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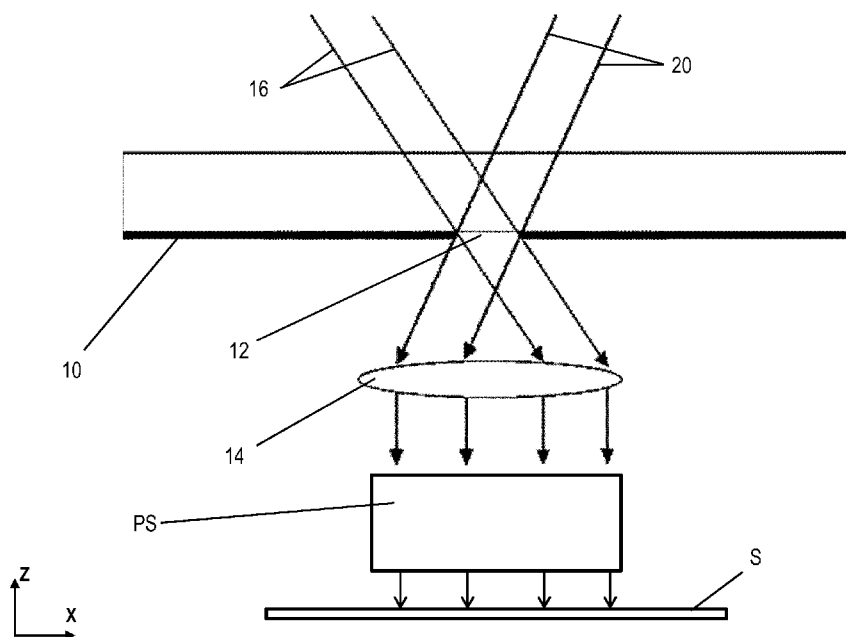


FIG. 2

(57) Abstract: A lithographic apparatus and method of making an apodization measurement for a lithographic apparatus, the method comprising forming a pupil spot in a pupil plane of the illumination system at a pupil coordinate; placing a plate having at least one pinhole at an object plane of the illumination system; placing an optical element at a distance from the pinhole equalling the focal length of the optical element which refracts the radiation beam such that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the optical element; measuring the transmission of the illumination system using a detector; and moving the pupil spot to a plurality of different pupil coordinates and repeating the measurement to obtain an apodization profile of the illumination system.

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Apodization measurement for lithographic apparatus

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 18159255.1 which was filed on
5 28 February 2018 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to an apparatus and method for apodization
measurement in a lithographic apparatus.

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BACKGROUND

[0003] A lithographic apparatus is a machine constructed to apply a desired pattern onto a substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). A lithographic apparatus may, for example, project a pattern (also often referred
15 to as “design layout” or “design”) of a patterning device (e.g., a mask) onto a layer of radiation-sensitive material (resist) provided on a substrate (e.g., a wafer).

[0004] As semiconductor manufacturing processes continue to advance, the dimensions of circuit elements have continually been reduced while the amount of functional elements, such as transistors, per device has been steadily increasing over decades, following a trend
20 commonly referred to as ‘Moore’s law’. To keep up with Moore’s law the semiconductor industry is chasing technologies that enable to create increasingly smaller features. To project a pattern on a substrate a lithographic apparatus may use electromagnetic radiation. The wavelength of this radiation determines the minimum size of features which are patterned on the substrate. Typical wavelengths currently in use are 365 nm (i-line), 248 nm, 193 nm and
25 13.5 nm. A lithographic apparatus, which uses extreme ultraviolet (EUV) radiation, having a wavelength within a range of 4 nm to 20 nm, for example 6.7 nm or 13.5 nm, may be used to form smaller features on a substrate than a lithographic apparatus which uses, for example, radiation with a wavelength of 193 nm.

[0005] Lens light non-uniformity is in general characterized in the image plane. Very tight
30 specifications are used in order to limit CD-variations (critical dimension variations) through the image field. When light non-uniformity appears in the pupil plane, (e.g., over the various angles at image level), CD-variations through pitch are expected. Light non-uniformity in the pupil plane is often referred to as apodization. In this sense, apodization describes the amplitude part of the pupil-transmission function (where aberrations describe the phase part of the pupil

transmission function). A uniform pupil transmission is often assumed, but this is generally not the case.

[0006] Apodization is a known optical phenomenon where the angular intensity distribution of a light beam is non-uniform and in particular where the intensity falls away at the edges of the beam. Apodization may be defined as the angular lens transmission.

[0007] Pupil measurements at wafer-level generally measure a combination of the illumination angular intensity and the lens apodization. No separation is made between lens and illuminator effects. This can be problematic since both induce different imaging effects.

10 SUMMARY

[0008] According to a first aspect of the present invention, there is provided a method of making an apodization measurement for an apparatus, for example a lithographic apparatus, having an illumination system which is configured to condition a radiation beam to have a desired spatial intensity distribution at a pupil plane of the illumination system and to focus the radiation beam in an object plane where a patterning device is located, and a projection system configured to project a patterned radiation beam onto a substrate, the method comprising forming a pupil spot in the pupil plane of the illumination system at a pupil coordinate; placing a plate having at least one pinhole at the object plane of the illumination system; placing an optical element at a distance from the pinhole equalling the focal length of the optical element which refracts the radiation beam such that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the optical element; measuring the transmission of the illumination system and the projection system using a detector; and moving the pupil spot to a plurality of different pupil coordinates and repeating the measurement to obtain an apodization profile of the illumination system.

[0009] The method may further comprise moving the pupil spot to the plurality of different pupil coordinates such that the apodization profile is measured over the full numerical aperture of the apparatus.

[00010] The optical element may be a convex lens downstream of the pinhole.

[00011] The optical element may be a concave lens upstream of the pinhole.

[00012] The plate may have a plurality of pinholes.

[00013] There may be a plurality of optical elements placed at different positions.

[00014] The plate may be a patterning device.

[00015] The detector may be a spot sensor and/or an interferometer sensor located at a substrate level.

[00016] The method may further comprise measuring the total apodization profile of the illumination system and the projection system, and then subtracting the apodization profile of the illumination system from the total apodization profile to obtain the apodization profile of the projection system.

5 [00017] According to a second aspect of the present invention, there is provided a method of making an apodization measurement for an apparatus, for example a lithographic apparatus, having an illumination system which is configured to condition a radiation beam to have a desired spatial intensity distribution at a pupil plane of the illumination system and to focus the radiation beam in an object plane where a patterning device is located, and a projection system
10 configured to project a patterned radiation beam onto a substrate, the method comprising: forming a pupil spot in the pupil plane of the illumination system at a pupil coordinate; placing a plate having at least one pinhole at the object plane of the illumination system; placing an optical element at a distance from the pinhole equalling the focal length of the optical element which refracts the radiation beam such that the radiation beam is on an optical axis which
15 corresponds with the centre of a pupil plane in the optical element; measuring the transmission of the illumination system using a detector; and moving the pupil spot to a plurality of different pupil coordinates and repeating the measurement to obtain an apodization profile of the illumination system.

[00018] The method may further comprise moving the pupil spot to the plurality of different
20 pupil coordinates such that the apodization profile is measured over the full numerical aperture of the apparatus.

[00019] The optical element may be a convex lens downstream of the pinhole.

[00020] The optical element may be a concave lens upstream of the pinhole.

[00021] The plate may have a plurality of pinholes.

25 [00022] There may be a plurality of optical elements placed at different positions.

