# A SCATTEROMETER, A LITHOGRAPHIC APPARATUS AND A FOCUS ANALYSIS METHOD

## FIELD

**[0001]** The present invention relates to methods of inspection usable, for example, in the manufacture of devices by lithographic techniques and to methods of manufacturing devices using lithographic techniques.

## BACKGROUND

**[0002]** 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 that instance, 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. comprising 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. Known lithographic apparatus include so-called steppers, in which each target portion is irradiated by exposing an entire pattern onto the target portion at one time, 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.

**[0003]** In order to determine features of the substrate, such as its alignment, a beam is reflected off the surface of the substrate, for example at an alignment target, and an image is created on a camera of the reflected beam. By comparing the properties of the beam before and after it has been reflected off the substrate, the properties of the substrate can be determined. This can be done, for example, by comparing the reflected beam with data stored in a library of known measurements associated with known substrate properties.

**[0004]** When detecting features of the pattern it is important that the pattern be in the focal plane of the optics. Present methods for determining whether a pattern on a substrate is in focus are the so-called "knife edge" method described in EP 1 628 164. However, this method is complicated and requires complex parts.

SUMMARY

**[0005]** It is desirable to provide an alternative method and apparatus for detecting whether the substrate is in focus.

According to an aspect of the invention, there is provided a scatterometer for measuring a property of a substrate, the apparatus comprising:

- a radiation projector configured to project radiation;
- a high numerical aperture lens configured to project said radiation onto said substrate;
- a first detector configured to detect the cross-sectional area of said reflected radiation having an intensity above a first predetermined value; and
- a second detector configured to detect the cross-sectional area of said reflected radiation having an intensity above a second predetermined value,

wherein said high numerical aperture lens projects radiation reflected from said substrate towards the back focal plane or a conjugate of the front focal plane of said high numerical aperture lens and said detectors are arranged such that said first detector is arranged in front of said back focal plane of said high numerical aperture lens, between said high numerical aperture lens and the back focal plane of said high numerical aperture lens, and said second detector is arranged behind the back focal plane of said high numerical aperture lens or said detectors are arranged such that said first detector is arranged in front of a conjugate of the front focal plane of said high numerical apertures lens, between said high numerical aperture lens and the conjugate of the front focal plane of the high numerical aperture lens and said second detector is arranged behind the conjugate of the front focal plane of said high numerical aperture lens.

According to a further aspect of the invention there is provided a measurement apparatus for measuring the height of a surface of a lithographic substrate, the measurement apparatus comprising a source arranged to generate a radiation beam, a moveable objective lens arranged to move a focal plane of the radiation beam with respect to the substrate, an aperture arranged to pass focused

radiation reflected from the substrate, and a detector arranged to detect the radiation passed by the aperture.

According to a further aspect of the invention there is provided a focus analysis method for detecting whether a substrate is in the focal plane of a lens, said method comprising:

- projection radiation through a high numerical aperture lens and onto said substrate using a radiation projector;
- detecting a first cross-sectional area of said radiation having an intensity above a first predetermined value, reflected by said substrate and through said high numerical aperture lens;
- detecting a second cross-sectional area of said radiation having an intensity above a second predetermined value, reflected by said substrate and through said high numerical aperture lens,

wherein said first step of detecting the first cross-sectional area of said reflected radiation beam detects said radiation beam between said high numerical aperture lens and the back focal plane of said high numerical aperture lens or a conjugate of the front focal plane of said high numerical aperture lens and said step of detecting the second cross-sectional area of said reflected radiation beam detects the reflected radiation beam behind the back focal plane of said high numerical aperture lens or behind the conjugate of the front focal plane of said high numerical aperture lens respectively.

According to a further aspect of the invention there is provided a method of measuring the height of a surface of a lithographic substrate, the method comprising generating a radiation beam, using a moveable objective lens to move a focal plane of the radiation beam with respect to the substrate, passing radiation reflected from the substrate through an aperture arranged to pass focused radiation, and detecting the radiation passed by the aperture.

According to a further aspect of the invention there is provided a device manufacturing method comprising the focus control method described above.

