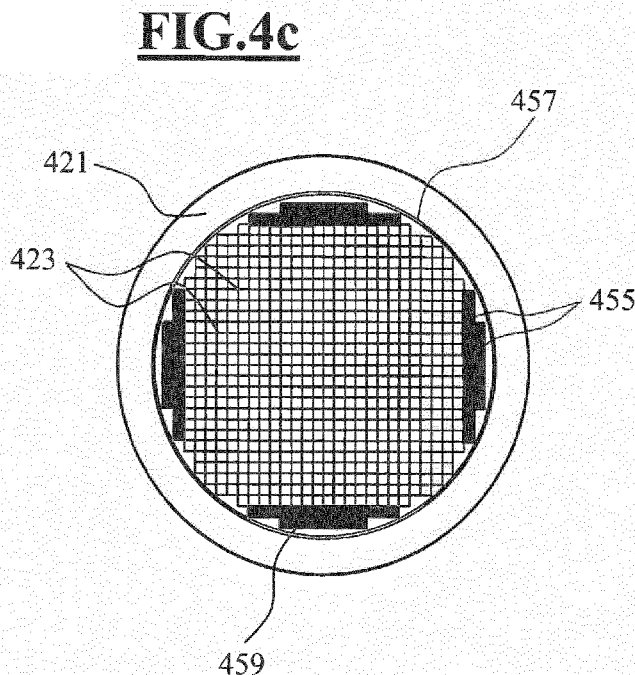




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(54) Title: ILLUMINATION OPTICAL UNIT



(57) Abstract: The invention relates to an illumination optical unit for EUV microlithography comprising a first optical element having a plurality of first reflective facet elements. Furthermore, the illumination optical unit comprises a second optical element (421) having a plurality of second reflective facet elements (423), wherein the plurality of first reflective facet elements comprises at least 75% of all the reflective facet elements of the first optical element. In this case, each first reflective facet element of the plurality of first reflective facet elements is embodied in such a way that, during the operation of the illumination optical unit, it generates an illuminated region at the location of an assigned second facet element of the plurality of second reflective facet elements. The second reflective facet elements (423) each have a reflective surface and the illuminated regions are in each case smaller than the reflective surface of the assigned second reflective facet element (423). In addition, all of said illuminated regions lie within a maximum of six continuous pairwise disjoint zones (459). Furthermore, there is a circle (457) having a minimum diameter which encloses all of said zones (459), wherein the first and/or second reflective facet elements are embodied in such a way that the ratio of the area content of the circle (457) to the sum of the area contents of the zones (459) is greater than 2.5, in particular greater than 4.



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5 Illumination optical unit

Description

10 The present invention relates to an illumination optical unit for EUV microlithography comprising a first optical element having a plurality of first reflective facet elements and a second optical element having a plurality of second reflective facet elements. Furthermore, the invention relates to a microlithography projection exposure apparatus comprising an illumination optical unit of this type.

15 Microlithography projection exposure apparatuses serve for producing microstructured components by means of a photolithographic method. In this case, a structure-bearing mask, the so-called reticle, is illuminated with the aid of a light source unit and an illumination optical unit and is imaged onto a photosensitive layer with the aid of a projection optical unit. For this purpose, the structure-bearing mask is arranged in an object plane of the projection optical unit
20 and the photosensitive layer is arranged at the location of an image plane of the projection optical unit. In this case, the light source unit makes available a radiation which is directed into the illumination optical unit. The illumination optical unit serves for making available at the location of the structure-bearing mask a uniform illumination with a predetermined angle-dependent intensity distribution. For this purpose, various suitable optical elements are provided
25 within the illumination optical unit. The structure-bearing mask illuminated in this way is imaged onto a photosensitive layer with the aid of the projection optical unit. In this case, the resolution capability of such a projection optical unit is influenced by various factors.

30 Firstly, the smaller the wavelength λ of the radiation used, the smaller the structures which can be imaged. For this reason, it is advantageous to use radiation in the range of extreme ultraviolet (EUV), that is to say having the wavelength $\lambda = 5 \text{ nm} - 15 \text{ nm}$.

Secondly, the maximum achievable resolution is determined by the numerical aperture (NA) of the projection optical unit. The larger the numerical aperture of the projection optical unit, the
35 smaller the structures which can be imaged.

A further variable that determines the resolution of the imaging is the angular distribution of the illumination radiation at the location of the structure-bearing mask. In accordance with the Abbe theory of imaging, not every radiation illuminating the structure-bearing mask contributes

5 equally well to the image of the mask. In this case, the illumination radiation is characterized according to its illumination angle, i.e. the angle between the illumination radiation and the chief ray at the location of the structure-bearing mask. The illumination radiation which contributes best to image formation is also dependent on the exact structure of the structure-bearing mask. In the case of a structure-bearing mask having parallel dense lines whose spacings are near the
10 resolution limit, the mask should ideally be illuminated with illumination radiation which, firstly, is at as large an angle as possible with respect to the chief ray and, secondly, runs perpendicularly to the direction of the parallel lines. A so-called dipole illumination necessarily results from these two properties. At the resolution limit, this is the sole illumination radiation which contributes to image formation. If the structure-bearing mask were additionally
15 illuminated e.g. along the chief ray, then this additional radiation would lead only to a diffuse background brightness in the image plane. A high-contrast image can only be achieved by means of the radiation with large illumination angles. For further details with regard to the Abbe theory of imaging, reference is made to "Handbook of optical systems: Vol. 2 Physical image formation, chapter 21, The Abbe theory of imaging", Wiley VCH 2005.

20 These three influencing variables on the smallest feature size that can be imaged (critical dimension, CD) are often combined in the formula

$$CD = k \frac{\lambda}{NA}$$

25 In this case, the influence of the angular distribution on the feature size is parameterized in the so-called k factor.

Against the background of these theoretical insights, the object of the present invention is to
30 develop the known illumination optical units for EUV microlithography to the effect that as high a proportion as possible of the illumination radiation at the mask is made available at angles which contribute particularly well to the imaging.

This object is achieved by means of an illumination optical unit for EUV microlithography
35 comprising a first optical element having a plurality of first reflective facet elements and a second optical element having a plurality of second reflective facet elements. In this case, the plurality of first reflective facet elements comprises at least 75%, in particular at least 90%, of all the reflective facet elements of the first optical element. Furthermore, each first

5 reflective facet element of the plurality of first reflective facet elements is embodied in such a way that, during the operation of the illumination optical unit, it generates an illuminated region at the location of an assigned second facet element of the plurality of second reflective facet elements. In this case, the second reflective facet elements each have a reflective surface and the illuminated regions are in each case smaller than the reflective surface of the
10 assigned second reflective facet element. In this case, all these illuminated regions lie within a maximum of six, in particular a maximum of four, continuous pairwise disjoint zones. This explicitly also includes the case where there is one continuous zone in which all the regions lie. Furthermore, there is a circle having a minimum diameter which encloses all of said zones, wherein the first and/or second reflective facet elements are embodied in such a way
15 that the ratio of the area content of the circle to the sum of the area contents of the zones is greater than 2.5, in particular greater than 4.

What is thereby achieved is that the illumination radiation is configured with the aid of the illumination optical unit such that the illumination radiation reaches the structure-bearing
20 mask at large illumination angles. This has the effect that the radiation contributes to a high-contrast image even in the case of structures near the resolution limit.

In one embodiment of the invention, the second optical element is arranged in an exit pupil plane of the illumination optical unit or is imaged into an exit pupil plane of the illumination
25 optical unit. This has the advantage that the intensity distribution on the second optical element directly correlates with the angular distribution of the radiation at the location of the structure-bearing mask.

In a further configuration of the illumination optical unit according to the invention, at least
30 one first reflective facet element of the plurality of first reflective facet elements comprises an aspherical reflective surface, the form of which is chosen in such a way that the illuminated region produced by said facet element during the operation of the illumination optical unit is reduced relative to the use of a spherical reflective surface. What is thereby achieved is that particularly small illuminated regions arise at the location of the assigned
35 second reflective facet elements. This in turn makes it possible that the second reflective facet elements can be made smaller and can therefore be packed more densely, without radiation being lost. If the illuminated regions are larger than the reflective surfaces of the associated second reflective facet elements, then radiation losses inevitably occur, since radiation is incident alongside the corresponding second reflective facet elements. By virtue

5 of the fact that particularly small illuminated regions are realized, it is thus possible to arrange a larger number of second reflective facet elements in the zones of the second optical element which correspond to illumination angles which contribute particularly well to imaging, and this is possible without having to accept higher radiation losses. This makes it possible overall to preconfigure a larger proportion of the illumination radiation such that it
10 impinges on the structure-bearing mask at illumination angles which contribute particularly well to the imaging.

Within the meaning of this application, an illuminated region is reduced relative to the use of a spherical reflective surface for a first reflective facet element having only one position if
15 the following calculation specification is fulfilled: proceeding from a punctiform source plasma, the illuminated region on the assigned second reflective facet element is calculated if an assigned first reflective facet element having a spherical reflective surface is used. The radius of curvature of the spherical reflective surface is then varied until the minimum illuminated region is obtained. An illuminated region is at a minimum when it lies within a
20 circle having a minimum radius R_1 . Next, instead of the spherical reflective surface, the aspherical reflective surface is inserted into the calculation and the illumination region is determined. If this illumination region lies within a circle having the radius R_2 and R_2 is less than R_1 , then the illuminated region is reduced relative to the use of a spherical reflective surface within the meaning of this application.

25 In one configuration of the invention the illumination optical unit has at least one first reflective facet element of the plurality of first reflective facet elements that comprises a spherical reflective surface. Spherical surfaces have the advantage that they are much easier and cheaper to produce than aspherical surfaces. Surprisingly the inventors found out that not
30 all first facet elements have to be equipped with aspherical surfaces. The advantageous effects of the invention can be realized also if there are still some first facet elements with a spherical surface. Especially it is satisfactory if all first reflective facet elements of the plurality of first reflective facet elements that have a maximal angle of incidence that is smaller than a predetermined value comprise a spherical reflective surface. These first facet
35 elements show only a small amount of astigmatism so that aspherical surfaces are not needed to reduce the size of the corresponding illuminated regions. The predetermined value is 10° , preferred 7.5° , more preferred 5° . The smaller the maximal angle of incidence is the smaller is the amount of astigmatism.

5 In one development of the illumination optical unit, each first reflective facet element of the plurality of first reflective facet elements has at least two positions, such that, in the first position during the operation of the illumination optical unit, it generates a first illuminated region at the location of an assigned second facet element of the plurality of second reflective facet elements and, in the second position during the operation of the illumination optical unit, it generates a second illuminated region at the location of a further assigned second facet element of the plurality of second reflective facet elements. This allows the variable setting of intensity distributions over the second optical element and thus a variable setting of the angular distribution at the location of the structure-bearing mask. The angular distribution can thereby be adapted to the exact structure of the mask to be imaged. In this configuration the maximal angle of incidence on a first facet element has to be understood as the maximal value of the angle incidence over all different positions.

Such positions can be realized particularly easily by virtue of each first reflective facet element of the plurality of first reflective facet elements having a reflective optical surface having a normal vector, and the positions of the first reflective facet elements differing in the orientation of the normal vector.

In one specific development, at least one reflective facet element of the plurality of reflective first facet elements has at least two positions chosen in such a way that the distance between the at least one reflective facet element and the first illuminated region differs from the distance between the at least one reflective facet element and the second illuminated region by not more than 5%, in particular by not more than 3%. This has the advantage that even when a first reflective facet element having a spherical reflective surface is used, both the first and the second illuminated region are relatively small. As is explained with reference to Figure 7, there is exactly one radius of curvature of a spherical surface with which a minimum first illuminated region is generated. In this case, an illuminated region is at a minimum where it lies within a circle having a minimum radius R_1 . If the same spherical surface is then used for generating a second illuminated region, the second illuminated region is typically not at a minimum. However, if the distances do not deviate from one another very much according to the invention, then the size of the second illuminated region is in the vicinity of the minimum radius and both the first illuminated region and the second illuminated region are relatively small. The radius of curvature of the spherical reflective surface is ideally chosen such that during the imaging of a punctiform source plasma, a first illuminated region lying within a circle having the radius R_1 arises in the first position, and

5 an illuminated region lying within a circle having the radius R_2 arises in the second position. In this case, the radius of curvature is not chosen such that R_1 or R_2 is at a minimum, but rather so as to result in an optimum compromise. This means that the maximum of R_1 and R_2 is at a minimum.

10 One option to realize that the distance between the at least one reflective facet element and the first illuminated region differs from the distance between the at least one reflective facet element and the second illuminated region is not more than 5%, is the arrangement of first facet elements on reference bodies that are tilted with respect to each other. Instead of
15 arranging all first facet elements on a reference plane they are mounted in groups. Each group of first facet elements belongs to a reference body wherein all reference bodies are tilted with respect to each other. Details on this configuration are found in the German patent application DE102010003169A1 that is incorporated by reference.

20 A further option to realize that the distance between the at least one reflective facet element and the first illuminated region differs from the distance between the at least one reflective facet element and the second illuminated region is not more than 5% is the appropriate assignment of second facet elements to each of the first facet elements.

25 In one development of the invention, at least one first reflective facet element of the plurality of first reflective facet elements comprises an aspherical reflective surface, the form of which is chosen in such a way that the first and the second illuminated region produced by said facet element during the operation of the illumination optical unit is reduced relative to the use of a spherical reflective surface. What is thereby achieved is that particularly small illuminated regions arise at the location of the assigned second reflective facet elements. This
30 in turn makes it possible that the second reflective facet elements can be made smaller and can thus be packed more densely, without radiation being lost, because the illuminated regions are larger than the reflective surfaces of the associated second reflective facet elements. In this way, it is possible to arrange a larger number of second reflective facet elements in the zones of the second optical element which correspond to illumination angles which contribute particularly well to imaging. This makes it possible overall to preconfigure
35 a larger proportion of the illumination radiation such that it impinges on the structure-bearing mask at illumination angles which contribute particularly well to the imaging.

