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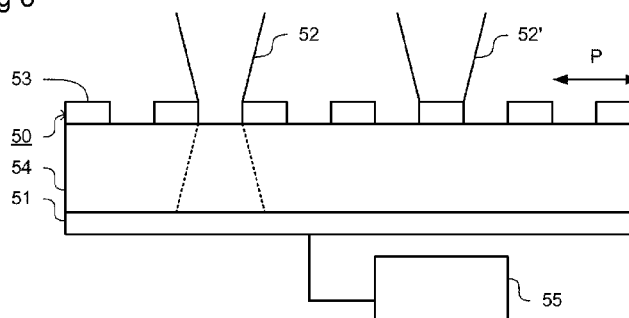
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(54) Title: LITHOGRAPHIC APPARATUS, METHOD FOR MEASURING RADIATION BEAM SPOT FOCUS AND DEVICE MANUFACTURING METHOD

Fig 6



(57) Abstract: A spot focus sensor system is provided for a lithographic apparatus, the system including a grating arranged such that a radiation beam spot is projected onto the grating by the projection system of the lithographic apparatus at a plurality of different locations on the grating, a radiation intensity sensor configured to detect the intensity of radiation from the radiation beam spot passing through or reflected from the grating, and a controller configured to determine a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

LITHOGRAPHIC APPARATUS, METHOD FOR MEASURING RADIATION BEAM SPOT FOCUS AND DEVICE MANUFACTURING METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

- 5 **[0001]** This application claims the benefit of US provisional application 61/451,950, which was filed on March 11th, 2011 and which is incorporated herein in its entirety by reference.

Field

- 10 **[0002]** The present invention relates to a lithographic apparatus, a method for measuring radiation beam spot focus and a method for manufacturing a device.

Background

- 15 **[0003]** A lithographic apparatus is a machine that applies a desired pattern onto a substrate or part of a substrate. A lithographic apparatus may be used, for example, in the manufacture of integrated circuits (ICs), flat panel displays and other devices or structures having fine features. In a conventional lithographic apparatus, a patterning device, which may be referred to as a mask or a reticle, may be used to generate a circuit pattern corresponding to an individual layer of the IC, flat panel display, or other device. This pattern may be transferred on
20 (part of) the substrate (e.g. silicon wafer or a glass plate), e.g. via imaging onto a layer of radiation-sensitive material (resist) provided on the substrate.

- 25 **[0004]** Instead of a circuit pattern, the patterning device may be used to generate other patterns, for example a color filter pattern, or a matrix of dots. Instead of a conventional mask, the patterning device may comprise a patterning array that comprises an array of individually controllable elements that generate the circuit or other applicable pattern. An advantage of such a “maskless” system compared to a conventional mask-based system is that the pattern can be provided and/or changed more quickly and for less cost.

- 30 **[0005]** Thus, a maskless system includes a programmable patterning device (e.g., a spatial light modulator, a contrast device, etc.). The programmable patterning device is programmed (e.g., electronically or optically) to form the desired patterned beam using the array of individually controllable elements. Types of programmable patterning devices include micro-

mirror arrays, liquid crystal display (LCD) arrays, grating light valve arrays, arrays of self-emissive contrast devices and the like.

Summary

5 **[0006]** A maskless lithographic apparatus may be provided with, for example, an optical column to create a pattern on a target portion of a substrate. The optical column may be provided with: a self emissive contrast device configured to emit a beam and a projection system configured to project at least a portion of the beam onto the target portion. The apparatus may be provided with an actuator to move the optical column or a part thereof with respect to the
10 substrate. Thereby, the beam may be moved with respect to the substrate and optionally the substrate is moved with respect to the beam. By switching “on” or “off” the self-emissive contrast device during the movement, a pattern on the substrate may be created.

[0007] In a lithographic process, it is desirable that the image projected onto a substrate is accurately focused. In particular, in some maskless lithography arrangements, the focusing
15 range may be relatively small in comparison to a mask based system with the same critical dimension. For example, in a maskless system, a plurality of lenses may be each used to project spots of radiation onto the substrate, resulting in a relatively small focusing range. Accordingly, a system may provide focus adjustment such as adjusting the focus or adjusting that the image is focused on the substrate by, for example, adjusting the relative position between the substrate
20 relative and the projection system in a direction parallel to the optical axis of the projection system.

[0008] In addition to being able to provide focus adjustment, it is desirable to be able to measure the focus of each of the beams of radiation forming a spot of radiation on the substrate. This can be done, for example, by projecting each beam or radiation onto an image sensor
25 capable of measuring the diameter of the spot of radiation. The focus may then be adjusted until the spot diameter is a desired size and/or the system may determine the distance from the projection system at which the spot is the desired diameter. However, it may be difficult to obtain the desired accuracy of the focusing system and/or such an arrangement may require a relatively expensive image sensor and/or the system may not be able to perform the focus
30 measurement sufficiently quickly.

[0009] It is therefore desirable, for example, to provide an improved focusing system, for

example including an improved focus measurement system.

[0010] According to an embodiment of the invention, there is provided a lithographic apparatus, comprising:

a programmable patterning device, configured to provide a plurality of
5 radiation beams;

a projection system, configured to project the plurality of radiation beams onto a substrate to form respective spots of radiation; and

a spot focus sensor system comprising:

a grating, arranged such that at least one of the radiation beam spots may be successively
10 projected onto a plurality of different locations on the grating in order to perform a radiation spot focus measurement;

a radiation intensity sensor, configured to detect the intensity of radiation from the radiation beam spot passing through or reflected from the grating at the plurality of locations; and

15 a controller, configured to determine a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

[0011] According to an embodiment of the invention, there is provided a method for measuring radiation beam spot focus in a lithographic apparatus comprising:

a programmable patterning device, configured to provide a plurality of
20 radiation beams; and

a projection system, configured to project the plurality of radiation beams onto a substrate to form respective spots of radiation;

the method comprising:

successively projecting at least one of the radiation beam spots onto a plurality of
25 different locations on a grating;

using a radiation intensity sensor to detect the intensity of radiation from the radiation beam spot passing through the or reflected from grating at the plurality of locations; and determining a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

30 **[0012]** According to an embodiment of the invention, there is provided a device manufacturing method, comprising:

using the above method to measure the radiation beam spot focus of at least one of a plurality of radiation beams in a lithographic apparatus; and

using the determined spot focus value to control at least one parameter of the lithographic apparatus while projecting the plurality of beams of radiation onto a substrate.

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Brief Description of the Drawings

[0013] 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:

10 **[0014]** - Figure 1 depicts a part of a lithographic apparatus according to an embodiment of the invention;

[0015] - Figure 2 depicts a top view of a part of the lithographic apparatus of Figure 1 according to an embodiment of the invention;

15 **[0016]** - Figure 3 depicts a highly schematic, perspective view of a part of a lithographic apparatus according to an embodiment of the invention;

[0017] - Figure 4 depicts a schematic top view of projections by the lithographic apparatus according to Figure 3 onto a substrate according to an embodiment of the invention;

[0018] - Figure 5 depicts an arrangement of a system to control focus according to an embodiment of the invention;

20 **[0019]** - Figure 6 schematically depicts an arrangement of a spot focus sensor system according to an embodiment of the present invention;

[0020] - Figure 7 depicts expected output of a radiation intensity sensor that may be used in an embodiment of the invention;

25 **[0021]** - Figure 8 depicts an arrangement of a sensor system according to an embodiment of the present invention;

[0022] - Figures 9 and 10 depict variations of the arrangement of a spot focus sensor system according to an embodiment of the present invention; and

[0023] - Figure 11 depicts a spot focus sensor system according to an embodiment of the present invention.

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Detailed Description

[0024] Figure 1 schematically depicts a schematic cross-sectional side view of a part of a lithographic apparatus. In this embodiment, the lithographic apparatus has individually controllable elements substantially stationary in the X-Y plane as discussed further below although it need not be the case. The lithographic apparatus 1 comprises a substrate table 2 to hold a substrate, and a positioning device 3 to move the substrate table 2 in up to 6 degrees of freedom. The substrate may be a resist-coated substrate. In an embodiment, the substrate is a wafer. In an embodiment, the substrate is a polygonal (e.g. rectangular) substrate. In an embodiment, the substrate is a glass plate. In an embodiment, the substrate is a plastic substrate. In an embodiment, the substrate is a foil. In an embodiment, the lithographic apparatus is suitable for roll-to-roll manufacturing.

[0025] The lithographic apparatus 1 further comprises a plurality of individually controllable self-emissive contrast devices 4 configured to emit a plurality of beams. In an embodiment, the self-emissive contrast device 4 is a radiation emitting diode, such as a light emitting diode (LED), an organic LED (OLED), a polymer LED (PLED), or a laser diode (e.g., a solid state laser diode). In an embodiment, each of the individually controllable elements 4 is a blue-violet laser diode (e.g., Sanyo model no. DL-3146-151). Such diodes may be supplied by companies such as Sanyo, Nichia, Osram, and Nitride. In an embodiment, the diode emits UV radiation, e.g., having a wavelength of about 365 nm or about 405 nm. In an embodiment, the diode can provide an output power selected from the range of 0.5 - 200 mW. In an embodiment, the size of laser diode (naked die) is selected from the range of 100 – 800 micrometers. In an embodiment, the laser diode has an emission area selected from the range of 0.5 - 5 micrometers². In an embodiment, the laser diode has a divergence angle selected from the range of 5 – 44 degrees. In an embodiment, the diodes have a configuration (e.g., emission area, divergence angle, output power, etc.) to provide a total brightness more than or equal to about $6.4 \times 10^8 \text{ W}/(\text{m}^2 \cdot \text{sr})$.

[0026] The self-emissive contrast devices 4 are arranged on a frame 5 and may extend along the Y-direction and/or the X direction. While one frame 5 is shown, the lithographic apparatus may have a plurality of frames 5 as shown in Figure 2. Further arranged on the frame 5 is lens 12. Frame 5 and thus self-emissive contrast device 4 and lens 12 are substantially stationary in the X-Y plane. Frame 5, self-emissive contrast device 4 and lens 12 may be moved in the Z-direction by actuator 7. Alternatively or additionally, lens 12 may be moved in the Z-

direction by an actuator related to this particular lens. Optionally, each lens 12 may be provided with an actuator.

[0027] The self-emissive contrast device 4 may be configured to emit a beam and the projection system 12, 14 and 18 may be configured to project the beam onto a target portion of the substrate. The self-emissive contrast device 4 and the projection system form an optical column. The lithographic apparatus 1 may comprise an actuator (e.g. motor 11) to move the optical column or a part thereof with respect to the substrate. Frame 8 with arranged thereon field lens 14 and imaging lens 18 may be rotatable with the actuator. A combination of field lens 14 and imaging lens 18 forms movable optics 9. In use, the frame 8 rotates about its own axis 10, for example, in the directions shown by the arrows in FIG. 2. The frame 8 is rotated about the axis 10 using an actuator e.g. motor 11. Further, the frame 8 may be moved in a Z direction by motor 7 so that the movable optics 9 may be displaced relative to the substrate table 2.

[0028] An aperture structure 13 having an aperture therein may be located above lens 12 between the lens 12 and the self-emissive contrast device 4. The aperture structure 13 can limit diffraction effects of the lens 12, the associated self-emissive contrast device 4, and/or of an adjacent lens 12 / self-emissive contrast device 4.

