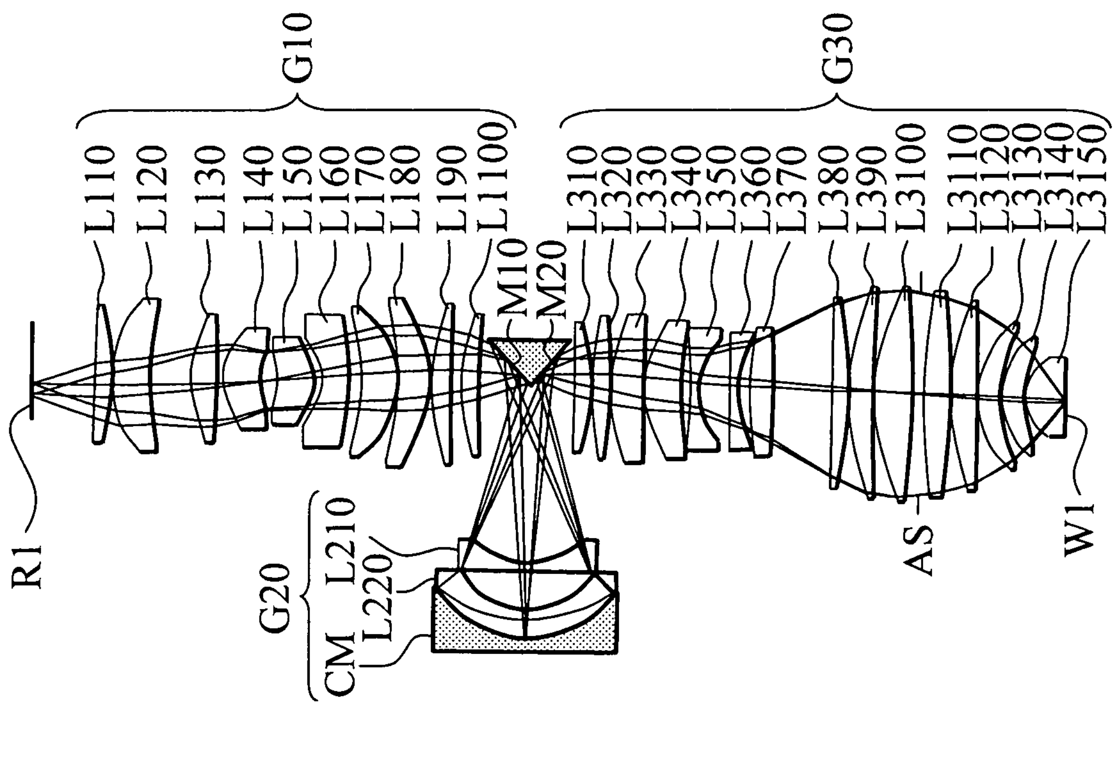

G10
G30
L110
L120
L130
L140
L150
L160
L170
L180
L190
L1100
M10
M20
L310
L320
L330
L340
L350
L360
L370
L380
L390
L3100
L3110
L3120
L3130
L3140
L3150
R1
G20
L210
L220
CM
AS
W1

