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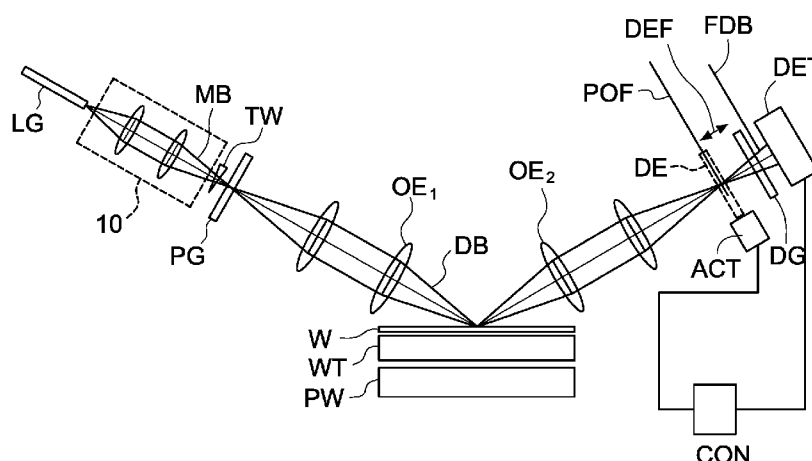


Fig. 2

(57) Abstract: A level sensor senses a local height of a portion of a surface of a semiconductor substrate. The level sensor comprises an optical system that has a projection grating and a detector. In operational use when the substrate is present, the optical system images the projection grating on the detector via reflection off the surface. The level sensor senses the local height from the imaging of the projection grating on the detector. The level sensor comprises an actuator for adjusting the imaging by the optical system.

LEVEL SENSOR AND LITHOGRAPHIC APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

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This application claims priority of EP application 16159030.2 which was filed on 7 March 2016 and which is incorporated herein in its entirety by reference.

10 BACKGROUND

Field of the Invention

The present invention relates to a level sensor and a lithographic apparatus comprising such a level sensor.

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Description of the Related Art

A lithographic apparatus is a machine that applies a desired pattern onto a substrate, usually onto a target portion of the substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a case, a patterning device, which is alternatively referred to as a mask or a reticle, may be used to generate a circuit pattern to be formed on an individual layer of the IC. This pattern can be transferred onto a target portion (e.g. including part of, one, or several dies) on a substrate (e.g. a silicon wafer). Transfer of the pattern is typically via imaging onto a layer of radiation-sensitive material (resist) provided on the substrate. In general, a single substrate will contain a network of adjacent target portions that are successively patterned. Conventional lithographic apparatus include so-called steppers, in which each target portion is irradiated by exposing an entire pattern onto the target portion at once, and so-called scanners, in which each target portion is irradiated by scanning the pattern through a radiation beam in a given direction (the "scanning"-direction) while synchronously scanning the substrate parallel or anti-parallel to this direction. It is also possible to transfer the pattern from the patterning device to the substrate by imprinting the pattern onto the substrate.

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In lithography, a flatness of the substrate (e.g. the wafer) may be measured and e.g. stored as a height map. The height map may be used to position a relevant target portion of the substrate at an appropriate height, in order to provide that, when projecting a pattern onto the target portion of the substrate, that target portion is positioned within a focal range (depth of

focus) of a projection system (e.g., a projection lens) of the lithographic apparatus. Compiling the height map is also referred to as “level sensing”. The level sensing may be performed by a level sensor. The level sensor may be integral to a lithographic apparatus or may be a separate measurement arrangement. The level sensor may make use of an optical measurement, by means of projecting a measurement beam onto the substrate and detecting a reflection thereof. In certain detection schemes, use may be made of gratings in an optical path of the measurement beam, e.g. a projection grating upstream of the substrate and a detection grating downstream of the substrate.

Consider a level sensor having a projection grating, a detection grating and a detector. The projection grating is imaged on the substrate surface at an angle relative to the (ideal) surface normal. The image is reflected by the wafer surface and re-imaged on the detection grating. Due to the oblique incidence, a variation in the substrate’s height will shift the image of the projection grating on the detection grating over a certain distance. The shifted image of the projection grating is partially transmitted by the detection grating. The detector detects an intensity of the transmitted image. The intensity is indicative of the substrate’s local height. In other words, a height variation of the surface of the substrate results in a variation in the image transmitted by the detection grating, allowing deriving height information from the detector signal. In a measurement principle as may be applied, the optical path of the image of the projection grating should be accurately set, so as to provide that the projection grating is correctly imaged onto the detection grating.

A manual calibration of the positions of the projection grating and the detection grating in respect of each other may be performed during manufacturing and/or calibration of the lithographic apparatus or of the level sensor. . During such (re-) calibrations, a calibration beam may be applied and the relative positions of the projection grating and the detection grating may be manually adjusted, so as to provide that the calibration beam correctly projects the projection grating onto the detection grating.

Apart from the fact that calibration of the level sensor at the customer’s site may increase a down-time of a lithographic process, an accuracy of such manual calibrations may be limited: On the one hand, this may be the case as, for safety reasons, the calibration is typically performed using light at a different wavelength than the measurement beam as applied during level sensing. Furthermore, environmental conditions, e.g. a temperature, at which the calibration is performed may differ from the environmental conditions during level sensing in operational use when the lithographic apparatus system is closed and fully conditioned. A distance between the projection grating and the detection grating may be relatively large. A

temperature difference between e.g. calibration and operational use may result in an optical frame (to which the gratings are mounted) to exhibit thermal deformation effects. The thermal deformation effects of the optical frame may cause the relative positions of the gratings to deviate during operation of the lithographic apparatus from the positions as set or adjusted during calibration.

SUMMARY

It is desirable to provide an improved level sensor calibration.

An aspect of the invention relates to a level sensor that is configured to sense a local height of a portion of a surface of an object. The level sensor comprises an optical system. The optical system comprises a projection grating and a detector. In operational use when the object is present, the optical system is operative to image the projection grating on the detector via reflection off the surface. The level sensor is configured to sense the local height from the imaging of the projection grating on the detector. The level sensor comprises an actuator for adjusting the imaging by the optical system.