The focus control method described above may be implemented using a control system.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0008]** 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:

**[0009]** Figure 1a depicts a lithographic apparatus;

**[00010]** Figure 1b depicts a lithographic cell or cluster;

**[00011]** Figure 2 depicts a scatterometer;

**[00012]** Figure 3 depicts the general operating principle of measuring an angle resolved spectrum in the pupil plane of a high-NA lens;

**[00013]** Figures 4a and 4b depict arrangements according to the invention;

**[00014]** Figure 5 depicts an alternative arrangement according to the invention;

**[00015]** Figures 6A – 6C depicts patterns of radiation detected on the detectors when the substrate is in and out of focus;

**[00016]** Figures 7A and 7B depict detectors according to the invention;

**[00017]** Figures 8 – 10 depict alternative detectors according to the invention; and

**[00018]** Figure 11 depicts an alternative embodiment of the invention.

DETAILED DESCRIPTION

**[00019]** Figure 1a schematically depicts a lithographic apparatus. The apparatus comprises:

**[00020]** an illumination system (illuminator) IL configured to condition a radiation beam B (e.g. UV radiation or EUV radiation).

**[00021]** a support structure (e.g. a mask table) MT constructed to support a patterning device (e.g. a mask) MA and connected to a first positioner PM configured to accurately position the patterning device in accordance with certain parameters;

**[00022]** a substrate table (e.g. a wafer table) WT constructed to hold a substrate (e.g. a resist-coated wafer) W and connected to a second positioner PW configured to accurately position the substrate in accordance with certain parameters; and

**[00023]** 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. comprising one or more dies) of the substrate W.

**[00024]** 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.

**[00025]** The 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 support structure can use mechanical, vacuum, electrostatic or other clamping techniques to hold the patterning device. The support structure may be a frame or a table, for example, which may be fixed or movable as required. The 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."

**[00026]** 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 such as to create a pattern in a target portion of the substrate. It should be noted that the pattern imparted to the radiation beam may not exactly correspond to the desired pattern in the target portion of the substrate, for example if the pattern includes phase-shifting features or so called assist 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.

**[00027]** 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 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.

**[00028]** The term "projection system" used herein should be broadly interpreted as encompassing 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".

**[00029]** 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).

**[00030]** The lithographic apparatus may be of a type having two (dual stage) or more substrate tables (and/or two or more mask tables). In such "multiple stage" machines the additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while one or more other tables are being used for exposure.

**[00031]** 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 are well known in the art for increasing 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 liquid is located between the projection system and the substrate during exposure.

**[00032]** Referring to Figure 1a, 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 comprising, 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.

**[00033]** The illuminator IL may comprise an adjuster AD for adjusting the angular intensity distribution of the radiation beam. Generally, at least the outer and/or inner radial extent (commonly referred to as $\sigma$-outer and $\sigma$-inner, respectively) of the intensity distribution in a pupil plane of the illuminator can be adjusted. In addition, the illuminator IL may comprise 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.

**[00034]** The radiation beam B is incident on the patterning device (e.g., mask MA), which is held on the 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 positioner 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 positioner PM and another position sensor (which is not explicitly depicted in Figure 1a) 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 positioner PM. Similarly, movement of the substrate table WT 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.

**[00035]** The depicted apparatus could be used in at least one of the following modes:

**[00036]** 1. In step mode, the mask table MT and the substrate table WT 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 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.

**[00037]** 2. In scan mode, the mask table MT and the substrate table WT 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 relative to the mask table MT 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.

**[00038]** 3. In another mode, the mask table MT is kept essentially stationary holding a programmable patterning device, and the substrate table WT is moved or scanned while a pattern imparted to the 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 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.

**[00039]** Combinations and/or variations on the above described modes of use or entirely different modes of use may also be employed.

**[00040]** As shown in Figure 1b, the lithographic apparatus LA (controlled by a lithographic apparatus control unit LACU) forms part of a lithographic cell LC, also sometimes referred to a lithocell (lithographic cell) or cluster, which also includes apparatus to perform pre- and post-exposure processes on a substrate. Conventionally these include spin coaters SC to deposit resist layers, developers DE to develop exposed resist, chill plates CH and bake plates BK. A substrate handler, or robot, RO picks up substrates from input/output ports I/O1, I/O2, moves them between the different process apparatus and delivers then to the loading bay LB of the lithographic apparatus. These devices, which are often collectively referred to as the track, are under the control of a track control unit TCU which is itself controlled by the supervisory control system SCS, which also controls the lithographic apparatus via its control unit LACU. Thus, the different apparatus can be operated to maximize throughput and processing efficiency.