[0029] The depicted apparatus may be used by rotating the frame 8 and simultaneously moving the substrate on the substrate table 2 underneath the optical column. The self-emissive contrast device 4 can emit a beam through the lenses 12, 14, and 18 when the lenses are substantially aligned with each other. By moving the lenses 14 and 18, the image of the beam on the substrate is scanned over a portion of the substrate. By simultaneously moving the substrate on the substrate table 2 underneath the optical column, the portion of the substrate which is subjected to an image of the self-emissive contrast device 4 is also moving. By switching the self-emissive contrast device 4 “on” and “off” (e.g., having no output or output below a threshold when it is “off” and having an output above a threshold when it is “on”) at high speed under control of a controller, controlling the rotation of the optical column or part thereof, controlling the intensity of the self-emissive contrast device 4, and controlling the speed of the substrate, a desired pattern can be imaged in the resist layer on the substrate.

[0030] Figure 2 depicts a schematic top view of the lithographic apparatus of Figure 1 having self-emissive contrast devices 4. Like the lithographic apparatus 1 shown in Figure 1, the lithographic apparatus 1 comprises a substrate table 2 to hold a substrate 17, a positioning device

3 to move the substrate table 2 in up to 6 degrees of freedom, an alignment/level sensor 19 to determine alignment between the self-emissive contrast device 4 and the substrate 17, and to determine whether the substrate 17 is at level with respect to the projection of the self-emissive contrast device 4. As depicted the substrate 17 has a rectangular shape, however also or
5 alternatively round substrates may be processed.

[0031] The self-emissive contrast device 4 is arranged on a frame 15. The self-emissive contrast device 4 may be a radiation emitting diode, e.g., a laser diode, for instance a blue-violet laser diode. As shown in Figure 2, the self-emissive contrast devices 4 may be arranged into an array 21 extending in the X-Y plane.

10 **[0032]** The array 21 may be an elongate line. In an embodiment, the array 21 may be a single dimensional array of self-emissive contrast devices 4. In an embodiment, the array 21 may be a two dimensional array of self-emissive contrast device 4.

[0033] A rotating frame 8 may be provided which may be rotating in a direction depicted by the arrow. The rotating frame may be provided with lenses 14, 18 (shown in Figure 1) to
15 provide an image of each of the self-emissive contrast devices 4. The apparatus may be provided with an actuator to rotate the optical column comprising the frame 8 and the lenses 14, 18 with respect to the substrate.

[0034] Figure 3 depicts a highly schematic, perspective view of the rotating frame 8 provided with lenses 14, 18 at its perimeter. A plurality of beams, in this example 10 beams, are
20 incident onto one of the lenses and projected onto a target portion of the substrate 17 held by the substrate table 2. In an embodiment, the plurality of beams are arranged in a straight line. The rotatable frame is rotatable about axis 10 by means of an actuator (not shown). As a result of the rotation of the rotatable frame 8, the beams will be incident on successive lenses 14, 18 (field lens 14 and imaging lens 18) and will, incident on each successive lens, be deflected thereby so
25 as to travel along a part of the surface of the substrate 17, as will be explained in more detail with reference to Fig. 4. In an embodiment, each beam is generated by a respective source, i.e. a self-emissive contrast device, e.g. a laser diode (not shown in Figure 3). In the arrangement depicted in Figure 3, the beams are deflected and brought together by a segmented mirror 30 in order to reduce a distance between the beams, to thereby enable a larger number of beams to be projected
30 through the same lens and to achieve resolution requirements to be discussed below.

[0035] As the rotatable frame rotates, the beams are incident on successive lenses and,

each time a lens is irradiated by the beams, the places where the beams are incident on a surface of the lens, moves. Since the beams are projected on the substrate differently (with e.g. a different deflection) depending on the place of incidence of the beams on the lens, the beams (when reaching the substrate) will make a scanning movement with each passage of a following lens. This principle is further explained with reference to Figure 4. Figure 4 depicts a highly schematic top view of a part of the rotatable frame 8. A first set of beams is denoted by B1, a second set of beams is denoted by B2 and a third set of beams is denoted by B3. Each set of beams is projected through a respective lens set 14, 18 of the rotatable frame 8. As the rotatable frame 8 rotates, the beams B1 are projected onto the substrate 17 in a scanning movement, thereby scanning area A14. Similarly, beams B2 scan area A24 and beams B3 scan area A34. At the same time of the rotation of the rotatable frame 8 by a corresponding actuator, the substrate 17 and substrate table are moved in the direction D, which may be along the X axis as depicted in Figure 2, thereby being substantially perpendicular to the scanning direction of the beams in the area's A14, A24, A34. As a result of the movement in direction D by a second actuator (e.g. a movement of the substrate table by a corresponding substrate table motor), successive scans of the beams when being projected by successive lenses of the rotatable frame 8, are projected so as to substantially abut each other, resulting in substantially abutting areas A11, A12, A13, A14 (areas A11, A12, A13 being previously scanned and A14 being currently scanned as shown in Figure 4) for each successive scan of beams B1, resulting in areas A21, A22, A23 and A24 (areas A21, A22, A23 being previously scanned and A24 being currently scanned as shown in Figure 4) for each successive scan of beams B2 and resulting in areas A31, A32, A33 and A34 (areas A31, A32, A33 being previously scanned and A34 being currently scanned as shown in Figure 4) for each successive scan of beams B3. Thereby, the areas A1, A2 and A3 of the substrate surface may be covered with a movement of the substrate in the direction D while rotating the rotatable frame 8. The projecting of multiple beams through a same lens allows processing of a whole substrate in a shorter timeframe (at a same rotating speed of the rotatable frame 8), since for each passing of a lens, a plurality of beams scan the substrate with each lens, thereby allowing increased displacement in the direction D for successive scans. Viewed differently, for a given processing time, the rotating speed of the rotatable frame may be reduced when multiple beams are projected onto the substrate via a same lens, thereby possibly reducing effects such as deformation of the rotatable frame, wear, vibrations, turbulence, etc. due to high

rotating speed. In an embodiment, the plurality of beams are arranged at an angle to the tangent of the rotation of the lenses 14, 18 as shown in Figure 4. In an embodiment, the plurality of beams are arranged such that each beam overlaps or abuts a scanning path of an adjacent beam.

[0036] A further effect of the aspect that multiple beams are projected at a time by the same lens, may be found in relaxation of tolerances. Due to tolerances of the lenses (positioning, optical projection, etc), positions of successive areas A11, A12, A13, A14 (and/or of areas A21, A22, A23 and A24 and/or of areas A31, A32, A33 and A34) may show some degree of positioning inaccuracy in respect of each other. Therefore, some degree of overlap between successive areas A11, A12, A13, A14 may be required. In case of for example 10% of one beam as overlap, a processing speed would thereby be reduced by a same factor of 10% in case of a single beam at a time through a same lens. In a situation where there are 5 or more beams projected through a same lens at a time, the same overlap of 10% (similarly referring to one beam example above) would be provided for every 5 or more projected lines, hence reducing a total overlap by a factor of approximately 5 or more to 2% or less, thereby having a significantly lower effect on overall processing speed. Similarly, projecting at least 10 beams may reduce a total overlap by approximately a factor of 10. Thus, effects of tolerances on processing time of a substrate may be reduced by the feature that multiple beams are projected at a time by the same lens. In addition or alternatively, more overlap (hence a larger tolerance band) may be allowed, as the effects thereof on processing are low given that multiple beams are projected at a time by the same lens.

[0037] Alternatively or in addition to projecting multiple beams via a same lens at a time, interlacing techniques could be used, which however may require a comparably more stringent matching between the lenses. Thus, the at least two beams projected onto the substrate at a time via the same one of the lenses have a mutual spacing, and the lithographic apparatus may be arranged to operate the second actuator so as to move the substrate with respect to the optical column to have a following projection of the beam to be projected in the spacing.

[0038] In order to reduce a distance between successive beams in a group in the direction D (thereby e.g. achieving a higher resolution in the direction D), the beams may be arranged diagonally in respect of each other, in respect of the direction D. The spacing may be further reduced by providing a segmented mirror 30 in the optical path, each segment to reflect a respective one of the beams, the segments being arranged so as to reduce a spacing between the

beams as reflected by the mirrors in respect of a spacing between the beams as incident on the mirrors. Such effect may also be achieved by a plurality of optical fibers, each of the beams being incident on a respective one of the fibers, the fibers being arranged so as to reduce along an optical path a spacing between the beams downstream of the optical fibers in respect of a spacing between the beams upstream of the optical fibers.

[0039] Further, such effect may be achieved using an integrated optical waveguide circuit having a plurality of inputs, each for receiving a respective one of the beams. The integrated optical waveguide circuit is arranged so as to reduce along an optical path a spacing between the beams downstream of the integrated optical waveguide circuit in respect of a spacing between the beams upstream of the integrated optical waveguide circuit.

[0040] A system may be provided to control the focus of an image projected onto a substrate. The arrangement may be provided to adjust the focus of the image projected by part or all of an optical column in an arrangement as discussed above.

[0041] As depicted in Figure 5, the focus adjustment arrangement may include a radiation beam expander 40 that is arranged such that the image of the programmable patterning device 4 projected onto the field lens 14, discussed above, is projected via the radiation beam expander 40. The field lens 14 and the imaging lens 18, discussed above, are arranged such that an image projected onto the field lens 14 is projected onto a substrate supported on the substrate table 2. Therefore, by adjusting the position, in a direction substantially parallel to the optical axis 46 of the projection system, of the image projected onto the field lens 14, the focus of the image formed at the level of the substrate may be adjusted. As will be discussed further below, the radiation beam expander 40 is used to provide such an adjustment of the position of the image projected onto the field lens 14.

[0042] This may be advantageous because it means that focus adjustment may be performed without adjusting the position of the substrate relative to the projection system. This may enable accurate focus control independently for different areas located across the full width of the illumination field on the substrate. For example, each optical column, or part thereof, may have independent capability to adjust the focus of the image it is projecting onto the substrate.

[0043] Furthermore, such an arrangement may not require adjusting the position of the field lens 14 or the imaging lens 18 in a direction parallel to the optical axis 46 of the projection system. Such control may be difficult in an arrangement in which, as discussed above, the field

lens 14 and the imaging lens 18 are arranged to move in a direction perpendicular to the optical axis 46 of the projection system. For example, as depicted in Figure 5, and consistent with the arrangements discussed above, the field lens 14 and the imaging lens 18 may be mounted to a movable (e.g., rotating) frame 8 that is driven by a first actuator system 11.

5 **[0044]** The radiation beam expander 40 may be formed from a pair of axially aligned positive lenses 41, 42. The lenses 41, 42 may be fixedly positioned relative to each other, for example by means of a rigid support frame 43.

10 **[0045]** In an embodiment, the radiation beam expander 40 may be configured such that it is both object-space telecentric and image-space telecentric. It will be understood that, by object-space telecentric, it is meant that the entrance pupil is located at infinity and, by image-space telecentric, it is meant that the exit pupil is located at infinity.

15 **[0046]** A second actuator system 44 may be provided and arranged to control the position of the radiation beam expander 40 in a direction substantially parallel to the optical axis 46 of the projection system. In particular, the second actuator system 44 may be configured to act on the support frame 43 in order to adjust the position of the first and second lens 41, 42 relative to the field lens 14 while maintaining the relative positions of the first and second lenses 41, 42.

20 **[0047]** The second actuator system 44 may be configured to help ensure that the radiation beam expander 40 only moves in a direction substantially parallel to the optical axis 46 so that there is substantially no movement of the radiation beam expander 40 in a direction perpendicular to the optical axis 46 of the projection system. Movement of the radiation beam expander 40 in the direction parallel to the optical axis 46 of the projection system is used to adjust the position of the image of the programmable patterning device 4 projected onto the field lens 14.

