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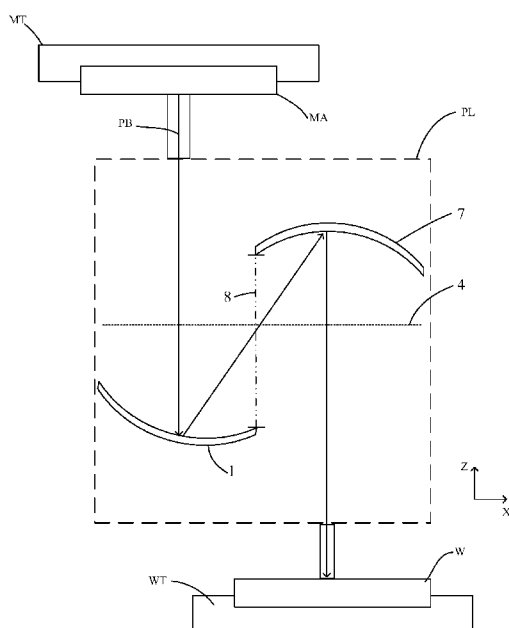


Fig. 4

(57) Abstract: A device manufacturing method comprising providing a lithographic apparatus configured to project a radiation beam patterned by a reticle onto a target portion of a substrate; determining a lithographic error; determining a correction profile configured to reduce the lithographic error; and, applying the correction profile to the patterned radiation beam by actuating a deformable reflector configured to reflect the patterned radiation beam, the deformable reflector being.

Lithographic Apparatus and Method

CROSS-REFERENCE TO RELATED APPLICATIONS

5 [0001] This application claims priority of EP application 17151719.6 which was filed on 17 January 2017 and which is incorporated herein in its entirety by reference.

FIELD

10 [0002] The present invention relates to a lithographic apparatus and a device manufacturing method.

BACKGROUND

[0003] A lithographic apparatus is a machine that applies a desired pattern onto a target portion of a substrate. Lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In that circumstance, a patterning device, which is alternatively referred to as a mask or a reticle, may be used to generate a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto a target portion (e.g. comprising part of, one or several dies) on a substrate (e.g. a silicon wafer) that has a layer of radiation-sensitive material (resist). In general, a single substrate will contain a network of adjacent target portions that are successively exposed. Known lithographic apparatus include so-called steppers, in which each target portion is irradiated by exposing an entire pattern onto the target portion in one go, and so-called scanners, in which each target portion is irradiated by scanning the pattern through the beam in a given direction (the “scanning”-direction) while synchronously scanning the substrate parallel or anti parallel to this direction.

25 [0004] Throughout a device manufacturing process, lithographic errors such as, for example, overlay errors and/or focus errors may arise from a number of different sources. Known lithographic apparatus may be limited in their ability to correct for such lithographic errors. It is desirable to provide, for example, a device manufacturing method that obviates or mitigates one or more of the problems of the prior art, whether identified herein or elsewhere.

SUMMARY

[0005] According to a first aspect of the invention, there is provided a device manufacturing method, the method comprising providing a lithographic apparatus configured to project a radiation beam patterned by a reticle onto a target portion of a substrate, determining a lithographic error, determining a correction profile configured to reduce the lithographic error; and, applying the correction profile to the patterned radiation beam by actuating a deformable reflector configured to reflect the patterned radiation beam, the deformable reflector being located proximate a field plane.

[0006] The shape of a wavefront of radiation reflecting from the deformable reflector may be adjusted via deformation of the deformable reflector. The wavefront may be adjusted such that a lithographic error, such as an overlay error, is reduced. The deformable reflector is advantageously capable of reducing lithographic errors that originate from a wide range of different sources. The deformable reflector is advantageously capable of reducing lithographic errors across a field plane of a lithographic apparatus.

[0007] Actuation of the deformable reflector may occur during projection of the patterned radiation beam. Actuating the deformable reflector during projection of the patterned radiation beam advantageously allows a lithographic error present within a single target portion of the substrate and/or a lithographic error present between different target portions of the substrate to be reduced whilst a pattern is being projected onto the substrate.

[0008] Applying the correction profile may additionally include actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a second field plane. Actuating a second deformable reflector advantageously allows focus errors to be reduced.

[0009] The correction profile may compensate for at least up to 4th order field plane variation of an overlay error in an x-direction of the field plane.

[0010] The correction profile may compensate for at least up to 3rd order field plane variation of an overlay error in a y-direction of the field plane.

[0011] The correction profile may compensate for at least up to 2nd order field plane variations of Zernike Z [3, 1] and/or Zernike Z [3, 3] and/or Zernike Z [3, -3].

[0012] The correction profile may compensate for at least up to 1st order field plane variations of Zernike Z [3, -1].

[0013] The correction profile may compensate for an overlay error that has greater than 3rd order field plane variation.

[0014] The correction profile may compensate for different imaging characteristics arising from different illumination settings of the lithographic apparatus.

5 [0015] The correction profile may compensate for a difference between projection characteristics of different lithographic apparatus.

[0016] The correction profile may compensate for a lithographic error caused by substrate processing effects.

10 [0017] The lithographic apparatus may comprise a support structure configured to support the reticle, and the correction profile may compensate for a lithographic error caused by a deformation of the reticle resulting from the support structure supporting the reticle.

[0018] The correction profile may compensate for a lithographic error caused by a change in temperature of the reticle.

15 [0019] The lithographic apparatus may comprise a substrate table configured to hold the substrate and the correction profile may compensate for a lithographic error caused by a deformation of the substrate resulting from the substrate table holding the substrate.

[0020] The correction profile may compensate for a lithographic error caused by a change in temperature of the substrate.

20 [0021] The lithographic apparatus may comprise a pellicle configured to protect the reticle and the correction profile may compensate for a lithographic error caused by a deformation of the pellicle resulting from movement of the reticle.

[0022] The correction profile may compensate for overlay errors that occur within about 20 mm of an edge of the substrate.

25 [0023] Actuation of the deformable reflector may occur during projection of the patterned radiation beam, and applying the correction profile may additionally include actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a third field plane, and the correction profile may compensate for at least up to 2nd order field plane variations of Zernike Z [2, 0].

30 [0024] Actuation of the deformable reflector may occur during projection of the patterned radiation beam, and applying the correction profile may additionally include actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector, the

second deformable reflector being located proximate a fourth field plane, and the correction profile may compensate for a topography of the reticle.

[0025] Actuation of the deformable reflector may occur during projection of the patterned radiation beam, and applying the correction profile may additionally include actuating a second
5 deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a fifth field plane, and the correction profile may compensate for a topography of the substrate.

[0026] Actuation of the deformable reflector may occur during projection of the patterned radiation beam, and applying the correction profile may additionally include actuating a second
10 deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a sixth field plane, and the correction profile may compensate for substrate edge roll-off effects.

[0027] Actuation of the deformable reflector may occur during projection of the patterned radiation beam, and applying the correction profile may additionally include actuating a second
15 deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a seventh field plane, and the correction profile may compensate for focus errors associated with greater than 2nd order field plane variations of a Zernike.

[0028] The radiation beam may be an extreme ultraviolet radiation beam.

[0029] Each of the first to seventh field planes may be the same field plane. One or more of
20 the first to seventh field planes may be different field planes.

[0030] According to a second aspect of the invention, there is provided a device manufactured according to the first aspect of the invention or any of its associated options.

[0031] According to a third aspect of the invention, there is provided a lithographic apparatus
25 comprising an illumination system for providing a beam of radiation, a support structure for supporting patterning device, the patterning device serving to impart the radiation beam with a pattern in its cross-section, a substrate table for holding a substrate, a projection system for projecting the patterned radiation beam onto a target portion of the substrate, a deformable reflector configured to reflect the patterned radiation beam, the deformable reflector being located
30 proximate a field plane, and a controller configured to perform the method of the first aspect of the invention or any of its options.

[0032] According to a fourth aspect of the invention, there is provided a device manufacturing method, the method comprising providing a lithographic apparatus configured to project an extreme ultraviolet radiation beam patterned by a reticle onto a target portion of a substrate, determining a lithographic error, determining a correction profile configured to reduce the lithographic error, and applying the correction profile to the patterned extreme ultraviolet radiation beam by actuating a deformable reflector configured to reflect the patterned extreme ultraviolet radiation beam.

[0033] The deformable reflector need not be located in a pupil plane of the lithographic apparatus. The deformable reflector may be located in a location other than a pupil plane of the lithographic apparatus. The deformable reflector may be located in a location other than proximate a field plane of the lithographic apparatus.

[0034] Actuation of the deformable reflector may occur during projection of the patterned extreme ultraviolet radiation beam.

[0035] Applying the correction profile may additionally include actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector.

[0036] The correction profile may compensate for up to 3rd order field plane variations of a Zernike.

[0037] According to a fifth aspect of the invention, there is provided a device manufactured according to the fourth aspect of the invention or any of its associated options.

[0038] According to a sixth aspect of the invention, there is provided a lithographic apparatus comprising an illumination system for providing a beam of extreme ultraviolet radiation, a support structure for supporting patterning device, the patterning device serving to impart the extreme ultraviolet radiation beam with a pattern in its cross-section, a substrate table for holding a substrate, a projection system for projecting the patterned extreme ultraviolet radiation beam onto a target portion of the substrate, a deformable reflector configured to reflect the patterned extreme ultraviolet radiation beam, and a controller configured to perform the method of the fourth aspect of the invention or any of its associated options.

BRIEF DESCRIPTION OF THE DRAWINGS

[0039] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which corresponding reference symbols indicate corresponding parts, and in which:

- 5 - Figure 1 schematically depicts a lithographic apparatus comprising a deformable reflector according to an embodiment of the invention;
- Figure 2 schematically depicts a deformable reflector according to an embodiment of the invention;
- Figure 3 schematically depicts a portion of a lithographic apparatus comprising a
10 deformable reflector according to an embodiment of the invention;
- Figure 4 schematically depicts a portion of a lithographic apparatus comprising two deformable reflectors according to an embodiment of the invention;
- Figure 5 schematically depicts the effect of pellicle deformation on radiation passing through the pellicle; and,
- 15 - Figure 6 shows a process according to an embodiment of the invention.