**[00041]** In order that the substrates that are exposed by the lithographic apparatus are exposed consistently for each layer of resist, there are certain properties of the substrate that need to be measured to determine whether there are changes in alignment, rotation, etc., that must be compensated for by the lithographic apparatus. A separate inspection apparatus is used to determine the properties of the substrates, and in particular, how the properties of different substrates or different layers of the same substrate vary from layer to layer.

**[00042]** The properties of the surface of a substrate W may be determined using a sensor such as a scatterometer such as that depicted in Figure 2. The scatterometer comprises a broadband (white light) radiation projector 2 which projects radiation onto a substrate W. The reflected radiation is passed to a spectrometer detector 4, which measures a spectrum 10 (intensity as a function of wavelength) of the specular reflected radiation. From this data, the structure or profile giving rise to the detected spectrum may be reconstructed, e.g. by Rigorous Coupled Wave Analysis and non-linear regression or by comparison with a library of simulated spectra as shown at the bottom of Figure 2. In general, for the reconstruction the general form of the structure is known and some parameters are assumed from knowledge of the process by which the structure was made, leaving only a few parameters of the structure to be determined from the scatterometry data.

**[00043]** The scatterometer may be a normal-incidence scatterometer or an oblique-incidence scatterometer. Variants of scatterometry may also be used in which the reflection is measured at a range of angles of a single wavelength, rather than the reflection at a single angle of a range of wavelengths.

**[00044]** Scatterometers for measuring properties of a substrate may measure, in the pupil plane 11 of a high numerical aperture lens, the properties of an angle-resolved spectrum reflected from the substrate surface W at a plurality of angles and wavelengths as shown in Figure 3. Such a scatterometer may comprise a radiation projector 2 for projecting radiation onto the substrate and a detector 14 for detecting the reflected spectra. The pupil plane is the plane in which the radial position of radiation defines the angle of incidence and the angular position defines azimuth angle of the radiation. The detector 14 is placed in the pupil plane of the high numerical aperture lens. The numerical aperture may be high and preferably at least 0.9 and more preferably at least 0.95. Immersion scatterometers may even have lenses with numerical apertures over 1.

**[00045]** Some angle-resolved scatterometers only measure the intensity of scattered light. However, more recent scatterometers allow several wavelengths to be measured simultaneously at a range of angles. The properties measured by the scatterometer for different wavelengths and angles may be the intensity of transverse magnetic- and transverse electric-polarized light and the phase difference between the transverse magnetic- and transverse electric-polarized light.

**[00046]** Using a broadband light source (i.e. one with a wide range of light frequencies or wavelengths – and therefore of colors) is possible, which gives a large etendue, allowing the mixing of multiple wavelengths. The plurality of wavelengths in the broadband preferably each has a bandwidth of, say, $\delta\omega$ and a spacing, therefore, of at least $2\delta\omega$ (i.e. twice the wavelength). Several "sources" of radiation can be different portions of an extended radiation source which have been split using, say, fiber bundles. In this way, angle resolved scatter spectra can be measured at multiple wavelengths in parallel. A 3-D spectrum (wavelength and two different angles) is measured, which contains more information than a 2-D spectrum. This allows more information to be measured which increases metrology process robustness. This is described in more detail in EP1,628,164A.

**[00047]** A scatterometer that may be used with the present invention is shown in Figure 3. The radiation of the radiation projector 2 is collimated using lens system 12 through interference filter 13 and polariser 17, reflected by partially reflected surface 16 and is focused onto substrate W via a microscope objective lens 15. The radiation is then transmitted through partially reflective surface 16 into a CCD detector in the back projected pupil plane 11 in order to have the scatter spectrum detected. The pupil plane 11 is at the focal length of the lens system 15. A detector and high aperture lens are placed at the pupil plane. The pupil plane may be re-imaged with auxiliary optics since the pupil plane of a high-NA lens is usually located inside the lens.

