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(71) Applicant *(for all designated States except US)*: **NIKON CORPORATION** [JP/JP]; 12-1, Yurakucho 1-chome, Chiyoda-ku, Tokyo, 1008331 (JP).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **KITA, Naonori** [JP/JP]; c/o NIKON CORPORATION, 12-1, Yurakucho 1-chome, Chiyoda-ku, Tokyo, 1008331 (JP).

(74) Agents: **HASEGAWA, Yoshiki** et al.; SOEI PATENT AND LAW FIRM, Marunouchi MY PLAZA (Meiji Yasuda Life Bldg.) 9th fl., 1-1, Marunouchi 2-chome, Chiyoda-ku, Tokyo, 1000005 (JP).

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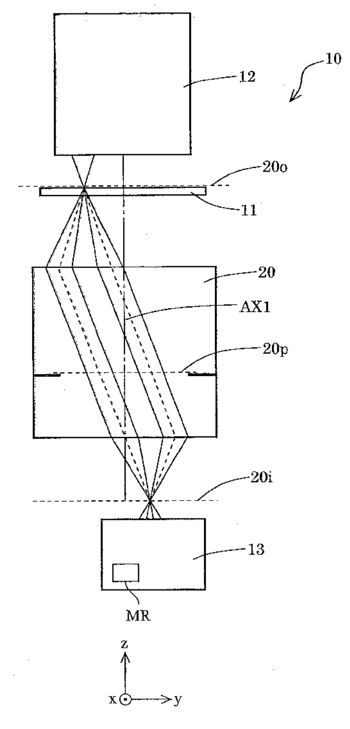
[Continued on next page]

(54) Title: MEASURING METHOD AND MEASURING APPARATUS OF PUPIL TRANSMITTANCE DISTRIBUTION, EXPOSURE METHOD AND EXPOSURE APPARATUS, AND DEVICE MANUFACTURING METHOD

Fig.8



(57) Abstract: The present invention relates to a measuring apparatus and others for accurately and quickly measuring a pupil transmittance distribution of an optical system to be examined, with a relatively low load. The measuring apparatus for measuring the pupil transmittance distribution of the optical system to be examined has a diffraction grating which can be mounted on a first surface in an optical Fourier transform relation with a pupil of the optical system to be examined, an illumination optical system which makes a beam inclined relative to the optical axis, incident to a predetermined position on the first surface so that a + first-order diffracted beam, generated through the diffraction grating, passes through a first pupil partial region in an effective region of the pupil and so that a ? first-order diffracted beam, generated through the diffraction grating, passes through a second pupil partial region, and a measuring unit which measures an intensity of the + first-order diffracted beam, having traveled via the first pupil partial region and the optical system to be examined, and an intensity of the ? first-order diffracted beam, having traveled via the second pupil partial region and the optical system to be examined, and the measuring apparatus determines a ratio of a pupil transmittance in the first pupil partial region and a pupil transmittance in the second pupil partial region, based on a measured value of the intensity of the + first-order diffracted beam and a measured value of the intensity of the ? first-order diffracted beam.

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DESCRIPTION

MEASURING METHOD AND MEASURING APPARATUS OF PUPIL TRANSMITTANCE DISTRIBUTION, EXPOSURE METHOD AND EXPOSURE APPARATUS, AND DEVICE MANUFACTURING METHOD

Technical Field

[0001] The present invention relates to a measuring method and measuring apparatus of pupil transmittance distribution, an exposure method and exposure apparatus, and a device manufacturing method. More particularly, the present invention relates to measurement of a pupil transmittance distribution of a projection optical system mounted on an exposure apparatus used, for example, in manufacturing devices such as semiconductor devices or liquid crystal display devices by a photolithography process.

Background Art

[0002] The photolithography process for manufacture of the semiconductor devices and others is carried out using an exposure apparatus for implementing projection exposure to project a pattern image on a mask (or a reticle) onto a photosensitive substrate (a wafer or a glass plate coated with a photoresist, or the like) through a projection optical system. There is a recently proposed method of measuring a pupil transmittance distribution of the projection optical system in a mounted state on the exposure apparatus on an as-needed basis, in order to improve the contrast of the pattern image formed through the projection optical system (e.g., cf. Non-Patent Document 1).

[0003] In the measuring method disclosed in Non-Patent Document

1, a thin parallel light beam is made normally incident to a predetermined position on a bright/dark type diffraction grating set on the object plane of the projection optical system being an optical system to be examined, and zero-order light and ± first-order diffracted beams generated through the diffraction grating are detected near the image plane of the projection optical system. Then the pupil transmittance distribution of the projection optical system is measured based on the detection result of the intensity of the zero-order light and the detection result of the ± first-order diffracted beams. The "pupil transmittance distribution of an optical system" means a transmittance distribution of a transmittance filter under the condition that by considering light passing an arbitrary position in an effective region of a pupil and defining a ratio of the intensity before incidence and the intensity after emission of the light, the ratio in an ideal optical state in which the transmittance filter is located at the pupil position is coincident with that in a state of an actual optical system.

Patent Document 1: European Patent Application Laid-Open No. 779530 (corresponding to Japanese Patent Application (Translation of PCT Application) Laid-Open No. H10-503300)

Patent Document 2: U.S. Patent No. 6,900,915 (corresponding to Japanese Patent Application Laid-Open No. 2004-78136)

Patent Document 3: U.S. Patent No. 7,095,546 (corresponding to Japanese Patent Application (Translation of PCT Application) Laid-Open No. 2006-524349)

Patent Document 4: Japanese Patent Application Laid-Open No. 2006-113437

Patent Document 5: U.S. Patent Application Laid-Open No.

2008/0030707A1

Patent Document 6: U.S. Patent Application Laid-Open No. 2008/0252876A1 (corresponding to Japanese Patent Application (Translation of PCT Application) Laid-Open No. 2008-502126)

Patent Document 7: U.S. Patent Application Laid-Open No. 2002/0001088A1

Patent Document 8: U.S. Patent Application Laid-Open No. 2005/0078287A1

Patent Document 9: Japanese Patent Application Laid-Open No. 2004-304135

Patent Document 10: U.S. Patent Application Laid-Open No. 2007/0296936 (corresponding to International Publication No. WO2006/080285)

Patent Document 11: International Publication No. WO99/49504

Patent Document 12: Japanese Patent Application Laid-Open No. H6-124873

Patent Document 13: Japanese Patent Application Laid-Open No. H10-303114

Patent Document 14: U.S. Patent Application Laid-Open No. 2006/0170901

Patent Document 15: U.S. Patent Application Laid-Open No. 2007/0146676

Non-Patent Document 1: Kazuya Sato et al., "Measurement of transmittance variation of projection lenses depending on the light paths using a grating-pinhole mask," Proceedings of SPIE Vol. 4346, pp. 379-386, 2001

Disclosure of the Invention

Problems that the Invention is to Solve

[0004] The inventors conducted research on the conventional measuring method of pupil transmittance distribution and found the following problem. Specifically, in the measuring method disclosed in Non-Patent Document 1, the intensity of the ± first-order diffracted light components out of diffracted beams generated through the bright/dark type diffraction grating becomes considerably smaller than that of the zero-order light component, and it is thus necessary to detect each of the components using a very wide dynamic range; it is therefore difficult to accurately measure the pupil transmittance distribution. Furthermore, in order to detect the ± first-order diffracted light components passing a plurality of positions distributed across the entire pupil effective region, it is necessary to prepare a plurality of diffraction gratings with mutually different pitches of bright/dark patterns and to repeat the measurement with each of the diffraction gratings with variation in pitch direction, and the load of the measurement is relatively too high to implement quick measurement.

[0005] The present invention has been accomplished in order to solve the above-described problem and it is an object of the present invention to provide a measuring method and measuring apparatus capable of accurately and quickly measuring a pupil transmittance distribution of an optical system to be examined, with a relatively low load. Another object of the present invention is to provide an exposure apparatus, exposure method, and device manufacturing method capable of forming a pattern image with high contrast, using the measuring method and measuring apparatus for accurately and quickly measuring a pupil transmittance distribution of a projection optical system mounted.

Means for Solving the Problems

[0006] In order to solve the above problem, an embodiment of the present invention provides a measuring method of measuring a pupil transmittance distribution of an optical system to be examined. An aspect of the measuring method comprises a beam supplying step, a beam diffracting step, a region passing step, an intensity measuring step, and a transmittance ratio calculating step. The beam supplying step is to supply a first beam to a predetermined position on a first surface in an optical Fourier transform relation with a pupil of the optical system to be examined. The beam diffracting step is to impart a first phase value to light passing through a first phase region on the first surface and to impart a second phase value different from the first phase value to light passing through a second phase region adjacent to the first phase region, thereby diffracting the first beam. The region passing step is to let a + first-order diffracted beam of the first beam, which is generated through diffraction of the first beam, pass through a first pupil partial region in an effective region of the pupil, and to let a − first-order diffracted beam of the first beam, which is generated through diffraction of the first beam, pass through a second pupil partial region apart from the first pupil partial region in the effective region. The intensity measuring step is to measure an intensity of the + first-order diffracted beam of the first beam, which has traveled via the first pupil partial region and the optical system to be examined, and an intensity of the − first-order diffracted beam of the first beam, which has traveled via the second pupil partial region and the optical system to be examined. The transmittance ratio calculating step is to calculate a ratio of a pupil transmittance in the first pupil partial region and a pupil transmittance in the second pupil partial region, based on a measured value of the intensity of the + first-order diffracted beam of the first beam and a measured value of the intensity of the − first-order diffracted beam of the first beam.