In an embodiment, the actuator is configured to adjust at least one of: a position of the projection grating; a further position of the detector; an orientation of the projection grating; and a further orientation of the detector.

In a further embodiment, the optical system comprises a detection grating. In operational use when the object is present, the optical system is operative to image the projection grating on the detector via reflection off the surface and transmission via the detection grating. The actuator is configured to adjust at least one of: a position of the detection grating; and an orientation of the detection grating.

In a further embodiment, the optical system comprises an optical component. The optical component comprises at least one of: a lens and a mirror. The actuator is configured to adjust at least one of: a position of the optical component; and an orientation of the optical component.

In a further embodiment, the detector is operative to detect an attribute of the imaging of the projection grating on the detector. The level sensor has a control device configured for driving the actuator under control of the attribute.

The invention also relates to a lithographic apparatus configured for imaging a patterned beam of radiation on a substrate under control of a height map of the substrate. The lithographic apparatus comprises a level sensor as discussed supra. The level sensor is operative to compile the height map via sensing respective local height values of respective portions of the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

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

- Figure 1 depicts a lithographic apparatus according to an embodiment of the invention;
- Figure 2 depicts a highly schematic view of a level sensor according to an embodiment of the invention; and
- Figures 3A, 3B and 3C depict graphs illustrating ways to set the level sensor in focus.

DETAILED DESCRIPTION

Figure 1 schematically depicts a lithographic apparatus according to one embodiment of the invention. The apparatus includes an illumination system (illuminator) IL configured to condition a radiation beam B (e.g. UV radiation or any other suitable radiation), a mask support structure (e.g. a mask table) MT constructed to support a patterning device (e.g. a mask) MA and connected to a first positioning device PM configured to accurately position the patterning device in accordance with certain parameters. The apparatus also includes a substrate table (e.g. a wafer table) WT or "substrate support" constructed to hold a substrate (e.g. a resist-coated wafer) W and connected to a second positioning device PW configured to accurately position the substrate in accordance with certain parameters. The apparatus further includes a projection system (e.g. a refractive projection lens system) PS configured to project a pattern imparted to the radiation beam B by patterning device MA onto a target portion C (e.g. including one or more dies) of the substrate W.

The illumination system may include various types of optical components, such as refractive, reflective, magnetic, electromagnetic, electrostatic or other types of optical components, or any combination thereof, for directing, shaping, or controlling radiation.

The mask support structure supports, i.e. bears the weight of, the patterning device. It

holds the patterning device in a manner that depends on the orientation of the patterning device, the design of the lithographic apparatus, and other conditions, such as for example whether or not the patterning device is held in a vacuum environment. The mask support structure can use mechanical, vacuum, electrostatic or other clamping techniques to hold the patterning device.

5 The mask support structure may be a frame or a table, for example, which may be fixed or movable as required. The mask support structure may ensure that the patterning device is at a desired position, for example with respect to the projection system. Any use of the terms “reticle” or “mask” herein may be considered synonymous with the more general term “patterning device.”

10 The term “patterning device” used herein should be broadly interpreted as referring to any device that can be used to impart a radiation beam with a pattern in its cross-section so as to create a pattern in a target portion of the substrate. It should be noted that the pattern imparted to the radiation beam may not exactly correspond to the desired pattern in the target portion of the substrate, for example if the pattern includes phase-shifting features or so called assist
15 features. Generally, the pattern imparted to the radiation beam will correspond to a particular functional layer in a device being created in the target portion, such as an integrated circuit.

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

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

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

The lithographic apparatus may be of a type having two (dual stage) or more substrate tables or “substrate supports” (and/or two or more mask tables or “mask supports”). In such

“multiple stage” machines the additional tables or supports may be used in parallel, or preparatory steps may be carried out on one or more tables or supports while one or more other tables or supports are being used for exposure.

The lithographic apparatus may also be of a type wherein at least a portion of the substrate may be covered by a liquid having a relatively high refractive index, e.g. water, so as to fill a space between the projection system and the substrate. An immersion liquid may also be applied to other spaces in the lithographic apparatus, for example, between the mask and the projection system. Immersion techniques can be used to increase the numerical aperture of projection systems. The term “immersion” as used herein does not mean that a structure, such as a substrate, must be submerged in liquid, but rather only means that a liquid is located between the projection system and the substrate during exposure.

Referring to figure 1, the illuminator IL receives a radiation beam from a radiation source SO. The source and the lithographic apparatus may be separate entities, for example when the source is an excimer laser. In such cases, the source is not considered to form part of the lithographic apparatus and the radiation beam is passed from the source SO to the illuminator IL with the aid of a beam delivery system BD including, for example, suitable directing mirrors and/or a beam expander. In other cases the source may be an integral part of the lithographic apparatus, for example when the source is a mercury lamp. The source SO and the illuminator IL, together with the beam delivery system BD if required, may be referred to as a radiation system.

The illuminator IL may include an adjuster AD configured to adjust the angular intensity distribution of the radiation beam. Generally, at least the outer and/or inner radial extent (commonly referred to as σ -outer and σ -inner, respectively) of the intensity distribution in a pupil plane of the illuminator can be adjusted. In addition, the illuminator IL may include various other components, such as an integrator IN and a condenser CO. The illuminator may be used to condition the radiation beam, to have a desired uniformity and intensity distribution in its cross-section.

The radiation beam B is incident on the patterning device (e.g., mask MA), which is held on the mask support structure (e.g., mask table MT), and is patterned by the patterning device. Having traversed the mask MA, the radiation beam B passes through the projection system PS, which focuses the beam onto a target portion C of the substrate W. With the aid of the second positioning device PW and position sensor IF (e.g. an interferometric device, linear encoder or capacitive sensor), the substrate table WT can be moved accurately, e.g. so as to position different target portions C in the path of the radiation beam B. Similarly, the first positioning

device PM and another position sensor (which is not explicitly depicted in Figure 1) can be used to accurately position the mask MA with respect to the path of the radiation beam B, e.g. after mechanical retrieval from a mask library, or during a scan. In general, movement of the mask table MT may be realized with the aid of a long-stroke module (coarse positioning) and a short-stroke module (fine positioning), which form part of the first positioning device PM. Similarly, movement of the substrate table WT or "substrate support" may be realized using a long-stroke module and a short-stroke module, which form part of the second positioner PW. In the case of a stepper (as opposed to a scanner) the mask table MT may be connected to a short-stroke actuator only, or may be fixed. Mask MA and substrate W may be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2. Although the substrate alignment marks as illustrated occupy dedicated target portions, they may be located in spaces between target portions (these are known as scribe-lane alignment marks). Similarly, in situations in which more than one die is provided on the mask MA, the mask alignment marks may be located between the dies.

