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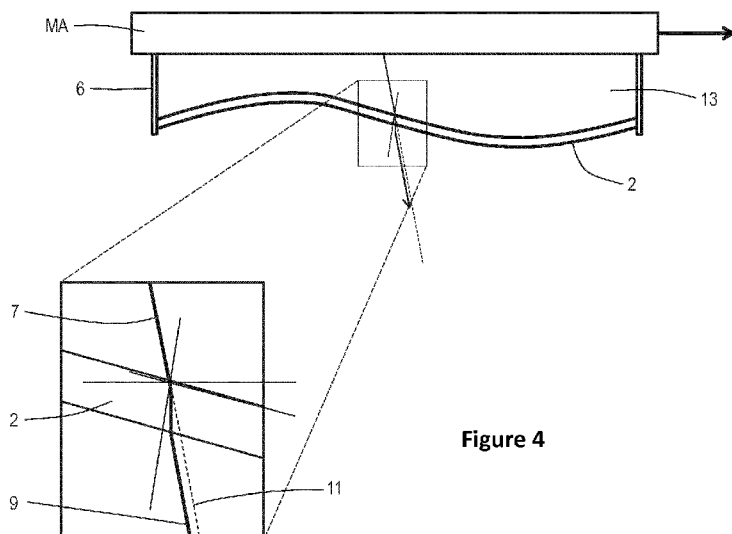


Figure 4

(57) **Abstract:** A method of controlling a lithographic apparatus having an exposure mode configured to expose a wafer held by a substrate table to an image of a pattern on a production reticle via a projection system, wherein in the exposure mode the production reticle is held at a reticle stage and is protected by a pellicle. The method comprises determining characteristics of the projecting in a calibration mode. The determining comprises moving the reticle stage holding a further reticle protected by a further pellicle, the further reticle having a mark. During the moving the further reticle is illuminated with radiation to form an aerial image of the mark, the aerial image is projected via the projection system onto a sensor and the projected aerial image is sensed as received at the sensor. The characteristics of the sensed aerial image are determined.

Scanning Measurement System

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 15197301.3 which was filed on
5 1 December 2015 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to a measurement system capable of determining
parameters such as, for example, overlay errors caused by deformation of a transparent film in an
10 imaging system. The measurement system may be used in connection with a lithographic
apparatus.

BACKGROUND

[0003] A lithographic apparatus is a machine constructed to apply a desired pattern onto
15 a substrate. A 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
20 (resist). In general, a single substrate will contain a network of adjacent target portions that are
successively exposed to a beam of radiation. 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 a beam of radiation in a given direction (the “scanning”-direction) while
25 synchronously scanning the substrate parallel or anti-parallel to this direction.

[0004] The patterning device may be protected from contamination by a transparent film
known as a pellicle. The act of scanning the pattern through a beam of radiation may deform the
pellicle. Deformations of the pellicle cause overlay errors to occur at the substrate. It is
desirable to determine the presence of such overlay errors, amongst other parameters, in order to
30 correct for them.

[0005] It is an object of the present invention to provide a system and method of determining, amongst other parameters, overlay errors caused by a deformation of a pellicle which at least partially addresses one or more of the problems of the prior art, whether identified herein or elsewhere.

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SUMMARY

[0006] According to a first aspect described herein, there is provided a method of controlling a lithographic apparatus having an exposure mode configured to expose a wafer held by a substrate table to an image of a pattern on a production reticle via a projection system, wherein in the exposure mode the production reticle is held at a reticle stage and is protected by a pellicle. The method comprises determining characteristics of the projecting in a calibration mode. The determining comprises moving the reticle stage holding a further reticle protected by a further pellicle, the further reticle having a mark. During the moving the further reticle is illuminated with radiation to form an aerial image of the mark, the aerial image is projected via the projection system onto a sensor and the projected aerial image is sensed as received at the sensor. The characteristics of the sensed aerial image are determined. The controlling comprises moving in the exposure mode at least one of the projection system, the reticle stage and the substrate table during the exposing in dependence on the characteristics.

[0007] Performing a scanning motion while making measurements provides an accurate representation of the effects of a scanning motion that may occur in the exposure mode, such as, for example, fading effects and/or pellicle deformation effects. Using a sensor to measure errors, such as, for example, pellicle deformation effects is more convenient and less time consuming than carrying out a measurement exposure on a test die. Fitting a pellicle to the reticle and performing measurements while scanning the reticle allows pellicle deformation effects such as overlay errors to be emulated and measured in the calibration mode of a lithographic apparatus. Making measurements in the calibration mode that are representative of effects that occur in the exposure mode is advantageous as the measurements may be subsequently used to make corrections to and improve an exposure in the exposure mode, e.g., improved overlay.

[0008] The sensor may comprise a detector and a detector grating configured to receive the aerial image and transmit radiation to the detector.

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[0009] A calibration measurement may be performed to position the detector grating in linear alignment with the aerial image prior to the determining.

[00010] Linear alignment may comprise an alignment between the aerial image and the detector grating in which the detected intensity varies linearly with the position of the detector in
5 a direction perpendicular to the movement of the reticle.

[00011] The mark may comprise a grating line that extends along a direction parallel to the movement of the reticle.

[00012] The detector grating may comprise a first grating line that corresponds to the grating line of the mark.

10 [00013] For example, the first grating line may be aligned with the grating line of the mark in a direction perpendicular to a scanning direction of the reticle and in a direction parallel to the scanning direction of the reticle. The first grating line and the grating line of the mark may have different lengths in the scanning direction of the reticle. The first grating line may comprise a plurality of further grating lines that extend along a direction perpendicular to the movement of
15 the reticle.

[00014] The mark may comprise one or more second grating lines that extend along a direction perpendicular to the movement of the reticle.

[00015] The grating line of the mark may comprise the one or more second grating lines.

[00016] The mark may be configured to diffract radiation passing through it.

20 [00017] Movement of the reticle stage during the determining may be initiated before radiation is received at the sensor.

[00018] The further reticle may be a calibration reticle.

[00019] The further reticle may be the production reticle.

[00020] The mark may be located outside an image field of the production reticle.

25 [00021] According to a second aspect described herein there is provided a lithographic apparatus comprising an illumination system configured to condition a radiation beam, a reticle stage constructed to hold a reticle, the reticle having a pattern and being protected by a pellicle, a substrate table constructed to hold a wafer, a projection system configured to expose the wafer to an image of the pattern, a positioning apparatus configured to move the reticle stage, wherein the
30 lithographic apparatus further comprises, a computer readable medium for storing computer

readable code wherein the code causes the lithographic apparatus to perform the method described above.

[00022] According to a third aspect described herein there is provided a computer readable medium for storing computer readable code wherein the code causes a lithographic apparatus to perform the method described above.

BRIEF DESCRIPTION OF THE DRAWINGS

[00023] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

[00024] Figure 1 schematically depicts a lithographic system comprising a scanning measurement system according to a particular example embodiment of the invention;

- Figure 2 schematically depicts a pellicle fitted to a patterning device;
- Figure 3 (a)-(c) schematically depicts a patterning device with a pellicle fitted to at three different times during an exposure scan;

- Figure 4 schematically depicts the effect of pellicle deformation on an intended optical path of incident radiation passing through a pellicle;

- Figure 5 schematically depicts a scanning measurement system;
- Figure 6 (a)-(c) schematically depicts an alignment between an aerial image of a reticle mark and a detector grating at three different times during a reference measurement;

- Figure 7 (a)-(c) schematically depicts the alignment between a deformed aerial image of the reticle mark and a detector grating at three different times during a measurement scan;

- Figure 8 schematically depicts an arrangement of a reticle having two marks and a sensor having two detector gratings;

- Figure 9 schematically depicts another reticle mark and detector grating arrangement;

- Figure 10 is a flowchart indicating the processes taken in using the scanning measurement system to preemptively correct for errors at an exposure stage of a lithographic apparatus.