[00023] The plate and the detector may be part of or comprised in a patterning device spot sensor located at a patterning device level.

[00024] According to a third aspect of the present invention, there is provided an apparatus comprising: an illumination system which is configured to condition a radiation beam to have
30 a desired spatial intensity distribution at a pupil plane of the illumination system and to focus the radiation beam in an object plane where a patterning device is located; a projection system configured to project a patterned radiation beam onto a substrate; a plate having at least one pinhole located at the object plane of the illumination system; an optical element located at a distance from the pinhole equalling the focal length of the optical element which refracts the

radiation beam such that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the optical element; and a detector configured to measure the transmission of the illumination system and the projection system; wherein the illumination system is configured to form a pupil spot in the pupil plane of the illumination system at a pupil coordinate; and wherein the illumination system is configured to move the pupil spot to a plurality of different pupil coordinates and to repeat the measurement to obtain an apodization profile of the illumination system.

[00025] The optical element may be a convex lens downstream of the pinhole.

[00026] The optical element may be a concave lens upstream of the pinhole.

10 [00027] The plate may be a patterning device.

[00028] The detector may be a spot sensor and/or an interferometer sensor located at a substrate level.

[00029] According to a fourth aspect of the present invention, there is provided an apparatus comprising: an illumination system which is configured to condition a radiation beam to have a desired spatial intensity distribution at a pupil plane of the illumination system and to focus the radiation beam in an object plane where a patterning device is located; a projection system configured to project a patterned radiation beam onto a substrate; a plate having at least one pinhole located at the object plane of the illumination system; an optical element located at a distance from the pinhole equalling the focal length of the optical element which refracts the radiation beam such that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the optical element; and a detector configured to measure the transmission of the illumination system; wherein the illumination system is configured to form a pupil spot in the pupil plane of the illumination system at a pupil coordinate; and wherein the illumination system is configured to move the pupil spot to a plurality of different pupil coordinates and to repeat the measurement to obtain an apodization profile of the illumination system.

[00030] The optical element may be a convex lens downstream of the pinhole.

[00031] The optical element may be a concave lens upstream of the pinhole.

[00032] The plate and the detector may be part of or comprised in a patterning device spot sensor located at a patterning device level.

BRIEF DESCRIPTION OF THE DRAWINGS

[00033] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 depicts a schematic overview of a lithographic apparatus;
- Figure 2 depicts a schematic overview of part of a lithographic apparatus with a plate and a convex lens upstream of a projection system according to an embodiment of the invention;
- 5 - Figure 3 depicts a schematic overview of part of a lithographic apparatus with a plate and a concave lens upstream of a projection system according to an embodiment of the invention;
- Figure 4 depicts a schematic overview of part of a lithographic apparatus with a plate and a convex lens upstream of a sensor according to an embodiment of the invention;
- 10 - Figure 5 depicts a schematic overview of part of a lithographic apparatus with a plate and a concave lens upstream of a sensor according to an embodiment of the invention.

DETAILED DESCRIPTION

[00034] In the present document, the terms “radiation” and “beam” are used to encompass all
15 types of electromagnetic radiation, including ultraviolet radiation (e.g., with a wavelength of 365, 248, 193, 157 or 126 nm) and EUV (extreme ultra-violet radiation, e.g., having a wavelength in the range of about 5-100 nm).

[00035] The term “reticle”, “mask” or “patterning device” as employed in this text may be broadly interpreted as referring to a generic patterning device that can be used to endow an
20 incoming radiation beam with a patterned cross-section, corresponding to a pattern that is to be created in a target portion of the substrate. The term “light valve” can also be used in this context. Besides the classic mask (transmissive or reflective, binary, phase-shifting, hybrid, etc.), examples of other such patterning devices include a programmable mirror array and a programmable LCD array.

25 [00036] Figure 1 schematically depicts a lithographic apparatus LA. The lithographic apparatus LA includes an illumination system (also referred to as illuminator) IL configured to condition a radiation beam B (e.g., UV radiation, DUV radiation or EUV radiation), a mask support (e.g., a mask table) MT constructed to support a patterning device (e.g., a mask) MA and connected to a first positioner PM configured to accurately position the patterning device
30 MA in accordance with certain parameters, a substrate support (e.g., a wafer table) WT constructed to hold a substrate (e.g., a resist coated wafer) W and connected to a second positioner PW configured to accurately position the substrate support in accordance with certain parameters, and a projection system (e.g., a refractive projection lens system) PS

configured to project a pattern imparted to the radiation beam B by patterning device MA onto a target portion C (e.g., comprising one or more dies) of the substrate W.

[00037] In operation, the illumination system IL receives a radiation beam from a radiation source SO, e.g., via a beam delivery system BD. The illumination system IL may include various types of optical components, such as refractive, reflective, magnetic, electromagnetic, electrostatic, and/or other types of optical components, or any combination thereof, for directing, shaping, and/or controlling radiation. The illuminator IL may be used to condition the radiation beam B to have a desired spatial and angular intensity distribution in its cross section at a plane of the patterning device MA.

[00038] The term “projection system” PS used herein should be broadly interpreted as encompassing various types of projection system, including refractive, reflective, catadioptric, anamorphic, magnetic, electromagnetic and/or electrostatic optical systems, or any combination thereof, as appropriate for the exposure radiation being used, and/or for other factors such as the use of an immersion liquid or the use of a vacuum. Any use of the term “projection lens” herein may be considered as synonymous with the more general term “projection system” PS.

[00039] The lithographic apparatus LA may be of a type wherein at least a portion of the substrate may be covered by a liquid having a relatively high refractive index, e.g., water, so as to fill a space between the projection system PS and the substrate W – which is also referred to as immersion lithography. More information on immersion techniques is given in US6952253, which is incorporated herein by reference.

[00040] The lithographic apparatus LA may also be of a type having two or more substrate supports WT (also named “dual stage”). In such “multiple stage” machine, the substrate supports WT may be used in parallel, and/or steps in preparation of a subsequent exposure of the substrate W may be carried out on the substrate W located on one of the substrate support WT while another substrate W on the other substrate support WT is being used for exposing a pattern on the other substrate W.

[00041] In operation, the radiation beam B is incident on the patterning device, e.g. mask, MA which is held on the mask support MT, and is patterned by the pattern (design layout) present on patterning device MA. Having traversed the mask MA, the radiation beam B passes through the projection system PS, which focuses the beam onto a target portion C of the substrate W. With the aid of the second positioner PW and a position measurement system IF, the substrate support WT can be moved accurately, e.g., so as to position different target portions C in the path of the radiation beam B at a focused and aligned position. Similarly, the

first positioner PM and possibly another position sensor (which is not explicitly depicted in Figure 1) may be used to accurately position the patterning device MA with respect to the path of the radiation beam B. Patterning device MA and substrate W may be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2. Although the substrate alignment marks P1, P2 as illustrated occupy dedicated target portions, they may be located in spaces between target portions. Substrate alignment marks P1, P2 are known as scribe-lane alignment marks when these are located between the target portions C.

[00042] To clarify the invention, a Cartesian coordinate system is used. The Cartesian coordinate system has three axes, i.e., an x-axis, a y-axis and a z-axis. Each of the three axes is orthogonal to the other two axes. A rotation around the x-axis is referred to as an Rx-rotation. A rotation around the y-axis is referred to as an Ry-rotation. A rotation around about the z-axis is referred to as an Rz-rotation. The x-axis and the y-axis define a horizontal plane, whereas the z-axis is in a vertical direction. The Cartesian coordinate system is not limiting the invention and is used for clarification only. Instead, another coordinate system, such as a cylindrical coordinate system, may be used to clarify the invention. The orientation of the Cartesian coordinate system may be different, for example, such that the z-axis has a component along the horizontal plane.