The depicted apparatus could be used in at least one of the following modes:

1. In step mode, the mask table MT or "mask support" and the substrate table WT or "substrate support" are kept essentially stationary, while an entire pattern imparted to the radiation beam is projected onto a target portion C at one time (i.e. a single static exposure). The substrate table WT or "substrate support" is then shifted in the X and/or Y direction so that a different target portion C can be exposed. In step mode, the maximum size of the exposure field limits the size of the target portion C imaged in a single static exposure.
2. In scan mode, the mask table MT or "mask support" and the substrate table WT or "substrate support" are scanned synchronously while a pattern imparted to the radiation beam is projected onto a target portion C (i.e. a single dynamic exposure). The velocity and direction of the substrate table WT or "substrate support" relative to the mask table MT or "mask support" may be determined by the (de-)magnification and image reversal characteristics of the projection system PS. In scan mode, the maximum size of the exposure field limits the width (in the non-scanning direction) of the target portion in a single dynamic exposure, whereas the length of the scanning motion determines the height (in the scanning direction) of the target portion.
3. In another mode, the mask table MT or "mask support" is kept essentially stationary holding a programmable patterning device, and the substrate table WT or "substrate support" is moved or scanned while a pattern imparted to the radiation beam is projected onto a target portion C. In this mode, generally a pulsed radiation source is employed and the programmable

patterning device is updated as required after each movement of the substrate table WT or "substrate support" or in between successive radiation pulses during a scan. This mode of operation can be readily applied to maskless lithography that utilizes programmable patterning device, such as a programmable mirror array of a type as referred to above.

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

Figure 2 depicts a highly schematic view of a level sensor as may be applied in lithography. The level sensor comprises a light source LG which generates a measurement light beam. Illumination optics IO comprises e.g. a lens or a lens system, which projects the measurement beam onto a projection grating PG. The projection grating PG patterns the incident measurement beam. The thus patterned measurement beam DB is projected – e.g. using suitable projection lenses - onto the substrate W whose height map is to be measured. A reflection of the patterned measurement beam DB off the upper surface of the substrate is in turn projected – e.g. using suitable further projection lenses - onto a detection grating DG. The light of the reflected patterned measurement beam that is transmitted by the detection grating, the light being indicated in the diagram of Fig 2 by FDB, is projected onto a detector DET. An example of an implementation of such detector DET is described in US patent 8,351,024 of Den Boef et al., herein incorporated by reference.

The projection grating and detection grating may be formed by any suitable patterning elements, the patterning elements being transmissive (as illustrated) or reflective (in another embodiment, not illustrated). The level sensor thus images the projection grating via reflection off the upper surface of the substrate onto the detector, here via the detection grating. A height variation of the surface of the substrate translates into a displacement of the image of the projection grating on the detection grating. The displacement affects the light eventually incident on the detector DET. The detector DET produces a detector output signal indicative of the light received. The detector DET may be configured to produce an output signal indicative of the intensity of the light received, such as a photodetector. Alternatively, the detector may have been configured to produce an output signal representative of a spatial distribution of the intensity received, such as a camera.

30 In other embodiments, the detector grating may be omitted, and the detector DET may be placed at the position, where in Figure 2 the detector grating DG is placed. Such configuration provides a more direct detection of the image of the projection grating.

Reverting to the embodiment as depicted in Figure 2: Figure 2 depicts two positions of the detection grating DG: a dotted position wherein the detection grating is in a plane of focus

POF of an image of the projection grating, and a non-dotted position wherein the detection grating is out of focus over a defocus distance DEF.

According to an aspect of the invention, the level sensor further comprises an actuator ACT which is configured to position the projection grating in respect of the detection grating or vice versa. Alternatively, the actuator ACT is configured to position the detector DET with respect to at least one of the projection grating and detection grating or vice versa. As known, an actuator is a type of motor that is responsible for moving or controlling a mechanism or system. Figure 2 depicts an example wherein the actuator positions the detection grating. Alternatively, an actuator is provided (not shown) that positions the projection grating. As another example a first actuator is provided that positions the projection grating and a second actuator is provided that positions the detection grating. Generally speaking, in the embodiment as depicted in Figure 2, the actuator sets a relative position of the projection grating and the detection grating, i.e. the relative position of the gratings in respect of each other. Alternatively, the actuator may (re-) position or re-orient an optical element present in the projection optics of the level sensor. This provides that a focal plane of the projection of the projection grating onto the detection grating is adapted by means of moving the optical element, e.g., a lens element or a mirror. In Figure 2, an example of such optical element is indicated as a lens OE1 between the projection grating PG and the substrate W, and another example of such optical element is indicated as another lens OE2 in the projection optics located between the substrate W and the detection grating DG.

In the example where the detection grating is omitted, as described above, the actuator may act on the position of the projection grating, the position of the detector or the position of an optical element in the projection optics of the level sensor, thus adjusting a position of a focal plane of the projection of the projection grating and a position of the detector in respect of each other. Accordingly, in general terms, the actuator is configured to adjust a relative position of the detector and a focal plane (Fig. 2: POF) of the image of the projection grating. The actuator may provide for any displacement of the plane of focus of the image of the projection grating relative to the detector: a displacement in a direction parallel to or antiparallel to the propagation of the measurement beam, a tilting of the plane of focus and/or a change of a field curvature of the plane of focus. In the latter case, the actuator may controllably deform, e.g., an optical element such as the lens OE1 or the other lens OE2 in the projection optics. The actuator may accordingly comprise respective actuator elements. The actuator may for example comprise a piezo actuator or a Lorentz actuator.