DETAILED DESCRIPTION

[0040] Although specific reference may be made in this text to the use of lithographic apparatus in the manufacture of ICs, it should be understood that the lithographic apparatus
20 described herein may have other applications, such as the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid-crystal displays (LCDs), thin film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms “wafer” or “die” herein may be considered as synonymous with the more general terms “substrate” or “target portion”, respectively. The
25 substrate referred to herein may be processed, before or after exposure, in for example a track (a tool that typically applies a layer of resist to a substrate and develops the exposed resist) or a metrology or inspection tool. Where applicable, the disclosure herein may be applied to such and other substrate processing tools. Further, the substrate may be processed more than once, for example in order to create a multi-layer IC, so that the term substrate used herein may also refer
30 to a substrate that already contains multiple processed layers.

[0041] The terms “radiation” and “beam” used herein encompass all types of electromagnetic radiation, including ultraviolet (UV) radiation (e.g. having a wavelength of 365, 248, 193, 157 or 126 nm) and extreme ultra-violet (EUV) radiation (e.g. having a wavelength in the range of 5-20 nm), as well as particle beams, such as ion beams or electron beams.

5 [0042] The term “patterning device” used herein should be broadly interpreted as referring to a device that can be used to impart a radiation beam with a pattern in its cross-section such as to create a pattern in a target portion of the substrate. It should be noted that the pattern imparted to the radiation beam may not exactly correspond to the desired pattern in the target portion of the substrate. Generally, the pattern imparted to the radiation beam will correspond to a particular
10 functional layer in a device being created in the target portion, such as an integrated circuit.

[0043] A patterning device may be transmissive or reflective. Examples of patterning device include masks, programmable mirror arrays, and programmable LCD panels. Masks are well known in lithography, and include mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types. An example of a programmable
15 mirror array employs a matrix arrangement of small mirrors, each of which can be individually tilted so as to reflect an incoming radiation beam in different directions; in this manner, the reflected beam is patterned.

[0044] The support structure holds the patterning device. It holds the patterning device in a way depending on the orientation of the patterning device, the design of the lithographic apparatus,
20 and other conditions, such as for example whether or not the patterning device is held in a vacuum environment. The support can use mechanical clamping, vacuum, or other clamping techniques, for example electrostatic clamping under vacuum conditions. The support structure may be a frame or a table, for example, which may be fixed or movable as required and which may ensure that the patterning device is at a desired position, for example with respect to the projection system.
25 Any use of the terms “reticle” or “mask” herein may be considered synonymous with the more general term “patterning device”.

[0045] The term “projection system” used herein should be broadly interpreted as encompassing various types of projection system, including refractive optical systems, reflective optical systems, and catadioptric optical systems, as appropriate for example for the exposure
30 radiation being used, or for other factors such as the use of an immersion fluid 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”.

[0046] The illumination system may also encompass various types of optical components, including refractive, reflective, and catadioptric optical components for directing, shaping, or
5 controlling the beam of radiation, and such components may also be referred to below, collectively or singularly, as a “lens”.

[0047] The lithographic apparatus may be of a type having two (dual stage) or more substrate tables (and/or two or more support structures). In such “multiple stage” machines the additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while
10 one or more other tables are being used for exposure.

[0048] The lithographic apparatus may also be of a type wherein the substrate is immersed in a liquid having a relatively high refractive index, e.g. water, so as to fill a space between the final element of the projection system and the substrate. Immersion techniques are well known in the art for increasing the numerical aperture of projection systems.

[0049] Figure 1 schematically depicts a lithographic apparatus according to a particular embodiment of the invention. The apparatus comprises:

- an illumination system (illuminator) IL to condition a beam PB of radiation (e.g. UV radiation);
- a support structure MT to support a patterning device (e.g. a mask) MA and connected to
20 first positioning device PM to accurately position the patterning device with respect to item PL;
- a substrate table (e.g. a wafer table) WT for holding a substrate (e.g. a resist coated wafer) W and connected to second positioning device PW for accurately positioning the substrate with respect to item PL; and
- a projection system (e.g. a refractive projection lens) PL configured to image a pattern
25 imparted to the radiation beam PB by patterning device MA onto a target portion C (e.g. comprising one or more dies) of the substrate W and including a deformable reflector for use in an embodiment of the present invention.

[0050] As here depicted, the apparatus is of a transmissive type (e.g. employing a transmissive mask). Alternatively, the apparatus may be of a reflective type (e.g. employing a programmable
30 mirror array of a type as referred to above).

[0051] The illuminator IL receives a beam of radiation from a radiation source SO. The source and the lithographic apparatus may be separate entities, for example when the source is an excimer laser. In such cases, the source is not considered to form part of the lithographic apparatus and the radiation beam is passed from the source SO to the illuminator IL with the aid of a beam delivery system BD comprising for example suitable directing mirrors and/or a beam expander. In other cases the source may be integral part of the apparatus, for example when the source is a mercury lamp. The source SO and the illuminator IL, together with the beam delivery system BD if required, may be referred to as a radiation system.

[0052] The illuminator IL may comprise adjusting means AM for adjusting the angular intensity distribution of the beam. Instructions provided to the adjusting means AM may be referred to as illumination settings. Different illumination settings may, for example, provide different modes of illumination, e.g. dipole illumination, quadrupole illumination, etc. Generally, at least the outer and/or inner radial extent (commonly referred to as -outer and -inner, respectively) of the intensity distribution in a pupil plane of the illuminator can be adjusted. In addition, the illuminator IL generally comprises various other components, such as an integrator IN and a condenser CO. The illuminator provides a conditioned beam of radiation PB, having a desired uniformity and intensity distribution in its cross section.

[0053] The radiation beam PB is incident on the patterning device (e.g. mask) MA, which is held on the support structure MT. Having traversed the patterning device MA, the beam PB passes through the lens PL, which focuses the beam onto a target portion C of the substrate W. With the aid of the second positioning device PW and position sensor IF (e.g. an interferometric device), the substrate table WT can be moved accurately, e.g. so as to position different target portions C in the path of the beam PB. Similarly, the first positioning device PM and another position sensor (which is not explicitly depicted in Figure 1) can be used to accurately position the patterning device MA with respect to the path of the beam PB, e.g. after mechanical retrieval from a mask library, or during a scan. In general, movement of the object tables MT and WT will be realized with the aid of a long-stroke module (coarse positioning) and a short-stroke module (fine positioning), which form part of the positioning device PM and PW. However, in the case of a stepper (as opposed to a scanner) the support structure MT may be connected to a short stroke actuator only, or may be fixed. Patterning device MA and substrate W may be aligned using patterning device alignment marks M1, M2 and substrate alignment marks P1, P2.

[0054] The depicted apparatus can be used in the following preferred modes:

1. In step mode, the support structure MT and the substrate table WT are kept essentially stationary, while an entire pattern imparted to the beam PB is projected onto a target portion C in one go (i.e. a single static exposure). The substrate table WT is then shifted in the X and/or Y
5 direction so that a different target portion C can be exposed. In step mode, the maximum size of the exposure field limits the size of the target portion C imaged in a single static exposure.

2. In scan mode, the support structure MT and the substrate table WT are scanned synchronously while a pattern imparted to the beam PB is projected onto a target portion C (i.e. a single dynamic exposure). The velocity and direction of the substrate table WT relative to the
10 support structure MT is determined by the (de-)magnification and image reversal characteristics of the projection system PL. In scan mode, the maximum size of the exposure field limits the width (in the non-scanning direction) of the target portion in a single dynamic exposure, whereas the length of the scanning motion determines the height (in the scanning direction) of the target portion.

15 3. In another mode, the support structure MT is kept essentially stationary holding a programmable patterning device, and the substrate table WT is moved or scanned while a pattern imparted to the beam PB is projected onto a target portion C. In this mode, generally a pulsed radiation source is employed and the programmable patterning device is updated as required after each movement of the substrate table WT or in between successive radiation pulses during a scan.
20 This mode of operation can be readily applied to maskless lithography that utilizes programmable patterning device, such as a programmable mirror array of a type as referred to above.

[0055] Combinations and/or variations on the above described modes of use or entirely different modes of use may also be employed.

[0056] Figure 2 schematically depicts a deformable reflector 1 according to an embodiment of
25 the invention. In the example of Figure 2, the deformable reflector 1 comprises a generally rectangular array of actuating elements 2. The array of actuating elements 2 may take any desired form, e.g. the array of actuating elements 2 may be generally circular. The deformable reflector 1 may comprise a larger or smaller number of actuating elements than that shown in Figure 2. The deformable reflector 1 may, for example, comprise from about 50 actuating elements to about 200
30 actuating elements. . Each actuating element may be configured to actuate a different portion 3 of the deformable reflector 1. In the example of Figure 2 the actuating elements, and their

corresponding portions 3, are generally square shaped. The actuating elements and the portions 3 of the deformable reflector 1 may take any desired shape, e.g. generally circular, generally rectangular, etc. In the example of Figure 2 the deformable reflector is generally rectangular. The deformable reflector 1 may take any desired shape, e.g. the deformable reflector 1 may be generally
5 circular. The deformable reflector 1 may be curved or flat. The surface area of the deformable reflector 1 and/or the surface area of the array of actuating elements 2 may be selected as desired. For example, the surface area of the deformable reflector 1 and/or the array of actuating elements 2 may be dependent at least in part upon the projection system of the lithographic apparatus in which the deformable reflector 1 is located.

10 **[0057]** The actuating elements may be configured to deform portions 3 of the deformable reflector 1 such that the portions 3 of the deformable reflector 1 move in a direction normal to the surface of the deformable reflector 1 (i.e. along the z-axis). The actuating elements are configured to move the portions 3 of the deformable reflector 1 from a resting position in which the actuating element exerts no force on the portion 3 to an active position in which the actuating element exerts
15 a force on the portion 3. The actuating elements may be configured to move the portions along the z-axis across a range of about 50 nm in the positive z direction and about 50 nm in the negative z direction, thus allowing a range of movement of about 100 nm along the z-axis. The actuating elements may, for example, be configured to move the portions along the z-axis in increments of about 0.1 nm. The actuating elements may be configured to move portions 3 of the deformable
20 reflector 1 across greater or smaller ranges and by greater or smaller increments. As will be appreciated, the distance by which the actuating elements are able to deform the deformable reflector 1 may be determined in part by a thickness of the deformable reflector 1 and/or a material from which the deformable reflector 1 is formed. A deformable reflector that is suitable for use in an EUV lithographic apparatus may be thicker than a deformable reflector that is suitable for use
25 in a UV lithographic apparatus.

