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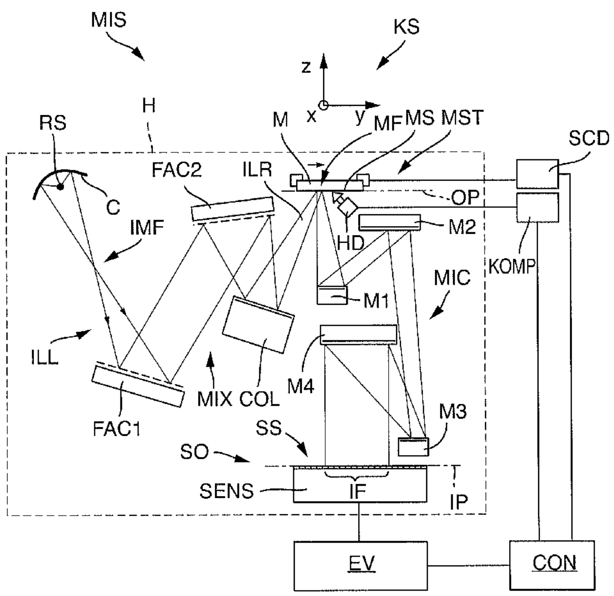


Fig. 1

**(57) Abstract**: A mask inspection system for inspecting a reflective mask using electromagnetic radiation with a working wavelength λ from the extreme ultraviolet region (EUV), comprises a microscope system (MIC) for magnifying imaging of an object arranged in an object plane (OP) of the microscope system in an image plane which is optically conjugate to the object plane; a mask holding device which is configured to hold the mask in such a way that a mask surface (MS) to be examined is arranged in the region of the object plane (OP) of the microscope system; an illumination system (ILL) for receiving radiation from an EUV radiation source and for generating illumination radiation (ILR), which impinges on the mask surface (MS) in a measurement field (MF); a sensor device with a sensor surface (SS), which is arranged in the image plane (IP) of the microscope system or in a plane optically conjugate to the image plane, and an evaluation device (EV) connected to the sensor device. In order to carry out a scanning operation, the mask is moved parallel to the object plane and parallel to a scanning plane in such a way that regions of the mask surface adjoining one another in the scanning direction can successively be moved into the measurement field and the evaluation device is configured for integrating signals, captured in a spatially resolved fashion on the sensor surface, in-phase to the movement of the mask. The mask inspection system is characterized by a compensation device (KOMP) for actively compensating deformations in the mask surface, induced in the region of the measurement field (MF) by the illumination radiation (ILR), for reducing surface gradients in the region of the measurement field compared to a mask surface in absence of the compensation.

WO 2014/019870 A1

# Description

# Mask inspection method and mask inspection system for EUV-masks

The following disclosure is based on German Patent Application No. 10 2012 213 794.7 filed on August 3, 2012, which is incorporated into this application by reference.

## BACKGROUND OF THE INVENTION

### Technical field

The invention relates to a mask inspection method for inspecting a reflective mask using electromagnetic radiation with a working wavelength λ from the extreme ultraviolet region (EUV) and to a mask inspection system suitable for carrying out the mask inspection method.

### Prior art

These days, it is predominantly microlithographic projection exposure methods that are used for producing semiconductor components and other fine-structured parts. In the process, use is made of masks (reticles) which carry the pattern of a structure to be imaged, e.g. a line pattern of a layer of a semiconductor component. In a projection exposure apparatus, the pattern is positioned between an illumination system and a projection lens in the region of the object plane of the projection lens and illuminated by illumination radiation provided by the illumination system. The radiation modified by the pattern passes as projection radiation through the projection lens, which images the pattern on the substrate to be exposed, the latter generally being coated by a radiation-sensitive layer (resist). In general, there is a reducing imaging of the pattern on the substrate in this case, e.g. in the ratio 4:1 or 5:1.

In order to be able to produce evermore finer structures, projection exposure apparatuses were developed in recent years, which operate with moderate numerical apertures and substantially obtain an increase in the resolution capability by the short wavelengths of the utilized electromagnetic radiation from the extreme ultraviolet region (EUV). Here, in particular, wavelengths in the region between 5 nm and 30 nm are employed.

Radiation from the extreme ultraviolet region (EUV-radiation) cannot be guided or focused sufficiently with the aid of refractive optical elements since the short wavelengths are strongly absorbed by the known materials which are optically transparent at longer wavelengths or by other materials. Hence, mirror systems are used for EUV lithography. The utilized masks, which are also referred to as EUV-masks below, are reflective masks.

A reflective mask for EUV-lithography comprises a substrate, which, on its front side, carries a structured coating which forms the pattern and has a reflective effect on EUV-radiation. The substrate normally consists of a material with a particularly low thermal expansion, e.g. silica glass. The reflecting coating is designed as a multilayer arrangement, which has many layer pairs with alternating low refractive and high refractive layer material and has a reflective effect on the utilized EUV-radiation in the style of the Bragg reflector. Applied to this reflective coating are radiation-absorbing regions made of an absorber material, e.g. titanium nitride, tantalum nitride or chromium. The absorbing regions stand tall on the coating; radiation-reflecting regions of the coating remain between the elevated regions. The elevated radiation-absorbing regions and the lower lying radiation-reflecting regions form the pattern of the mask.

The production of the masks is very complicated and must occur with great accuracy since mask defects of the order of 1 nm can already lead to intolerable defects in the generated structures.

Thus, during the production of EUV-masks, mask inspection methods and mask inspection systems are employed, which are able to localize automatically and optionally to identify mask defects at the relevant order of magnitude. If possible, a mask repair for removing the detected defect follows a mask inspection. WO 2011161243 A1 describes, in an exemplary fashion, a method and a device for identifying defects and repairing EUV masks. In order to obtain the necessary resolution capabilities, these systems usually operate with the same working wavelength that is also employed during the subsequent microlithographic production process, for example at approximately 13.5 nm. Such systems are often referred to actinic mask inspection systems or at-wavelength mask inspection systems.

There is the need for mask inspection systems which are able to localize and qualify even the smallest mask defects automatically within a relatively short period of time.

## SUMMARY OF THE INVENTION

It is an object of the invention to provide a mask inspection method and a mask inspection system, which render it possible to localize automatically and quantify accurately even the smallest mask defects on structured EUV masks within a relatively short period of time.

This object is achieved by a mask inspection method having the features of Claim 1, and by a mask inspection system having the features of Claim 9. Advantageous developments are specified in the dependent claims. The wording of all claims is made content of the description by reference.

The claimed invention is based in part on the discovery that there can be irreversible information losses in the case of mask inspection methods or mask inspection systems of the type mentioned at the outset due to deformations of the mask surface induced by the illumination radiation. This problem, which was identified first by the inventors, is removed or the effects thereof are decisively reduced if thermally induced surface gradients in the region of the measurement field are, compared to a mask surface without the compensation, removed or reduced to such a large extent that the evaluation of the measurement results is no longer impaired thereby to the extent that it interferes. Surface gradients extending parallel to the scanning direction of the scanning operation were identified as particularly problematic in this case. However, compensation in other directions can likewise be useful and be provided.

The claimed invention engages with the causes of the potentially critical information losses, and so it is possible to provide improved mask inspection systems, by means of which even the smallest mask defects in structured EUV masks can efficiently be localized automatically and qualified accurately.

The procedure in which the mask is heated in a surrounding area of the measurement field in accordance with a predeterminable two-dimensional heating profile by using a heating device which is separate from the illumination system, with the heating of the surrounding area starting before a measurement in the measurement field, was found to be particularly efficient. Hence, the mask to be examined is preheated temporally before the measurement in order to reduce or completely avoid the buildup of impairing surface gradients. The surrounding area to be preheated in this case comprises at least one portion lying in front of the measurement field in the scanning direction, i.e. in that region which the measurement field runs into during the scanning operation. What this can achieve is that the heat influx during the measurement from the illumination radiation is no longer able to lead to very impairing surface gradients. In some embodiments, the surrounding area encloses the whole measurement field, and so the mask can, in relation to the measurement field, be preheated at all times.

In the case of appropriately equipped mask inspection systems, the compensation device comprises a heating device, separate from the illumination system, for heating the mask in accordance with a predeterminable two-dimensional heating profile. Here, the phrase “two-dimensional heating profile” denotes a two-dimensional influx or a two-dimensional generation of heat energy on or in the mask in accordance with a predeterminable spatial distribution. The heating device can heat the mask before the scanning and during the scanning with a predeterminable spatial distribution of the introduced heat power in order, for example, to heat the aforementioned surrounding area of the measurement field prior to a measurement.

The heating of the mask by the separate heating device is preferably contactless, and so structural interventions on the mask or mechanical contacting of the mask can be avoided. In some embodiments, the heating device is, to this end, embodied as a radiation heating device for radiating heating radiation onto the mask. The phrase “heating radiation” in this case denotes general heat-generating radiation, with the heat being created in the irradiated region of the mask. A radiation heating device is also compatible with a measurement in vacuo.

The wavelengths of the heating radiation can lie in a different spectral region than those of the EUV illumination radiation employed for the measurement. In particular, the heating device can operate using infrared radiation, by means of which a particularly effective heat influx or heating-power influx into the mask is possible.

It was found to be expedient in many cases for components of the heating device to be arranged in such a way that the mask is irradiated by heating radiation on the side of the mask surface to be examined, i.e. on the front side. The heat influx is then brought about on exactly the same side of the mask as on which the deformation problem caused by the illumination radiation occurs, and so a particularly targeted compensation is possible. Alternatively or additionally, it is also possible for the mask to be heated from the opposite mask rear side. Heating from the rear side can also be brought about in contactless fashion by heating radiation. Optionally, contacting heating devices and cooling devices can also be provided on the rear side.

A particularly efficient compensation of thermal deformations is achieved in some embodiments by virtue of the fact that the heating device is switched between a first configuration and at least one second configuration depending on the time profile of the irradiation of the measurement field by illumination radiation. As a result, it is possible to achieve different two-dimensional heating profiles or different spatial distributions of the heat influx according to a predetermined temporal scheme.