[0007] Another aspect of the measuring method provided by an embodiment of the present invention also comprises a beam supplying step, a beam diffracting step, a region passing step, an intensity measuring step, and a transmittance ratio calculating step. The beam supplying step is to supply a first beam inclined relative to an optical axis of an optical system to be examined, to a predetermined position on a first surface in an optical Fourier transform relation with a pupil of the optical system to be examined. The beam diffracting step is to diffract the first beam. The region passing step is to let a + first-order diffracted beam of the first beam, which is generated through diffraction of the first beam, pass through a first pupil partial region in an effective region of the pupil, and let a − first-order diffracted beam of the first beam, which is generated through diffraction of the first beam, pass through a second pupil partial region apart from the first pupil partial region in the effective region. The intensity measuring step is to measure an intensity of the + first-order diffracted beam of the first beam, which has traveled via the first pupil partial region and the optical system to be examined, and an intensity of the − first-order diffracted beam of the first beam, which has traveled via the second pupil partial region and the optical system to be examined. The transmittance ratio calculating step is to calculate a ratio of a pupil transmittance in the first pupil partial region and a pupil transmittance in the second pupil partial region, based on a measured value of the intensity of the + first-order diffracted beam of the first beam and a measured value of the intensity of the − first-order diffracted beam of the first beam.

[0008] An embodiment of the present invention provides a program for letting a processing unit execute the measuring method of one of the above aspects. An embodiment of the present invention provides a recording medium storing such a program.

[0009] An embodiment of the present invention provides a controlling method of exposure apparatus. The controlling method of exposure apparatus controls an exposure apparatus comprising an illumination optical system for illuminating a predetermined pattern, and a projection optical system for forming an image of the predetermined pattern on a photosensitive substrate. Specifically, the controlling method comprises changing an illumination condition for illumination of the predetermined pattern, based on the measurement result of a pupil transmittance distribution of the projection optical system measured by the measuring method of one of the above aspects.

[0010] An embodiment of the present invention provides an exposure method. An aspect of the exposure method comprises illuminating a predetermined pattern, and performing exposure to transfer the predetermined pattern onto a photosensitive substrate, using a projection optical system. Specifically, the foregoing aspect of the exposure method comprises changing an illumination condition for illumination of the predetermined pattern, based on the measurement result of a pupil transmittance distribution of the projection optical system measured by the measuring method of one of the above aspects.

[0011] Another aspect of the exposure method provided by an embodiment of the present invention also comprises illuminating a predetermined pattern, and performing exposure to transfer the predetermined pattern onto a photosensitive substrate, using a projection optical system. Specifically, the other aspect of the exposure method uses a pattern created based on the measurement result of a pupil transmittance distribution of the projection optical system measured by the measuring method of one of the above aspects.

[0012] An embodiment of the present invention provides a device manufacturing method using the exposure method of one of the above aspects. The device manufacturing method comprises an exposure step, a mask layer forming step, and a processing step. The exposure step is to perform exposure to transfer a predetermined pattern onto a photosensitive substrate, using the exposure method of one of the above aspects. The mask layer forming step is to develop the photosensitive substrate with the predetermined pattern transferred thereon and thereby form a mask layer in a shape corresponding to the predetermined pattern on a surface of the photosensitive substrate. The processing step is to process the surface of the photosensitive substrate through the mask layer.

[0013] An embodiment of the present invention provides a measuring apparatus for measuring a pupil transmittance distribution of an optical system to be examined. The measuring apparatus comprises a diffraction grating, an illumination optical system, and a measuring unit. The diffraction grating is an optical element which can be mounted on a first surface in an optical Fourier transform relation with a pupil of the optical system to be examined and which diffracts light reaching thereto. The illumination optical system makes a beam inclined relative to an optical axis of the optical system to be examined, incident to a predetermined position on the first surface so that a + first-order diffracted beam of the light, which is generated via the diffraction grating set on the first surface, passes through a first pupil partial region in an effective region of the pupil and so that a − first-order diffracted beam of the light, which is generated via the diffraction grating, passes through a second pupil partial region apart from the first pupil partial region in the effective region. The measuring unit measures an intensity of the + first-order diffracted beam of the light, which has traveled via the first pupil partial region and the optical system to be examined, and an intensity of the − first-order diffracted beam of the light, which has traveled via the second pupil partial region and the optical system to be examined. Particularly, the measuring apparatus determines a ratio of a pupil transmittance in the first pupil partial region and a pupil transmittance in the second pupil partial region, based on a measured value of the intensity of the + first-order diffracted beam of the light and a measured value of the intensity of the − first-order diffracted beam of the light.

[0014] An embodiment of the present invention provides an exposure apparatus comprising an illumination optical system for illuminating a predetermined pattern, and a projection optical system for forming an image of the predetermined pattern on a photosensitive substrate. An aspect of the exposure apparatus comprises a control unit which controls the illumination optical system in order to switch an illumination condition of the predetermined pattern, based on the measurement result of a pupil transmittance distribution of the projection optical system measured by the measuring method according to one of the aforementioned aspects.

[0015] Another aspect of the exposure apparatus provided by an embodiment of the present invention also comprises an illumination optical system for illuminating a predetermined pattern, and a projection optical system for forming an image of the predetermined pattern on a photosensitive substrate. The other aspect of the exposure apparatus comprises the aforementioned measuring apparatus for measuring a pupil transmittance distribution of the projection optical system.

[0016] An embodiment of the present invention provides a device manufacturing method using the exposure apparatus according to one of the aforementioned aspects. The device manufacturing method comprises an exposure step, a mask layer forming step, and a processing step. The exposure step is to perform exposure to transfer the predetermined pattern onto the photosensitive substrate, using the exposure apparatus according to one of the aforementioned aspects. The mask layer forming step is to develop the photosensitive substrate with the predetermined pattern transferred thereon, and thereby form a mask layer in a shape corresponding to the predetermined pattern on a surface of the photosensitive substrate. The processing step is to process the surface of the photosensitive substrate through the mask layer.

[0017] An embodiment of the present invention provides a measurement reticle used in carrying out any one of the aforementioned measuring methods. The measurement reticle has the first phase region and the second phase region formed on a surface thereof.

[0018] An embodiment of the present invention provides an aperture stop used in carrying out the measuring method of the other aspect. The aperture stop comprises an aperture formed at a position apart from an optical axis of an illumination optical system, in order to form a light intensity distribution localized at the position apart from the optical axis of the illumination optical system on a first conjugate plane optically conjugate with the pupil in an optical path of the illumination optical system for supplying the first beam.

[0019] An embodiment of the present invention provides a spatial light modulator used in carrying out the measuring method of the other aspect. The spatial light modulator provides an angle distribution to a beam traveling toward a first conjugate plane, in order to form a light intensity distribution localized at a position apart from an optical axis of an illumination optical system on the first conjugate plane optically conjugate with the pupil in an optical path of the illumination optical system for supplying the first beam.

[0020] An embodiment of the present invention provides a controlling method of a spatial light modulator used in carrying out the measuring method of the other aspect. The controlling method of the spatial light modulator controls the spatial light modulator so as to provide an angle distribution to a beam traveling toward a first conjugate plane, in order to form a light intensity distribution localized at a position apart from an optical axis of an illumination optical system on the first conjugate plane optically conjugate with the pupil in an optical path of the illumination optical system for supplying the first beam.

[0021] An embodiment of the present invention provides a program for letting a processing unit execute the foregoing controlling method of the spatial light modulator. An embodiment of the present invention provides a recording medium storing such a program.

[0022] Each of embodiments according to the present invention will become fully understood in view of the following detailed description and accompanying drawings. These embodiments will be presented by way of illustration only and should not be construed as limiting the invention.

[0023] The scope of further application of the present invention will become clear from the following detailed description. However, the detailed description and specific examples, showing the preferred embodiments of the present invention, are provided by way of illustration only, and it is clear that various modifications and improvements in the scope of the present invention are obvious to those skilled in the art in view of the detailed description.

Effects of the Invention

[0024] In the measuring apparatus according to an embodiment of the invention, the intensities of the ± first-order diffracted light components as measurement targets out of the diffracted beams generated through the phase diffraction grating mounted on the object plane in the optical Fourier transform relation with the pupil of the optical system to be examined are equal to each other, and therefore the measuring unit is able to accurately detect each of the diffracted light components, using a relatively narrow dynamic range, and to accurately measure the pupil transmittance distribution of the optical system to be examined. Since the regions where the respective diffracted light components pass through the pupil of the optical system to be examined can be varied by simply changing the angle of incidence of the measurement beam incident to the phase diffraction grating stationarily mounted on the object plane of the optical system to be examined, the pupil transmittance distribution of the optical system to be examined can be quickly measured with a relatively low load.