[0058] An actuating element may, for example, comprise a piezoelectric actuator. A voltage may be applied to the piezoelectric actuator to cause deformation of the piezoelectric actuator. Deformation of the piezoelectric actuator may cause the portion 3 of the deformable reflector 1 in which the piezoelectric actuator is located to deform. Applying a greater voltage to the
30 piezoelectric actuator may cause greater deformation of the piezoelectric actuator, and thereby

greater deformation of the portion 3 of the deformable reflector 1 in which the piezoelectric actuator is located.

[0059] By actuating the actuating elements and deforming portions of the deformable reflector 1, a wavefront of radiation reflecting from the deformable reflector 1 may be adjusted. The scale of adjustment of a wavefront of which the deformable reflector 1 is capable may be determined in part by the area of the portions 3 of the deformable reflector 1 which may be deformed by the actuating elements. That is, using smaller actuating elements to deform smaller portions of the deformable reflector 1 may enable finer adjustments of a wavefront reflecting from the deformable reflector 1 than using larger actuating elements to deform larger portions of the deformable reflector 1. One actuating element may, for example, be configured to actuate a portion 3 of the deformable reflector 1 that has an area within the range of about 25 mm² to about 500 mm². In general, an actuating element may be configured to actuate a portion 3 of the deformable reflector 1 having any desired area.

[0060] The alignment of an image to its intended position on a substrate may be referred to as overlay. Inaccuracies in the alignment of an image to its intended position on a substrate may be known as overlay errors. The wavefront may be adjusted such that a lithographic error, such as an overlay error and/or a focus error, is reduced. In order to reduce a lithographic error, the lithographic error is first determined. The lithographic error may be determined via direct measurement (e.g. using a detector system), indirect measurement (e.g. performing a lithographic exposure in a resist and analysing the resist) and/or prediction (e.g. by inputting data into a computer model and executing the computer model). For example, data relating to lithographic errors may be measured and input into a computer model. The computer model may be configured to receive data and perform calculations using that data in order to predict a lithographic error.

[0061] Once the lithographic error has been determined, a correction profile for the patterned radiation beam may be determined. The correction profile is configured to reduce the lithographic error when the correction profile is applied to the patterned radiation beam. The correction profile may comprise modifications of a wavefront required to reduce a lithographic error. The correction profile is applied to the patterned radiation beam by actuating the actuating elements to deform portions 3 of the deformable reflector 1. Some portions 3 may not undergo deformation. Different portions may be deformed by different amounts and/or in different directions. The portions that are to be deformed and the amount of deformation to apply to those portions may be determined

by a processor configured to receive the correction profile and calculate the deformations of portions of the deformable reflector 1 needed to apply the correction profile to the patterned radiation beam.

[0062] Figure 3 schematically depicts a portion of a lithographic apparatus comprising a deformable reflector 1. In the example of Figure 3, the deformable reflector 1 is located within a projection system of a lithographic apparatus, such as the projection system PL of Figure 1. The projection system PL may comprise a plurality of other optical elements such as mirrors, lenses, etc. (not shown in Figure 3).

[0063] A subaperture of the deformable reflector 1 may be defined as an area of the deformable reflector 1 across which incident radiation is focussed onto the same field position (i.e. the same position on the substrate W). A distance between the deformable reflector 1 and the field plane 4 may determine in part an overlap of subapertures of the deformable reflector 1. The deformable reflector 1 is located proximate a field plane 4. That is, the deformable reflector 1 is located at a distance from the field plane 4 such that a subaperture at the centre of the array of actuating elements does not overlap with a subaperture at an edge of the array of the actuating elements. The deformable reflector 1 may be configured such that, for example, a subaperture of the deformable reflector 1 has a diameter of about 50 mm. The deformable reflector 1 may be proximate multiple field planes.

[0064] A patterned radiation beam PB entering the projection system PL may interact with other optical elements (not shown in Figure 3) before being incident on the deformable reflector 1. The radiation PB reflects from the deformable reflector 1 and is incident upon a reflector 5. The radiation PB reflects from the reflector 5 and may then interact with other optical elements in the projection system PL before exiting the projection system PL and being incident on a substrate W held by a substrate table WT. Other arrangements of the deformable reflector 1 are possible. Actuation of the deformable reflector 1 may occur during projection of the patterned radiation beam PB. Alternatively, actuation of the deformable reflector 1 may occur before projection of the patterned radiation beam PB and the portions of the deformable reflector 1 may be held in their new positions during projection of the patterned radiation beam PB. The deformable reflector 1 may be used in combination with other optical element manipulators present in the projection system PL to correct for a lithographic error.

[0065] Figure 4 schematically depicts a portion of a lithographic apparatus comprising two deformable reflectors 1, 7. In the example of Figure 4, the two deformable reflectors 1, 7 oppose each other across the same field plane 4. A separation 8 between the deformable reflectors 1, 7 may be varied. Actuation of the two deformable reflectors 1, 7 may take place during projection of a patterned radiation beam PB. Actuating the two deformable reflectors 1, 7 during projection of a patterned radiation beam PB may allow a focus error to be reduced.

[0066] Specific overlay lithographic errors and corresponding applications of the deformable reflector 1 are discussed below.

[0067] A projection system PL of a lithographic apparatus comprises intrinsic optical aberrations due to, for example, real optical elements, such as lenses, having imperfections. Information relating to optical aberrations may be represented as a wavefront shape in a pupil plane of an optical system. The wavefront shape may be expressed as a combination of polynomials, e.g. Zernike polynomials for optical systems comprising a circular pupil. Different polynomials may represent different types of optical aberrations. For example, a first Zernike polynomial may represent a tilt aberration whereas a second Zernike polynomial may represent a defocus aberration. Zernike polynomials are often categorized as being either odd (i.e. asymmetric) or even (i.e. symmetric). Different categories of Zernike polynomials may correspond to different projection system characteristics. For example, even Zernike polynomials may correspond to focus errors whereas odd Zernike polynomials may correspond to overlay errors. In general, the Zernike polynomials may be categorized in any desired manner. The dual index American National Standards Institute (ANSI) Zernike numbering scheme will be used in the following discussion of Zernikes.

[0068] Radiation reaching different positions on the field plane of an optical system (e.g. the surface of a substrate in a lithographic apparatus) travels through different parts of the projection system and experiences different aberrations. That is, the wavefront shape at the pupil plane varies per position in the field plane. The variation across the field plane of each Zernike of a wavefront may be expressed by combinations of polynomials of different orders. For example, the field plane variation of a lower order Zernike (e.g. Z [1, 1], the Zernike that represents a horizontal tilt of the wavefront shape) may be expressed by a combination of different polynomials. Considering field plane variations of higher order Zernike polynomials provides more information about optical aberrations present in the projection system and/or how corrections may be induced within the

projection system via adjustments made to optical elements present within the projection system. However, field plane variations described by higher order Zernike polynomials may be more difficult to compensate for than field plane variations described by lower order Zernike polynomials.

5 [0069] Known methods of reducing lithographic errors include manipulating (e.g. moving and/or tilting) lenses present in the projection system and/or changing a wavelength of radiation provided to the projection system to compensate for field plane variations of Zernikes. However, known methods of reducing lithographic errors are only be able to compensate for lithographic errors resulting from 1st order, 2nd order and/or 3rd order field plane variations of Zernikes of a
10 wavefront. For example, known methods of reducing lithographic errors may only be able to compensate for up to 3rd order field plane variations of the low order Zernike that represents a horizontal tilt of the wavefront shape (i.e. Z [1, 1]) and/or up to 2nd order field plane variations of the low order Zernike that represents a vertical tilt of the wavefront shape (i.e. Z [1, -1]). The order of field plane variations that may be corrected for may vary between different Zernikes.

15 [0070] Known methods of reducing lithographic errors by manipulating lenses may require more time (e.g. about 50 ms) to manipulate the lenses between different positions than is available during projection of the patterned radiation beam and/or during a lithographic exposure of a substrate. Known methods of reducing lithographic errors by manipulating lenses may therefore not allow manipulation of lenses to occur during projection of the patterned radiation beam. That
20 is, the lenses may have to be manipulated before projection of a patterned radiation beam and held in that position during projection of the patterned radiation beam, thus limiting the ability of known methods to reduce lithographic errors.

[0071] A deformable reflector comprising actuating elements may be capable of performing fine adjustments (i.e. actuators (such as piezoelectric actuators) can provide deformations of the
25 deformable reflector on the nanometre scale) of a wavefront that is incident upon the deformable reflector. The fine adjustments of a wavefront that are made possible by the deformable reflector allow for a reduction of lithographic errors that correspond to higher orders of field plane variations than known methods of reducing lithographic errors. For example, the deformable reflector may be used to apply a correction profile that compensates for at least up to 4th order field plane
30 variations of the Zernike that represents a horizontal tilt aberration of the wavefront shape (i.e. Z [1, 1]). As another example, the deformable reflector may be used to apply a correction profile

that compensates for at least up to 3rd order field plane variations of the Zernike that represents a vertical tilt aberration of the wavefront shape (i.e. Z [1, -1]). The deformable reflector may be used to apply a correction profile that compensates for at least up to 2nd order field plane variations of the Zernikes that represent horizontal coma and/or trefoil aberrations (i.e. Z [3, 1], Z [3, 3] and/or Z [3, -3]). The deformable reflector may be used to apply a correction profile that compensates for at least up to 1st order field plane variations of the Zernike that represents a vertical coma aberration (i.e. Z [3, -1]). The deformable reflector may be used to apply a correction profile that compensates for field plane variations of other Zernikes. The deformable reflector may be used to apply a correction profile compensates for overlay errors associated with greater than 3rd order field plane variations of a Zernike. The deformable reflector may be used to apply a correction profile that compensates for field plane variations of Zernikes up to 9th order field plane variations of Zernikes. In some embodiments, a deformable reflector may be provided that is able to apply a correction profile that compensates for field plane variations of Zernikes that are greater than 9th order field plane variations of Zernikes. In general, however, it will be appreciated that the higher the order of field plane variations of Zernikes that the deformable reflector is capable of compensating for, the more complicated the deformable reflector may be to construct and operate. A balance between the complexity of the deformable reflector and a correction capability of the deformable reflector may be selected as desired.