In the process, preferably, the surrounding area and the region of the measurement field are actively heated by the heating device in phases without illumination radiation radiating into the measurement field in a first configuration and active heating of the measurement field by means of the separate heating device is reduced or interrupted and only the surrounding area is heated in phases where illumination radiation is radiated into the measurement field. As a result, it is possible to generate a heating profile which complements the heating profile generated by the illumination radiation. This complementary heating profile is preferably designed in such a way that the heating profile generated by the illumination radiation is added to in such a way that there is a substantially uniform power input of heating power in the region of the measurement field and in the surrounding area. If the measurement region and the surrounding area surrounding it are thus heated more or less uniformly over a certain period of time, which includes the period of time of the measurement, it is possible to avoid or strongly reduce impairing surface gradients in the region of the measurement field, particularly in the edge region of the measurement field. The validity of the measurement results can be increased thereby.

To this end, provision can be made in a mask inspection system for the heating device to have a heating radiation source and a switchable or controllable heating radiation distribution device, which, for generating different two-dimensional heating profiles, i.e. for generating different spatial distributions of heat influx, can be switched between a first configuration and at least one second configuration. A switchable heating radiation distribution device can for example operate using stops, by means of which predeterminable regions of a relatively large illuminated region can, if necessary, be blocked in such a way that heating radiation does not impinge on the mask in the blocked region. Work is preferably performed with heating radiation distribution devices which generate no or only a few radiation losses by virtue of the heating radiation originating from the heating radiation source being able to be modified in a controlled fashion in respect of its spatial distribution and/or in respect of its beam angular distribution.

In one embodiment, the distribution or redistribution of the heating radiation for the purposes of generating different spatial heating profiles is obtained with the aid of one or more diffractive optical elements (DOEs), which substantially bring about a redistribution of heating radiation by diffraction on diffractive structures.

Alternatively or additionally, a switchable heating radiation distribution device can also comprise refractive elements in the form of lens elements and/or prisms and/or arrays of lens elements or prisms, which can be switched accordingly.

In other variants, a reflective heating radiation distribution device is employed. By way of example, this can comprise a multi-mirror array (MMA), which comprises a multiplicity of separately controllable individual mirrors, which can, for example, be tilted about tilt axes extending orthogonally to one another in order to reflect the impinging heating radiation into different regions of the area of the mask to be illuminated.

Alternatively or additionally, it is also possible to employ spatial modulators for heating radiation within the scope of a switchable heating radiation distribution device. A spatial radiation modulator, which can also be referred to as a spatial light modulator (SLM), is configured to impress a spatial modulation onto the influenced radiation. By way of example, this can be an electronically controllable radiation modulator or an optically controllable radiation modulator, which is effective for the selected heating radiation.

The compensation device can be operated on the basis of data or compensation scenarios by way of a feed-forward control. In some embodiments, a measurement-supported compensation is carried out, for the purposes of which the corresponding mask inspection system is equipped with a measuring device.

In some embodiments, provision is made for a measuring device in the form of a spatially resolving temperature measuring device for measuring the temperature of the mask surface to be inspected in a spatially resolved fashion and for controlling the compensation device using measurement results from this measuring device.

It is also possible to use a measuring device by means of which the surface form or the surface deformation, i.e. directly the variable to be influenced, can be measured. To this end, provision can for example be made for optical systems, which emit a measurement beam onto the mask surface and evaluate information in the measurement beam reflected by the mask surface.

This application also discloses a combination of a reflective mask, which comprises a mask surface provided with a pattern and has a reflective effect on electromagnetic radiation with a working wavelength λ from the extreme ultraviolet region, and an electronic record, generated by a mask inspection system, of defect data generated by a mask inspection method of the type described here with the aid of the mask inspection system of the type described here. For each detected defect, the defect data can contain spatial data for a corresponding location of the detected defect in relation to a coordinate system of the mask.

A record of defect data generated in such a way or a measurement log which can be obtained in this fashion can, for example, serve as a basis for a potentially possible mask repair. The record can be available in an electronically processable form. It is also possible for a physical record to be generated, for example in the form of a printed document, which can be forwarded together with the measured mask.

By way of example, the mask can be examined completely for defects with the aid of the mask inspection method or the mask inspection system. The measurement log can contain a complete list of all positions on the mask at which defects are situated. The defect or log can serve as a basis for a decision as to whether or not a mask can be used further directly after the examination. In the negative case (no direct further use), the mask can be subjected to a more in-depth examination, in which the mask is imaged in accordance with the conditions present in the lithographic process at the one or more defect positions listed in the measurement log. A defect position imaged thus can then be examined in respect of its functionality. In the negative case (functionality is not as desired), the mask can be rejected or subjected to a repair scenario.

The above and further features are evident not only from the claims but also from the description and from the drawings, wherein the individual features can in each case be realized by themselves or as a plurality in the form of sub-combinations in an embodiment of the invention and in other fields and can constitute advantageous and inherently protectable embodiments. Exemplary embodiments of the invention are illustrated in the drawings and explained in greater detail below.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows components of an embodiment of an actinic mask inspection system for inspecting a reflective mask using EUV-radiation;

Figure 2 shows a top view of a structured mask surface with measurement field;

Figure 3 shows a schematic section through a mask in the region of the measurement field during a measurement;

Figure 4 schematically shows the time profile of the orientation of the mask surface at the location of a point P for different times of a pass through the measurement field;

Figure 5 shows a schematic surface profile in the x-direction perpendicular to the scanning direction;

Figures 6 and 7 show schematic illustrations of typical measurement errors, which can be created by fading,

Figures 8 and 9 show schematic illustrations of typical measurement errors, which can be traced back to defocusing errors;

Figure 10 shows, in 10A to 10C, schematic top views of a mask in one embodiment of a mask inspection method with thermal compensation of thermally induced surface deformations;

Figure 11 shows, in 11A, a measurement without compensation and, in 11B, a measurement with compensation;

Figure 12 shows a first embodiment of a heating device for reducing thermally induced surface gradients in the region of the measurement field;

Figure 13 shows a second embodiment of a heating device for reducing thermally induced surface gradients in the region of the measurement field; and

Figure 14 shows an embodiment of a mechanical manipulation device for reducing thermally induced surface gradients in the region of the measurement field.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 shows components of an embodiment of a mask inspection system MIS for inspecting a reflective mask M using electromagnetic radiation with a working wavelength λ from the extreme ultraviolet region (EUV). A Cartesian system coordinate system KS is specified for spatial orientation purposes. The mask inspection system is configured for actinic mask inspection, which permits large area regions of structured mask surfaces of EUV masks to be examined for mask defects in a relatively short period of time with high spatial resolution using EUV radiation.

The mask inspection system is operated using the radiation from a primary radiation source RS. An illumination system ILL serves for receiving the radiation from the primary radiation source and for forming illumination radiation ILR, which, in the region of a measurement field MF, impinges on the mask surface MS, of the mask M, to be examined (see also Figure 2). The pattern PAT of the mask is situated on the structured mask surface.

During operation, the mask is held by a mask holding device MST, which is configured and arranged in such a way that the mask surface MS to be examined is arranged in the region of the object plane OP of a microscope system MIC following in the beam path. The object plane lies in an x-y plane perpendicular to the z-direction of the system coordinate system. The microscope system MIC serves for magnifying imaging of the region of the mask surface, lying in the region of the measurement field MF, in the image plane IP of the microscope system, which image plane is optically conjugate to the object plane OP and parallel to the object plane.

A sensor device SD of the mask inspection system has a sensor SENS with a planar, radiation-sensitive sensor surface SS, which extends in two dimensions and is arranged in the image plane of the microscope system or in a plane optically conjugate thereto. By way of example, the sensor can be an EUV-sensitive CCD sensor. A magnified image of that section of the mask surface which, at the measurement time, lies in the region of the measurement field MF impinges on the sensor surface at any measurement time. Connected to the sensor device is an evaluation device EV, which evaluates the images or the image signals of the sensor SENS in accordance with predetermined evaluation methods using means from image processing.

The primary radiation source RS can, for example, be a laser plasma source or a gas discharge source or a synchrotron-based radiation source. Such radiation sources generate radiation in the extreme ultraviolet region (EUV region), in particular with wavelengths between 5 nm and 15 nm. So that the illumination system ILL and the microscope system MIC can operate in this wavelength region, they are constructed with components reflective to EUV radiation. These components are coated with optical coatings which reflect the EUV radiation to the best possible extent and can, for example, be optimized for working wavelengths of approximately 13.5 nm or approximately 6.9 nm.

A mirror with a reflective effect on radiation from the EUV region (EUV mirror) typically comprises a substrate, onto which a multilayer arrangement with a reflective effect on radiation from the extreme ultraviolet region has been applied, which multilayer arrangement comprises many layer pairs with, alternately, relatively low refractive and relatively high refractive layer material and acts in the style of a distributed Bragg reflector. Layer pairs for EUV mirrors are often constructed using the layer material combinations molybdenum/silicon (Mo/Si) and/or ruthenium/silicon (Ru/Si).

The radiation emitted by the radiation source RS is collected by means of a collector C and routed into the illumination system ILL after forming an intermediate focus IMF. The illumination system comprises a mixing unit MIX and a collector unit COL. The mixing unit MIX substantially consists of two facet mirrors FAC1, FAC2. The first facet mirror FAC1 is arranged in a plane which is optically conjugate to the object plane OP of the microscope system MIC. It is therefore also referred to as field facet mirror. The second facet mirror FAC2 is arranged in a pupil plane of the illumination system, which pupil plane is optically conjugate to a pupil plane of the microscope system MIC. It is therefore also referred to as pupil facet mirror.

The individual mirroring facets (individual mirrors) of the first facet mirror FAC1 are imaged into the measurement field MF with the aid of the pupil facet mirror FAC2 and the collector unit COL situated downstream in the beam path. The spatial (local) illumination intensity distribution on the field facet mirror FAC1 determines the local illumination intensity distribution in the measurement field. The spatial (local) illumination intensity distribution on the pupil facet mirror FAC2 determines the illumination angular intensity distribution in the measurement field MF.