DETAILED DESCRIPTION

[00025] 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

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 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 to a substrate that already contains multiple processed layers.

[00026] 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 4-20 nm), as well as particle beams, such as ion beams or electron beams. EUV radiation may have a wavelength of less than 10 nm, for example within the range of 4-10 nm such as 6.7 nm or 6.8 nm.

[00027] 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 functional layer in a device being created in the target portion, such as an integrated circuit.

[00028] 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 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.

[00029] The support structure holds the patterning device. It holds the patterning device in a way that depends on the orientation of the patterning device, the design of the lithographic apparatus, 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. Any use of the terms “reticle” or “mask” herein may be considered synonymous with the more general term “patterning device”.

[00030] 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 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”.

[00031] The term “illumination system” used herein may encompass various types of optical components, including refractive, reflective, and catadioptric optical components for directing, shaping, or controlling the beam of radiation, and such components may also be referred to below, collectively or singularly, as a “lens”.

[00032] 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.

[00033] Figure 1 schematically depicts a lithographic apparatus according to a particular example embodiment. The apparatus comprises:

- a. an illuminator IL to condition a beam PB of radiation (e.g. DUV radiation).
- b. a support structure (which may be referred to as a mask table) MT to support a patterning device (e.g. a mask) MA and connected to first positioning device PM to accurately position the patterning device with respect to item PL;
- c. a substrate table (which may be referred to as a wafer table) WT2 for holding a substrate (e.g. a resist coated wafer) W2 and connected to second positioning device PW2 for

accurately positioning the substrate with respect to item PL, the second positioning device PW2 comprising a sensor apparatus SA located beside the substrate W2;

d. another substrate table WT1 for holding a substrate W1 and connected to third positioning device PW3 for accurately positioning the substrate with respect to an alignment system AS;

e. a processor PR configured to receive measurements from the sensor apparatus SA and determine alignment and error information from the measurements;

f. a controller CN configured to receive information from the processor PR and make corresponding adjustments to item PL; and

g. a projection system (e.g. a refractive projection lens) PL configured to image a pattern 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 W2.

[00034] 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 mirror array of a type as referred to above).

[00035] 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. The source SO and the illuminator IL, together with the beam delivery system BD if required, may be referred to as a radiation system.

[00036] The illuminator IL may comprise adjusting means AM for adjusting the angular intensity distribution of the beam. Generally, at least the outer and/or inner radial extent 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.

[00037] 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 W2. With the aid of the second positioning device PW2 and position sensor IF (e.g. an interferometric device), the substrate table WT2 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 tables MT and WT2 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 PW2. 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.

[00038] The lithographic apparatus may for example move the patterning device MA and the substrate W2 with a scanning motion when projecting the pattern from the patterning device onto a target portion C. Cartesian coordinates are indicated in Figure 1. As is conventional, the z-direction corresponds with an optical axis of the radiation beam PB. In an embodiment in which the lithographic apparatus is a scanning lithographic apparatus, the y-direction corresponds with the direction of scanning motion.

[00039] As depicted, the lithographic apparatus may be of a type having two (dual stage) or more substrate tables WT1, WT2. In a dual stage lithographic apparatus two substrate tables WT1, WT2 are provided in order to allow properties of one substrate W1 to be measured while exposure of another substrate W2 is taking place ("exposure of a substrate" means projection of patterned radiation onto the substrate as described above).

[00040] The patterning device MA may be protected from contaminant particles by a thin transparent film known as a pellicle. The pellicle is positioned at a distance from the patterning device MA that is sufficient that any particles that are incident upon the surface of the pellicle are not in the focal plane of the radiation beam PB. This separation between the pellicle and the mask MA, acts to reduce the extent to which any particles on the surface of the pellicle impart a pattern to the radiation beam PB. It will be appreciated that where a particle is present in the beam of radiation PB, but at a position that is not in a focal plane of the beam of radiation PB (i.e., not at the surface of the mask MA), then any image of the particle will not be in focus at the surface of the substrate W. In some embodiments, the separation between the pellicle and the mask MA may, for example, be between 2 mm and 3mm (e.g. around 2.5 mm).

[00041] Figure 2 is a schematic diagram of a pellicle 2 fitted to a patterning device MA. The patterning device MA has a patterned surface 4. A pellicle frame 6 which supports the pellicle 2 is provided with an attachment mechanism 8. The attachment mechanism 8 may be configured to allow the pellicle frame 6 to be removably attachable to the mask MA (i.e. to allow the pellicle frame 6 to be attachable to and detachable from the mask MA). The attachment mechanism 8 is configured to engage with an attachment feature (not shown) provided on the mask MA. The attachment feature may, for example, be a protrusion which extends from the mask MA. The attachment mechanism 8 may, for example, comprise a locking member which engages with the protrusion and secures the pellicle frame 6 to the mask MA. A contamination particle 10 was incident upon the pellicle 2 and is held by the pellicle 2. The pellicle 2 holds the contamination particle 10 sufficiently far from the patterned surface 4 of the mask MA that it is not imaged onto substrates by the lithographic apparatus.

[00042] It will be appreciated that the pellicle 2 may be formed from different material depending upon the characteristics of the lithographic apparatus and that the choice of pellicle may affect the distortion induced image errors. For example, the lithographic apparatus of Figure 1 is a deep ultraviolet (DUV) lithography apparatus which uses DUV radiation to illuminate a patterning device MA then the pellicle 2 used may be a DUV transparent pellicle, e.g. an amorphous fluoropolymer such as Cytop. Another type of lithography apparatus uses Extreme Ultraviolet (EUV) radiation (an example of which is described in, and depicted in Figures 1 and 2 of, US20150253679, "Lithographic Method and Apparatus", the entire contents of which are incorporated herein by reference). If a lithographic apparatus uses EUV radiation to illuminate a patterning device MA then the pellicle of that lithographic apparatus may be an EUV transparent pellicle, and other suitable materials may be used to form the EUV transparent pellicle. The pellicle 2 may, for example, be formed from a material such as polysilicon (pSi) film. Polysilicon (pSi) film is substantially transparent to EUV radiation. A pellicle may alternatively be formed from some other material which is substantially transparent to EUV radiation, for example graphene, silicene, etc. By the terms EUV transparent pellicle and DUV transparent pellicle, or a film substantially transparent for EUV radiation or DUV radiation, herein it is meant that the pellicle 2 transmits at least 65% of incident EUV radiation or DUV radiation, preferably at least 80% and more preferably at least 90% of incident EUV radiation or DUV radiation. A capping layer which may help to reduce the effect of hydrogen radicals,

plasma and traces of oxygen on the pellicle 2 may be provided. The capping layer may be provided both on the pellicle 2 and on the pellicle frame 6.

[00043] Referring to the DUV lithographic apparatus of Figure 1, when the patterning device MA is moved during a photolithographic exposure scan the pellicle 2 may deform due to differences in local air pressures. When the patterning device MA moves during a photolithographic exposure scan the local air pressures around the pellicle 2 may fluctuate and act on different parts of the pellicle 2. The fluctuating air pressures acting on the pellicle 2 cause deformation of the pellicle 2. The deformation of the pellicle 2 depends on parameters such as the speed and direction of movement of the pellicle 2 during a photolithographic exposure scan. For EUV lithography apparatuses, pellicle deflections may be induced causes other than gas pressure gradients, e.g., by the pellicle's inertia. For example, the pellicle of an EUV lithography apparatus may be attached along its sides to a frame that is moved together with the patterning device. Owing to the stiffness of the pellicle's material the free area of the pellicle is pulled by the parts of the pellicle attached to the frame. Due to gravity and thermal expansion the pellicle may sag. In some embodiments, the patterning device of an EUV lithography apparatus may be of a reflective type. Accordingly, pressure waves in the pellicle's material are induced by forces and torques that dynamically distort the radiation path twice: the incident light via the pellicle to the patterning device and then the reflected light from the patterning device via the pellicle to the downstream components of the lithography apparatus.

