



- (51) International Patent Classification:
G03F 7/20 (2006.01)
- (21) International Application Number:
PCT/EP2016/050145
- (22) International Filing Date:
7 January 2016 (07.01.2016)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
15156219.6 24 February 2015 (24.02.2015) EP
- (71) Applicant: ASML NETHERLANDS B.V. [NL/NL]; P.O.
Box 324, 5500 AH Veldhoven (NL).
- (72) Inventors: KLINKHAMER, Jacob, Fredrik, Friso; PO
Box 324, 5500 AH Veldhoven (NL). WEERTS, Koen,
Peter, Marie; PO Box 324, 5500 AH Veldhoven (NL).
- (74) Agent: KETTING, Alfred; ASML Netherlands B.V., PO
Box 324, 5500 AH Veldhoven (NL).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: LITHOGRAPHIC APPARATUS, MANIPULATOR SYSTEM AND METHOD OF CONTROLLING CURVATURE OF A FOCAL PLANE

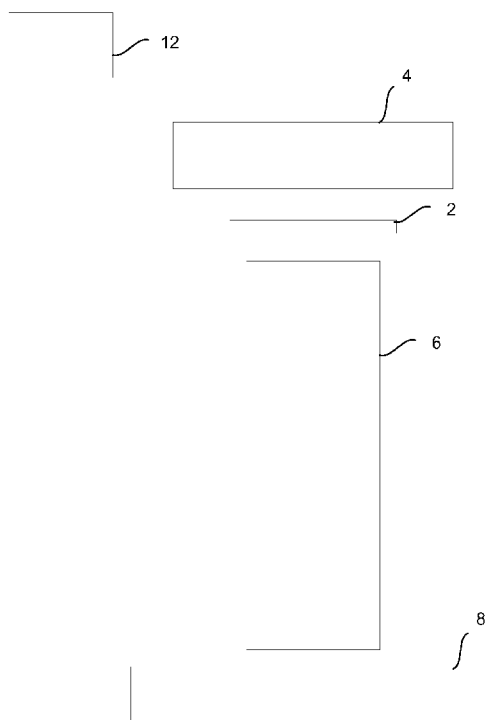


FIG. 2

(57) Abstract: A lithographic apparatus comprises a substrate table (WT) configured to hold a substrate (W), a projection system (6) configured to project a patterned radiation beam onto a target portion of the substrate, the projection system having a focal plane, a manipulator (2) comprising a plate and at least one actuator operable to deform the plate thereby to alter a shape of the focal plane, and a controller configured to control operation of the at least one actuator thereby to control curvature of the focal plane.



Published:

— *with international search report (Art. 21(3))*

LITHOGRAPHIC APPARATUS, MANIPULATOR SYSTEM AND METHOD OF CONTROLLING CURVATURE OF A FOCAL PLANE

CROSS REFERENCE TO RELATED APPLICATIONS

- 5 **[0001]** This application claims priority of EP application 15156219.6 which was filed on 2015-Feb-24 and which is incorporated herein in its entirety by reference.

FIELD

- 10 **[0002]** The present invention relates to a lithographic apparatus, and associated manipulator and method, and the control of a focal plane of the lithographic apparatus.

BACKGROUND

- 15 **[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

- 30 **[0004]** As the required sizes of features formed using lithographic techniques become smaller, there are increasingly stringent requirements for the accuracy and resolution of the lithographic apparatus. In general it is desired that the substrate is positioned precisely at the focal plane of a projection system of the lithographic apparatus such that a sharp image obtained from the patterning device is formed across the whole of the substrate surface.

- 35 **[0005]** In practice, the surface of the substrate may not be perfectly flat, for example due to edge roll-off effects in which manufacturing constraints mean that there can be variations in the shape or thickness of the substrate at edge regions of the substrate, for example within 1mm to 5mm of the edge of the substrate. Such variations can mean that even if the focal

plane were to be perfectly flat it would not coincide with the surface of the substrate over the whole area of the substrate.

[0006] Furthermore, variation in components and operating parameters of the lithographic apparatus itself, for example the projection optics of the lithographic apparatus, can cause variation of the shape and position of the focal plane, such that the focal plane may not be flat. For instance, heating effects arising from transmission of the radiation beam that forms the image on the substrate can cause distortion of one or more components of the projection system or other part of the lithographic apparatus, such as the reticle, which can in turn affect the position and shape of the focal plane.

[0007] Various suggestions have been made as to how to control the curvature of the focal plane. For example, it has been suggested to use a curved reticle to provide a curved focal plane. However, this requires careful grabbing of the reticle in order not to induce additional overlay effects, and for best results also requires frequent variation of the reticle shape during radiation exposure.

[0008] It has also been suggested to manipulate the focus curvature of the lens or lenses of the projection system. However, manipulating the curvature of lens internal mirrors is sensitive and requires modifications in the centre of the lens. Another suggestion is based upon varying the operational wavelength, which has a similar effect to changing a lens curvature. However, varying the operational wavelength also induces other effects that can only be corrected by adding other sensitive manipulation options in the centre of the lens.

[0009] Another suggestion based on manipulation of the focus requires a system with two glass plates with varying curvature positioned directly below the reticle, where one plate moves horizontally with respect to the other (Alvarez principle). However, such systems require high end mechatronics and require much space.

[0010] It has also been suggested to use a system with two glass plates and a water-filled cavity in between the plates, placed directly under the reticle, where the curvature of one plate is varied. However, this requires a water-filled cavity directly above the lens, which may result in a significant risk of damage.

[0011] It is known that even a single plate whose curvature is varied can result in a variation in focus. However in the context of a lithographic apparatus it is significant that variation in one parameter, such as focus, can also effect other optical parameters or effects. There are various known techniques for reducing unwanted optical effects in a lithographic system, for example represented as residual Zernike errors. However, space and performance constraints in lithographic systems are significant, and introduction of a further component,

for instance to control focal plane, can have significant knock-on effects on capacity to control or reduce unwanted effects arising from other components of the system.

SUMMARY

5 [0012] According to an aspect of the invention, there is provided a lithographic apparatus comprising a substrate table configured to hold a substrate, a projection system configured to project a patterned radiation beam onto a target portion of the substrate, the projection system having a focal plane, a manipulator comprising a plate and at least one actuator operable to deform the plate thereby to alter a shape of the focal plane, and a controller configured to
10 control operation of the at least one actuator thereby to control curvature of the focal plane.

[0013] Use of a manipulator comprising a deformable plate and associated actuator(s) may provide a particularly simple and effective way of controlling curvature of a focal plane of a lithographic apparatus. The controller may be configured to control the curvature of the focal plane to reduce the curvature thus to flatten the focal plane. The controller may be
15 configured to control the curvature of the focal plane to more closely align the focal plane with the surface of the substrate. The manipulator comprising a deformable plate, and which may be operable to control the curvature of the plate, may be referred to as a plate manipulator.

[0014] The deformation of the plate by operation of the at least one actuator may cause a
20 change in magnification, and the apparatus may further comprise a further manipulator operable to at least partially counteract said change in the magnification.

[0015] The combination of the manipulator and further manipulator may provide for effective control of focal plane curvature whilst counteracting associated magnification effects.

25 [0016] The further manipulator may form part of the projection system.

[0017] The further manipulator may comprise at least one movable optical element. The controller may be configured to control movement of the movable optical element thereby to at least partly counteract said change in magnification. The further manipulator may be operable to move said at least one optical element, for example at least one lens of the
30 projection system, along an optical axis of the projection system thereby to at least partly counteract said change in magnification.

[0018] The controlling of operation of the at least one actuator to control the curvature of the focal plane may comprise controlling operation of the at least one actuator to reduce curvature of the focal plane. The controlling of operation of the at least one actuator to

control the curvature of the focal plane may comprise controlling operation of the at least one actuator to control and/or reduce at least one aberration.

[0019] The controlling of operation of the at least one actuator to control focal plane curvature may comprise controlling and/or reducing at least one focus curvature component.

5 The at least one focus curvature component may comprise a focus curvature component having a single turning point, for example a single turning point for the area of the substrate.