5 Within the meaning of this application, an illuminated region is reduced relative to the use of a spherical reflective surface for a first reflective facet element having a plurality of positions if the following calculation specification is fulfilled: proceeding from a punctiform source plasma, the illuminated regions are calculated for all positions if an assigned first reflective facet element having a spherical reflective surface is used. The radius of curvature of the
10 spherical reflective surface is then varied until the minimum illuminated regions are obtained. In this case, a plurality of illuminated regions is at a minimum when each region lies within a circle having an assigned radius and the maximum over all radii is at a minimum. Next, instead of the spherical reflective surface, the aspherical reflective surface is inserted into the calculation and the illumination regions are determined. If these illumination
15 regions in each case lie within a circle having an assigned radius and the maximum over these radii is less than the maximum over the radii in the case of the spherical surface, then the illuminated regions are reduced relative to the use of a spherical reflective surface within the meaning of this application.

20 In one specific configuration of the illumination optical unit, the aspherical surface is a segment from an ellipsoid. An ellipsoid has the advantage that it generates an optimum point imaging. In a further configuration the aspherical surface has a toroidal shape. A toroidal shape is a very good approximation to a segment of an ellipsoid. In addition it is easier to manufacture a reflective surface with a toroidal shape than with an ellipsoidal shape.

25 One configuration of the illumination optical unit according to the invention is distinguished by the fact that each first reflective facet element of the plurality of first reflective facet elements comprises an associated actuator for altering the orientation of the normal vector. This allows a simple realization of first reflective facet elements which have at least two
30 positions.

In one development, the illumination optical unit comprises a measuring system for determining the position of the illuminated regions generated by each first reflective facet element of the plurality of first reflective facet elements during the operation of the
35 illumination optical unit. Operation of the illumination optical unit during which possible deviations from the desired state are registered is thereby made possible. In particular, on the basis of the signals of the measuring system, the operation of the illumination optical unit can be stopped if the deviations from the desired state exceed a critical amount.

5 In one specific configuration, for at least one reflective first facet element of the plurality of first reflective facet elements, the actuator contained is connected to the measuring system via a control unit, thus resulting in a control loop in order to control the position of the corresponding illuminated region in such a way that more than 90% of the illuminated region lies on the reflective surface of the assigned second facet element. Stable operation of the illumination optical unit is thereby made possible since possible deviations from the desired state are registered and corrected.

10 In one configuration, the measuring system comprises at least one radiation detector arranged on the periphery of the reflective surface of the assigned second facet element. As a result, incorrect positioning of the illuminated regions can readily be detected since, in the desired state of the illumination optical unit, only a minimum proportion of the radiation reaches the radiation detectors. As soon as a misalignment occurs, however, a signal arises at the corresponding radiation detector.

15 Alternatively, the measuring system comprises at least one temperature sensor which detects the heating of the assigned second facet element during the operation of the illumination optical unit. Since the second facet elements heat up on account of partial absorption of the impinging radiation, the intensity of the impinging radiation can be deduced from a temperature change. Therefore, temperature sensors make possible a measuring system that is easy to produce.

20 In a further configuration, the measuring system comprises at least one radiation detector arranged below a reflective coating of the assigned second reflective facet element. In this case, either an opening can be provided in the reflective coating in order to allow radiation to pass to the radiation detector or, in the case of a continuous reflective coating, the residual proportion of the impinging radiation can be detected. Both embodiments allow a highly precise measurement of the impinging radiation. In this case, it is possible to determine not only the exact position of the illuminated regions, but additionally also the intensity of the impinging radiation. More precise monitoring of the illumination optical unit during operation is thereby achieved.

30 A microlithography projection exposure apparatus comprising an above-described illumination optical unit has the advantages that have been described with regard to the illumination optical unit.

5

The invention is explained in greater detail with reference to the drawings.

Figure 1 shows a schematic illustration of a projection exposure apparatus comprising an illumination optical unit and a projection optical unit.

10

Figure 2a shows an illustration of a projection exposure apparatus comprising an illumination optical unit and a projection optical unit for use with EUV radiation.

Figure 2b shows a plan view of the first optical element of the illumination optical unit according to Figure 2a.

15

Figure 2c shows a plan view of the second optical element of the illumination optical unit according to Figure 2a.

20

Figure 3 shows a projection exposure apparatus comprising an alternative illumination optical unit and an alternative projection optical unit for use with EUV radiation.

Figure 4a shows a plan view of the second optical element according to Figure 2c during the operation of the illumination optical unit in a first state.

25

Figure 4b shows a plan view of the second optical element according to Figure 2c during the operation of the illumination optical unit in a second state.

Figure 4c shows a plan view of the second optical element according to Figure 2c during the operation of the illumination optical unit in a third state.

30

Figures 5a, 5b and 5c show the construction and the functioning of a first reflective facet element having at least two positions.

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Figure 6 shows an excerpt from an illumination optical unit in which a reflective facet element of the first optical element comprises an aspherical reflective surface.

Figure 7 shows in detail the disadvantages that were overcome by a reflective facet element of the first optical element having an aspherical reflective surface.

5

Figures 8a and 8b show, with the aid of an excerpt from the illumination optical unit, the effect of a first reflective facet element having at least two positions which differ in terms of the orientation of the normal vector.

10 Figure 8c, 8d, 8e, 8f show the results of the optimization with spherical and ellipsoidal first facet elements.

Figures 9a and 9b show, with the aid of excerpts from the second optical element, what advantages are achieved by a measuring system according to the invention.

15

Figure 10 shows, in a schematic illustration, the manner of action of the control loop according to the invention.

20

Figures 11a, 11b, 11c, 11d show the problems that arise if the sizes of the illuminated regions are too large to fit onto the second facet elements using a schematic drawing.

25

The reference signs have been chosen such that objects illustrated in figure 1 have been provided with one-digit or two-digit numbers. The objects illustrated in the further figures have reference signs having three or more digits, wherein the last two digits indicate the object and the preceding digit indicates the number of the figure in which the object is illustrated. Therefore, the reference numerals of identical objects which are illustrated in a plurality of figures correspond in terms of the last two digits. If appropriate, the description of these objects can be found in the text concerning a previous figure.

30

Figure 1 shows a schematic illustration of a microlithography projection exposure apparatus 1. The microlithography projection exposure apparatus 1 comprises, inter alia, the light source unit 3 and the illumination optical unit 5 for illuminating an object field in the object plane 9, in which a structure-bearing mask 13 is arranged. A further part of the microlithography projection exposure apparatus 1 is a projection lens 7 for imaging the structure-bearing mask 13 onto a substrate 15, the so-called wafer. This substrate 15 contains a photosensitive layer, which is chemically altered during exposure. This is then referred to as a lithographic step. In this case, the structure-bearing mask 13 is arranged in the object plane 9 and the substrate 15 is arranged in the image plane 11 of the projection lens 7. In this case, the illumination optical unit 5 and the projection lens 7 comprise a multiplicity of optical elements. These optical elements can in this

35

case be embodied either in refractive fashion or in reflective fashion. Combinations of refractive and reflective optical elements within the illumination optical unit 5 or the projection lens 7 are also possible. Likewise, the structure-bearing mask 13 can be embodied either in reflective fashion or in transmissive fashion. Such microlithography projection exposure apparatuses consist completely of reflective components particularly when they are operated with radiation having a wavelength of < 193 nm, in particular having a wavelength in the extreme ultraviolet range (EUV) of 5 to 15 nm.

Microlithography projection exposure apparatuses 1 are often operated as so-called scanners. That means that the structure-bearing mask 13 is moved through a slot-shaped illumination field along a scanning direction, while the substrate 15 is correspondingly moved in the image plane 11 of the projection lens 7. In this case, the ratio of the speeds of structure-bearing mask 13 and substrate 15 corresponds to the magnification of the projection lens 7, which is usually less than 1, in particular equal to $\frac{1}{4}$.

Figure 2a shows one configuration of a microlithography projection exposure apparatus 201 comprising an illumination optical unit 205 and a projection lens 207. The illumination optical unit 205 in this case comprises a first optical element 217 having a plurality of reflective first facet elements 219 and a second optical element 221 having a plurality of second reflective facet elements 223. A first telescope mirror 225 and a second telescope mirror 227 are arranged in the light path downstream of the second optical element 221, said telescope mirrors both being operated with normal incidence, that is to say that the radiation impinges on both mirrors at an angle of incidence of between 0° and 45° . In this case, the angle of incidence is understood to be the angle between incident radiation and the normal to the reflective optical surface. A deflection mirror 229 is arranged downstream in the beam path and directs the radiation impinging on it onto the object field 231 in the object plane 209. The deflection mirror 229 is operated with grazing incidence, that is to say the radiation impinges on the mirror at an angle of incidence of between 45° and 90° . A reflective structure-bearing mask is arranged at the location of the object field 231, and is imaged into the image plane 211 with the aid of the projection lens 207. The projection lens 207 comprises six mirrors 233, 235, 237, 239, 241 and 243. All six mirrors of the projection lens 207 each have a reflective optical surface extending along a surface that is rotationally symmetrical about the optical axis 245.

Figure 2b shows a plan view of the first optical element 217, which comprises a plurality of first reflective facet elements 219. In the embodiment illustrated, the first optical element 217 has a

5 total of 108 first reflective facet elements 219. Each of the first reflective facet elements 219 has a reflective surface for reflecting the impinging radiation.

Figure 2c shows a corresponding plan view of the second optical element 221 having a plurality of second reflective facet elements 223. In the embodiment illustrated, the second optical
10 element 221 has a total of 716 second reflective facet elements 223.

The microlithography projection exposure apparatus according to figure 2a furthermore comprises a light source unit 203, which directs radiation onto the first optical element 217. In this case, the light source unit 203 comprises a source plasma 247, which emits radiation in the
15 wavelength range of 5-15 nm. A collector mirror 248 is used to collect the radiation of the source plasma. The light source unit 203 can be designed in various embodiments. A laser plasma source (LPP) is illustrated. With this type of source, a narrowly delimited source plasma 247 is generated by a small material droplet being produced by means of a droplet generator 249 and being brought to a predetermined location, where the material droplet is irradiated with a high-
20 energy laser 250, such that the material undergoes transition to a plasma state and emits radiation in the wavelength range of 5 to 15 nm. In this case, the laser 250 can be arranged in such a way that the laser radiation falls through an opening 251 in the collector mirror 248 before it impinges on the material droplet. By way of example, an infrared laser having a wavelength of 10 μm is used as the laser 250. Alternatively, the light source unit 203 can also be embodied as a
25 discharge source in which the source plasma 247 is generated with the aid of a discharge.

The radiation generated by means of the light source unit 203 then illuminates the first reflective optical element 217. The collector mirror 248 and the first reflective facet elements 219 have an optical effect such that images of the source plasma 247 arise at the locations of the second
30 reflective facet elements 223 of the second optical element 221. For this purpose, firstly the focal length of the collector mirror 248 and that of the first facet elements 219 are chosen in accordance with the spatial distances. This is done, for example, by providing the reflective optical surfaces of the first reflective facet elements 219 with suitable curvatures. Secondly, the first reflective facet elements 219 have a reflective optical surface with a normal vector whose
35 direction defines the orientation of the reflective optical surface in space, wherein the normal vectors of the reflective surfaces of the first facet elements 219 are oriented in such a way that the radiation reflected by a first facet element 219 impinges on an assigned second reflective facet element 223. The optical element 221 is arranged in a pupil plane of the illumination optical unit 205, which is imaged onto the exit pupil plane with the aid of the mirrors 225, 227

5 and 229. In this case, the exit pupil plane of the illumination optical unit 205 corresponds exactly to the entrance pupil plane 253 of the projection lens 207. Consequently, the second optical element 221 lies in a plane that is optically conjugate with respect to the entrance pupil plane 253 of the projection lens. For this reason, the intensity distribution of the radiation on the second optical element 221 is in a simple relationship with the angle-dependent intensity distribution of the radiation in the region of the object field 231. In this case, the entrance pupil plane 253 of the projection lens 207 is defined as the plane perpendicular to the optical axis 245 in which the chief ray 254 intersects the optical axis 245 at the midpoint of the object field 231.

The task of the second facet elements 223 and of the downstream optics comprising the mirrors 225, 227 and 229 is to image the first facet elements 219 in a superimposing fashion onto the object field 231. In this case, superimposing imaging is understood to mean that the images of the first reflective facet elements 219 lie in the object plane and at least partly overlap there. For this purpose, the second reflective facet elements 223 have a reflective optical surface with a normal vector whose direction defines the orientation of the reflective optical surfaces in space. For each second facet element 223, the direction of the normal vector is chosen such that the facet element 219 assigned to it is imaged onto the object field 231 in the object plane 209. Since the first facet elements 219 are imaged onto the object field 231, the form of the illuminated object field 231 corresponds to the outer form of the first facet elements 219. The outer form of the first facet elements 219 is therefore usually chosen to be arcuate such that the long boundary lines of the illuminated object field 231 run substantially arcuately about the optical axis 245 of the projection lens 207.

Figure 3 shows a further configuration of the microlithography projection exposure apparatus. In this case, the projection exposure apparatus 301 comprises the illumination optical unit 305 and the projection lens 307. In contrast to the projection lens 207 illustrated in figure 2a, the projection lens 307 according to figure 3 has a negative vertex focal length of the entrance pupil. That is to say that the entrance pupil plane 353 of the projection lens 307 is arranged in the light path upstream of the object field 331. If the chief ray 354 is extended further, without taking account of the reflection at the structure-bearing mask at the location of the object field 331, then the chief ray intersects the optical axis 345 in the plane 353a. If account is taken of the reflection at the structure-bearing mask at the location of the object field 331 and at the deflection mirror 329, then the plane 353a coincides with the entrance pupil plane 353. In the case of such projection lenses having a negative vertex focal length of the entrance pupil, the chief rays at different object field points at the location of the object field 331 have a divergent ray path in the

5 light direction. Projection lenses of this type are known from US 2009/0079952A1. In this embodiment, too, the exit pupil plane of the illumination optical unit 305 coincides with the entrance pupil plane 353 of the projection lens 307.