Brief Description of the Drawings

[0025] Fig. 1 is a drawing schematically showing a configuration of a measuring apparatus for measurement of a pupil transmittance distribution according to the first embodiment;

Fig. 2 is a drawing schematically showing a configuration of a phase type diffraction grating shown in Fig. 1;

Fig. 3 is a drawing schematically showing an internal configuration of an illumination optical system shown in Fig. 1;

Fig. 4 is a drawing schematically showing an internal configuration of a measuring unit shown in Fig. 1;

Fig. 5 is a drawing showing a state in which a calibration phase diffraction grating and others are formed on an entrance plane of an objective optical system in the measuring unit;

Fig. 6 is a drawing showing a state in which an aperture stop is arranged at a position of an illumination pupil;

Fig. 7 is a drawing showing a pair of pupil partial regions where ± first-order diffracted beams generated through a diffraction grating pass through a pupil of an imaging optical system;

Fig. 8 is a drawing showing a state in which a pair of beams are obliquely incident simultaneously to a predetermined position on a diffraction grating to generate first ± first-order diffracted beams and second ±

first-order diffracted beams;

Fig. 9 is a drawing for explaining a technique for detecting an error of the measurement result caused by a pupil transmittance distribution of the objective optical system in the measuring unit;

Fig. 10 is a drawing schematically showing an internal configuration of a PDI/LDI type measuring unit;

Fig. 11 is a drawing showing a state in which a calibration phase diffraction grating and others are formed on an entrance plane of an optically transparent substrate in the measuring unit of Fig. 10;

Fig. 12 is a drawing schematically showing a major configuration of a measuring unit making use of a shearing interferometer;

Fig. 13 is a drawing showing a state in which a calibration phase diffraction grating and others are formed on an entrance plane of an optically transparent substrate in the measuring unit of Fig. 12;

Fig. 14 is a drawing schematically showing a configuration of an exposure apparatus according to the second embodiment of the present invention;

Fig. 15 is a drawing schematically showing an internal configuration of an illumination optical system shown in Fig. 14;

Fig. 16 is a drawing showing a measurement state of a pupil transmittance distribution of a projection optical system in the second embodiment;

Fig. 17 is a drawing showing a state in which a measurement aperture stop is arranged at a position of an illumination pupil;

Fig. 18 is a drawing schematically showing a phase grating formed on a measurement reticle shown in Fig. 14;

Fig. 19 is a drawing showing four pupil partial regions where ± first-order diffracted beams generated through a measurement reticle from one aperture of a measurement aperture stop pass through a pupil of the projection optical system;

Fig. 20 is a drawing showing thirty six pupil partial regions where ± first-order diffracted beams generated through a measurement reticle from nine apertures of a measurement aperture stop pass through the pupil of the projection optical system;

Fig. 21 is a drawing showing sixteen pupil partial regions where ± first-order diffracted beams and ± third-order diffracted beams generated through a measurement reticle from one aperture of a measurement aperture stop pass through the pupil of the projection optical system;

Fig. 22 is a drawing showing thirty two pupil partial regions where ± first-order diffracted beams and ± third-order diffracted beams generated through a measurement reticle from two adjacent apertures of a measurement aperture stop pass through the pupil of the projection optical system;

Fig. 23 is a drawing for explaining a technique for supplementing relative ratio information of pupil transmittance distribution of the projection optical system;

Fig. 24 is a flowchart showing steps of manufacturing semiconductor devices; and

Fig. 25 is a flowchart showing steps of manufacturing a liquid crystal device such as a liquid crystal display device.

Description of the Reference Numerals

[0026] 10, 10'···measuring apparatus; 11···diffraction grating; 12···illumination optical system; 13, 13A, 13B···measuring unit; 20···imaging optical system; 51···beam sending system; 52···beam shape varying unit;

53 ··· micro fly's eye lens; 54 ··· illumination aperture stop; 54a ··· measurement aperture stop; 55···condenser optical system; 56···mask blind; 57···illumination imaging optical system; LS, 21···light source; IL ··· illumination optical system; TR ··· measurement reticle; CR ··· controller; MR···memory (recording medium); M···mask; MS···mask stage; PL···projection optical system; W···wafer; and WS···wafer stage.

Best Modes for Carrying Out the Invention

[0027] Embodiments of the present invention will be described on the basis of the accompanying drawings. Fig. 1 is a drawing schematically showing a configuration of a measuring apparatus for pupil transmittance distribution according to the first embodiment. Specifically, the first embodiment is an application to a measuring apparatus 10 for measuring a pupil transmittance distribution of imaging optical system 20 as an optical system to be examined. In Fig. 1, the z-axis is set along a direction of a normal to an image plane 20i of the imaging optical system 20, the y-axis along a direction parallel to the plane of Fig. 1 on the image plane 20i, and the x-axis along a direction normal to the plane of Fig. 1 on the image plane 20i.

[0028] The measuring apparatus 10 of the first embodiment is provided with a phase type diffraction grating 11 which can be mounted on an object plane 20o of the imaging optical system 20, an illumination optical system 12 which makes a measurement beam incident at a predetermined position on the object plane 20o (and, therefore, at a predetermined position on the diffraction grating 11), and a measuring unit 13 which measures the intensity of the measurement beam having traveled through the imaging optical system 20. The diffraction grating

11, as shown in Fig. 2, has a form in which first phase regions 11a to impart a first phase value to transmitted light and second phase regions 11b to impart a second phase value different by π from the first phase value, to transmitted light are alternately arranged along one direction.

[0029] It is assumed in the description hereinafter that the diffraction grating 11 is mounted so that the pitch direction of the phase regions 11a, 11b coincides with the y-direction and so that a diffraction optical surface thereof coincides with the object plane 20o. It is also assumed that the imaging optical system 20 and the illumination optical system 12 are coaxially arranged so that their optical axes AX1 and AX2 (cf. Fig. 3) are aligned along a straight line extending in the z-direction. The illumination optical system 12, as shown in Fig. 3, is provided with a spatial light modulator 12a and a first relay optical system 12b which form a predetermined light intensity distribution on an illumination pupil 12p, based on light from a light source 21, an aperture stop 12c which can be inserted into or retracted from an illumination optical path at the illumination pupil 12p, and a second relay optical system 12d which guides light having passed through the aperture stop 12c, to the object plane 20o of the imaging optical system 20.

[0030] The light source 21 supplies, for example, the light to be used in the imaging optical system 20. The spatial light modulator 12a applicable herein is a diffractive optical element, a mirror array, or the like. The mirror array is a spatial light modulator with a plurality of mirror elements individually controllable as arrayed in a predetermined plane, and its configuration and action are disclosed, for example, in Patent Documents 1 to 4 above. The illumination pupil 12p is in an optical

Fourier transform relation with the object plane 20o of the imaging optical system 20 and is located at a position optically conjugate with a pupil 20p of the imaging optical system 20. The disclosures of Patent Documents 1 to 4 above are incorporated herein by reference.

[0031] The measuring unit 13, as shown in Fig. 4, is provided with an objective optical system 13a which forms a plane 13p in an optical Fourier transform relation with the image plane 20i of the imaging optical system 20, and a photoelectric detector 13b which has a detection surface 13ba arranged along the plane 13p, and is configured so as to be integrally movable along the xy plane. Namely, the objective optical system 13a is arranged in an optical path between the plane 13p optically conjugate with the pupil 20p of the imaging optical system 20, and the imaging optical system 20, and the detection surface 13ba of the photoelectric detector 13b is arranged along the pupil plane 13p of the objective optical system 13a. The photoelectric detector 13b applicable herein is, for example, a solid-state image sensing device such as a CCD image sensor or CMOS image sensor, an image pickup tube, or the like.

[0032] A planoconvex lens 13aa with a plane along the image plane 20i of the imaging optical system 20 is arranged at a position nearest to the imaging optical system 20, in the objective optical system 13a. Formed on the entrance plane 13i of the planoconvex lens 13aa are, as shown in Fig. 5, a shield portion 13e, for example, made of chromium or chromium oxide, a measurement aperture 13f, a calibration pinhole 13g for calibration of wavefront aberration measurement result, and a calibration phase diffraction grating 13h for calibration of pupil transmittance distribution measurement result. The portions except for the calibration phase diffraction grating 13h in the configuration of the measuring unit 13 are disclosed, for example, in Patent Document 5 above. The disclosure of Patent Document 5 above is incorporated herein by reference. The measuring unit 13 may be a processing unit (computer) with a recording medium such as a memory MR, and this memory MR stores a program for letting the processing unit execute a measuring method, and controlling methods of exposure apparatus and the spatial modulator 12a according to the present embodiment.

[0033] For facilitating understanding of action of the measuring apparatus 10, a case using an aperture stop 12c with a single aperture 31 of a circular shape as shown in Fig. 6 will be considered below as the simplest example. In Fig. 6, a circle indicated by a dashed line around the optical axis AX2 as a center represents an effective region on the illumination pupil 12p. The aperture stop 12c is mounted so that the center of the aperture 31 is located apart in the − y-direction from the optical axis AX2, and a beam is incident to a required region including the aperture 31 on the aperture stop 12c. In this case, the aperture stop 12c functions as a localized beam forming unit which forms a circular localized beam with a light intensity distribution localized at a position apart from the optical axis AX2 on the illumination pupil 12p optically conjugate with the pupil 20p of the imaging optical system 20.

