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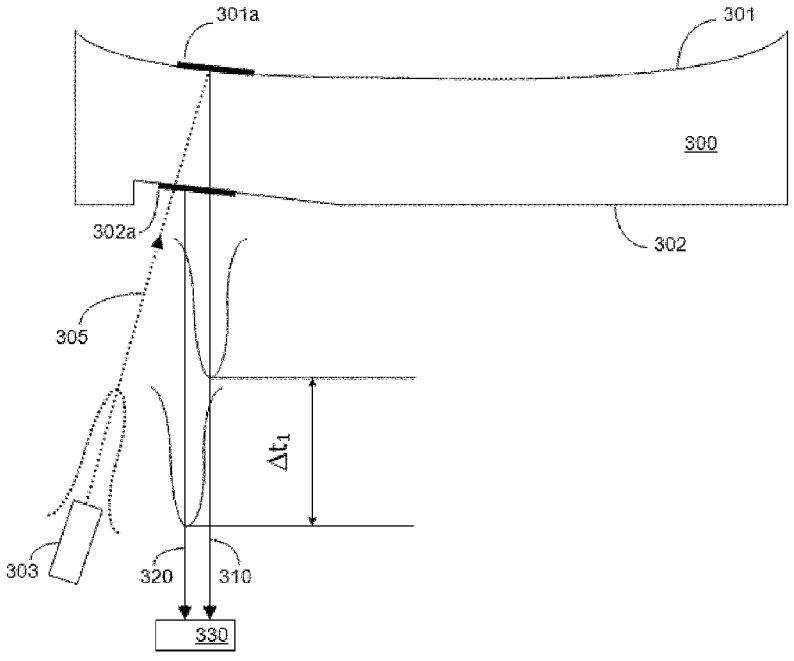
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(54) Title: METHOD AND APPARATUS FOR DETERMINING THE HEATING STATE OF AN OPTICAL ELEMENT IN A MICROLITHOGRAPHIC OPTICAL SYSTEM

Fig. 3a



(57) Abstract: The invention relates to a method and an apparatus for determining the heating state of an optical element in a microlithographic optical system, wherein the method includes the following steps: producing, using a light source (303), a first partial beam (310) that is transmitted through the optical element (200, 300) and a second partial beam (320) that is not transmitted through the optical element, and determining the heating state of the optical element on the basis of a measurement of the time-of-flight difference between the first partial beam and the second partial beam, wherein the first partial beam (310) and the second partial beam (320) are reflected at different faces of the optical element (200, 300).

[Continued on next page]

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Method and apparatus for determining the heating state of an optical element in a microlithographic optical system

This application claims priority of German Patent Application DE 10 2018 216 628.5 filed on September 27, 2018. The content of this application is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the invention

The invention relates to a method and an apparatus for determining the heating state of an optical element in a microlithographic optical system.

Prior art

Microlithography is used for producing microstructured components, such as for example integrated circuits or LCDs. The microlithography process is carried out in what is called a projection exposure apparatus, which comprises an illumination device and a projection lens. The image of a mask (= reticle) illuminated by means of the illumination device is in this case projected by means of the projection lens onto a substrate (for example a silicon wafer) coated with a light-sensitive layer (photoresist) and arranged in the image plane of the projection lens, in order to transfer the mask structure to the light-sensitive coating of the substrate.

In projection lenses designed for the EUV range, i.e. at wavelengths of e.g. approximately 13 nm or approximately 7 nm, owing to the lack of availability of suitable light-transmissive refractive materials, mirrors are used as optical components for the imaging process. One problem which arises in practice is that, among other things as a result of absorption of the radiation emitted by the EUV light source, the EUV mirrors heat up and thus undergo an associated thermal expansion or deformation, which in turn can negatively affect the imaging properties of the optical system.

To take this effect into account, it is known, among other things, to use a material with ultra-low thermal expansion ("Ultra Low Expansion Material"), for example a titanium silicate glass sold by Corning Inc. with the name ULE™ as the mirror substrate material and to set what is known as the zero-crossing temperature in a region near the optical effective face. At this zero-crossing temperature, which lies at around ϑ= 30°C for example for ULE™, the coefficient of thermal expansion has in its temperature dependence a zero crossing in the vicinity of which no thermal expansion or only negligible thermal expansion of the mirror substrate material takes place.

However, in practice the problem arises here that an EUV mirror is exposed during operation of the microlithographic projection exposure apparatus to changing intensities of the incident electromagnetic radiation, specifically both locally, for example due to the use of illumination settings with an intensity that varies over the optical effective face of the respective EUV mirror, and also temporally, wherein the relevant EUV mirror typically heats up in particular at the beginning of the microlithographic exposure process from a comparatively low temperature to its operating temperature reached in the lithography process.