25 **[0048]** A controller 45 may be provided that is adapted to control the second actuator 44 in order to move the radiation beam expander 40 in an appropriate manner in order to provide the desired focus control of the image projected onto the substrate. In particular, movement of the radiation beam expander 40 along the optical axis 46 of the projection system is proportional to the consequent focus shift at the substrate. Accordingly, the controller may store a certain multiple for the system and use this to convert a desired focus shift at the substrate to an appropriate movement of the radiation beam expander 40. Subsequently, the controller 45 may
30 control the second actuator system 44 in order to provide the desired movement.

[0049] The desired focus shift at the level of the substrate may be determined, for example, from a measurement of the position of the substrate 17 and/or substrate table 2, in conjunction with a measurement of the distortion of the upper surface of the substrate at a target portion on which an image is to be projected. This may be combined with previously determined
5 information regarding the spot focus of each of the beams of radiation projected onto the substrate. The distortions of the upper surface of the substrate may be mapped prior to exposure of the pattern on the substrate and/or may be measured for each portion of the substrate immediately before the pattern is projected onto that portion of the substrate.

[0050] The multiple relating the movement of the radiation beam expander 40 to the
10 focus shift at the substrate may be determined by the formula below:

$$(1/B^2)/(A^2 - 1)$$

in which A is the magnification of the radiation beam expander 40 and B is the magnification of
15 the optical system from the lens 14 onto which the radiation beam expander projects an image of the programmable patterning device, to the substrate, namely the magnification of the combination of the field lens 14 and the imaging lens 18.

[0051] In an arrangement, the magnification of the combined system of the field lens 14 and the imaging lens 18 may be 1/15 (i.e. demagnification) and the magnification of the radiation
20 beam expander 40 may be 2. Accordingly, using the formula above, it will be seen that for a focus shift of 25 μm at the level of the substrate, the movement of the radiation beam expander should be 1.875 mm.

[0052] As noted above, the focusing arrangement may be provided separately for each optical column within a lithographic apparatus. Accordingly, it will be appreciated that each
25 optical column may include a respective radiation beam expander 40 and associated actuator system 44 arranged to move the respective radiation beam expander 40 in a direction substantially parallel to the optical axis 46 of the projection system.

[0053] Figure 6 depicts an arrangement of a spot focus sensor system according to an embodiment of the present invention. As shown, it includes a grating 50 and a radiation intensity
30 sensor 51, such as a photodiode or other photodetector. The grating 50 and radiation intensity sensor 51 are arranged such that the radiation intensity sensor 51 may detect the intensity of

radiation that passes through the grating 50 when a radiation beam 52 is projected onto the grating 50.

[0054] In the arrangement depicted, the grating 50 may be formed as a plurality of chrome strips 53 formed on a substrate 54. Other constructions of grating may be used. The substrate 54 may be selected to be substantially transparent to the radiation, for example formed from SiO₂. The radiation intensity sensor 51 may be formed on the opposite side of the substrate 54 from the grating 50. The pitch P of the grating 50 may be selected to be the same order of magnitude as, for example the same as, the desired spot size of the beams of radiation to be projected onto the substrate.

[0055] As shown in Figure 6, if a relatively focused beam 52 is projected onto the grating 50, such that the spot is incident on a gap between the chrome strips 53 of the grating 50, substantially all of the radiation beam intensity may be transmitted through to the radiation intensity sensor 51, resulting in a maximum possible radiation intensity received at the radiation intensity sensor 51. In contrast, if the radiation beam 52' is incident on one of the chrome strips 53, little or none of the radiation beam may be transmitted through to the radiation intensity sensor 51, resulting in a minimum possible radiation intensity received at the radiation intensity sensor 51.

[0056] The spot focus sensor system may be configured to scan the radiation beam 52 across the grating 50 such that it is projected onto the grating 50 at a plurality of locations (and/or cause the grating 50 to move with respect to the beam 52 such that the beam 52 is incident on the grating 50 at a plurality of locations). If, as shown in Figure 6, the beam or radiation 52 is relatively well focused at the level of the grating, there will be a significant contrast between the maximum and minimum radiation intensity levels received at the radiation intensity sensor 51.

[0057] However, if the radiation beam 52 is not well focused at the level of the grating, there will be no points at which substantially all of the beam 52 passes through a gap between adjacent chrome strips 53 and no point at which substantially all of the radiation beam 52' will be incident on a single chrome strip 53 and therefore not transmitted to the radiation intensity sensor 51. Accordingly, in this case, the difference between the maximum and minimum radiation intensity received at the radiation intensity sensor 51 will be reduced.

[0058] Accordingly, the spot focus sensor system may include a controller 55 configured

to control the spot focus sensor system. It may be configured to receive signals from the radiation intensity sensor 51 corresponding to the radiation intensity levels received at the radiation intensity sensor 51. From these signals, the controller 55 may determine the focus of the beam 52 at the grating 50. For example, the controller 55 may determine a spot focus value.

5 This may represent a measure of the extent of focus of the beam 52 for the position of the grating 50 relative to the projection system. Alternatively or additionally, the spot focus value may represent a distance from the projection system to a point at which the radiation beam 52 is at best focus or an acceptable focus.

[0059] As discussed above, in order for the controller 55 to have sufficient data to
 10 determine the spot focus value, the beam 52 is projected onto the grating 50 at a plurality of locations. This enables the identification of the maximum and minimum radiation intensity levels received at the radiation intensity sensor 51 to be identified. The controller 55 may be configured to control relative movement between the grating 50 and the beam 52 during a spot focus measurement. Accordingly, the controller 55 may control, directly or indirectly via a controller
 15 of the lithographic apparatus, one or more actuator systems used to move one or both of the grating 50 and one or more components of the projection system that may be used to move the beam 52.

[0060] Figure 7 depicts schematically the signal I that may be output from the radiation intensity sensor 51 as there is relative movement between the radiation beam 52 and the grating
 20 50, namely signal I at a range of positions of the grating 50 relative to the radiation beam 52. As shown, the signal I includes a plurality of maxima and a plurality of minima, corresponding to the radiation beam 52 being projected onto the space between the chrome strips 53 and onto the chrome strips 53, respectively.

[0061] In order to determine the spot focus value, the controller 55 may analyze a signal
 25 from the radiation intensity sensor 51 in order to identify a value for the maximum intensity $I_{\max}$ and a value for the minimum intensity $I_{\min}$. From this, the controller 55 may determine a contrast value. For example, the contrast value C_v may be determined from the equation:

$$C_v = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

It should be appreciated, however, that another definition of contrast may be used.

[0062] Accordingly, the controller 55 may obtain a numerical value of the contrast from which to determine the spot focus value. A pair of values of the contrast value determined for different positions of the surface of the grating 50 relative to the projection system in a direction parallel to the optical axis of the beam 52 could be used in order to determine the spot focus value. However, such a system may be inconvenient because it may be necessary to provide calibration to take account of, for example, variations of the intensity of the beam of radiation and variations of the response of the radiation intensity sensor 51.

[0063] Accordingly, in an embodiment, the spot focus sensor system is configured to determine the contrast value for several positions of the surface of the grating 50 relative to the projection system in a direction parallel to the optical axis of the beam 52. By identifying the location of the grating 50 in the direction parallel to the optical axis of the beam 52 at which the contrast value reaches its maximum, it is possible to identify the position of best focus and therefore the spot focus value.

[0064] In an embodiment, the controller 55 may be configured to receive information corresponding to the position of the grating 50 relative to the projection system in the direction parallel to the optical axis of the beam 52 and/or to be able to control, directly or indirectly, the position of the surface of the grating 50 on which the beam 52 is incident relative to the projection system.

[0065] In an embodiment, the spot focus sensor system may be configured to determine contrast values for a plurality of locations of the surface of the grating 50 on which the beam 52 is incident relative to the projection system in a direction parallel to the optical axis of the beam 52. The controller 55 may then identify the position of best focus by selecting the position at which the contrast value has the highest value identified.

[0066] In an alternative embodiment, the controller 55 may fit a curve that relates the location of the surface of the grating 50 on which the beam 52 is incident relative to the projection system in the direction parallel to the optical axis of the beam 52 to the determined contrast values. The controller 55 may then determine the point of best focus, and in turn the spot focus value, by identifying the position corresponding to the maximum of the curve.

[0067] Such an arrangement may have improved accuracy because it may reduce the effect of any errors in the system. This may be particularly relevant because the system may have

relatively high sensitivity to errors close to the position of best focus. For example, the change in contrast value for a given movement of the grating 50 relative to the projection system may be relatively small close to the position of best focus. By including measurements of the contrast value from positions away from the point of best focus, accuracy may be improved.

5 **[0068]** As shown in Figure 8, the grating 50 and optionally the associated radiation intensity sensor 51 of the spot focus sensor system may be provided on the substrate table WT of the lithographic apparatus. For example, as shown, the grating 50 may be provided in a region adjacent to the location at which the substrate W may be located. Such a location may be advantageous because the actuator system 60 provided to control the position of the substrate
10 table WT relative to the projection system during formation of a pattern on the substrate W may be used to control the position of the grating 50 during a measurement of the spot focus value.

[0069] For example, the actuator system 60 to control the position of the substrate table WT may be used to scan the grating 50 relative to the beam 52 in a direction substantially perpendicular to the optical axis of the beam 52 in order that the beam 52 is projected onto a
15 plurality of locations on the grating 50 so as to determine a contrast value.

[0070] The actuator system 60 for the substrate table WT may also or alternatively be used to adjust the position of the substrate table WT, and therefore the grating 50, in a direction substantially parallel to the beam 52. Accordingly, the process may be repeated at multiple positions in the direction parallel to the optical axis of the beam 52 in order to obtain multiple
20 measurements of the contrast value, as discussed above, in order to find the position at which the contrast value is maximized.

[0071] In an embodiment, the actuator system 60 to control the position of the substrate table WT may be able to tilt an upper surface of the substrate table WT to be at an oblique angle relative to the optical axis of the beam 52, as shown in Figure 9 (it will be appreciated that Figure
25 9 depicts an exaggerated view). Accordingly, the upper surface of the grating 50, which may be parallel to the upper surface of the substrate table WT, may also be at an oblique angle relative to the optical axis of the beam 52.

[0072] Subsequently, the actuator system 60 to control the position of the substrate table WT may move the substrate table, and therefore the grating 50, in a direction substantially
30 perpendicular to the optical axis of the beam 52. In such an arrangement, it will be appreciated that the beam 52 may be projected onto one region of the grating 50 at a first distance from the

projection system in the direction parallel to the optical axis of the beam 52 and onto a second region of the grating 50 at a different distance from the projection system in the direction parallel to the optical axis of the beam 52.

[0073] Therefore, from a single relative scan movement between the beam 52 and the grating 50 so that the beam 52 goes across the grating 50, the controller 55 may obtain sufficient data to determine the contrast values for a plurality of regions of the grating that are each at different distances from the projection system in the direction parallel to the optical axis of the beam 52. From this, the controller may determine the point of maximum contrast value, and therefore the spot focus value. Such a procedure may be faster to perform than one in which the grating 50 is separately and repeatedly scanned by the beam 52 at different positions of the substrate table WT relative to the projection system in the direction parallel to the optical axis of the beam 52.

[0074] As depicted in Figure 10, instead or in addition to tilting the substrate table WT using the actuator system 60, the grating 50 may be arranged such that its upper surface is permanently at an oblique angle relative to the upper surface of the substrate table WT. For example, the substrate 54 used to separate the grating 50 from the radiation intensity sensor 51 may be wedge-shaped, as depicted in Figure 10. Additionally or alternatively, the grating 50 may have its own actuator to cause the tilt of the grating 50.