[0020] Focal plane curvature components may be represented using Zernike polynomials, which may vary over the image field, and the controller may be configured to operate the actuators to control deformation of the plate manipulator, to provide desired values for, or to
10 reduce the values of, one or more suitable Zernike polynomials, for example including their variation over the image field, for instance thereby to control and/or reduce at least one focus curvature component.

[0021] A focus curvature component having a single turning point may comprise a component for which a variation of vertical position of the focal plane with lateral position
15 has a single peak for the area of the substrate.

[0022] The controlling of operation of the at least one actuator to provide a desired curvature may comprise controlling operation of the at least one actuator to control and/or reduce said focus curvature component having a single turning point, with substantially no other constraints.

20 [0023] The at least one focus curvature component may comprise at least one of a focus curvature component having two turning points, and/or a focus curvature component having three turning points, and/or a focus curvature component having four or more turning points.

[0024] A focus curvature component having n turning points may comprise a component for which a variation of vertical position of the focal plane with lateral position has n turning
25 points (e.g. peak(s) and/or trough(s)) for the area of the substrate

[0025] The controlling of operation of the at least one actuator to control curvature of the focal plane may comprise controlling operation of the at least one actuator to reduce focal plane curvature.

[0026] The controlling of operation of the at least one actuator to control curvature of the
30 focal plane may comprise controlling operation of the at least one actuator to reduce a roll-off effect.

[0027] The at least one actuator may comprise a plurality of actuators. The plurality of actuators may comprise at least 5 independently operable actuators, optionally at least 10

independently operable actuators, further optionally at least 20 independently operable actuators.

[0028] The manipulator may have substantially no optical power when the plate is undeformed.

5 [0029] The manipulator may be located at or close to a field plane, or at or close to a conjugate of the field plane.

[0030] The at least one actuator may comprise a plurality of actuators arranged in at least two rows of actuators around a region of the plate through which the patterned radiation beam passes in operation.

10 [0031] The plate may comprise a planar plate comprising, when undeformed, opposing substantially parallel faces through which the patterned radiation beam passes in operation.

[0032] The deformation of the plate by the actuators may cause the plate to behave as a meniscus lens and/or to form a meniscus shape.

[0033] The controller may be configured to control operation of the at least one actuator
15 thereby simultaneously to both control the curvature of the focal plane and to provide at least one further desired image effect.

[0034] The at least one further desired image effect may comprise a reduction in blurring or image fading errors.

[0035] The manipulator may be between the projection system and the substrate table.

20 [0036] The lithographic apparatus may further comprise a support structure for holding a patterning device, wherein the patterning device forms the pattern of the patterned radiation beam, and the manipulator is between the support structure and the projection system.

[0037] In a further aspect of the invention, which may be provided independently, there is provided a manipulator system for use with a lithographic apparatus, comprising a plate and
25 at least one actuator operable to deform the plate thereby to alter a shape of a focal plane of the lithographic apparatus, and a controller configured to control operation of the actuators thereby to control curvature of the focal plane.

[0038] In another aspect of the invention, there is provided a method of controlling curvature of a focal plane of a lithographic apparatus comprising operating at least one
30 actuator to deform a plate through which a patterned radiation beam is projected, thereby to control curvature of the focal plane.

[0039] Features in one aspect may be provided as features in any other aspect as appropriate. For example, features of any one of a sensor, apparatus or method may be provided as features of any one other of a sensor, apparatus or method. Any feature or

features in one aspect may be provided in combination with any suitable feature or features in any other aspect.

BRIEF DESCRIPTION OF THE DRAWINGS

- 5 [0040] 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:
- Figure 1 depicts a lithographic apparatus according to an embodiment of the invention;
 - 10 - Figure 2 is a schematic illustration showing a lithographic apparatus including a manipulator according to an embodiment;
 - Figure 3 is a schematic illustration of the manipulator included in the embodiment of Figure 2;
 - Figure 4 is a schematic illustration of the lithographic apparatus of Figure 2, a plate of the manipulator deformed to form a meniscus shape;
 - 15 - Figure 5A is a plot of the simulated variation is a plot of the simulated variation of the position of the focus in a direction perpendicular to the substrate plane as a function of distance in a lateral direction along the plane of the substrate for the embodiment of Figures 2 and 3;
 - 20 - Figure 5B is a plot of change (dx, dy) in image overlays in the x and y directions in an xy plane aligned with the substrate surface as a function of position in the x or y direction;
 - Figure 5C is a plot of the value of the Z_5 Zernike polynomial as a function of lateral position on the substrate;
 - Figure 6 is a plot of the displacements of the actuators 22 used to produce the focus correction illustrated in Figure 5A;
 - 25 - Figure 7 is a schematic illustration of the displacements of the actuators 22 used to produce the focus correction illustrated in Figure 5A;
 - Figure 8A is a further plot of the simulated variation of the value of the Z_2^4 Zernike polynomial as a function of distance in a lateral direction along the plane of the substrate, for different fading weight values; and
 - 30 - Figure 8B is a plot of Z_5 penalties for a series of values of fading weight

DETAILED DESCRIPTION

[0041] 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.

[0042] 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.

[0043] 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.

[0044] A patterning device may be transmissive or reflective. Examples of patterning devices 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.

[0045] 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, 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
5 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”.

10 [0046] 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
15 synonymous with the more general term “projection system”.

[0047] The illumination system may also 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”.

20 [0048] 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 one or more other tables are being used for exposure.

[0049] The lithographic apparatus may also be of a type wherein the substrate is
25 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.

[0050] Figure 1 schematically depicts a lithographic apparatus according to a particular embodiment of the invention. The apparatus comprises:

- 30 - an illumination system (illuminator) IL to condition a beam PB of radiation (e.g. UV radiation or EUV radiation).
- a support structure (e.g. a support structure) 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;

- 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 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.

[0051] 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).

[0052] 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 an 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.

[0053] 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 (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.

[0054] 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.

[0055] 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 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 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.

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. 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.

[0056] Combinations and/or variations on the above described modes of use or entirely different modes of use may also be employed.

[0057] It is a feature of embodiments that a manipulator is also provided that can control curvature of a focal plane of the lithographic apparatus. Such a manipulator is shown in Figure 2, which is a schematic illustration showing a lithographic apparatus according to an

embodiment. The lithographic apparatus of Figure 2 includes each of the components shown in Figure 1.

[0058] It can be seen from Figure 2 that the manipulator 2 is positioned between a patterning device stage 4 and projection system 6. A substrate stage 8 is also shown in Figure 2. The patterning device stage 4 comprises the support structure MT and patterning device MT of Figure 1. The projection system 6 corresponds to the projection system PS/PL of Figure 1. The substrate stage 8 comprises the substrate table WT, the substrate W and the positioning device PW. The other components of the embodiment of Figure 1 are also included in the embodiment of Figure 2 but are not shown in the figure for clarity.

[0059] The embodiment of Figure 2 includes a controller 12. The controller 12 is configured to control operation of actuators associated with the manipulator 2, in order to control a focal plane of the apparatus at the wafer. The controller 12 may be in the form of a dedicated control unit that is in communication with a control system (not shown) that controls operation of the lithographic apparatus and components of the lithographic apparatus thereby to control the lithographic process. Alternatively the controller 12 may form part of such a control system. The controller 12 may be in the form of a computer configured to execute at least one control algorithm, for example as represented by an executable computer program. Alternatively or additionally, the controller 12 may comprise dedicated hardware, software or a mixture of hardware or software. In some embodiments the controller 12 may comprise one or more ASICs, FPGAs or other dedicated circuitry.

[0060] The manipulator 2 of the embodiment is shown schematically in Figure 3 and comprises a planar plate 20 comprising, when undeformed, opposing substantially parallel faces through which a patterned radiation beam can pass.

[0061] The plate 20 may be made of any suitable material that is sufficiently transparent to the radiation used to apply the pattern to the substrate, for example radiation of a selected wavelength within a range 4nm to 500nm, or in a range 4nm to 25nm, or in a range 100nm to 400nm or equal to one of 365nm, 248nm, 193nm, 157nm or 126nm, depending on the particular operating parameters of the lithographic apparatus. The plate 20 is formed of material such that it can be reversibly deformed sufficiently to provide a desired change in focal plane without causing any significant damage to the material. The plate 20 of the embodiment of Figure 2 is formed of glass, for example fused silica.