One approach for overcoming the above-described problem and in particular for avoiding surface deformation caused by varying introductions of heat into an EUV mirror and associated optical aberrations includes the use of pre-

heaters for example on the basis of infrared radiation. With such pre-heaters, active mirror heating can take place in phases of comparatively low absorption of EUV useful radiation, wherein said active mirror heating is correspondingly decreased as the absorption of the EUV useful radiation increases.

Closed-loop control of the operation of such pre-heaters that is performed with the goal of maintaining a mirror temperature that is as constant as possible (typically the above-mentioned zero-crossing temperature) requires knowledge of the radiation power that is incident in each case on the relevant mirror so that the preheating power can be adapted accordingly. For this purpose, temperature sensors are used (in addition to infrared cameras which are not always practical due to installation space), for example in the form of thermocouples or (e.g. NTC) temperature sensors based on electrical resistance, which can be mounted typically in a force-fitting or cohesive manner at different positions of the respective mirror.

By mounting such thermocouples, however, it is possible that undesirable mechanical stresses are induced in the mirror substrate, wherein in addition – in particular when a multiplicity of temperature sensors are required for ascertaining a spatially varying temperature distribution within the mirror – the production complexity is significantly increased and possibly the mechanical stability of the mirror is impaired.

With regard to the prior art, reference is made, merely by way of example, to DE 36 05 737 A1, DE 10 2005 004 460 A1 and WO 2012/069351 A1.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and an apparatus for determining the heating state of an optical element in a microlithographic optical system, which make possible knowledge of the heating state that is as accurate as possible while avoiding the above-described problems.

This object is achieved by the method in accordance with the features of independent claim 1 and the apparatus in accordance with the features of coordinate claim 14.

A method according to the invention for determining the heating state of an optical element in a microlithographic optical system includes the following steps:

- producing, using a light source, a first partial beam that is transmitted through the optical element and a second partial beam that is not transmitted through the optical element; and
- determining the heating state of the optical element on the basis of a measurement of the time-of-flight difference between the first partial beam and the second partial beam;

wherein the first partial beam and the second partial beam are reflected at different faces of the optical element.

The invention is in particular based on the concept of performing a time-of-flight comparison between at least two partial beams to determine the heating state of an optical element, with one of the partial beams being transmitted through the optical element and the other not being transmitted through the optical element. The invention here takes advantage of the fact that the refractive index of the material of the optical element that acts on the transmitted partial beam is temperature-dependent, resulting in the fact that there is also a temperature dependence with respect to the time of flight of the partial beam

passing through the optical element that is in turn dependent on the refractive index.

In particular, the present invention includes the concept of performing a time-of-flight comparison between partial beams that have been reflected at different faces of the optical element that is to be characterized in terms of the heating state thereof, wherein said different faces may furthermore in particular be mutually opposite surfaces of the optical element. In an optical element in the form of a mirror, the time-of-flight difference between a partial beam reflected at the optical effective face (that is to say the “front side”) of the mirror (which partial beam is consequently not transmitted through the mirror) and a partial beam that is reflected at the “rear side” of said mirror (and is thus transmitted through the mirror material) can be ascertained, for example when realizing the invention, wherein both partial beams are produced by splitting the same light beam that is incident on the mirror from the light source. Such a configuration has the advantage that, for the two partial beams used with respect to the measurement of the time-of-flight difference, beam paths that substantially coincide outside the optical element are present, with the result that effects occurring along the beam path (for example in the form of “streaks” in the respective atmosphere) likewise coincide and increased measurement accuracy can thus ultimately be attained.

According to one embodiment, a surface treatment for increasing the reflectivity for the first partial beam (that is transmitted through the optical element) and/or the second partial beam (that is not transmitted through the optical element) is performed on the optical element. Said surface treatment can comprise for example the application of a reflective coating and/or the performance of a polishing process and can typically be performed, in the above-described application of a mirror, on the rear side of the mirror (which is typically not yet sufficiently reflective as opposed to the optical effective face, or front side). In other embodiments, it is possible, if necessary, for such surface treatment for increasing the reflectivity also to be performed for the second partial beam (that is not transmitted through the optical element).

According to one embodiment, a frequency-modulated light source is used as the light source. In this configuration, it is possible according to the invention to use what is known as the “LIDAR principle”, in which the beat frequency of a superposition signal, produced by superposing the two partial beams, is determined and used for determining the time-of-flight difference.

However, the invention is not limited to such LIDAR-based time-of-flight determination, but also comprises embodiments in which the time-of-flight determination is performed in any other (for example electronic) way.

The fact that a non-interferometric time-of-flight measurement (in particular in the form of said LIDAR principle) is performed in the method according to the invention here has, among other things, the advantage of a susceptibility to disturbances as concerns vibrations that is comparatively lower – for example in relation to interferometric test methods – such that, overall, a particularly robust method can be realized.