[0072] The deformable reflector may be used to apply a correction profile that corrects for lithographic errors that are not caused by optical aberrations of the projection system (e.g. lithographic errors caused by a deformation of a reticle/and or the substrate, a change in temperature of the reticle and/or the substrate, substrate processing effects, etc.) as well as lithographic errors that are caused by optical aberrations of the lithographic apparatus. Lithographic errors such as overlay errors and/or focus errors that are not caused by aberrations are discussed in greater detail below. A lithographic error may be expressed in the form of field plane variations of the lithographic error having different polynomial orders. A correction profile may be applied that adjusts the wavefront of radiation reflecting from the deformable reflector such that a lithographic error that is not caused by optical aberrations is reduced. For example, the deformable reflector may reduce at least up to 4th order field plane variations of an overlay error in an x-direction of the field plane by, for example, applying a correction profile that adjusts a Z [1, 1] of the wavefront reflecting from the deformable reflector. As another example, the

deformable reflector may reduce at least up to 3rd order field plane variations of an overlay error in a y-direction of the field plane by, for example, applying a correction profile that adjusts a Z [1, -1] of the wavefront reflecting from the deformable reflector.

[0073] A correction profile that is to be applied to a wavefront may be determined by
5 determining a lithographic error, determining a correction to the lithographic error and converting the correction into a desired wavefront adjustment. It will be understood that each step of determining the lithographic error, determining the correction and converting the correction into a desired wavefront adjustment may be performed in any of a number of appropriate ways. The correction profile (i.e. adjustments to the wavefront that reduce the lithographic error) may then
10 be determined, e.g. by determining a value of a Zernike that induces a wavefront adjustment that reduces the lithographic error. The correction profile may then be translated to a deformation of the deformable reflector that is required to apply the correction profile to a wavefront reflecting from the deformable reflector. The effect of an incremental move of each actuating element on the wavefront of radiation at different field plane positions may be measured and stored in a
15 memory. An incremental move of an actuating element may, for example, include moving the actuating element by about 0.1 nm along the z-axis. The information stored in the memory may be referred to as reflector dependencies.

[0074] The reflector dependencies may be used when carrying out the translation of the correction profile to a deformation of the deformable reflector. For example, the correction profile
20 and the reflector dependencies may be provided to an algorithm that is configured to determine an actuation of the actuating elements that best applies the correction profile to a wavefront. The algorithm may, for example, be a least squares algorithm. Other types of algorithm may be used, e.g. algorithms that account for limitations of movement of the actuating elements. The actuating elements of the deformable reflector may then be actuated such that the portions of the deformable
25 reflector are at the z-positions needed to apply the correction profile to the wavefront. A wavefront incident on the actuated deformable reflector is adjusted on reflection from the deformable reflector such that the determined lithographic errors (e.g. overlay errors and/or focus errors) are reduced.

[0075] Some device manufacturing processes include performing a lithographic exposure on
30 a layer of the substrate using a first set of illumination settings and then performing a second lithographic exposure on a different layer of the substrate using different illumination settings.

Using different illumination settings for different lithographic exposures may mean that radiation passes through different parts of the projection system during the first and second lithographic exposures. The radiation may therefore experience different aberrations when different illumination settings are used for different exposures. The different aberrations experienced by a wavefront when using different illumination settings may result in lithographic errors such as an overlay error between layers of a substrate that have been exposed to radiation using different illumination settings.

[0076] A correction profile may be determined that matches lithographic errors experienced when using a first set of illumination settings to lithographic errors experienced when using a different set of illumination settings. Matching lithographic errors between different illumination modes may, for example, improve an overlay between substrate layers that are exposed using the different illumination settings. For example, a first layer of a substrate may be exposed using a dipole illumination mode and a different layer of the substrate may be exposed using an annular illumination mode. Lithographic errors may be measured when using illumination settings that produce the dipole illumination mode and when using illumination settings that produce the annular illumination mode. A correction profile may be determined and applied to the radiation beam that causes the radiation beam to experience lithographic errors associated with the annular illumination mode when using the dipole illumination mode. The correction profile may, for example, be determined in a two-step process. The first step may include determining a correction profile that reduces lithographic errors experienced under the dipole illumination mode as much as possible. The second step may include determining a correction profile that modifies the reduced lithographic errors such that they match the lithographic errors experienced during the annular illumination mode as much as possible. The deformable reflector may be used to match the lithographic errors experienced when using different illumination settings, including greater than 3rd order field plane variations of the lithographic errors.

[0077] Some device manufacturing processes include performing lithographic exposures on different layers of a substrate. Different layers may be exposed to patterned radiation using different lithographic apparatus. Different lithographic apparatus may have different projection characteristics. The projection characteristics may comprise characteristics such as, for example, information relating to existing optical aberrations in the projection system (which may have been determined through suitable measurement, e.g. using a detector arrangement or by performing an

exposure in a resist, or which may be known *a priori*, e.g. the projection characteristics may have been predicted using a model).

[0078] The correction profile may correct for a difference between projection characteristics of different lithographic apparatus. For example, a first layer of the substrate may undergo a lithographic exposure in an EUV lithographic apparatus and a different layer of the substrate may undergo a lithographic exposure in a UV lithographic apparatus. The EUV lithographic apparatus and the UV lithographic apparatus may comprise different aberrations, and therefore cause different lithographic errors. An overlay error between the different layers of the substrate may be reduced by matching an overlay error experienced when using the EUV lithographic apparatus with an overlay error experienced when using the UV lithographic apparatus. Lithographic errors may be measured when using the EUV lithographic apparatus and when using the UV lithographic apparatus. A correction profile may be determined and applied to the radiation beam that causes the radiation beam to experience lithographic errors associated with the EUV lithographic apparatus when using the UV lithographic apparatus. The correction profile may, for example, be determined in a two-step process. The first step may include determining a correction profile that reduces lithographic errors experienced when using the UV lithographic apparatus as much as possible. The second step may include determining a correction profile that modifies the reduced lithographic errors such that they match the lithographic errors experienced when using the EUV lithographic apparatus as much as possible. The deformable reflector may be used to match the lithographic errors experienced when using different lithographic apparatus, including greater than 3rd order field plane variations of the lithographic errors.

[0079] In some device manufacturing methods, the substrate may be processed between different lithographic exposures. That is, one layer of the substrate may be exposed to patterned radiation and then the substrate may be removed from the lithographic apparatus to undergo substrate processing such as, for example, polishing, etching, baking, etc. After substrate processing, the substrate may be inserted into the same lithographic apparatus (or a different lithographic apparatus) and another layer of the substrate may be exposed to a patterned radiation beam. Substrate processing may result in lithographic errors. Lithographic errors resulting from substrate processing may be referred to as substrate processing effects. For example, etching a layer of the substrate may alter stresses acting within the substrate (e.g. stresses across scribe lanes of a substrate) and the positions of features present on the substrate may change from their intended

positions as a result of the changing stresses within the substrate. As another example, baking of the substrate may cause thermal deformation of the substrate which may result in the positions of features present on the substrate changing from their intended positions.

[0080] The correction profile may correct for substrate processing effects. For example, a first layer of a substrate may be exposed in a first lithographic exposure. The substrate may be removed from the lithographic apparatus and undergo substrate processing. The substrate may then be re-inserted into the lithographic apparatus and the next layer of the substrate may undergo a second lithographic exposure. A lithographic error (e.g. an overlay error) between the first layer and the second layer may be measured, e.g. by carrying out a lithographic exposure in resist on the substrate and measuring an overlay error of projected features such as, for example, product features and/or alignment features present on the substrate. A correction profile may be determined that reduces the measured lithographic error when the correction profile is applied to the radiation beam via actuation of the deformable reflector. The correction profile may then be applied to the radiation beam in future exposures to reduce the lithographic error. Different correction profiles may be determined for different combinations of lithographic apparatus and substrate processing. The deformable reflector may be used to reduce a lithographic error caused by substrate processing effects, including greater than 3rd order field plane variations of the lithographic error.

[0081] The lithographic apparatus may comprise a support structure configured to support the reticle. By supporting the reticle, the support structure may induce an unwanted deformation of the reticle. For example, the reticle may be clamped to the support structure, e.g. via vacuum clamping or electrostatic clamping. The act of clamping the reticle to the support structure may deform the reticle from its resting shape. A deformation of the reticle may introduce a lithographic error such as, for example, an overlay error.

[0082] The correction profile may correct for a deformation of the reticle resulting from the support structure supporting the reticle. Different methods of supporting the reticle may be used in different lithographic apparatus. For example, a UV lithographic apparatus may comprise vacuum clamping on the support structure to support the reticle whereas an EUV lithographic apparatus may comprise electrostatic clamping on the support structure to support the reticle. The different methods of supporting the reticle may cause different lithographic errors. A first layer of a substrate may be exposed to patterned radiation using an EUV lithographic apparatus and a

second layer of the substrate may be exposed to patterned radiation using a UV lithographic apparatus, thus different lithographic errors resulting from the use of different support structures may be experienced during different lithographic exposures. The deformable reflector may be used to reduce a lithographic error caused by the support structure supporting the reticle, including
5 greater than 3rd order field plane variations of the lithographic error.

[0083] During a lithographic exposure the temperature of the reticle may change. The reticle may undergo thermal deformation as a result of the reticle changing temperature. For example, the reticle may absorb energy from the radiation beam that is incident on the reticle and the temperature of the reticle may increase. The reticle may undergo thermal expansion when the
10 temperature of the reticle increases. Thermal deformation of the reticle may introduce a lithographic error such as, for example, an overlay error.

[0084] The correction profile may correct for a change in temperature of the reticle. For example, a computer model may be used to predict a lithographic error resulting from the reticle changing temperature. The computer model may be calibrated by comparing its results with the
15 results of a lithographic exposure of a substrate comprising a resist. The results of the computer model may be used to determine a correction profile that is configured to reduce the lithographic error. Alternatively, known alignment sensors such as, for example, the PARIS sensor may be used to measure wavefront aberrations. The measured wavefront aberrations may then be used to determine the correction profile. The correction profile may be applied to a patterned radiation
20 beam via actuation of the deformable reflector. The deformable reflector may be used to reduce a lithographic error caused by a change in temperature of the reticle, including greater than 3rd order field plane variations of the lithographic error.

[0085] The lithographic apparatus may comprise a substrate table configured to hold the substrate. For example, the substrate table may comprise burls that are configured to support the
25 substrate. The burls may impart a force on the substrate that causes the substrate to deform. Deformation of the substrate may introduce a lithographic error. Different substrate tables may cause different deformations of the substrate. Deformation caused by a substrate table holding the substrate may change through the lifetime of a substrate table. For example, burls may deteriorate over time and consequently the forces the burls impart to the substrate may change over time. The
30 force imparted to the substrate by the burls may contribute to substrate edge roll-off effects which are described in more detail below.