[0075] As discussed above, the projection system may be configured to include one or more moving optical elements in order that the beams of radiation may be scanned across the substrate W during formation of an image on the substrate. In such a lithographic apparatus, the projection system may be used during the determination of a spot focus value to scan the beam 52 across the grating 50. Accordingly, no actuator system may be necessary to move the grating 50 in a direction substantially perpendicular to the optical axis of the beam 52 in order to project the beam 52 onto the plurality of locations on the grating 50 for determination of one or more contrast values.

[0076] In such an arrangement, the grating 50 may be arranged at an oblique angle to the optical axis of the beam 52, as discussed above, such that the spot focus value may be determined without moving the grating 50 relative to the projection system.

[0077] Alternatively, the upper surface of the grating 50 may be arranged to be perpendicular to the optical axis of the beam 52. In that case, an actuator system, for example the

actuator system 60 used to control the position of the substrate table WT, may be used to move the grating 50 through a plurality of positions relative to the projection system in the direction parallel to the optical axis of the beam 52 in order to obtain a plurality of contrast values, from which the spot focus value may be determined.

5 [0078] In the embodiments discussed above, the grating 50 and the radiation intensity sensor 51 of the spot focus sensor system may be located on the substrate table WT. Such an arrangement may be convenient because it may permit the inspection of the one or more beams of radiation projected by the projection system periodically in order to determine the spot focus value without providing significant additional equipment within the lithographic apparatus.

10 [0079] In a system having a plurality of radiation beams projected by the projection system, the spot focus value may be determined for one or more of the beams of radiation each time there is a convenient suspension of production using the lithographic apparatus, for example when a new substrate is loaded. In an arrangement, all of the beams of radiation may be inspected every time an inspection takes place. Alternatively or additionally, only a proportion of
15 the beams may be inspected during some or all of the inspections. In that case, the beams of radiation inspected in each inspection may be scheduled such that, over a given number of inspections, each beam of radiation is inspected at least once.

[0080] It should also be appreciated that the spot focus sensor system need not be provided to the substrate table WT. Accordingly, for example, a separate system may be
20 provided that may include an actuator system to move the grating to the necessary position to inspect the one or more beams of radiation while the substrate table WT is away from the projection system. This may occur, for example, during loading and/or unloading of a substrate from the substrate table.

[0081] Figure 11 depicts an arrangement of a grating 50 for use in the spot focus sensor
25 system according to an embodiment of the present invention. As shown, the grating 50 includes first and second grating parts 50a, 50b that are arranged at different distances from the projection system in the direction parallel to the optical axis of the beam 52. In a single relative scan between the radiation beam 52 and the grating 50, the controller 55 may obtain respective contrast values for the first and second grating parts 50a, 50b.

30 [0082] Such an arrangement may beneficially be used to determine the spot focus value because the variation of the contrast values with the position of the grating relative to the

projection system may be substantially symmetric about the point of best focus. Accordingly, when the plane of best focus 61 is half way between the upper surfaces of the first and second grating parts 50a, 50b, as depicted in Figure 11, the contrast values for each of the first and second grating parts 50a, 50b will be substantially the same. Therefore, the controller 55 may be configured to determine the spot focus value from an identification of the position of the grating 50 at which the contrast values for the first and second grating parts 50a, 50b are substantially the same.

[0083] In order to identify this position, the controller may control an actuator system, such as any of those discussed above, to iteratively adjust the position of the grating 50 relative to the projection system in the direction parallel to the optical axis of the beam 52 until the contrast values for the first and second grating parts 50a, 50b are substantially the same, namely when the difference between them is below a certain threshold. At this point, the first grating part 50a is above the plane of best focus 61 and the second grating part 50b is below the plane of best focus 61.

[0084] Alternatively, the controller 55 may control the actuator system to scan the grating 50 through a range of positions relative to the projection system in the direction parallel to the optical axis of the beam 52, determining contrast values for each of the first and second grating parts 50a, 50b at each position. From this, the controller 55 may identify the position at which the contrast values for the first and second grating parts 50a, 50b are substantially the same. For example, it may select the position at which the two contrast values are most similar. Alternatively, the controller 55 may fit a curve to the relationship between the difference between the two contrast values and the distance of the grating 50 from the projection system and select the distance corresponding to the minimum of the curve.

[0085] In an arrangement, the grating 50 may be constructed such that the distance between the first and second grating parts 50a, 50b in the direction parallel to the optical axis of the beam 52 is the same order of magnitude as the depth of focus of the system. In such an arrangement, it may be provided that, at the point at which the contrast values for the first and second grating parts 50a, 50b are substantially equal, namely where the plane best focus 61 is halfway between them, neither of the first and second grating parts 50a, 50b are close to the plane of best focus 61. At the plane of best focus 61, the contrast values may vary least for a given variation in the position, and are therefore relatively sensitive to noise in the system, as

discussed above. Accordingly, because in this arrangement the first and second grating parts 50a, 50b are arranged to be away from the plane of best focus 61, improved accuracy may be achieved.

[0086] Although the above description has referred to the spot sensor system configured to inspect a single beam 52 in order to determine a spot focus value for that beam of radiation, the spot focus sensor system may be configured to inspect a plurality of beams of radiation simultaneously. For example, a plurality of beams of radiation may be simultaneously projected onto the grating 50 if it is a suitable size. A plurality of radiation intensity sensors 51 may be provided in order to simultaneously determine contrast values for each of the beams of radiation projected onto the grating 50. Alternatively, a single radiation intensity sensor 51 may be configured to be able to discriminate between the intensity of radiation from each of the plurality of beams of radiation that passes through the grating.

[0087] Although the above description has referred to the use of a grating 50 that is transmissive, such that, for example, the lithographic apparatus may be arranged with the grating 50 provided between the projection system and the radiation intensity sensor, such that the radiation intensity sensor 51 detects the radiation from the spot of radiation passing through the grating 50, this need not be the case. For example, a reflective grating may be used. In that case, the radiation intensity sensor may be provided on the same side of the grating as the projection system to detect radiation from the spot of radiation that is reflected from the grating. In an embodiment, the radiation intensity sensor may be mounted to, or otherwise incorporated into, the projection system.

[0088] Although particular embodiments have been described in the context of moving the grating 50 in a direction parallel to the optical axes of the beams of radiation in order to provide sufficient data to determine the spot focus value, this need not be the case. In particular, alternatively or additionally, the point of focus of one or more of the beams of radiation may be moved in the direction parallel to the optical axes of the beams of radiation, providing the same effect. Accordingly, all of the embodiments discussed above in which the grating is moved in a direction parallel to the optical axes of the beams of radiation may be modified to be implemented by means of moving the point of focus of the beams of radiation. The point of focus of the beams of radiation may be adjusted by using a focus adjustment system such as those described above.

[0089] The lithographic apparatus may include a position measurement system that may be used to determine the position of the spot focus sensor system relative to another element within the lithographic apparatus in order that the spot focus value determined by the spot focus sensor system may be used to control the operation of the lithographic apparatus. For example, such a system may be used to measure the position of the spot focus sensor system relative to the projection system and/or relative to the upper surface of a substrate within the lithographic apparatus.

[0090] Further, the information from the spot focus sensor system as described above may be used to adjust one or more parameters of the lithographic apparatus during a subsequent process to project the beams of radiation onto a substrate, namely during a subsequent process performed as part of a device manufacturing method.

[0091] In accordance with a device manufacturing method, a device, such as a display, integrated circuit or any other item may be manufactured from the substrate on which the pattern has been projected.

[0092] In an embodiment, there is provided a lithographic apparatus, comprising: a programmable patterning device, configured to provide a plurality of radiation beams; a projection system, configured to project the plurality of radiation beams onto a substrate to form respective spots of radiation; and a spot focus sensor system comprising: a grating, arranged such that at least one of the radiation beam spots may be successively projected onto a plurality of different locations on the grating in order to perform a radiation spot focus measurement, a radiation intensity sensor, configured to detect the intensity of radiation from the radiation beam spot passing through or reflected from the grating at the plurality of locations, and a controller, configured to determine a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

[0093] In an embodiment, the lithographic apparatus further comprises a substrate table, configured to support the substrate, wherein the grating is mounted to an upper surface of the substrate table. In an embodiment, the lithographic apparatus further comprises an actuator system, configured to move the substrate table in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation, wherein, during a radiation spot focus measurement, the actuator system is used to move the grating relative to the radiation beam spot such that it is projected onto a plurality of different locations on the grating. In an embodiment,

the projection system is configured such that it may scan the plurality of beams of radiation across the substrate in a direction substantially perpendicular to the optical axes of the beams of radiation; and during a radiation spot focus measurement, the projection system is used to project the radiation beam spot onto a plurality of different locations on the grating. In an embodiment, the controller is configured to determine a contrast value for the difference between maximum and minimum detected radiation intensities for at least one region of the grating that includes a plurality of the different locations, and to use the at least one contrast value in order to determine the spot focus value. In an embodiment, the contrast value is determined based on: $C_v =$

$$\frac{I_{\text{Max}} - I_{\text{Min}}}{I_{\text{Max}} + I_{\text{Min}}} \quad \text{where } C_v \text{ is the contrast value, } I_{\text{max}} \text{ is the maximum detected radiation intensity}$$

for the region of the grating and I_{min} is the minimum detected radiation intensity for the region of the grating. In an embodiment, the lithographic apparatus further comprises a focus adjustment system, configured to control the position of the point of focus of the radiation beam from which the spot is derived in a direction substantially parallel to the optical axis of the radiation beam; and wherein the controller is configured to determine respective contrast values for one or more regions of the grating for different positions of the point of focus of the radiation beam, and to determine the spot focus value from a determination of a position of the point of focus that corresponds to the maximum contrast value. In an embodiment, the controller is configured to determine respective contrast values for one or more regions of the grating in which the surface of the grating is at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation, and to determine the spot focus value from a determination of a position of the surface of the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation that corresponds to the maximum contrast value. In an embodiment, the controller is configured to determine the spot focus value from the position corresponding to the highest contrast value determined from the detected radiation intensities. In an embodiment, the controller is configured to determine contrast values for at least three different positions in the direction substantially parallel to the optical axes of the plurality of beams of radiation, to fit a curve to the relationship between the contrast values and the corresponding positions, and to determine the spot focus value from the position corresponding to the maximum of the curve. In an embodiment, the lithographic apparatus comprises an actuator system configured to move the grating in the direction substantially

parallel to the optical axes of the plurality of beams of radiation; and wherein the contrast values are determined for a single region of the grating at different positions in the direction. In an embodiment, the lithographic apparatus comprises an actuator system configured to move the grating in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation; and wherein the surface of the grating is arranged at an oblique angle to the optical axes of the plurality of beams of radiation and the contrast values are determined for respective different regions of the grating. In an embodiment, the surface of the grating is substantially parallel to the upper surface of the substrate table; the actuator system is configured to control the substrate table such that the upper surface of the substrate table is substantially perpendicular to the optical axes of the plurality of beams of radiation when they are projected onto the substrate and at an oblique angle to the optical axes of the plurality of beams of radiation when they are projected onto the grating; and the contrast values are determined for respective different regions of the grating. In an embodiment, the grating comprises first and second grating parts, arranged at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and the controller is configured to determine first and second contrast values, respectively, for regions of the grating in each of the first and second grating parts and to compare the first and second contrast values in order to determine the spot focus value. In an embodiment, the lithographic apparatus further comprises an actuator system configured to adjust the position of the grating relative to the projection system in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and wherein the controller is configured to determine the spot focus value from an identification of the position of the grating at which the first and second contrast values are substantially the same. In an embodiment, the lithographic apparatus further comprises a focus adjustment system, configured to control the position of the point of focus of the radiation beam from which the spot is derived in a direction substantially parallel to the optical axis of the radiation beam; and wherein the controller is configured to determine the spot focus value from an identification of the position of the point of focus of the radiation beam at which the first and second contrast values are substantially the same. In an embodiment, the controller is configured to identify the position by iteratively adjusting the position based on the comparison of the first and second contrast values until the difference between the first and second contrast values is below a certain threshold. In an embodiment, the controller is configured to identify the position by adjusting the position

through a range of positions, for which each of the first and second contrast values are determined, and identifying from the plurality of first and second contrast values the position at which they are substantially the same. In an embodiment, the grating is transmissive and arranged between the projection system and the radiation intensity sensor. In an embodiment, the grating is reflective and the radiation intensity sensor is mounted to the projection system. In an embodiment, the spot focus system is configured to determine simultaneously respective spot focus values for a plurality of the radiation beam spots.

