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(54) **A method of optimizing a model, a method of measuring a property, a device manufacturing method, a spectrometer and a lithographic apparatus.**

(57) A set of parameters used in a model of a spectrometer includes free parameters and fixed parameters. A first set of values for the parameters is set and the model is used to generate a first spectrum. A value of one of the fixed parameters is changed and a second spectrum is generated. An inverse of the model of the spectrometer is then applied to the second spectrum to generate a set of values for the parameters, the values being the same as the first set of values except for one or more of the free parameters. 1f the free parameter has significantly changed the fixed parameter is designated a free parameter.

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A METHOD OF OPTIMIZING A MODEL, A METHOD OF MEASURING A PROPERTY, A DEVICE MANUFACTURING METHOD, A SPECTROMETER AND A LITHOGRAPHIC APPARATUS

FIELD

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

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. 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. 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.

In order to monitor the lithographic process, it is desirable to measure parameters of the patterned substrate, for example the overlay error between successive layers formed in or on it. There are various techniques for making measurements of the microscopic structures formed in lithographic processes, including the use of scanning electron microscopes and various specialized tools. One form of specialized inspection tool is a scatterometer in which a beam of radiation is directed onto a target on the surface of the substrate and properties of the scattered or reflected beam are measured. By comparing the properties of the beam before and after it has been reflected or scattered by the substrate, the properties of the substrate may be determined. This may be done, for example, by comparing the reflected beam with data stored in a library of known measurements associated with known substrate properties. Two main types of scatterometer are known. Spectroscopic scatterometers direct a broadband radiation beam onto the substrate and measure the spectrum (intensity as a function of wavelength) of the radiation scattered into a particular narrow angular range. Angularly resolved scatterometers use a monochromatic radiation beam and measure the intensity of the scattered radiation as a function of angle.

Models are often used to simulate results from scatterometers or spectrometers. To determine a critical dimension, a modeled signal may be matched to a measured signal. Within the model there are many parameters (such as the thickness or reflectivity of layers of the substrate) which may be varied to generate a modeled spectrum which matches the measured signal. With many different parameters varying freely the matching process is extremely time consuming to run. Too many free parameters may result in an unstable matching process or erroneous set of parameters due to the fact that there may exist more than one combination of these parameters that have virtually equal modeled spectra. Consequently, many of the parameters are often fixed while just a few are varied. However, it may be difficult to determine which parameters may be left free while the others are fixed.

There may be some correlation between the impact of different parameters on the modeled spectrum and present methods of determining which parameters to leave free involve the use of a cross-correlation matrix. A value for each of the parameters is selected and a base spectrum generated. A parameter is varied by a small amount, another spectrum is generated and the change of the spectrum is determined. This is repeated for each of the parameters and the resulting spectra changes between the different parameters are compared to generate the cross-correlation matrix. If a high correlation between two parameters is found at most one of them should be left free. However, while this correlation matrix supports the selection of free and fixed parameters, the use is limited since it may not show the impact of correlation between the spectral change for more than two parameters, it does not give any indication of the impact of the noise in the measured signal on the model with a specific free parameter selection nor does it show the impact of errors in the value of the fixed parameters on the free parameters during the matching process or on the quality of the match.

Furthermore the cross-correlation matrix provides no information about the effect of converting a free parameter to a fixed parameter. Changing a free parameter to a fixed parameter or vice versa could have an unexpected effect on other parameters.

SUMMARY

It is desirable to provide method of modeling a spectra with an improved method of free parameter selection.

According to an aspect of the invention, there is provided a method of optimizing a model of a spectrometer, the spectrometer being configured to measure a property of a substrate, the model having at least two parameters, the parameters including a first free parameter, the method including a) setting a first set of values for the parameters; b) generating a first simulated spectrum of the spectrometer from the first set of values using the model; c) changing the value of a second parameter by a first predetermined amount to form a second set of values for the parameters, the second parameter not being the free parameter; d) generating a second simulated spectrum of the spectrometer from the second set of values using the model; e) using a second model to find a third set of values for the parameters from the second simulated spectrum, the second model being arranged such that the third set of values generates substantially the second simulated spectrum using the first model and such that the third set of parameters are the same as the first set of parameters except for the first free parameter; f) determining the difference between the first free parameter in the third set of values for the parameters and the free parameter in the first set of values; and g) using the difference as a figure of merit for the choice of free and fixed parameters in the model.

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 1a depicts a lithographic apparatus in accordance with an embodiment of the invention;

Figure 1b depicts a lithographic cell or cluster in accordance with an embodiment of the invention;

Figure 2 depicts a first scatterometer in accordance with an embodiment of the invention;

Figure 3 depicts a second scatterometer in accordance with an embodiment of the invention; and

Figure 4 depicts a process according to an embodiment of the invention.

DETAILED DESCRIPTION

Figure 1a schematically depicts a lithographic apparatus. The apparatus includes an illumination system (illuminator) IL configured to condition a radiation beam B (e.g. UV radiation or DUV radiation); 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; 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; anda projection system (e.g. a refractive projection lens system) PL 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 support structure 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."

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.

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.

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".

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 (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.

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.