FIG.17

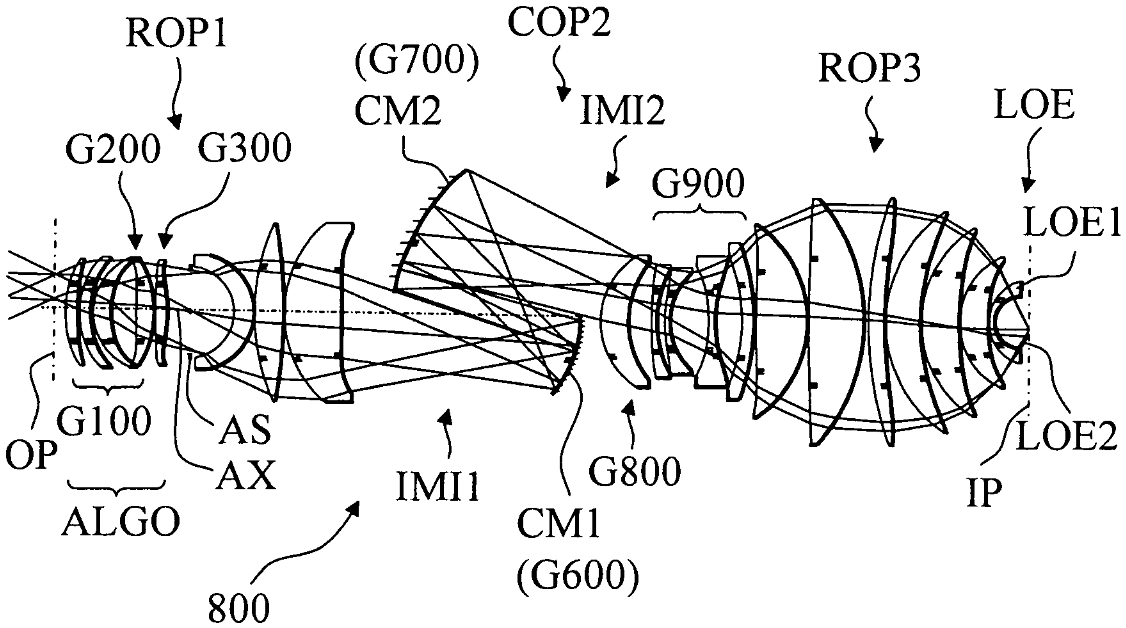

ROP1
COP2
(G700)
CM2
IMI2
ROP3
LOE
G200
G300
G900
LOE1
G100
AS
OP
AX
IMI1
G800
LOE2
IP
ALGO
CM1
(G600)
800

FIG.18

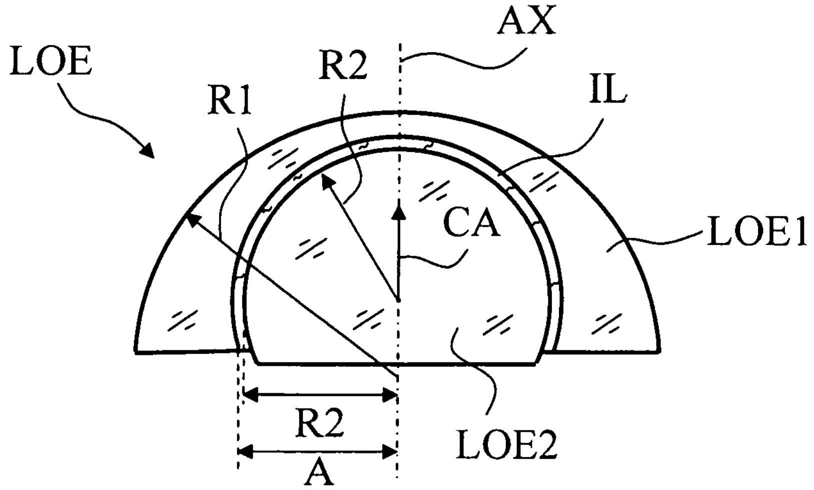

AX
LOE
R2