[00043] Apodization refers to the transmission variation of the optics as a function of pupil coordinates σ_x and σ_y . Generally, apodization may occur in the illuminator IL and in the projection system PS. Thus, the lithographic apparatus LA will have a total apodization profile which includes contributions from an apodization profile of the illuminator IL and an apodization profile of the projection system PS. T_{ILL} is the apodization of the illuminator, and T_{PL} is the apodization of the projection lens (projection system PS). The total apodization profile T_{total} can be described with Equation 1:

$$T_{total}(\sigma_x, \sigma_y) = T_{ILL}(\sigma_x, \sigma_y) * T_{PL}(\sigma_x, \sigma_y).$$

[00044] However, generally, a lithographic apparatus LA only measures the total apodization profile. This may, for example, be by using a sensor S that can measure the intensity for each pupil coordinate σ_x, σ_y . The sensor S is located at the substrate W level with a standard patterning device MA in position at patterning device level. In this case, the apodization profiles of the illuminator IL and the projection system PS are not known separately.

[00045] The sensor S may be an interferometer sensor S, e.g., a shearing interferometer. Shearing interferometers are common path interferometers and therefore, advantageously, no secondary reference beam is required to measure the wavefront (i.e., a locus of points with the same phase). The shearing interferometer may comprise a diffraction grating, for example a

two dimensional grid, in an image plane of the projection system (i.e., the substrate table WT) and a detector arranged to detect an interference pattern in a plane that is conjugate to a pupil plane of the projection system PS. The interference pattern is related to the derivative of the phase of the radiation with respect to a coordinate in the pupil plane in the shearing direction.

5 The detector may comprise an array of sensing elements such as, for example, charge coupled devices (CCDs). In one example, the diffraction grating is sequentially scanned in two perpendicular directions, which may coincide with axes of a coordinate system of the projection system PS (x and y) or may be at an angle such as, for example, 45 degrees to these axes. Scanning may be performed over an integer number of grating periods, for example one
10 or two grating periods. The scanning averages out phase variations in one direction, allowing phase variations in the other direction to be reconstructed. This allows the wavefront to be determined as a function of both directions. The projection system PS of a state of the art lithographic apparatus LA may not produce visible fringes and therefore the accuracy of the determination of the wavefront can be enhanced using phase stepping techniques such as, for
15 example, moving the diffraction grating. Stepping may be performed in the plane of the diffraction grating and in a direction perpendicular to the scanning direction of the measurement. The stepping range may be one grating period, and at least three (uniformly distributed) phase steps may be used. Thus, for example, three scanning measurements may be performed in the y-direction, each scanning measurement being performed for a different
20 position in the x-direction. This stepping of the diffraction grating effectively transforms phase variations into intensity variations, allowing phase information to be determined.

[00046] Apodization of the projection system PS contributes to variations in proximity between different lithographic apparatuses LA. Proximity refers to the delta (change) in critical dimension (CD) between different types of features that are printed simultaneously (e.g., CD-deltas between isolated and dense lines, or horizontal and vertical lines, or different pitches).
25 This proximity effect is generally considered acceptable if it is the same for all lithographic apparatuses LA. This is because proximity can be calibrated during the process optimization phase, which is always performed before high volume production. However, the process optimization phase is a lengthy and costly process and so is usually only performed on a small
30 number of lithographic apparatuses LA.

[00047] Proximity becomes an issue when different lithographic apparatuses LA have different proximity effects because this invalidates the process optimization method. Since not all lithographic apparatuses LA have the same proximity effects, the process needs to be

optimized for each lithographic apparatus LA, which in some cases, is not possible or significantly increases costs.

[00048] Knowing the apodization of the projection system PS for a lithographic apparatus LA enables proximity variations to be better understood. Thus, to quantify the proximity variation
5 from one lithographic apparatus LA to another, a measurement method is needed for measuring the apodization of the projection system PS.

[00049] Within a typical illumination system IL, the beam is shaped and controlled such that at a pupil plane the beam has a desired spatial intensity distribution, also referred to as an illumination mode. Examples of types of illumination modes are conventional, dipole,
10 asymmetric, quadrupole, hexapole and annular illumination modes. This spatial intensity distribution at the pupil plane effectively acts as a secondary radiation source for producing the illumination beam. Following the pupil plane, the radiation is typically focused by an optical element (e.g., a lens) group referred to hereafter as “coupling optics”. The coupling optics couples the focused radiation into an integrator, such as a quartz rod. In other examples, fly-
15 eyes optics in combination with condenser lenses may be used for the integration function. In this situation, the condenser lens after the fly-eyes creates the angular intensity distribution at the object. The function of the integrator is to improve the homogeneity of the spatial and/or angular intensity distribution of the illumination beam.

[00050] The spatial intensity distribution at the pupil plane is converted to an angular intensity
20 distribution at the object being illuminated by the coupling optics, because the pupil plane substantially coincides with the front focal plane of the coupling optics. Controlling the spatial intensity distribution at the pupil plane can be done to improve the processing latitudes when an image of the illuminated object is projected onto a substrate. In particular, spatial intensity distributions with dipolar, annular or quadrupole off-axis illumination modes have been
25 proposed to enhance the resolution and/or other parameters of the projection, such as sensitivity to projection lens aberrations, exposure latitude and depth of focus. It will be appreciated that these examples of illumination modes are not limiting and there may be many other types of illumination modes in use.

[00051] The radiation beam B may be shaped and controlled at the pupil plane such that a
30 pupil spot is formed at a desired pupil coordinate (σ_x and σ_y coordinate). This pupil spot is then transmitted through the illuminator IL until it is focused in an object plane where the patterning device MA is located.

[00052] Figure 2 shows part of the lithographic apparatus LA after (i.e., downstream of) the illuminator IL. In particular, Figure 2 shows a plate, which in this exemplary case is a reticle

10 (i.e., a patterning device MA) which is illuminated with radiation that has passed through the illuminator IL. The reticle 10 is positioned in the object plane of the illuminator IL.

[00053] The reticle 10 has a pinhole 12 that allows radiation from the illuminator IL to pass through the reticle 10 to the projection system PS. Located with the pinhole 12 is an optical
5 element, in this exemplary case a convex lens 14 (a positive lens), located downstream of the pinhole 12 before the projection system PS. The convex lens 14 is placed at a distance from the pinhole 12, which equals the focal length of the convex lens 14. Although only one pinhole 12 and one convex lens 14 is shown, in other examples, there may be a plurality of pinholes 12 and convex lenses 14 located at several positions along the reticle 10, e.g., at different x- and
10 or y-coordinates. The plurality on pinholes 12 allows the apodization to be measured on several locations in the field. Each pinhole 12 may have a corresponding convex lens 14.

[00054] A radiation beam 16 has passed through the illuminator IL from a first pupil spot formed at a desired pupil coordinate (σ_x and σ_y coordinate) at the pupil plane. The spot-size of the pupil spot should be less than the desired resolution of the apodization measurement. There
15 should be a single pupil spot for each measurement. The radiation beam 16 from the first pupil spot passes through the pinhole 12 and the convex lens 14. Since the convex lens 14 is at a distance from the pinhole 12 equal to the focal length of the convex lens 14, the convex lens 14 refracts the radiation beam 16 such that the radiation beam 16 is on or propagates along an optical axis, which corresponds with the centre of a pupil plane in the convex lens 14, i.e., σ_x
20 $= \sigma_y = 0$.