[00044] Figure 3 schematically depicts a patterning device MA with a pellicle 2 fitted to it via a pellicle frame 6 at three different times (a), (b) and (c) during a photolithographic exposure scan. The patterning device MA is scanned through a radiation beam PB in the positive y direction in the example of figure 3. The radiation beam PB is imparted with a pattern on passing through the patterning device MA, and is then incident on a projection system PL configured to image the pattern imparted to the radiation beam PB onto a target portion of a substrate (not shown).

[00045] The images on the right-hand side of figure 3 are magnified schematic depictions of the patterning device MA and pellicle 2 shown on the corresponding images on the left-hand side of figure 3. The images on the right-hand side of figure 3 provide examples of how the pellicle 2 may deform during an exposure scan. The deformation of the pellicle 2 may change throughout the exposure scan due to changing air pressures over the surface of the pellicle 2. As

can be seen in figure 3, the deformation of the pellicle 2 is not uniform throughout the depicted exposure scan. A tangent line 5 to a portion of the pellicle 2 located beneath the radiation beam PB changes angle with respect to the radiation beam PB in each of the images (a), (b) and (c). In general the pellicle 2 deformation is neither uniform nor stable throughout an exposure scan.

5 Deformation of the pellicle 2 is more likely to occur when the scan motion is relatively fast, such as, for example, when the patterning device MA and pellicle frame 6 move at a speed of approximately 4 ms^{-1} .

[00046] Pellicle deformation results in the surface of the pellicle 2 tilting with respect to incident radiation PB. That is, the angle of the normal of the deformed pellicle surface with
10 respect to the z axis (shown in figure 3) is different to that of a non-deformed pellicle 2. Radiation PB incident on a deformed pellicle has a different angle of incidence than it would have with a non-deformed pellicle. As can be seen in the images on the right-hand side of figure 3, the tangent line 5 to the portion of the pellicle 2 beneath the radiation beam PB is not perpendicular to the incident radiation PB.

15 [00047] Figure 4 schematically depicts the effect of pellicle deformation on an intended optical path 11 of incident radiation 7 passing from a pellicle cavity 13 (i.e. the space between the patterned surface of the patterning device and the pellicle) through the pellicle 2 of the DUV lithography apparatus of Figure 1. The incident radiation 7 refracts as it passes through the deformed pellicle 2. The refraction causes the incident radiation 7 to deviate from its intended
20 optical path 11. The extent of the optical path deviation depends on the refractive index of the pellicle 2, the refractive index of the pellicle cavity 13 and the angle of incidence of the radiation. As can be seen in the magnified portion of figure 4, the optical path of the refracted radiation 9 has shifted with respect to its intended position 11 as a result of the pellicle 2 deformation.

25 [00048] 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 W2 may be known as overlay errors. The optical path deviations caused to radiation as a result of the pellicle deformation may result in overlay errors occurring at the substrate W2. That is, the image imparted to the radiation beam PB by the patterning device MA is misaligned with its
30 intended position on the substrate W2 due to optical path deviations caused by the deformed pellicle 2.

[00049] 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 2 through which the radiation beam PB passed before illuminating that point of the die. For example, a pellicle 2 region which has undergone a large deformation will typically cause a large overlay error for a die exposed to radiation passing through that pellicle region.

[00050] The pellicle 2 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 (positive y direction) and scan-down (negative y direction) respectively as the scans typically take place in opposite directions along the same axis.

[00051] It will be appreciated that, as described above, where the patterning device is reflective (e.g. as it may be in an EUV lithography apparatus), the radiation will have traversed the pellicle twice, but that the effect as illustrated for the DUV lithography apparatus is similar.

[00052] Dual-stage lithographic apparatus, such as the one depicted in figure 1, comprise a measurement stage WT1 as well as an exposure stage WT2. The measurement stage WT1 is used to determine various characteristics of a substrate W, such as its topography and positioning. A number of errors associated with the lithographic apparatus such as, for example, magnification errors, focus errors and overlay errors, as well as the positioning of the substrate W2 with respect to the patterning device MA may be measured at the exposure stage WT2.

[00053] Error measurements performed at the exposure stage WT2 may be used to correct for errors that occur during a photolithographic exposure at the exposure stage WT2. For example, magnification error measurements may be provided to the processor PR that analyses the magnification error measurements. The processor PR may then provide information to the controller CN that adjusts components and/or parameters of the lithographic apparatus in order to correct for the magnification error measurements in preparation for an exposure scan. The controller CN may, for example, make adjustments to the projection system PL in order to correct for the measured magnification errors. As another example, the controller CN may make adjustments to the position of the substrate table WT2 by providing instructions to the second positioning device PW2. As a further example, the controller CN may make adjustments to

parameters of the radiation beam PB such as, for example, adjusting the wavelength of the radiation beam PB by providing instructions to the radiation system. In general, the controller CN may adjust one or more components of a lithographic apparatus in response to the information provided by the processor PR.

5 [00054] Error measurements are typically performed with the patterning device MA kept stationary. Keeping the patterning device MA stationary during error measurement does not account for the errors introduced by pellicle 2 deformation during exposure scans. This is because pellicle 2 deformation is a result of a scanning motion of the patterning device MA during an exposure scan, and the patterning device does not undergo a scanning motion during
10 stationary measurement.

[00055] One method of accounting for the scanning motions of the patterning device MA made during an exposure scan and the related pellicle 2 deformation involves carrying out a similar scanning motion of the patterning device MA during measurement at the exposure stage WT2. That is, the pellicle 2 deformation may be accounted for by performing a measurement
15 scan that replicates an exposure scan. The measurement scan that determines pellicle 2 deformation effects may be performed within a lithographic apparatus. The measurement scan that determines pellicle 2 deformation effects may be performed outside of a lithographic apparatus such as, for example, in an independent scanning measurement system. The results of the measurement scan may be analyzed to provide instructions for controlling a lithographic
20 apparatus. The set of instructions may be stored on a computer readable medium storing computer readable code. The computer readable medium storing the instructions for controlling a lithographic apparatus may be provided to the lithographic apparatus in order to control the lithographic apparatus. The measurement scan may take place as part of a calibration mode of a lithographic apparatus. The measurement scan involves movement of the patterning device MA.
25 The more accurately the measurement scan at the exposure stage WT2 can replicate the exposure scan, the more accurately overlay errors and focus errors may be determined and corrected for.

[00056] Figure 5 is a schematic depiction of a scanning measurement system 12. The scanning measurement system 12 comprises a reticle MA with a pellicle frame 6 holding a pellicle 2. The reticle has a mark 14. The mark 14 may comprise a grating line. The length and
30 orientation of the grating line with respect to the reticle MA may depend on what quantity is being measured during a measurement scan. For example, to determine magnification errors

present along the x direction of the reticle MA, the mark 14 may comprise a grating line extending along a substantial portion of the reticle's length in the y direction. As another example, to determine image curvature errors along the y direction of the reticle MA, the mark 14 may comprise a grating line extending along a small portion of the reticle's length in the x direction. The width of the grating line may be configured to diffract radiation incident on it. The reticle mark 14 is exposed to radiation during measurement. A projection system PL projects an image of the mark 14 onto the substrate table 16. The substrate table 16 holds a sensor that comprises a detector grating 18 above a detector 20. The detector 20 may, for example, be a photodiode. The detector grating 18 is similar in width and orientation to the mark 14 on the reticle MA. The image of the mark 14 at the sensor on the substrate table 16 is known as an aerial image.