A control device CON drives the actuator in order to cause the actuator to adjust the

relative position of the projection grating and the detection grating. The above relates to (re-) adjustment of the position of the projection grating, of the position of the detection grating, of the position of the optical element or of the position of the detector by means of an actuator. Similarly, the actuator can be used for remotely (re-) adjusting the orientation of the projection
5 grating, of the orientation of the detection grating, of the orientation of the optical element OE, or of the orientation of the detector.

The positioning of the projection grating and the detection grating in respect of each other, and/or the positioning of an optical element in the projection optics of the level sensor, enables an in-focus projection of the projection grating onto the detection grating. As a result,
10 an accurate level sensing may be performed, as adverse effects associated with a defocus, e.g. due to a deviation of the relative position of the projection grating and the detection grating may be avoided. Similarly, in case the detection grating is omitted, as described above, the actuator may provide that a plane of focus of an image of the projection grating is provided at a detection surface of the detector, so as to implement an in focus detection. As a result, an
15 accurate level sensing may be performed, as adverse effects associated with a defocus may be avoided. Some of such adverse effects are described below.

As known, during a lithographic process, layers may be provided on the substrate, such as a resist layer (also referred to as a “photosensitive layer”), that covers etched, or otherwise processed, other layers. In case of an ideally reflective resist layer forming the substrate surface,
20 the reflected beam propagates to, and is projected onto the detector, with a uniform angular intensity distribution, i.e., seen in a direction perpendicular to the direction of propagation. Due to optical properties of the resist layer and the further layers below, an inhomogeneity in angular intensity distribution may be created. As the level sensor provides for an imaging of the projection grating in focus onto the detection grating, or on the detector, respectively, an
25 inhomogeneous angular intensity distribution will not, or only to a minor extent, have an effect on an intensity distribution of the light as received at the detector DET, as the inhomogeneous reflected measurement beam is imaged in focus. In case, however, the distance between the projection grating and the detection grating deviates from the ideal distance, the imaging of the projection grating onto the detection grating may get out of focus. Similarly, if the detection
30 grating is omitted, the image of the projection grating onto the detector may get out of focus. If the image is out of focus, the inhomogeneous angular intensity distribution due to e.g. refractive optical properties of the resist layer and the further layers below, results in an inhomogeneous projection onto the detector DET. The level sensor interprets a displacement of the beam onto the detector (which results in a change of the amount of light received at the

detector) as a height variation of the substrate. The inhomogeneous angular intensity distribution of the measurement beam having interacted with the substrate (in the case of resist etc.) may therefore be interpreted by the detector as an in-height displacement of the beam on the detector, thus causing a measurement error in case the projection grating and the detection
5 grating are out of focus.

Accordingly, such defocus errors may contribute to a total error budget of the lithographic projection process.

By providing the actuator that adjusts the relative position of a focal plane of the image of the projection grating in respect of the detector, and the control device that controls the position
10 of the actuator, height variations of the beam on the detector – as a result of e.g. optical properties of the layers on the substrate - may be reduced. Therefore, a level sensing accuracy may be increased.

Accordingly, instead of opening up the lithographic apparatus for manually adjusting the relative positions or orientations of the relevant components of the level sensor, the actuator
15 now enables controlled remote adjustment under environmental conditions (e.g., temperature, using light from the light source LG) similar to those present in operational use. This contributes to achieving higher accuracy in creating the height map, referred to above.

Furthermore, if the effect is known that a specific resist layer has on the intensity distribution of the measurement beam received at the detector, the processing of the detector
20 signal can be modified for compiling the height map and/or the actuator controls the positioning of the focal plane to compensate at least partly for the effect of the resist layer. The control device CON may thus be controlled itself by specific information representative of the optical properties of the stack of layers on the substrate W.

In an embodiment, an output signal, i.e. a measurement signal, of the detector DET is
25 supplied to a sensing input of the control device CON, if needed via a suitable transcoder, a transducer or another signal- conversion device. The control device may be configured to drive, e.g. in a calibration mode, the actuator to set the relative position, in the focus direction, of the image plane of the projection grating in dependence on the output signal of the detector. The control device CON may hence be configured to operate in at least two different modes
30 (different operating states): a measurement mode in which the control device may maintain a set position, and a calibration mode in which the control device may set a new relative position, in the focus direction, of the image plane of the projection grating in respect of the detector (i.e. adjust the relative position). In the calibration mode, the detector output signal may be applied in order to control driving the actuator so as to set the relative position, in the focus direction, of

the image plane of the projection grating in respect of the detector. Hence, the detector output signal may be applied in the calibration mode to set the relative position, in the focus direction, of the image plane of the projection grating in respect of the detector. By using the detector output signal during the calibration, little extra equipment will be required, and an accurate calibration may be performed as the detector output signal itself is involved in the calibration. Plural calibration strategies may be envisaged, some examples of which will be described in the below.

A calibration strategy may include that the control device is configured to operate in the calibration mode as follows.

The control device drives the actuator to successively assume a plurality of the relative positions of the focal plane of the image of the projection grating in respect of the detector, such as displacing the detection grating DG over a range of positions, the range including the positions of the detection grating DG as depicted in Figure 2. Thereby, plural different relative positions are successively set, e.g. stepwise using an incremental step size in relative position. For each relative position, the detector output signal is received by the control device. Using an optimization criterion, an optimum detector output signal is derived by the control device from the actual detector output signals. The skilled person may come up with various examples of such optimisation criterion, some of which will be described below. The control device drives the actuator to set the the relative position of the focal plane of the image of the projection grating in respect of the detector based on the relative position at which the optimum detector output signal was detected. Thus, plural relative positions are set, and at each relative position, the detector output signal is detected.