[0034] A beam through the aperture 31 of the aperture stop 12c travels through the second relay optical system 12d to be incident as a beam inclined relative to the optical axis AX1 of the imaging optical system 20 (and, therefore, relative to the optical axis AX2 of the illumination optical system 12), to a predetermined position on the diffraction grating 11 (and, therefore, to a predetermined position on the object plane 20o of the imaging optical system 20). The position of incidence of the oblique beam to the diffraction grating 11 is variably determined, for example, by a field stop (not shown) located at or near a position optically conjugate with the object plane 20o in the optical path of the second relay optical system 12d consisting of a plurality of lenses or by a field stop (not shown) located at a position immediately in front of the object plane 20o.

[0035] For simplicity of description, it is assumed below that the illumination pupil 12p of the illumination optical system 12 and the pupil 20p of the imaging optical system 20 are in a conjugate relation to form an erect image of the illumination pupil 12p on the pupil 20p with respect to the x-direction and the y-direction. With reference to Figs. 1 and 7, of diffracted light generated by oblique incidence to the diffraction grating 11, a + first-order diffracted beam 40a (or 40b) passes a pupil partial region 41a in an effective region 20pe of the pupil 20p of the imaging optical system 20 and a − first-order diffracted beam 40b (or 40a) passes a pupil partial region 41b apart from the pupil partial region 41a in the pupil effective region 20pe, each of which is emitted from the imaging optical system 20. The pupil partial regions 41a and 41b have a circular shape as the aperture 31 does, and have the same size.

[0036] The pupil partial regions 41a and 41b are located at positions symmetric with respect to a point 41c on a straight line passing the optical axis AX1 and extending in the y-direction on the pupil effective region 20pe. The point 41c herein is a center of a region which a zero-order beam passes on the pupil 20p if the zero-order beam is generated through the diffraction grating 11 (which is indicated by a dashed line in Fig. 1). Namely, the center position 41c between the pupil partial regions 41a and 41b is dependent upon the position of the aperture 31 of the aperture stop 12c. The size of the pupil partial regions 41a and 41b is dependent upon the size of the aperture 31 of the aperture stop 12c. The center-center distance between the pupil partial regions 41a and 41b is dependent upon the pitch of the phase regions 11a, 11b in the diffraction grating 11.

[0037] With reference to Figs. 1, 3, and 5, the + first-order diffracted beam 40a through the pupil partial region 41a and imaging optical system 20 and the − first-order diffracted beam 40b through the pupil partial region 41b and imaging optical system 20 travel through the measurement aperture 13f of the measuring unit 13 to enter the objective optical system 13a. The first-order diffracted beams 40a, 40b through the objective optical system 13a impinge on the detection surface 13ba arranged on the pupil plane 13p of the objective optical system 13a, to be detected by the photoelectric detector 13b. For clarity of the drawing, Fig. 1 shows a state in which the measuring unit 13 is arranged with a space below the image plane 20i of the imaging optical system 20.

[0038] It is assumed below for simplicity of description that the intensity of the + first-order diffracted beam 40a and the intensity of the − first-order diffracted beam 40b generated through the diffraction grating 11 are identical with each other and that a ratio of the intensities of the + first-order diffracted beam 40a and the − first-order diffracted beam 40b at the image plane 20i of the imaging optical system 20 is coincident with a ratio of the intensities of the + first-order diffracted beam 40a and the − first-order diffracted beam 40b detected on the detection surface 13ba of the measuring unit 13. In other words, it is assumed that the measuring unit 13 is able to accurately measure the intensity ratio of the + first-order diffracted beam 40a and the − first-order diffracted beam 40b at the image plane 20i of the imaging optical system 20, without being affected by a pupil transmittance distribution of the objective optical system 13a or the like.

[0039] In this case, the measuring apparatus 10 calculates a ratio of a pupil transmittance in the pupil partial region 41a and a pupil transmittance in the pupil partial region 41b, based on a measured value of the intensity of the + first-order diffracted beam 40a and a measured value of the intensity of the − first-order diffracted beam 40b, and measures a pupil transmittance distribution of the imaging optical system 20 about the pupil partial regions 41a and 41b eventually. The pupil transmittance distribution to be measured by the measuring apparatus 10 is not a distribution of absolute values of pupil transmittances in the pupil effective region 20pe, but relative ratio information of pupil transmittance distribution, e.g., a normalized distribution with the pupil transmittance of 1 at the center of the pupil effective region 20pe (or at the position of the optical axis AX1).

[0040] For measuring the pupil transmittance distribution of the imaging optical system 20 about the pair of pupil partial regions 41a and 41b spaced from each other, the measuring apparatus 10 is configured so that the aperture 31 is arranged at a position optically corresponding to the midpoint 41c in a line segment connecting the center of the pupil partial region 41a and the center of the pupil partial region 41b. This means that a set of ratios of pupil transmittances in any paired pupil partial regions are obtained by repeating the measurement with the measuring unit 13 with step movement of the aperture stop 12c along the xy plane so as to locate the aperture 31 at a position corresponding to a pair of pupil partial regions to be measured in the pupil effective region 20pe and, therefore, that a pupil transmittance distribution of the imaging optical system 20 can be measured about a desired number of pupil partial regions according to a desired distribution.

[0041] Specifically, the relative information of pupil transmittances among a desired number of pupil partial regions distributed across the entire pupil effective region 20pe is obtained by successively determining the ratio of pupil transmittances in any pair of pupil partial regions while performing step movement of the aperture stop 12c along the xy plane and thereby changing the angle of incidence of the measurement light to the diffraction grating 11. Then a two-dimensional pupil transmittance distribution of the imaging optical system 20 is directly obtained as a functional distribution, for example, by the Zernike fitting process for a distribution of relative values of these discrete pupil transmittances in the pupil effective region 20pe. For the technique of obtaining the functional distribution by the Zernike fitting process for the distribution of discrete measured values, reference can be made to the ordinary Zernike fitting process for wavefront aberration, and it can be calculated by the linear least-squares method.

[0042] In the measuring apparatus 10, the diffraction grating 11 also generates zero-order light, ± third-order diffracted light, ± fifth-order diffracted light, etc. due to manufacturing error of the diffraction grating. In this case, the ± third-order diffracted light, ± fifth-order diffracted light, etc. should be excluded from the measurement and set away from the ± first-order diffracted beams of measurement targets on the pupil 20p of the imaging optical system 20. In practice, however, the intensity of the ± fifth-order diffracted light (and higher-order diffracted light) is negligibly smaller than the intensity of the ± first-order diffracted beams of measurement targets. A setting technique for avoiding overlapping of the ± first-order diffracted beams with the zero-order light and ± third-order diffracted light on the pupil of the optical system to be examined will be specifically described in the second embodiment.

[0043] In the measuring apparatus 10, as described above, the diffraction grating 11 can be mounted on the object plane 20o in the optical Fourier transform relation with the pupil 20p of the imaging optical system 20 as an optical system to be examined. The illumination optical system 12 makes the inclined beam relative to the optical axis AX1 of the imaging optical system 20 (provided, however, that inclusion of a normally incident beam is not excluded) incident to the predetermined position on the object plane 20o so that the + first-order diffracted beam 40a generated through the diffraction grating 11 on the object plane 20o passes through the pupil partial region 41a in the pupil effective region 20pe and so that the − first-order diffracted beam 40b generated through the diffraction grating 11 passes through the pupil partial region 41b apart from the pupil partial region 41a in the pupil effective region 20pe. The measuring unit 13 measures the intensity of the + first-order diffracted beam 40a having traveled via the pupil partial region 41a and the imaging optical system 20 and the intensity of the − first-order diffracted beam 40b having traveled via the pupil partial region

41b and the imaging optical system 20.

[0044] Since the measuring apparatus 10 of the first embodiment employs the phase diffraction grating 11 in which the two types of phase regions 11a and 11b are alternately arranged, the intensities of the ± first-order diffracted light components as measurement targets among the diffracted beams generated through the diffraction grating 11 are equal to each other. As a consequence, high-accuracy detection of each diffracted light component can be performed using a relatively narrow dynamic range by the photoelectric detector 13b of the measuring unit 13 and therefore the pupil transmittance distribution of the imaging optical system 20 can be measured with high accuracy. Since the measuring apparatus uses the phase diffraction grating 11 in which the two types of phase regions 11a and 11b with the phase difference of π are alternately arranged, it is able to perform high-accuracy detection of each component, without affecting the measurement of the intensities of the ± first-order diffracted light components by generation of the zero-order light which is an unmeasured beam.