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 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 for adjusting 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 support structure (e.g., mask table) MT, and is patterned by the patterning device. Having traversed the patterning device (e.g. mask) MA, the radiation beam B passes through the projection system PL, 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, 2-D 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 1) can be used to accurately position the patterning device (e.g. 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 support structure (e.g. 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 support structure (e.g. mask table) MT may be connected to a short-stroke actuator only, or may be fixed. Patterning device (e.g. 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 patterning device (e.g. 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 support structure (e.g. 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.

2. In scan mode, the support structure (e.g. 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 support structure (e.g. mask table) MT may be determined by the (de-)magnification and image reversal characteristics of the projection system PL. In scan mode, the maximum size of the exposure field limits the width (in the non-scanning direction) of the target portion in a single dynamic exposure, whereas the length of the scanning motion determines the height (in the scanning direction) of the target portion.

3. In another mode, the support structure (e.g. 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.

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

As shown in Figure 1b, the lithographic apparatus LA forms part of a lithographic cell LC, also sometimes referred to a lithocell 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 lithography control unit LACU. Thus, the different apparatus can be operated to maximize throughput and processing efficiency.

In order that the substrates that are exposed by the lithographic apparatus are exposed correctly and consistently, it is desirable to inspect exposed substrates to measure properties such as overlay errors between subsequent layers, line thicknesses, critical dimensions (CD), etc.. If errors are detected, adjustments may be made to exposures of subsequent substrates, especially if the inspection can be done soon and fast enough that other substrates of the same batch are still to be exposed. Also, already exposed substrates may be stripped and reworked – to improve yield – or discarded – thereby avoiding performing exposures on substrates that are known to be faulty. In a case where only some target portions of a substrate are faulty, further exposures can be performed only on those target portions which are good.

An 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. The inspection apparatus may be integrated into the lithographic apparatus LA or the lithocell LC or may be a stand-alone device. To enable most rapid measurements, it is desirable that the inspection apparatus measure properties in the exposed resist layer immediately after the exposure. However, the latent image in the resist has a very low contrast – there is only a very small difference in refractive index between the parts of the resist which have been exposed to radiation and those which have not – and not all inspection apparatus have sufficient sensitivity to make useful measurements of the latent image. Therefore measurements may be taken after the post-exposure bake step (PEB) which is customarily the first step carried out on exposed substrates and increases the contrast between exposed and unexposed parts of the resist. At this stage, the image in the resist may be referred to as semi-latent. It is also possible to make measurements of the developed resist image – at which point either the exposed or unexposed parts of the resist have been removed – or after a pattern transfer step such as etching. The latter possibility limits the possibilities for rework of faulty substrates but may still provide useful information.

Figure 2 depicts a scatterometer SM1 which may be used in an embodiment of the present invention. It includes a broadband (white light) radiation projector 2 which projects radiation onto a substrate 6. The reflected radiation is passed to a spectrometer detector 4, which measures a spectrum 10 (intensity (I) as a function of wavelength (λ)) of the specular reflected radiation. From this data, the structure or profile giving rise to the detected spectrum may be reconstructed by processing unit PU, 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. Such a scatterometer may be configured as a normal-incidence scatterometer or an oblique-incidence scatterometer.

Another scatterometer that may be used with an embodiment of the present invention is shown in Figure 3. In this device, the radiation emitted by radiation source 2 is focused using lens system 12 through interference filter 13 and polarizer 17, reflected by partially reflected surface 16 and is focused onto substrate W via a microscope objective lens 15, which has a high numerical aperture (NA), preferably at least 0.9 and more preferably at least 0.95. Immersion scatterometers may even have lenses with numerical apertures over 1. The reflected radiation then transmits through partially reflective surface 16 into a detector 18 in order to have the scatter spectrum detected. The detector may be located in the back-projected pupil plane 11, which is at the focal length of the lens system 15, however the pupil plane may instead be re-imaged with auxiliary optics (not shown) onto the detector. 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 is preferably a two-dimensional detector so that a two-dimensional angular scatter spectrum of the substrate target can be measured. The detector 18 may be, for example, an array of CCD or CMOS sensors, and may use an integration time of, for example, 40 milliseconds per frame.

A reference beam is often used for example to measure the intensity of the incident radiation. To do this, when the radiation beam is incident on the beam splitter 16 part of it is transmitted through the beam splitter as a reference beam towards a reference mirror 14. The reference beam is then projected onto a different part of the same detector 18.

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 tunable rather than including a set of different filters. A grating could be used instead of interference filters.

The detector 18 may measure the intensity of scattered light at a single wavelength (or narrow wavelength range), the intensity separately at multiple wavelengths or integrated over a wavelength range. Furthermore, the detector may separately measure the intensity of transverse magnetic- and transverse electric-polarized light and/or the phase difference between the transverse magnetic- and transverse electric-polarized light.

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 $\delta\lambda$ and a spacing of at least $2\delta\lambda$ (i.e. twice the bandwidth). Several "sources" of radiation can be different portions of an extended radiation source which have been split using 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) can be 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.

The target on 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, performed by processing unit PU, from knowledge of the printing step and/or other scatterometry processes.