[0086] The correction profile may correct for a deformation of the substrate resulting from the substrate table holding the substrate. For example, a topography measurement system may be used to measure a topography of the substrate when the substrate is held by the substrate table. The measured topography of the substrate may be provided to a computer model that is configured to
5 convert the measured topography to a predicted overlay error. The predicted overlay error may be used to determine a correction profile. Alternatively, overlay errors resulting from a deformation of the substrate may be determined by carrying out a lithographic exposure in resist on the substrate and measuring an overlay error of projected features such as, for example, product features and/or alignment features present on the substrate. The measured overlay error may be used to determine
10 a correction profile. The deformable reflector may be used to reduce a lithographic error caused by deformation of the substrate resulting from the substrate table holding the substrate, including greater than 3rd order field plane variations of the lithographic error.

[0087] During a lithographic exposure the temperature of the substrate may change. The substrate may undergo thermal deformation as a result of the substrate changing temperature. For
15 example, the substrate may absorb energy from the patterned radiation beam that is incident on the substrate and the temperature of the substrate may increase. The substrate may undergo thermal expansion and deform when the temperature of the substrate increases. Deformation of the substrate may cause a lithographic error such as an overlay error. The correction profile may correct for a change in temperature of the substrate. The deformable reflector may be used to
20 reduce a lithographic error caused by a change in temperature of the substrate, including greater than 3rd order field plane variations of the lithographic error.

[0088] The lithographic apparatus may comprise a pellicle configured to protect the reticle. Figure 5 schematically depicts the effect of pellicle deformation on an intended optical path 11 of incident radiation PB passing from a pellicle cavity 13 (i.e. the space between the patterned surface
25 of the patterning device and the pellicle) through the pellicle 12. The pellicle 12 is secured to the reticle MA via a support frame 10. The incident radiation PB refracts as it passes through the deformed pellicle 12. The refraction causes the incident radiation PB to deviate from its intended optical path 11. The extent of the optical path deviation depends on the refractive index of the pellicle 12, the refractive index of the pellicle cavity 13 and the angle of incidence of the radiation
30 PB. As can be seen in the magnified portion of Figure 5, the optical path of the refracted radiation 9 has shifted with respect to its intended position 11 as a result of the pellicle deformation. The

optical path deviations caused to radiation as a result of the pellicle deformation may result in lithographic errors such as overlay errors occurring at the substrate. That is, the image imparted to the radiation beam PB by the patterning device MA is misaligned with its intended position on the substrate due to optical path deviations caused by the deformed pellicle 12.

5 [0089] The misalignment caused to a projected image by pellicle deformation results in overlay errors at an exposed die. The overlay error at an exposed point of a die caused by pellicle deformation depends on the region of the pellicle 12 through which the radiation beam PB passed before illuminating that point of the die. For example, a pellicle region which has undergone a large deformation will typically cause a large overlay error for a die exposed to radiation passing
10 through that pellicle region. The pellicle deformation and its associated overlay error are also dependent on the direction in which the exposure scan is taking place. In contemporary lithographic apparatus there are two directions in which the patterning device MA is scanned during exposure. The two scan directions may be referred to as scan-up and scan-down respectively as the scans typically take place in opposite directions along the same axis.

15 [0090] The correction profile may correct for a deformation of the pellicle resulting from movement of the reticle. For example, measurements of the lithographic errors caused by deformation of the pellicle may be used to determine a correction profile that acts to reduce the measured lithographic error. The correction profile may then be applied to the radiation beam PB via actuation of the deformable reflector. The deformable reflector may be used to reduce a
20 lithographic error caused by deformation of the pellicle resulting from movement of the reticle, including greater than 3rd order field plane variations of the lithographic error.

[0091] The correction profile may compensate for overlay errors that occur within about 20 mm of an edge of the substrate. For example, overlay errors associated with substrate roll-off effects may be reduced by applying a correction profile using the deformable reflector.

25 [0092] Actuation of the deformable reflector may occur during projection of the patterned radiation beam. Referring again to Figure 4, applying the correction profile may additionally include actuating a second deformable reflector 7 configured to reflect radiation PB reflected by the deformable reflector 1, the second deformable reflector 7 being located proximate a field plane 4. Actuation of two deformable reflectors 1, 7 may allow a focus error to be compensated for.
30 Specific focus errors and corresponding applications of two deformable reflectors 1, 7 that are actuated during projection of a patterned radiation beam are discussed below.

[0093] The actual topography of a reticle MA may differ from the expected topography of the reticle MA due to, for example, inaccuracies when forming the reticle MA, deterioration of the reticle MA through its lifetime, clamping the reticle to the support structure MT, etc. The correction profile may correct for a topography of the reticle MA. The deformable reflectors 1, 7 may be used to reduce the lithographic errors caused by a topography of the reticle MA, including lithographic errors associated with greater than 2nd order field plane variations of Zernikes. The deformable reflectors 1, 7 may be used to compensate for a topography of the reticle MA such that required specifications of the reticle MA may be relaxed. That is, the use of two deformable reflectors 1, 7 may enable a lower quality reticle MA to be used because the deformable reflectors 1, 7 are compensating for the loss in reticle quality. Use of the deformable reflectors 1, 7 therefore may allow a less expensive reticle MA to be used in a lithographic apparatus.

[0094] The actual topography of a substrate W may differ from the expected topography of the substrate W due to, for example, inaccuracies when forming the substrate W, inaccuracies when processing (i.e. polishing, etching, baking, etc.) the substrate W, deterioration of the substrate W through its lifetime, deformation of the substrate W caused by clamping of the substrate W to the substrate table WT, etc. The correction profile may correct for a topography of the substrate W. The deformable reflectors 1, 7 may be used to reduce the lithographic errors caused by a topography of the substrate W, including lithographic errors associated with greater than 2nd order field plane variations of Zernikes. For example, a different correction profile may be applied to the radiation beam for each target portion of the substrate W to account for topography variations across the surface of the substrate W.

[0095] The correction profile may correct for substrate edge roll-off effects. The topography of the substrate varies more within 20 mm of an edge of the substrate compared to the rest of the substrate. Stresses in the substrate W (e.g. stresses across scribe lanes of the substrate) may contribute to substrate edge roll-off effects. As discussed earlier, burr forces may contribute to substrate roll-off effects. Substrate edge roll-off effects may contribute to lithographic errors that occur within 20 mm of an edge of the substrate. The deformable reflectors 1, 7 may be used to apply a correction profile that reduces focus errors occurring within 20 mm of the edge of the substrate.

[0096] The correction profile may correct for a focus aberration. For example, actuating the deformable reflectors 1, 7 during projection of the patterned radiation beam may enable the

application of a correction profile that compensates for at least up to 2nd order field plane variations of the Zernike that represents a defocus aberration (i.e. a parabolic wavefront shape that may be expressed by Zernike Z [2, 0]). The deformable reflectors 1, 7 may apply a correction profile that compensates for focus errors associated with greater than 2nd order field plane variations of a Zernike.

[0097] Known lithographic apparatus comprise a topography measurement system. The topography measurement system, e.g. a level sensor, may be used to measure focus errors. The deformable reflectors 1, 7 may be used to apply a correction profile that compensates for focus errors associated with greater than 2nd order field plane variations of a Zernike. A computer model may receive the measured focus errors and predict overlay errors that may result from the measured focus errors. A single deformable reflector 1 or two deformable reflectors 1, 7 may be used to apply a correction profile that compensates for the overlay errors that are predicted by the computer model.

[0098] Figure 6 shows a process according to an embodiment of the invention. In step S1, a lithographic apparatus configured to project a radiation beam patterned by a reticle onto a target portion of a substrate is provided. In step S2, a lithographic error is determined. In step S3, a correction profile configured to reduce the lithographic error is determined. In step S4, the correction profile is applied to the patterned radiation beam by actuating a deformable reflector configured to reflect the patterned radiation beam, the deformable reflector being located proximate a field plane. Step S4 may optionally include providing a second deformable reflector located proximate a field plane and wherein applying the correction profile additionally includes actuating the second deformable reflector configured to reflect radiation reflected by the deformable reflector.

[0099] A deformable reflector may be used to apply a correction profile configured to reduce a lithographic error associated with an EUV lithographic apparatus. EUV lithographic apparatus may comprise a reflector that is not located proximate a field plane of the lithographic apparatus. The reflector may be modified such that the reflector is a deformable reflector. For example, with reference to Figure 2, actuating elements 2 may be added to a reflector in an EUV lithographic apparatus in order to form a deformable reflector according to the present invention.

[00100] A deformable reflector present in an EUV lithographic apparatus may be formed from an ultra-low expansion material. The deformable reflector in an EUV lithographic apparatus may

be further from a field plane of the lithographic apparatus compared to a deformable reflector that is introduced to a UV lithographic apparatus. The deformable reflector in the EUV lithographic apparatus need not be located proximate a pupil plane of the lithographic apparatus. The deformable reflector need not be located in a pupil plane of the lithographic apparatus. The
5 deformable reflector may be located in a location other than a pupil plane of the lithographic apparatus.

[00101] As discussed above in relation to Figure 2, the surface area of the deformable reflector 1 and/or the surface area of the array of actuating elements 2 may be selected as desired. The surface area of the deformable reflector 1 and/or the array of actuating elements 2 may be
10 dependent at least in part upon the projection system of the lithographic apparatus in which the deformable reflector 1 is located. For example, an EUV lithographic apparatus may comprise a deformable reflector 1 that is not located proximate a field plane. The scale of adjustment of a wavefront of which the deformable reflector 1 is capable may be determined in part by the area of the portions 3 of the deformable reflector 1 which may be deformed by the actuating elements.
15 The portions may have a larger surface area in EUV than UV. There may be a lower number of actuating elements 2 per unit area of a deformable reflector 1 that is present in an EUV lithographic apparatus compared to a deformable reflector present in a UV lithographic apparatus.