[00057] A calibration measurement may be performed to move the mark 14 and the detector grating 18 into a desired alignment before a measurement scan takes place. During a calibration measurement the substrate table 16 is stepped in the x direction whilst pulses of radiation from, for example, a laser pass through the scanning measurement system 12. The intensity of radiation detected by the detector 20 is dependent on the alignment between the aerial image of the mark 14 and the detector grating 18 on the substrate table 16.

[00058] The graph to the right of figure 5 shows the intensity of radiation detected by the detector 20 as the substrate table 16 is stepped in the x direction underneath the length of the reticle MA during a calibration measurement. The more aligned the aerial image and the detector grating 18 are, the higher the detected intensity is. The circled region of the graph is the point of alignment between the aerial image and the detector grating 18 at which the detected intensity varies linearly with the position of the detector 20 in the x direction. This alignment may be known as linear alignment. Having the aerial image and the detector grating 18 linearly aligned allows errors such as magnification errors that are perpendicular to the scan-up or scan-down directions to be determined in a relatively simple manner. This is because the misalignment of the aerial image with the detector grating 18 in the x direction varies linearly with the detected intensity of radiation. For example, as the reticle MA is scanned along the y axis during a measurement scan, errors present along the x direction may be determined in a relatively simple manner from the detected intensity of radiation due to its linear relationship with image misalignment in the x direction. Having the aerial image and the detector grating 18

in other alignments is possible. However, linear alignment allows for relatively simple extraction of imaging error information via its linear relationship with the detected intensity.

[00059] A reference measurement may take place once the aerial image and the detector grating 18 have been moved into linear alignment. The reference measurement involves stepping the reticle MA in the scan-up or scan-down direction whilst keeping the substrate table 16 stationary. The reticle MA is stepped to the positions that measurements will take place during a subsequent scanning measurement. The purpose of the reference measurement is to determine the intensity of radiation detected at each position along the reticle mark 14 without any pellicle 2 deformation effects present. This allows a direct comparison to be made with the intensity signal detected during a measurement scan with pellicle 2 deformations present.

[00060] Figure 6 is a schematic depiction of the alignment between an aerial image 22 of a reticle mark 14 and the detector grating 18 at three different times a), b) and c) during a reference measurement. The aerial image 22 of the reticle mark 14 is in linear alignment with the detector grating 18 in the example of figure 6. The graph in figure 6 shows the detected intensity of radiation throughout the reference measurement. In the example of figure 6 the alignment between the aerial image 22 and the detector grating 18 does not change throughout the reference measurement. The graph shows that the detected intensity of radiation remains constant when the alignment between the aerial image 22 and the detector grating 18 does not change. As the reticle MA is stepped rather than scanned there are insignificant amounts of scanning-induced pellicle 2 deformations present during the reference measurement.

[00061] Once the reference measurement has been made, a scanning measurement may take place to determine imaging errors in a direction perpendicular to the scan-up or scan-down directions of the reticle MA. During a scanning measurement the substrate table 16 remains stationary and the reticle MA is scanned in the directions in which it would be scanned during a photolithographic exposure. The scanning speed of the reticle MA may be selected to provide an accurate replication of a photolithographic exposure scan. The reticle MA may be protected using a pellicle 2 that will be used (or is the same or similar to a pellicle that will be used) during a subsequent photolithographic exposure scan. Pulses of radiation are fired through the reticle mark 14 throughout the measurement scan. With a reticle MA having a length of, for example, 140mm, the speed of the reticle MA during the scan being, for example, 3.2 ms^{-1} and a laser

pulse frequency of, for example, 6kHz, it would be possible to take approximately 250 measurements across the full length of the reticle MA.

[00062] Figure 7 is a schematic depiction the alignment between a deformed aerial image 24 of the reticle mark 14 and the detector grating 18 at three different times a), b) and c) during a measurement scan. The aerial image 24 of the mark 14 may have become deformed due to, for example, pellicle deformation effects. The graph in the lower portion of figure 7 shows the detected intensity throughout the measurement scan. The detected intensity depends on the alignment between the aerial image 24 of the reticle mark 14 and the detector grating 18. As can be seen in figure 7, the degree of alignment between the aerial image 24 and the detector grating 18 changes throughout the measurement scan due to the deformed shape of the aerial image 24. At time a) the aerial image 24 and the detector grating 18 are close to being linearly aligned, and the detected intensity is relatively high. At time b) the aerial image 24 and the detector grating 18 are not well aligned, hence the detected intensity is low. At time c) the aerial image 24 and the detector grating 18 are close to being linearly aligned again and the detected intensity has increased to its original value.

[00063] Figure 8 is a schematic diagram of an arrangement of a reticle MA having two marks 14 and a sensor 26 having two detector gratings 18, each having a detector (not visible in figure 8) underneath them. A greater or smaller number of marks 14, detector gratings 18 and detectors may be used. The positions of the marks 14 on the reticle MA and the position of detector gratings 18 on the sensor 26 may be different to those shown in the example of figure 8. The arrangement shown in figure 8 may be used to measure imaging errors in a direction perpendicular to the scanning direction of the reticle MA, for example, magnifications of the aerial image 24 in the x direction. The arrangement comprises semi-isolated reticle marks 14 (i.e. the marks 14 are separated in the x direction by a distance that is significantly larger than the width of the marks in the x direction) that traverse a substantial portion of the length of the reticle MA in the y direction. Correspondingly positioned detector gratings 18 are located on the sensor 26. The reticle MA is scanned in the y direction during a measurement scan and the detected intensity of radiation at the sensor may be used to determine imaging errors in the x direction. Errors present in the y direction may be determined mathematically from the imaging errors determined in the x direction by way of a simulation using relevant physical theorems and

mathematics such as, for example, a computer model. Alternatively the imaging errors in the y direction may be measured independently.

[00064] Figure 9 is a schematic diagram of another reticle mark 14 and detector grating 18 arrangement. The arrangement shown in figure 9 may be used to measure imaging errors in a direction parallel to the scanning direction of the reticle MA such as, for example, curvature of the aerial image 24 in the y direction. The arrangement depicted in the example of figure 9 comprises three columns of multiple small marks 14 on the reticle MA and three columns of detector gratings 18 on the sensor. The detector grating 18 comprises two grating in each column. A greater or smaller number of marks 14, columns and detector gratings 18 may be used. Each of the three columns of marks 14 is at a respective different x position along the reticle MA. In the example of figure 9, the detector grating 18 spacing in the y direction is larger than the mark 14 spacing in the y direction in order to ensure that an intensity signal is present at all times throughout the scanning measurement. That is, there will be an intensity signal present regardless of the reticle MA position at any time at which a laser pulse is fired.

[00065] The magnitude of the detected intensity signal depends on the alignment between the detector gratings 18 and the marks 14. Performing a reference measurement (i.e. stepping the reticle MA in the scan-up or scan-down direction whilst keeping the substrate table 16 stationary) with the reticle mark 14 and detector grating 18 arrangement shown in figure 9 would provide a sinusoidal signal of detected intensity. The results of a scanning measurement may then be compared to the sinusoidal signal resulting from the reference measurement in order to determine errors in a direction parallel to the scan-up and scan-down directions of the reticle MA. It is not necessary to have the marks 14 and the detector gratings 18 in linear alignment to measure imaging errors in a direction parallel to the scan-up and scan-down directions of the reticle MA.