According to one embodiment, the heating state is determined with the additional inclusion of a model describing the thermal behaviour of the optical element. It is hereby possible to take account in particular of the fact that initially only the “integral effect” of the heating state is deduced by way of the determination according to the invention of the time-of-flight difference between the partial beam that is not transmitted through the optical element and the partial beam that is transmitted through the optical element and, in this respect, no spatial resolution within the meaning of a determination of the temperature at different positions within the optical element is achieved yet. With the aforementioned inclusion of a model describing the thermal behaviour of the optical element, it is possible to deduce, from the measurement signals that have been ascertained in accordance with the invention, a temperature distribution within the optical element on the basis of a typical (for example exponential) temperature profile.

According to one embodiment, the optical element has a transmittance for the first partial beam (that has not been transmitted through the optical element) of at least 10%, in particular of at least 20%, especially of at least 50%. The transparency of the optical element that is sufficient in this context can occur either, when a concrete material (for example a typical mirror substrate material such as ULE or Zerodur) is specified, by a corresponding selection of the wavelength of the light source (for example at least 400 nm, especially at least 500 nm, in the case of the materials ULE or Zerodur), or, when the wavelength of the light beam produced by the light source that is used according to the invention is specified, the material of the optical element can be correspondingly selected, for example by the concrete composition or formula for the corresponding optimization of the transmission behaviour being adapted for the above-mentioned mirror substrate materials such as ULE or Zerodur.

In the embodiments of the invention, the method comprises the production of a plurality of partial beams that are transmitted through the optical element along different optical paths, wherein the heating state is then determined on the basis of measurements of the time-of-flight difference between in each case one of said partial beams and a partial beam that is not transmitted through the optical element. In other words, in such embodiments, a plurality of test beam paths are provided for characterizing the heating state using partial beams from different directions (in the sense of tomography) to attain in this respect an improved spatial resolution with respect to the determination of the heating state of the optical element.

According to one embodiment, the optical element is a mirror.

In accordance with one embodiment, the optical element is designed for an operating wavelength of less than 30 nm, in particular less than 15 nm.

Based on the determination of the heating state, pre-heating of the optical element to at least partially compensate temporal changes in the heating state of the optical element occurring during the operation of the optical system is

performed in accordance with one embodiment. In further embodiments, compensation of optical aberrations caused by the heating state in the optical system can also be performed by way of suitable manipulators (for example adaptive mirrors). Alternatively or in addition, correspondingly compensating changes in the gas pressure, the radiation intensity, the radiation wavelength and/or the illumination setting in the respective optical system can also be performed here.

According to one embodiment, the determination of the heating state is performed during the operation of the optical system (for example of a microlithographic projection exposure apparatus).

Further configurations of the invention can be gathered from the description and the dependent claims.

The invention will be explained in greater detail below on the basis of an exemplary embodiment that is illustrated in the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In the figures:

Figure 1 shows a schematic illustration of the possible construction of a microlithographic projection exposure apparatus designed for operation in the EUV range; and

Figures 2-3 show schematic illustrations for explaining possible embodiments of a method according to the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Figure 1 shows a schematic illustration of a projection exposure apparatus 100 which is designed for operation in the EUV range and in which the invention is able to be realized in an exemplary manner.

According to Figure 1, an illumination device of the projection exposure apparatus 100 comprises a field facet mirror 103 and a pupil facet mirror 104. The light from a light source unit comprising in the example an EUV light source (plasma light source) 101 and a collector mirror 102 is directed onto the field facet mirror 103. A first telescope mirror 105 and a second telescope mirror 106 are arranged in the light path downstream of the pupil facet mirror 104. A deflection mirror 107 is arranged downstream in the light path, said deflection mirror directing the radiation that is incident thereon onto an object field in the object plane of a projection lens comprising six mirrors 121-126. At the location of the object field, a reflective structure-bearing mask 131 is arranged on a mask stage 130, said mask being imaged with the aid of the projection lens into an image plane in which a substrate 141 coated with a light-sensitive layer (photoresist) is situated on a wafer stage 140.

During operation of the microlithographic projection exposure apparatus 100, the electromagnetic radiation that is incident on the optical effective face or on the face of incidence of the mirrors that are present is partially absorbed and, as explained in the introductory part, results in the development of heat and an associated thermal expansion or deformation, which in turn can lead to an impairment of the imaging properties.

The method according to the invention, or the apparatus according to the invention, for determining the heating state of an optical element can in particular be used for example on any desired mirror of the microlithographic projection exposure apparatus 100 of Figure 1.

Below, construction and function of a method according to the invention are described in an exemplary embodiment with reference to the schematic illustrations of Figures 2-3.

According to the invention, the heating state of an optical element such as for example a mirror of the microlithographic projection exposure apparatus of Figure 1 is determined based on a measurement of the time-of-flight difference between two partial beams, only one of which is transmitted through the relevant optical element or the mirror. On account of the temperature dependence of the refractive index of the material of the optical element, the given dependence of said time-of-flight difference on said refractive index has the result that the time-of-flight difference that is measured according to the invention can be used as a measure of the temperature in the material of the optical element.