[00102] As will be appreciated, the distance by which the actuating elements are able to deform the deformable reflector 1 may be determined in part by a thickness of the deformable reflector 1 and/or a material from which the deformable reflector 1 is formed. As discussed above, a
20 deformable reflector that is suitable for use in an EUV lithographic apparatus may be thicker than a deformable reflector that is suitable for use in a UV lithographic apparatus. The actuating elements may be configured to deform portions 3 of the deformable reflector 1 such that the portions 3 of the deformable reflector 1 move in a direction normal to the surface of the deformable
25 reflector 1 (i.e. along the z-axis). The actuating elements are configured to move the portions 3 of the deformable reflector 1 from a resting position in which the actuating element exerts no force on the portion 3 to an active position in which the actuating element exerts a force on the portion 3. The actuating elements 2 may be configured to move the portions 3 along the z-axis across a smaller distance in an EUV lithographic apparatus compared to a UV lithographic apparatus.

[00103] The method of using one or more deformable reflectors proximate a field plane to correct for lithographic errors may be retrofitted to existing lithographic apparatus without
30

requiring a significant redesign of the lithographic apparatus. For example, actuating elements may be attached (e.g. glued) to a reflector that already exists in a projection system of a known lithographic apparatus to make the reflector a deformable reflector. The deformable reflector may then be used to carry out the methods of correcting lithographic errors described herein. The

5 deformable reflector may be actuated to apply different correction profiles at any desired frequency. For example, a correction profile may be applied to the deformable reflector per lot of substrates, per substrate, per target portion of a substrate or during exposure of a single target portion of a substrate. In general, the lithographic error that is reduced by use of one or more deformable reflectors may be determined via direct measurement (e.g. using a detector system),

10 indirect measurement (e.g. performing a lithographic exposure in a resist and analysing the resist) and/or prediction (e.g. by inputting data into a computer model and executing the computer model).

[00104] It will be appreciated that different applications of the deformable reflector described above may be combined in any combination. While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as

15 described. The description is not intended to limit the invention.

CLAIMS:

1. A device manufacturing method, the method comprising:
providing a lithographic apparatus configured to project a radiation beam patterned by a
5 reticle onto a target portion of a substrate;
determining a lithographic error;
determining a correction profile configured to reduce the lithographic error; and,
applying the correction profile to the patterned radiation beam by actuating a deformable
reflector configured to reflect the patterned radiation beam, the deformable reflector being located
10 proximate a field plane.
2. The method of claim 1, wherein actuation of the deformable reflector occurs during
projection of the patterned radiation beam.
- 15 3. The method of claim 1 or claim 2, wherein applying the correction profile additionally
includes actuating a second deformable reflector configured to reflect radiation reflected by the
deformable reflector, the second deformable reflector being located proximate a second field
plane.
- 20 4. The method of any preceding claim, wherein the correction profile compensates for at least
up to 4th order field plane variation of an overlay error in an x-direction of the field plane.
5. The method of any preceding claim, wherein the correction profile compensates for at least
up to 3rd order field plane variation of an overlay error in a y-direction of the field plane.
25
6. The method of any preceding claim, wherein the correction profile compensates for at least
up to 2nd order field plane variations of Zernike Z [3, 1] and/or Zernike Z [3, 3] and/or Zernike Z
[3, -3].
- 30 7. The method of any preceding claim, wherein the correction profile compensates for at least
up to 1st order field plane variations of Zernike Z [3, -1].

8. The method of any preceding claim, wherein the correction profile compensates for an overlay error that has greater than 3rd order field plane variation.

9. The method of any preceding claim, wherein the correction profile compensates for different imaging characteristics arising from different illumination settings of the lithographic apparatus.

10. The method of any preceding claim, wherein the correction profile compensates for a difference between projection characteristics of different lithographic apparatus.

11. The method of any preceding claim, wherein the correction profile compensates for a lithographic error caused by substrate processing effects.

12. The method of any preceding claim, wherein the lithographic apparatus comprises a support structure configured to support the reticle, and wherein the correction profile compensates for a lithographic error caused by a deformation of the reticle resulting from the support structure supporting the reticle.

13. The method of any preceding claim, wherein the correction profile compensates for a lithographic error caused by a change in temperature of the reticle.

14. The method of any preceding claim, wherein the lithographic apparatus comprises a substrate table configured to hold the substrate and wherein the correction profile compensates for a lithographic error caused by a deformation of the substrate resulting from the substrate table holding the substrate.

15. The method of any preceding claim, wherein the correction profile compensates for a lithographic error caused by a change in temperature of the substrate.

16. The method of any preceding claim, wherein the lithographic apparatus comprises a pellicle configured to protect the reticle and wherein the correction profile compensates for a lithographic error caused by a deformation of the pellicle resulting from movement of the reticle.

5 17. The method of any preceding claim, wherein the correction profile compensates for overlay errors that occur within about 20 mm of an edge of the substrate.

18. The method of any preceding claim, wherein actuation of the deformable reflector occurs during projection of the patterned radiation beam, and wherein applying the correction profile
10 additionally includes actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a third field plane, and wherein the correction profile compensates for at least up to 2nd order field plane variations of Zernike Z [2, 0].

15 19. The method of any preceding claim, wherein actuation of the deformable reflector occurs during projection of the patterned radiation beam, and wherein applying the correction profile additionally includes actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a fourth field plane, and wherein the correction profile compensates for a topography of the reticle.

20 20. The method of any preceding claim, wherein actuation of the deformable reflector occurs during projection of the patterned radiation beam, and wherein applying the correction profile additionally includes actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a
25 fifth field plane, and wherein the correction profile compensates for a topography of the substrate.

21. The method of any preceding claim, wherein actuation of the deformable reflector occurs during projection of the patterned radiation beam, and wherein applying the correction profile additionally includes actuating a second deformable reflector configured to reflect radiation
30 reflected by the deformable reflector, the second deformable reflector being located proximate a sixth field plane, and wherein the correction profile compensates for substrate edge roll-off effects.

22. The method of any preceding claim, wherein actuation of the deformable reflector occurs during projection of the patterned radiation beam, and wherein applying the correction profile additionally includes actuating a second deformable reflector configured to reflect radiation reflected by the deformable reflector, the second deformable reflector being located proximate a
5 seventh field plane, and wherein the correction profile compensates for focus errors associated with greater than 2nd order field plane variations of a Zernike.

23. The method of any preceding claim, wherein the radiation beam is an extreme ultraviolet radiation beam.

24. A device manufactured according to any of claims 1 to 23.

25. A lithographic apparatus comprising:

an illumination system for providing a beam of radiation;

15 a support structure for supporting patterning device, the patterning device serving to impart the radiation beam with a pattern in its cross-section;

a substrate table for holding a substrate;

a projection system for projecting the patterned radiation beam onto a target portion of the substrate;

20 a deformable reflector configured to reflect the patterned radiation beam, the deformable reflector being located proximate a field plane; and,

a controller configured to perform the method of any of claims 1 to 23.

26. A device manufacturing method, the method comprising:

25 providing a lithographic apparatus configured to project an extreme ultraviolet radiation beam patterned by a reticle onto a target portion of a substrate;

determining a lithographic error;

determining a correction profile configured to reduce the lithographic error; and,

applying the correction profile to the patterned extreme ultraviolet radiation beam by

30 actuating a deformable reflector configured to reflect the patterned extreme ultraviolet radiation beam.

27. The method of claim 26, wherein actuation of the deformable reflector occurs during projection of the patterned extreme ultraviolet radiation beam.

28. The method of claim 26 or claim 27, wherein applying the correction profile additionally
5 includes actuating a second deformable reflector configured to reflect extreme ultraviolet radiation reflected by the deformable reflector.

29. The method of any of claims 26 to 28, wherein the correction profile compensates for up
to 3rd order field plane variations of a Zernike.

10

30. A device manufactured according to any of claims 26 to 29.

31. A lithographic apparatus comprising:

an illumination system for providing a beam of extreme ultraviolet radiation;

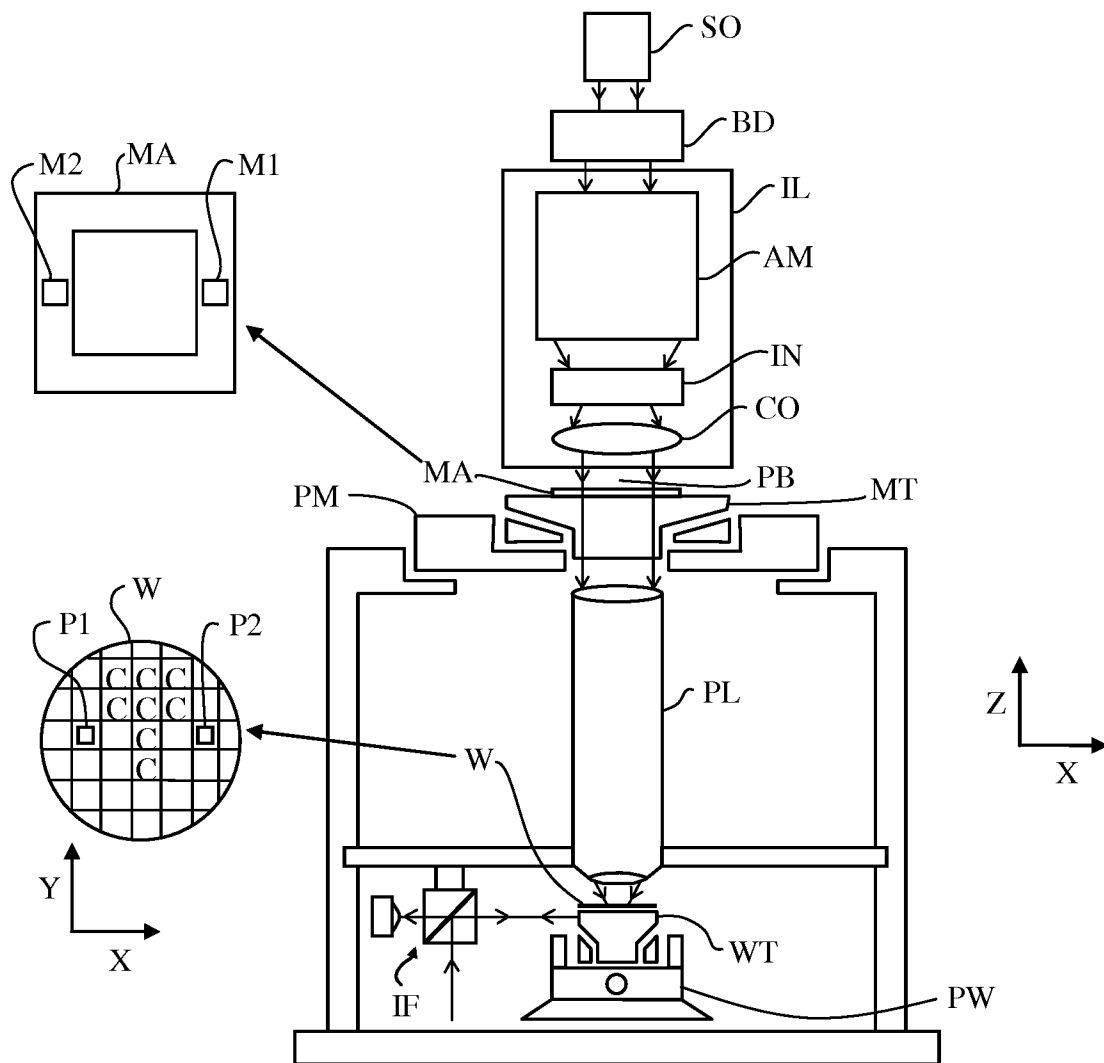
15 a support structure for supporting patterning device, the patterning device serving to impart the extreme ultraviolet radiation beam with a pattern in its cross-section;

a substrate table for holding a substrate;

a projection system for projecting the patterned extreme ultraviolet radiation beam onto a target
portion of the substrate;

20 a deformable reflector configured to reflect the patterned extreme ultraviolet radiation beam;
and,

a controller configured to perform the method of any of claims 26 to 29.