**[00048]** A reference beam is often used for example to measure the intensity of the incident radiation. When the radiation beam is incident on the beam splitter 16 part of it is transmitted through the beam splitter towards a reference mirror 14. The reference beam is then projected onto a different part of the same CCD detector 18.

**[00049]** The pupil plane of the reflected radiation is imaged on the CCD detector with an integration time of, for example, 40 milliseconds per frame. In this way, a

two-dimensional angular scatter spectrum of the substrate targets is imaged on the detector. The detector may be, for example, an array of CCD or CMOS sensors.

**[00050]** A set of interference filters 13 is available to select a wavelength of interest in the range of, say, 405 - 790 nm or even lower, such as 200 - 300 nm. The interference filter may be tuneable rather than comprising a set of different filters. A grating could be used instead of interference filters.

**[00051]** The substrate W may be a grating which is printed such that after development, the bars are formed of solid resist lines. The bars may alternatively be etched into the substrate. This pattern is sensitive to chromatic aberrations in the lithographic projection apparatus, particularly the projection system PL, and illumination symmetry and the presence of such aberrations will manifest themselves in a variation in the printed grating. Accordingly, the scatterometry data of the printed gratings is used to reconstruct the gratings. The parameters of the grating, such as line widths and shapes, may be input to the reconstruction process from knowledge of the printing step and/or other scatterometry processes.

**[00052]** Figure 4a depicts an arrangement according to the invention in which radiation is projected through the high numerical aperture lens 15 and through a focussing lens 21. The radiation is then projected onto a first detector 30 and a second detector 31. As described below the detector detects the amount (or cross-sectional area) of radiation above predetermined intensity levels. The detector may be one or more photodiodes, CCDs or CMOS. However, in this embodiment the detectors are at least partially transmissive such that the radiation is transmitted through the detectors and onto further optical elements. The detectors are preferably arranged equidistant along the optical path from the back focal plane, BFP, of the high numerical aperture lens 15 or equidistant from a conjugate of the substrate plane, as shown in Figure 4b. Assuming no transmissive losses between the detectors, if the substrate is in focus the cross-sectional area of the radiation above predetermined intensity levels (the spot size) will be the same at both detectors, as shown in Figure 6a and a simple comparator can be used to determine whether the substrate is in focus. However, if the substrate is too far from the numerical aperture the spot size will be greater in the first detector than the second detector, as shown in Figure 6b. Conversely, if the substrate is out of focus to close to the high numerical aperture lens the spot size in the second detector will be greater than that in the first detector, as shown in Figure 6c.

**[00053]** An alternative arrangement according to a preferred embodiment of the invention is shown in Figure 4b. In this embodiment a partially transmissive mirror 22 is placed in the path of the projection beam PB after the high numerical aperture lens. The partially transmissive mirror 22 deflects a portion of the radiation towards a focus branch which includes the focussing lens 21 together with first detector 30 and second detector 31. In this embodiment the first detector 30 and second detector 31 are placed either side and preferably equidistant of a conjugate substrate plane (a conjugate of the front focal plane of the high numerical aperture lens). The second detector need therefore not be partially transmissive. As an alternative to the transmissive mirror a beam splitter could also be used.

**[00054]** The predetermined intensity levels measured on the first and second detectors may not be the same. For example, if there are transmissive losses between the first and second detectors the predetermined intensity level above which radiation is measured may be greater for the first detector than the second detector. Some calibration may be required to determine the necessary predetermined intensity levels.

**[00055]** Although this example has just a first detector 30 and a second detector 31 each of the first detector and second detector could be divided into a plurality of sub-detectors as shown in Figures 7a and 7. Figure 7a depicts the first detector divided into a plurality of first sub-detectors, 32, 33, 34 and Figure 7 depicts the second detector divided into a plurality of second sub-detectors 37, 38, 39. The focus area is then given by:

$(I_{32} + I_{34} + I_{38}) - (I_{33} + I_{37} + I_{39})$

**[00056]** where $I_{32}$ is the amount of radiation above a first predetermined intensity level incident on sub-detector 32, $I_{37}$ is the amount of radiation about a second predetermined intensity level incident on sub-detector 37 etc.