Figure 2 initially shows in a schematic and highly simplified illustration an optical element 200 in the form of a mirror, the optical effective face of which, or front side, is designated “201” and the rear side of which is designated “202”. “201a” and “202a” designate partial regions of the front side 201 and rear side 202 which are to provide the reflective interfaces for the aforementioned partial beams that are used to determine the time-of-flight difference. While the optical effective face is already sufficiently reflective in the case of a mirror, it is also possible for suitable surface processing to be performed on the rear side 202 in the region 202a to provide sufficient reflectivity, such as by applying a coating and/or performing a polishing process, wherein in addition, as indicated in Figure 2a, a corresponding processing of the rear side 202 can furthermore result in the region 202a extending substantially with the same gradient and a parallel offset to the region 201a that is located on the front side 201. With this configuration it is possible to ensure substantially coinciding beam paths for the partial beams reflected at the relevant regions 201a, 202a, with the result that effects occurring along the respective beam path cancel each other out in the determination of the time-of-flight difference.

The schematic illustrations of Figure 3a and Figure 3b serve for illustrating the functional principle of the method according to the invention, wherein components of substantially identical function as or components that are analogous to Figure 2 are designated with reference signs that are increased by "100".

According to Figures 3a-3b, of a light beam 305 that is radiated in by a light source 303, a first partial beam 310 is transmitted through the optical element 300 or the mirror and reflected at the region 301a of the front side of the optical element 300, whereas a second partial beam 320, likewise produced from the light beam 305, is already reflected at the region 302a of the rear side 302 and is thus not transmitted through the optical element 300 or the mirror.

"340" in Figure 3b schematically illustrates a region of the optical element 300, through which the first partial beam 310 passes, with a temperature that deviates compared to Figure 3a. Passing through said region 340 results for the first partial beam 310 in a change in the optical path length and consequently also a change in the time-of-flight difference between the partial beams 310, 320 in the transition from the scenario pursuant to Figure 3a to the scenario pursuant to Figure 3b as a result of the temperature dependence of the refractive index. The measurement of said time-of-flight difference can thus be used according to the invention for characterizing the heating state of the optical element 300 or the mirror. The time difference Δt between the two partial beams 310, 320 is calculated by

$$\Delta t = 2 \int_{Lower\ side}^{Upper\ side} n(x)dx \frac{1}{c*\cos\alpha} = 2\,\bar{n}D\frac{1}{c*\cos\alpha} \qquad (1)$$

wherein c is the speed of light, n(x) is the location-dependent refractive index, $\bar{n}$ is the average refractive index, D is the geometric thickness of the optical element 300 at the relevant location and α is the angle of incidence on the interfaces 301a, 302a. In a good approximation, locally the refractive index n, pursuant to

$$n(T + \Delta T) = n(T) + \frac{\partial n}{\partial T}\Delta T \qquad (2),$$

is dependent on a temperature that deviates as compared to a reference temperature. The change in refractive index that is thus associated with a change in the temperature along the respectively traversed region in the optical element 300 upon transition from Figure 3a to Figure 3b in turn results in a time-of-flight difference between the two partial beams 310, 320, which is calculated by

$$\Delta t_2 - \Delta t_1 = 2 * (n' - n) * D/(c * cos\alpha) \qquad (3).$$

In further embodiments, the beam path of the partial beam that is transmitted through the optical element 300 or the mirror can also be selected in another suitable manner, in particular also parallel to the optical effective face or at an angle through the optical element, depending on the concrete application situation (in particular on the concrete geometry of the optical element and installation space situation), or a plurality of partial beams can pass through the optical element from different directions to achieve a greater spatial resolution.

Without the invention being limited hereto, the aforementioned determination of the time-of-flight difference can be effected in particular using the “LIDAR principle” that is known per se. In this case, a frequency-modulated light source is used as the light source 303 for producing the light beam 305. The measurement signals corresponding to the first partial beam 310 and the second partial beam 320 are supplied (possibly via a signal coupler) to a detector 330, wherein the beat frequency, captured on the detector side, of the superposition of said signals is characteristic of the time-of-flight difference between the partial beams 310, 320: In the case of a superposition of signals with the time delay Δt, the following relationship exists between the beat frequency Ω and the chirp rate ξ :

$$\Omega := \xi \cdot \Delta t \qquad (4)$$

A quantitative consideration produces, starting from a typical order of magnitude of the coefficient $\frac{\partial n}{\partial T}$ of $10^{-5}K^{-1}$ for a change in the average temperature by 5K with an exemplary thickness of the optical element of 200 mm, a change in the optical path length by 20 µm according to a time-of-flight difference of $7*10^{-14}$ seconds.

Pre-heating of the optical element 300 or mirror for at least partially compensating the temporal changes of the heating state can be effected based on the determination of the heating state according to the invention. Furthermore, compensation of optical aberrations caused by said heating state in the optical system can also be performed by way of suitable manipulators (for example adaptive mirrors). As a result, it is thus possible to obtain a design of the optical system that is robust with respect to thermal influences and to ensure a consistently high imaging quality.