10 A further difference with respect to the embodiment according to figure 2a is that here the source plasma 347 is firstly imaged onto an intermediate focus 352 with the aid of the collector mirror 348. Said intermediate focus 352 is then imaged onto the second reflective facet elements 323 of the second optical element 321 with the aid of the first reflective facet elements 319 of the first optical element 317.

15 It goes without saying that the embodiments in Figures 2a and 3 can also be combined with one another. It is possible to use both a positive vertex focal length (as in Figure 2a) together with an intermediate focus (as in Figure 3), and a negative vertex focal length without an intermediate focus.

20 Figures 4a, 4b and 4c show different views of the second optical element having second reflective facet elements in the same illustration as Figure 2c. Since the first optical element, illustrated in Figure 2b, has a total of 108 second reflective facet elements, each of which generates an illuminated region at the location of an assigned second facet element during the operation of the illumination optical unit, there is a maximum of 108 illuminated regions on the
25 second optical element. Depending on the configuration of the first optical element having first reflective facet elements, said illuminated regions lie at different positions of the second optical element. This means that, depending on the configuration of the first optical element, the first reflective facet elements are assigned to different second reflective facet elements. In one configuration of the first optical element, the first reflective facet elements have a reflective
30 optical surface with a normal vector directed such that, during the operation of the illumination optical unit, illuminated regions are generated at the location of specific second reflective facet elements 455. In Figure 4a, these illuminated second reflective facet elements 455 are illustrated as filled in. In total there is a number of 84 illuminated second reflective facet elements 455 in the case of the configuration according to Figure 4a. Accordingly, of the 108 first reflective facet
35 elements only 84 first reflective facet elements are required in order to achieve the illumination of the second optical element 421 as illustrated in Figure 4a. Consequently, only $84/108 = 77.8\%$ of all the first reflective facet elements belong to the plurality of first reflective facet elements. The radiation which impinges on the remaining first reflective facet elements is not forwarded in the direction of the structure-bearing mask and therefore does not contribute to the illumination

5 of the mask and to image formation. For this purpose, e.g. diaphragms can be provided or the first reflective facet elements have a reflective surface with a normal vector directed such that the radiation impinges on a second reflective facet element whose reflective surface has an orientation such that the radiation is not reflected in the direction of the structure-bearing mask. In principle, it is desirable for the percentage of the first reflective facet elements which belong
10 to the plurality of first reflective facet elements to be as large as possible in order to provide a high intensity of the illumination radiation at the location of the structure-bearing mask. However, the radiation must also impinge on the structure-bearing mask at the correct illumination angle in order to contribute appreciably to the imaging. Otherwise, the radiation would adversely influence the optical properties of the projection optical unit, e.g. as a result of
15 heating, but would not contribute to image formation. In this case, it is advantageous for the radiation already to be filtered out within the illumination optical unit in the manner described above. For the important application of structures having parallel dense lines whose spacing is near the resolution limit, that illumination radiation which reaches the structure-bearing mask at the largest illumination angle contributes best to image formation. This is precisely that radiation
20 which also impinges on the second reflective facet elements arranged on the periphery of the second optical element. In the case of the second optical element illustrated according to Figure 2c, these are precisely the illuminated second reflective facet elements 455 marked in Figure 4a. In the case of the configuration illustrated in Figure 4a, therefore, more than 75% of all the first reflective facet elements contribute to the illumination of the structure-bearing mask.
25 Moreover, these first reflective facet elements have a reflective optical surface with a normal vector oriented such that the illuminated regions arise on the outer periphery of the second optical element. In particular, all these illuminated regions lie within an annular zone 459 enclosed by a circle 457 having a minimum diameter. In order to achieve the effect that as far as possible only the illumination angles which contribute particularly well to the imaging are
30 present at the location of the structure-bearing mask, it furthermore holds true that the ratio of the area content of the circle to the sum of the area contents of the zones 459 is greater than 2.5, in particular greater than 4. In the present case, the circle has a diameter of 32, thus resulting in a total area content of the circle of approximately 804, and the illuminated regions have a total area that is less than the sum of the reflective surfaces of the illuminated second reflective facet
35 elements 455, of which there are in each case 84 having the area content 1, such that the ratio is greater than $804/84 = 9.57$. Since the exact dimensionings are dependent on the exact choice of the imaging scales, this description has dispensed with specifying the amounts with dimensions. Instead, the outer dimensioning of the second reflective facet elements was fixed at 1.

Figure 4b shows, in an illustration similar to Figure 4a, a second possible configuration of the illumination optical unit, in which the illuminated second reflective facet elements 455 are arranged in the form of a dipole. Such an arrangement of the illuminated second reflective facet elements 455 leads to an illumination angle distribution at the location of the structure-bearing mask in which, firstly, the impinging radiation has large illumination angles and, secondly, the angular distribution has a specific preferred axis, namely the dipole axis. Such an angular distribution is particularly well suited to the imaging of mask structures whose direction is perpendicular to the dipole axis. In the case of this configuration there are 100 illuminated second reflective facet elements 455, such that likewise 100 of the 108 first reflective facet elements belong to the plurality of the first reflective facet elements. This is a percentage of 92.6%. In the case of this configuration, the illuminated regions lie within two continuous pairwise disjoint zones 459 corresponding to the poles of the dipole. Furthermore, there is a circle 457 having a minimum diameter that encloses all these zones. The area content of the circle having the minimum diameter is once again 804 and the sum of the area contents of the two zones is greater than the sum of the area contents of the reflective optical surfaces of the illuminated second reflective facet elements 455 and is accordingly greater than 100, such that the ratio is greater than 8.04 and thus greater than 2.5 and greater than 4.

Figure 4c illustrates a further configuration, in which the illuminated regions lie within four continuous pairwise disjoint zones arranged in the form of a quadrupole. In this case, there are a total of 88 illuminated second reflective facet elements 455, such that accordingly the plurality of first reflective facet elements likewise comprises 88 first reflective facet elements, which corresponds to a proportion of $88/108 = 81\%$ of all the reflective facet elements of the first optical element. The four continuous pairwise disjoint zones are enclosed by a circle 457 having a minimum diameter, the radius of which is 16. Therefore, the area content of the circle having the minimum diameter is approximately 804. The sum of the area contents of the zones 459 is greater than the sum of the area contents of the reflective surfaces of the illuminated second reflective facet elements 455 and is accordingly greater than 88. Therefore, the ratio of the area content of the circle to the sum of the area contents of the zones is greater than $804/88=9.1$ and thus greater than 2.5 and in particular also greater than 4.

Figure 5a schematically shows a mechanical embodiment of a first reflective facet element 519. In this case, the first reflective facet element 519 has a reflective optical surface 561 with a normal vector 563a perpendicular to the optical surface 561 at the main point. The direction of the normal vector 563a thus indicates the orientation of the reflective optical surface 561 in

5 space. Moreover, the first reflective optical element 519 has four actuators 565a, 565b, 565c, 565d, which can be used to alter the orientation of the reflective optical surface 561. Figure 5b illustrates a plan view of the first reflective optical element according to Figure 5a. A Cartesian coordinate system having an x-axis and a y-axis is additionally shown. Since the actuators 565a, 565b, 565c, 565d are at a distance from one another both in the x-direction and in the

10 y-direction, the actuators 565a, 565b, 565c, 565d enable a rotation of the reflective optical surface 561 both about the x-axis and about the y-axis. Figure 5c shows the first reflective optical element 519 in a second position, in which the reflective optical surface 561 has a different orientation in contrast to the position shown in Figure 5a. The normal vectors 563a and 563b thus form an angle different than 0° . The mirror substrate 567 has been rotated about the

15 pivot point 568. This was achieved by virtue of the fact that the actuators 565a, 565b, 565c and 565d in the position according to Figure 5c have a different extent perpendicular to the mirror carrier 569.

Figure 6 shows an excerpt from an illumination optical unit according to the invention. In

20 contrast to the more schematic beam path which is shown in Figure 3 and has been taken over here in a dashed fashion, the exact beam path is illustrated in a solid fashion for a first reflective optical element 619. The first reflective optical element 619 images the intermediate focus 652 onto the illuminated second reflective facet element 655 assigned to it. Accordingly, an illuminated region 671 is generated on the reflective surface of the illuminated second reflective

25 facet element 655. It is advantageous if said illuminated region 671 has an area that is as small as possible. What is thereby achieved is that the second reflective facet elements 623 can be made relatively small, wherein the illuminated regions are still in each case smaller than the reflective surface of the corresponding assigned second reflective facet element. Such a small embodiment of the second reflective facet elements has the advantage that the latter can be packed relatively

30 densely, such that a larger number of second reflective facet elements can be arranged in the zones of the second optical element 621 which correspond to illumination angles which contribute particularly well to image formation. Therefore, it is desirable for the best possible imaging of the intermediate focus 652 onto the zone 671 to take place. An ideal point imaging of the intermediate focus 652 onto the zone 671 arises exactly when the corresponding first

35 reflective facet element 619 has a reflective optical surface which is aspherical and a segment from the ellipsoid 666 whose focal points coincide with the intermediate focus 652 and the zone 671.

5 Figure 7 shows, by contrast, the ray path such as arises when a spherical reflective surface is used. The intermediate focus 752, which is not situated at the focus 772 of the spherical reflective surface 773, is not imaged exactly onto a point. While the rays 774a and 774b running in the yz plane intersect at the location 775a, the rays 774c and 774d running at an angle with respect to the yz plane intersect at the location 775b, which is further away from the spherical reflective surface 773 than the location 775a. The point 775a is therefore the meridional focal point and the point 775b is the sagittal focal point. Between these two focal points 775a and 775b, a position arises at which the illuminated region becomes exactly circular. At this location, the image is a circular unsharp spot, called the circle of confusion 776. On account of this astigmatism described, when a spherical reflective surface 773 is used, even during the imaging of a punctiform intermediate focus 752, an extended illuminated region always arises, which in this case corresponds to the circle of confusion 776. One possibility for reducing the illuminated region is the use of an aspherical reflective surface in contrast to the spherical reflective surface illustrated in Figure 7. It is known that the astigmatism described above can be reduced by such a use of aspheres. An optimum imaging in which the meridional and the sagittal focal point coincide arises when using an aspherical surface that is a segment from an ellipsoid. This is illustrated in Figure 6.

Figures 8a and 8b each likewise show an excerpt from an illumination optical unit according to the invention, wherein Figure 8a differs from Figure 8b in that one of the first reflective facet elements 819 of the first optical element 817 assumes a first position in Figure 8a and a second position in Figure 8b. In the first position, the first reflective facet element 819 generates a first illuminated region 871a at the location of an assigned second reflective facet element. This is illustrated in Figure 8a. By contrast, Figure 8b shows that the first reflective facet element 819 in the second position, during the operation of the illumination optical unit, generates a second illuminated region 871b at the location of a further assigned second reflective facet element. In the configuration according to Figure 8a, the first reflective facet element 819 is at a distance from the first illuminated region 871 which is designated by 877a. In the configuration according to Figure 8b, in which the first reflective facet element 819 is in the second position, the first reflective facet element 819 is at a distance from the second illuminated region 871b, which is identified by 877b.

Generally speaking two different types of imaging errors arise that enlarge the illuminated regions 871a and 871b. On the one hand there is the astigmatism that is explained with reference to figure 7. On the other hand there is the defocus error that occurs due to the variation in the

- 5 distance 877a and 877b when tilting the first facet elements 819. According to the invention, these two positions are chosen in such a way that the distance 877a and the distance 877b differ by not more than 5%, preferably by not more than 3%. What is thereby achieved is that both the illuminated region 871a and the illuminated region 871b are small enough to be appropriately matched to the respective reflective surface of the corresponding second reflective facet element.
- 10 Even if the reflective surface of the first reflective facet element 819 is chosen in such a way that an optimum point image of the intermediate focus 852 arises as illuminated region 871a, then the result inevitably is that, on account of the altered distance 877b in comparison with 877a, an blurred image of the intermediate focus 852 occurs at the second position as illuminated region 871b. According to the invention, the two positions are chosen in such a way that the two
- 15 distances differ by not more than 5%, in particular by not more than 3%. According to a further aspect of the invention the reflective surface of the first optical element is aspherical in such a way that the smallest possible illumination regions 871a and 871b are generated in both positions.
- 20 Figure 8c, 8d, 8e, 8f show the results of the optimization with spherical and ellipsoidal first facet elements. The results are presented for an ensemble of 11 exemplary first facet elements. Each first facet element can assume two different positions. Therefore it can produce two different illuminated regions at the location of two assigned second reflective facet elements. The following table shows the variation of the distances between each first facet element and its
- 25 illuminated regions.

Number of first facet element	Variation of distances
1	1.26%
2	1.02%
3	0.30%
4	1.94%
5	1.89%
6	2.04%
7	1.30%
8	0.76%
9	0.05%
10	0.58%

5

The two positions of all eleven first facet elements are chosen in such a way that the two distances differ by not more than 3%. This has been realized by an arrangement of first facet elements on reference bodies that are tilted with respect to each other. Details on this configuration are found in the German patent application DE102010003169A1 that is

10 incorporated by reference.

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Figure 8c shows the results for the diameter of the illuminated regions. For the eleven first facet elements the radius of curvature of the spherical surface has been chosen such that during the imaging of a punctiform source plasma, a first illuminated region lying within a circle having the radius R_1 arises at the first position, and an illuminated region lying within a circle having the radius R_2 arises at the second position. The radius of curvature has been chosen such that the maximum of R_1 and R_2 is at a minimum. Figure 8c shows the maximal value for the radius after optimization of the spherical surfaces by using dots. The same procedure can be repeated by using ellipsoidal first facet elements. The results for the radii of the illuminated regions for such

20 first facet elements are plotted using '+'. All results are shown in terms of an average radius R_0 . For all eleven first facet elements the size of the illuminated regions has been reduced by using ellipsoidal first facet elements. Basically the whole astigmatism has been eliminated so that only the defocus error due to the different distances is left.