IL
R1
CA
LOE1
R2
A
LOE2

FIG.19

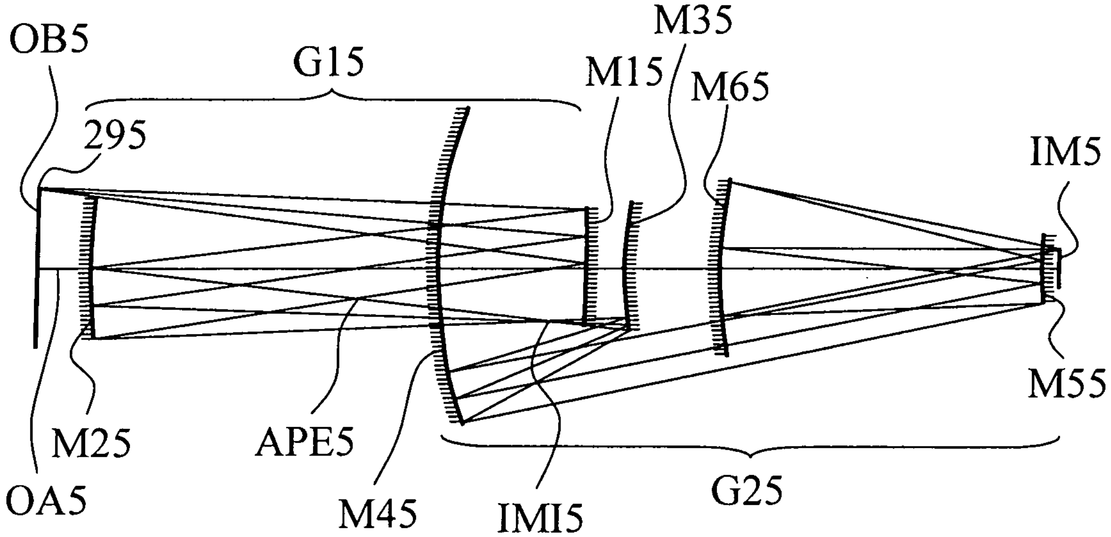


FIG.20

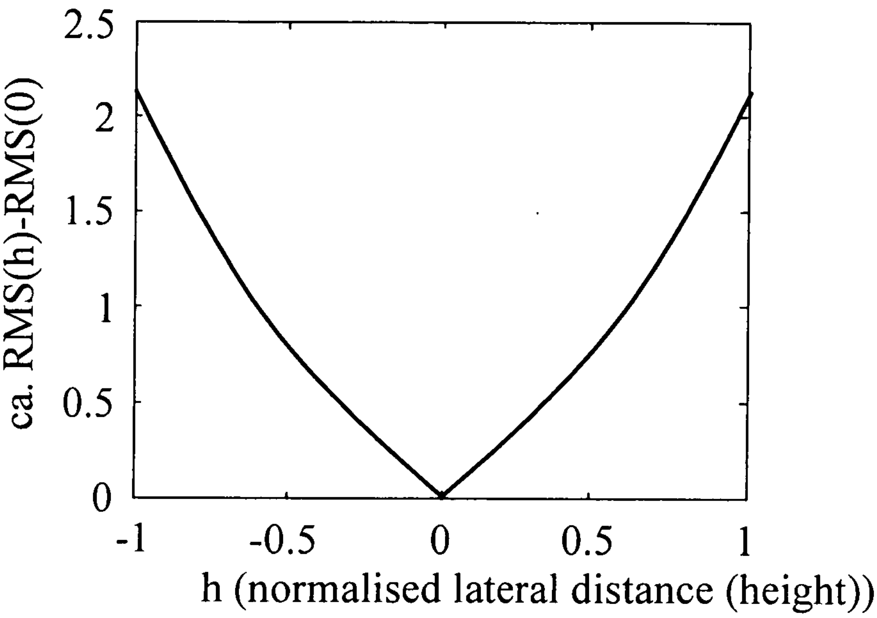

2.5
2
1.5
1
0.5
0
ca. RMS(h)-RMS(0)
-1
-0.5
0
0.5
1
h (normalised lateral distance (height))