The illumination system therefore forms the EUV radiation and, using the latter, illuminates the measurement field MF as homogeneously as possible. In the exemplary case, the measurement field MF is rectangular. In the exemplary case, the width MFX of the measurement field is approximately 300 µm in the x-direction, while the height MFY is approximately 200 µm in the y-direction. The side lengths of the measurement field in the x-direction and in the y-direction typically lie significantly below 1 mm, e.g. between 100 µm and 800 µm. By contrast, the masks to be examined generally have side lengths of 100 mm or more, e.g. of 100 mm to 200 mm. The measurement field MF is therefore smaller than the area of the mask surface to be examined by several orders of magnitude.

The microscope system MIC is an optical imaging system with a magnifying effect, which is designed using curved mirrors only, preferably using an even number of mirrors, e.g. four or six mirrors. There are also embodiments with an odd number of mirrors, e.g. with three mirrors. The magnification factor or the linear magnification ß between object plane and image plane is preferably at least 100, in particular between 200 and 1000, e.g. between 500 and 800. The image field IF lying in the image plane IP is greater than the measurement field MF by the linear magnification.

The microscope system MIC comprises four mirrors M1 to M4, which follow one another in the imaging beam path. A first mirror M1 receives the radiation originating from the object plane OP and reflected by the mask M in the measurement field, and reflects it at an angle to the second mirror M2, which reflects the radiation in the direction of the third mirror M3. The latter reflects the radiation to the fourth mirror M4, which reflects the radiation into the image field IF on the sensor surface SS.

All optical components of the mask inspection system MIS are housed in an evacuable housing H (or in several interconnected housings). The mask inspection system is operated in vacuo and is controlled by a central control unit CON.

Since the measurement field MF is several orders of magnitude smaller than the region to be examined on the mask surface MS, the mask surface is scanned during the mask inspection method in order to ensure a complete inspection without gaps. To this end, the mask holding device MST is guided movably in the y-direction and coupled to a scanner drive SCD, which can, at a predeterminable scanning speed, move the mask holding device with the held mask in a scanning direction SCN extending parallel to the y-direction. During a scanning operation, the mask is moved parallel to the object plane and parallel to the scanning direction SCN in such a way that regions of the mask surface, adjacent to one another in the scanning direction, are successively moved into the measurement field MF, which is stationary in relation to the system co-ordinate system KS, and then moved out of it again. For illustrative purposes, Figure 2 illustrates the position of the measurement field MF at a first measurement time $t_1$ using dashed lines and at a later, second measurement time $t_2 > t_1$ using full lines. A measurement strip with the width MFX can be passed over using a linear scanning operation. After this, the mask holding device is displaced parallel to the x-direction by an absolute value less than or equal to MFX, before a further scanning operation scans an adjacent measurement strip.

During a scanning operation, different images successively fall into the image field IF, which is optically conjugate to the measurement field MF, at the stationary sensor surface SS. In the process, the image of a specific point on the mask migrates parallel to the y-direction over the sensor surface such that the associated image point impinges onto the sensor surface at positions offset to one another in the y-direction at different measurement times. In order nevertheless to obtain an image of the mask surface, true to the structure, for evaluation purposes, the evaluation device is configured in such a way that signals captured on the sensor surface in a spatially resolved manner are integrated in-phase with the movement of the mask. Hence, a scan-integrated image is evaluated.

The inventors have identified that such mask inspection methods can be impaired to a particular extent by thermally induced deformations of the mask surface. Specific problems will be explained in more detail on the basis of Figures 3 to 9. To this end, Figure 3 shows a schematic y-z section through a reflective mask M in the region of the measurement field MF during a measurement. A multi-ply-multilayer-coating ML with Mo/Si layer pairs and/or Ru/Si layer pairs, which reflects EUV radiation, was applied on one side of the plate-shaped silica-glass substrate SUB of the mask M. The pattern PAT of the mask is formed by a structured absorber layer on this coating.

It is known that, in the case of such layer systems, a not insignificant portion of the impinging radiation energy is absorbed on or in the mask, particularly in the region of the coating. This leads to a thermal load on the mask and can lead to thermally induced deformations of the mask, particularly in the region of the mask surface MS.

In order to keep thermally induced deformations of reflective masks as low as possible, materials with a relatively low coefficient of thermal expansion are often used for the mask substrate (see e.g. WO 2010/020337 A1).

It was identified that the risk of thermally induced surface deformations is significantly larger in mask inspection systems than in projection exposure apparatuses since the power densities in the illuminated region of mask inspection systems are significantly higher than in the subsequent lithographic process, i.e. during the application within an EUV projection exposure apparatus. The power density of the EUV radiation impinging on the measurement field MF in the relatively small measurement field can be more than ten times or more than twenty times or more than thirty times greater than the power density which subsequently occurs in the object field of the projection lens during the lithographic process. Accordingly, the extent of the thermal deformation of the mask surface is greater.

A further problem is that, as a result of the scanning process during the mask inspection of a deformed mask surface, irreversible information losses can occur during the evaluation. The mask M in Figure 3 is moved from left to right through the measurement field MF in the scanning direction SCN. In the process, a specific point P on the mask surface enters the measurement field at the entry edge IN and, after passing through the measurement field, leaves said measurement field at an exit edge OUT.

As long as the region of the point is still outside of the measurement field MF, there is substantially no thermal load. Directly after entering into the measurement field, the temperature T in the region in the vicinity of the surface will increase due to the irradiation. This temperature increase continues substantially throughout the whole duration of the passage of the point P through the measurement field as a result of the continued radiation, until the point P finally reemerges from the measurement field.

The ongoing temperature increase leads to a thermal expansion of the materials, increasing over time, in the vicinity of the mask surface MS, with the extent of the thermal expansion still being relatively low in the vicinity of the entry edge IN and increasing in the direction of the exit edge OUT. There is also a small thermal outflow from the region of the measurement field, particularly in the region of the exit edge. Overall, this results in an asymmetrical surface profile parallel to the scanning direction SCN. In the exemplary case, this appears as arching in the direction of the microscope lens, but it could also be formed as an indent or trough.

It can immediately be seen that the surface deformation also results in a deformation of the wavefront running through the microscope system, which wavefront leads to the image being created on the sensor surface. Aberrations are created, which will still be analyzed in more detail.

Figure 4 schematically illustrates the time profile of the orientation of the mask surface at the location of the point P with the aid of the surface normal N for various times $t_0$ to $t_n$ of a passage through the measurement field. At the time $t_0$, the observed point moves into the measurement field and it leaves the measurement field (OUT) at the time $t_{n+1}$.

Figure 5 schematically shows the profile of the surface, i.e. the surface shape, in the x-direction, extending perpendicular to the scanning direction, within the measurement field for two different measurement times $t_2$ and $t_n$. Here too, the arrows denote the local surface normals N of the surface, to be precise at five positions Pos 1 to Pos 5 which are spaced apart in the x-direction. In both illustrations (Figure 4 and 5), regions with strong surface gradients can be identified on the basis of the particularly oblique orientation of the normal vectors N.

The differently pronounced surface gradients within the measurement field lead to characteristic defects during the image generation and the subsequent integrating image evaluation, which should be explained in an illustrative fashion on the basis of Figures 6 and 7. Here, Figure 6 shows the local profile of the positions of the image points P’, belonging to the mask point P, on the sensor surface SS, i.e. in the image field optically conjugate to the measurement field. What is shown is the position of the image point at the x-position 3, i.e. in the center of the image field in the x-direction. The measurement times $t_1$ to $t_n$ are spaced apart at the same time intervals.

It is possible to identify, on account of the surface gradients running in the scanning direction, that the positions of the image points on the sensor surface are no longer equidistant from one another. However, the in-phase addition of images in the evaluation device is based on a constant speed of the examined mask in the scanning direction during the image recordings. Hence the unequal distances of the image points on the sensor surface during the in-phase superposition thereof lead to the image point AV (actual value) in the scanning direction (y-direction), established by image addition or integration, appearing to be smeared or elongated. By comparison, to the right thereof, the unaffected intended value TV (target value) is illustrated in the form of a round point.

This “smearing” of image points or of measurement values during the scanning integration is also referred to as “fading” herein. During the integration during the image evaluation, some of the useful information is irrevocably lost on account of fading. In the exemplary case, this can be understood by virtue of the fact that it is not possible to gather from the shape of the image point, elongated in the y-direction, which individual displacements at the different measurement times overall have contributing to the smearing. As a result of the smearing of the measurement signal, there is a risk of incorrectly interpreting the measurement results.

Figure 7 shows a corresponding illustration of problems during the measurement field generation for the positions 1 to 5 on the x-axis in accordance with Figure 5. The orientation of the surface does not change for the point in the center of the measurement field (Pos 3) while passing through the measurement field, and so the surface normal is the same at all times (in particular at $t_2$ and $t_n$) and therefore remains unchanged in time. During the scanning integration, the corresponding image point is accordingly always situated precisely at the position expected due to the speed of the mask at the various measurement times, and so the time integration of the various image signals shows a true image of the region around this surface point, represented by a round point.

At the edges of the measurement field (for example at positions 1 and 5), by contrast, the surface gradient (oblique position of the local surface compared to the object plane) increases evermore with increasing duration of stay in the measurement field, leading to the corresponding image points in the image field running away evermore strongly in the lateral direction (i.e. parallel to the x-direction) as time increases. In the scanning integration, this effect becomes noticeable as smearing of the image point parallel to the x-direction. The extent of the smearing, proceeding from the center of the measurement field, increases in both directions toward the edges, namely in opposite directions in accordance with the different signs of the surface gradients.

From these schematically illustrated examples, it is possible to see that the thermally induced surface deformation in conjunction with the integration of image signals during the evaluation can lead to a fading effect with corresponding, irreversible losses of information.