[00066] Carrying out measurement scans at the exposure stage WT2 simulates the effects present during an exposure scan at the exposure stage WT2 because radiation PB exits an exposure aperture of the same illuminator IL and is incident on a reticle MA and the same projection system PL for both scans. Use of a production reticle for measurement scans at the exposure stage WT2 is highly representative of exposure scans at the exposure stage WT2 as the same reticle MA is used at both stages. The measurement scan may be carried out with the production reticle at the exposure stage WT2 and then the second positioning device PW2 may

move the exposure stage WT2 such that a subsequent exposure scan may take place with the substrate W2 using corrections determined from the results of the measurement scan. It is preferable to have the reticle marks located outside an image field of the production reticle in order to avoid disturbing the pattern present in the image field of the production reticle. The pellicle deformation effects present outside the image field 36 of the production reticle are representative of the pellicle deformation effects present across the image field of the production reticle. The pellicle deformation effect present across the image field of the production reticle may be calculated from the measurements made outside the image field of the production reticle by the scanning measurement system 12. Parameters such as focus errors, overlay errors and the alignment of the aerial image 24 with respect to the detector grating 18 may be determined from the results of the measurement scans and any subsequent image field calculations.

[00067] Using a calibration reticle for measurement scans performed by the scanning measurement system 12 has the advantage of having reticle marks 14 positioned anywhere across the calibration reticle rather than just having reticle marks outside the image field of the calibration patterning device. The pellicle deformation effects may be measured across the entire calibration reticle rather than being measured outside its image field and subsequently calculated for the image field. In general, any reticle MA of any suitable shape or size with reticle marks 14 having any suitable shape, size or pattern may be used within the scanning measurement system 12.

[00068] As the deformation experienced by the pellicle 2 is different for different reticle MA scanning directions, multiple measurement scans may take place in the different reticle scanning directions for sufficient measurement of pellicle deformation effects.

[00069] The scanning measurement system 12 is not limited to measuring a single aerial image per measurement scan. Multiple reticle marks 14 may be illuminated with pulses of radiation. Multiple detector gratings 18 and associated detectors 20 may be used to measure the multiple aerial images during a single measurement scan.

[00070] Figure 10 is a flowchart indicating an example process which may be used to preemptively correct for errors at the exposure stage WT2 of a lithographic apparatus. With reference also to figure 1, the process begins at step S1 with the scanning measurement system 12 performing one or more measurement scans in a calibration mode. Once the detector 20 has received the radiation pulses transmitted by the detector grating 18 during a measurement scan it

may pass the output signals to the processor PR. At step S2, the processor PR may receive a number of measurements from the detector 20. At step S3, the processor PR may determine one or more parameters from the measurements such as, for example, focus errors, overlay errors, pellicle deformation effects and the alignment of the aerial image with respect to the detector grating 18. At step S4, the processor PR may provide the determined parameters to a controller CN which is configured to receive the parameters and make adjustments to the lithographic apparatus to correct for the parameters at step S5. Alternatively the controller CN may comprise a processor capable of determining parameters from measurements made by the scanning measurement system 12. The adjustments made to the lithographic apparatus by the controller CN may preemptively correct for the errors determined by the processor PR for an exposure scan at the exposure stage WT2. Once the adjustments have been made to the lithographic apparatus an exposure scan in an exposure mode may take place at the exposure stage WT2 at step S6.

[00071] The frequency with which the scanning measurement system 12 performs measurement scans in a lithographic apparatus may be determined by the stability of the pellicle 2 deformation effect. That is, the less stable the pellicle 2 deformation effect is, the more advantageous it is to carry out measurement scans frequently. If, for example, the pellicle 2 deformation effect is significantly different for each substrate W2 then it would be preferable to perform a measurement scan before each exposure scan takes place. However, the greater the frequency of measurement scans the less time is available for carrying out exposure scans, which will negatively affect the throughput of the lithographic apparatus. Wafers may be provided to the lithographic apparatus in batches. It may be preferable to perform a measurement scan each time a new batch of wafers is provided to the lithographic apparatus. It may be preferable to perform a measurement scan each time a new pellicle 2 is fitted to patterning device MA. It may be preferable to perform a measurement scan each time a different patterning device MA is to be used in the lithographic apparatus. Alternatively, it may be beneficial to perform measurement scans daily, or weekly, or monthly etc. In general, the measurement scans may be performed at a desired frequency.

[00072] 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 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.

[00073] Embodiments of the invention may be implemented in hardware, firmware,
5 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 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
10 memory (RAM); magnetic disk storage media; optical storage media; flash memory devices; electrical, optical, acoustical or other forms of propagated signals (e.g. carrier 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
15 devices, processors, controllers, or other devices executing the firmware, software, routines, instructions, etc.

[00074] 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 above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the
20 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 controlling a lithographic apparatus having an exposure mode configured to expose a wafer held by a substrate table to an image of a pattern on a production reticle via a projection system, wherein in the exposure mode the production reticle is held at a reticle stage and is protected by a pellicle, the method comprising determining characteristics of the projecting in a calibration mode;

the determining comprises:

moving the reticle stage holding a further reticle protected by a further pellicle, the further reticle having a mark;

during the moving:

illuminating the further reticle with radiation to form an aerial image of the mark;

projecting the aerial image via the projection system onto a sensor; and

sensing the projected aerial image as received at the sensor;

determining the characteristics of the sensed aerial image; and
the controlling comprises moving in the exposure mode at least one of the projection system, the reticle stage and the substrate table during the exposing in dependence on the characteristics.

2. The method of claim 1, wherein the sensor comprises a detector and a detector grating configured to receive the aerial image and transmit radiation to the detector.

3. The method of claim 2, wherein a calibration measurement is performed to position the detector grating in linear alignment with the aerial image prior to the determining.

4. The method of any one of claims 1 to 3, wherein the mark comprises a grating line that extends along a direction parallel to the movement of the reticle.

5. The method of claim 4, wherein the detector grating comprises a first grating line that corresponds to the grating line of the mark.

6. The method of any one of claims 1 to 5, wherein the mark comprises one or more second grating lines that extend along a direction perpendicular to the movement of the reticle.

7. The method of any one of claims 1 to 6, wherein the mark is configured to diffract radiation passing through it.

8. The method of any one of claims 1 to 7, wherein movement of the reticle stage during the determining is initiated before radiation is received at the sensor.

9. The method of any one of claims 1 to 8, wherein the further reticle is a calibration reticle.

10. The method of any one of claims 1 to 9, wherein the further reticle is the production reticle.

11. The method of claim 10, wherein the mark is located outside an image field of the production reticle.

12. A lithographic apparatus comprising:

an illumination system configured to condition a radiation beam;

a reticle stage constructed to hold a reticle, the reticle having a pattern and being protected by a pellicle;

a substrate table constructed to hold a wafer;

a projection system configured to expose the wafer to an image of the pattern;

a positioning apparatus configured to move the reticle stage, wherein the lithographic apparatus further comprises:

a computer readable medium for storing computer readable code wherein the code causes the lithographic apparatus to perform the method of any one of claims 1 to 11.

13. A computer readable medium for storing computer readable code wherein the code causes a lithographic apparatus to perform the method of any one of claims 1 to 12.