**Fig. 1**

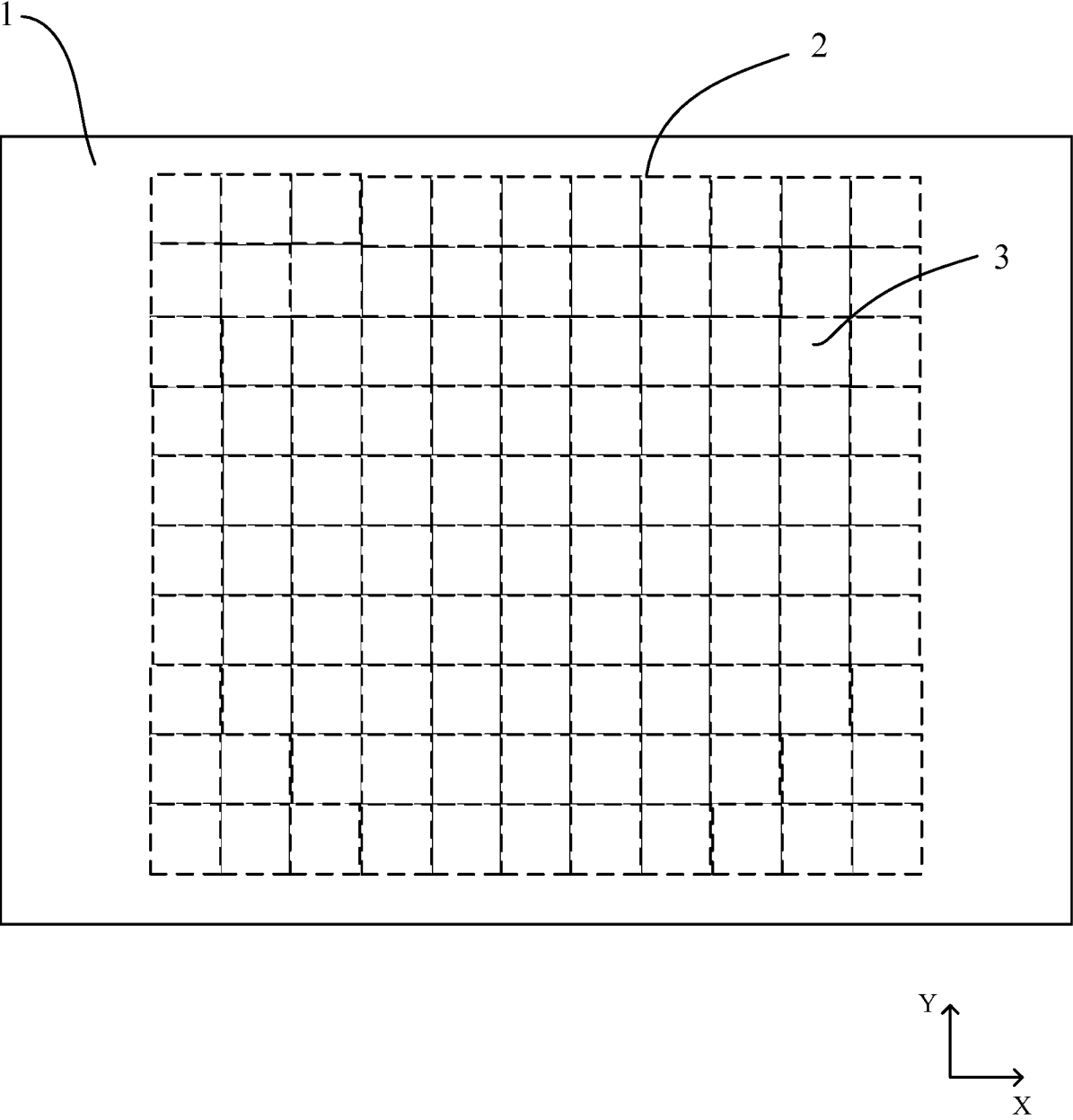


Fig. 2

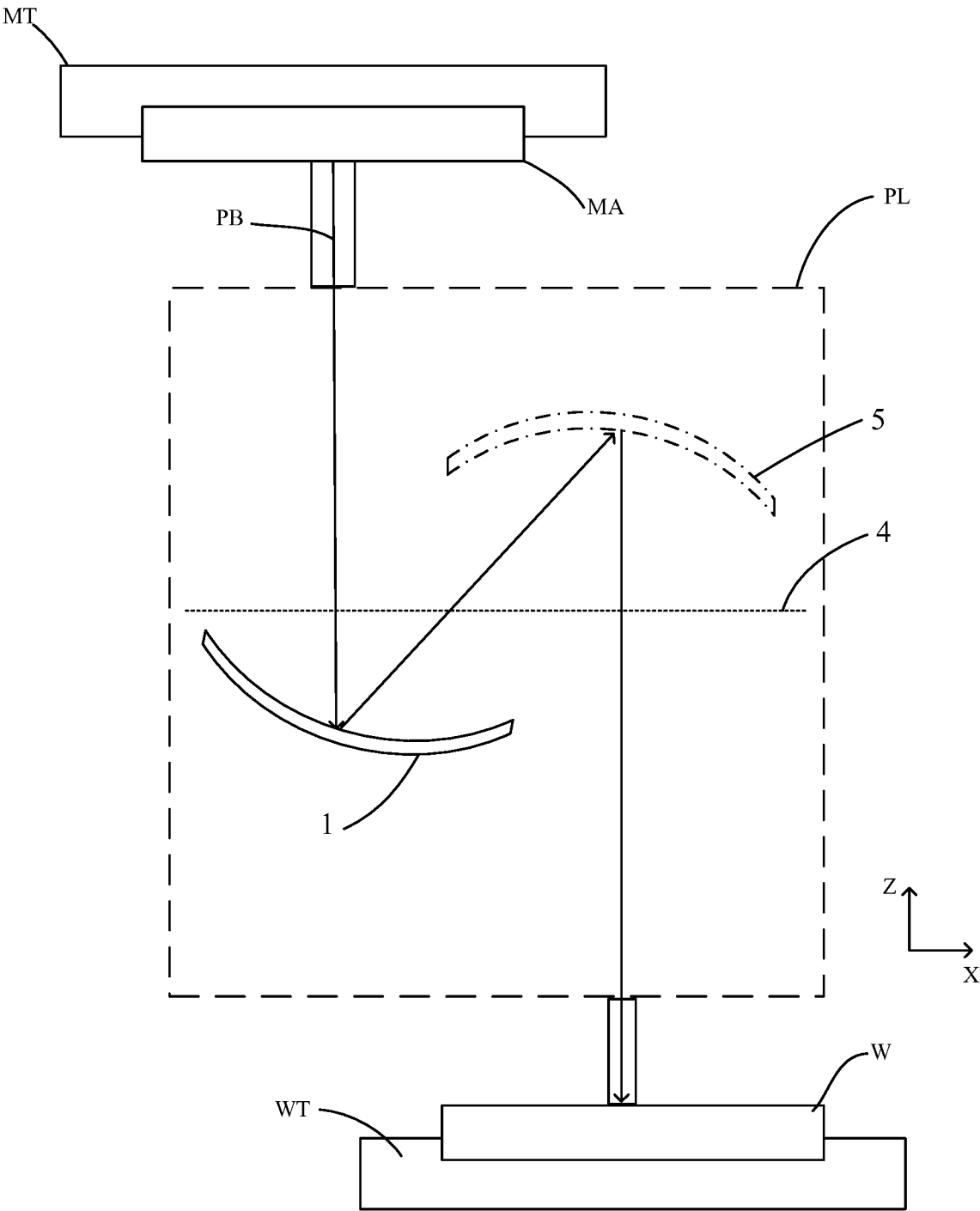


Fig. 3

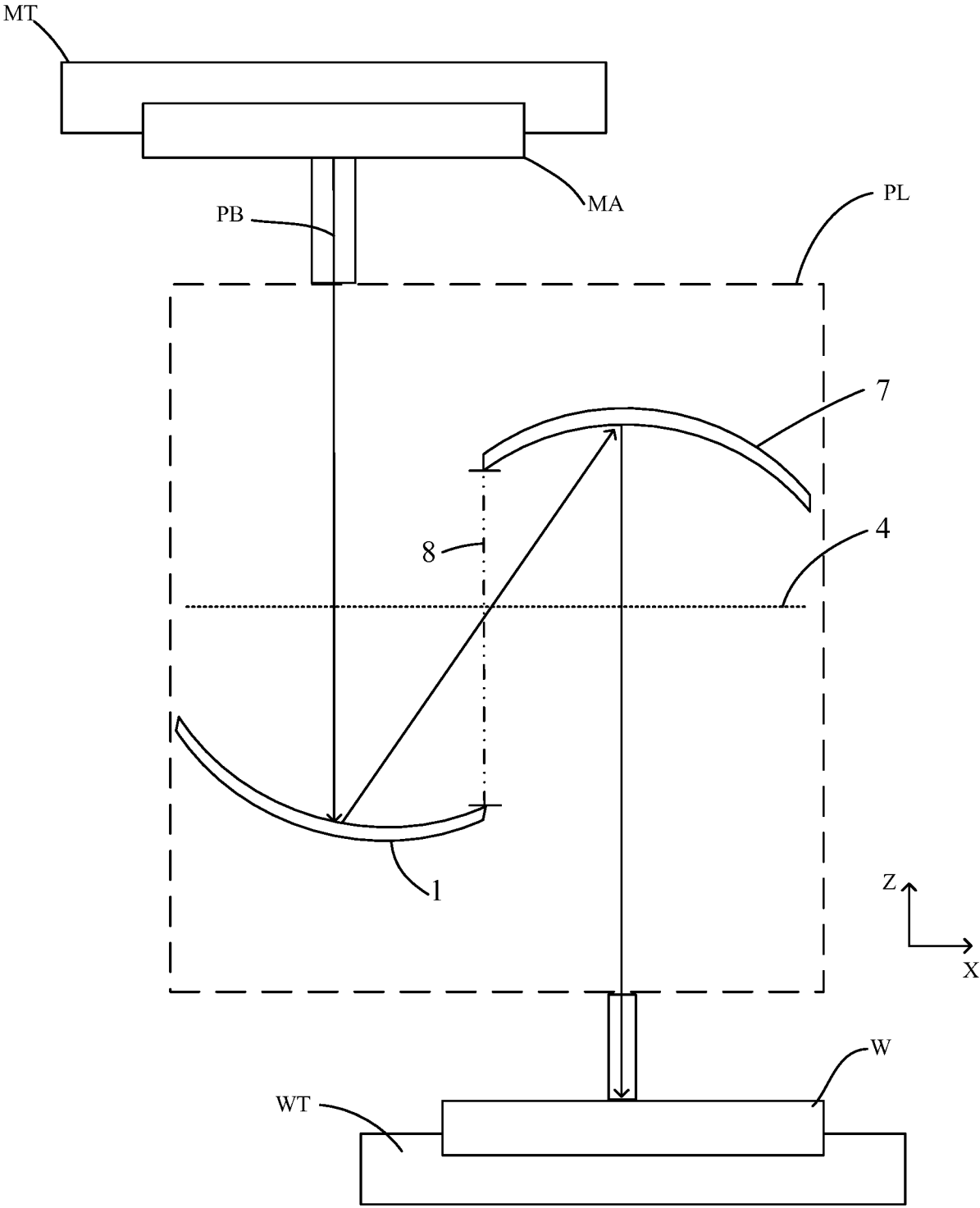


Fig. 4

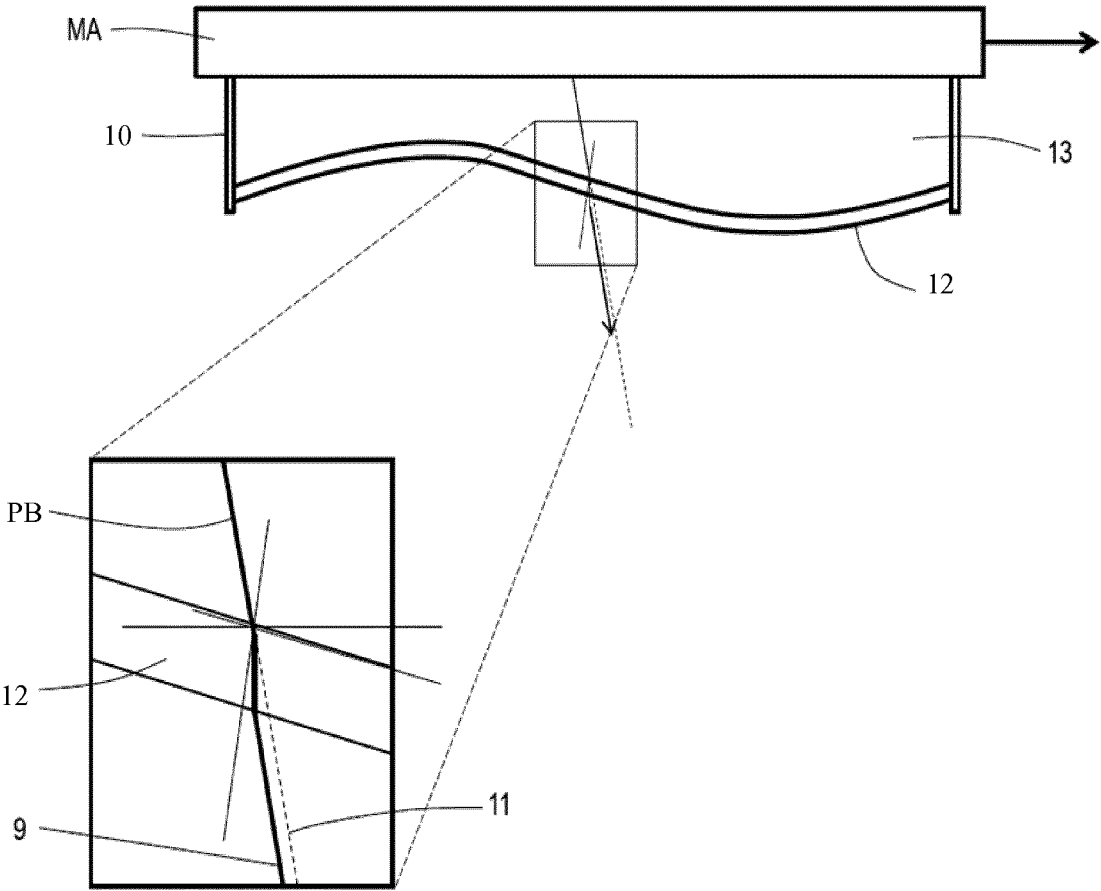
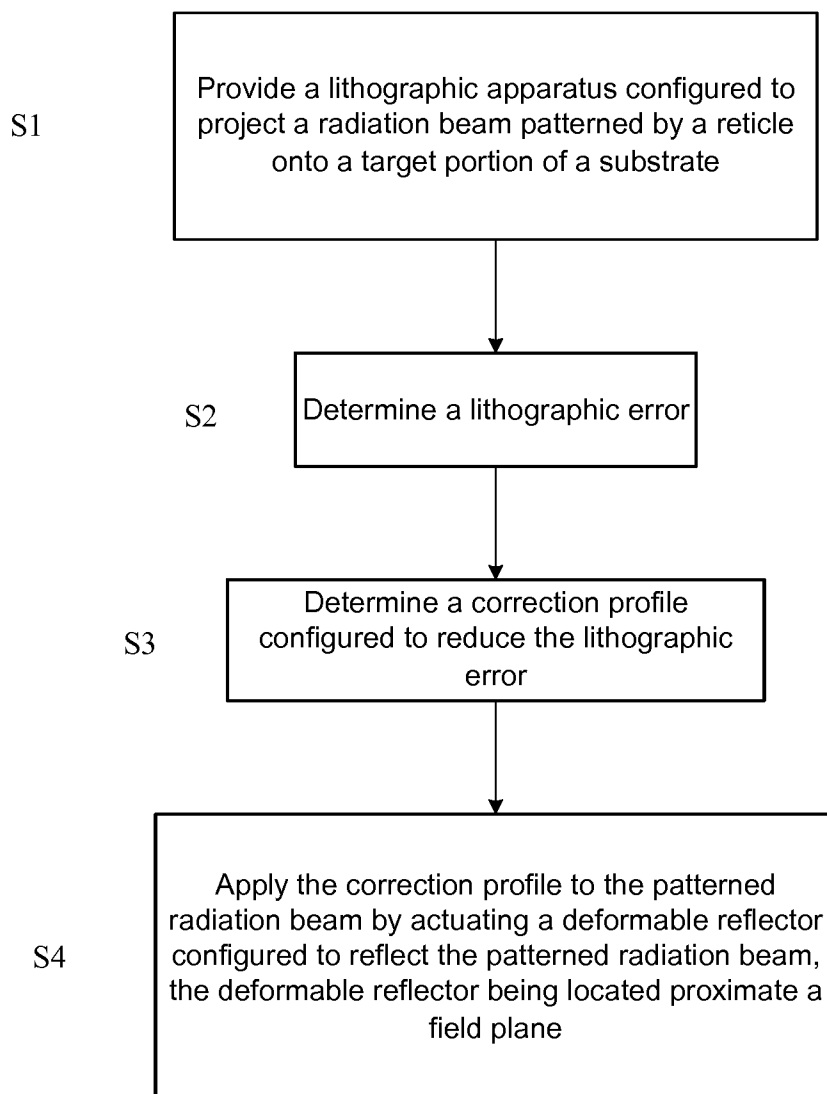


Fig. 5

**Fig. 6**

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/083212

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 G02B7/18 G02B26/08
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 G02B

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 2015/022799 A1 (MANN HANS-JUERGEN [DE] ET AL) 22 January 2015 (2015-01-22)	1,2, 4-26, 29-31
Y	paragraphs [0047], [0052], [0064] - [0066]; figure 2	3
X	DE 10 2014 218474 A1 (ZEISS CARL SMT GMBH [DE]) 17 March 2016 (2016-03-17)	1,2, 4-27, 29-31
Y	paragraphs [0053], [0112], [0113]; figure 3	3,28
X	US 2005/162762 A1 (NOVAK W T [US]) 28 July 2005 (2005-07-28)	26,31
Y	paragraphs [0026], [0047], [0048], [0063]; figure 1	3,28



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

29 March 2018

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2017/083212

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2015022799 A1	22-01-2015	CN 102150068 A	10-08-2011
		CN 102937742 A	20-02-2013
		DE 102008046699 A1	11-03-2010
		JP 5600680 B2	01-10-2014
		JP 6103507 B2	29-03-2017
		JP 2012502490 A	26-01-2012
		JP 2015029107 A	12-02-2015
		KR 20110053273 A	19-05-2011
		TW 201015235 A	16-04-2010
		US 2011165522 A1	07-07-2011
		US 2015022799 A1	22-01-2015
		WO 2010028748 A1	18-03-2010

DE 102014218474 A1	17-03-2016	CN 107077074 A	18-08-2017
		DE 102014218474 A1	17-03-2016
		EP 3195060 A1	26-07-2017
		JP 2017528775 A	28-09-2017
		KR 20170053713 A	16-05-2017
		TW 201621470 A	16-06-2016
		US 2017168399 A1	15-06-2017
		WO 2016041805 A1	24-03-2016

US 2005162762 A1	28-07-2005	US 2005162762 A1	28-07-2005
		US 2006193065 A1	31-08-2006