A further possible contribution to possible measurement errors can be created by virtue of the fact that the mask surface runs out of the object plane OP, which is optically conjugate to the image plane IP, as a result of the thermal deformations, and so a point on the mask is no longer imaged as much in focus on the sensor over time. As a result, defocusing errors could emerge during the imaging. These could superimpose on the above-described errors due to the lateral running away of image points. For explanatory purposes, Figure 8 shows, in both partial figures, the sensor plane SS with two beams coinciding in the direction of the sensor plane, which beams have left the microscope system on the image side. In the left partial figure, the sensor plane SS lies in the region of the focus, and so this results in in-focus imaging. The right partial image shows that there has been defocusing of the magnitude of $\Delta z_S$ as a result of thermal deformations of the mask, and so the image point in the sensor plane SS will appear to be larger than in the case of an in-focus image point. The corresponding deviation of the position of the mask point P from its intended position in the object plane OP in the case of an un-deformed mask is denoted by Δz (cf. Figure 4).

The corresponding effects in the image plane and during the scanning integration are illustrated schematically in Figure 9. In the upper partial image (FOC), the profile of the positions of the image points without focusing error, known from Figure 6, and, to the right thereof, the corresponding effect during the scanning integration are shown. In the lower partial figure (DEF), a corresponding illustration with additional defocusing can be seen. It is possible to see that the image of the point appears enlarged on all sides or smeared on all sides in the scan-integrated measurement signal.

In order to avoid or reduce such problems, the mask inspection system MIS comprises a compensation device KOMP for active compensation of deformations of the mask surface in the region of the measurement field MF, induced by the illumination radiation ILR. The compensation acts in the direction of reducing local surface gradients, i.e. local increases and/or decreases relative to the object plane in the region of the measurement field compared to a mask surface without the compensation.

An option for avoiding or reducing the impairment of the measurement results by thermally induced deformations in the region of the measurement field in preferred embodiments consists of counteracting the local surface deformations by virtue of a region around the measurement field being pre-heated or heated using a heating device HD prior to the measurement, so that thermal gradients cannot, or only to a much reduced extent compared to without the pre-heating, be formed during the measurement. This results in a reduction or complete avoidance of surface gradients in the measurement field, and so the aforementioned measurement errors can largely be avoided.

In the left-hand partial Figure 10A, Figure 10 shows a section of the front side of a mask M with a shaded measurement field MF, which is just being irradiated by EUV illumination radiation. In the left-hand partial Figure 11A of Figure 11, the surface deformation caused by the illumination radiation ILR and the deformation of the wave fronts WF in the radiation reflected by the mask surface MS resulting therefrom are illustrated schematically.

The central and right-hand partial Figure 10B and 10C of Figure 10 schematically show how such problems can be avoided in embodiments of the invention. As explained above, the measurement takes place in a scanning fashion. As a countermeasure to counter the thermal deformations, a large enough surrounding area SA around the measurement field is preheated prior to the measurement, so that there are no and/or only insignificant thermal deformations during the later irradiation of the measurement field by EUV radiation. In this respect, Figure 10B shows that a surrounding area, rectangular in the example, with SA (surrounding area) is heated beyond the surface temperature $T_0$ of the remaining mask surface to a temperature $T_1 > T_0$ using a heating device. To the extent that there is no measurement and therefore no EUV illumination radiation is impinging on the region of the measurement field, the region of the measurement field is also heated by the separate heating device. Since substantially the same temperature prevails throughout the whole heated region, there are no thermally induced surface gradients in the region of the measurement field. Surface gradients are only created in the transition region between the heated zone and the non-heated surroundings, but these are spatially far outside the region of the measurement field.

If a measurement now takes place such that EUV illumination radiation is radiated into the region of the measurement field, the region of the measurement field is heated by the EUV illumination radiation. During these times, the spatial heating profile of the heating device is set in such a way that the region of the measurement field is only heated by the illumination radiation ILR and not by the external heating device. The heating device then merely maintains the temperature in the surrounding area surrounding the measurement field.

The power of the separate heating device is ideally set in such a way that the heat influx generated by the heating device substantially corresponds to that heat influx which is caused in the region of the measurement field by the EUV illumination radiation. As a result, the mask surface remains substantially planar or non-deformed both in the region of the measurement field and also at the edge of the measurement field in the transition region to the surrounding area, even during the measurement. This results in a situation, schematically illustrated in Figure 11B, of a planar mask surface MS, which reflects the impinging illumination radiation ILR in the direction of the downstream microscope system without deformation of the wavefront.

Figures 12 and 13 are used to explain two different embodiments of heating devices which are suitable for compensating thermally induced surface gradients in the region of the measurement field by targeted heat influx according to precisely defined local heating profiles in such a way that surface deformations in the region of the measurement field are largely avoided.

In the embodiment of Figure 12, the heating device HD has a heating radiation source (not illustrated in any more detail), which emits infrared radiation IR. Components of the heating device are arranged in such a way that the heating radiation impinges obliquely on the mask surface provided with the pattern PAT from the front side facing the microscope system. Arranged in the beam path of the heating radiation is an IR-transmissive first diffractive optical element DOE1, the structures of which diffracting infrared light spatially deform the infrared radiation in such a way that the heating radiation impinges with a predetermined shape and magnitude on the mask surface in the surrounding area SA, with the region of the measurement field also being irradiated by IR-radiation. The heating radiation reflected by the mask surface falls into a beam trap DP and is therefore unable to impair the measurement.

The region heated by infrared radiation is heated uniformly, and so the mask surface is planar in the heated region. The level of the mask surface in the z-direction is slightly raised compared to the surrounding cooler regions of the mask, with it being possible for relatively large surface gradients to result in the edge region of the heated region. By setting the z-position of the mask with the aid of the mask holding device MST, this z-offset is compensated for, and so the heated mask surface lies in the region of the object plane of the microscope system. It can be seen from the schematic diagram situated thereover that that heat influx Q as a result of the infrared heating device at this time is largely uniform in the whole surrounding area around the measurement field and in the measurement field, and drops away sharply in the edge regions.

Figure 12B shows the heating device in a second configuration, which is switched to when a measurement takes place and, accordingly, illumination radiation ILR is radiated into the region of the measurement field MF by the illumination system ILL. During these phases, there is a heat influx Q in the measurement field MF as a result of the absorption EUV radiation. This part of the heat influx is denoted by “EUV” in the diagram situated thereover. During this phase of the measurement, the heating device is switched into a second configuration, in which, in place of the first diffractive element DOE1, a second diffractive optical element DOE2 is arranged in the beam path of the infrared heating radiation. The diffractive structures thereof are configured in such a way that the heating radiation continues to heat the whole part of the surrounding area surrounding the measurement field MF, with, however, no more heating radiation impinging on the region of the measurement field MF. The power of the heating radiation is allocated in such a way that the heat influx generated by the infrared radiation has substantially the same magnitude as the heat influx on the mask surface generated by the EUV radiation. What this achieves is that there is substantially no change in the local heat influx at the transition from the time period prior to the measurement to the time period during the measurement, and so there are also no thermally induced surface deformations and, in particular, no surface gradients. Therefore the mask surface remains planar in the region of the measurement field and in the surrounding area, and the measurement is not impaired by surface deformations.

In the embodiment of Figure 12, the heating device comprises a heat radiation distribution device with two diffractive optical elements, which can alternately be introduced into the beam path and transmit infrared radiation. These can be physically separate optical elements or one integral optical element with regions having different diffractive structures.

It is also possible to use a heating device with a reflective heat radiation distribution device. To this end, Figure 13 schematically shows components of another heating device, in which the infrared radiation IR originating from a heat radiation source is directed onto the front side of the mask using a multi-mirror array MMA. The multi-mirror array has a multiplicity of small individual mirrors, the orientations of which can be modified individually with the aid of suitable actuating elements in reaction to control signals from a control device such that different beam angular distributions of the reflected radiation emerge. The procedure when switching between a phase without illumination of the measurement field (Figure 13A) and a measurement phase with illumination of the measurement field using EUV illumination radiation (Figure 13B) is the same as in the embodiment of Figure 12, which is why reference is made to the description there.

As an alternative to the illustrated embodiments, or in addition thereto, there can also be heating from the rear side of the mask facing away from the mask surface MS.

In other embodiments, a reduction of thermally induced surface deformations during the mask inspection is achieved by virtue of the fact that the mask is actively cooled during the measurement using a suitable cooling device. By way of example, cooling can take place from the rear side of the mask, for example by blowing coolant gas thereon. Use can also be made of other cooling devices, which can be switched or controlled in a spatially dependent manner, e.g. cooling devices with Peltier elements.

Cooling can be utilized in combination with heating, for example in order to achieve a more precise spatial and temporal control of the thermal distribution.

It is furthermore possible to undertake a compensation of thermally induced surface deformations by means of suitable manipulators which mechanically engage on the mask. By way of example, a manipulator MAN can comprise a multiplicity of individually actuatable actuating elements SE, which engage on the rear side of the mask and, as a reaction to local heating in the region of the measurement field, are actuated in such a way that a deformation is counteracted (Figure 14).

The control of a compensating engagement can be brought about on the basis of data, established in advance during a calibration method, by way of a feed-forward control. It is also possible to equip the mask inspection system with a measuring device and carry out a measurement-supported compensation.

By way of example, the measurement device can be a spatially resolving temperature measuring device for measuring the temperature of the mask surface, or a measuring device by means of which the surface deformation, i.e. the form of the mask surface, can be measured. The compensation can then be controlled on the basis of the data captured by the measuring device. By way of example, the external heating device can be incorporated in a closed-loop control.

To this end, a deformation of the surface of the mask is measured in one embodiment. Surface deformation data are generated therefrom, which, for example, describe the extent and the spatial distribution of the surface deformations on the structured mask surface in a suitable manner. The control of the heating device (or any other compensation device) is then carried out depending on the surface-deformation data. This enables particularly precise setting of a sought-after surface profile, even in the case of varying operational conditions.

Alternatively, or in addition thereto, it is also possible to measure the local current heat distribution of the mask and to derive control commands therefrom for the heating device or any other compensation device. A temperature distribution measuring device can either be facing the structured front side of the mask (i.e. the pattern) or be situated on the rear side of the mask facing away from the pattern.