For example, at each relative position of the focal plane of the image of the projection grating in respect of the detector, one measures a sensitivity of the detector output signal to a stimulus. The stimulus may for example be formed by a movement of the substrate W in the vertical direction (via moving the substrate table WT in the vertical direction, the vertical direction being substantially perpendicular to the top surface of the substrate) or a movement of a wedge TW (discussed in more detail below) or of another optical element in the optical path of the measurement beam of the level sensor. In case the measurement beam of the level sensor is made to reflect off the substrate table WT itself, the stimulus may be formed by a movement of the substrate table WT in the vertical direction. Due to such stimulus, a sensitivity of the detector output signal to the stimulus may be measured, and a most suitable response of the detector output signal to the stimulus may be selected. The relative position of the focal plane of the image of the projection grating in respect of the detector at which the detector output

signal provides a most suitable response, may provide a most suitable relative position, in focus direction, of the image plane of the projection grating in respect of the detector. That most suitable relative position is then to be used during the level sensing in operational use. Hence, the control device drives the actuator to set the relative position accordingly. In case the stimulus is formed by a disturbance, the optimisation criterion may be a minimum, i.e. the relative position, in focus direction, of the image plane of the projection grating in respect of the detector at which a minimum effect of the disturbance is established, may be the one providing optimum focussing. In case the stimulus is formed by a change of the substrate height, the optimisation criterion may be a maximum, i.e. the relative position at which a maximum sensitivity to height change is established, may be the one providing optimum focussing of the projection grating on the detection grating.

As described above, the lithographic apparatus comprises a substrate table WT, configured to hold the substrate whose height map is to be determined, and the lithographic apparatus also comprises a positioner PW configured to position the substrate table, which holds the substrate, relative to the projection system PS of the lithographic apparatus. In order to perform the sensitivity measurement and set the relative position of the focal plane of the image of the projection grating in respect of the detector, the control device may further be configured to operate as follows in the calibration mode: the control device communicates with the positioner PW so as to have the positioner PW move, for each relative position, in focus direction, of the image plane of the projection grating in respect of the detector, the position of the substrate table to plural successive vertical positions. For example the positioner PW successively moves the substrate table to two, three or more vertical positions. At each of the vertical positions of the substrate table, the detector output signal of the detector is detected. Then, for each relative position of the focal plane of the image of the projection grating in respect of the detector, a value of a conversion factor CONV is derived from the detector output signal as a function of the vertical position of the substrate table. The conversion factor may for example be a gain factor indicative of the amount of change in the output signal of the detector for a unit change in vertical position. The gain value is in fact a measure for the contrast. For clarity: in an imaging system, an object and an image of the object are said to be in “best focus” if the contrast of the image is optimal, i.e., the image is as sharp as possible. The contrast gets worse when moving away from the optimal focus. Other possibilities for the conversion factor may include a maximum range of the detector output signal, for example when moving the substrate table in vertical direction. The optimum relative position, in focus direction, of the image plane of the projection grating in respect of the detector is established

by the control device from a maximum value of the conversion factor, i.e. the relative position where a maximum sensitivity is established, is taken as the relative position where the projection grating is projected onto the detection grating/resp. onto the detector in focus or closest to being in focus.

5 An example of such a conversion factor CONV is depicted in Figure 3A, representing a curve fitted to the (finite number of) values of the conversion factor as measured. The diagram of Fig.3A gives the values of the conversion factor CONV, as measured as a function of the relative distance (indicated as “PG-DG def”) between the projection grating and the detection grating along the path of the measurement beam. A change of conversion factor near the
10 relative position, corresponding to the optimum focus, may be low, reflected in a rather flattening of the conversion curve near the top. Noise or other disturbances may influence a process of seeking a maximum MAX in the set of conversion factors measured. Accordingly, in an embodiment, a second-order polynomial is fitted to the values of the conversion factor and a top of the resulting curve is calculated and taken as the maximum value MAX of the
15 conversion factor CONV. Hence, noise or other disturbances may have little effect on the determining of the maximum value of the conversion factor.

In case the conversion factor is implemented as a maximum range of the detector output signal, e.g. when moving the substrate table in vertical direction, a second-order polynomial may likewise be fitted to the measurements and a curve similar to the one as illustrated in
20 Fig.3A may be obtained likewise, whereby the top of the curve indicates a maximum value of the conversion factor.

Preferably, the set-accuracy is determined of the actuator ACT that operates on the projection grating, or on the detection grating, or on the detector. Note that the actuator ACT may be implemented by a piezo-actuator. As known, a piezo actuator may enable position
25 adjustment at small increments and exhibits a high stiffness, thus providing a positioning which is robust against mechanical vibrations, etc. Alternatively, the actuator may comprise a voice-coil actuator, also referred to as a “Lorentz actuator”.

In a piezo actuator, hysteresis may occur, introducing inaccuracies between actuation voltage and position. The effect of hysteresis might be avoided by implementing a positional
30 feedback control loop. For cost reasons and for reasons of volume available, however, it is preferred to operate the actuator ACT in open-loop mode (i.e. without having the need for internal positional feedback control loop). Therefore, a method is proposed, different from the one above, to measure the most favorable position (in-focus position) of the object being positioned by the actuator: the projection grating, the detection grating or the detector. The

proposed method is as follows.

As discussed above, the level sensor images the projection grating onto the substrate resulting in an array of discrete spots on the substrate that get illuminated. Consider a dedicated test substrate or a dedicated structure (also referred to as a “fiducial”) on the substrate table
5 itself. The dedicated test substrate or the dedicated structure on the substrate table has two adjacent areas that differ in optical properties. The two areas may have different stacks of layers. The different stacks are chosen such that the measurement beams reflected off these different stacks assume an as large as possible difference in the angular dependency of the reflectance (also known as “apodization”). Now each of the multiple spots in the array
10 sequentially illuminates the different areas. That is, one area receives at the start all spots and the other none, and gradually the number of spots in the area first-mentioned decreases and the number of spots in the area last mentioned increases. As a result, the detector output signals in this sequence are representative of gradually going from one area to the adjacent area. The output signals could be interpreted as “height values”. The difference in interpreted height
15 values as measured via the level sensor depends on the defocus distance “PG-DG def” between the projection grating and the detection grating in a linear manner. While moving the relevant object (the projection grating or the detection grating or the detector) through the position of best focus the height difference is measured along with the contrast (e.g., via the gain as mentioned earlier). The maximum value of the second order polynomial discussed above can
20 then be determined on the basis of the height difference as measured.

Fig.3B presents a diagram giving the thus interpreted height difference Δh , as measured, as a function of the relative distance (indicated as “PG-DG def”) between the projection grating and the detection grating along the path of the measurement beam. The range of relative distances, at which measurements are made, includes the distance associated with best-focus.
25 A linear curve is fitted through the measurement points.