[00055] The radiation beam 16 continues through the projection system PS until it is incident on a detector, which in this example is the sensor S, which can measure the transmission of the total optical system (i.e., the illuminator IL and the projection system PS). In this example, the sensor S is located at substrate level, i.e., at the z-position of the substrate W. In this example,
25 the sensor S is a spot sensor. The spot sensor measures the total radiation intensity falling on it, regardless of the particular angle at which it is incident on the sensor, i.e., the spot sensor measures radiation intensity for all angles. The spot sensor can make the apodization measurement. This is because all the radiation beam rays reaching substrate W level have $\sigma_x = \sigma_y = 0$. That is, since the convex lens 14, in combination with the pinhole 12, means that the
30 radiation beam 16 is along an optical axis which corresponds with the centre of a pupil plane in the convex lens 14, the spot sensor being unable to determine the intensity at a particular angle is not an issue. Thus, the spot sensor may be used to determine the apodization profile.

[00056] In other examples, the sensor S may be an interferometer sensor, such as the interferometer described above in relation to Figure 1. The pixels in the interferometer sensor

each detect a small part of the radiation with a well-defined incidence angle. The energy for each pixel can be summed to get full intensity. The interferometer sensor can measure the intensity for each pupil coordinate σ_x , σ_y and therefore can provide the apodization measurement. In other examples, the detector may be a spot sensor and an interferometer sensor. The advantage of the spot sensor is that the transmission of the optical system can be measured very accurately (up to ~0.05%).

[00057] The pupil spot is moved to different pupil coordinates to produce a second radiation beam 20 coming from a different angle towards the pinhole 12. This second radiation beam 20 corresponds to a second pupil spot formed at a desired pupil coordinate (σ_x and σ_y coordinate) at the pupil plane. This second radiation beam 20 travels through the pinhole 12 and is also refracted by the convex lens 14 such that it is on or propagates along the optical axis, which corresponds with the centre of a pupil plane in the convex lens 14.

[00058] Although only two radiation beams are shown in Figure 2, there may be several radiation beams from several different pupil spots. In general, the pupil spots are moved to different pupil coordinates and measurements are repeated to obtain a transmission profile of the total optical system.

[00059] The pupil spot may be moved to the necessary number of pupil coordinates such that the transmission profile of the total optical system is measured over the full numerical aperture NA of the lithographic apparatus LA while correcting for inaccuracy introduced by a drifting source intensity or a drifting optical system (optical column) transmission. In practice, this is done by repeating the measurement at $\sigma_x = \sigma_y = 0$ in between each pupil coordinate measurement.

[00060] Each of the radiation beams 16, 20 from the pupil spots are refracted to be on or along an optical axis, which corresponds with the centre of a pupil plane in the convex lens 14. Thus, in the transmission measurement of the total optical system, as a function of the σ -coordinate, the projection system PS contribution remains constant. This means that the measured transmission profile of the optical system produces the apodization profile of the illuminator T_{ILL} . In other words, there is no contribution to the apodization measurement from the projection system PS in this situation and so the apodization of the illuminator IL equals the total apodization of the optical system – see Equation 1 above.

[00061] The convex lens 14 also gives a certain contribution to the measured transmission profile. However, this can be corrected with a known profile either based on the optical design or based on a calibrated profile.

[00062] As mentioned previously, the total apodization of the optical system T_{total} of the lithographic apparatus LA with a standard patterning device MA in position may be measured which gives apodization contributions from both the illuminator IL and the projection system PS. In this case, a measurement of the total apodization of the optical system T_{total} can be obtained. Using this T_{total} measurement and the measurement of T_{ILL} , the apodization of the projection system PS (T_{PL}) may be calculated using Equation 2:

$$T_{\text{PL}}(\sigma_x, \sigma_y) = T_{\text{total}}(\sigma_x, \sigma_y) / T_{\text{ILL}}(\sigma_x, \sigma_y).$$

[00063] More generally, the total apodization profile of the illumination system IL and the projection system PS may be measured. Then the apodization profile of the illumination system IL is subtracted from the total apodization profile of the optical system to obtain the apodization profile of the projection system PS.

[00064] Following the procedure outlined above, the apodization profile of the illuminator IL and the apodization profile of the projection system PS can be isolated from each other and individually known. These apodization profiles may then be used to provide information on proximity issue e.g., in high volume production.

[00065] The apodization profile of the illuminator IL may be used to make the illuminator IL correct for the apodization profile of the illuminator IL only, i.e., the illuminator IL would not be correcting for total apodization, only for illuminator IL apodization.

[00066] Figure 3 shows a similar apparatus to that shown in Figure 2 except the convex lens 14 has been replaced with a concave lens 22 (a negative lens) upstream of the reticle 24, which has a wider pinhole 26 than the reticle 10 of Figure 2. The pinhole 26 is wider in the reticle 24 to allow the radiation from the concave lens 22 to pass through the reticle 24. The projection system PS and the sensor S are the same as shown in Figure 2.

[00067] Radiation beams 16, 20 from the illuminator IL are incident on the concave lens 22. After passing through the concave lens 22 and the pinhole 26, the radiation beams 16, 20 continue through the projection system PS until they are incident on the sensor S which can measure the transmission of the total optical system (i.e., the illuminator IL and the projection system PS).

[00068] The radiation beams 16, 20 in Figure 3 follow a different path from those in Figure 2 but are also refracted by the concave lens 22 such that they are on the optical axis which corresponds with the centre of a pupil plane in the concave lens 22, i.e., $\sigma_x = \sigma_y = 0$. This is because the concave lens 22 is at a distance from the pinhole 26 equal to the focal length of the concave lens 22.

[00069] Therefore, in the transmission measurement of the total optical system, as a function of the σ -coordinate, the projection system PS contribution remains constant. This means that the measured transmission profile of the optical system produces the apodization profile of the illuminator T_{ILL} . Thus, the apodization profile of the illuminator T_{ILL} may be obtained from the apparatus of Figure 3 in a similar way to the apparatus of Figure 2.

[00070] Figure 4 shows another example apparatus for measuring the transmission of the illuminator IL versus the σ -coordinate to produce the apodization profile of the illuminator (T_{ILL}). The apparatus shown in Figure 4 is similar to Figure 2 except that the projection system PS has been replaced with a sensing part 28 of a reticle-stage-sensor (RSS) 30. The sensing part 28 of the RSS 30 is analogous to the sensor S of Figure 2, which may be a spot sensor.

[00071] The RSS 30 is located in the object plane of the illuminator IL and includes a RSS plate 32 with a pinhole 34, which is analogous to the reticle 10 with a pinhole 12 of Figure 2. More generally, the RSS plate 32 and the sensing part 28 of the RSS 30 are part of or comprised in a reticle-stage-sensor 30 located at reticle level.

[00072] In a similar way to as shown in Figure 2, the RSS 30 of Figure 4 includes a convex lens 36, which is located between the RSS plate 32 and the sensing part 28 of the RSS 30. The convex lens 36 is at a distance from the pinhole 34 equal to the focal length of the convex lens 36.

[00073] Radiation beams 16, 20 from the illuminator IL are incident on the RSS plate 32. After passing through the pinhole 34 and the convex lens 36, the radiation beams 16, 20 are incident on the sensing part 28 of the RSS 30, which can measure the transmission of the illuminator IL.