Referring to Figure 4, the parameters used in a spectrometer such as the thickness of layers of the substrate are measured or estimated by the user. These values are input into a model, S2 of the spectrometer as a first set of values, M1 for the parameters to generate a modeled spectrum, T3.

One or more of the parameters is designated a free parameter and the remaining parameters are fixed parameters. One of the fixed parameters is changed by a small amount, for example by an amount representative of the variation or error in the determination of the fixed parameter, to form a second set of values, M4 and the model of the spectrometer run again, S5. This generates a second spectrum, T6 which will differ from the first spectrum.

An inverse of the model of the spectrometer is then applied, S7 to the second spectrum, with the fixed parameters being the same values as the values from the first set of values, M1. However, as the spectrum differs from the first spectrum the free parameter will differ and thus a third set of values, M8 for the parameters will be generated. The first and third set of values are then compared, S9. If the value for any of the free parameters differs significantly between the first and third set of data, it indicates that the measured values for the free parameters are highly sensitive to errors in the fixed parameters. Thus even a small error in the estimated or measured value for this fixed parameter would lead to a significant error in the resulting measurement of the free parameters. Thus, if the difference between one or more of the free parameters in the first and third set of data exceeds a predetermined level the chosen designation of free and fixed parameters is rejected. The same second spectrum can be used to generate further sets of values, each set of values being the same as the first set of values except for the designated free parameters, the set of free parameters which differs being a different set for each set of values.

Using the model the third set of values may be used to generate a spectrum. This may be compared to the spectrum generated using the first set of values to give a further indication of the merit of selection of free parameters.

This process is repeated for each of the fixed parameters in relation to all chosen sets of free parameters.

The model of the spectrometer and a given profile may be linearized for small changes in the model parameters. Linearization may drastically increase the speed of generating new spectra and doing the inverse modeling.

Two predictions may be made from the model regarding error contributions in the free parameters. The first concerns in what magnitude errors in the fixed parameters are transferred into errors in the free parameters (and hence in the measurements). The error in the fixed parameter may be estimated if its source is known, it may be metrology noise, or process variations. With the proposed method we know the impact on the free parameters. The second concerns variations in the intensity as seen by detector 4. The source of these variations may be e.g. photon noise or vibrations in the metrology tool and the magnitude of the variations can be determined from repeatability measurements. With the proposed method we can calculate how this noise on the intensity translates into noise on the free parameters. How the intensity noise is translated into noise on the free parameters is dependent on the choice of free parameters. The choice of the fixed and free parameters in the model may be based upon an optimal balance between the two error contributions.

In addition to the fixed parameters and free parameters, there may also be dependent parameters which are coupled to the free parameters, for example being a fixed proportion of the free parameters. The same method may be applied to determine the impact of the coupling between the dependent parameters and the free parameters on the sensitivity of the free parameters and the dependent parameters to variations on the fixed parameters.

This method may be applied to many different types of parameters such as the thickness of layers of the substrate, reflectivity of layers of the substrate, the refractive index and absorption coefficient of materials used and parameters indicating the shape of the measured structure, as well as parameters in the spectrometry model such as the gain of the photon detector.

Although the embodiment above uses an inverse of a model of the spectrometer this may often be extremely time consuming so an approximation to an inverse of a model of the spectrometer may be often used in an embodiment, especially an inverse of a linearized version of the model.

The spectrometer may include a data handling unit configured to optimize a model of the spectrometer. The data handling unit may include a readable medium encoded with machine executable instructions configured to optimize the model of the spectrometer.

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 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.

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.

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.

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.

The descriptions above are intended to be illustrative, not limiting. Other aspects of the invention are set out as in the following numbered clauses.

1. A method of optimizing a model of a spectrometer, the spectrometer being configured to measure a property of a substrate, the model having at least two parameters, the parameters comprising a first free parameter, the method comprising:

setting a first set of values for the parameters;

generating a first simulated spectrum of the spectrometer from the first set of values using the model;

changing the value of a second parameter by a first predetermined amount to form a second set of values for the parameters, the second parameter being different from the free parameter;

generating a second simulated spectrum of the spectrometer from the second set of values using the model;

using a second model to find a third set of values for the parameters from the second simulated spectrum, the second model being arranged such that the third set of values generates substantially the second simulated spectrum using the first model and such that the third set of parameters are the same as the first set of parameters except for the first free parameter;

determining the difference between the first free parameter in the third set of values for the parameters and the free parameter in the first set of values; and

selecting the free and fixed parameters in the model based on the difference.

2. A method according to clause 1, wherein the selecting includes using the difference as a figure of merit for the choice of the free and fixed parameters in the model.

3. A method according to clause 1, wherein the selecting comprises determining whether the difference between the first free parameter in the third set of values for the parameters and the free parameter in the first set of values differ by more than a second predetermined amount and if the difference is greater than the second predetermined amount the second parameter is designated a free parameter.

4. A method according to clause 1, further comprising :

generating a third simulated spectrum of the spectrometer from the third set of values; and

comparing the first simulated spectrum and the third simulated spectrum and selecting the free and fixed parameters based on the difference.