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Patent Claims

1. Mask inspection method for inspecting a reflective mask using electromagnetic radiation with a working wavelength λ from the extreme ultraviolet region (EUV), comprising the following steps:

holding the mask between an illumination system and a microscope lens of a mask inspection system in such a way that a mask surface, provided with a pattern, of the mask is arranged in the region of an object plane of the microscope lens;

illuminating a measurement field on the mask surface using illumination radiation provided by the illumination system;

carrying out a scanning operation by moving the mask parallel to the object plane and parallel to a scanning direction in such a way that regions of the mask surface adjacent to one another in the scanning direction are successively moved into the measurement field;

successively imaging each region of the mask surface moved into the measurement field with a magnifying scale in a sensor plane, optically conjugate to the object plane, of a spatially resolving sensor of the mask inspection system;

generating, in a spatially resolved fashion, image signals of the regions of the mask surface respectively arranged in the measurement field using the sensor;

in-phase evaluating of the image signals detected during the scanning operation, wherein, during the evaluation, image signals are integrated in-phase,

characterized by:

compensation of deformations of the mask surface in the region of the measurement field, induced by the illumination radiation, in order to reduce surface gradients in the region of the measurement field compared to a mask surface without the compensation.

2. Mask inspection method according to Claim 1, characterized by heating the mask in a surrounding area of the measurement field in accordance with a predeterminable two-dimensional heating profile by using a heating device which is separate from the illumination system, with

the heating of the surrounding area starting before a measurement in the measurement field.

3. Mask inspection method according to Claim 2, wherein the heating device is switched between a first configuration and a second configuration depending on the time profile of the irradiation of the measurement field by illumination radiation, with, preferably, the surrounding area and the region of the measurement field not impinged upon by illumination radiation being actively heated by the heating device in phases without illumination radiation radiating into the measurement field in the first configuration and active heating of the measurement field being reduced or interrupted and only the surrounding area being heated in phases where illumination radiation is radiated into the measurement field.

4. Mask inspection method according to Claim 2 or 3, wherein the heating device is used to generate a heating profile, which complements the heating profile generated by the illumination radiation, the complementary heating profile preferably being designed in such a way that the heating profile generated by the illumination radiation is added to in such a way that there is a substantially uniform power input of heating power in the region of the measurement field and in the surrounding area.

5. Mask inspection method according to Claim 2, 3 or 4, wherein there is contactless heating of the masks by the heating device, in particular by virtue of heating radiation being radiated onto the mask.

6. Mask inspection method according to Claim 5, wherein the mask is irradiated by heating radiation on the side of the mask surface to the examined.

7. Mask inspection method according to one of the preceding claims, wherein the mask is actively cooled during the measurement by means of a cooling device, with cooling preferably taking place from the rear side of the mask.

8. Mask inspection device according to one of the preceding claims, wherein the mask inspection system comprises a measuring device and

the compensation is controlled on the basis of measurement signals captured by the measuring device, with, preferably, the temperature of the mask surface and/or the form of the mask surface being measured in a spatially resolved fashion.

9. Mask inspection system for inspecting a reflective mask using electromagnetic radiation with a working wavelength λ from the extreme ultraviolet region (EUV), comprising:

a microscope system (MIC) for magnifying imaging of an object arranged in an object plane (OP) of the microscope system in an image plane which is optically conjugate to the object plane;

a mask holding device which is configured to hold the mask in such a way that a mask surface (MS) to be examined is arranged in the region of the object plane (OP) of the microscope system;

an illumination system (ILL) for receiving radiation from an EUV radiation source and for generating illumination radiation (ILR), which impinges on the mask surface (MS) in a measurement field (MF);

a sensor device with a sensor surface (SS), which is arranged in the image plane (IP) of the microscope system or in a plane optically conjugate to the image plane, and

an evaluation device (EV) connected to the sensor device,

the mask being movable parallel to the object plane and parallel to the scanning plane for carrying out a scanning operation in such a way that regions of the mask surface adjoining one another in the scanning direction can successively be moved into the measurement field;

and the evaluation device being configured for integrating signals, captured in a spatially resolved fashion on the sensor surface, in-phase to the movement of the mask;

characterized by

a compensation device (KOMP) for actively compensating deformations in the mask surface, induced in the region of the measurement field (MF) by the illumination radiation (ILR), for reducing surface gradients in the region of the measurement field compared to a mask surface in absence of the compensation.

10. Mask inspection system according to Claim 9, wherein the compensation device comprises a heating device (HD), separate from the

illumination system (ILL), for heating the mask (M) in accordance with a predeterminable two-dimensional heating profile.

11. Mask inspection system according to Claim 10, wherein the heating device is configured as a radiation heating device for irradiating the mask with heating radiation (IR), the components of the heating device preferably being arranged in such a way that the mask can be irradiated with heating radiation from the side of the mask surface to be examined.

12. Mask inspection system according to Claim 10 or 11, wherein the heating device (HD) is configured in such a way that the mask (M) can be heated at least intermittently in a surrounding area (SA) of the measurement field (MF) in according with a predeterminable two-dimensional heating profile.

13. Mask inspection system according to one of Claims 10 to 12, wherein the heating device (HD) comprises a heating radiation source and a controllable heating radiation distribution device, which, for generating different heating profiles, can be switched between a first configuration and a second configuration, with, preferably, the surrounding area and the region of the measurement field being heatable by the heating device in the first configuration and only the surrounding area being heatable in the second configuration.

14. Mask inspection system according to Claim 13, wherein the heating radiation distribution device is configured in such a way that the heating radiation (IR) originating from the heating radiation source can be modified in respect of its spatial distribution and/or in respect of its radiation angular distribution substantially without radiation loss, the heating radiation distribution device preferably comprising a diffractive optical elements (DOE) which has a diffractive effect on the heating radiation or a controllable multi-mirror array (MMA).

15. Mask inspection system according to one of Claims 10 to 14, characterized by a measuring device for generating measurement signals which represent at least one property of the mask surface, the compensation device (KOMP) being controllable on the basis of the

measurement signals, the measuring device preferably being designed as a spatially resolving temperature measuring device or as a spatially resolving measuring device in the form of the mask surface.

16. Mask inspection system according to Claim 9, characterized in that the compensation device engages mechanically on the mask, the compensation device preferably comprising a manipulator (NAM) with a multiplicity of individually actuatable actuating elements (SE), which engage on the rear side of a mask and, reacting to a local heating in the region of the measurement field, can be actuated in such a way that the deformation of the mask surface is counteracted.

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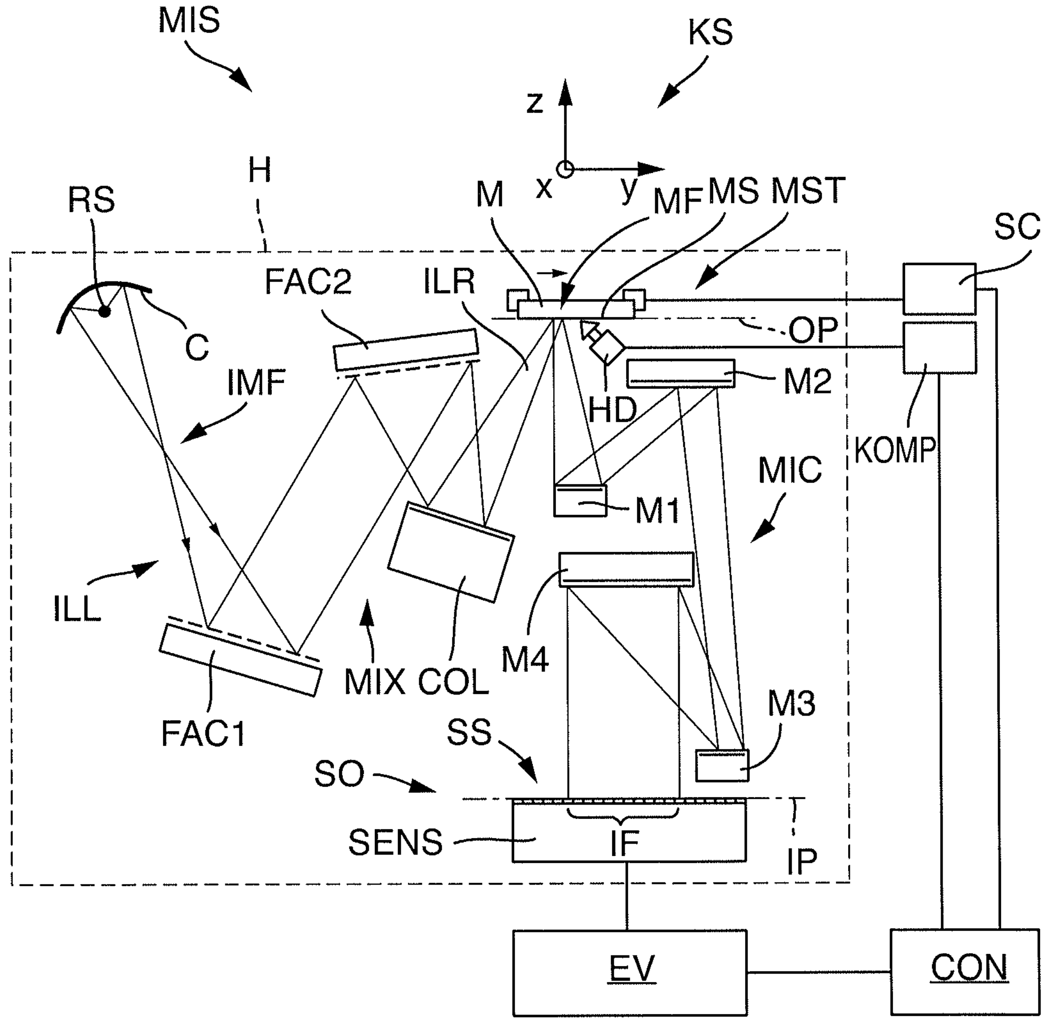
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Fig. 1