25

Figure 8d shows once more a comparison between the usage of spherical first facet elements and ellipsoidal first facet elements. The squares in figure 8d represent the difference between the maximal values shown in figure 8c. One can see from this figure that the size reduction due to the ellipsoidal first facet elements is not the same for the different first facet elements. For example, although for some facet elements the reduction can be more than 30% of the average

30 radius, there are also facet elements like facet element number nine, where the improvement is less than 10%. These facet elements produce already with spherical surfaces a small illuminated region. Therefore there is no need to use ellipsoidal, toroidal or other aspherical surfaces for these facet elements. By using aspherical first facet elements only for those first facet elements where there is really a need for them, the production cost can be greatly reduced. This is because

35 the production of spherical surface is much easier and cheaper than the production of an aspherical surface.

5 Figure 8e shows the different sizes of the illuminated regions depending on the position of the first facet elements. After the spherical or ellipsoidal surface has been optimized using the above explained procedure the size of the illuminated regions can still depend on the position of the first facet element. For each of the eleven first facet elements figure 8e shows the difference between the radii of the illuminated regions corresponding to the two different positions. It can
10 easily be seen that the elliptical first facet elements produce two illuminated regions that have almost the same radius. On the other hand the sizes of the illuminated regions for the spherical facet element show large variations.

Figure 8f shows an excerpt from an illumination optical unit according to the invention. Drawn
15 is the illumination path of the illumination radiation that is reflected by the first facet element 819a and by the first facet element 819b. It can easily be seen that the reflection angle at the first facet element 819a is much smaller than at the first facet element 819b. This has two reasons. On the one hand there is the assignment of the second facet elements. But even if both first facet elements 819a and 819b would reflect the radiation in the direction of the same second
20 facet element 823 the reflection angle at the element 819b would still be larger than at the element 819a. This is simply due to the position of the first facet element 819a on the first facet mirror 817. This variation of the angle of incidence causes the different amount of astigmatism that occurs during imaging the intermediate focus 852. The larger the angle of incidence the larger is the astigmatism error. First facet element with a small angle of incidence like the first
25 facet element 819a show only a small amount of astigmatism and can therefore be equipped with spherical surfaces. But first facet elements with a large angle of incidence like the first facet element 819b show a large amount of astigmatism and are equipped therefore with an aspherical reflective surface.

30 Figure 9a shows a plan view of an excerpt from the second reflective optical element. Six second reflective facet elements 923 with their respective reflective optical surfaces 970 are illustrated. The illuminated regions 971 are illustrated in a hatched fashion. Of said regions, the illuminated regions 971a and 971b lie on the reflective surface 970b of the same second reflective facet element. The illuminated regions 971a and 971b are generated by two different first reflective
35 facet elements. Therefore, the radiation in the illuminated regions 971a and 971b also impinges from different directions on the second reflective facet element having the optical surface 970b. However, the reflective optical surface 970b has a normal vector oriented in such a way that only the radiation impinging in the region 971b is reflected in the direction of the structure-bearing mask. By contrast, the radiation impinging in the region 971a is reflected in an incorrect

5 direction, such that it does not reach the structure-bearing mask. The radiation impinging in the region 971a should actually have impinged on the reflective optical surface 970a in order to be reflected in the direction of the structure-bearing mask. However, even a small error in the orientation of the reflective optical surface of the associated first reflective facet element has the effect that the region 971a is misaligned and does not reach the correct reflective optical surface 970a. Given a typical distance of 1 m between the first reflective facet elements and their associated illumination region, an angular error in the orientation of the normal vector of the reflective surface of the first optical element of 1 mrad leads to a displacement of the illumination region by 2 mm. The orientation of the normal vector of the first reflective optical facet elements therefore has to be defined extremely precisely. In order to define this orientation so precisely, however, it is necessary to determine the position of the illuminated regions 971. The measuring system illustrated in Figure 9b is provided for this purpose. In the embodiment according to Figure 9b, radiation detectors 981 are arranged on the periphery of the reflective surface of the six second reflective facet elements 923. Given optimum alignment of the first reflective facet elements, no radiation whatsoever should be incident on the radiation detectors 981, since the illuminated regions 971 lie completely on the respective reflective optical surface 970. As soon as a region 971a does not assume the correct position, because e.g. the normal vector of the corresponding first reflective optical element changes its position on account of heating of the corresponding first reflective optical element, a signal arises at the corresponding radiation detector 981. Said signal can be used to subsequently correct the orientation of the corresponding normal vector with the aid of actuators in order to shift the region 971a back to the reflective surface 970.

Figure 10 schematically shows such subsequent correction with the aid of a control loop. The illustration shows four second reflective facet elements 1023a, 1023b, 1023c, 1023d and one first reflective facet element 1019 having a reflective optical surface 1061 having a normal vector 1063. The position of the normal vector 1063 in space and hence the orientation of the reflective optical surface 1061 are defined with the aid of four actuators 1065a, 1065b, 1065c and 1065d, as described with reference to Figures 5a, 5b and 5c. Accordingly, the actuators can be used to set the position at which the illuminated region 1071 arises. In a manner corresponding to the explanation concerning Figure 9b, the second reflective facet element 1023a is provided with radiation detectors 1081a, which generate a signal as soon as the illuminated region 1071 is incident on the radiation detectors 1081a. The measuring system formed by the radiation detectors 1081a is connected to the actuators 1065a, 1065b, 1065c and 1065d via a control unit 1083, thus resulting in a control loop in order to control the position of the illuminated regions

5 1071 by closed-loop control in such a way that more than 90%, preferably more than 95%, of the illuminated region 1071 lies on the reflective surface of the assigned second reflective facet element 1023a. In this case, the control unit 1083 generates, with the aid of the signals of the measuring system, a control signal used to drive the actuators 1065a, 1065b, 1065c and 1065d. Furthermore, Figure 10 illustrates three alternative embodiments for the measuring system. The
10 second reflective facet element 1023b comprises a radiation detector 1081b arranged below a reflective coating 1085 of the assigned second reflective facet element. In this case, a central opening 1087 is provided in the reflective coating 1085 in order to allow radiation to pass to the radiation detector 1081b. In this case, a signal arises at the radiation detector 1081b if the position of the normal vector 1063 is correct and the illuminated region lies on the reflective
15 surface of the corresponding assigned second reflective facet element 1023b. In an alternative form, the radiation detector 1023c is likewise arranged below a reflective coating 1085 of the assigned second reflective facet element, but no opening is provided. In this case, the radiation detector 1081c detects the residual proportion of the impinging radiation that passes through the reflective coating 1085. In a further alternative embodiment, the measuring system comprises a
20 temperature sensor 1089 connected to the second reflective facet element 1023d. With the aid of the temperature sensor 1089, it is possible indirectly to ascertain whether the illuminated region 1071 has the correct position. This makes use of the fact that heating of the second reflective facet element 1023d is caused by the impinging radiation. In the case of an incorrect setting of the normal vector 1063, this has the effect of e.g. that two illumination regions become situated
25 on the same second reflective facet element, as is illustrated in Figure 9a on the basis of the illumination regions 971a and 971b. This would lead to significantly greater heating of the corresponding second reflective facet element. In return, the heating of the adjacent second reflective facet element turns out to be significantly less than expected, since no illumination region impinges here. From these signals of the temperature sensors, too, therefore, with the aid
30 of the control unit 1083 it is possible to generate a control signal in order to suitably drive the actuators 1065a, 1065b, 1065c and 1065d.

Figures 11a,b,c,d show once more the problems that arise if the size of the illuminated regions 1171 are too large to fit onto the second facet elements 1123. Figure 11a shows an ideal imaging.
35 The radiation from the intermediate focus 1152 is reflected by the first facet element 1119 so that an illuminated region 1171 is produced at the position of an assigned second facet element 1123. The illuminated region 1171 is an ideal image of the intermediate focus 1152. As explained with reference to figures 2a, 2b and 2c the second facet element images the first facet elements 1119 in onto the object field. Depending on the embodiment additional optical elements might be used

5 between the second facet element and the object field. At the position of the object field a radiation intensity distribution I is therefore produced. This radiation intensity distribution I is sketched in the right part of figure 11a. The direction x coincides with the long extension of the first facet elements 1119. The second direction within the object plane that is orthogonal to the x-direction coincides with the scanning direction of the microlithography projection exposure apparatus. Since each point of the mask is moved along this scanning direction through the object field it is common to integrate the intensity distribution over the scanning direction. Therefore the intensity distribution I is a function of x only.

If the illuminated region 1171 fits completely onto the second facet element 1123 the whole radiation is reflected in the direction of the object field. This would result into the intensity distribution 1191 that is shown using a solid line. But since some radiation is lost because the illuminated area 1171 is larger than the second facet element 1153, the intensity is slightly reduced. This results in the intensity distribution 1193 that is shown using a dashed line.

Although some radiation is lost the intensity distribution is still uniform and shows no dependency on x. Unfortunately this is only the case if the illuminated region corresponds to an ideal image of the intermediate focus. If the imaging has errors like astigmatism the effect is much worse. Figure s 11b, 11c and 11d show the effects of these errors. The first facet element 1119 is positioned such that the radiation that is reflected by the centre of the first facet element 1119 hits the centre of the second facet element 1123. So the illuminated region that is produced only by the radiation that has been reflected by the centre of the first facet element is centred at the position of the second facet element. Figure 11b shows the light path of the radiation that is reflected by right side of the first facet element 1119. Due to the imaging errors the illuminated region that is produced by this radiation is not centred at the position of the second facet element 1123. Instead it is slightly shifted to the left. In the same way the illuminated region produced by the radiation that is reflected from the left side of the first facet element is shifted slightly to the right. This is shown in figure 11c. Together the illuminated region 1171 shown in figure 11d is no longer an ideal image of the intermediate focus but is slightly stretched. This has no effect if the illuminated region fits completely onto the second facet element 1123. But if illuminated region is larger like in figure 11d some radiation is lost but the additional problem is that the radiation is not homogenously lost. From figure 11b and 11c one can see that the amount of lost radiation is larger for the radiation that is reflected by the left and right side of the first facet element compared to the radiation that has been reflected by the centre of the first facet element. And since the first facet element 1119 is imaged onto the object field, the radiation intensity distribution I at the object field shows the same tendency. The dashed line 1195 that represents the radiation intensity distribution at the object field is higher in the centre than at the edges. The

5 reason is simply that more radiation originating from the edges of the first facet element 1119
has been lost. This effect gets even worse if the radiation source is not correctly positioned or
changes its position slightly during the use of the microlithography apparatus. If the intermediate
focus 11 changes its position the illuminated region 1171 changes its position accordingly. In
10 such a case even the radiation that is reflected by the centre of the first facet element is no longer
centred at the position of the second facet element. Therefore the inhomogeneity of the radiation
loss is even larger. By the use of aspherical first facet elements the size of the illuminated
regions can be reduced so that less radiation is lost. In addition the effect of imaging errors can
be almost avoided so that the radiation loss is almost homogenous. Therefore the uniformity of
15 the radiation at object plane is increased and furthermore the system gets more stable against
position errors of the light source.

5 Patent Claims

1. Illumination optical unit (5, 205, 305) for EUV microlithography comprising a first optical element (217, 317, 617, 817) having a plurality of first reflective facet elements (219, 319, 519, 619, 819, 1019),
10 and a second optical element (221, 321, 421, 621, 821) having a plurality of second reflective facet elements (223, 323, 423, 623, 823, 923, 1023),
wherein the plurality of first reflective facet elements (219, 319, 519, 619, 819, 1019) comprises at least 75% of all the reflective facet elements of the first optical element (217, 317, 617, 817),
15 wherein each first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality of first reflective facet elements (219, 319, 519, 619, 819, 1019) is embodied in such a way that, during the operation of the illumination optical unit (5, 205, 305), it generates an illuminated region (971) at the location of an assigned second facet element (223, 323, 423, 623, 823, 923, 1023) of the plurality of second reflective facet elements (223, 323, 423, 623, 823, 923, 1023),
20 wherein the second reflective facet elements (223, 323, 423, 623, 823, 923, 1023) each have a reflective surface and the illuminated regions are in each case smaller than the reflective surface (970) of the assigned second reflective facet element (223, 323, 423, 623, 823, 923, 1023),
25 wherein all of said illuminated regions (971) lie within a maximum of six continuous pairwise disjoint zones (459) and there is a circle (457) having a minimum diameter which encloses all of said zones (459),
characterized in that
the first and/or second reflective facet elements are embodied in such a way that the ratio
30 of the area content of the circle (457) to the sum of the area contents of the zones (459) is greater than 2.5, in particular greater than 4.
2. Illumination optical unit according to Claim 1,
characterized in that
35 the second optical element (221, 321, 421, 621, 821) is arranged in an exit pupil plane (253, 353) of the illumination optical unit (5, 205, 305) or is imaged into an exit pupil plane (253, 353) of the illumination optical unit (5, 205, 305).