[0045] Furthermore, the measuring apparatus is able to quickly measure the pupil transmittance distribution of the imaging optical system 20 with a relatively low load by simply performing the step movement of the aperture stop 12c with the single aperture 31 a required number of times along the xy plane, without need for changing the posture of the diffraction grating 11 (to change the pitch direction) or for replacing the diffraction grating 11 with another diffraction grating having a different property (e.g., a different pitch). In other words, the measuring apparatus is able to quickly measure the pupil transmittance distribution of the imaging optical system 20 with a relatively low load, by simply changing the angle of incidence of the measurement light to the diffraction grating 11 by the step movement of the aperture 31 of the aperture stop 12c along the xy plane in a state in which the diffraction grating 11 is stationarily set.

[0046] It is important in the measuring apparatus 10 of the first embodiment that the pupil partial regions 41a and 41b be separated from each other in order to accurately detect the intensities of the respective diffracted light components, and it is also important that the size of the pupil partial regions 41a, 41b (and, therefore, the size of the aperture 31) be controlled at some small level in order to accurately measure the pupil transmittance distribution. Namely, since the center-center distance between the pair of pupil partial regions 41a, 41b optically corresponding to the aperture 31 of the aperture stop 12c does not have to be set excessively large, the pitch of the phase regions 11a and 11b in the diffraction grating 11 does not have to be set excessively small, which eventually facilitates manufacture of the diffraction grating 11.

[0047] In the description about the above-described first embodiment, the measurement by the measuring unit 13 is repeatedly carried out with the step movement of the aperture stop 12c provided with the single aperture 31. However, without having to be limited to this, it is also possible to use an aperture stop provided with a plurality of apertures, and use of such an aperture stop reduces the number of step movements and, therefore, the number of measurements by the measuring unit, thereby permitting quicker measurement of the pupil transmittance distribution of the imaging optical system 20. As an example, Fig. 8 shows a setup wherein a first beam and a second beam through a pair of apertures arranged in symmetry in the y-direction with the optical axis AX2 in between on the illumination pupil 12p are simultaneously obliquely incident to a predetermined position on the diffraction grating 11 to generate first ± first-order diffracted beams from the first beam and second ± first-order diffracted beams from the second beam.

[0048] It is also possible to adopt another setup using an aperture stop 12c with a plurality of apertures arranged according to a required distribution, wherein beams as many as the apertures are simultaneously supplied to a predetermined position on the diffraction grating 11 and the pupil transmittance distribution of the imaging optical system 20 is collectively measured based on ± first-order diffracted beams generated from the respective beams. In this case, there is no need for the step movement of the aperture stop 12c and the measurement by the measuring unit 13 is only one measurement, thereby enabling the quickest measurement of the pupil transmittance distribution. A technique for collectively measuring the pupil transmittance distribution of the optical system to be examined, using the aperture stop with a plurality of apertures will be specifically described in the second embodiment.

[0049] In the description about the above-described first embodiment, the aperture stop 12c functions as a localized beam forming unit which forms the circular localized beam with the light intensity distribution localized at the position apart from the optical axis AX2 on the illumination pupil 12p. However, without having to be limited to this, a variety of forms can be contemplated as to the number, shape, size, position, etc. of the localized beam or beams formed on the illumination pupil. Specifically, it is possible, for example, to provide an aperture of a polygonal shape in order to form a localized beam of a polygonal shape, or to arrange an aperture at the position of the optical axis AX2 as well so as to include a localized beam localized at the position of the optical axis AX2.

[0050] Instead of the aperture 12c or in addition to the aperture stop 12c, the spatial light modulator 12a may be arranged to function as a localized beam forming unit. In this case, the spatial light modulator 12a as a localized beam forming unit provides an angle distribution to the beam traveling toward the illumination pupil 12p, in order to form at least one light intensity distribution localized at a position apart from the optical axis AX2 on the illumination pupil 12p. Specifically, the spatial light modulator 12a applicable may be only diffractive optical elements, only a mirror array, or a combination of a diffractive optical element and a mirror array.

[0051] In the case using only the diffractive optical elements, it is necessary to prepare a plurality of diffractive optical elements with different properties and to set a required diffractive optical element in the illumination optical path according to an angle of incidence necessary for the beam incident to the diffraction grating 11. In the case using only the mirror array, it is sufficient that a plurality of mirror elements be individually controlled according to an angle of incidence necessary for the beam incident to the diffraction grating 11. Specifically, by individually controlling the plurality of mirror elements in the mirror array, one or more beams may be made successively incident to the diffraction grating 11 with change in the angle of incidence, or a plurality of beams with various angles of incidence may be made simultaneously incident to the diffraction grating 11.

[0052] In the description about the above-described first embodiment, the diffraction grating 11 used is the phase diffraction grating having the form in which the two types of phase regions 11a and 11b with the phase difference of π are alternately arranged along one direction. However, without having to be limited to this, a variety of forms can be contemplated as to the specific configuration of the diffraction grating. For example, it is possible to use a diffraction grating in a form in which two types of phase regions with an appropriate phase difference except for π are alternately arranged along one direction. In this case, the zero-order light is generated, but it is possible to adopt such a setup that the zero-order light is excluded from the measurement and that the zero-order light does not overlap with the ± first-order diffracted beams on the pupil 20p of the imaging optical system 20.

[0053] It is also possible, for example, to use a diffraction grating wherein two types of rectangular phase regions are arranged so as to form a check flag pattern, i.e., a diffraction grating in a form wherein two types of rectangular phase regions are arranged in a checkered pattern. In this case, a pair of + first-order diffracted beams and a pair of − first-order diffracted beams are generated from a beam incident to the diffraction grating. A technique for measuring the pupil transmittance distribution of the optical system to be examined, using a diffraction grating in a form in which two types of rectangular phase regions with the phase difference of π are arranged in a checkered pattern will be specifically described in the second embodiment.

[0054] Furthermore, a bright/dark type diffraction grating may also be used instead of the phase type diffraction grating 11. In this case, the pupil transmittance distribution of the optical system to be examined can be quickly measured with a relatively low load while changing the angle of incidence of the measurement light incident to the diffraction grating stationarily mounted at the position in the optical Fourier transform relation with the pupil of the optical system to be examined. Namely, there is no need for preparing a plurality of diffraction gratings with different pitches of bright/dark patterns and repeating the measurement with each diffraction grating while changing the pitch direction.

[0055] In the description about the above-described first embodiment, it is assumed that the measuring unit 13 can accurately measure the intensity ratio of the + first-order diffracted beam 40a and the − first-order diffracted beam 40b, without being affected by the pupil transmittance distribution of the objective optical system 13a. However, if the influence of the pupil transmittance distribution of the objective optical system 13a is not so small as negligible, the following technique can be applied to detect an error of the measurement result due to the pupil transmittance distribution of the objective optical system 13a and calibrate the measurement result of the pupil transmittance distribution of the imaging optical system 20 therewith.

[0056] For performing the operation to detect the error of the measurement result due to the pupil transmittance distribution of the objective optical system 13a (i.e., a calibration operation of the measuring unit 13), as shown in Fig. 9, a plane-parallel plate 14 with the same thickness and same refractive index as the diffraction grating 11, for example, is mounted instead of the diffraction grating 11 on the object plane 20o of the imaging optical system 20. Then the measuring unit 13 is positioned along the xy plane so that a beam from the aperture 31 having entered a predetermined position on the plane-parallel plate 14 (the same position as the position of incidence of the measurement beam to the diffraction grating 11) and having traveled through the imaging optical system 20 passes the calibration phase diffraction grating 13h. The calibration phase diffraction grating 13h has a form in which two types of phase regions with the phase difference of π are alternately arranged along the y-direction, as the diffraction grating 11 does.

[0057] In this case, for example, the calibration beam (beam not diffracted by the plane-parallel plate 14) having been emitted from the aperture 31 of the aperture stop 12c mounted as shown in Fig. 6 and having passed through the plane-parallel plate 14 and imaging optical system 20 is diffracted by the calibration phase diffraction grating 13h. A + first-order diffracted beam 42a (or 42b) and a − first-order diffracted beam 42b (or 42a) generated through the calibration phase diffraction grating 13h travel through the objective optical system 13a to impinge on the detection surface 13ba of the photoelectric detector 13 arranged on the pupil plane 13p of the objective optical system 13a.

[0058] The measuring unit 13 measures the intensity of the + first-order diffracted beam 42a and the intensity of the − first-order diffracted beam 42b. The calibration phase diffraction grating 13h is configured so as to make the + first-order diffracted beam 42a corresponding to the + first-order diffracted beam 40a described with reference to Fig. 1 and make the − first-order diffracted beam 42b corresponding to the − first-order diffracted beam 40b. As a result, the measuring unit 13 calibrates the calculation result of the ratio of pupil transmittances in the pair of pupil partial regions 41a, 41b, using the measured values of intensities of the + first-order diffracted beam 42a and the − first-order diffracted beam 42b. Furthermore, the measurement by the measuring unit 13 is repeated with step movement of the aperture stop 12c with the aperture 31 along the xy plane, thereby calibrating the calculation result of the ratio of pupil transmittances in any pair of pupil partial regions in the pupil effective region 20pe of the imaging optical system 20. In this manner, the measuring apparatus is able to detect the error of the measurement result due to the pupil transmittance distribution of the objective optical system 13a and calibrate the measurement result of the pupil transmittance distribution of the imaging optical system 20 therewith.