[0062] The plate 20 of the embodiment has a thickness of 2.8mm, and is of rectangular shape with planar dimensions of 150 mm by 100 mm. Any other suitable thickness and

planar dimensions may be used. For example, the thickness may be in a range 1mm to 10mm in some embodiments.

[0063] The manipulator 2 also comprises a plurality of actuators 22 arranged around a central region of the plate 20 through which the patterned radiation beam can pass in operation. In this embodiment, the plurality of actuators are provided in two rows around the central region, but any other suitable arrangement of actuators can be used in alternative embodiments.

[0064] In the embodiment of Figures 2 and 3, 40 actuators are provided and each of the actuators is independently operable under control of the controller 12. The actuators of the embodiment are piezoelectric actuators, each of which is operable to apply a desired force to the plate 20 under control of the controller 12 in order to provide a desired deformation of the plate 20. In alternative embodiments any other suitable type of actuator that can be used to apply a precisely controlled force to the plate 20 may be provided. In some embodiments, an actuator that is configured to apply air or other gas pressure to the plate 20 to deform the plate 20 may be used as well as or instead of piezoelectric actuators.

[0065] Any suitable number of actuators can be provided in alternative embodiments. It has been found that by providing a sufficiently large number of independently operable actuators, control of the shape and position of the focal plane can be improved. However, an increased number of actuators can also produce additional complexity and additional space requirements. In some embodiments, a smaller number of actuators is used, for example even just a single actuator in certain embodiments.

[0066] The plate 20 is located at or near a field plane of the lithographic apparatus, or at or near a conjugate of the field plane. By the plate 20 being located near to a field plane or conjugate plane may be meant, for example, that there is no optical element with refractive power between the plate and the field plane or conjugate plane. In the embodiment of Figures 2 and 3, the plate 20 is close to the patterning device, in this case within 9mm of the patterning device.

[0067] In operation of the embodiment of Figures 2 and 3, the controller 12 controls operation of the actuators 22 to deform the plate 20 thereby to control curvature of the focal plane, for example to provide a desired curvature of the focal plane at the substrate. In the undeformed state the plate 20 has substantially no optical power. In one mode of operation, the actuators 22 are operated to distort the plate 22 into the shape of a meniscus lens. Figure 4 illustrates schematically the embodiment of Figure 2 in which the plate 22 has been distorted into the shape of a meniscus lens.

[0068] Although more complex distortions of the plate 20 and/or focal plane can be provided, in one mode of operation the controller 12 controls distortion of the plate 22 to provide, compensate for, or reduce a smooth curvature of the focal plane in which a variation of vertical position of the focal plane with lateral position along the plane of the substrate has a single peak or trough for the area of the substrate. Such a variation can be referred to as a focus curvature having a single turning point (for example, a single maximum or minimum value of vertical position). Such a focus curvature can be obtained by suitably controlling the distortion of the plate. It has been found that by providing a smooth curvature of the focal plane with a single peak over the area of the substrate, significantly improved alignment of focal plane with substrate surface can be provided, without too severe a penalty in relation to other optical parameters, for example astigmatism or other optical aberrations.

[0069] It has been found that the use of a single deformable plate as a focus manipulator affects the magnification of the image. In the embodiment of Figures 2 and 3, a further manipulator is provided that is operated, by controller 12 or other control component, to counteract at least partially the change in the magnification of the projected image at the substrate caused by the deformation of the plate 20. It has been found that existing, known components of projection system 6 that are used to control magnification (for example, by moving a refractive or reflective components within the projection system along the optical axis 6) even in the absence of the manipulator 2 can be used to control the magnification sufficiently well to compensate adequately for the magnification changes induced by the manipulator 2. This mechanism for controlling magnification is similar to that used in zoom lenses in photography. Thus, in some cases the manipulator 2 can be introduced into known lithographic apparatus, e.g. products of the ASML product line TWINSCAN NXT, without the need to introduce additional magnification components and thus without additional space penalty. Alternatively, in other embodiments a suitable, additional, dedicated manipulator can be used to provide the magnification compensation.

[0070] In the embodiment of Figures 2 and 3 the movement of actuators required to obtain a particular deformation of the plate 20, and the consequent effect of the curvature of the focal plane is determined in accordance with an optical model based on known physical and optical principles, and on actual measurements and calibration data of the lithographic apparatus itself. The use of such optical models is well known in modelling and controlling operation of lithographic apparatus, for example to determine the effect on the image of the various optical components of the lithographic apparatus and the operation or alteration of such components. Any suitable optical modelling technique can be used. The optical model

can be run by the controller 12 and/or control system of the lithographic apparatus but more commonly optical modelling would be performed in advance, and a control algorithm and/or look-up table would be stored by the controller 12 and/or control system. Such control algorithm and/or look-up table provides respective displacements and/or other operating parameter(s) for each of the actuators to provide one or more desired curvatures of the focal plane.

[0071] The actual or expected focal plane positional variation, for example focal plane curvature, that may be present when the manipulator is present or undeformed, or in the absence of the manipulator, can be measured or estimated, for example by examination and/or measurement of actual substrates that have been lithographically processed using the lithographic apparatus and patterning device in question. Alternatively or additionally an aerial image sensor can be used to measure directly the projected image provided by the lithographic apparatus and patterning device. If so desired, the manipulator 2 can then be used to reduce the curvature of the focal plane that is present.

[0072] Figure 5A is a plot of the simulated variation of the position of the focus in a direction perpendicular to the substrate plane as a function of distance in a lateral direction along the plane of the substrate for the embodiment of Figures 2 and 3. Values are plotted for the case where the plate 20 of the manipulator 2 is not deformed (shown as a dashed line) and the case (shown as a dashed-dotted line) where the plate 20 is deformed under control of the controller 12 in order to reduce the curvature of the focal plane. It can be seen that each of the plots has a single turning point. It can also be seen that the dashed-dotted line is significantly flatter than the dashed line and thus that operation of the manipulator by deformation of the plane 20 does apply a curvature to the focal plane that at least partially counteracts the focal plane curvature produced by the lithographic apparatus when the plate 20 is not deformed or is not present.

[0073] In the case of the embodiment of Figures 2 and 3, the expected focus curvature is around $20\text{nm}/\text{cm}^2$ in the absence of the manipulator 2 or with no deformation of the manipulator, which corresponds to the plotted values of the dashed line of Figure 5A. Operation of the manipulator reduces the focal plane curvature by around 90% in this case (reduction from a maximum value of around 10 nm to a maximum value of around 1 nm in the plots of Figure 5A).

[0074] The operation of the plate manipulator 2 also affects image overlays. Figure 5B is a plot of changes (dx, dy) in image overlays in the x (and y) directions in an xy plane aligned with the substrate surface as a function of position in the x (or y) direction, caused by

operation of the plate manipulator 2 to produce the reduction in focus curvature shown in Figure 5A according to the model. It can be seen that the maximum offset penalty is around 0.25nm. In the system under consideration, as a guideline an offset penalty 0.1 nm for each 1 nm of focus correction is allowable. In this case around 9 nm of focus correction is obtained
5 for around 0.25 nm of offset penalty, which is clearly within the guideline tolerance.

[0075] The operation of the manipulator 2 also affects astigmatism properties of the image. In optical analysis the astigmatism can be represented by the value of the Z_2^2 Zernike polynomial. Figure 5C is a plot of the value of the Z_2^2 Zernike polynomial as a function of lateral position on the substrate, caused by operation of the plate manipulator 2 to produce the
10 reduction in focus curvature shown in Figure 5A according to the model. It can be seen that the maximum magnitude of the Z_2^2 polynomial is around 0.45 nm, which leads to around 1.15 nm of astigmatism. That is within acceptable bounds for the system under consideration.

[0076] Figure 6 is a plot of the displacements of the actuators 22 used to produce the
15 focus correction illustrated in Figure 5A. The maximum actuator displacements needed to produce a desired focus correction can be important parameters in practice, as there will be limits on the maximum displacement that is allowable or achievable in a practical lithographic apparatus. In this case, it can be seen that the maximum displacement of any of the actuators to achieve the desired focus correction is around 1.5 μm according to the model.
20 That compares to the maximum displacement that would reasonably be allowed for the system in question of around 1.8 μm . Thus, the displacements are within tolerance. The corresponding displacements of actuators associated with the further manipulator to achieve the desired magnification compensation have a maximum of around 3.5 $\mu\text{m}/\mu\text{rad}$, which is less than the maximum allowed limit of around 5 $\mu\text{m}/\mu\text{rad}$ to be within tolerance for the
25 system in question.