[0094] In an embodiment, there is provided a method for measuring radiation beam spot focus in a lithographic apparatus comprising: a programmable patterning device, configured to provide a plurality of radiation beams, and a projection system, configured to project the plurality of radiation beams onto a substrate to form respective spots of radiation, the method comprising: successively projecting at least one of the radiation beam spots onto a plurality of different locations on a grating; detecting the intensity of radiation from the radiation beam spot passing through or reflected from the grating at the plurality of locations; and determining a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

[0095] In an embodiment, the lithographic apparatus comprises a substrate table configured to support the substrate, and the grating is mounted to an upper surface of the substrate table; and the method further comprises using an actuator system to move the substrate table in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation during a radiation spot focus measurement, such that the radiation beam spot is projected onto a plurality of different locations on the grating. In an embodiment, during a radiation spot focus measurement, the projection system is used to scan the radiation beam spot across a plurality of different locations on the grating. In an embodiment, the method comprises determining a contrast value for the difference between maximum and minimum detected radiation intensities for at least one region of the grating that includes a plurality of the different locations; and using the at least one contrast value in order to determine the spot focus value. In

an embodiment, the contrast value is determined based on: $C_v = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}}$ where C_v is the

contrast value, I_{max} is the maximum detected radiation intensity for the region of the grating and I_{min} is the minimum detected radiation intensity for the region of the grating. In an embodiment, the method comprises: determining respective contrast values for one or more regions of the

grating in which the surface of the grating is at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and determining the spot focus value from a position of the surface of the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation that corresponds to the

5 maximum contrast value. In an embodiment, the method comprises determining the spot focus value from the position of the surface of the grating corresponding to the highest contrast value determined from the detected radiation intensities. In an embodiment, the method comprises: determining contrast values for at least three different positions of the surface of the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation;

10 fitting a curve to the relationship between the contrast values and the corresponding positions; and determining the spot focus value from the position corresponding to the maximum of the curve. In an embodiment, the method comprises: using an actuator system to move the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation; and determining the contrast values for a single region of the grating at different positions in the

15 direction. In an embodiment, the method comprises: using an actuator system to move the grating in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation, wherein the surface of the grating is arranged at an oblique angle to the optical axes of the plurality of beams of radiation; and determining the contrast values for respective different regions of the grating. In an embodiment, the method comprises: using the actuator system to

20 control the substrate table such that the upper surface of the substrate table is at an oblique angle to the optical axes of the plurality of beams of radiation when they are projected onto the grating, wherein the surface of the grating is substantially parallel to the upper surface of the substrate table; and determining the contrast values for respective different regions of the grating. In an embodiment, the grating comprises first and second grating parts, arranged at different respective

25 positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and the method comprises determining first and second contrast values, respectively, for regions of the grating in each of the first and second grating parts and comparing the first and second contrast values in order to determine the spot focus value. In an embodiment, the method further comprises: using an actuator system to adjust the position of the grating relative to the

30 projection system in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and determining the spot focus value from an identification of the position of the

grating at which the first and second contrast values are substantially the same. In an embodiment, the method comprises identifying the position of the grating by iteratively adjusting the position of the grating using the actuator system based on the comparison of the first and second contrast values until the difference between the first and second contrast values is below a certain threshold. In an embodiment, the method comprises: identifying the position of the grating by using the actuator system to move the grating through a range of positions, for which each of the first and second contrast values are determined; and identifying from the plurality of first and second contrast values the position at which they are substantially the same. In an embodiment, the method comprises determining simultaneously respective spot focus values for a plurality of the radiation beam spots. In an embodiment, there is provided a device manufacturing method, comprising: using a method described herein to measure the radiation beam spot focus of at least one of a plurality of radiation beams in a lithographic apparatus; and using the determined spot focus value to control at least one parameter of the lithographic apparatus controlling the projecting of the plurality of beams of radiation onto a substrate.

[0096] 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, flat-panel displays, 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), a metrology tool and/or an 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.

[0097] The term “lens”, where the context allows, may refer to any one of various types of optical components, including refractive, diffractive, reflective, magnetic, electromagnetic and electrostatic optical components or combinations thereof.

[0098] The lithographic apparatus may also be of a type wherein a surface of the substrate is immersed in a liquid having a relatively high refractive index, e.g. water, so as to fill a space between a final element of the projection system and the substrate. Immersion liquids may also be applied to other spaces in the lithographic apparatus, for example, between the
5 patterning device and a first element of the projection system. Immersion techniques are well known in the art for increasing the numerical aperture of projection systems.

[0099] Further embodiments according to the invention are provided in below numbered clauses:

1. A lithographic apparatus, comprising:

10 a programmable patterning device, configured to provide a plurality of radiation beams;
a projection system, configured to project the plurality of radiation beams onto a substrate to form respective spots of radiation; and

a spot focus sensor system comprising:

15 a grating, arranged such that at least one of the radiation beam spots may be successively projected onto a plurality of different locations on the grating in order to perform a radiation spot focus measurement,

a radiation intensity sensor, configured to detect the intensity of radiation from the radiation beam spot passing through or reflected from the grating at the plurality of locations, and

20 a controller, configured to determine a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

2. The lithographic apparatus according to clause 1, further comprising a substrate table, configured to support the substrate, wherein the grating is mounted to an upper surface of the
25 substrate table.

3. The lithographic apparatus according to clause 2, further comprising an actuator system, configured to move the substrate table in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation, wherein, during a radiation spot focus measurement,
30 the actuator system is used to move the grating relative to the radiation beam spot such that it is projected onto a plurality of different locations on the grating.

4. The lithographic apparatus according to any of the preceding clauses, wherein the projection system is configured such that it may scan the plurality of beams of radiation across the substrate in a direction substantially perpendicular to the optical axes of the beams of radiation; and

5 during a radiation spot focus measurement, the projection system is used to project the radiation beam spot onto a plurality of different locations on the grating.

5. The lithographic apparatus according to any of the preceding clauses, wherein the controller is configured to determine a contrast value for the difference between maximum and minimum detected radiation intensities for at least one region of the grating that includes a plurality of the different locations, and to use the at least one contrast value in order to determine the spot focus value.

6. The lithographic apparatus according to clause 5, wherein the contrast value is determined based on:

$$Cv = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}}$$

where Cv is the contrast value, I_{max} is the maximum detected radiation intensity for the region of the grating and I_{min} is the minimum detected radiation intensity for the region of the grating.

7. The lithographic apparatus according to clause 5 or clause 6, further comprising a focus adjustment system, configured to control the position of the point of focus of the radiation beam from which the spot is derived in a direction substantially parallel to the optical axis of the radiation beam; and

wherein the controller is configured to determine respective contrast values for one or more regions of the grating for different positions of the point of focus of the radiation beam, and to determine the spot focus value from a determination of a position of the point of focus that corresponds to the maximum contrast value.

8. The lithographic apparatus according to clause 5 or clause 6, wherein the controller is configured to determine respective contrast values for one or more regions of the grating in which the surface of the grating is at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation, and to determine the spot focus value from a determination of a position of the surface of the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation that corresponds to the maximum contrast value.

9. The lithographic apparatus according to clause 7 or clause 8, wherein the controller is configured to determine the spot focus value from the position corresponding to the highest contrast value determined from the detected radiation intensities.

10. The lithographic apparatus according to clause 7 or clause 8, wherein the controller is configured to determine contrast values for at least three different positions in the direction substantially parallel to the optical axes of the plurality of beams of radiation, to fit a curve to the relationship between the contrast values and the corresponding positions, and to determine the spot focus value from the position corresponding to the maximum of the curve.

11. The lithographic apparatus according to any of clauses 8 to 10, comprising an actuator system configured to move the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation; and
wherein the contrast values are determined for a single region of the grating at different positions in the direction.

12. The lithographic apparatus according to any of clauses 8 to 11, comprising an actuator system configured to move the grating in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation; and

wherein the surface of the grating is arranged at an oblique angle to the optical axes of the plurality of beams of radiation and the contrast values are determined for respective different regions of the grating.

13. The lithographic apparatus according to any of clauses 8 to 12 when dependent from clause 3, wherein:

the surface of the grating is substantially parallel to the upper surface of the substrate
5 table;

the actuator system is configured to control the substrate table such that the upper surface of the substrate table is substantially perpendicular to the optical axes of the plurality of beams of radiation when they are projected onto the substrate and at an oblique angle to the optical axes of the plurality of beams of radiation when they are projected onto the grating; and

10 the contrast values are determined for respective different regions of the grating.

14. The lithographic apparatus according to clause 5 or clause 6, wherein the grating comprises first and second grating parts, arranged at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and

15 the controller is configured to determine first and second contrast values, respectively, for regions of the grating in each of the first and second grating parts and to compare the first and second contrast values in order to determine the spot focus value.

15. The lithographic apparatus according to clause 14, further comprising an actuator system
20 configured to adjust the position of the grating relative to the projection system in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and

wherein the controller is configured to determine the spot focus value from an identification of the position of the grating at which the first and second contrast values are substantially the same.

25 16. The lithographic apparatus according to clause 14, further comprising a focus adjustment system, configured to control the position of the point of focus of the radiation beam from which the spot is derived in a direction substantially parallel to the optical axis of the radiation beam; and

30 wherein the controller is configured to determine the spot focus value from an identification of the position of the point of focus of the radiation beam at which the first and

second contrast values are substantially the same.

17. The lithographic apparatus according to clause 15 or clause 16, wherein the controller is configured to identify the position by iteratively adjusting the position based on the comparison
5 of the first and second contrast values until the difference between the first and second contrast values is below a certain threshold.

18. The lithographic apparatus according to clause 15 or clause 16, wherein the controller is configured to identify the position by adjusting the position through a range of positions, for
10 which each of the first and second contrast values are determined, and identifying from the plurality of first and second contrast values the position at which they are substantially the same.

19. The lithographic apparatus according to any of the preceding clauses, wherein the grating is transmissive and arranged between the projection system and the radiation intensity sensor.
15

20. The lithographic apparatus according to any of clauses 1 to 18, wherein the grating is reflective and the radiation intensity sensor is mounted to the projection system.

21. The lithographic apparatus according to any of the preceding clauses, wherein the spot
20 focus system is configured to determine simultaneously respective spot focus values for a plurality of the radiation beam spots.