5. A method according to clause 4, wherein the selecting includes using the difference as a second figure of merit for the choice of the free and fixed parameters.

6. A method according to clause 1, wherein the model includes a plurality of parameters, the method further comprising repeating the changing, the generating, the using and the determining for each parameter which has not previously been designated a free parameter, wherein during each repetition the value of a different second parameter which has not previously been designated a free parameter is changed in the changing.

7. A method according to clause 4, wherein the model includes a plurality of parameters, the method further comprising repeating the changing, the generating, the using and the determining for each free parameter, wherein during each repetition in the changing the set of third values is the same as the first set of values except for a first free parameter, the first free parameter changing for each repetition.

8. A method according to clause 1, wherein the second model is the inverse of the model.

9. A method according to clause 1, wherein the second model is the inverse of a linear version of the model.

10. A method according to clause 1, wherein the first predetermined amount is a percentage of the second parameter.

11. A method according to clause 3, wherein the second predetermined amount is a percentage of the first free parameter.

12. A method according to clause 1, wherein one of the parameters is the thickness of a layer forming part of the substrate.

13. A method according to clause 1, wherein the model comprises dependent parameters, the dependent parameters being related to at least one the free parameter by a predetermined relationship.

14. A method of configuring a spectrometer comprising a method of optimizing a model of a spectrometer, the spectrometer being configured to measure a property of a substrate, the model having at least two parameters, the parameters comprising a first free parameter, the method comprising:

setting a first set of values for the parameters;

generating a first simulated spectrum of the spectrometer from the first set of values using the model;

changing the value of a second parameter by a first predetermined amount to form a second set of values for the parameters, the second parameter being different from the free parameter;

generating a second simulated spectrum of the spectrometer from the second set of values using the model;

using a second model to find a third set of values for the parameters from the second simulated spectrum, the second model being arranged such that the third set of values generates substantially the second simulated spectrum using the first model and such that the third set of parameters are the same as the first set of parameters except for the first free parameter;

determining the difference between the first free parameter in the third set of values for the parameters and the free parameter in the first set of values; and

selecting the free and fixed parameters in the model based on the difference.

15. A method of measuring a property of a substrate comprising configuring a spectrometer according to clause 13 and measuring a reflected spectrum.

16. A device manufacturing method comprising:

using a lithographic apparatus to form a pattern on a substrate; and

determining a property of the pattern printed by a method including

optimizing a model of a spectrometer, the spectrometer being configured to measure a property of the substrate, the model having at least two parameters, the parameters comprising a first free parameter, the method comprising:

setting a first set of values for the parameters;

generating a first simulated spectrum of the spectrometer from the first set of values using the model;

changing the value of a second parameter by a first predetermined amount to form a second set of values for the parameters, the second parameter being different from the free parameter;

generating a second simulated spectrum of the spectrometer from the second set of values using the model;

using a second model to find a third set of values for the parameters from the second simulated spectrum, the second model being arranged such that the third set of values generates substantially the second simulated spectrum using the first model and such that the third set of parameters are the same as the first set of parameters except for the first free parameter;

determining the difference between the first free parameter in the third set of values for the parameters and the free parameter in the first set of values; and

selecting the free and fixed parameters in the model based on the difference; and

measuring a spectrum reflected by the pattern on the substrate.

17. A spectrometer configured to measure a property of a substrate, the apparatus comprising:

a radiation projector configured to project a radiation onto a substrate;

a detector configured to detect the radiation reflected from the substrate; and

a data handling unit configured to optimize a model of the spectrometer, the model having at least two parameters, the parameters comprising a free parameter, the optimization comprising:

setting a first set of values for the parameters;

generating a first simulated spectrum of the spectrometer with the first set of values using the model;

changing the value of a second parameter by a first predetermined amount to form a second set of values for the parameters, the second parameter being different from the free parameter;

generating a second simulated spectrum of the spectrometer with the second set of values using the model;

using a second model to calculate a third set of values for the parameters from the second simulated spectrum, the third set of values generating substantially the second simulated spectrum using the first model, the second model being arranged such that the third set of parameters are the same as the first set of parameters except for the free parameter;

determining the difference between the first free parameter in the third set of values for the parameters and the free parameter in the first set of values; and

selecting the free and fixed parameters in the model based on the difference.

18. A spectrometer according to clause 17, wherein the selecting includes using the difference as a figure of merit for the choice of free and fixed parameters.

19. A spectrometer according to clause 17, wherein the data handling unit includes a readable medium encoded with machine executable instructions configured to optimize the model of the spectrometer.

20. A lithographic apparatus comprising:

an illumination system arranged to illuminate a pattern;

a projection system arranged to project an image of the pattern onto a substrate; and

an angularly resolved spectrometer configured to measure a property of a substrate, the spectrometer comprising:

a radiation projector configured to project a radiation onto a substrate;

a detector configured to detect the radiation reflected from the substrate; and

a data handling unit configured to optimize a model of the spectrometer, the model having at least two parameters, the parameters comprising a free parameter, the optimization comprising:

setting a first set of values for the parameters;

generating a first simulated spectrum of the spectrometer with the first set of values using the model;

changing the value of a second parameter by a first predetermined amount to form a second set of values for the parameters, the second parameter being different from the free parameter;

generating a second simulated spectrum of the spectrometer with the second set of values using the model;

using a second model to calculate a third set of values for the parameters from the second simulated spectrum, the third set of values generating substantially the second simulated spectrum using the first model, the second model being arranged such that the third set of parameters are the same as the first set of parameters except for the free parameter;

determining the difference between the first free parameter in the third set of values for the parameters and the free parameter in the first set of values; and

selecting the free and fixed parameters in the model based on the difference.