- 5 3. Illumination optical unit (5, 205, 305) according to either of Claims 1-2,
characterized in that
at least one first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality
of first reflective facet elements (219, 319, 519, 619, 819, 1019) comprises an aspherical
reflective surface, the form of which is chosen in such a way that the illuminated region
10 (971) produced by said facet element (219, 319, 519, 619, 819, 1019) during the
operation of the illumination optical unit (5, 205, 305) is reduced relative to the use of a
spherical reflective surface.
- 15 4. Illumination optical unit (5, 205, 305) according to any of Claims 1-3,
characterized in that
at least one first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality
of first reflective facet elements (219, 319, 519, 619, 819, 1019) comprises a spherical
reflective surface.
- 20 5. Illumination optical unit (5, 205, 305) according to any of Claims 1-4,
characterized in that
all first reflective facet elements (219, 319, 519, 619, 819, 1019) of the plurality of first
reflective facet elements (219, 319, 519, 619, 819, 1019) that have a maximal angle of
incidence that is smaller than a predetermined value comprise a spherical reflective
25 surface.
- 30 6. Illumination optical unit (5, 205, 305) according to any of Claims 1-5,
characterized in that
each first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality of first
reflective facet elements (219, 319, 519, 619, 819, 1019) has at least two positions, such
that, in the first position during the operation of the illumination optical unit (5, 205,
305), it generates a first illuminated region (971) at the location of an assigned second
facet element (223, 323, 423, 623, 823, 923, 1023) of the plurality of second reflective
facet elements (223, 323, 423, 623, 823, 923, 1023) and, in the second position during the
35 operation of the illumination optical unit (5, 205, 305), it generates a second illuminated
region (971) at the location of a further assigned second facet element (223, 323, 423,
623, 823, 923, 1023) of the plurality of second reflective facet elements (223, 323, 423,
623, 823, 923, 1023).

- 5 7. Illumination optical unit (5, 205, 305) according to Claim 6,
characterized in that
each first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality of first
reflective facet elements (219, 319, 519, 619, 819, 1019) has a reflective optical surface
10 (561, 1061) having a normal vector (563, 1063), wherein the positions of the first
reflective facet elements (219, 319, 519, 619, 819, 1019) differ in the orientation of the
normal vector (563, 1063).
- 15 8. Illumination optical unit (5, 205, 305) according to either of Claims 6-7,
characterized in that
at least one reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality of
reflective first facet elements (219, 319, 519, 619, 819, 1019) has at least two positions
chosen in such a way that the distance between the at least one reflective facet element
20 (219, 319, 519, 619, 819, 1019) and the first illuminated region (971) differs from the
distance between the at least one reflective facet element and the second illuminated
region (971) by not more than 5%.
- 25 9. Illumination optical unit (5, 205, 305) according to any of Claims 6-8,
characterized in that
at least one first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality
of reflective first facet elements (219, 319, 519, 619, 819, 1019) comprises an aspherical
reflective surface, the form of which is chosen in such a way that the first and the second
30 illuminated region (971) produced by said facet element during the operation of the
illumination optical unit (5, 205, 305) is reduced relative to the use of a spherical
reflective surface.
10. Illumination optical unit (5, 205, 305) according to either of Claims 3 and 9,
characterized in that
the aspherical surface is a segment from an ellipsoid (666) or has a toroidal shape.
- 35 11. Illumination optical unit (5, 205, 305) according to any of Claims 7-10,
characterized in that
each first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality of first
reflective facet elements (219, 319, 519, 619, 819, 1019) comprises an associated

5 actuator (565) for altering the orientation of the normal vector (563, 1063).

12. Illumination optical unit (5, 205, 305) according to Claim 11,

comprising a measuring system for determining the position of the illuminated regions (971) generated by each first reflective facet element (219, 319, 519, 619, 819, 1019) of the plurality of first reflective facet elements (219, 319, 519, 619, 819, 1019) during the operation of the illumination optical unit (5, 205, 305).

13. Illumination optical unit (5, 205, 305) according to Claim 12,

characterized in that

for at least one reflective first facet element (219, 319, 519, 619, 819, 1019) of the plurality of first reflective facet elements (219, 319, 519, 619, 819, 1019), the actuator (565) contained is connected to the measuring system via a control unit (1083), thus resulting in a control loop, in order to control the position of the corresponding illuminated region (971) in such a way that more than 90% of the illuminated region (971) lies on the reflective surface (970) of the assigned second facet element (223, 323, 423, 623, 823, 923, 1023).

14. Illumination optical unit (5, 205, 305) according to either of Claims 12-13,

characterized in that

the measuring system comprises at least one radiation detector (1081a) arranged on the periphery of the reflective surface (970) of the assigned second facet element (223, 323, 423, 623, 823, 923, 1023).

15. Illumination optical unit (5, 205, 305) according to any of Claims 12-14,

characterized in that

the measuring system comprises at least one temperature sensor (1089) which detects the heating of the assigned second facet element (223, 323, 423, 623, 823, 923, 1023) during the operation of the illumination optical unit (5, 205, 305).

16. Illumination optical unit (5, 205, 305) according to any of Claims 12-15,

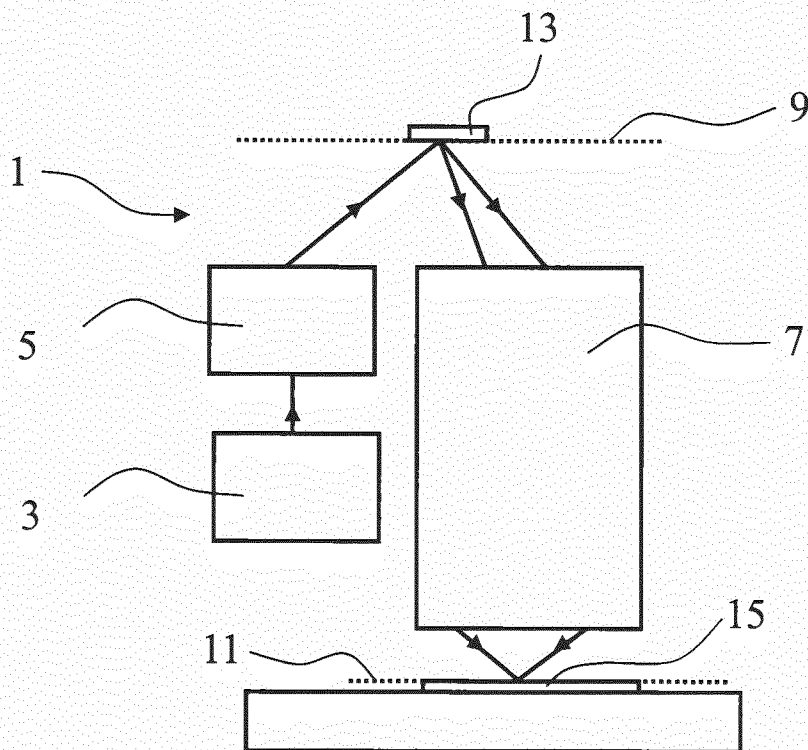
characterized in that

the measuring system comprises at least one radiation detector (1081b, 1081c) arranged below a reflective coating (1085) of the assigned second reflective facet element (223,

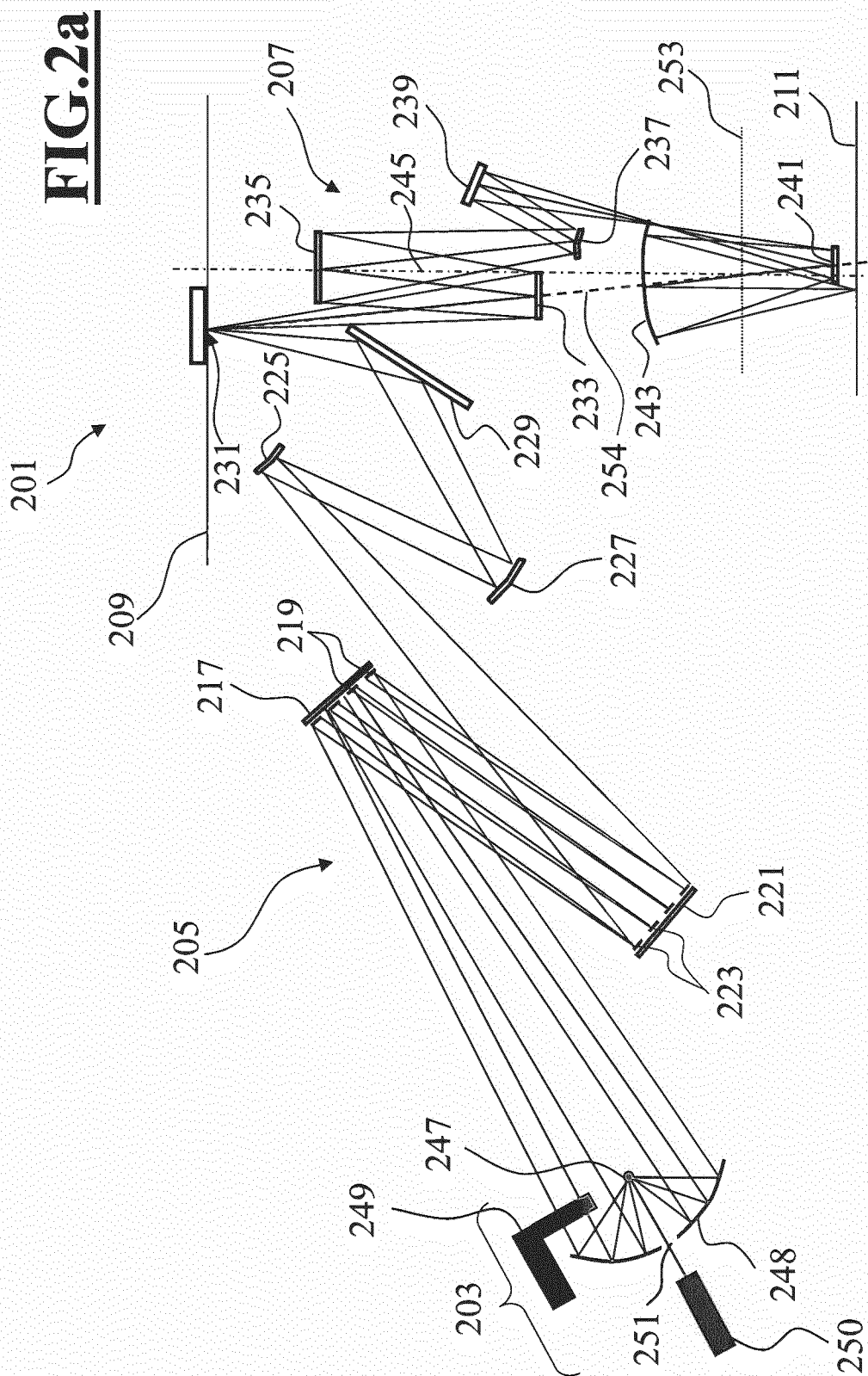
5 323, 423, 623, 823, 923, 1023).

17. Microlithography projection exposure apparatus (1, 201, 301) comprising an illumination optical unit (5, 205, 305) according to Claim 16.

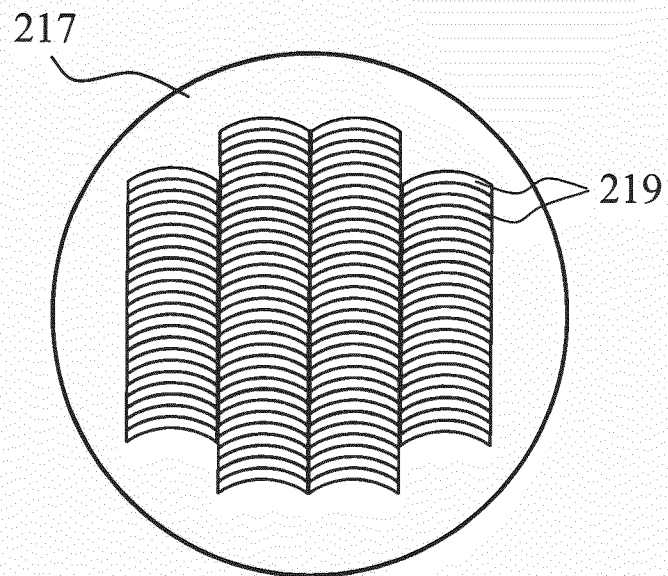
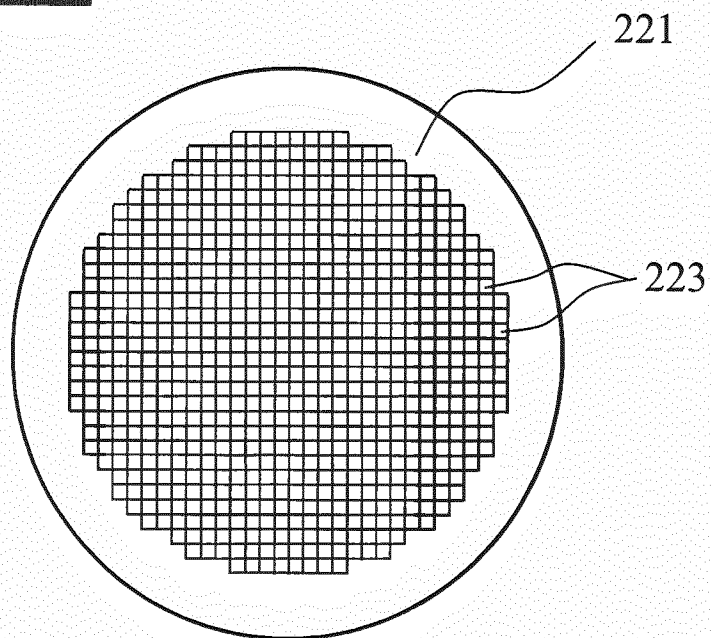
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FIG.1