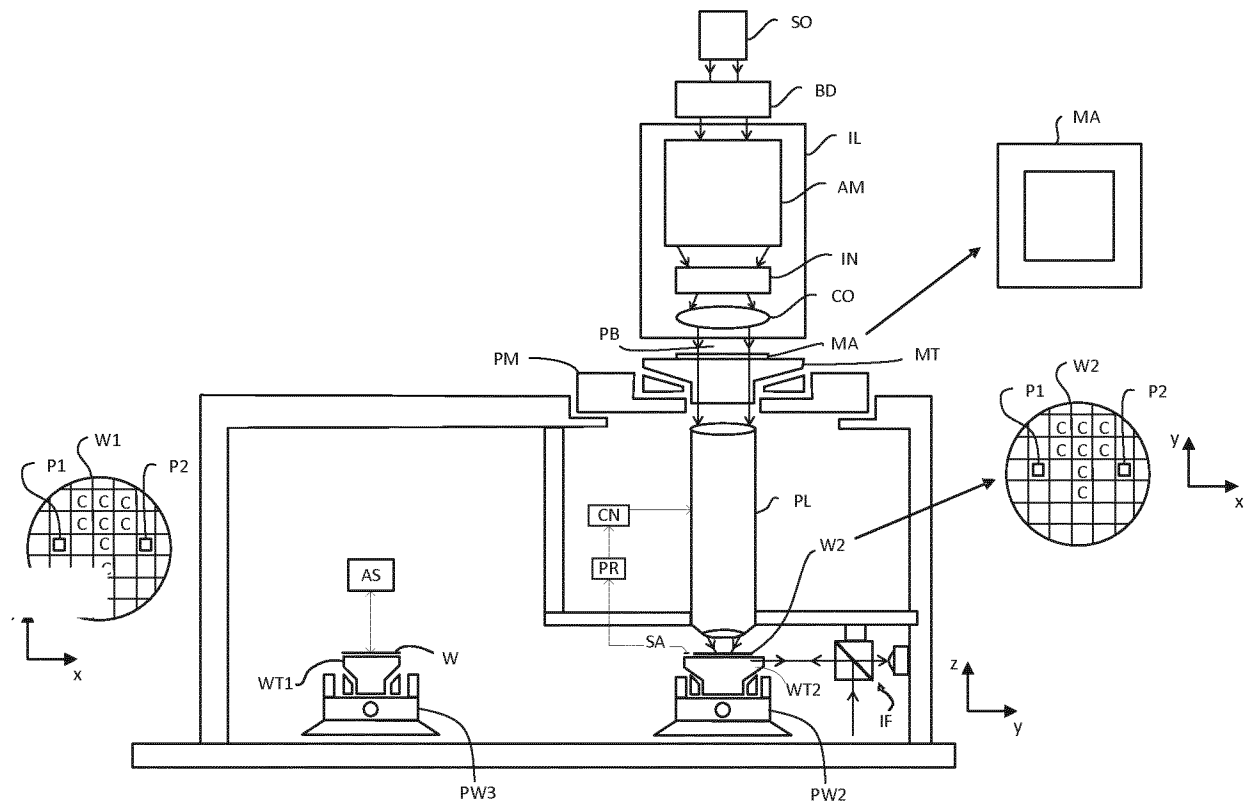


Figure 1

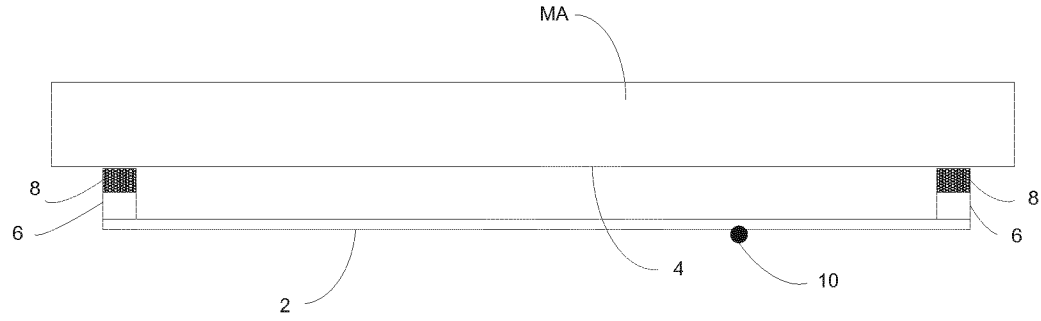


Figure 2

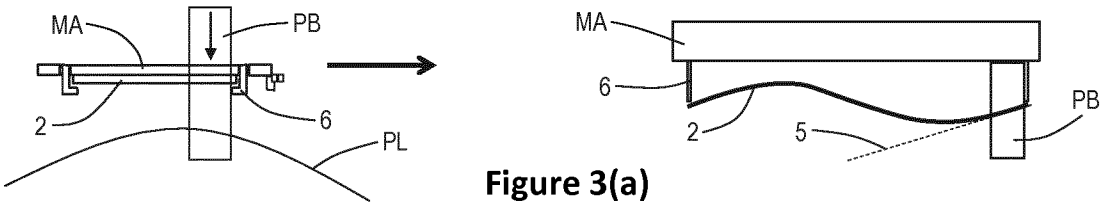


Figure 3(a)

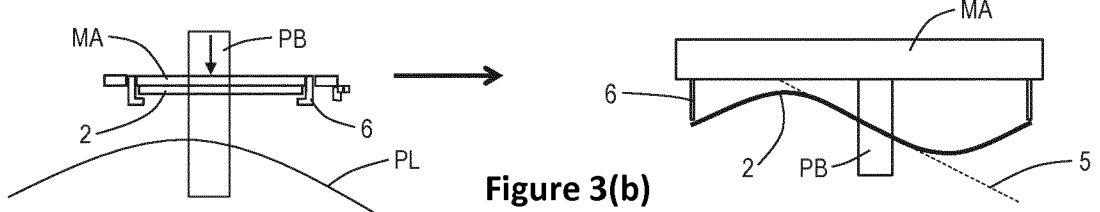


Figure 3(b)

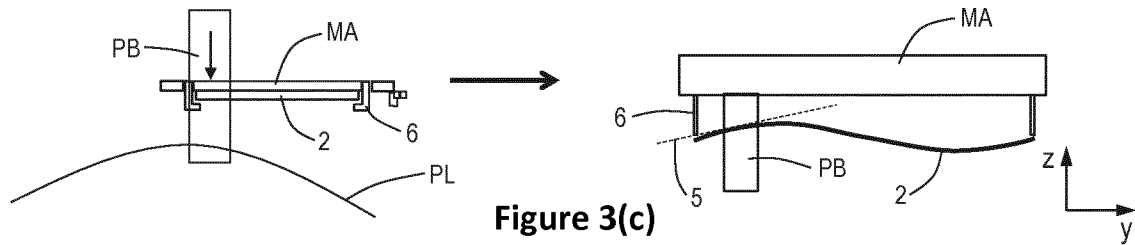


Figure 3(c)