**[00057]** Although Figures 7a and 7b depict the first and second detectors divided into sub-detectors along a horizontal direction, the detectors could be divided into sub-detectors in any number of ways. For example, Figure 8 depicts a detector divided into sub-detectors 42, 43, 44 along a vertical direction. Figure 9 depicts a detector divided into sub-detectors 51 to 59 in a grid arrangement and Figure 10 depicts a detector divided into sub-detectors 62, 63, 64 in concentric circles.

**[00058]** Figure 5 depicts an alternative arrangement to the arrangement of detectors shown in Figure 4. In this embodiment mirrors are used to project the radiation onto the detectors. A partially reflective mirror allows part of the radiation

to pass through and onto first detector 30 while the remaining radiation towards a second mirror 36 which reflects at least part of the radiation onto the second detector 35. The second mirror 36 may be either fully reflective or partially reflective and the second detector may be transmissive to allow the radiation to be projected onto further optics. Again, the detectors are preferably arranged equidistant along the path of the radiation from the back focal plane, BFP, of the high numerical aperture lens 15 or equidistant from a conjugate of the substrate plane.

**[00059]** Although the detectors are preferably arranged equidistant along the path of the radiation from the back focal plane of the high numerical aperture lens 15 or a conjugate of the substrate plane they need not be. If they are not equidistant from the back focal plane or a conjugate of the substrate plane calculations, rather than a simple comparison, can determine whether the relative spot sizes on the detectors indicate that the substrate is in focus or out of focus.

**[00060]** This method can be used in conjunction with other, conventional focus detection methods. For example, the different focus detection methods may occupy different optical branches.

**[00061]** An alternative embodiment of the invention is shown in figure 11, which schematically shows a measurement apparatus which may be used to monitor the height (i.e. position in the z-direction) of an uppermost surface of a substrate W. The height may be measured for example with respect to a reference plane (not shown), or with respect to an objective lens 106 of the apparatus.

**[00062]** The apparatus comprises a radiation source 102 which provides a beam of radiation. The radiation source 102 may for example be a laser (e.g. a diode laser). It is not essential that the radiation source is a laser; any suitable source may be used. A broadband radiation source may be used. Multiple radiation sources operating at different wavelengths may be used.

**[00063]** The apparatus further comprises a pair of lenses 104, 106 arranged to focus radiation from the radiation source to a focal plane FP. The second of these lenses will be referred to here as the objective lens 106 since it is located adjacent to the substrate W.

**[00064]** The objective lens 106 is connected to an actuator 107 which is arranged to move the objective lens in the z-direction (as indicated by a double headed arrow). The focal plane FP of the objective lens 106 thus also moves in the z-direction (also indicated by a double headed arrow).

**[00065]** An aperture 108 is provided in a focal plane located between the lenses. The aperture provides spatial filtering of the radiation beam. That is to say, it removes aberrations from the radiation beam. It is not essential that an aperture be provided (the intensity profile of the radiation beam may be sufficiently good without requiring an aperture to be used). The aperture is most effective when the radiation source 102 is a laser.

**[00066]** A beamsplitter 110 is located beneath the aperture, and is arranged to direct towards a detector 112 radiation which has been reflected and/or diffracted from the substrate W. An aperture 114 is located at a focal plane of the second lens 106. The diameter of the aperture may be matched with the diameter of the radiation beam in the plane of the aperture. The aperture should be sufficiently large that when the upper surface of the substrate W is located in the focal plane FP of the objective lens 106, then substantially all of the radiation beam passes through the aperture. In other words, the aperture diameter may be substantially equal to the diameter of the radiation beam when the radiation beam is focussed onto the upper surface of the substrate.

**[00067]** A third lens 116 focuses the radiation onto the detector 112. The detector may for example be a photodiode. An output from the detector 112 may pass to a controller 118.

**[00068]** In use, radiation emitted by the radiation source 102 is focused to onto the focal plane FP by the objective lens 106. The objective lens moves towards and away from the substrate W (i.e. in the z-direction), so that the focal plane moves from being above the substrate to being aligned with the substrate to being below the substrate. The source 102 and the lenses 104, 106 may be arranged such that the diameter of the radiation beam when it is focussed on the substrate (i.e. the diameter of the beam spot) is the same as the diameter of the radiation beam used by the scatterometer (the scatterometer is described above in relation to figure 3). It is not essential that the diameters are the same. The diameters may differ for example by up to one order of magnitude.