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FIG.2b**FIG.2c**

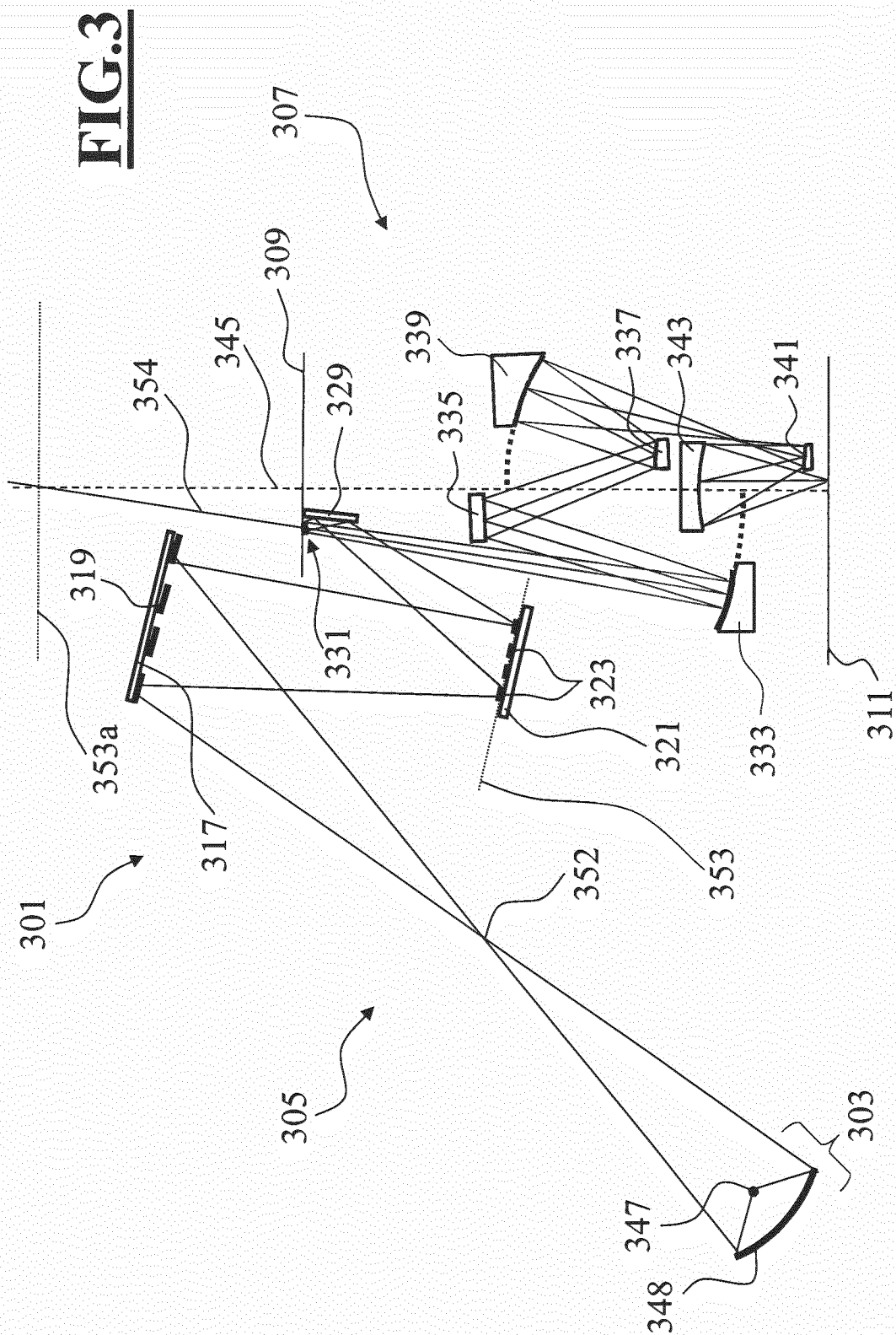
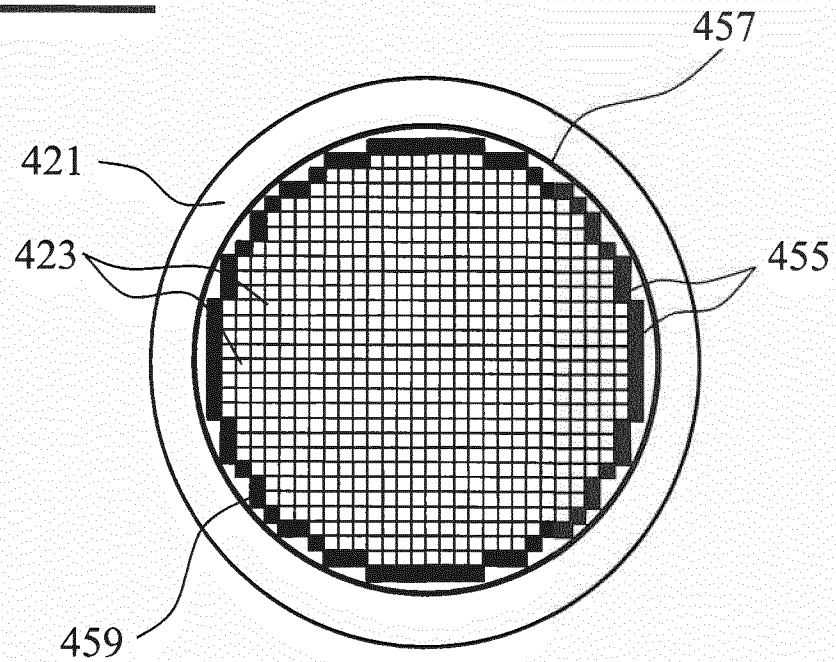
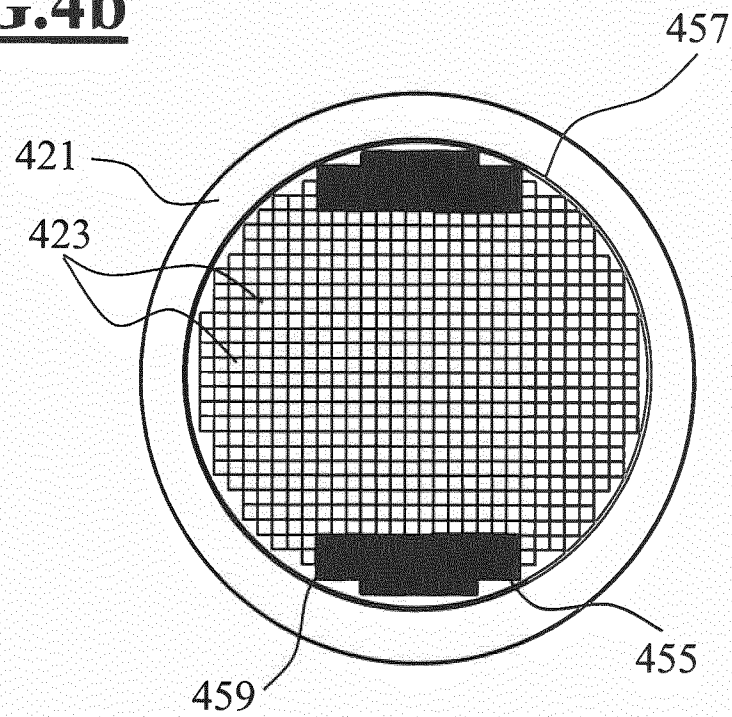
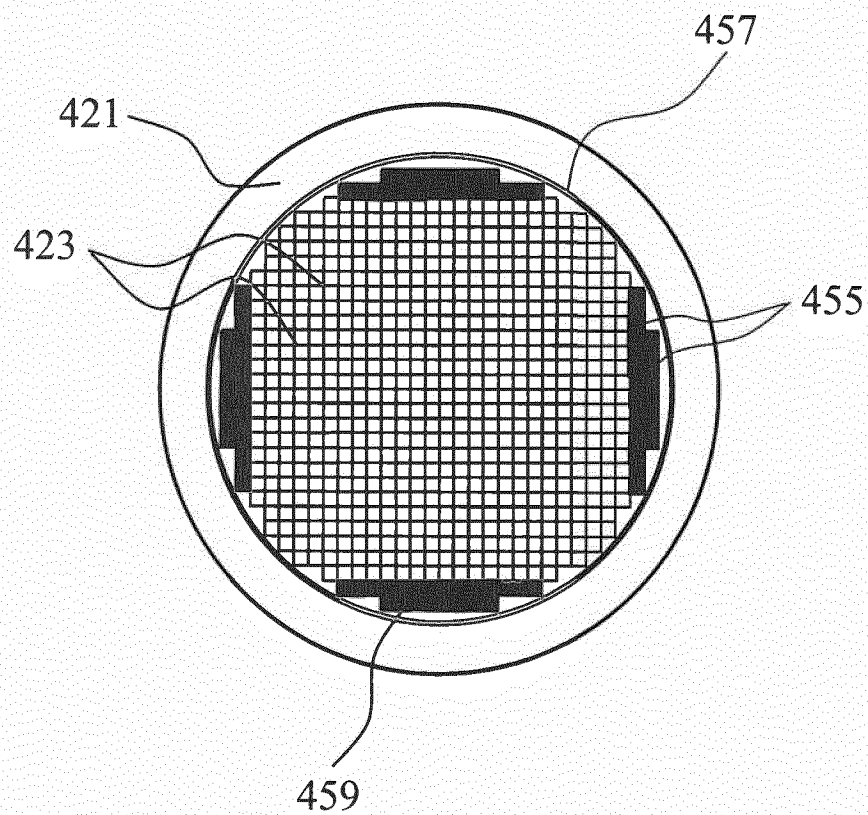
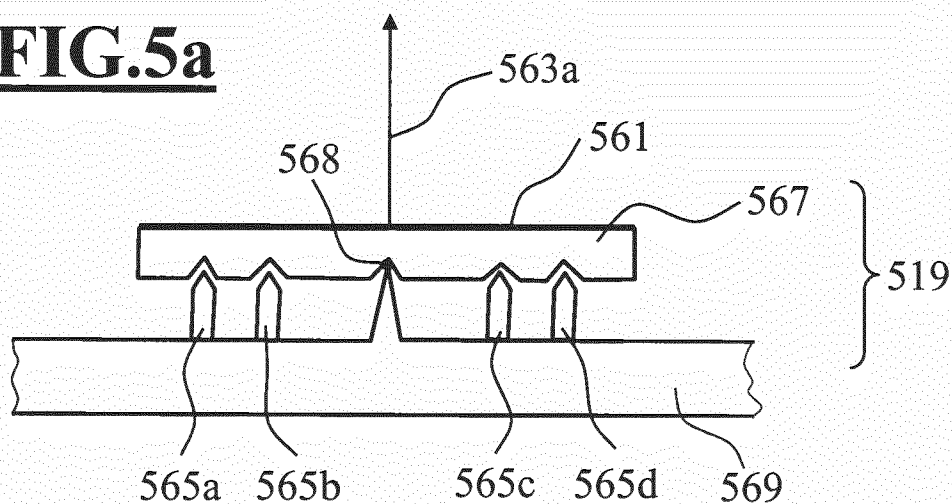
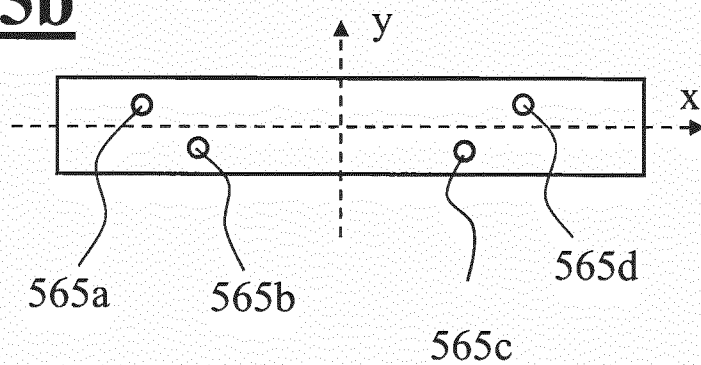
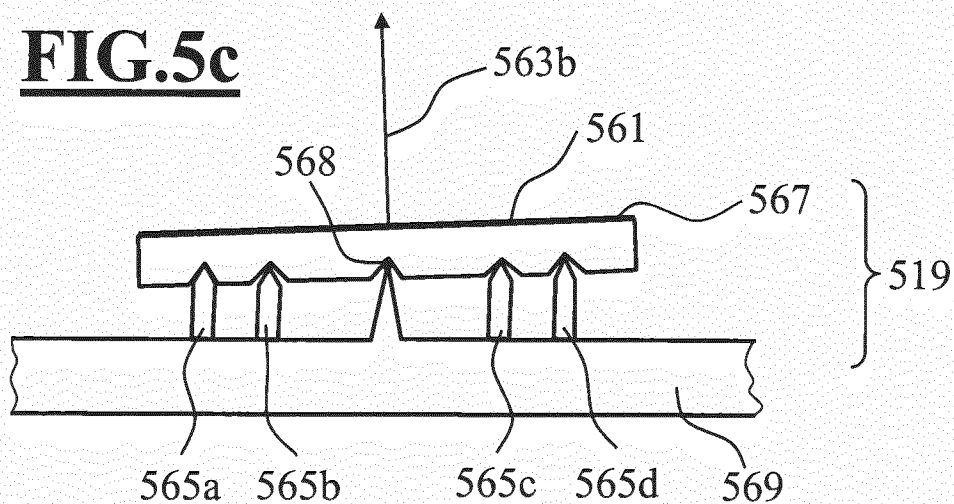