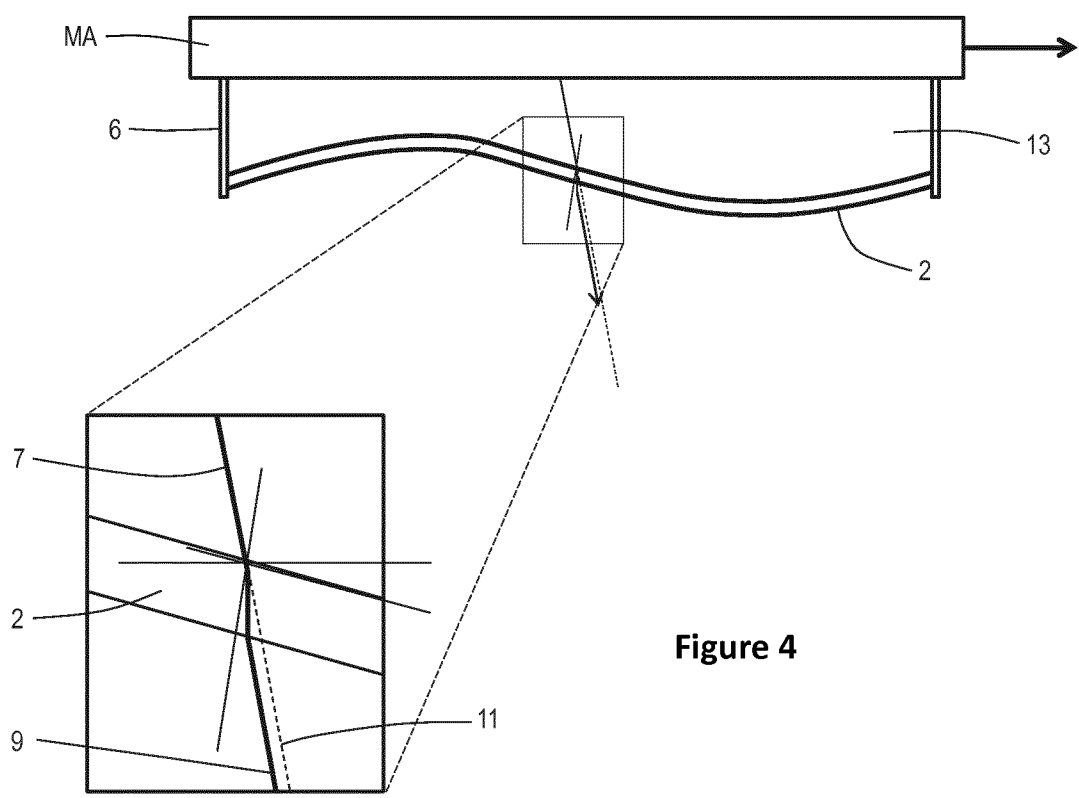


Figure 4

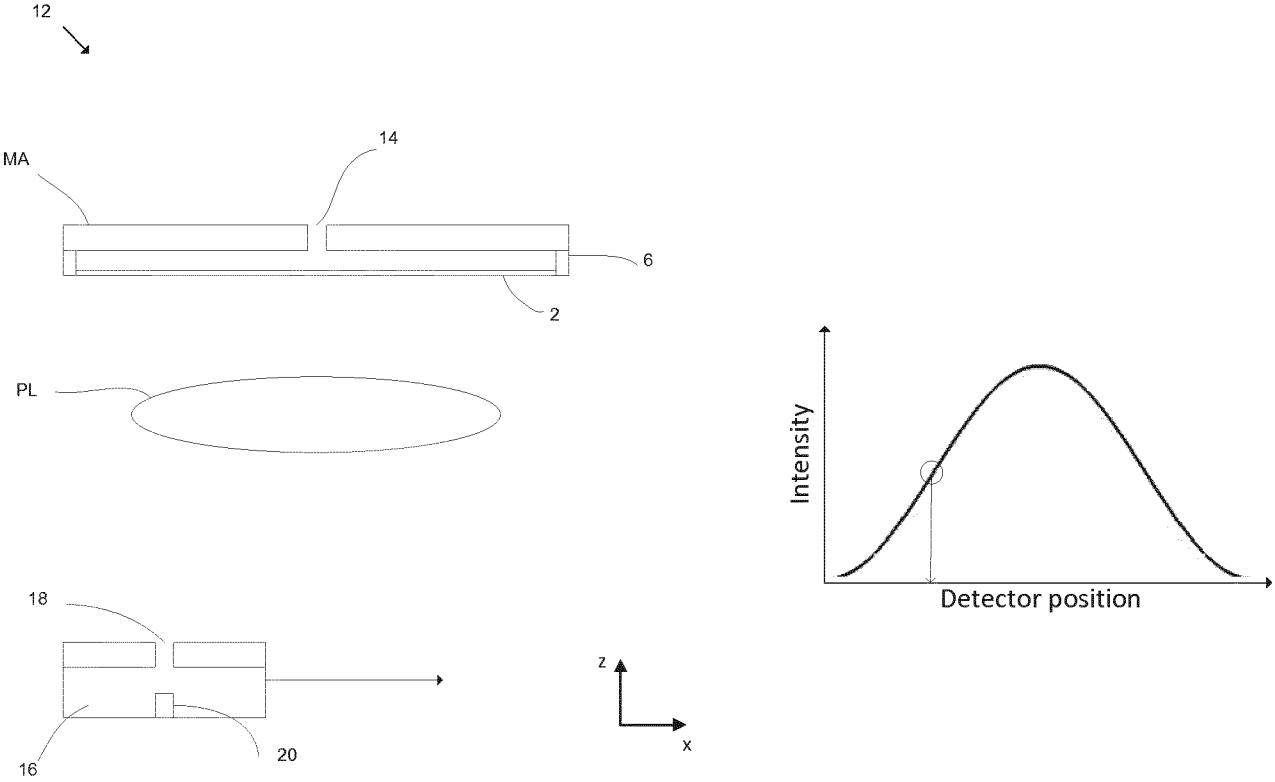


Figure 5

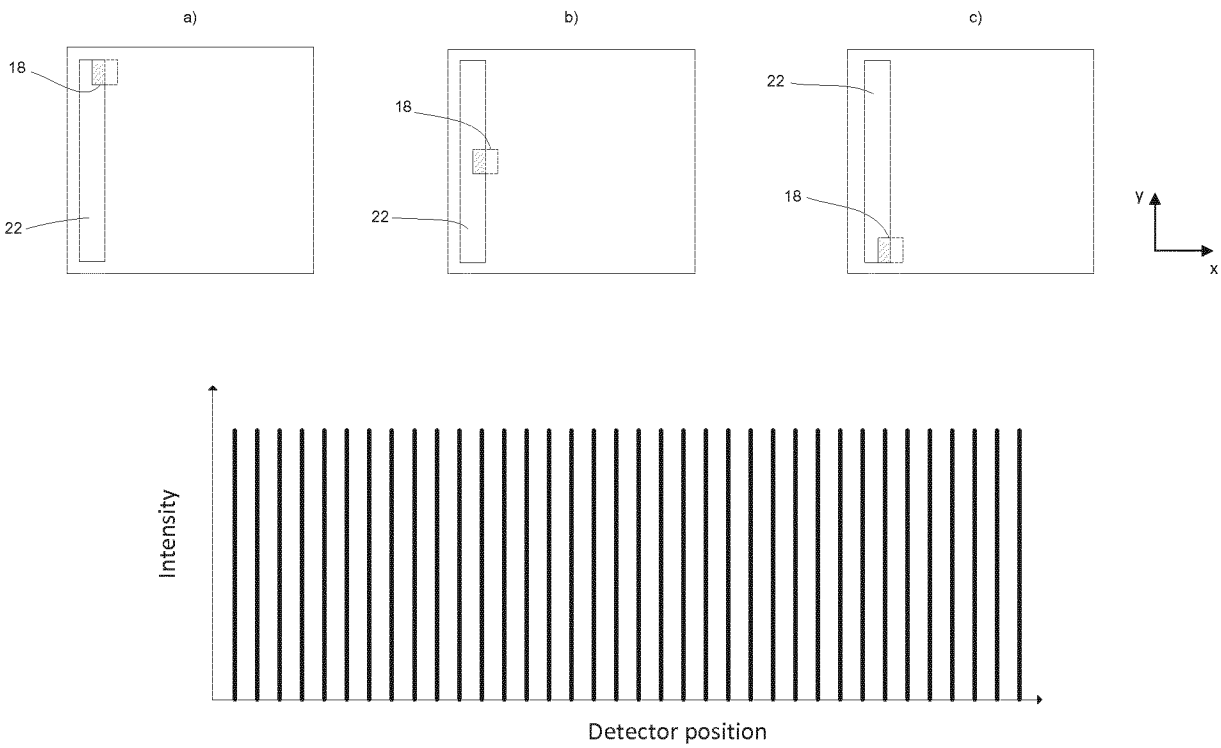


Figure 6

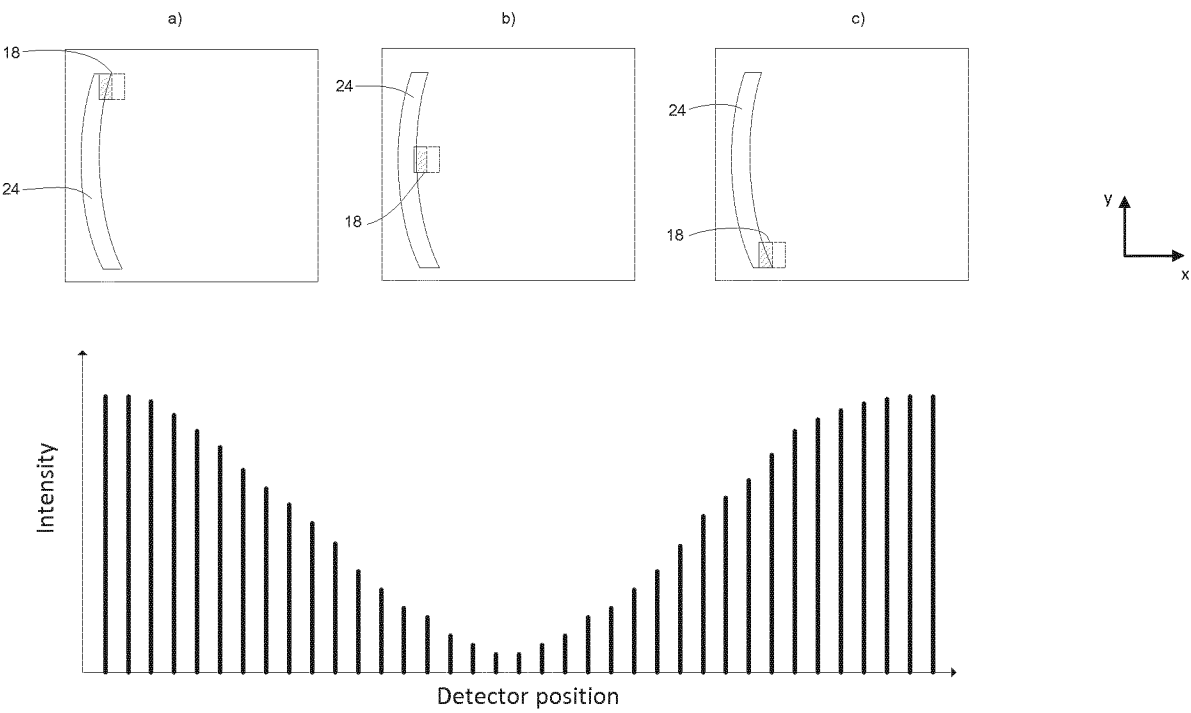


Figure 7

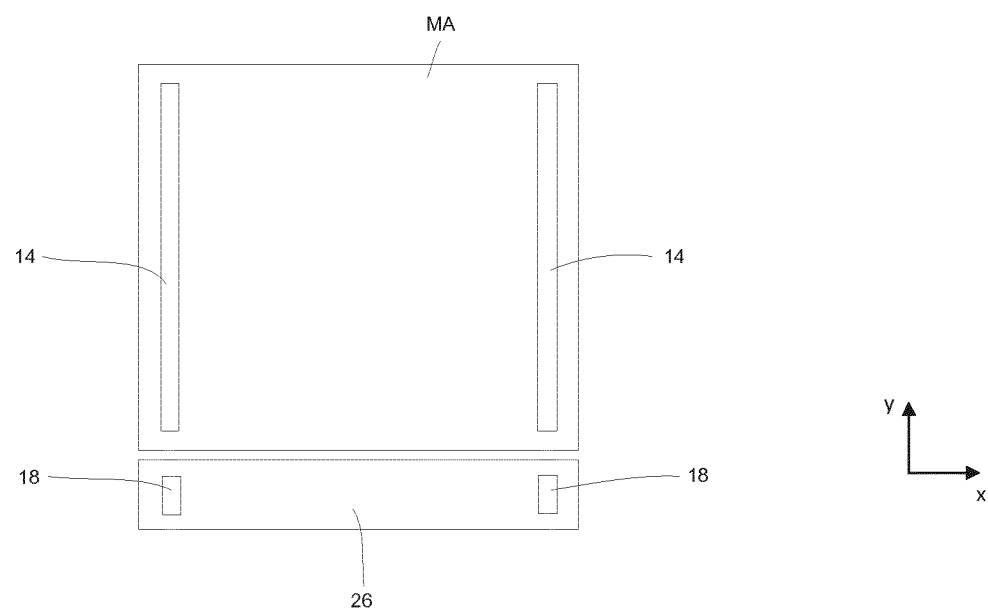


Figure 8

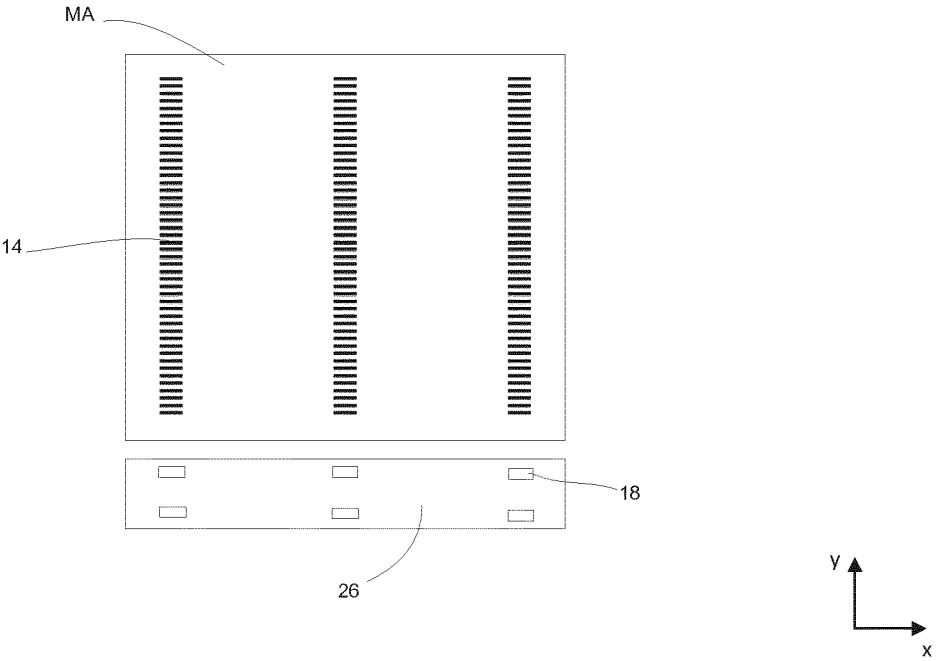
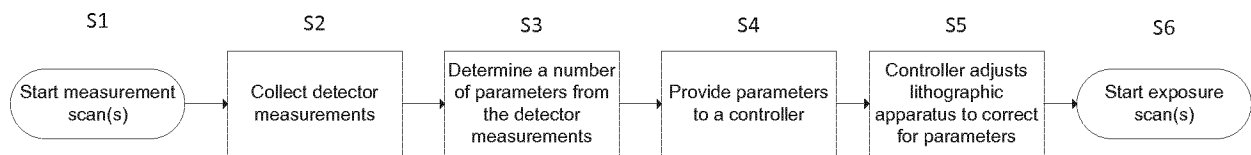


Figure 9

**Figure 10**

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/077039

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 G03F9/00
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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	EP 1 637 930 A2 (ASML NETHERLANDS BV [NL]) 22 March 2006 (2006-03-22) paragraph [0004] - paragraph [0147] figures 1-4,11,13 -----	1-13
Y	US 2004/109148 A1 (SHIMA SHINICHI [JP]) 10 June 2004 (2004-06-10) paragraph [0049] - paragraph [0058] figures 1-3 -----	1-13
A	US 2007/115452 A1 (MOEST BEARRACH [NL] ET AL) 24 May 2007 (2007-05-24) paragraph [0050] - paragraph [0052] figures 3,4 -----	1,4-6, 12,13
A	WO 2014/060149 A1 (ASML NETHERLANDS BV [NL]) 24 April 2014 (2014-04-24) the whole document -----	1,12,13



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

25 November 2016

Date of mailing of the international search report

02/12/2016

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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