[0059] When the aperture stop used is one provided with a plurality of apertures, it can reduce the number of step movements thereof and, therefore, the number of measurements by the measuring unit, thereby enabling quicker detection of the error of the measurement result due to the pupil transmittance distribution of the objective optical system 13a. In another case where the aperture stop used is one with a plurality of apertures arranged according to a required distribution, the measuring apparatus is able to simultaneously supply beams as may as the apertures to a predetermined position on the plane-parallel plate 14 and to collectively detect the error of the measurement result due to the pupil transmittance distribution of the objective optical system 13a on the basis of the ± first-order diffracted beams generated through the calibration phase diffraction grating 13h from the respective beams.

[0060] In accordance with the configuration of the diffraction grating 11 used in the measurement of the pupil transmittance distribution of the imaging optical system 20, the calibration phase diffraction grating 13h to be used can be a diffraction grating in a form in which two types of phase regions with an appropriate phase difference except for π, for example, are alternately arranged along one direction. The calibration phase diffraction grating 13h also applicable herein is a diffraction grating in which, for example, two types of rectangular phase regions are arranged so as to form a check flag pattern, i.e., a diffraction grating in a form in which two types of rectangular phase regions are arranged in a checkered pattern.

[0061] In the description about the above-described first embodiment, the measuring unit 13 has the objective optical system (measurement optical system) 13a, and the photoelectric detector 13b which detects the ± first-order diffracted light components through photoelectric conversion on the pupil plane (plane optically conjugate with the pupil 20p of the imaging optical system 20) 13p of the objective optical system 13a. However, a variety of forms can be contemplated as to the specific configuration of the measuring unit. For example, as shown in Fig. 10, it is also possible to use a measuring unit 13A employing a PDI (Point Diffraction Interferometer) or LDI (Line Diffraction Interferometer).

[0062] The PDI/LDI type measuring unit 13A as described above is provided with an optically transparent substrate 13Aa having a planar entrance surface 13Ai, and a photoelectric detector 13b having a detection surface 13ba arranged in contact with a planar exit surface 13Aj of the optically transparent substrate 13Aa. Formed on the entrance plane 13Ai of the optically transparent substrate 13Aa, as shown in Fig. 11, are a shield portion 13Ae, for example, made of chromium or chromium oxide, a measurement aperture 13Af, a pinhole 13Ag for generation of spherical reference wave, and a calibration phase diffraction grating 13Ah for calibration of the pupil transmittance distribution measurement result. The portions except for the calibration phase diffraction grating 13Ah in the configuration of the measuring unit 13A are disclosed, for example, in Fig. 3 of Published Japanese Translation of PCT Application No. 2008-502126 and U.S. Pat. Published Application No. 2008/0252876A1 corresponding thereto.

[0063] The measuring unit 13A causes interference between a wavefront from the optical system to be examined, passing through the measurement aperture 13Af, and a spherical wave appearing from the pinhole 13Ag for generation of spherical reference wave, to form interference fringes on the detection surface 13ba of the photoelectric detector 13b. The interference fringes contain information of wavefront aberration of the optical system to be examined. If the measuring unit is arranged to make light incident to the measurement aperture 13Af only, the light intensity distribution according to the pupil transmittance distribution of the optical system to be examined is formed on the detection surface 13ba. If the measuring unit is arranged to make light incident to the calibration phase diffraction grating 13Ah only, it is able to detect the error of the measurement result caused by the transmittance distribution of the optically transparent substrate 13Aa. The detection surface 13ba of the photoelectric detector 13b is in contact with the exit plane 13Aj of the optically transparent substrate 13Aa in order to receive rays with NA over 1.

[0064] It is also possible to use a measuring unit 13B making use of a shearing interferometer, for example as shown in Fig. 12. The measuring unit 13B, similar to the measuring unit 13A, is provided with an optically transparent substrate 13Ba having a planar entrance surface 13Bi, and a photoelectric detector 13b having a detection surface 13ba arranged so as to contact a planar exit surface 13Bj of the optically transparent substrate 13Ba. Formed on the entrance plane 13Bi of the optically transparent substrate 13Ba are, as shown in Fig. 13, a shield portion 13Be, for example, made of chromium or chromium oxide, a measurement aperture 13Bf, a diffraction grating 13Bg for measurement of wavefront, and a calibration phase diffraction grating 13Bh for calibration of the pupil transmittance distribution measurement result. The portions except for the measurement aperture 13Bf and the calibration phase diffraction grating 13Bh in the configuration of the measuring unit 13B are disclosed, for example, in Figs. 2 and 5 of Patent Document 6 above and in Patent Documents 7 and 8 above. The disclosures of Patent Documents 6 to 8 above are incorporated herein by reference.

[0065] In the measuring unit 13B, the wavefront from the optical system to be examined is horizontally shifted by the wavefront measurement diffraction grating 13Bg and interference occurs between mutually shifted wavefronts to form interference fringes on the detection surface 13ba of the photoelectric detector 13b. The interference fringes contain information of wavefront aberration of the optical system to be examined. If the measuring unit is arranged to make light incident to the measurement aperture 13Bf only, the light intensity distribution according to the pupil transmittance distribution of the optical system to be examined is formed on the detection surface 13ba. If the measuring unit is arranged to make light incident to the calibration phase diffraction grating 13Bh only, it is able to detect the error of the measurement result caused by the transmittance distribution of the optically transparent substrate 13Ba. The detection surface 13ba of the photoelectric detector 13b is in contact with the exit plane 13Bj of the optically transparent substrate 13Ba in order to receive rays with NA over 1.

[0066] Although the description about the above-described first embodiment contains no mention of the polarization state of the measurement beam to be supplied to the diffraction grating 11, it is sometimes the case that the pupil transmittance distribution of the imaging optical system 20 as an optical system to be examined is relatively significantly dependent upon the polarization state of incident light. In this case, the measuring apparatus may be arranged, for example, to measure the pupil transmittance distribution of the imaging optical system 20 for x-directional linear polarization using the measurement beam incident in a linearly polarized state of x-directional polarization to the diffraction grating 11 and to measure the pupil transmittance distribution of the imaging optical system 20 for y-directional linear polarization using the measurement beam incident in a linearly polarized state of y-directional polarization to the diffraction grating 11.

[0067] In the description about the above-described first embodiment, the ratio of pupil transmittances in the first pair of pupil partial regions is determined based on the ± first-order diffracted beams generated through the diffraction grating 11 from the first measurement beam having the first incidence angle, and the ratio of pupil transmittances in the second pair of pupil partial regions is determined based on the ± first-order diffracted beams generated through the diffraction grating 11 from the second measurement beam having the second incidence angle. It is noted, however, that the pupil transmittance ratio in the first pair of pupil partial regions and the pupil transmittance ratio in the second pair of pupil partial regions are not always measured under the same condition, and therefore it means that the ratio of the pupil transmittances in the first pair of pupil partial regions and the pupil transmittances in the second pair of pupil partial regions is not necessarily accurately determined.

[0068] Therefore, if necessary, the measuring apparatus may be configured to make a third measurement beam incident to the predetermined position on the diffraction grating 11 before or after the measurement with the first measurement beam and the second measurement beam and then obtain a ratio of pupil transmittances in the first pair of pupil partial regions and pupil transmittances in the second pair of pupil partial regions, thereby supplementing the relative ratio information of pupil transmittance distribution on the basis of the pupil transmittance ratio. At this time, the third measurement beam is made incident at a required angle of incidence to the diffraction grating 11 so that the + first-order diffracted beam generated through the diffraction grating 11 passes a pupil partial region in a first inclusion region including the first pair of pupil partial regions and so that the − first-order diffracted beam generated through the diffraction grating 11 passes a pupil partial region in a second inclusion region including the second pair of pupil partial regions. A technique for supplementing the relative ratio information of pupil transmittance distribution as described above will be specifically described in the second embodiment.

[0069] Fig. 14 is a drawing schematically showing a configuration of an exposure apparatus according to the second embodiment. Namely, the second embodiment is an application to the exposure apparatus provided with the measuring apparatus for measuring a pupil transmittance distribution of a projection optical system PL as an optical system to be examined. In Fig. 14, the Z-axis is set along a direction of a normal to a surface (transfer surface) of a wafer W being a photosensitive substrate, the Y-axis along a direction parallel to the plane of Fig. 14 in the surface of the wafer W, and the X-axis along a direction normal to the plane of Fig. 14 in the surface of the wafer W.

[0070] Referring to Fig. 14, the exposure apparatus of the second embodiment is configured to supply exposure light (illumination light) from a light source LS. The light source LS applicable herein is, for example, an ArF excimer laser light source which supplies light at the wavelength of 193 nm, or a KrF excimer laser light source which supplies light at the wavelength of 248 nm. The light emitted from the light source LS travels through an illumination optical system IL to illuminate a mask (reticle) M on which a pattern to be transferred is formed. In the case of the exposure apparatus of the step-and-repeat method, the illumination optical system IL illuminates an entire area of a rectangular pattern region on the mask M. In the case of the exposure apparatus of the step-and-scan method, the illumination optical system IL illuminates a long and thin rectangular region along the X-direction perpendicular to the Y-direction which is a scanning direction, in a rectangular pattern region.