[0077] Figure 7 is a schematic illustration of the displacements of the actuators 22 used to produce the focus correction illustrated in Figure 5A. In this case, the relative position and displacement of each of the actuators relative to the position of the central area (e.g. slit) of the plate manipulator through which the radiation passes in operation to form an image on the
30 substrate, are shown as three dimensional square columns.

[0078] It has been found, as shown in Figures 5A to 5C for example, that use of a plane manipulator 2, with associated magnification compensation using a further magnification manipulator, can lead to a significant improvement of focus variation, and significant

flattening of the focal plane to compensate, for example, for roll-off effects whilst producing astigmatism variations and actuator displacements that are within acceptable bounds.

[0079] The model used to produce the results of Figures 5A to 5C has also been applied to the case where there are 40 actuators, but not all independently actuatable, for example to the case where the 40 actuators are divided into 10 independently actuatable groups of actuators. In that case, it has been found that the reduction in focal plane curvature is lower than that obtained when all 40 actuators are independently actuatable.

[0080] The reduction in focal plane curvature illustrated in Figure 5A was obtained by controlling operation of the actuators 22 to deform the plate manipulator 2 to provide or compensate for a smooth curvature of the focal plane, and a variation of vertical position of the focal plane relative to the plane of the substrate with lateral position along the plane of the substrate having a single turning point (e.g. single peak or single trough) for the area of the substrate.

[0081] The focal plane curvature can be thought of as comprising several focal plane curvature components, with the variation of vertical position of the focal plane relative to the plane of the substrate with lateral position along the plane of the substrate having a single turning point (e.g. single peak or trough) over the area of the substrate mentioned in the preceding paragraph being one such component. Other more complex focal plane curvature components may also be present, and the overall focal plane curvature may be represented by the sum or combination of such components.

[0082] In alternative embodiments or modes of operation, the plate manipulator 2 may be deformed in order to control the focal plane to vary more frequently over the lateral position of the substrate. In one embodiment the controller controls the manipulator to provide or compensate for a focal plane variation having two or more turning points for the area of the substrate, for example a focal plane curvature component having a peak and a trough over the lateral position of the field such as an S-shaped variation. However, in the case of the embodiment of Figure 2, it was found that this would result in a reduction of the focal plane curvature represented by such an S-shape of only around 50%, from 5nm to 2.5 nm, for an additional 0.18 nm overlay penalty. For the system in question, the overlay penalty may be considered too high for the reduction in focal plane curvature. However, in alternative embodiments it may be chosen to control such focus planes varying more frequently over the lateral position of the substrate.

[0083] In some embodiments, the or modes of operation, the plate manipulator 2 may be deformed under control of the controller and actuators in order to provide or compensate for a

focal plane curvature components having more than two turning points, for example focal plane curvature components having three, four or any other desired number of turning points for the areas of the substrate.

[0084] In some embodiments, focal plane curvature components may be represented using zernike polynomials, and the controller may be configured to operate the actuators to control deformation of the plate manipulator, to provide desired values for, or to reduce the values of, one or more selected Zernike polynomials. In some embodiments, each focal plane curvature component has a respective, corresponding Zernike polynomial, which may vary over the image.

[0085] The reduction in focal plane curvature illustrated in Figure 5A was also obtained by controlling operation of the actuators 22 to deform the plate manipulator 2 to control the focus curvature for the optical system without being constrained to take into account blurring effects, as represented for example by fading weights. In alternative embodiments, if the operation of the actuators 22 to deform the plate manipulator 2 is controlled by the controller 12 to take into account and attempt to compensate for blur effects as represented by fading weights, it has been found that in the case of the embodiment of Figure 2 the reduction in focal plane curvature that can be obtained is reduced from around 90% to around 60%, and that the astigmatism penalty also increases.

[0086] Figure 8A is a similar plot to that of Figure 5A, and again is a plot of the simulated variation of the position of the focus in a direction perpendicular to the substrate plane as a function of distance in a lateral direction along the plane of the substrate for the embodiment of Figures 2 and 3. Values are plotted for the case where the plate 20 of the manipulator 2 is not deformed and thus has no optical power, shown as a dashed line 30 (which corresponds to the dashed line of Figure 5A), for a further case (shown as a dashed-dotted line 32) where the plate 20 is deformed under control of the controller 12 in order to reduce the curvature of the focal plane and in which the fading weight is set to zero, thus not taking into account blurring effects and only taking into account the focal plane curvature. Dashed-dotted line 32 corresponds to the dashed-dotted line of Figure 5A. Various intermediate cases are also plotted as dashed and/or dotted lines, in which plate 20 is deformed under control of the controller 12 in order to reduce the curvature of the focal plane and in which the fading weight is set to various, increasing values thus ensuring that the deformation of the plate 20 also attempts to compensate for blur effects represented by the fading weights as well as the focal plane curvature. As the fading weight is increased the reduction in focal plane curvature gradually decreases from 90% to around 60%. The

astigmatism penalty and overlay (dx, dy) penalty also increase as the fading weights increase. The Z_2^2 penalties are plotted in Figure 8B for a series of fading weights, with the maximum penalty for the maximum fading weight. As the fading weight is increased, blur effects decrease.

5 **[0087]** The embodiment of Figure 2, when controlled as described in relation to Figure 5 to 8, can achieve a 90% reduction in focal plane curvature, with acceptable penalties for astigmatism and other image effects, and with acceptable actuator displacements, when deformation of the planar manipulator 2 is controlled to control the focus curvature without
10 being constrained to control other imaging components and/or aberrations, for example astigmatism or blur effects, and when a further, magnification manipulator is used to compensate for magnification effects. Thus, roll-off effects or other focal plane curvature effects may effectively be reduced by suitable operation of the planar manipulator.

15 **[0088]** In other embodiments, the deformation of the planar manipulator may be controlled to control other imaging components, for example other Zernike polynomials or blur effects, as well as or instead of the focus curvature, although this may reduce the reduction in overall focal plane curvature that may be achieved.

[0089] 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 description is not intended to limit the invention.

CLAIMS:

1. A lithographic apparatus comprising:
a substrate table configured to hold a substrate;
5 a projection system configured to project a patterned radiation beam onto a target portion of the substrate, the projection system having a focal plane;
a manipulator comprising a plate and at least one actuator operable to deform the plate thereby to alter a shape of the focal plane; and
a controller configured to control operation of the at least one actuator thereby to
10 control curvature of the focal plane.
2. A lithographic apparatus according to Claim 1, wherein the deformation of the plate by operation of the at least one actuator causes a change in magnification, and the apparatus further comprises a further manipulator operable to at least partially counteract said change in
15 the magnification.
3. A lithographic apparatus according to Claim 2 wherein the further manipulator forms part of the projection system.
- 20 4. A lithographic apparatus according to Claim 3, wherein the further manipulator comprises at least one movable optical element, and the controller is configured to control movement of the movable optical element thereby to at least partly counteract said change in magnification.
- 25 5. A lithographic apparatus according to any preceding claim, wherein the controlling of operation of the at least one actuator to control the curvature of the focal plane comprises controlling operation of the at least one actuator to control and/or reduce at least one optical aberration.
- 30 6. A lithographic apparatus according to any preceding claim, wherein the controlling of operation of the at least one actuator to control the curvature of the focal plane comprises controlling operation of the at least one actuator to reduce curvature of the focal plane.

7. A lithographic apparatus according to any preceding claim, wherein the controlling of operation of the at least one actuator to control focal plane curvature comprises controlling and/or reducing at least one focus curvature component.

5 8. A lithographic apparatus according to Claim 7, wherein the at least one focus curvature component is a focus curvature component having a single turning point.

9. A lithographic apparatus according to Claim 8, wherein the controlling of operation of the at least one actuator to provide a desired curvature comprises controlling operation of the
10 at least one actuator to control and/or reduce said focus curvature component having a single turning point, with substantially no other constraints.