Even though the invention has been described on the basis of specific embodiments, numerous variations and alternative embodiments are apparent to a person skilled in the art, for example by combination and/or exchange of features of individual embodiments. Accordingly, it goes without saying for a person skilled in the art that such variations and alternative embodiments are concomitantly encompassed by the present invention, and the scope of the invention is restricted only within the meaning of the accompanying claims and the equivalents thereof.

Claims

1. Method for determining the heating state of an optical element in a microlithographic optical system, wherein the method includes the following steps:

   a) producing, using a light source (303), a first partial beam (310) that is transmitted through the optical element (200, 300) and a second partial beam (320) that is not transmitted through the optical element (200, 300); and

   b) determining the heating state of the optical element (200, 300) on the basis of a measurement of the time-of-flight difference between the first partial beam (310) and the second partial beam (320);

   wherein the first partial beam (310) and the second partial beam (320) are reflected at different faces of the optical element (200, 300).

2. Method according to Claim 1, characterized in that a frequency-modulated light source is used as a light source (303).

3. Method according to Claim 1 or 2, characterized in that step b) comprises a superposition of the first partial beam (310) and of the second partial beam (320), wherein the heating state of the optical element (200, 300) is determined on the basis of the beat frequency of said superposition.

4. Method according to one of the preceding claims, characterized in that the optical element (200, 300) has a transmittance for the first partial beam (310) of at least 10%, in particular of at least 20%, especially of at least 50%.

5. Method according to one of the preceding claims, characterized in that the light source (303) is designed for producing light having a wavelength of at least 400 nm, in particular of at least 500 nm.

6. Method according to one of the preceding claims, characterized in that a surface treatment is performed on the optical element (200, 300) for increasing the reflectivity for the first partial beam (310) and/or for the second partial beam (320).

7. Method according to one of the preceding claims, characterized in that the heating state is determined with additional inclusion of a model describing the thermal behaviour of the optical element (200, 320).

8. Method according to one of the preceding claims, characterized in that step a) comprises the production of a plurality of partial beams that are transmitted through the optical element along different optical paths, wherein the heating state is determined in step b) furthermore on the basis of measurements of the time-of-flight difference between in each case one of said partial beams and a partial beam that is not transmitted through the optical element (200, 300).

9. Method according to one of the preceding claims, characterized in that the optical element (200, 300) is a mirror.

10. Method according to one of the preceding claims, characterized in that the optical element (200, 300) is designed for an operating wavelength of less than 30 nm, in particular less than 15 nm.

11. Method according to one of the preceding claims, characterized in that, based on the determination of the heating state, pre-heating of the optical element (200, 300) for at least partially compensating temporal changes of the heating state of the optical element (200, 300) occurring during the operation of the optical system and/or compensation of optical aberrations caused by the heating state in the optical system is effected.

12. Method according to one of the preceding claims, characterized in that the heating state is determined during the operation of the optical system.

13. Method according to one of the preceding claims, characterized in that the optical system is a microlithographic projection exposure apparatus.

14. Apparatus for determining the heating state of an optical element in a microlithographic optical system, characterized in that the apparatus is configured to carry out a method according to one of the preceding claims.