[00074] The radiation beams 16, 20 in Figure 4 follow a similar path to those in Figure 2 (except not through the projection system PS) and are also refracted by the convex lens 36, such that they are on the optical axis which corresponds with the centre of a pupil plane in the convex lens 36, i.e., $\sigma_x = \sigma_y = 0$. This is because the convex lens 36 is at a distance from the pinhole 34 equal to the focal length of the convex lens 36.

[00075] This means that the radiation beams 16, 20 have $\sigma_x = \sigma_y = 0$ before the radiation beams 16, 20 reach the sensing part 28 of the RSS 30. This has the advantage that the contribution of the RSS 30 to the measured transmission profile versus σ -coordinate is reduced.

[00076] The apparatus of Figure 4 allows the apodization profile of the illuminator (T_{ILL}) to be obtained directly from the measurement of the transmission by the RSS 30. The RSS 30 gives a certain contribution to the measured transmission profile. However, this can be

corrected with a known profile either based on the optical design or based on a calibrated profile.

[00077] Figure 5 shows a reticle-stage-sensor (RSS) 38 similar to the RSS 30 of Figure 4 except the convex lens 36 has been replaced by a concave lens 40 upstream of a RSS plate 42 of the RSS 38. The RSS 38 functions in a similar way to the RSS 30 of Figure 4 except with the modifications required to move from the convex lens 36 after the RSS plate 32 of the RSS 30 to the concave lens 40 before the plate 42 of the RSS 38. For example, the pinhole 44 of the RSS plate 42 has been sized accordingly.

[00078] The radiation beams 16, 20 in Figure 5 follow a similar path to those in Figure 3 (except not through the projection system PS) and are also refracted by the concave lens 40 such that they are on the optical axis, which corresponds with the centre of a pupil plane in the concave lens 40, i.e., $\sigma_x = \sigma_y = 0$. This is because the concave lens 40 is at a distance from the pinhole 44 equal to the focal length of the concave lens 40.

[00079] The apparatus of Figure 5 allows the apodization profile of the illuminator (T_{ILL}) to be produced directly from the measurement of the transmission by the RSS 38 in a similar way to as described with reference to Figure 4.

[00080] In other examples, the RSS 30 of Figure 4 and 5 may comprise an interferometer sensor at the reticle level, which may measure the apodization profile of the illuminator IL. The optical elements and pinholes in the RSS plate 32, 42 may not be required when using the interferometer sensor in this set up. However, the interferometer sensor may still provide the apodization measurement of the illuminator with the optical elements and pinholes in the RSS plate 32, 42.

[00081] As mentioned with reference to Figure 2, although only two radiation beams 16, 20 are shown in Figures 3 to 5, there may be several radiation beams from several different pupil spots travelling through the optical systems. In general, the pupil spots are moved to different pupil coordinates and measurements are repeated to obtain the transmission profiles from the detectors. This allows the apodization profile for the illuminator IL to be obtained. In addition, the pupil spot may be moved to the necessary number of pupil coordinates, such that the transmission profile of the total optical system is measured over the full numerical aperture NA of the lithographic apparatus LA in Figures 3 to 5.

[00082] In other examples, the plates 24, 32, 42 in Figures 3 to 5 may have a plurality of pinholes 26, 34, 44 and there may be a plurality of optical elements 22, 36, 40.

[00083] Although the plates 10, 24, 32, 42 shown in Figures 2 to 5 are patterning devices MA for absorbing radiation (such as DUV radiation), in other examples, the plates may be reflective

(e.g., for use with EUV radiation). In this case, all the optical elements 14, 22, 36, 40 would need to be made of reflective optics, such as mirrors that refract radiation onto the optical axis. Hence, a convex mirror may be arranged upstream the pinhole or a concave mirror may be arranged downstream the pinhole.

5 [00084] Although specific reference may be made in this text to the use of a lithographic apparatus in the manufacture of ICs, it should be understood that the lithographic apparatus described herein may have other applications. Possible other applications include the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, flat-panel displays, liquid-crystal displays (LCDs), thin-film magnetic
10 heads, etc.

[00085] Although specific reference may be made in this text to embodiments of the invention in the context of a lithographic apparatus, embodiments of the invention may be used in other apparatus. Embodiments of the invention may form part of a mask inspection apparatus, a metrology apparatus, or any apparatus that measures or processes an object such
15 as a wafer (or other substrate) or mask (or other patterning device). These apparatus may be generally referred to as lithographic tools. Such a lithographic tool may use vacuum conditions or ambient (non-vacuum) conditions.

[00086] Although specific reference may have been made above to the use of embodiments of the invention in the context of optical lithography, it will be appreciated that the invention,
20 where the context allows, is not limited to optical lithography and may be used in other applications, for example imprint lithography.

[00087] Where the context allows, embodiments of the invention may be implemented in hardware, firmware, software, or any combination thereof. Embodiments of the invention may also be implemented as instructions stored on a machine-readable medium, which may be read
25 and executed by one or more processors. A machine-readable medium may include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computing device). For example, a machine-readable medium may include read only memory (ROM); random access memory (RAM); magnetic storage media; optical storage media; flash memory devices; electrical, optical, acoustical or other forms of propagated signals (e.g. carrier
30 waves, infrared signals, digital signals, etc.), and others. Further, firmware, software, routines, instructions may be described herein as performing certain actions. However, it should be appreciated that such descriptions are merely for convenience and that such actions in fact result from computing devices, processors, controllers, or other devices executing the

firmware, software, routines, instructions, etc. and in doing that may cause actuators or other devices to interact with the physical world.

[00088] While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The descriptions
5 above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the art that modifications may be made to the invention as described without departing from the scope of the claims set out below.

CLAIMS:

1. A method of making an apodization measurement for an apparatus having an illumination system and a projection system, the method comprising:
 - 5 forming a pupil spot in the pupil plane of the illumination system at a pupil coordinate;
focussing a radiation beam at a plate comprising at least one pinhole, the plate arranged at an object plane of the illumination system;
using at least one optical element at a distance from the at least one pinhole equalling the focal length of the at least one optical element which interacts with the radiation beam such
10 that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the at least one optical element;
measuring the transmission of the illumination system and the projection system using a detector; and
moving the pupil spot to a plurality of different pupil coordinates and repeating the
15 measurement to obtain an apodization profile of the illumination system.
2. The method of claim 1, wherein the at least one optical element is at least one of
a convex lens downstream of the at least one pinhole,
a concave lens upstream of the at least one pinhole,
20 a concave mirror downstream of the at least one pinhole, and
a convex mirror upstream of the at least one pinhole.
3. The method of claim 1 or 2, wherein the plate is a patterning device.
- 25 4. The method of any preceding claim, wherein the detector is at least one of
a spot sensor arranged at a patterning device level and
an interferometer sensor arranged at a substrate level.
5. The method of claim 4, further comprising the steps of
30 measuring the total apodization profile of the illumination system and the projection system, and
subtracting the apodization profile of the illumination system from the total apodization profile to obtain the apodization profile of the projection system.

6. A method of making an apodization measurement for an apparatus having an illumination system, the method comprising:

forming a pupil spot in the pupil plane of the illumination system at a pupil coordinate;

5 focussing a radiation beam at a plate comprising at least one pinhole, the plate arranged at the object plane of the illumination system;

using an optical element at a distance from the at least one pinhole equalling the focal length of the at least one optical element which interacts with the radiation beam such that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the at least one optical element;

10 measuring the transmission of the illumination system using a detector; and

moving the pupil spot to a plurality of different pupil coordinates and repeating the measurement to obtain an apodization profile of the illumination system.