10. A lithographic apparatus according to Claim 7 or 8, wherein the at least one focus curvature component comprises at least one of a focus curvature component having two
15 turning points, and/or a focus curvature component having three turning points, and/or a focus curvature component having four or more turning points.

11. A lithographic apparatus according to any preceding claim, wherein the controlling of operation of the at least one actuator to control curvature of the focal plane comprises
20 controlling operation of the actuators to reduce a roll-off effect.

12. A lithographic apparatus according to any preceding claim, wherein the at least one actuator comprises a plurality of actuators.

25 13. A lithographic apparatus according to Claim 12, wherein the plurality of actuators comprises at least 5 independently operable actuators, optionally at least 10 independently operable actuators, further optionally at least 20 independently operable actuators.

14. A lithographic apparatus according to any preceding claim, wherein the manipulator
30 has substantially no optical power when the plate is undeformed.

15. A lithographic apparatus according to any preceding claim, wherein the manipulator is located at or close to a field plane, or at or close to a conjugate of the field plane.

16. A lithographic apparatus according to any preceding claim, wherein the at least one actuator comprises a plurality of actuators arranged in at least two rows around a region of the plate through which the patterned radiation beam passes in operation.

5 17. A lithographic apparatus according to any preceding claim, wherein the plate comprise a planar plate comprising, when undeformed, opposing substantially parallel faces through which the patterned radiation beam passes in operation.

18. A lithographic apparatus according to any preceding claim, wherein the deformation of the plate by the actuators causes the plate to form a meniscus shape.

10

19. A lithographic apparatus according to any preceding claim, wherein the controller is configured to control operation of the at least one actuator thereby simultaneously to both control the curvature of the focal plane and to provide at least one further desired image effect.

15

20. A lithographic apparatus according to Claim 19, wherein the at least one further desired image effect comprises a reduction in blurring or image fading errors.

20

21. A lithographic apparatus according to any preceding claim, wherein the manipulator is between the projection system and the substrate table.

25

22. A lithographic apparatus according to any preceding claim, further comprising a support structure for holding a patterning device, wherein the patterning device forms the pattern of the patterned radiation beam, and the manipulator is between the support structure and the projection system.

30

23. A manipulator system for use with a lithographic apparatus, comprising:-
a plate and at least one actuator operable to deform the plate thereby to alter a shape of a focal plane of the lithographic apparatus; and
a controller configured to control operation of the at least one actuator thereby to control curvature of the focal plane.

24. A method of controlling curvature of a focal plane of a lithographic apparatus comprising operating at least one actuator to deform a plate through which a patterned radiation beam is projected, thereby to control curvature of the focal plane.