**[00069]** The movement of the focal plane FP means that the radiation is not always focused to a point on the substrate W. Instead, when the focal plane is above the substrate the radiation incident upon the substrate is defocused. This defocusing is reduced as the focal plane moves towards the substrate. The radiation is focused

when the focal plane is aligned with the substrate. It then becomes defocused again when the focal plane moves below the substrate.

**[00070]** Radiation which is reflected or diffracted from the substrate W passes via the beamsplitter 110 to the aperture 114. The aperture is located at a focal plane of the objective lens 106. The intensity of radiation which passes through the aperture will depend upon the extent to which the radiation was focused on the substrate by the objective lens. For example, if the radiation incident on the substrate is defocused then a lesser intensity of radiation will pass through the aperture than if the radiation incident on the substrate was focussed.

**[00071]** The third lens 116 focuses onto the detector 112 radiation which has passed through the aperture 114. The output from the detector 112 therefore provides an indication of when the upper surface of the substrate W is aligned with the focal plane FP of the objective lens 106. This may be used to monitor the height (i.e. the position in the z-direction) of the upper surface of the substrate W with respect to objective lens 106 (or some other reference plane).

**[00072]** Although the substrate is shown as being flat in figure 11, it is likely to have some surface structure arising from layers which have been provided on the substrate (for example patterned layers). The different layers may have different properties, and some of the layers may be semi-transparent. The apparatus shown in figure 11 provides a measurement of the height of the upper surface of the substrate which includes these layers. This is a useful measurement, because it allows optimal operation of the scatterometer (for example as shown in figure 3) to be achieved, by allowing the radiation beam of the scatterometer to be correctly focussed on the upper surface of the substrate.

**[00073]** Once the height of the upper surface of the substrate W has been determined, the radiation beam used by the scatterometer (see figure 3) may be correctly focussed onto the upper surface of the substrate. The controller 118 may achieve this by moving the substrate W in the z-direction by an appropriate amount based upon the output of the detector 112. This may be done for example by moving a substrate table (not illustrated) upon which the substrate rests.

**[00074]** Alternatively (or additionally), the controller 118 may be arranged to move the focal plane of the scatterometer. This may be achieved for example by moving the objective lens 15 of the scatterometer.

**[00075]** The substrate height measurement performed by the apparatus shown in figure 11 may be performed at a substrate location which is a predetermined distance away from a substrate location which is measured by the scatterometer. The substrate may be moved in a scanning motion (e.g. in the y-direction) beneath the measurement apparatus and the scatterometer, such that a predetermined time will elapse between the substrate height measurement taking place and the scatterometer measurement taking place. A corresponding time delay may be introduced between the measurement of the substrate height and any required movement of the substrate (or the objective lens of the scatterometer).

**[00076]** Alternatively, the measurement apparatus shown in figure 11 may be combined with the scatterometer shown in figure 3, for example such that both of them share a single objective lens (objective lens 15). Where this is done, no time delay is required between measurement of the substrate height and any required movement of the substrate (or the objective lens of the scatterometer).

**[00077]** When measuring the substrate height the controller 118 may take into account any movement of the substrate W which takes place in the z-direction.

**[00078]** In the description of figure 11, the term 'height' has been used to refer to the position of the upper surface of the substrate W in the z-direction. However, it is not essential that the substrate be horizontal, and so it is not essential that the surface of the substrate be facing upwards (the substrate may for example be vertically oriented). Therefore, the term height should be understood to mean the position of the surface of the substrate with respect to a reference plane that is substantially parallel to the surface of the substrate. This reference plane need not necessarily lie perpendicular to the z-direction.

**[00079]** 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.

**[00080]** 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 a 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.

**[00081]** 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, 355, 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.

**[00082]** The term "lens", where the context allows, may refer to any one or combination of various types of optical components, including refractive, reflective, magnetic, electromagnetic and electrostatic optical components.