7. The method of claim 6, further comprising moving the pupil spot to the plurality of
15 different pupil coordinates such that the apodization profile is measured over the full numerical aperture of the apparatus.

8. The method of claims 6 or 7, wherein the at least one optical element is at least one of
20 a convex lens downstream of the at least one pinhole,
a concave lens upstream of the at least one pinhole,
a concave mirror downstream of the at least one pinhole, and
a convex mirror upstream of the at least one pinhole.

9. An apparatus comprising:
25 an illumination system which is configured to condition a radiation beam to have a desired spatial intensity distribution at a pupil plane of the illumination system;
a projection system configured to project a patterned radiation beam onto a substrate:
a plate having at least one pinhole located at the object plane of the illumination system;
at least one optical element located at a distance from the at least one pinhole equalling
30 the focal length of the at least one optical element which interacts with the radiation beam such that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the at least one optical element; and
a detector configured to measure the transmission of the illumination system and the projection system;

wherein the illumination system is configured to form a pupil spot in the pupil plane of the illumination system at a pupil coordinate;

and wherein the illumination system is configured to move the pupil spot to a plurality of different pupil coordinates and to repeat the measurement to obtain an apodization profile of the illumination system.

10. The apparatus of claim 9, wherein the at least one optical element is at least one of a convex lens downstream of the at least one pinhole, a concave lens upstream of the at least one pinhole, a concave mirror downstream of the at least one pinhole, and a convex mirror upstream of the at least one pinhole.

11. The apparatus of claims 9 or 10, wherein the plate is a patterning device.

12. The apparatus of any of claims 9 to 11, wherein the detector is at least one of a spot sensor and an interferometer sensor located at a substrate level.

13. A apparatus comprising:

an illumination system which is configured to condition a radiation beam to have a desired spatial intensity distribution at a pupil plane of the illumination system and to focus the radiation beam in an object plane arranged to locate a patterning device;

a projection system configured to project a patterned radiation beam onto a substrate;

a plate having at least one pinhole located at the object plane of the illumination system;

at least one optical element located at a distance from the at least one pinhole equalling the focal length of the at least one optical element which interacts with the radiation beam such that the radiation beam is on an optical axis which corresponds with the centre of a pupil plane in the at least one optical element; and

a detector configured to measure the transmission of the illumination system;

wherein the illumination system is configured to form a pupil spot in the pupil plane of the illumination system at a pupil coordinate;

and wherein the illumination system is configured to move the pupil spot to a plurality of different pupil coordinates and to repeat the measurement to obtain an apodization profile of the illumination system.

14. The apparatus of claim 13, wherein the at least one optical element is at least one of
a convex lens downstream of the at least one pinhole,
a concave lens upstream of the at least one pinhole,
a concave mirror downstream of the at least one pinhole, and
5 a convex mirror upstream of the at least one pinhole.
15. The apparatus of claim 13 or 14, wherein the plate and the detector are part of or
comprised in a sensor located at a patterning device level.