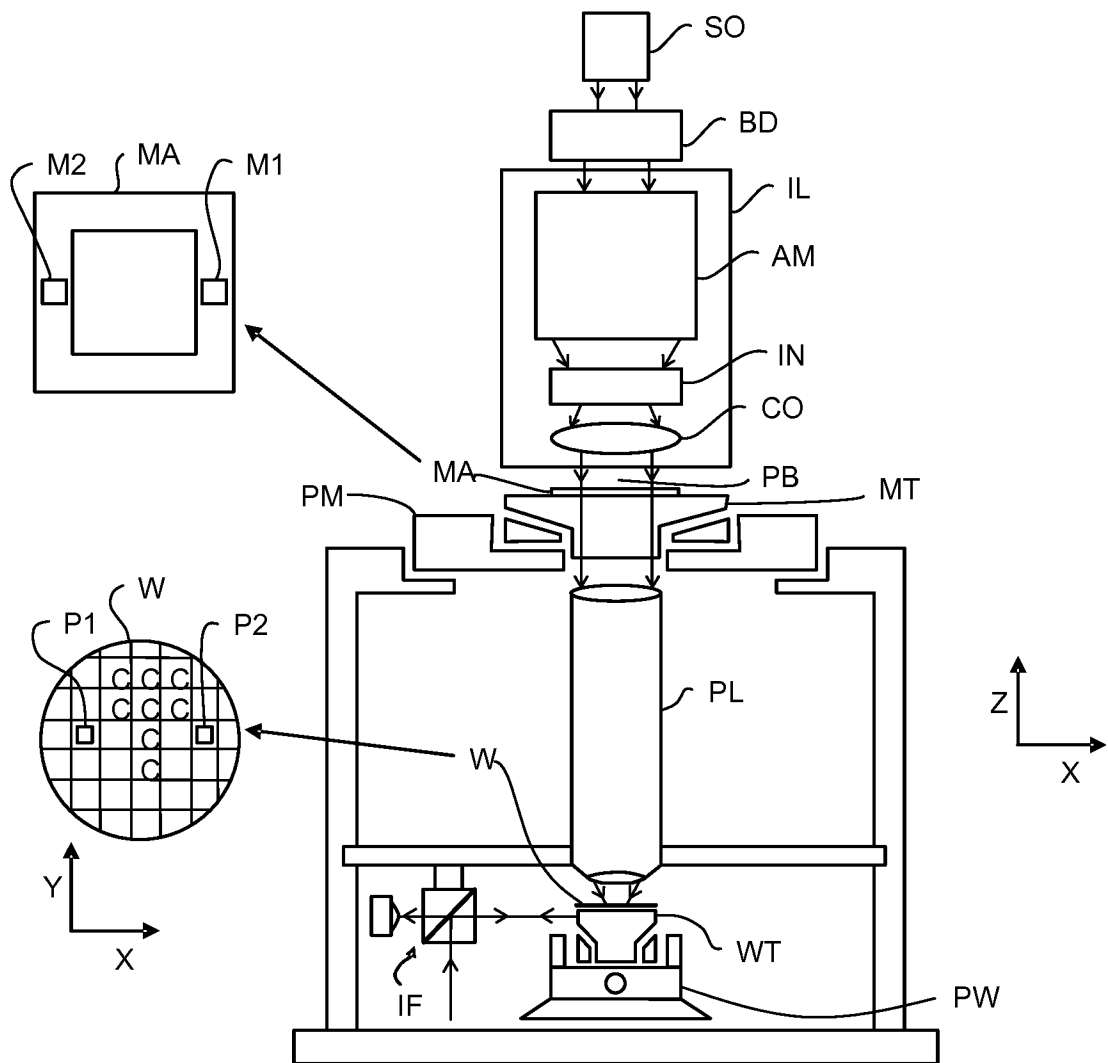


FIG. 1

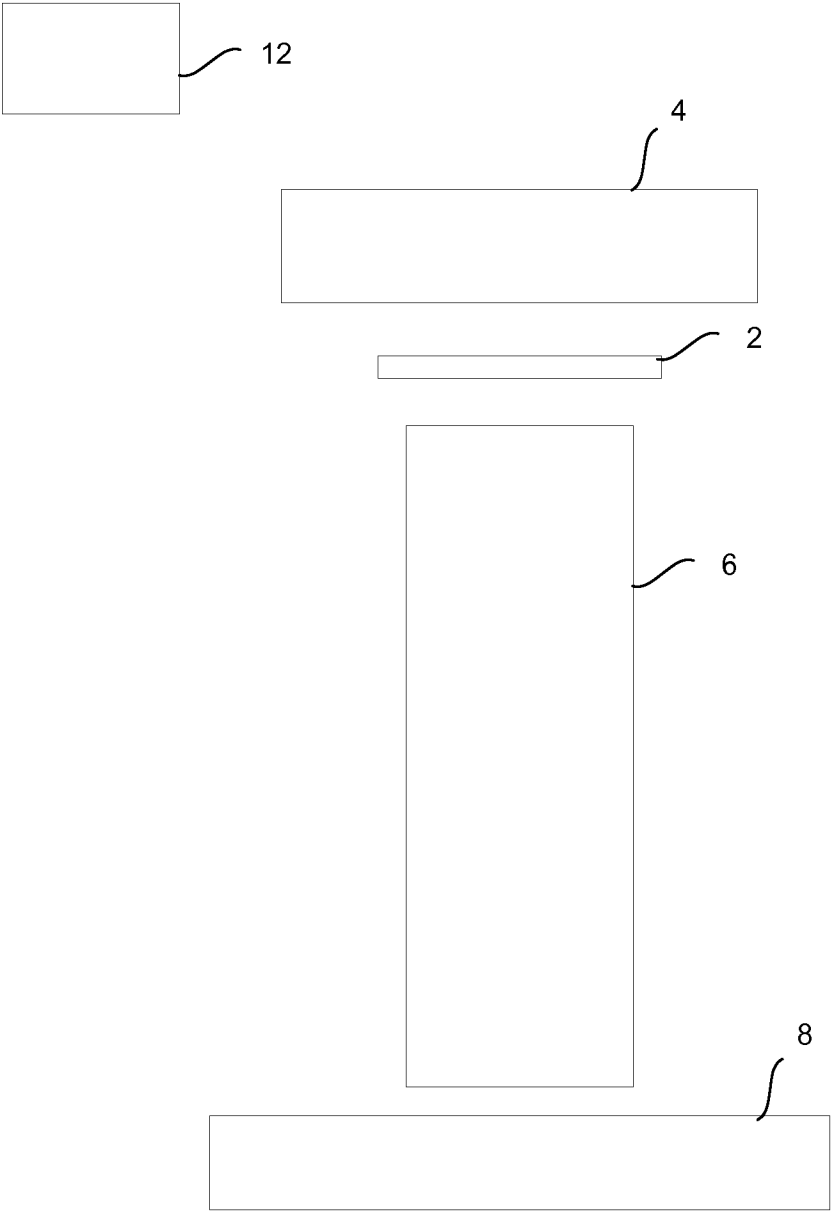


FIG. 2

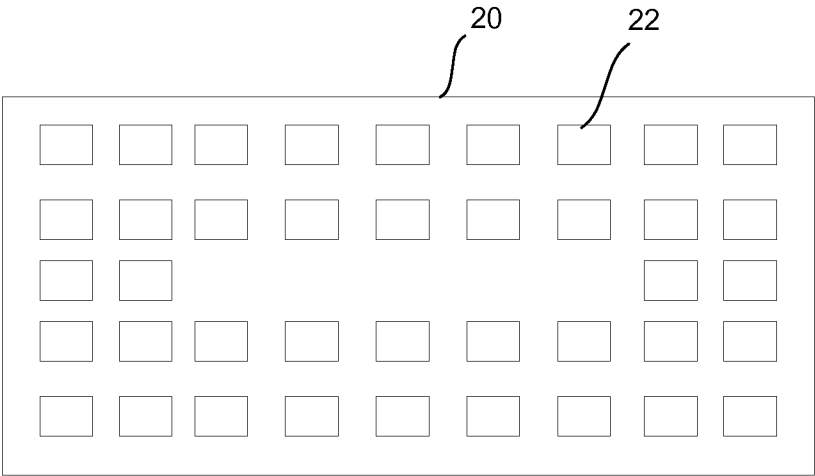


FIG. 3

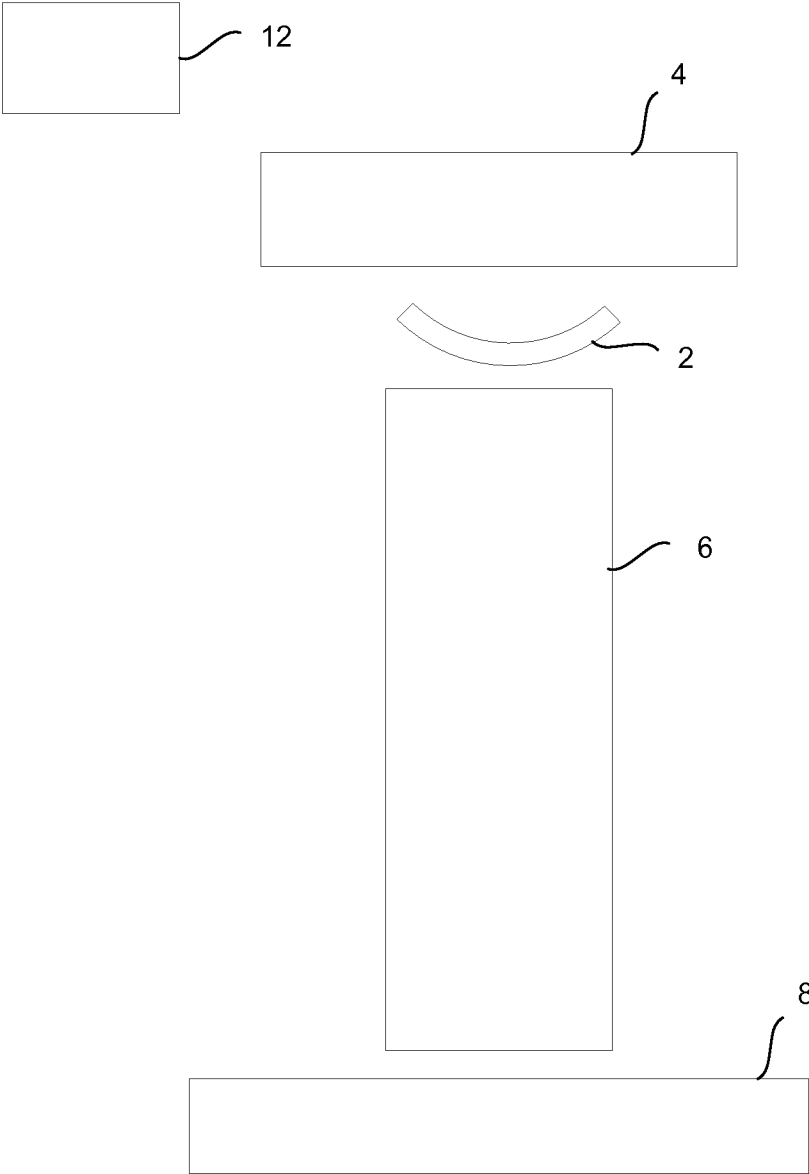


FIG. 4

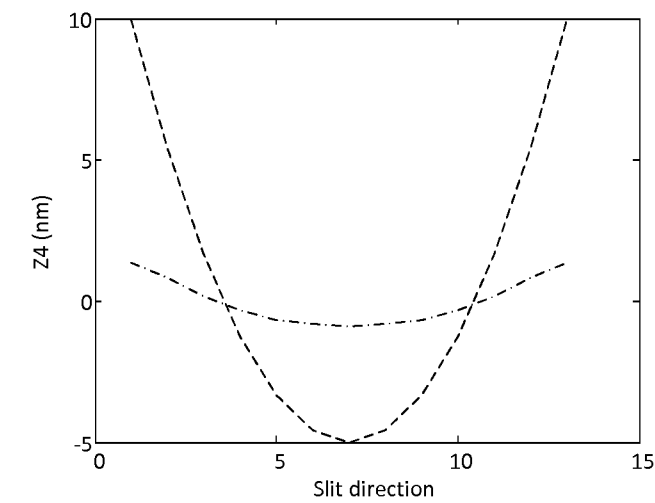


FIG. 5A

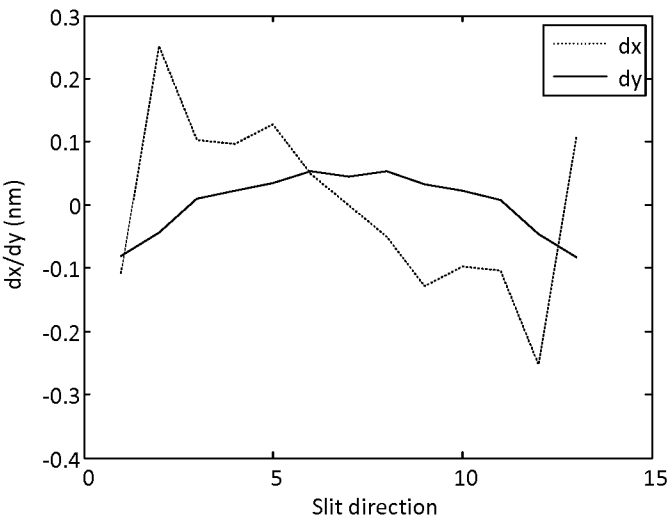


FIG. 5B

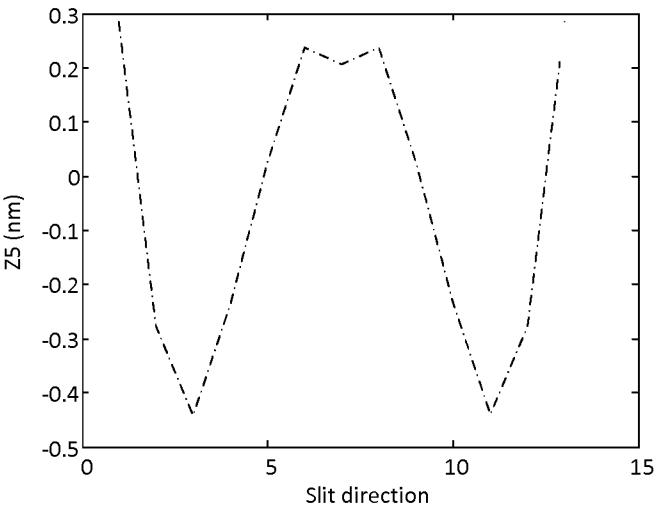


FIG. 5C

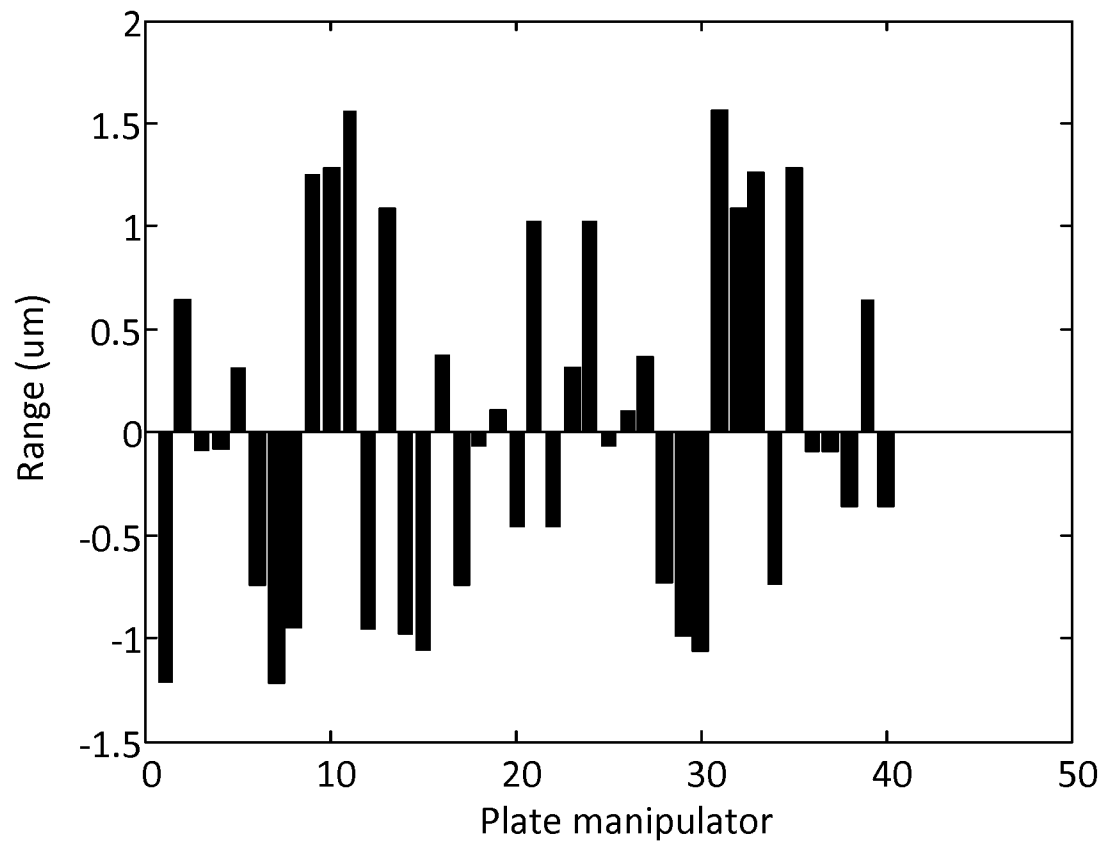


FIG. 6

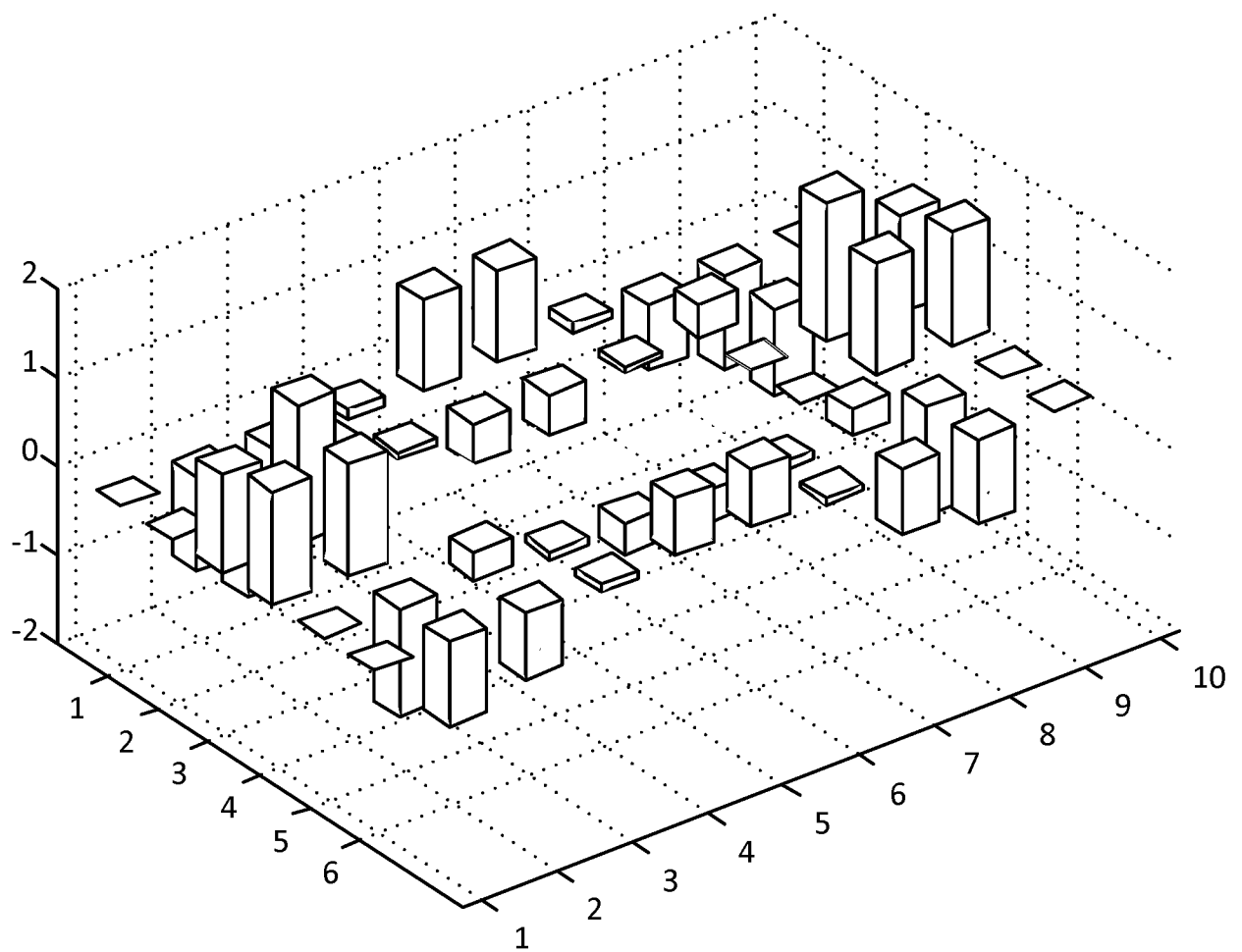


FIG. 7

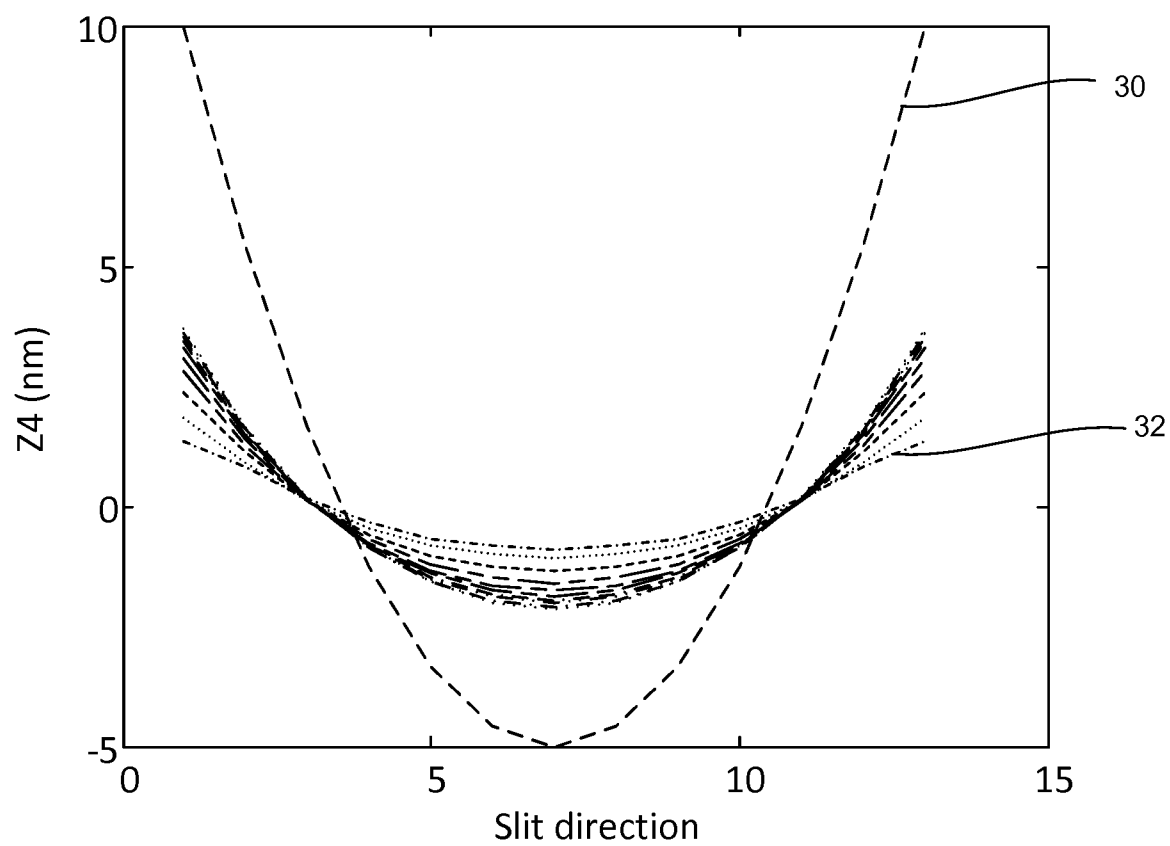


FIG. 8A

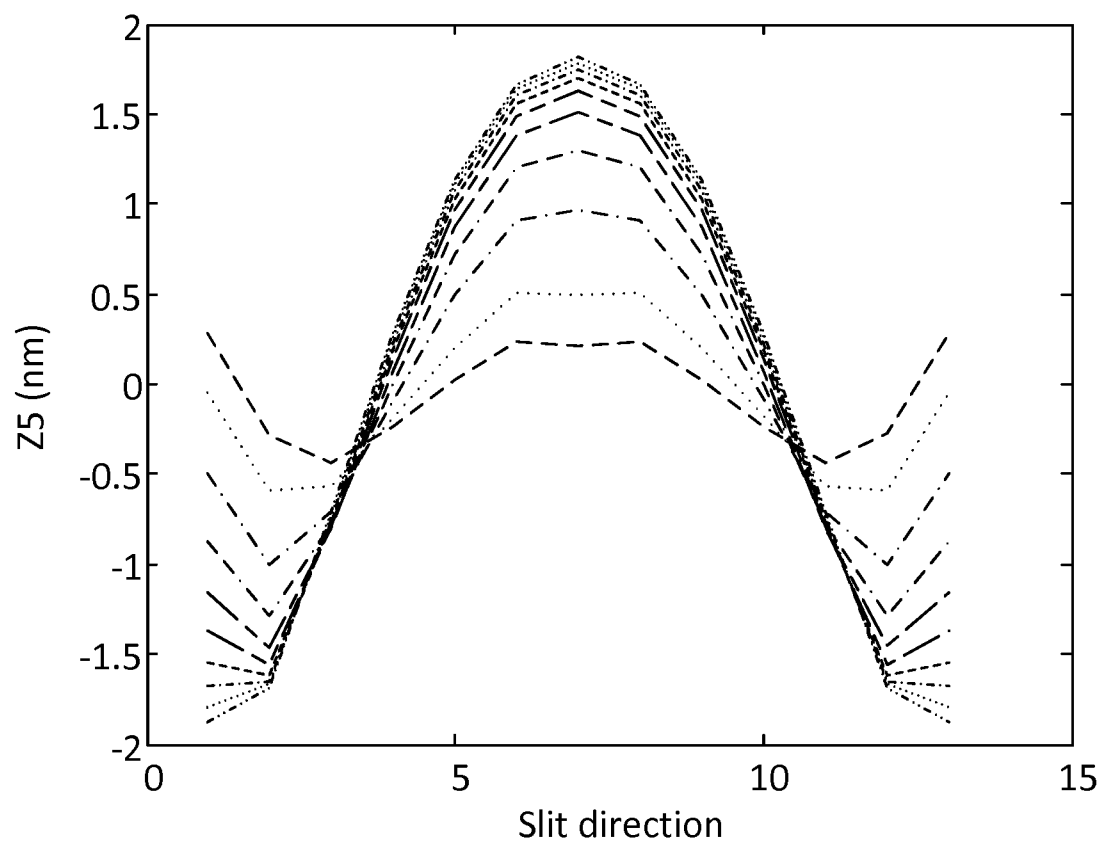


FIG. 8B

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2016/050145

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

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G03F G02B H01L

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