Subsequently, the actuator ACT is set iteratively, by setting and re-measuring the value of the height difference Δh until the specific value of the height difference is achieved that corresponds to the best focus. Note that neither the absolute value of the height nor the (e.g., thermal) drift of the level sensor will affect the specific value of the height difference that
30 corresponds to best focus. This is illustrated in the diagram of Fig.3C giving the conversion factor CONV as a function of the height difference Δh .

An example of the stimulus, provided by operating a test wedge TW, is provided below. The test wedge TW is located, e.g., between the input optics IO and the projection grating PG. The test wedge TW, as schematically indicated in Figure 2, is movable, e.g. by means of a

suitable test wedge actuator (not shown) under control of the control device CON. The control device may be arranged to, in the calibration phase, perform the following: At each relative position of the focal plane of the image of the projection grating in respect of the detector, the test wedge is moved between two positions in an optical path between the input optics and the projection grating. In an embodiment, the wedge is arranged proximate to the projection grating, at a side of the projection grating facing the input optics IO, causing light to be incident on the projection grating at a non-zero average angle. This provides for a non-telecentric imaging system. As a result, one obtains a high sensitivity of the output signal of the detector (i.e., of the measured height of the substrate) to the optical path length between the projection grating and the detection grating, i.e., to the amount of defocus PG-DG def. Such relationship between the height as measured and the amount of defocus is then a linear one. In case the insertion/removal of the test wedge does not result in a change of the detector output signal, the level sensor is in focus: the projection grating is projected in focus on the detection grating or on the detector, respectively. In other words, the control device receives from the detector, at each relative position of the focal plane of the image of the projection grating in respect of the detector, a signal representative of a displacement of the beam incident on the detector as a result of the movement of the test wedge in the optical path. The test wedge provides for an asymmetry (seen in the direction perpendicular to the direction of propagation of the measurement beam) in the measurement beam as projected onto the detector. As explained above, the more defocussed the projection grating is imaged onto the detector grating or on the detector, respectively, the larger is an effect of such asymmetry in beam distribution. Hence, the more defocus of the level sensor, the larger a disturbance by the test wedge may be. Accordingly, the optimum relative position of the focal plane of the image of the projection grating in respect of the detector may hence be established by the control device from a minimum value or zero value of the displacements of the beam as a result of the movement of the test wedge into the optical path. Such a disturbance factor for example results in a linear variation versus defocus "PG-DG def". A minimum one of the disturbances caused by the test wedge will then indicate the relative position of the projection grating and the detection grating wherein the projection grating and the detection grating are properly positioned, i.e., they are positioned in focus.

In the above example, a test substrate or a fiducial on the substrate table is used with different optical properties as discussed above to control the set-accuracy of the actuator. Another approach involves the tilting of the substrate table. In this approach, one looks at the shift of the so-called "Tilt-Independent-Point" (or: TIP) that is induced by the PG-DG defocus.

The definition of the TIP is the (X-position or) Y-position where the height sensed by the level sensor is unchanged if the substrate table were to pivot around an axis through that position: the (Ry or) Rx tilt. Consider for the purpose of the invention the TIP in Y position only. As known, the Y-direction is the scan direction of the lithographic apparatus.

5 The control device drives the positioner to tilt the substrate table into two different positions that are tilted in respect of each other. Hence, the measurement beam interacts with at least two positions of the substrate or of the fiducial. i.e. at least two locations on the substrate. The detector output signal at the two positions is detected. A height difference is derived from the detector output signal at the two positions that are tilted in respect of each other. Similarly
10 to above, the derived height difference is associated with the respective relative position of the focal plane of the image of the projection grating in respect of the optical detector. In this alternative, instead of applying two areas having different optical properties, the tilting of the substrate or the fiducial about an Rx axis provides that the measurement beam is reflected at different parts of the measurement beam near a point of focus of the measurement beam. The
15 tilting may result in a variation in the detector output signal, e.g. if the measurement beam is incident on the surface of the substrate (or fiducial) more or less close to a point of focus POF of the diffracted measurement beam. Thus, the detector output signal is measured at at least two positions which differ from each other in Rx tilt. Again, a curve of response of detector output signal to Rx tilt, versus actuator position, may be obtained. This curve may be linear.
20 Reflection outside the point of focus will affect a height measurement, due to e.g. refractive properties of the resist as explained above. Hence, in this embodiment, at least two different tilted positions of the substrate may be used instead of the two different areas on the test substrate. As a result, instead of using a special test substrate or a specific fiducial on the substrate table, a normal substrate, such as an unprocessed substrate, or a flat surface of the
25 substrate table may be used for these measurements.

Once the derived height differences have been associated to the respective relative position of the focal plane of the image of the projection grating in respect of the detector, the associated height differences may be applied to provide feedback concerning a relative position of the focal plane of the image of the projection grating in respect of the detector. In
30 case the control device has driven the actuator in order to set the relative position of the focal plane of the image of the projection grating in respect of the detector at the optimum position, the control device may verify the relative position of the focal plane of the image of the projection grating in respect of the detector as follows: the determining of the height difference as outlined above is repeated, and the determined height difference is compared with the height

difference associated with the relative position. In case a height difference is measured that does deviate from the height difference associated with the intended relative position, the control device may drive the actuator so as to correct the relative position and the position verification and actuator driving may be repeated as needed, thereby iteratively arriving at the intended position.

The level sensor as described in the present document may be comprised in a lithographic apparatus, such as a lithographic apparatus employing a transmissive or a reflective projection lens.

The control device may be formed by a separate control system, comprising e.g. a data processing system provided with suitable program instructions or may be implemented as a task or process on an existing data processing system of the level sensor or of the lithographic apparatus. 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.

Although specific reference may have been made above to the use of embodiments of the invention in the context of optical lithography, it will be appreciated that the invention may be used in other applications, for example imprint lithography, and where the context allows, is not limited to optical lithography. In imprint lithography topography in a patterning device defines the pattern created on a substrate. The topography of the patterning device may be pressed into a layer of resist supplied to the substrate whereupon the resist is cured by applying electromagnetic radiation, heat, pressure or a combination thereof. The patterning device is moved out of the resist leaving a pattern in it after the resist is cured.