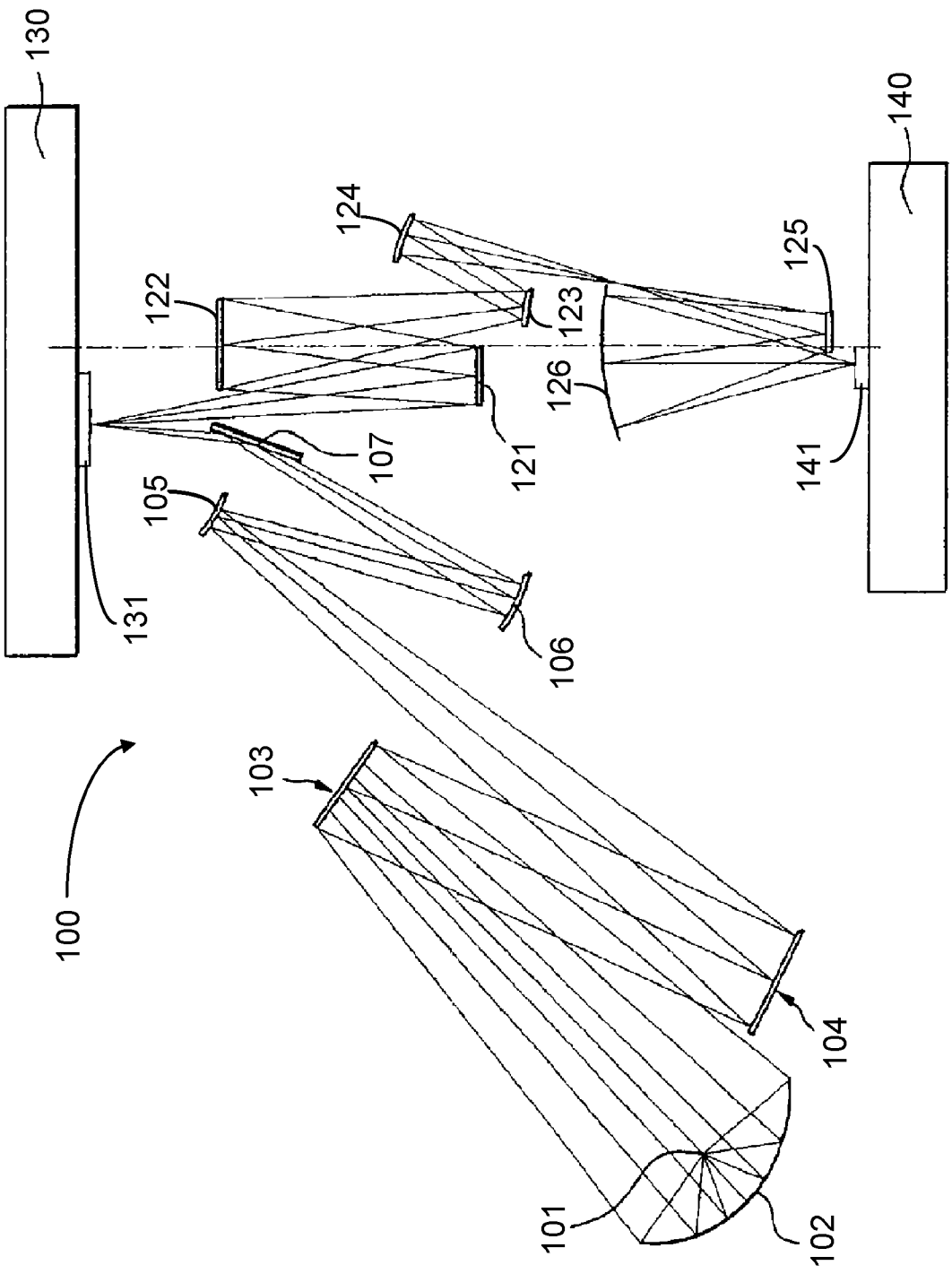

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Fig. 1

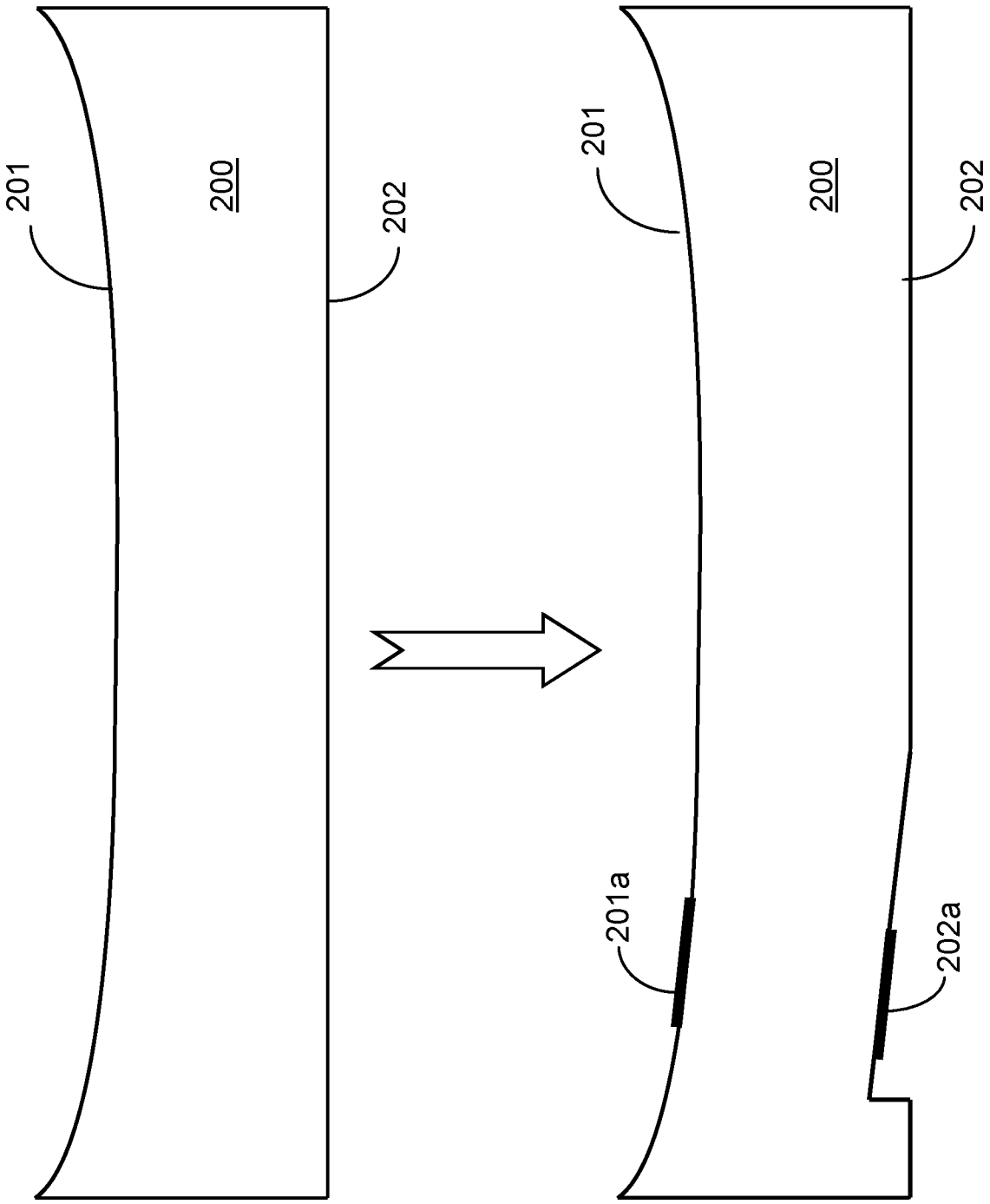


Fig. 2

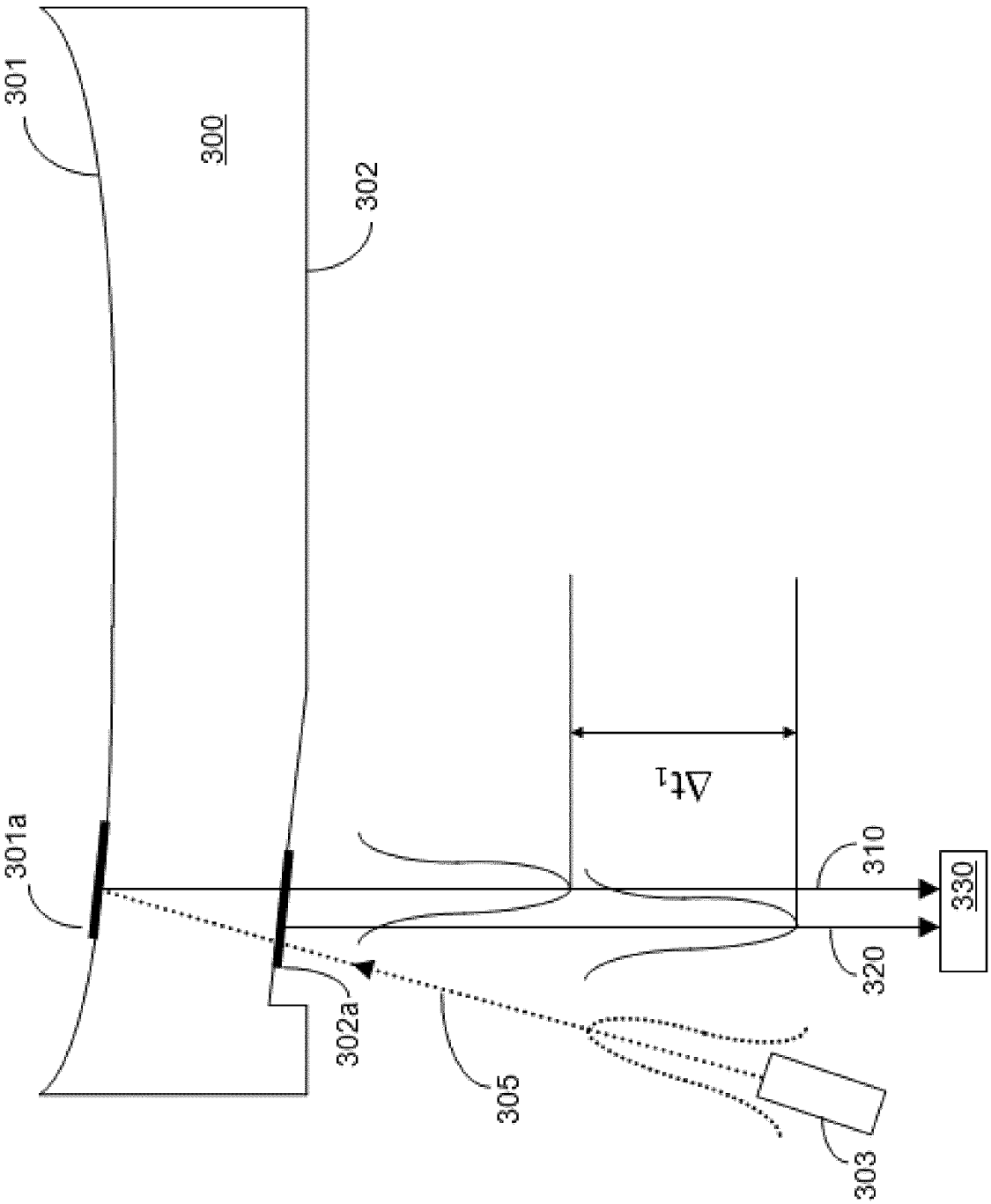


Fig. 3a

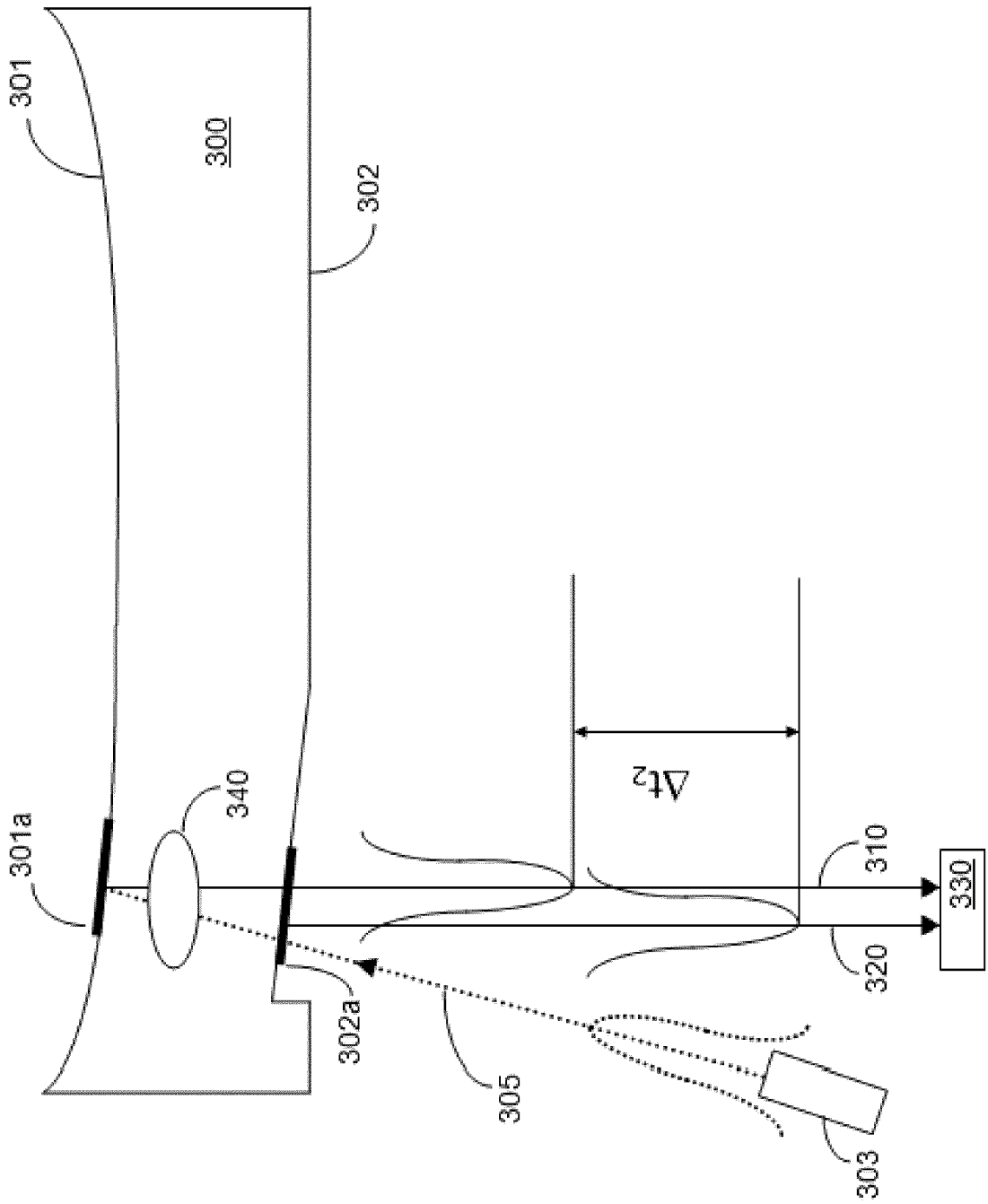


Fig. 3b

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/072210

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 G01K11/00 G02B7/18
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 G01W G01K G02B

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, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013/230073 A1 (VOGT PETER [DE] ET AL) 5 September 2013 (2013-09-05) cited in the application paragraphs [0071] - [0079]; figure 1	1-14
A	US 2010/135356 A1 (SCHULZ JOACHIM [DE]) 3 June 2010 (2010-06-03) paragraphs [0002], [0042]; figure 3a	1-14
A	US 2016/091798 A1 (PAULS WALTER [DE] ET AL) 31 March 2016 (2016-03-31) paragraphs [0069], [0070], [0155]	1-14

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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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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Information on patent family members

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