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/019169 A1 (CONRADI OLAF [DE] ET AL) 27 January 2011 (2011-01-27) abstract figures 1-3 paragraphs [0002], [0045], [0079] - [0089], [0093] - [0103] -----	1-24
X	US 2011/222039 A1 (VALENTIN CHRISTIAAN LOUIS [NL] ET AL) 15 September 2011 (2011-09-15) abstract figures 1-4 paragraphs [0002], [0008], [0015], [0030] - [0044] ----- -/-	1-15, 18-20,23 16,17, 21,22,24
A		

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

18 May 2016

Date of mailing of the international search report

30/05/2016

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Andersen, Ole

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2016/050145

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP H10 242048 A (CANON KK) 11 September 1998 (1998-09-11) abstract figure 8 paragraphs [0001], [0214], [0215] -----	1-24
A	US 2013/278911 A1 (LIMBACH GUIDO [DE] ET AL) 24 October 2013 (2013-10-24) abstract figure 5A paragraphs [0002], [0060] -----	1-24

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/050145

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2011019169 A1	27-01-2011	JP 5069232 B2 JP 2009503826 A US 2008239503 A1 US 2011019169 A1 WO 2007017089 A1	07-11-2012 29-01-2009 02-10-2008 27-01-2011 15-02-2007
US 2011222039 A1	15-09-2011	JP 5820905 B2 JP 2011192987 A JP 2014170965 A US 2011222039 A1	24-11-2015 29-09-2011 18-09-2014 15-09-2011
JP H10242048 A	11-09-1998	JP 3303758 B2 JP H10242048 A	22-07-2002 11-09-1998
US 2013278911 A1	24-10-2013	CN 101548240 A EP 2097789 A2 JP 5154564 B2 JP 2010511298 A KR 20090095575 A TW 200835952 A US 2009244509 A1 US 2013278911 A1 WO 2008064859 A2	30-09-2009 09-09-2009 27-02-2013 08-04-2010 09-09-2009 01-09-2008 01-10-2009 24-10-2013 05-06-2008