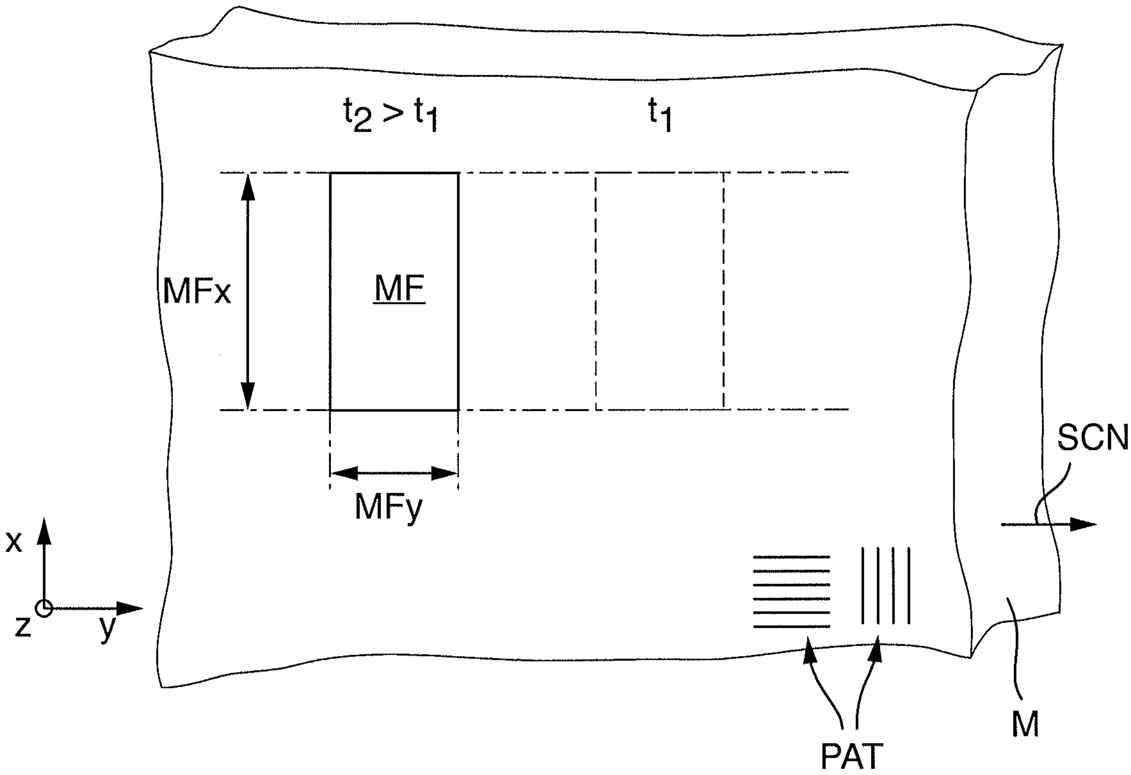
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Fig. 2

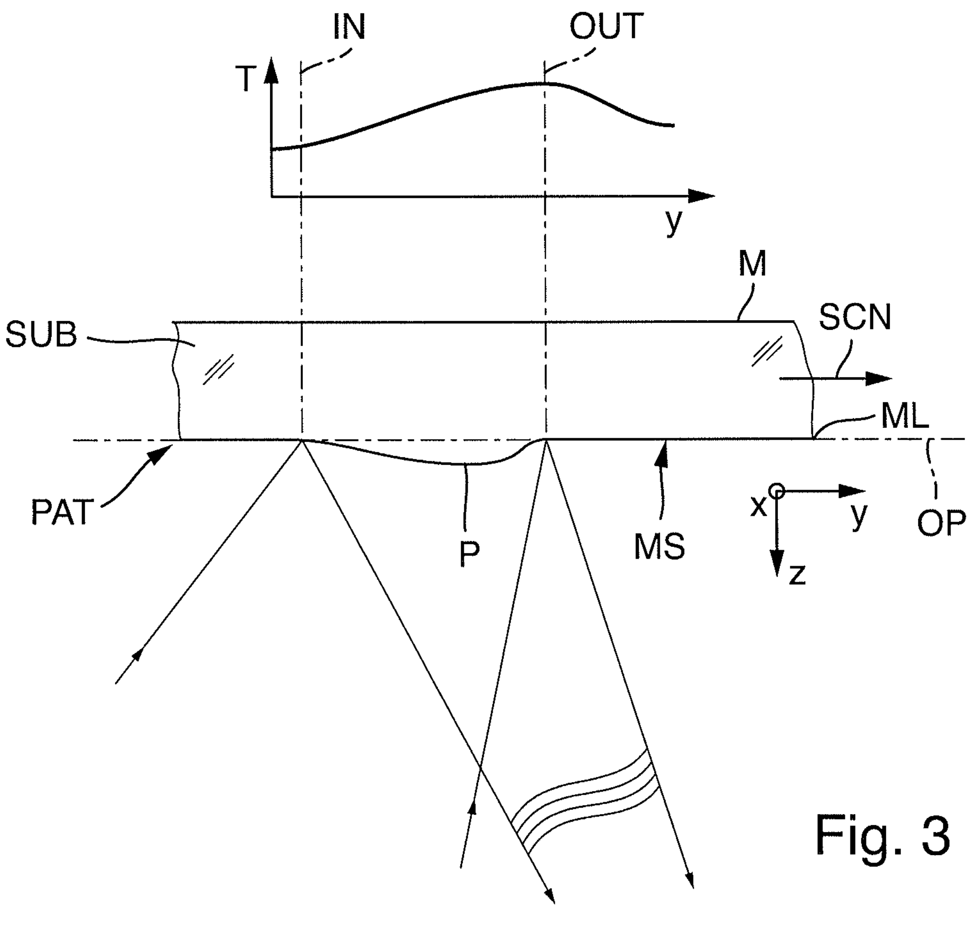
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Fig. 3