22. A method for measuring radiation beam spot focus in a lithographic apparatus comprising:

25 a programmable patterning device, configured to provide a plurality of radiation beams,
and

a projection system, configured to project the plurality of radiation beams onto a substrate to form respective spots of radiation,

the method comprising:

30 successively projecting at least one of the radiation beam spots onto a plurality of
different locations on a grating;

detecting the intensity of radiation from the radiation beam spot passing through or reflected from the grating at the plurality of locations; and

determining a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

5

23. The method according to clause 22, wherein the lithographic apparatus comprises a substrate table configured to support the substrate, and the grating is mounted to an upper surface of the substrate table; and

the method further comprises using an actuator system to move the substrate table in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation during a radiation spot focus measurement, such that the radiation beam spot is projected onto a plurality of different locations on the grating.

10

24. The method according to clause 22 or clause 23, wherein, during a radiation spot focus measurement, the projection system is used to scan the radiation beam spot across a plurality of different locations on the grating.

15

25. The method according to any of clauses 22 to 24, comprising:

determining a contrast value for the difference between maximum and minimum detected radiation intensities for at least one region of the grating that includes a plurality of the different locations; and

20

using the at least one contrast value in order to determine the spot focus value.

26. The method according to clause 25, wherein the contrast value is determined based on:

25

$$Cv = \frac{I_{Max} - I_{Min}}{I_{Max} + I_{Min}}$$

where Cv is the contrast value, I_{max} is the maximum detected radiation intensity for the region of the grating and I_{min} is the minimum detected radiation intensity for the region of the grating.

30

27. The method according to clause 25 or clause 26, comprising:

determining respective contrast values for one or more regions of the grating in which the surface of the grating is at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and

5 determining the spot focus value from a position of the surface of the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation that corresponds to the maximum contrast value.

28. The method according to clause 27, comprising determining the spot focus value from the
10 position of the surface of the grating corresponding to the highest contrast value determined from the detected radiation intensities.

29. The method according to clause 27, comprising:

determining contrast values for at least three different positions of the surface of the
15 grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation;

fitting a curve to the relationship between the contrast values and the corresponding positions; and

determining the spot focus value from the position corresponding to the maximum of the
20 curve.

30. The method according to any of clauses 27 to 29, comprising:

using an actuator system to move the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation; and

25 determining the contrast values for a single region of the grating at different positions in the direction.

31. The method according to any of clauses 27 to 29, comprising:

using an actuator system to move the grating in a direction substantially perpendicular to
30 the optical axes of the plurality of beams of radiation, wherein the surface of the grating is arranged at an oblique angle to the optical axes of the plurality of beams of radiation; and

determining the contrast values for respective different regions of the grating.

32. The method according to any of clauses 27 to 29 when dependent from clause 23, comprising:

5 using the actuator system to control the substrate table such that the upper surface of the substrate table is at an oblique angle to the optical axes of the plurality of beams of radiation when they are projected onto the grating, wherein the surface of the grating is substantially parallel to the upper surface of the substrate table; and

determining the contrast values for respective different regions of the grating.

10 33. The method according to clause 25 or clause 26, wherein the grating comprises first and second grating parts, arranged at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and

the method comprises determining first and second contrast values, respectively, for
15 regions of the grating in each of the first and second grating parts and comparing the first and second contrast values in order to determine the spot focus value.

34. The method according to clause 33, further comprising:

20 using an actuator system to adjust the position of the grating relative to the projection system in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and

determining the spot focus value from an identification of the position of the grating at which the first and second contrast values are substantially the same.

25 35. The method according to clause 34, comprising identifying the position of the grating by iteratively adjusting the position of the grating using the actuator system based on the comparison of the first and second contrast values until the difference between the first and second contrast values is below a certain threshold.

30 36. The method according to clause 34, comprising:

identifying the position of the grating by using the actuator system to move the grating

through a range of positions, for which each of the first and second contrast values are determined; and

identifying from the plurality of first and second contrast values the position at which they are substantially the same.

5

37. The method according to any of clauses 22 to 36, comprising determining simultaneously respective spot focus values for a plurality of the radiation beam spots.

38. A device manufacturing method, comprising:

10 using the method of any of clauses 22 to 37 to measure the radiation beam spot focus of at least one of a plurality of radiation beams in a lithographic apparatus; and

using the determined spot focus value to control at least one parameter of the lithographic apparatus controlling the projecting of the plurality of beams of radiation onto a substrate.

[00100] While specific embodiments of the invention have been described above, it will
15 be appreciated that the invention may be practiced otherwise than as described. For example, the invention may take the form of a computer program containing one or more sequences of machine-readable instructions configured to cause performance of a method as disclosed above, or a computer-readable data storage medium (e.g. semiconductor memory, magnetic or optical disk) having such a computer program stored therein.

20 **[00101]** The descriptions above are intended to be illustrative, not limiting. Thus, it will be apparent to one skilled in the art that modifications may be made to the invention as described without departing from the scope of the claims set out below.

CLAIMS:

1. A lithographic apparatus, comprising:

a programmable patterning device, configured to provide a plurality of radiation beams;

a projection system, configured to project the plurality of radiation beams onto a substrate to form respective spots of radiation; and

a spot focus sensor system comprising:

a grating, arranged such that at least one of the radiation beam spots may be successively projected onto a plurality of different locations on the grating in order to perform a radiation spot focus measurement,

a radiation intensity sensor, configured to detect the intensity of radiation from the radiation beam spot passing through or reflected from the grating at the plurality of locations, and

a controller, configured to determine a spot focus value from the detected radiation intensity corresponding to the plurality of locations.

2. The lithographic apparatus according to claim 1, further comprising a substrate table, configured to support the substrate, wherein the grating is mounted to an upper surface of the substrate table.

3. The lithographic apparatus according to claim 2, further comprising an actuator system, configured to move the substrate table in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation, wherein, during a radiation spot focus measurement, the actuator system is used to move the grating relative to the radiation beam spot such that it is projected onto a plurality of different locations on the grating.

4. The lithographic apparatus according to any of the preceding claims, wherein the projection system is configured such that it may scan the plurality of beams of radiation across the substrate in a direction substantially perpendicular to the optical axes of the beams of radiation; and

during a radiation spot focus measurement, the projection system is used to project the

radiation beam spot onto a plurality of different locations on the grating.

5. The lithographic apparatus according to any of the preceding claims, wherein the controller is configured to determine a contrast value for the difference between maximum and minimum detected radiation intensities for at least one region of the grating that includes a plurality of the different locations, and to use the at least one contrast value in order to determine the spot focus value.

6. The lithographic apparatus according to claim 5, further comprising a focus adjustment system, configured to control the position of the point of focus of the radiation beam from which the spot is derived in a direction substantially parallel to the optical axis of the radiation beam; and

wherein the controller is configured to determine respective contrast values for one or more regions of the grating for different positions of the point of focus of the radiation beam, and to determine the spot focus value from a determination of a position of the point of focus that corresponds to the maximum contrast value.

7. The lithographic apparatus according to claim 5, wherein the controller is configured to determine respective contrast values for one or more regions of the grating in which the surface of the grating is at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation, and to determine the spot focus value from a determination of a position of the surface of the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation that corresponds to the maximum contrast value.

8. The lithographic apparatus according to claim 6 or claim 7, wherein the controller is configured to determine the spot focus value from the position corresponding to the highest contrast value determined from the detected radiation intensities.

9. The lithographic apparatus according to claim 6 or claim 7, wherein the controller is configured to determine contrast values for at least three different positions in the direction

substantially parallel to the optical axes of the plurality of beams of radiation, to fit a curve to the relationship between the contrast values and the corresponding positions, and to determine the spot focus value from the position corresponding to the maximum of the curve.

5 10. The lithographic apparatus according to any of claims 7 to 9, comprising an actuator system configured to move the grating in the direction substantially parallel to the optical axes of the plurality of beams of radiation; and

wherein the contrast values are determined for a single region of the grating at different positions in the direction.

10

11. The lithographic apparatus according to any of claims 7 to 10, comprising an actuator system configured to move the grating in a direction substantially perpendicular to the optical axes of the plurality of beams of radiation; and

15 wherein the surface of the grating is arranged at an oblique angle to the optical axes of the plurality of beams of radiation and the contrast values are determined for respective different regions of the grating.

12. The lithographic apparatus according to any of claims 7 to 11 when dependent from claim 3, wherein:

20 the surface of the grating is substantially parallel to the upper surface of the substrate table;

the actuator system is configured to control the substrate table such that the upper surface of the substrate table is substantially perpendicular to the optical axes of the plurality of beams of radiation when they are projected onto the substrate and at an oblique angle to the optical axes of the plurality of beams of radiation when they are projected onto the grating; and

25

the contrast values are determined for respective different regions of the grating.

13. The lithographic apparatus according to claim 5, wherein the grating comprises first and second grating parts, arranged at different respective positions in a direction substantially parallel to the optical axes of the plurality of beams of radiation; and

30

the controller is configured to determine first and second contrast values, respectively, for

regions of the grating in each of the first and second grating parts and to compare the first and second contrast values in order to determine the spot focus value.

14. A method for measuring radiation beam spot focus in a lithographic apparatus

5 comprising:

a programmable patterning device, configured to provide a plurality of radiation beams,
and

a projection system, configured to project the plurality of radiation beams onto a substrate
to form respective spots of radiation,

10 the method comprising:

successively projecting at least one of the radiation beam spots onto a plurality of
different locations on a grating;

detecting the intensity of radiation from the radiation beam spot passing through or
reflected from the grating at the plurality of locations; and

15 determining a spot focus value from the detected radiation intensity corresponding to the
plurality of locations.

15. A device manufacturing method, comprising:

using the method of claims 14 to measure the radiation beam spot focus of at least one of
20 a plurality of radiation beams in a lithographic apparatus; and

using the determined spot focus value to control at least one parameter of the lithographic
apparatus controlling the projecting of the plurality of beams of radiation onto a substrate.