CONCLUSIE

1. Werkwijze voor het optimaliseren van een model van een spectrometer, waarbij de spectrometer is geconfigureerd om een eigenschap van een substraat te meten, waarin het model ten minste twee parameters heeft en de parameters een eerste vrije parameter omvatten, de werkwijze omvattende de volgende stappen:

- bepalen van een eerste waardenverzameling voor de parameters;

- genereren van een eerste gesimuleerd spectrum van de spectrometer op basis van de eerste waardenverzameling gebruik makend van het model;

- wijzigen van de waarde van een tweede parameter met een eerste voorafbepaalde hoeveelheid zodat een tweede waardenverzameling voor de parameters wordt gevormd, en waarbij the tweede parameter verschillend is van de vrije parameter;

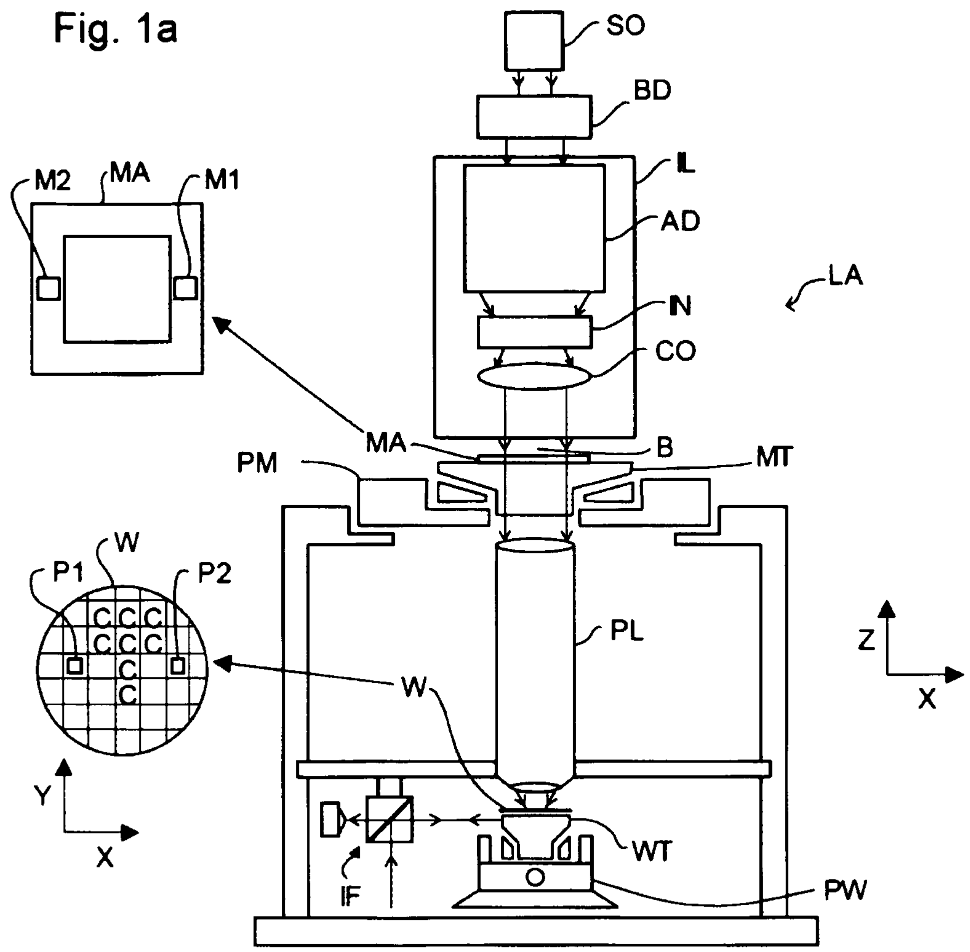
- genereren van een tweede gesimuleerd spectrum van de spectrometer op basis van de tweede waardenverzameling gebruik makend van het model;

- gebruiken van een tweede model om een derde waardenverzameling voor de parameters te vinden op basis van het tweede gesimuleerde spectrum waarbij het tweede model zodanig is opgesteld dat de derde waardenverzameling in hoofdzaak het tweede gesimuleerde spectrum genereert gebruik makend van het eerste model, en zodanig dat de derde parameterverzameling gelijk is aan de eerste parameterverzameling uitgezonderd de eerste vrije parameter;

- bepalen van het verschil tussen de eerste vrije parameter in de derde waardenverzameling voor de parameters en de vrije parameter in de eerste waardenverzameling; en

- selecteren van de vrije en vaste parameters in het model op basis van het verschil.