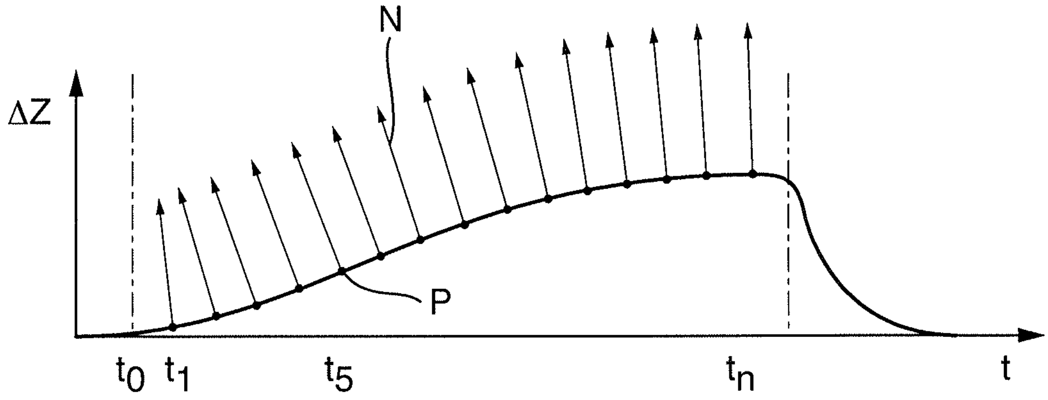


Fig. 4

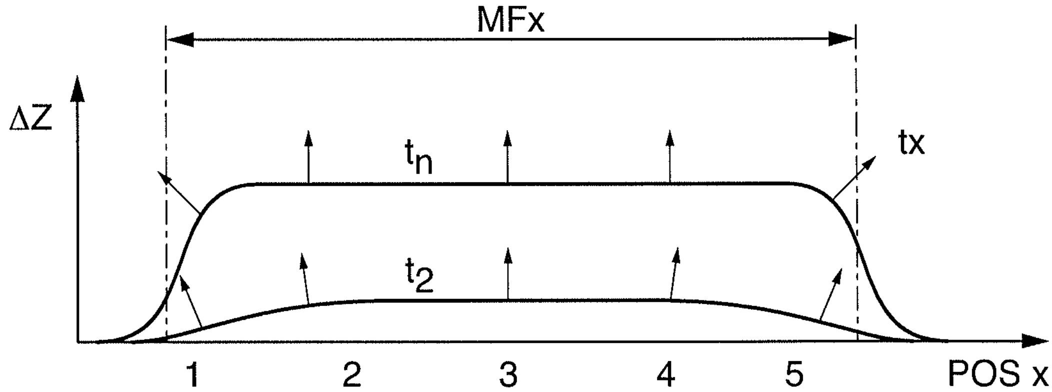


Fig. 5

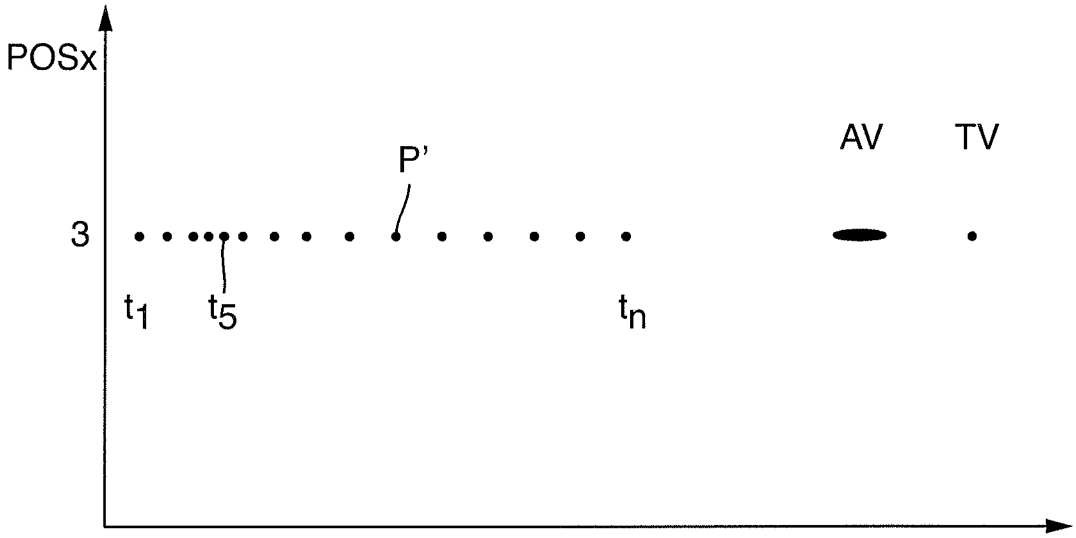


Fig. 6

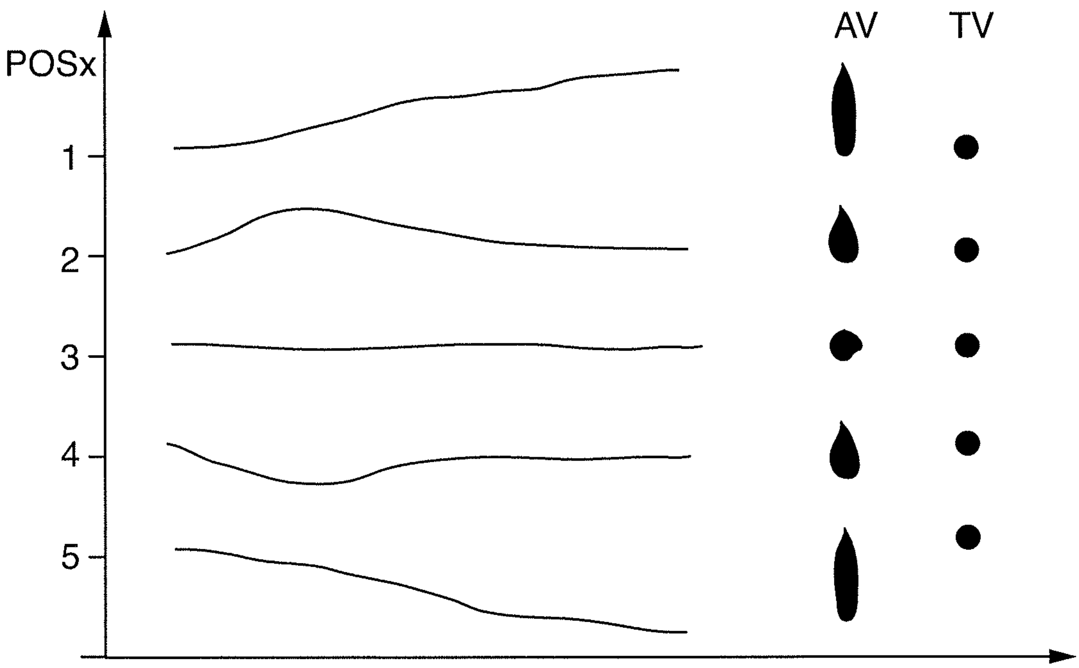


Fig. 7

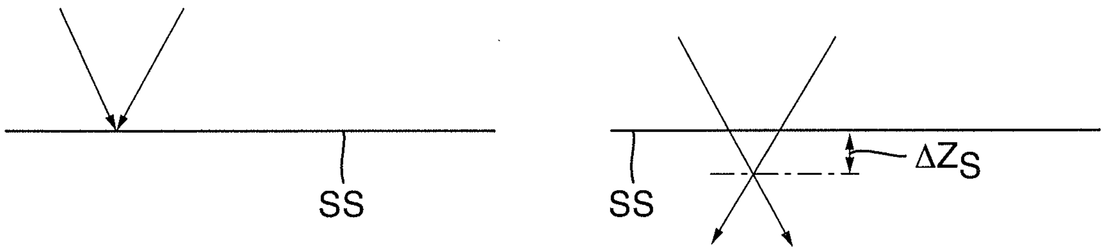


Fig. 8

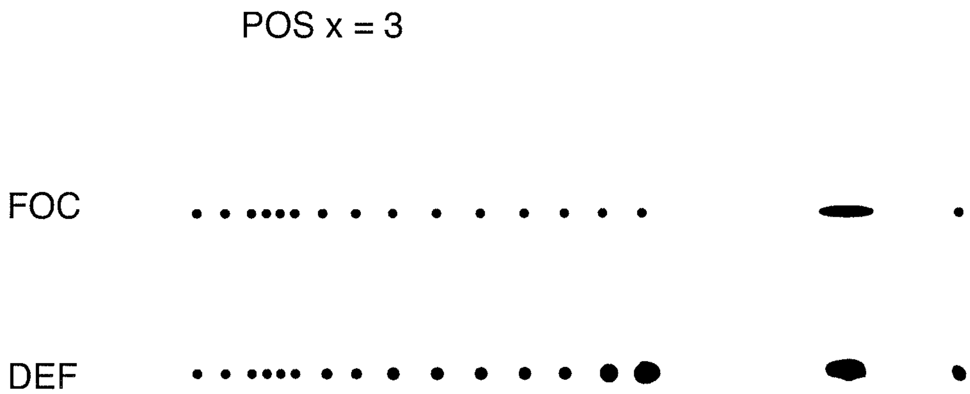


Fig. 9

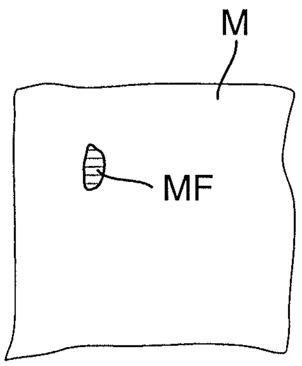


Fig. 10A

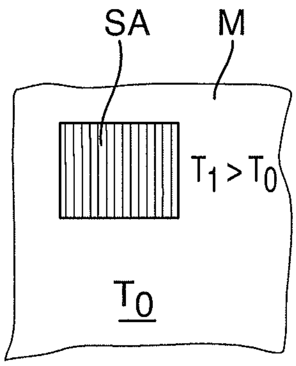


Fig. 10B

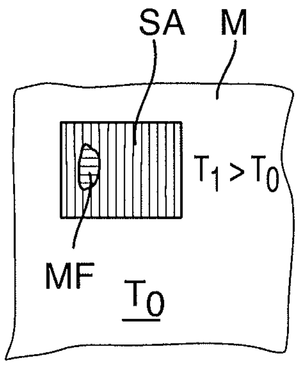


Fig. 10C

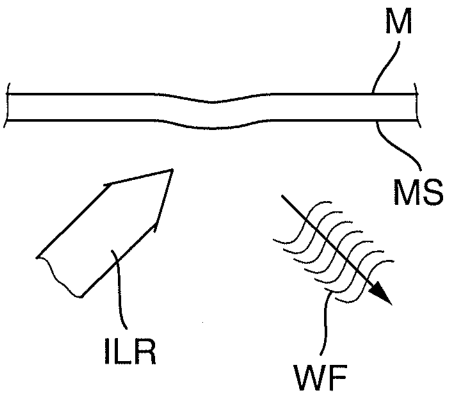


Fig. 11A

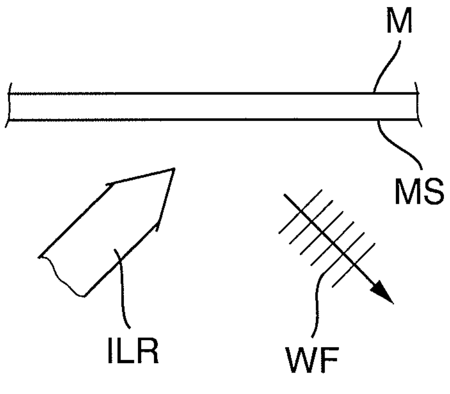


Fig. 11B

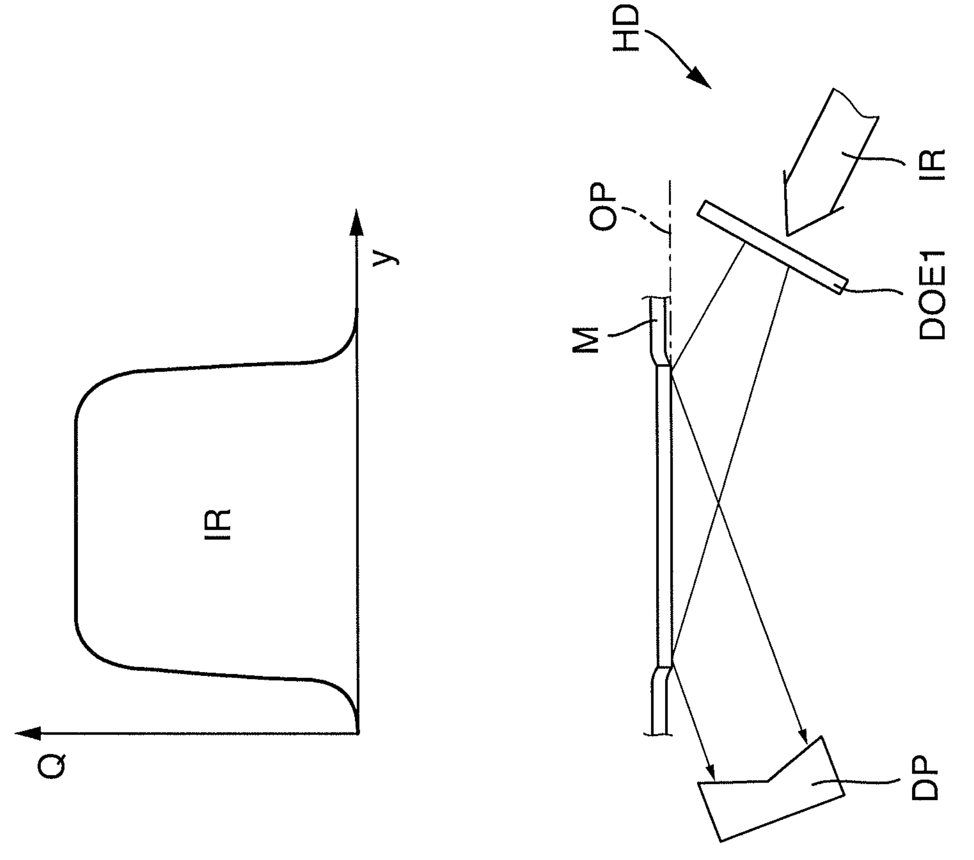


Fig. 12A

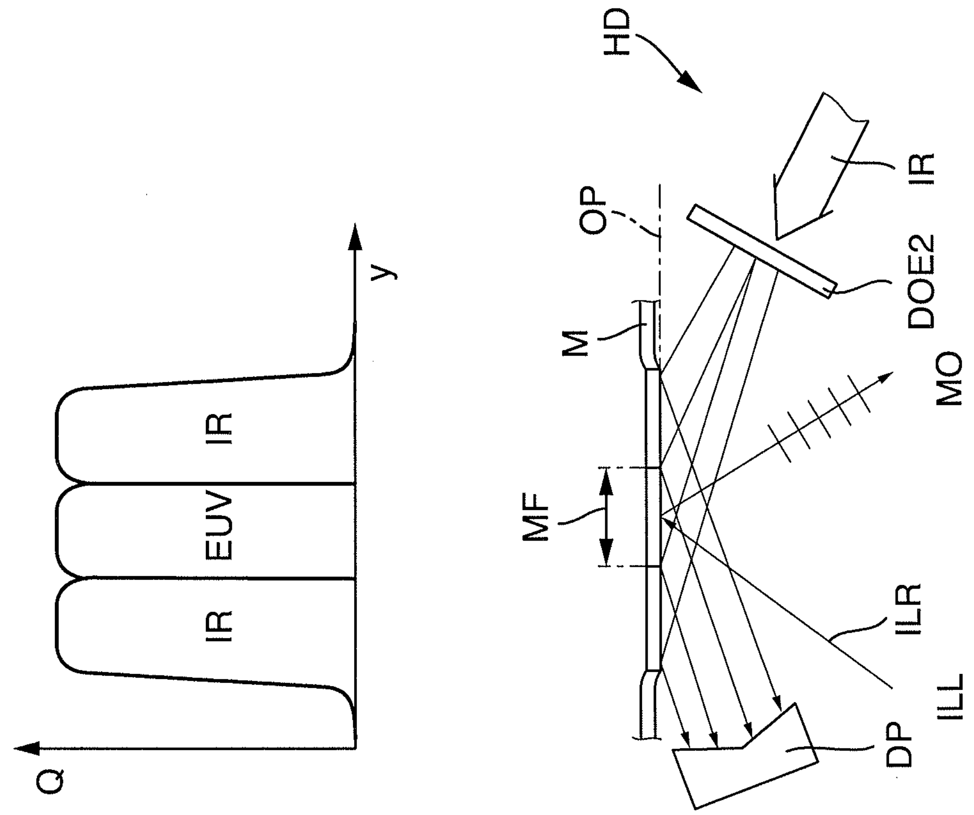


Fig. 12B

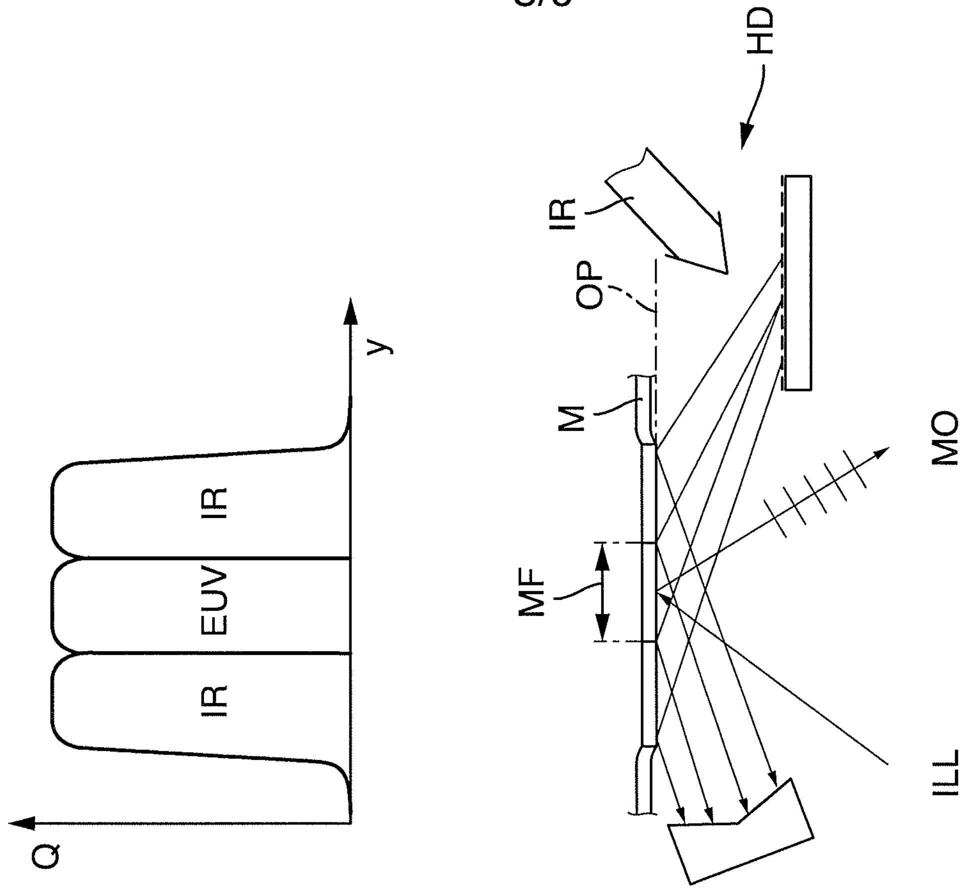


Fig. 13B

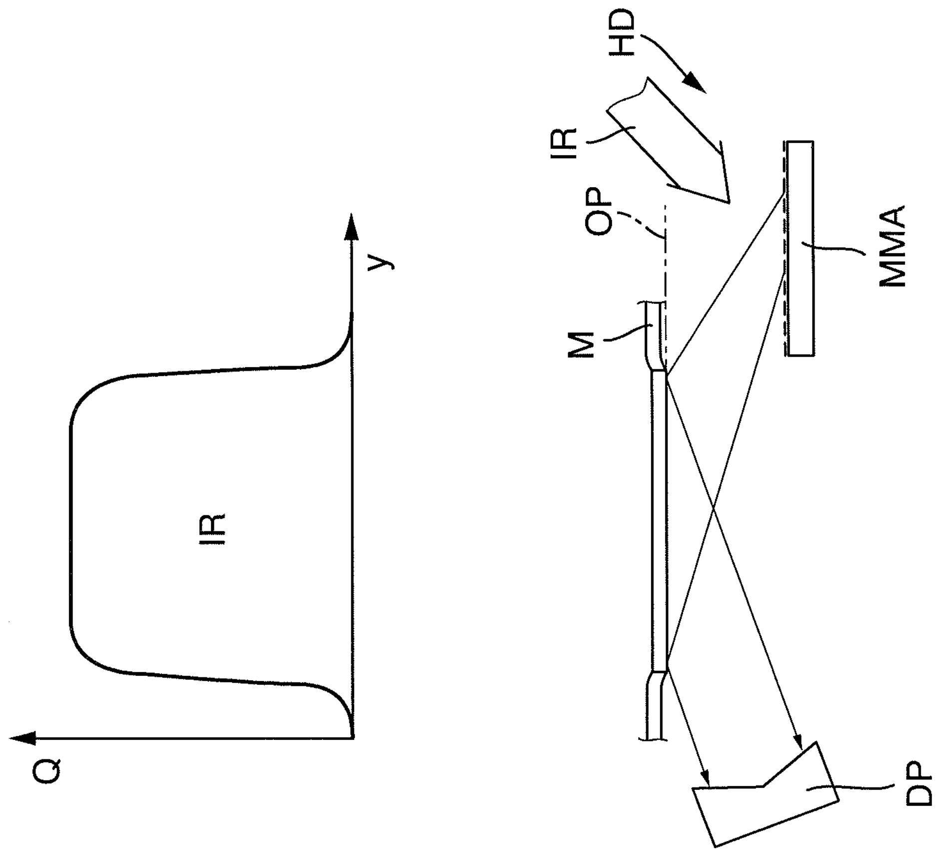


Fig. 13A

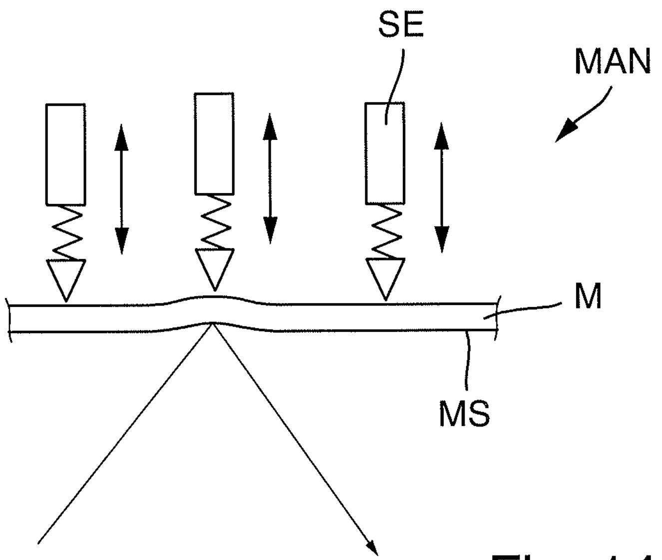


Fig. 14

# INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/065239

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 G03F1/00 G03F1/84 G03F1/24
ADD.

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

B. FIELDS SEARCHED

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

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

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

EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | HELLWEG DIRK ET AL: "AIMS EUV: the actinic aerial image review platform for EUV masks", EXTREME ULTRAVIOLET (EUV) LITHOGRAPHY II, SPIE, 1000 20TH ST. BELLINGHAM WA 98225-6705 USA, vol. 7969, no. 1, 17 March 2011 (2011-03-17), pages 1-10, XP060009102, DOI: 10.1117/12.879422 [retrieved on 2011-04-05] the whole document ----- -/-- | 1-16 |

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

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| Date of the actual completion of the international search | Date of mailing of the international search report |
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2

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2

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