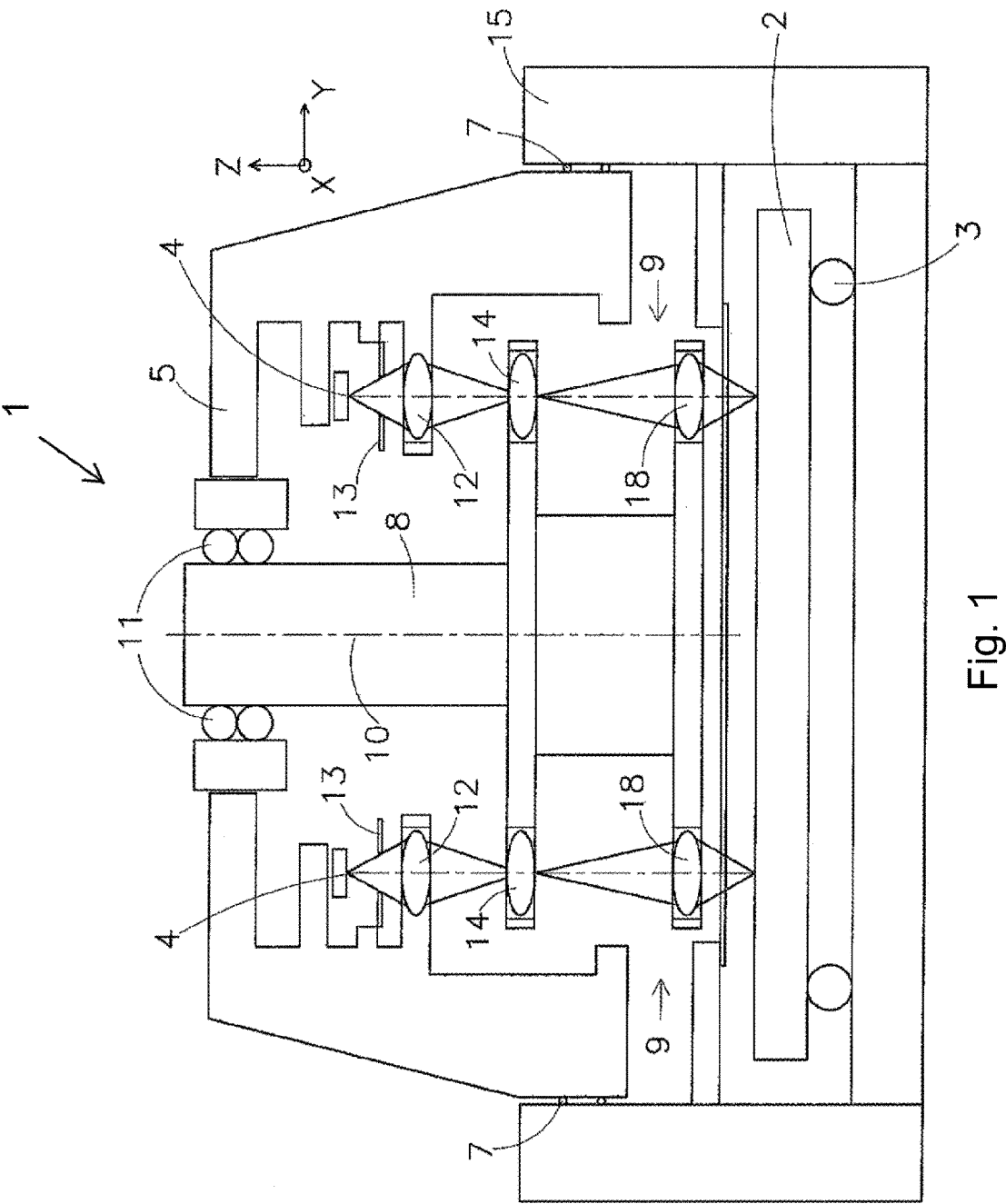
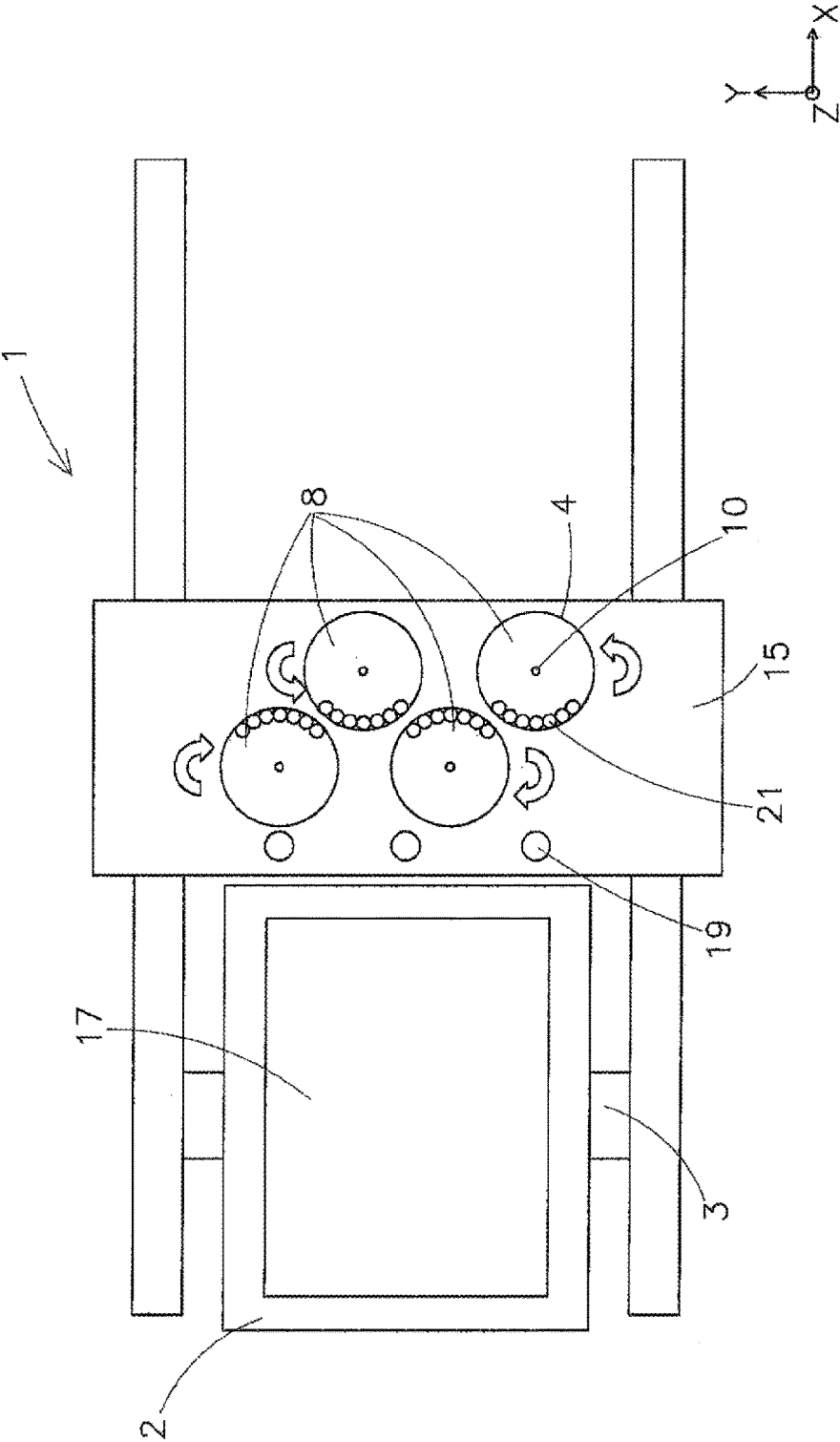