[0071] The beam emitted from the light source LS is incident, as shown in Fig. 15, into a beam sending system 51 having a well-known configuration. The beam entering the beam sending system 51 is shaped into a beam having a predetermined rectangular cross section, and then the shaped beam travels through a beam shape varying unit 52 to enter a micro fly's eye lens (or fly's eye lens) 53. The beam sending system 51 functions to guide the incident beam to the beam shape varying unit 52 while converting it into a beam having a cross section of appropriate size and shape, and to actively correct positional variation and angular variation of the beam incident to the beam shape varying unit 52 (and, in turn, to the micro fly's eye lens 53).

[0072] The beam shape varying unit 52 includes, for example, a spatial light modulator 52a and a relay optical system 52b and functions to vary the size and shape of an illumination field formed on an entrance plane of the micro fly's eye lens 53 and therefore to vary the size and shape of a substantial surface illuminant formed on a rear focal plane of the micro fly's eye lens 53. The spatial light modulator 52a applicable herein is, for example, a plurality of diffractive optical elements arranged so as to be switchable with respect to the illumination optical path in accordance with a control signal from a controller CR. A diffractive optical element is an optical element that converts a cross-sectional shape of an incident beam into another cross-sectional shape. In general, a diffractive optical element is constructed by forming steps at a pitch as long as the wavelength of exposure light (illumination light) in a substrate, and has an action to diffract an incident beam at desired angles.

[0073] The controller CR may be a processing unit (computer) having a recording medium such as a memory MR, and this memory MR stores a program for letting the processing unit execute the measuring method, and controlling methods of the exposure apparatus and the spatial modulator 52a according to the present embodiment.

[0074] The spatial light modulator 52a also applicable herein is, for example, a mirror array stationarily mounted with respect to the illumination optical path. The mirror array, as described above, is a spatial light modulator with a plurality of mirror elements individually controllable as arrayed in a predetermined plane. In the mirror array, the plurality of mirror elements are set in their respective predetermined orientations in accordance with a control signal from the controller CR and beams reflected at predetermined angles by the respective mirror elements form an illumination field of desired size and shape on the entrance plane of the micro fly's eye lens 53. The spatial light modulator 52a may also be a combination of a diffractive optical element and a mirror array.

[0075] The micro fly's eye lens 53 is, for example, an optical element consisting of a large number of microscopic lenses with a positive refractive power arrayed vertically and horizontally and densely, and is constructed by forming the microscopic lens group by etching on a plane-parallel plate. In the micro fly's eye lens, different from the fly's eye lens consisting of mutually isolated lens elements, the large number of microscopic lenses (microscopic refracting faces) are formed integrally without being isolated from each other. In terms of the configuration wherein the lens elements are arranged vertically and horizontally, however, the micro fly's eye lens is an optical integrator of the same wavefront division type as the fly's eye lens.

[0076] The rectangular microscopic refracting faces as unit wavefront division surfaces in the micro fly's eye lens 53 are of a rectangular shape similar to the shape of an illumination field to be formed on the mask M (and, therefore, the shape of an exposure region to be formed on the wafer W). The micro fly's eye lens 53 also applicable herein is, for example, a cylindrical micro fly's eye lens. The configuration and action of the cylindrical micro fly's eye lens are disclosed, for example, in U.S. Pat. No. 6,913,373.

[0077] The beam entering the micro fly's eye lens 53 is two-dimensionally divided by the large number of microscopic lenses to form a secondary light source (substantial surface illuminant consisting of a large number of small light sources: pupil intensity distribution) having a light intensity distribution approximately identical to a light intensity distribution formed on the entrance plane, on an illumination pupil ILp at or near its rear focal plane. Beams from the secondary light source formed on the illumination pupil ILp immediately after the micro fly's eye lens 53 are incident to an illumination aperture stop 54. The illumination aperture stop 54 is arranged on or near the rear focal plane of the micro fly's eye lens 53 and has an aperture (light transmitting portion) of a shape corresponding to the secondary light source.

[0078] The illumination aperture stop 54 is configured so as to be switchable with a plurality of aperture stops which are arranged to be inserted into or retracted from the illumination optical path and which have respective apertures of different sizes and shapes. A switching method of the illumination aperture stop 54 applicable herein is, for example, a well-known turret method or slide method. The illumination aperture stop 54 is arranged at a position optically conjugate with a pupil PLp of a below-described projection optical system PL and defines a range of contribution to illumination by the secondary light source. It is also possible to omit installation of the illumination aperture stop 54.

[0079] The beams from the secondary light source as limited by the illumination aperture stop 54 travel through a condenser optical system 55 to illuminate a mask blind 56 in a superimposed manner. In this way, a rectangular illumination field according to the shape and focal length of the rectangular microscopic refracting faces of the micro fly's eye lens 53 is formed on the mask blind 56 as an illumination field stop. Beams through a rectangular aperture (light transmitting portion) of the mask blind 56 are subjected to the condensing action of an illumination imaging optical system 57 and thereafter illuminate a mask M with a predetermined pattern thereon, in a superimposed manner. Namely, the illumination imaging optical system 57 forms an image of the rectangular aperture of the mask blind 56 on the mask M.

[0080] Light passing through a pattern surface of the mask M travels through the projection optical system PL, for example, having a demagnification ratio, to form a pattern image of the mask M in a unit exposure region on the wafer (photosensitive substrate) W coated with a photoresist. Namely, the mask pattern image is formed in a rectangular region similar to the entire pattern region of the mask M or in a long and thin rectangular region (still exposure region) in the X-direction, in the unit exposure region on the wafer W, so as to optically correspond to the illumination region on the mask M.

[0081] The mask M is held in parallel with the XY plane on a mask stage MS so that its pattern surface coincides with an object plane PLo of the projection optical system PL. The mask stage MS is equipped with a mechanism for moving the mask M in the X-direction, Y-direction, Z-direction, and directions of rotation around the Z-axis. The mask stage MS is provided with a moving mirror not shown, and a mask laser interferometer MIF using this moving mirror measures the X-directional position, Y-directional position, and rotational position around the Z-axis of the mask stage MS (and, therefore, the mask M) in real time.

[0082] The wafer W is held in parallel with the XY plane on a substrate stage WS so that its front surface (transfer surface) coincides with an image plane PLi of the projection optical system PL. The substrate stage WS is equipped with a mechanism for moving the wafer W in the X-direction, Y-direction, Z-direction, and directions of rotation around the Z-axis. The substrate stage WS is provided with a moving mirror not shown, and a substrate laser interferometer WIF using this moving mirror measures the X-directional position, Y-directional position, and rotational position around the Z-axis of the substrate stage WS (and, therefore, the wafer W) in real time.

[0083] The output from the mask laser interferometer MIF and the output from the substrate laser interferometer WIF are supplied to the controller CR. The controller CR controls the X-directional position, Y-directional position, and rotational position around the Z-axis of the mask M, based on the measurement result of the mask laser interferometer MIF. Namely, the controller CR transmits a control signal to the mechanism incorporated in the mask stage MS and this mechanism moves the mask stage MS on the basis of the control signal to adjust the X-directional position, Y-directional position, and rotational position around the Z-axis of the mask M.

[0084] The controller CR controls the Z-directional position (focus position) of the wafer W by the autofocus method in order to make the surface of the wafer W coincident with the image plane PLi of the projection optical system PL. The controller CR also controls the X-directional position, Y-directional position, and rotational position around the Z-axis of the wafer W, based on the measurement result of the substrate laser interferometer WIF. Namely, the controller CR transmits a control signal to the mechanism incorporated in the substrate stage WS, and this mechanism moves the substrate stage WS on the basis of the control signal to adjust the X-directional position, Y-directional position, and rotational position around the Z-axis of the wafer W.

[0085] In the step-and-repeat method, the pattern image of the mask M is collectively exposed in one unit exposure region out of a plurality of unit exposure regions set vertically and horizontally on the wafer W. Thereafter, the controller CR achieves step movement of the substrate stage WS along the XY plane to position another unit exposure region on the wafer W relative to the projection optical system PL. In this manner, the exposure apparatus repeatedly performs the full-shot exposure operation to collectively transfer the pattern image of the mask M to a unit exposure region on the wafer W.

[0086] In the step-and-scan method, the controller CR achieves scanning exposure to transfer the pattern image of the mask M to a unit exposure region on the wafer W with Y-directional movement of the mask stage MS and the substrate stage WS at a speed ratio according to the projection magnification of the projection optical system PL. Thereafter, the controller CR achieves step movement of the substrate stage WS along the XY plane to position another unit exposure region on the wafer W relative to the projection optical system PL. In this manner, the exposure apparatus repeatedly performs the scanning exposure operation to transfer the pattern image of the mask M to a unit exposure region on the wafer W.