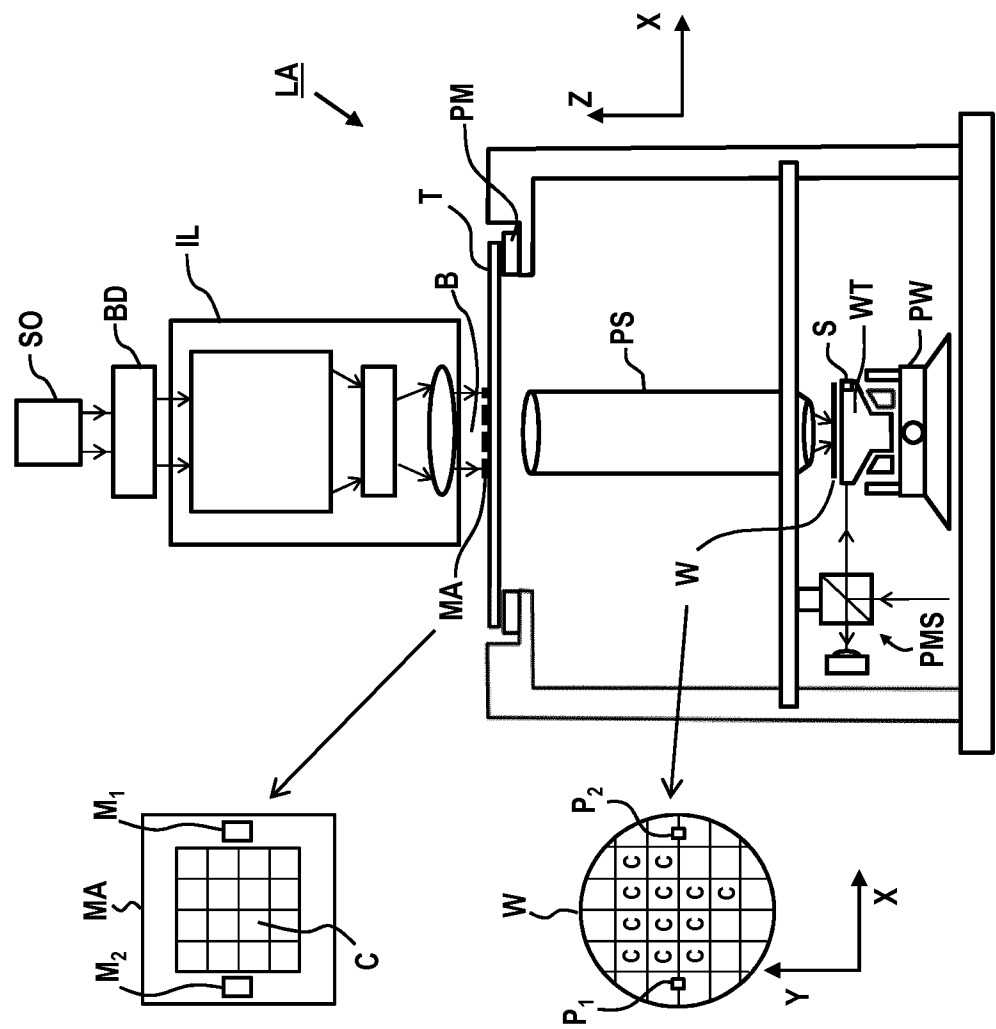


FIG. 1

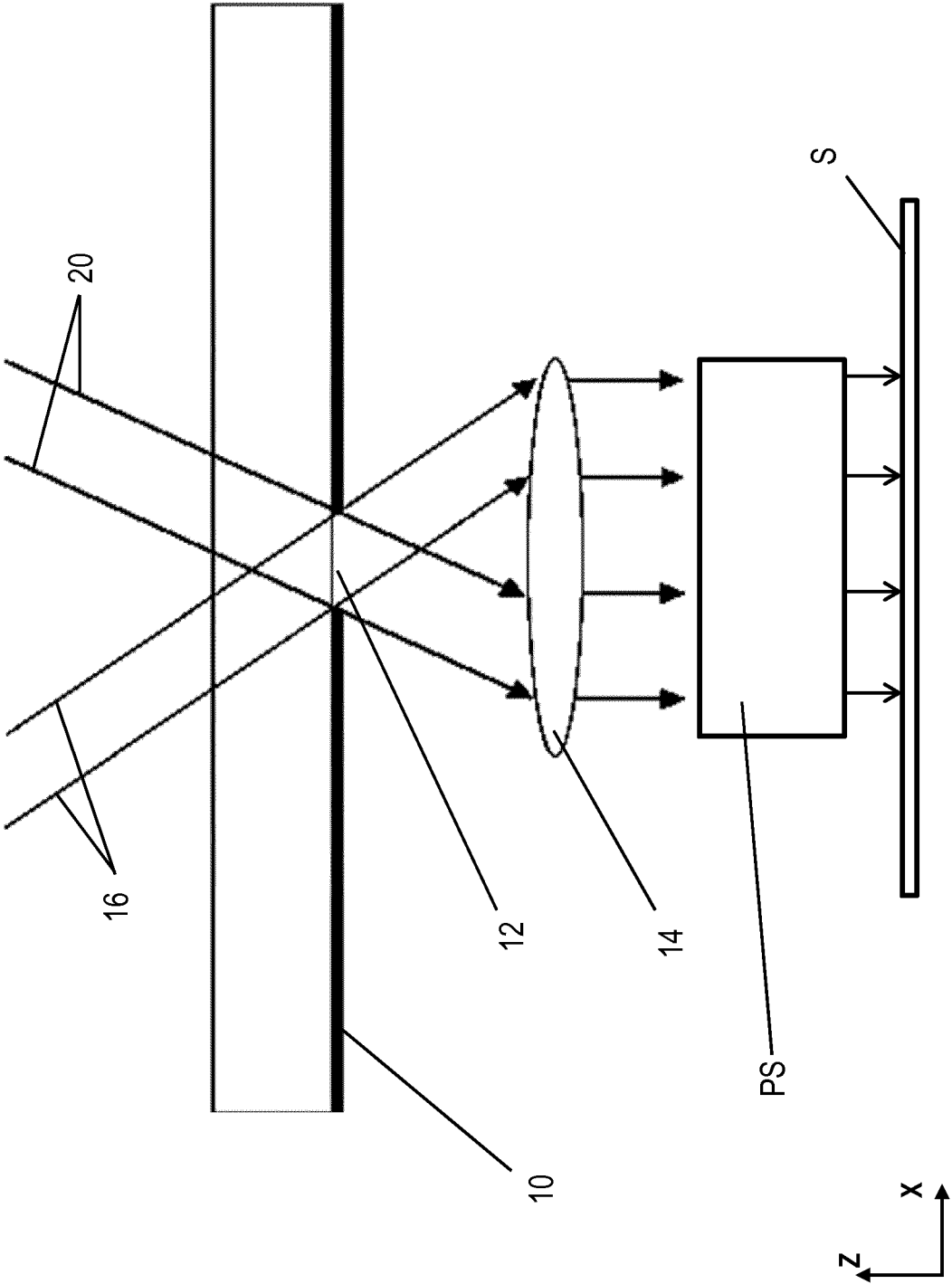


FIG. 2

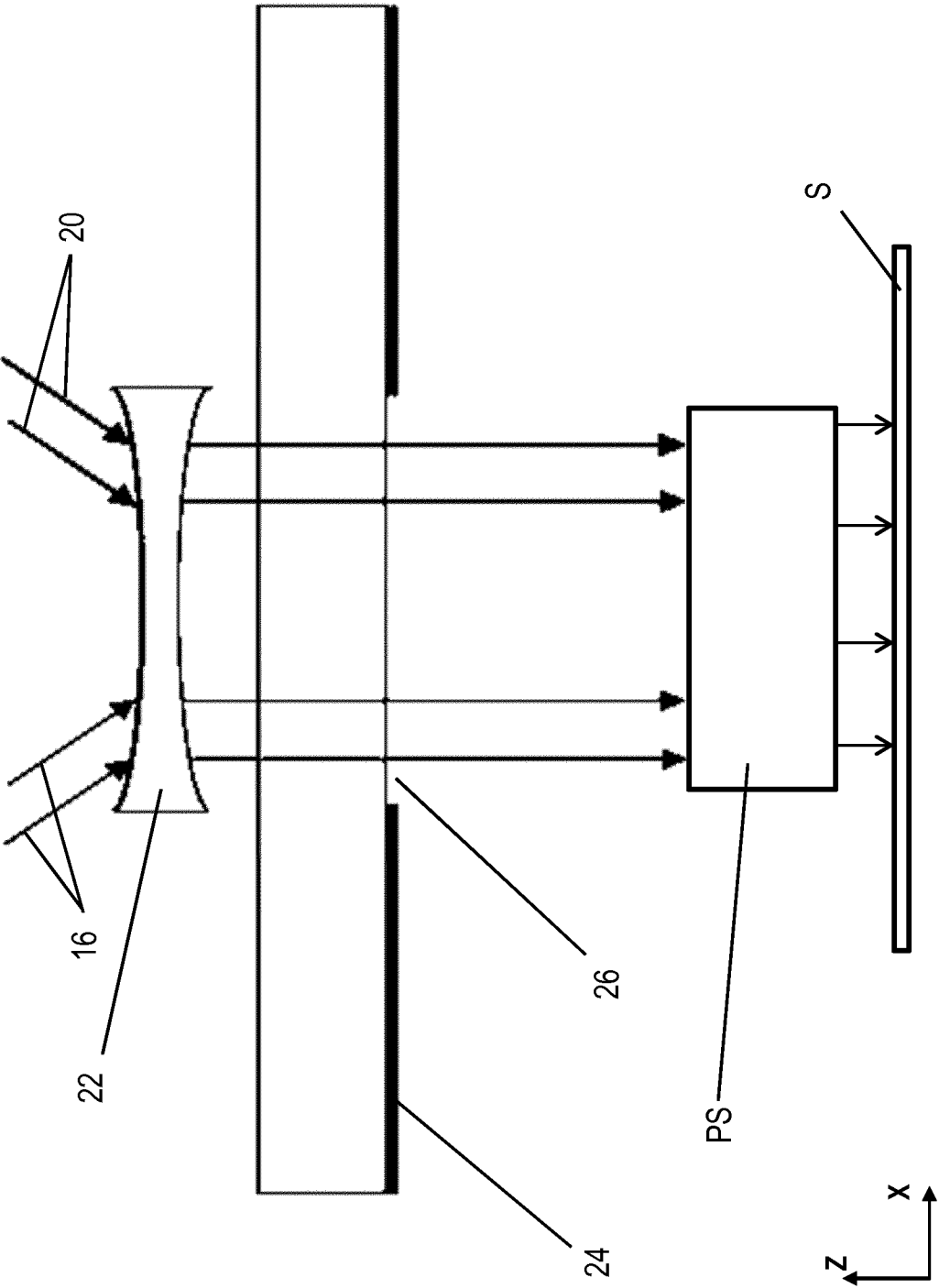


FIG. 3

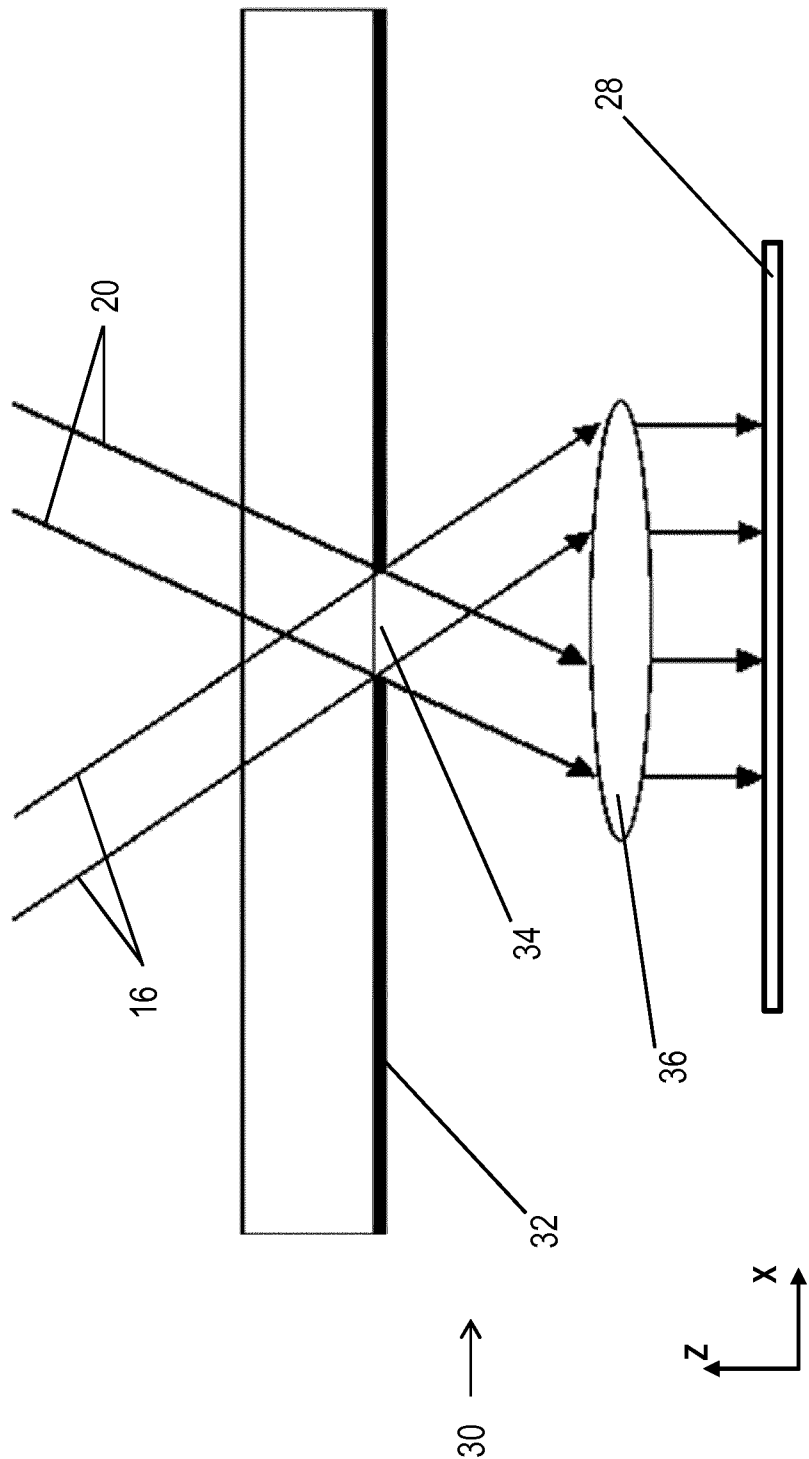


FIG. 4

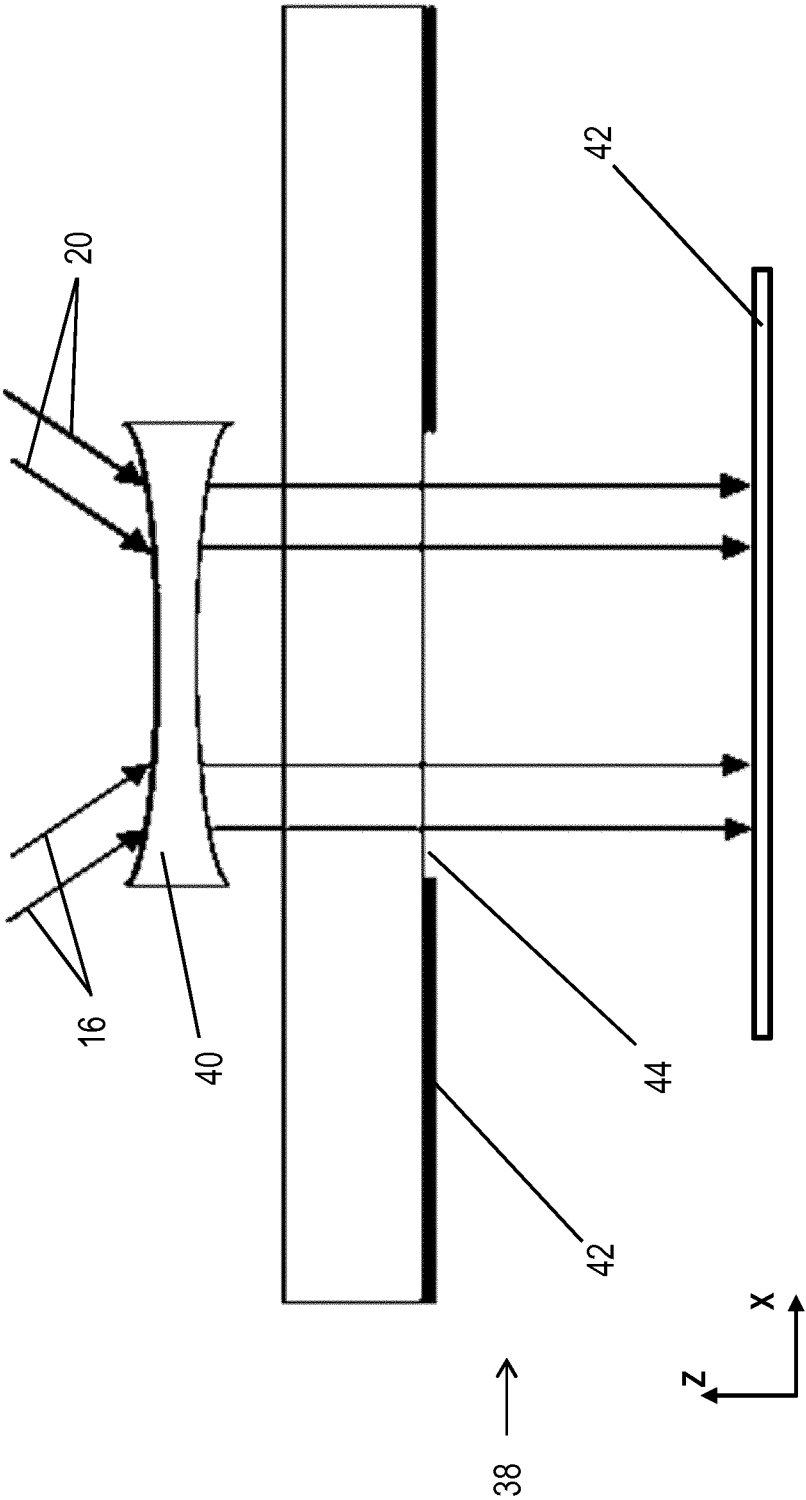


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/052592

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20
ADD.

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 practicable, 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.
X	US 2002/027648 A1 (VAN DER LAAN HANS [NL] ET AL) 7 March 2002 (2002-03-07) paragraphs [0085] - [0094], [0105], [0122], [0139]; figures 1, 10 -----	1-15
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A	US 2006/238736 A1 (MIYAHARU TAKAFUMI [JP] ET AL) 26 October 2006 (2006-10-26) paragraphs [0023] - [0027]; figures 1, 2 -----	1-15



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

2 May 2019

Date of mailing of the international search report

13/05/2019

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2019/052592

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