The terms “radiation” and “beam” used herein encompass all types of electromagnetic

radiation, including ultraviolet (UV) radiation (e.g. having a wavelength of or about 365, 248, 193, 157 or 126 nm) and extreme ultra-violet (EUV) radiation (e.g. having a wavelength in the range of 5-20 nm), as well as particle beams, such as ion beams or electron beams.

The term “lens”, where the context allows, may refer to any one or combination of
5 various types of optical components, including refractive, reflective, magnetic, electromagnetic and electrostatic optical components.

While specific embodiments of the invention have been described above, it will 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
10 machine-readable instructions describing a method as disclosed above, or a data storage medium (e.g. semiconductor memory, magnetic or optical disk) having such a computer program stored therein.

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
15 without departing from the scope of the claims set out below.

WHAT IS CLAIMED IS:

1. A level sensor configured to sense a local height of a portion of a surface of an object,
wherein:
5 the level sensor comprises an optical system;
 the optical system comprises a projection grating and a detector;
 in operational use when the object is present, the optical system is operative to image
the projection grating on the detector via reflection off the surface;
 the level sensor is configured to sense the local height from the imaging of the
10 projection grating on the detector;
 the level sensor comprises an actuator for adjusting the imaging by the optical system,
wherein the actuator is configured to adjust at least one of:
 a position of the projection grating;
 a further position of the detector; and
15 a further orientation of the detector.
2. The level sensor of claim 1, wherein:
 the optical system comprises a detection grating;
 in operational use when the object is present, the optical system is operative to image
20 the projection grating on the detector via reflection off the surface and transmission via the
detection grating; and
 the actuator is configured to adjust at least one of:
 a position of the detection grating; and
 an orientation of the detection grating.
25
3. The level sensor of claim 1, wherein:
 the optical system comprises an optical component;
 the optical component comprises at least one of: a lens and a mirror;
 the actuator is configured to adjust at least one of:
30 a position of the optical component; and
 an orientation of the optical component.
4. The level sensor of claim 1, wherein:

the detector is operative to detect an attribute of the imaging of the projection grating on the detector; and

the level sensor has a control device configured for driving the actuator under control of the attribute.

5

5. A lithographic apparatus configured for imaging a patterned beam of radiation on a substrate under control of a height map of the substrate, wherein

the lithographic apparatus comprises a level sensor of claim 1, 2, 3, or 4;

the level sensor is operative to compile the height map via sensing respective local

10 height values of respective portions of the substrate.