FIG.21

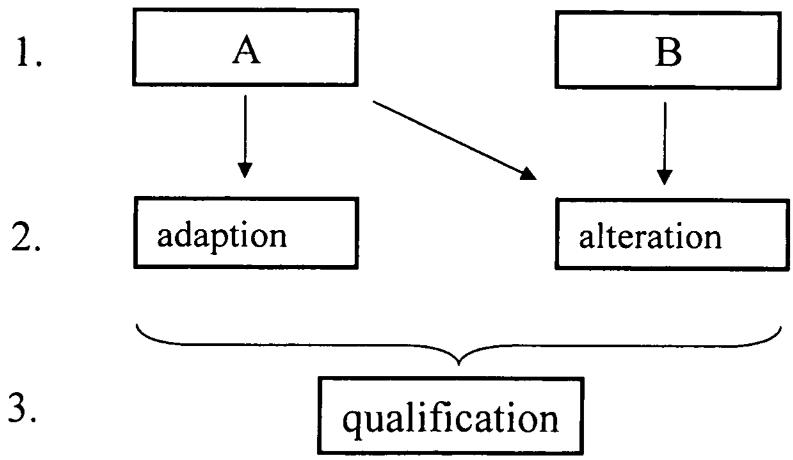
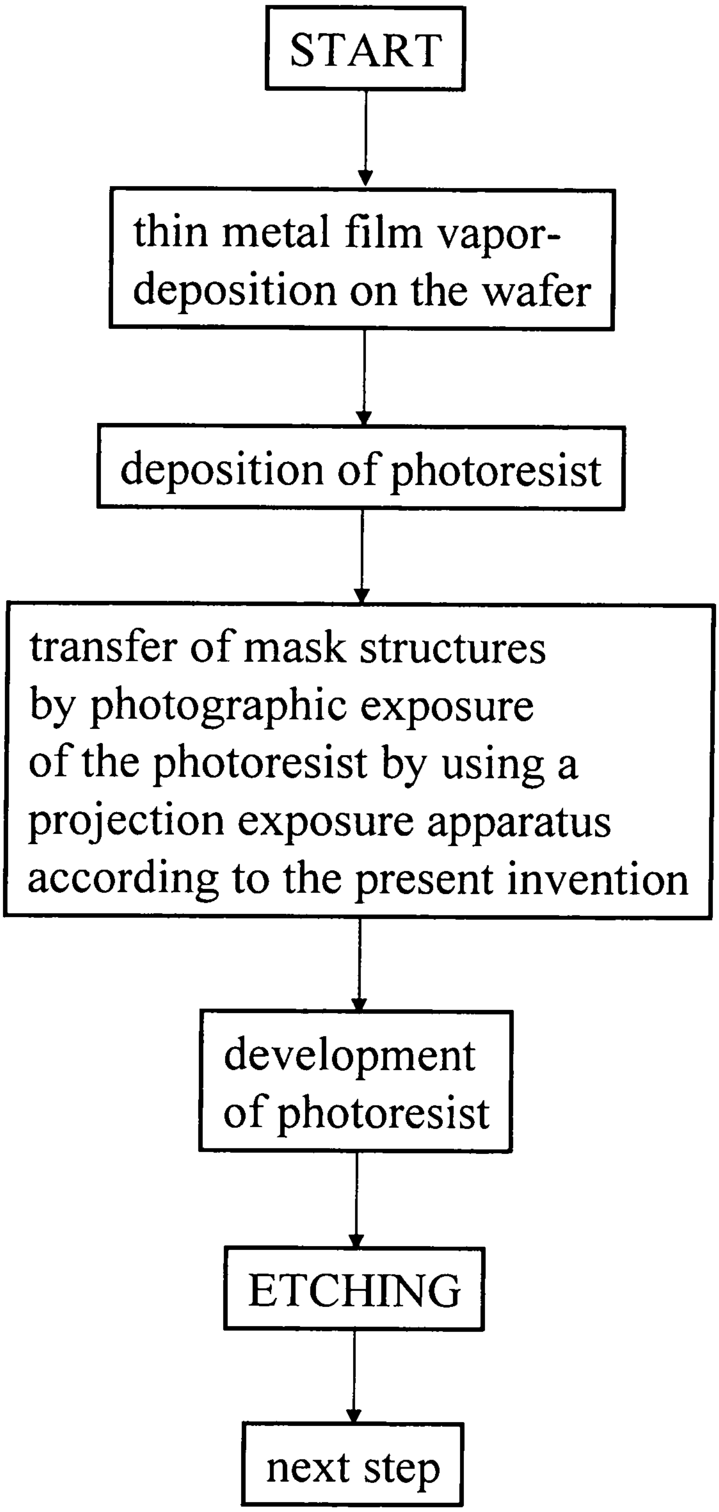

1.
2.
3.
A
B
adaption
alteration
qualification

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

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2008/004081

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2006/061225 A (ZEISS CARL SMT AG [DE]; CLAUSS WILFRIED [DE]; TOTZECK MICHAEL [DE]; MU) 15 June 2006 (2006-06-15) cited in the application pages 16-23; figures 2-4	1-9, 18-25, 44-52, 70,73,74
Y	WO 2006/128613 A (ZEISS CARL SMT AG [DE]; KALLER JULIAN [DE]; DODOC AURELIAN [DE]; FELDM) 7 December 2006 (2006-12-07) pages 31-33; figure 6	1-9, 18-25, 70,73,74
Y	US 2006/176461 A1 (SEKINE YOSHIYUKI [JP]) 10 August 2006 (2006-08-10) paragraphs [0001], [0004], [0036] - [0038]; figures 1,2a	1,70,73, 74

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 September 2008	08/10/2008

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Eisner, Klaus

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2008/004081

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2002/008911 A1 (SEKINE YOSHIYUKI [JP]) 24 January 2002 (2002-01-24)	27,28, 38,70, 73,74
Y	paragraphs [0019], [0020], [0067] - [0071]; figure 5 -----	44-52
A	US 2003/020893 A1 (KAWASHIMA HARUNA [JP]) 30 January 2003 (2003-01-30) paragraphs [0049] - [0057]; figures 1,2 -----	1-74

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2008/004081

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
WO 2006061225	A	15-06-2006	EP	1820050	A1	22-08-2007
			JP	2008523426	T	03-07-2008
			KR	20070085869	A	27-08-2007
WO 2006128613	A	07-12-2006	EP	1886190	A1	13-02-2008
			KR	20080036171	A	25-04-2008
US 2006176461	A1	10-08-2006	JP	2006222222	A	24-08-2006
US 2002008911	A1	24-01-2002	JP	2001264626	A	26-09-2001
			KR	20010092362	A	24-10-2001
			TW	508456	B	01-11-2002
US 2003020893	A1	30-01-2003	JP	3679736	B2	03-08-2005
			JP	2003017396	A	17-01-2003