FIG.4a**FIG.4b**

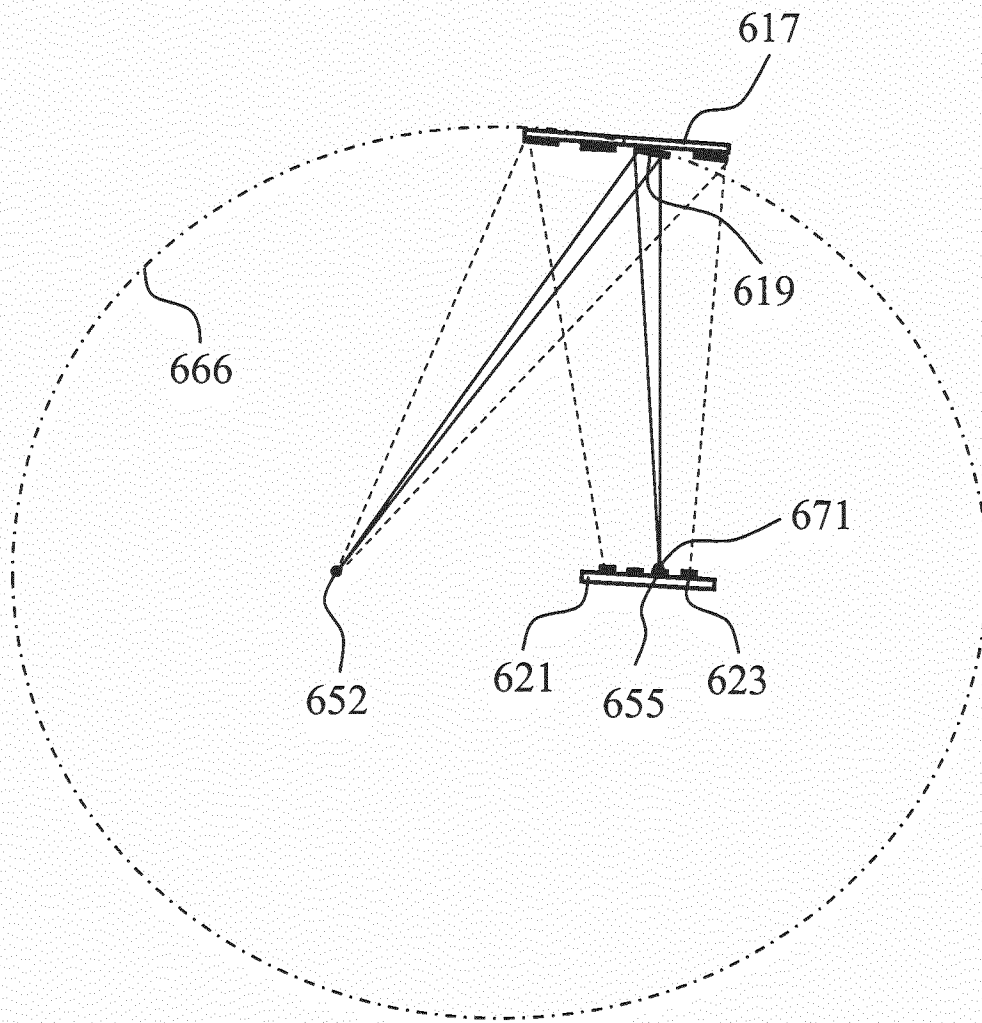
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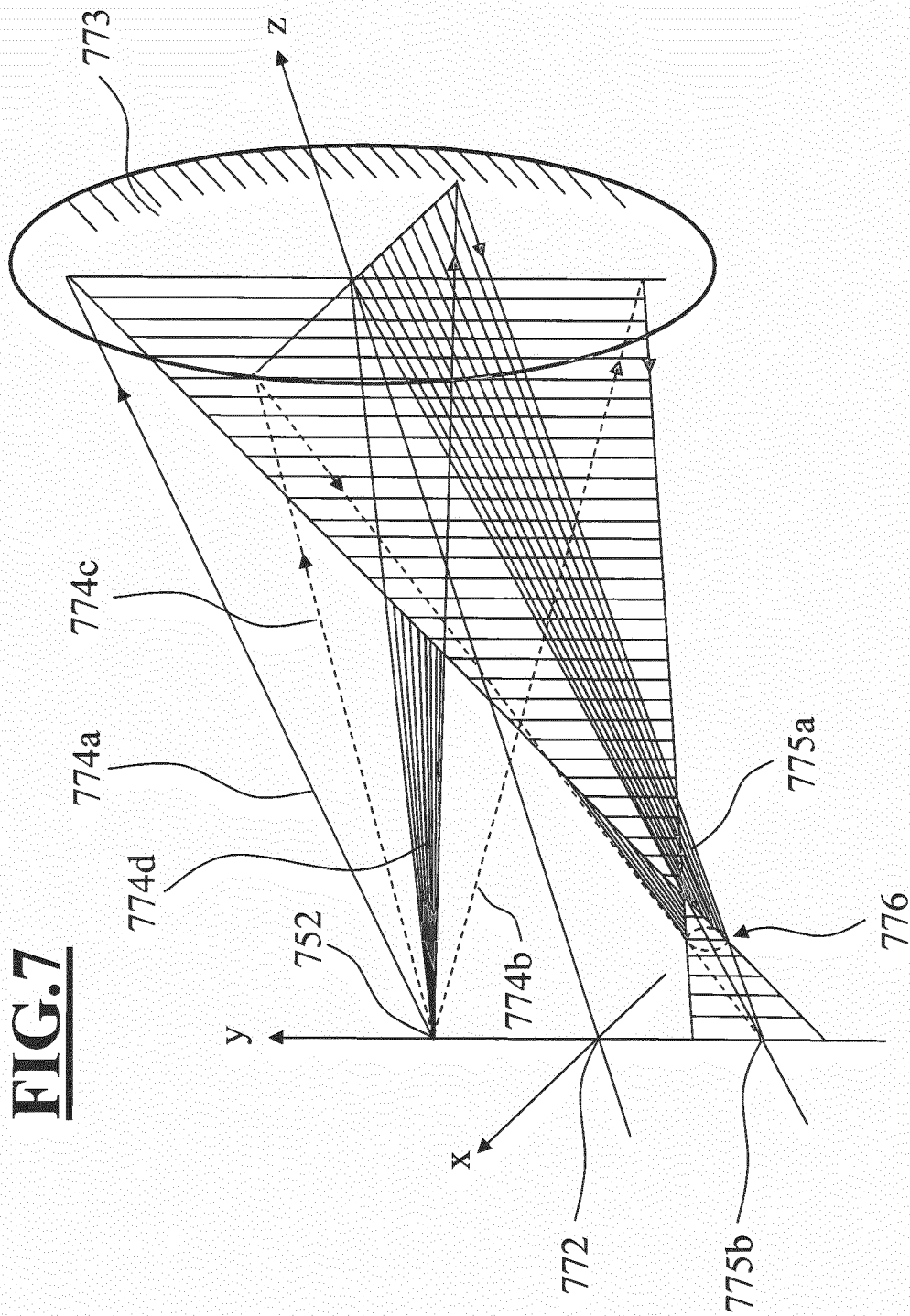
FIG.4c

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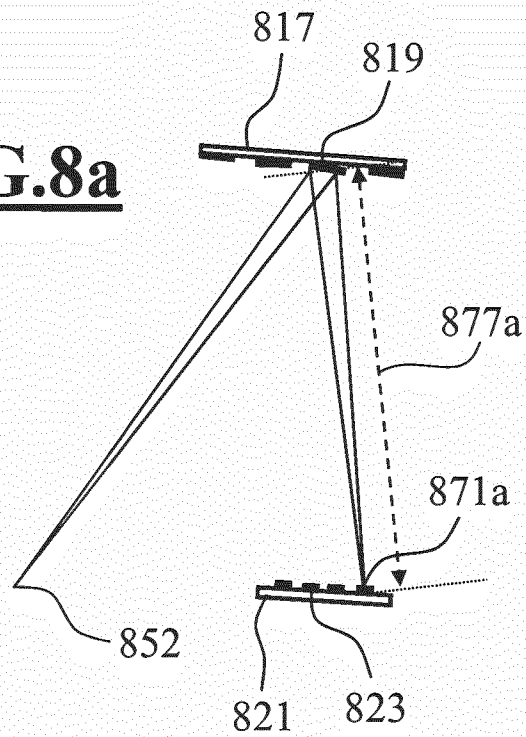
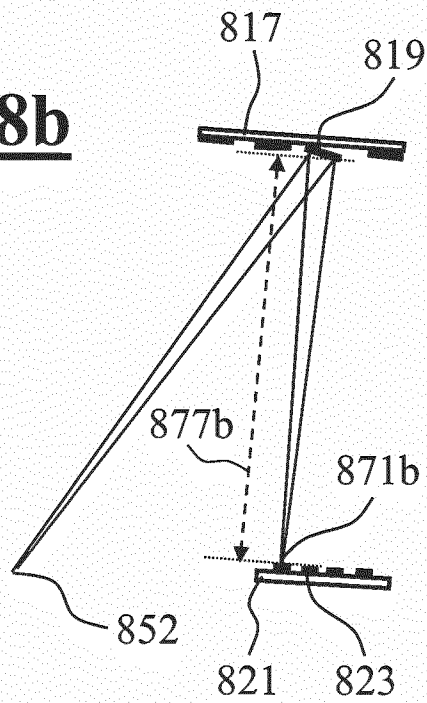
FIG.5a**FIG.5b****FIG.5c**

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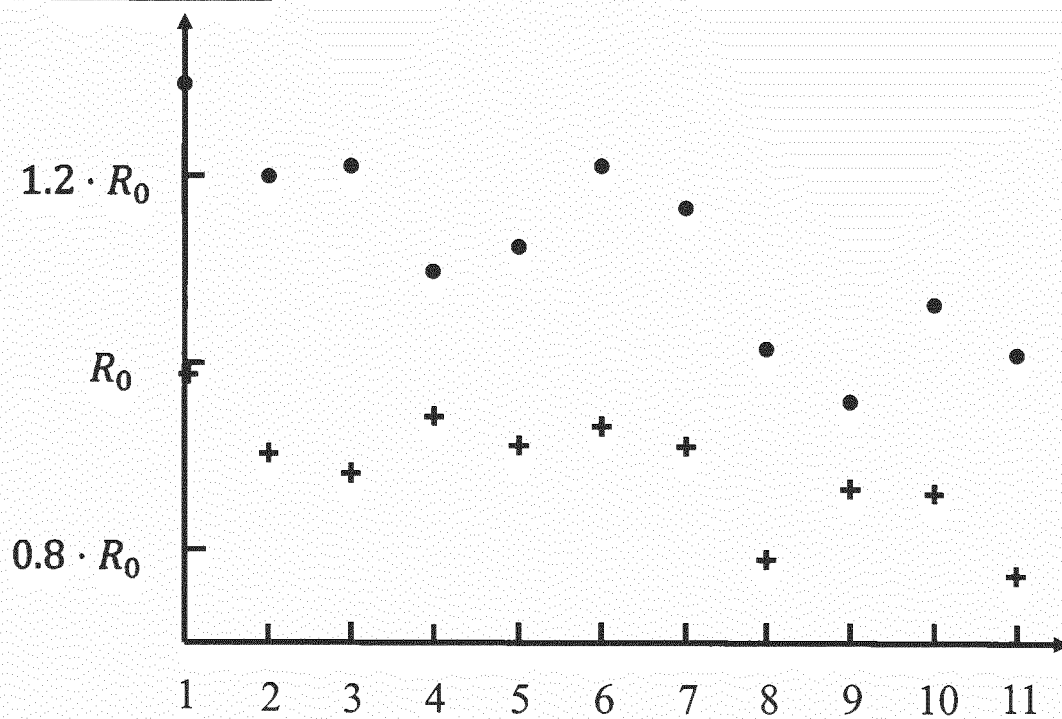
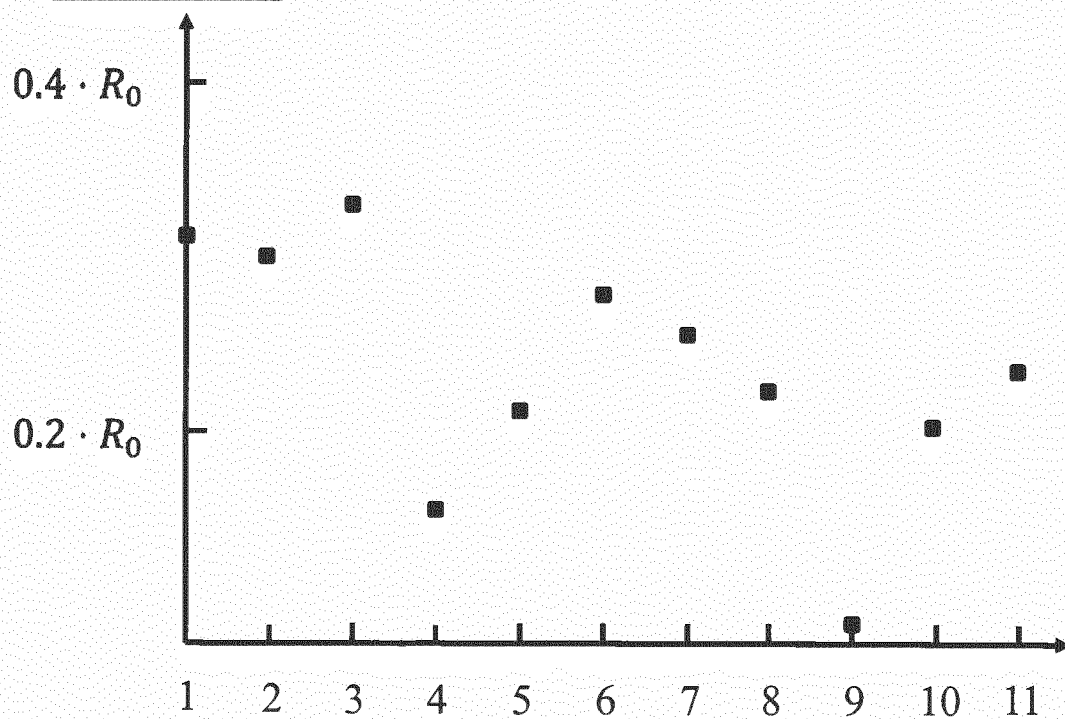
FIG.6