Fig. 1a



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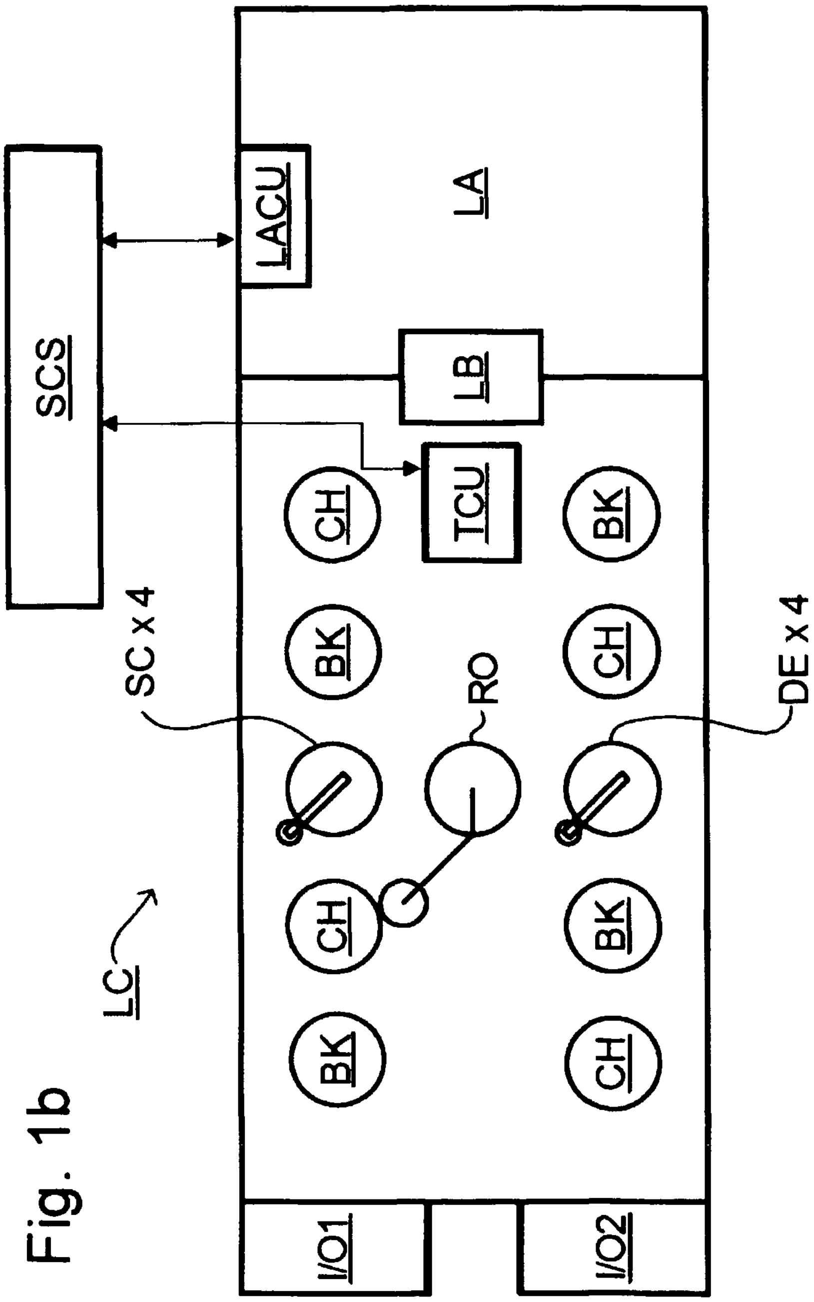
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Fig. 1b