Fig. 1



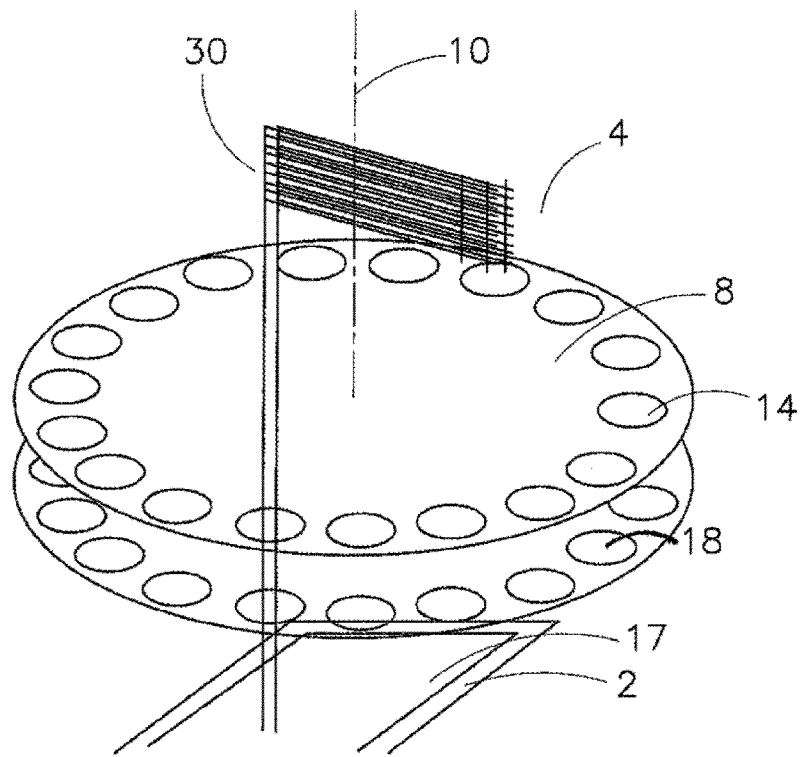


Fig. 3

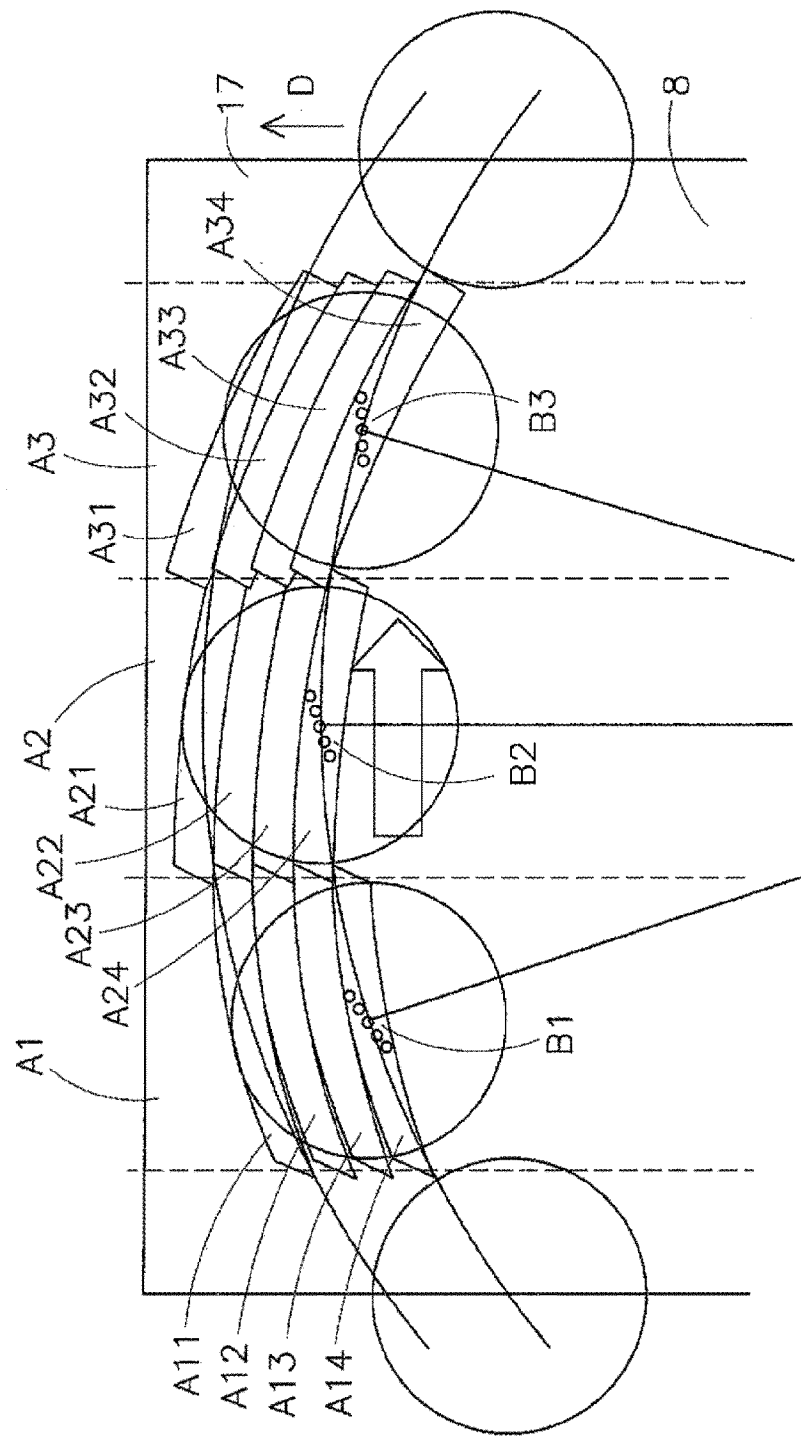


Fig. 4

5/7

Fig 5

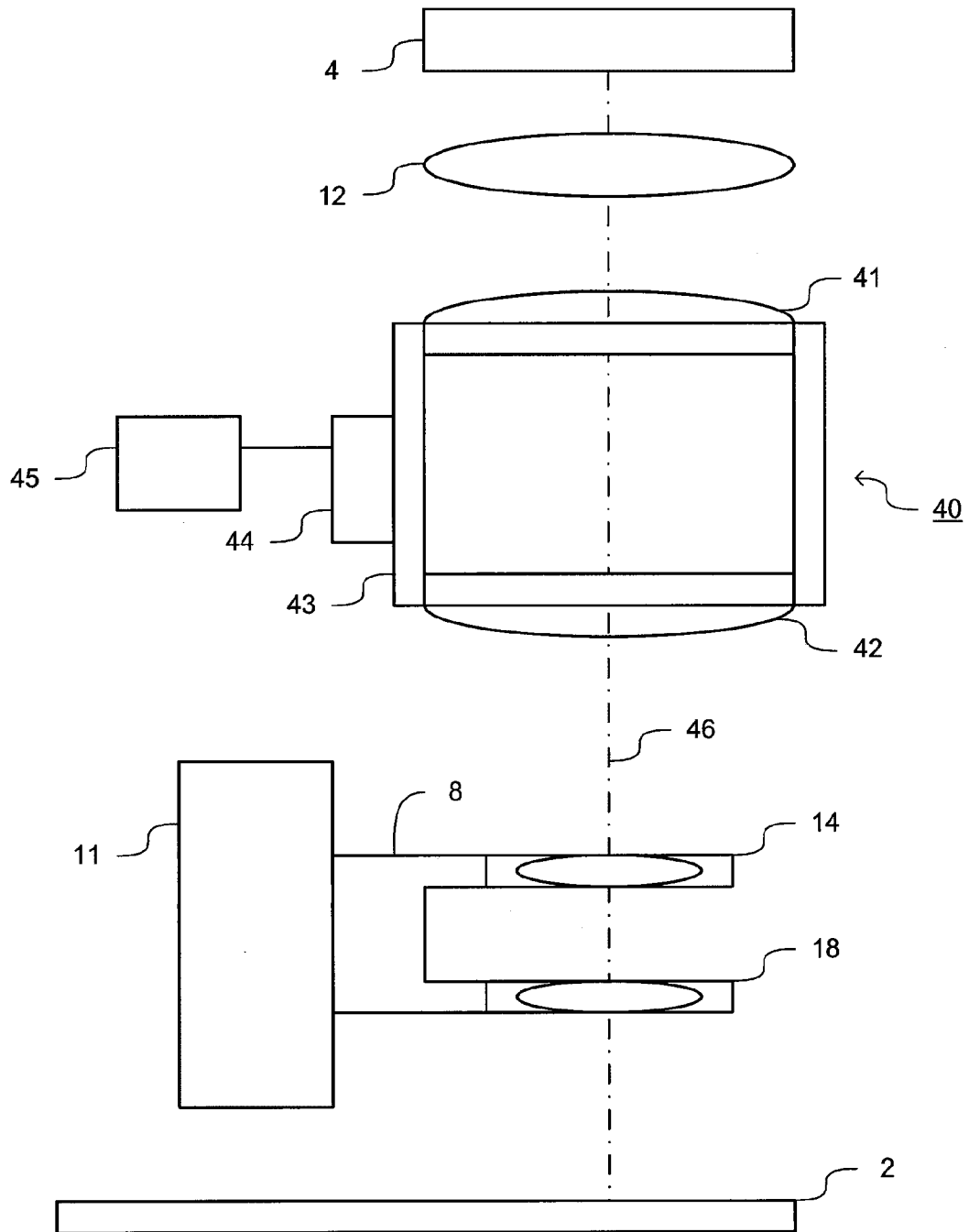


Fig 6

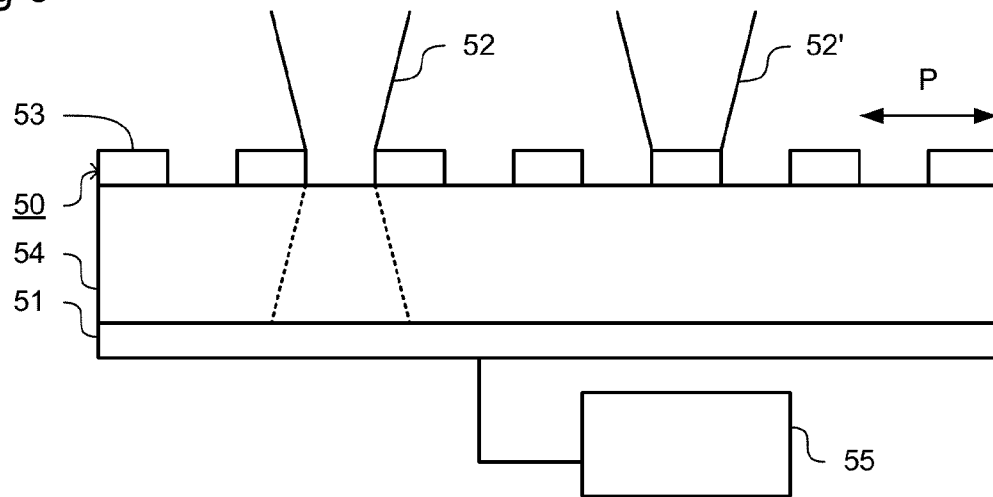


Fig 7

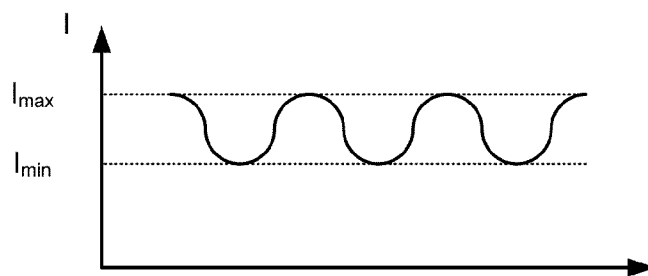


Fig 8

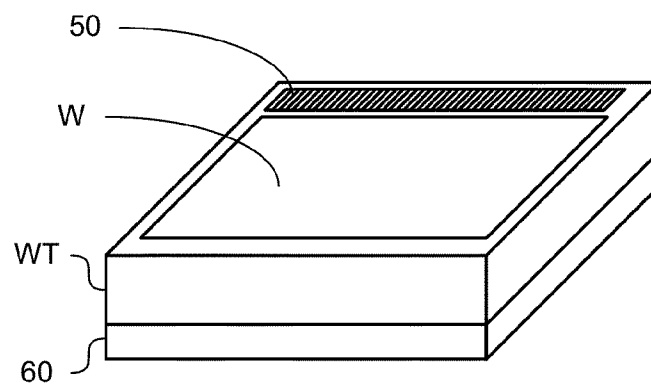


Fig 9

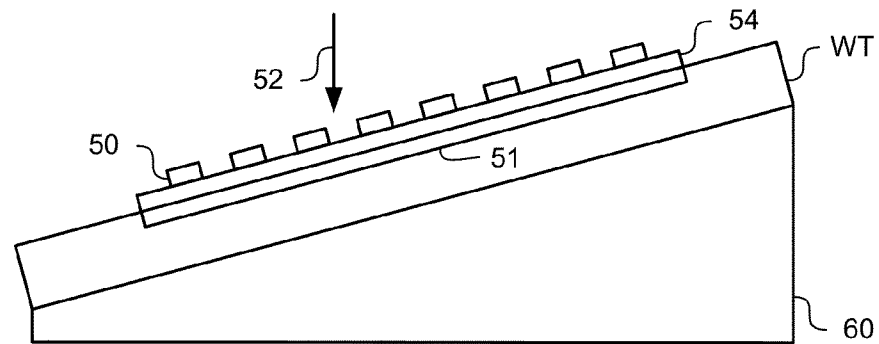


Fig 10

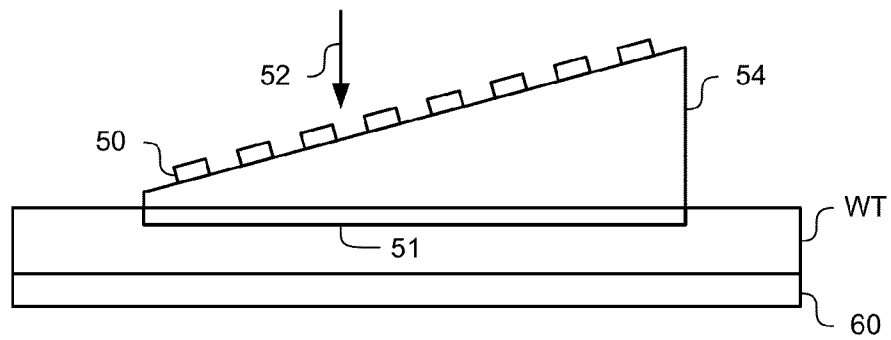
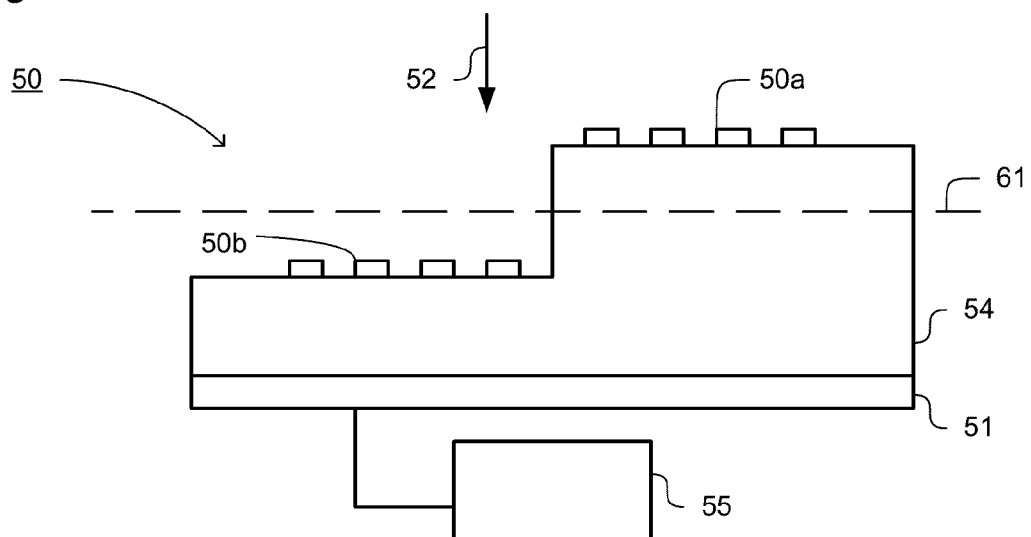


Fig 11



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/052588

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

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

B. FIELDS SEARCHED

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

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

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

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2005/200820 A1 (GUI CHENG-QUN [NL]) 15 September 2005 (2005-09-15) paragraphs [0006], [0049], [0068]; figure 5 -----	1-15
Y	US 6 476 382 B1 (ZHAI JINHUI [US] ET AL) 5 November 2002 (2002-11-05) column 1, lines 35-40; figure 1 column 2, line 13 - column 6, line 30 -----	1-15
Y	US 2010/294749 A1 (KEMPE MICHAEL [DE] ET AL) 25 November 2010 (2010-11-25) paragraphs [0003], [0008]; claims 25, 26 -----	5-13



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"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

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"&" document member of the same patent family

Date of the actual completion of the international search

31 May 2012

Date of mailing of the international search report

12/06/2012

Name and mailing address of the ISA/

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Authorized officer

Eisner, Klaus

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2012/052588

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