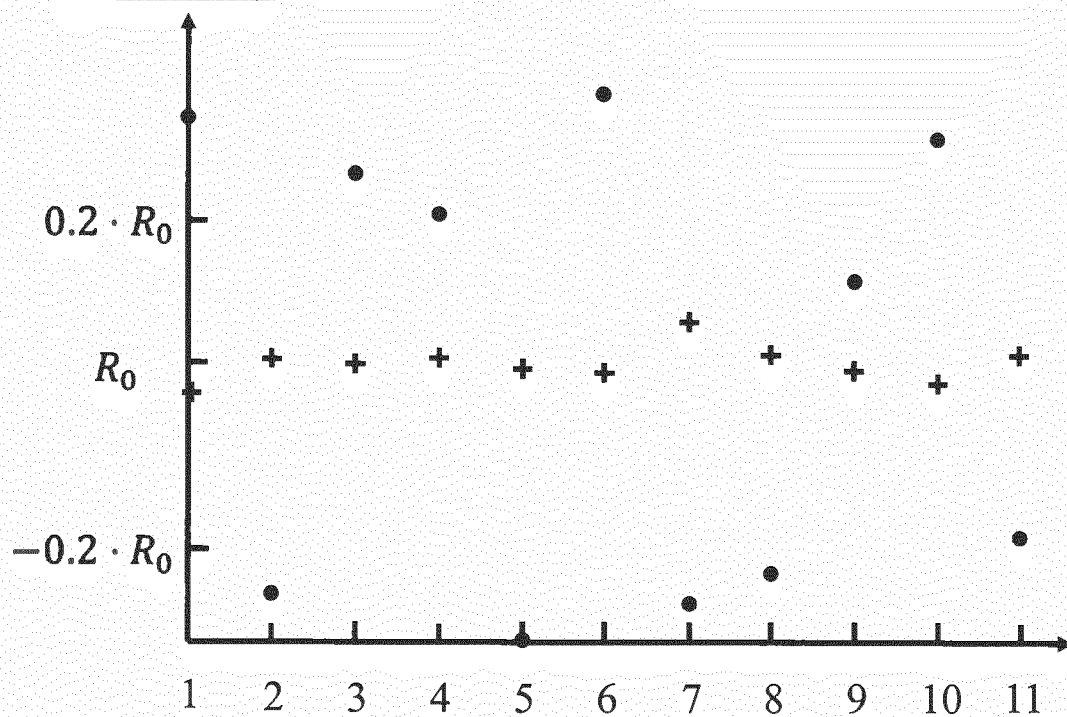
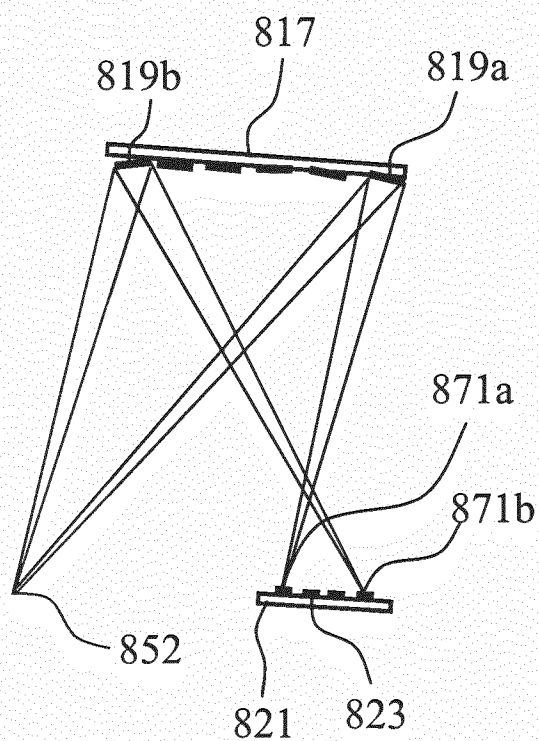
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FIG.8a**FIG.8b**

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FIG.8c**FIG.8d**

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FIG.8e**FIG.8f**

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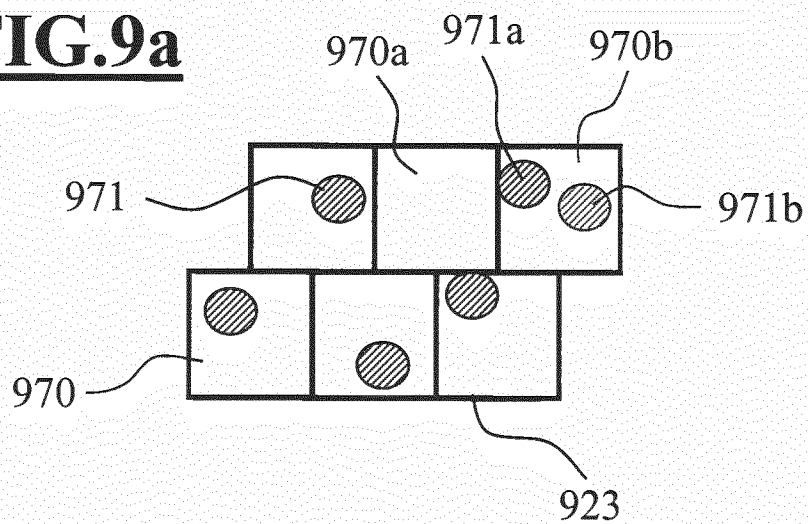
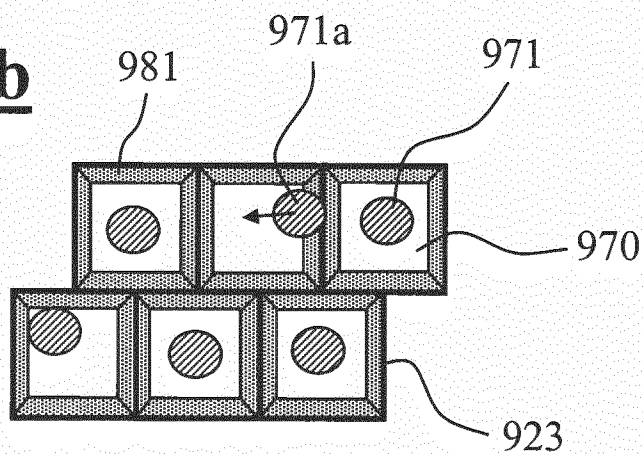
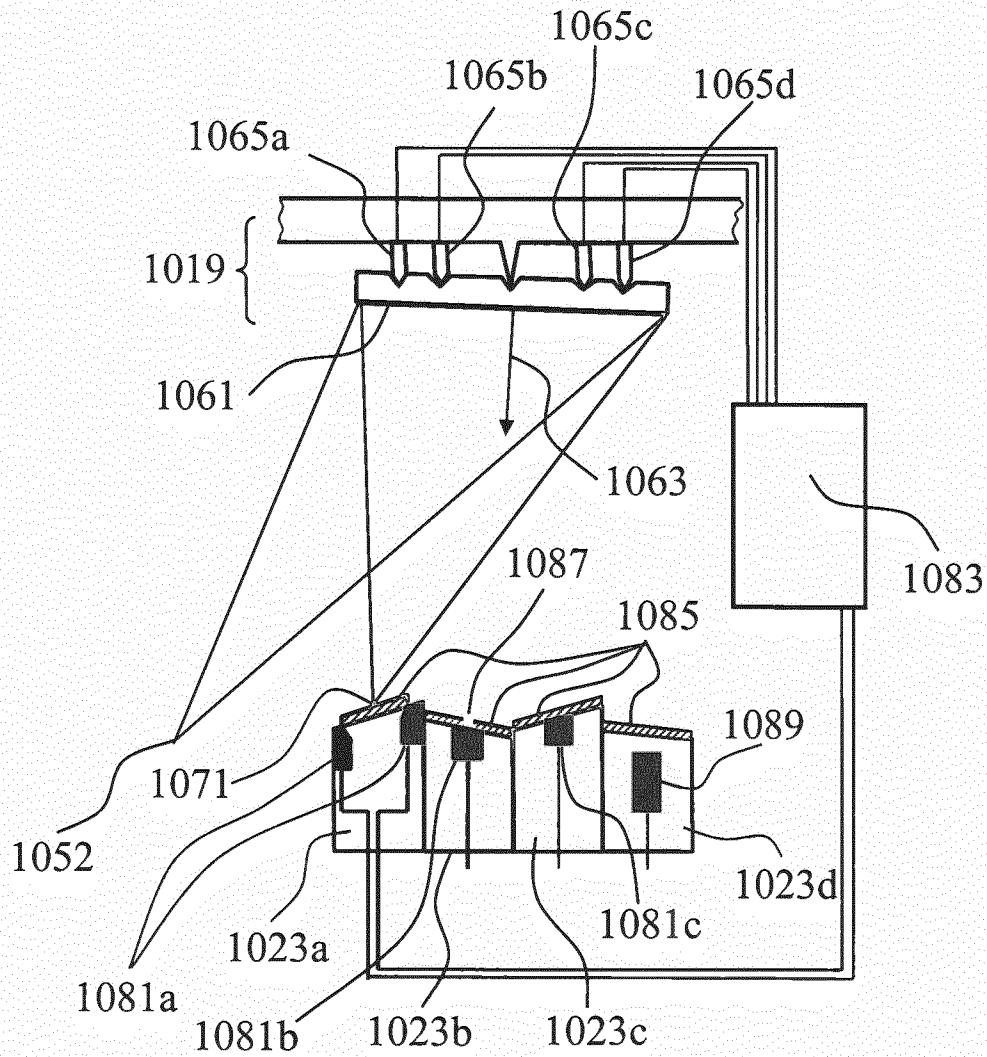
FIG.9a**FIG.9b**

FIG.10

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FIG.11a

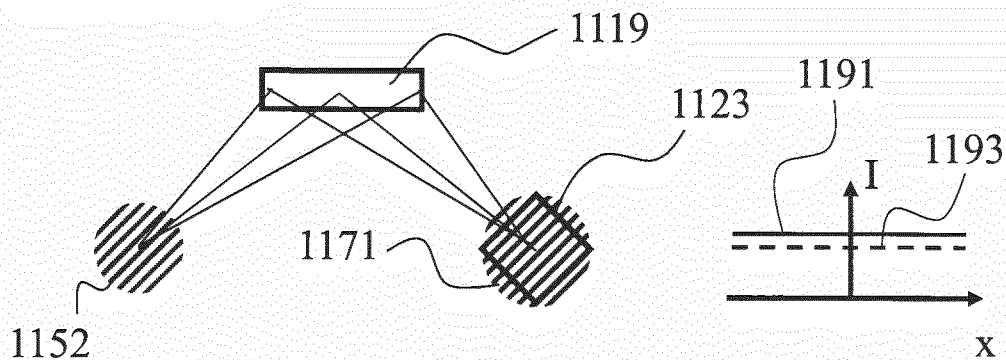


FIG.11b

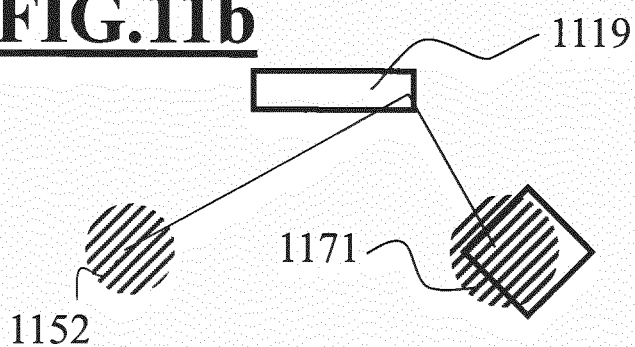


FIG.11c

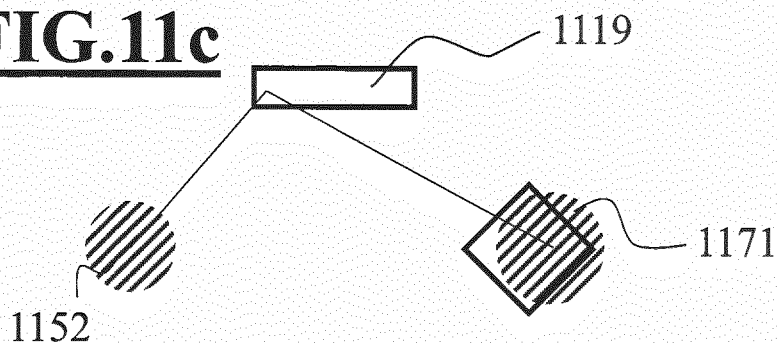
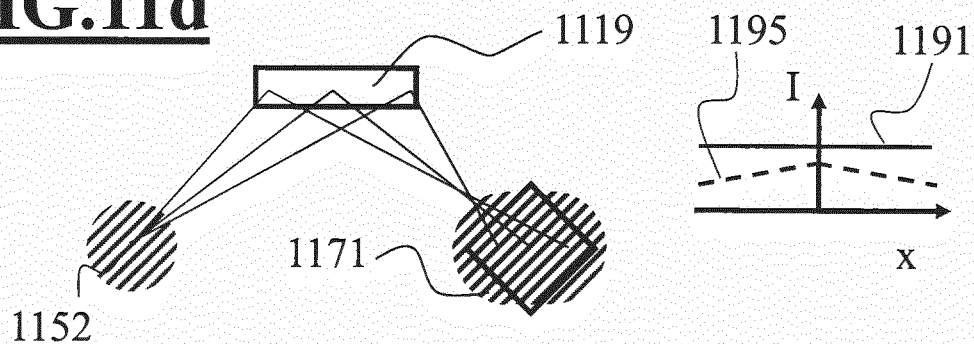


FIG.11d



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/058484

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20
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, 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.
X	US 2008/225259 A1 (SINGER WOLFGANG [DE] ET AL) 18 September 2008 (2008-09-18)	1,2,6,7,11
Y	paragraphs [0076] - [0087]; figures 5a, 5b, 6a, 6b3	3-5, 8-10, 12-14
Y	----- US 2008/225387 A1 (HAENZ JOACHIM [DE] ET AL) 18 September 2008 (2008-09-18) paragraphs [0026], [0027]; figure 1	3-5,9
Y	----- US 2010/231882 A1 (DINGER UDO [DE] ET AL) 16 September 2010 (2010-09-16) claims 10, 11	10
	----- -/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

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

"&" document member of the same patent family

Date of the actual completion of the international search

6 September 2012

Date of mailing of the international search report

25/09/2012

Name and mailing address of the ISA/

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NL - 2280 HV Rijswijk
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Fax: (+31-70) 340-3016

Authorized officer

Eisner, Klaus

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/058484

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	----- US 2011/012010 A1 (MAJOR ANDRAS G [DE]) 20 January 2011 (2011-01-20) paragraphs [0064] - [0069]; figures 2-4 -----	12-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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