Fig. 2

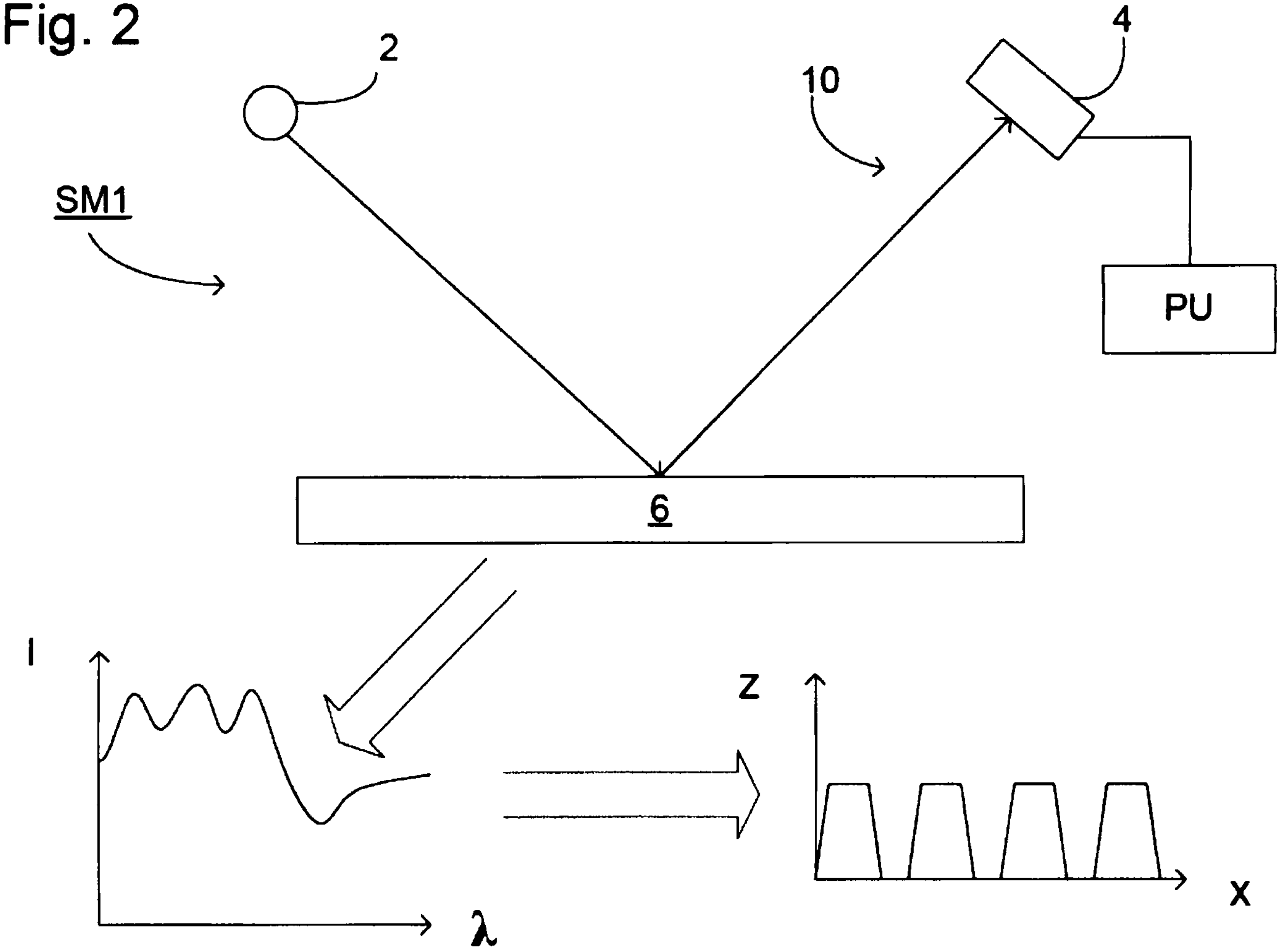


Fig. 3

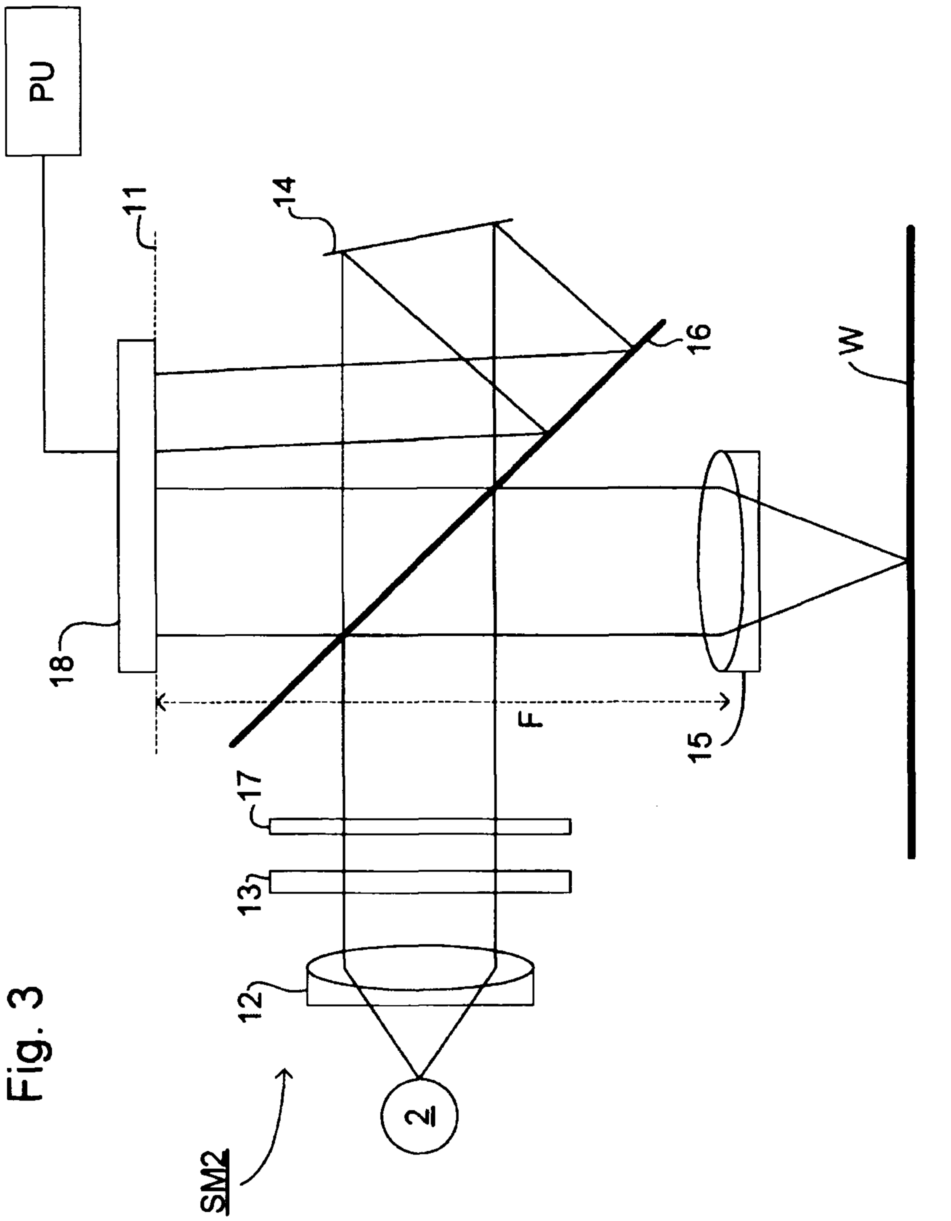
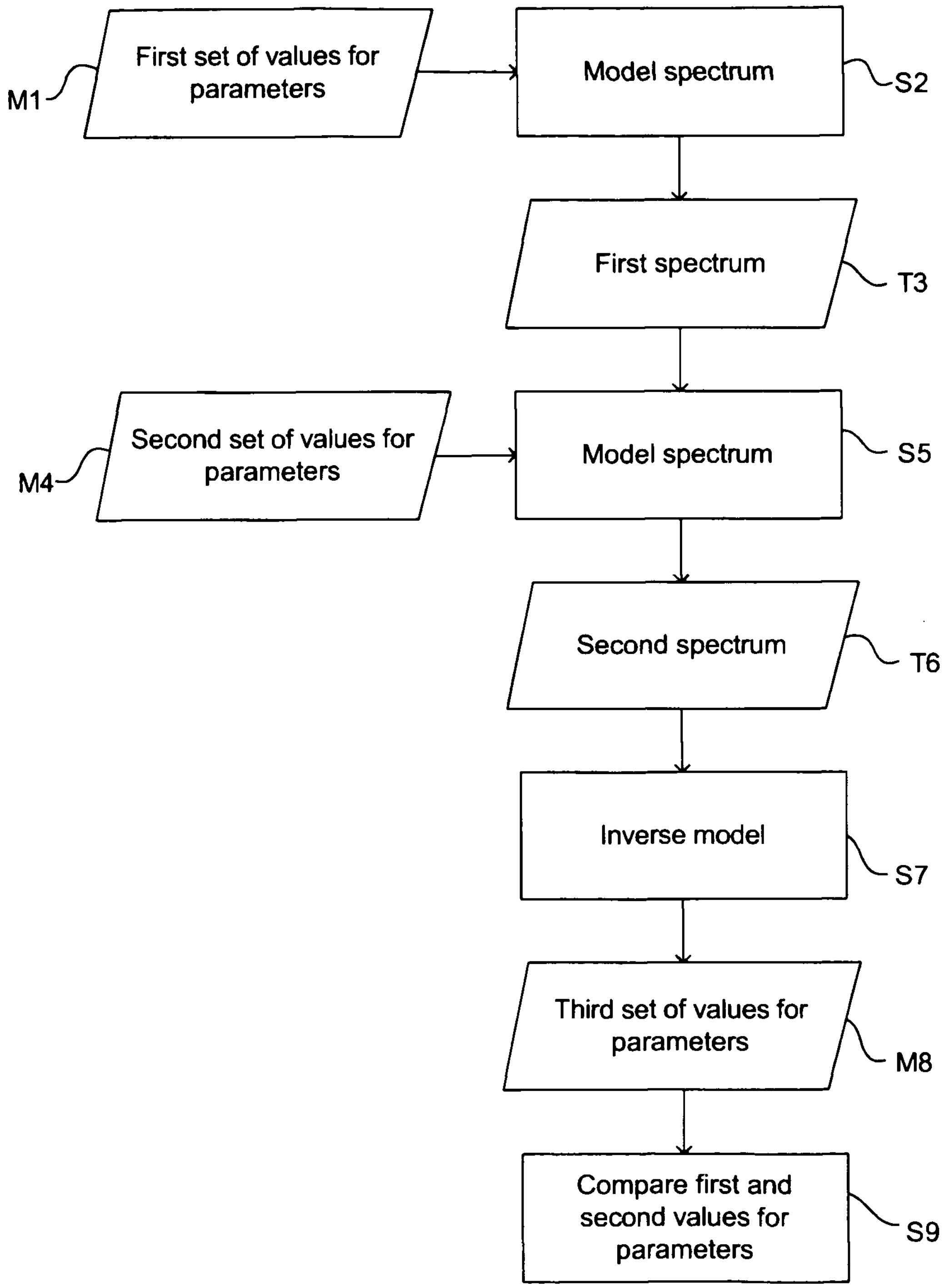


Fig. 4


M1
First set of values for parameters
Model spectrum
S2
First spectrum
T3
M4
Second set of values for parameters
Model spectrum
S5
Second spectrum
T6
Inverse model
S7
Third set of values for parameters
M8
Compare first and second values for parameters
S9