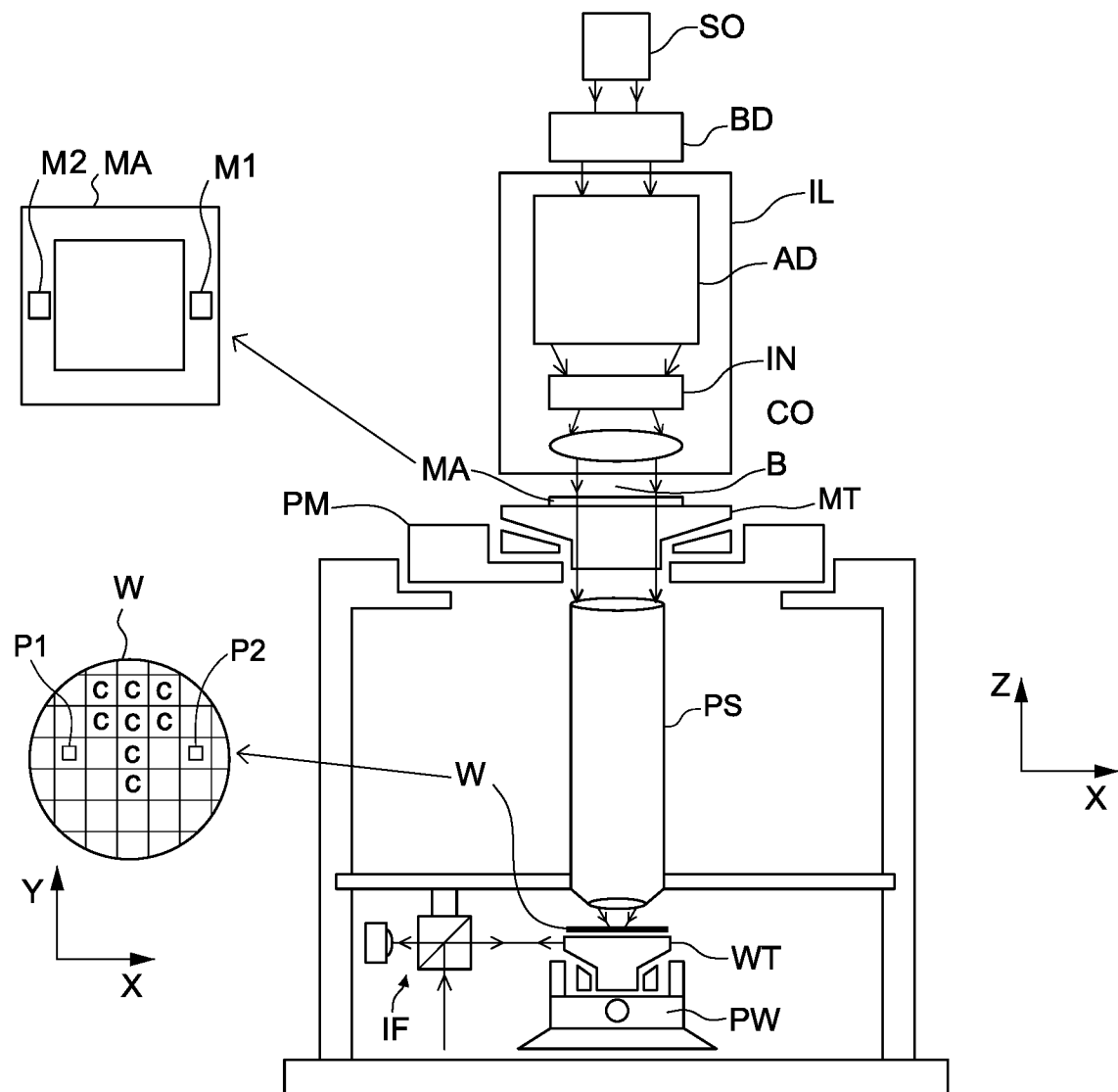


Fig. 1

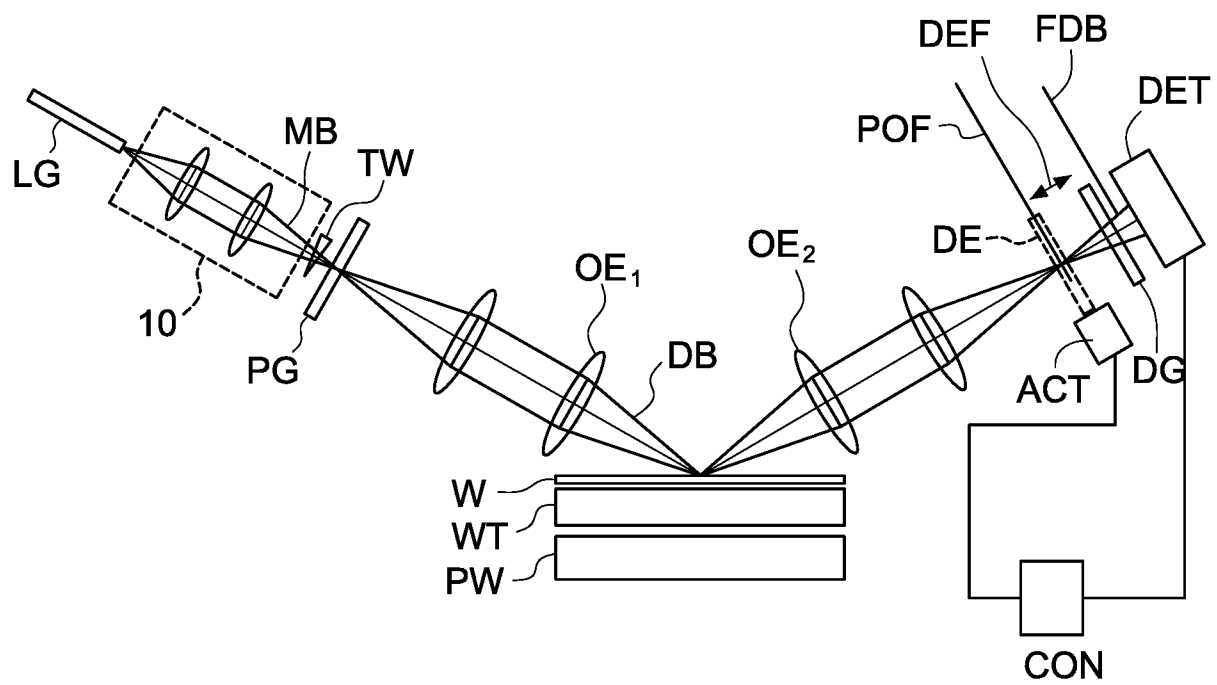


Fig. 2

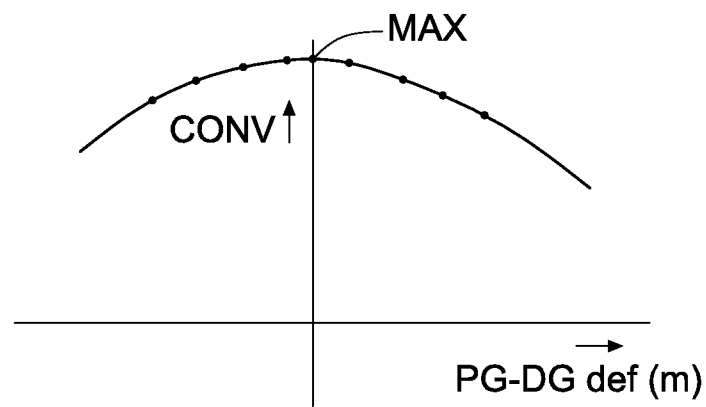


Fig. 3A

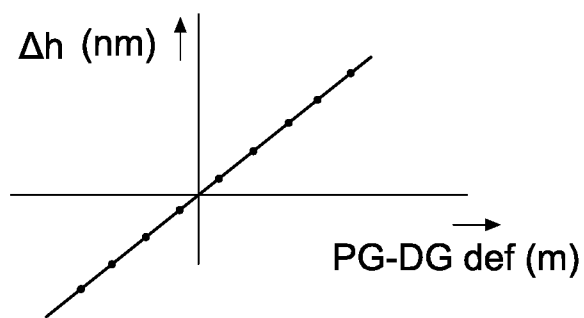


Fig. 3B

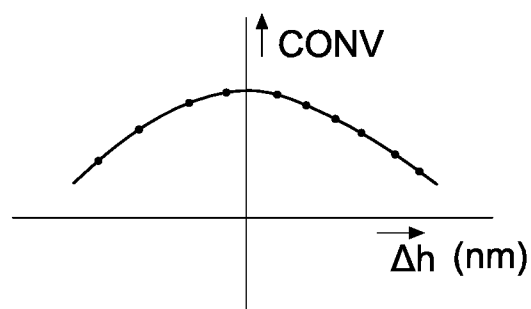


Fig. 3C

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/050847

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F9/00 G01B11/06 G01B11/25
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 G01B

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)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/279102 A1 (KO KUK-WON [KR] ET AL) 12 November 2009 (2009-11-12) abstract paragraphs [0014], [0032], [0034], [0043]; figures 3,9 -----	1,4,5
X	US 2014/362359 A1 (CHAO KUO-HUNG [TW] ET AL) 11 December 2014 (2014-12-11) paragraphs [0035] - [0038], [0043] - [0047]; figures 5,6 -----	1,2,4,5
X	US 2014/198320 A1 (PARK YOON DEOK [KR]) 17 July 2014 (2014-07-17) paragraphs [0003], [0037] - [0059]; figures 2,3 -----	1,3-5

☐

Further documents are listed in the continuation of Box C.

☒

See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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