**[00083]** 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 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.

**[00084]** 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.

We claim:

1. A scatterometer configured to measure a property of a substrate, the apparatus comprising: a high numerical aperture lens configured to project radiation onto the substrate and to project radiation redirected from the substrate towards a back focal plane of the high numerical aperture lens or towards a conjugate of a front focal plane of the high numerical aperture lens; a first detector configured to detect a first cross-sectional area of the redirected radiation having an intensity above a first value; and a second detector configured to detect a second cross-sectional area of the redirected radiation having an intensity above a second value, wherein the first detector is arranged in front of the back focal plane, between the high numerical aperture lens and the back focal plane, and the second detector is arranged behind the back focal plane, or the first detector is arranged in front of the conjugate of the front focal plane, between the high numerical aperture lens and the conjugate of the front focal plane, and the second detector is arranged behind the conjugate of the front focal plane.

2. The scatterometer of claim 1, further comprising an angle detector configured to detect an angle resolved spectrum of the redirected radiation.

3. The scatterometer of claim 1, wherein the first detector and the second detector are arranged equidistant from the back focal plane or the conjugate of the front focal plane along an optical path of the redirected radiation.

4. The scatterometer of claim 1, further comprising a comparator configured to compare a size of the first cross-sectional area of the redirected radiation having an intensity above the first value detected by the first detector and a size of the second cross-sectional area of the redirected radiation having an intensity above the second value detected by the second detector.

5. The scatterometer of claim 1, further comprising a first reflector configured to reflect the redirected radiation towards the first detector.

6. The scatterometer of claim 5, wherein the first reflector comprises a partially reflective mirror.

7. The scatterometer of claim 1, further comprising a second reflector configured to reflect the redirected radiation towards the second detector.

8. The scatterometer of claim 7, wherein the second reflector comprises a partially reflective mirror.

9. The scatterometer of claim 1, wherein the first detector comprises a plurality of first sub-detectors.

10. The scatterometer of claim 1, wherein the second detector comprises a plurality of second sub-detectors.

11. The scatterometer of claim 1, wherein the first value is the same as the second value.

12. The scatterometer of claim 1, wherein the first value is greater than the second value.

13. A measurement apparatus to measure a height of a surface of a lithographic substrate, the measurement apparatus comprising: a moveable objective lens arranged to move a focal plane of a radiation beam in a direction substantially perpendicular with respect to a plane of the substrate; an aperture arranged to pass focused radiation redirected from the substrate; and a detector arranged to detect the radiation passed by the aperture, the detected radiation being a measure of the height.

14. The measurement apparatus of claim 13, further comprising a controller arranged to monitor the output of the detector, and to apply an adjustment to a scatterometer arranged to measure a property of the substrate, the adjustment being arranged to compensate for the measured height of the substrate.

15. The measurement apparatus of claim 13, further comprising a controller arranged to monitor the output of the detector, and to apply an adjustment to a position of the substrate to compensate for the measured height of the substrate.

16. A focus analysis method for detecting whether a substrate is in the focal plane of a lens, the method comprising: projecting radiation through a high numerical aperture lens and onto the substrate; detecting a first cross-sectional area of radiation redirected by the substrate and passing through the high numerical aperture lens, having an intensity above a first value, the detecting the first cross-sectional area of the redirection radiation occurring between the high numerical aperture lens and a back focal plane of the high numerical aperture lens or between the high numerical aperture lens and a conjugate of a front focal plane of the high numerical aperture lens; and detecting a second cross-sectional area of the redirected radiation having an intensity above a second value, the detecting the second cross-sectional area of the redirected radiation occurring, respectively to the first detector, behind the back focal plane or behind the conjugate of the front focal plane.

17. The method of claim 16, further comprising comparing a size of the first cross-sectional area of the redirected radiation and a size of the second cross-sectional area of the redirected radiation.

18. The method of claim 16, further comprising detecting angles of a spectrum of redirected radiation.

19. A method of measuring the height of a surface of a lithographic substrate, the method comprising: generating a radiation beam; using a moveable objective lens to move a focal plane of the radiation beam in a direction substantially perpendicular with respect to a plane of the substrate; passing radiation redirected from the substrate through an aperture arranged to pass focused radiation; and detecting the radiation passed by the aperture, the detected radiation being a measure of the height.

20. The method of claim 19, further comprising applying an adjustment to a scatterometer arranged to measure a property of the substrate, the adjustment being arranged to compensate for the measured height of the substrate.

21. The method of claim 19, further comprising applying an adjustment to a position of the substrate to compensate for the measured height of the substrate.