[0087] Namely, in the step-and-scan method, the scanning exposure of the mask pattern is implemented in a region having the width equal to the long sides of the still exposure region and the length according to a scan amount (moving distance) of the wafer W, on the wafer W by synchronously moving (or scanning) the mask stage MS and the substrate stage WS and, therefore, the mask M and the wafer W along the Y-direction being the short-side direction of the rectangular still exposure region while performing the position controls of the mask M and the wafer W. It is assumed hereinafter that the projection optical system PL as an optical system to be examined, and the illumination optical system IL are coaxially arranged so that their axes AXp and AXi extend along a straight line extending in the Z-direction.

[0088] In the second embodiment, the mask M arranged on the illumination target surface of the illumination optical system IL is illuminated by Köhler illumination, using the secondary light source formed by the micro fly's eye lens 53, as a light source. For this reason, the position where the secondary light source is formed is optically conjugate with the position of an aperture stop AS of the projection optical system PL (and, therefore, with the position of the pupil PLp of the projection optical system PL), and thus the plane where the secondary light source is formed can be called an illumination pupil plane of the illumination optical system IL. Typically, the illumination target surface (the plane where the mask M is arranged or the plane where the wafer W is arranged if the illumination optical system is considered to include the projection optical system PL) is an optical Fourier transform plane for the illumination pupil plane.

[0089] The pupil intensity distribution is a light intensity distribution (luminance distribution) on the illumination pupil plane of the illumination optical system IL or on a plane optically conjugate with the illumination pupil plane. If the number of divisions of the wavefront by the micro fly's eye lens 53 is relatively large, a global light intensity distribution formed on the entrance plane of the micro fly's eye lens 53 exhibits a high correlation with a global light intensity distribution (pupil intensity distribution; pupil luminance distribution) of the entire secondary light source. For this reason, light intensity distributions on the entrance plane of the micro fly's eye lens 53 and on a plane optically conjugate with the entrance plane can also be called pupil intensity distributions.

[0090] The exposure apparatus of the second embodiment is provided with a measuring apparatus 13 for measuring the wavefront aberration of the projection optical system PL. The measuring apparatus

13 has the same configuration as the measuring apparatus 13 in the first embodiment and is attached to the substrate stage WS so that the x-, y-, and z-coordinates in Fig. 1 correspond to the X-, Y-, and Z-coordinates, respectively, in Fig. 14. The measuring apparatus 10' of the second embodiment (cf. Fig. 16) measures the pupil transmittance distribution of the projection optical system PL on an as-needed basis in a state in which it is mounted on the exposure apparatus, in order to improve the contrast of the pattern image formed through the projection optical system PL.

[0091] In measurement of the pupil transmittance distribution of the projection optical system PL, as shown in Fig. 16, a measurement aperture stop 54a is mounted instead of the illumination aperture stop 54 in the illumination optical system IL (if the installation of the illumination aperture stop 54 is omitted, the measurement aperture stop 54a is set at the position thereof), and a measurement reticle TR is mounted instead of the mask M. Furthermore, the substrate stage WS is moved in accordance with a command from the controller CR to position the measuring apparatus 13 so that the entrance plane 13i of the planoconvex lens 13aa coincides with the image plane PLi of the projection optical system PL and so that the measurement aperture 13f is arranged at a predetermined position on the image plane PLi (position where the measurement light through the projection optical system PL is incident to the image plane PLi). The measuring apparatus 10' is provided with the illumination optical system IL including the measurement aperture stop 54a installed at the illumination pupil ILp, the measurement reticle TR, and the measuring unit 13.

[0092] The measurement aperture stop 54a, as a relatively simple example, has nine apertures 61, 62, 63, 64, 65, 66, 67, 68, and 69 as shown in Fig. 17. For simplicity of description, it is assumed below that each of the apertures 61-69 is circular and that they have the same size. The apertures 61-64, 66-69 are assumed to be arrayed so that a center point of each aperture is coincident with a corner of a square with a center at the center aperture 65 or coincident with a midpoint of each side thereof. The measurement aperture stop 54a is assumed to be arranged so that the center point of the aperture 65 coincides with the axis AXi of the illumination optical system IL.

[0093] Specifically, the pitch Ppi of the apertures 61-69 can be set to approximately ten times the diameter Dpi of the apertures 61-69. If the diameter Dp of the apertures 61-69 is too large, pupil partial regions where the ± first-order diffracted beams generated through the respective apertures 61-69 and the phase grating of the measurement reticle TR pass through the pupil PLp of the projection optical system PL (i.e., diffraction spot images formed on the pupil PLp) will overlap in part with each other. The pitch Ppi of the apertures 61-69 is optional as to its absolute value, but it can be restricted so as to satisfy a predetermined relative relation with the pitch Pr of the phase grating of the measurement reticle TR as described below. However, if the pitch Ppi of the apertures 61-69 is too large, the partial overlap between the pupil partial regions can be readily avoided, but the transverse resolution of the pupil transmittance distribution information will be sacrificed in the case where the pupil transmittance distribution of the projection optical system PL is collectively measured without step movement of the measurement aperture stop 54a along the XY plane.

[0094] On the surface of the measurement reticle TR, as shown in Fig. 18, a phase grating (phase pattern) is formed in which rectangular first phase regions 11c to impart a first phase value to transmitted light and rectangular second phase regions 11d to impart a second phase value different by π from the first phase value to transmitted light are alternately arranged along two directions orthogonal to each other. In other words, the phase grating of the measurement reticle TR has a form in which the two types of rectangular phase regions 11c, 11d are arranged so as to form a check flag pattern (i.e., a form in which the two types of rectangular phase regions 11c, 11d are arranged in a checkered pattern).

[0095] It is assumed in the description hereinafter that each of the phase regions 11c, 11d is square and that they have the same size. The measurement reticle TR is assumed to be mounted so that the pitch directions of the phase regions 11c, 11d coincide with the X-direction and Y-direction and so that the diffractive optical surface coincides with the object plane PLo of the projection optical system PL. The pitch Pr of the phase regions 11c, 11d can be restricted so as to satisfy a predetermined relative relation with the pitch Ppi of the apertures 61-69 provided in the aperture stop 54a, as described below.

[0096] On the aperture stop 54a, a light beam is incident to a required region including the apertures 61-69 (e.g., a circular region including the apertures 61-69). In this case, a beam through the center aperture 65 is emitted from the illumination optical system IL, and is incident normally (or incident in parallel with the optical axis AXp of the projection optical system PL) to a predetermined position on the phase grating of the measurement reticle TR (and therefore to a predetermined position on the object plane PLo of the projection optical system PL). Beams through the apertures 61-64, 66-69 other than the aperture 65, i.e., circular localized beams with a light intensity distribution localized at the positions apart from the optical axis AXi on the illumination pupil ILp optically conjugate with the pupil PLp of the projection optical system PL are emitted from the illumination optical system IL and are incident as eight beams inclined relative to the optical axis AXp (and, therefore, relative to the optical axis AXi), to the predetermined position on the phase grating of the measurement reticle TR.

[0097] The incidence position of the nine beams to the measurement reticle TR is variably determined, for example, by the action of the mask blind 56. Alternatively, it is variably determined by a field stop (not shown) arranged near the mask blind 56, or a field stop (not shown) arranged at a position immediately in front of the object plane PLo, or the like. In this manner, the nine beams from the apertures 61-69 are simultaneously incident to the same position on the phase grating of the measurement reticle TR. It is assumed below for simplicity of description that the illumination pupil ILp of the illumination optical system IL and the pupil PLp of the projection optical system PL are in a conjugate relation to form an erect image of the illumination pupil ILp with respect to the X-direction and Y-direction on the pupil PLp.

[0098] When attention is focused on one beam incident to the measurement reticle TR, a pair of + first-order diffracted beams and a pair of − first-order diffracted beams as measurement targets out of diffracted beams generated through the phase grating of the measurement reticle TR pass through four pupil partial regions 60a in an effective region of the pupil PLp of the projection optical system PL, as shown in Fig. 19, and are emitted each from the projection optical system PL. The four pupil partial regions 60a are circular as the apertures 61-69 are, and have the same size. Respective centers of the four pupil partial regions 60a are located at corner positions of a square defined by four sides extending in the X-direction and Y-direction with a point 60c as a center.

[0099] The point 60c is a center of a region 60d where the zero-order light would pass through the pupil PLp if the zero-order light should be generated through the phase grating of the measurement reticle TR. Namely, the center position 60c of the four pupil partial regions 60a is dependent upon the positions of the associated apertures in the aperture stop 54a. The size of the pupil partial regions 60a is significantly dependent upon the size of each aperture 61-69 in the aperture stop 54a. The pitch Ppp of the pupil partial regions 60a is dependent upon the pitch Pr of the phase regions 11c, 11d in the phase grating of the measurement reticle TR.

[0100] Specifically, the pitch Ppp of the pupil partial regions 60a is represented by Eq (1) below, where λ represents the wavelength of the light and NAo the numerical aperture on the entrance side (object side) of the projection optical system PL. The distance Lpc between the center of each pupil partial region 60a and the point 60c is represented by Eq (2) below. In Eq (1) and Eq (2), the pitch Pr is normalized by the numerical aperture NAo of the beam incident to the projection optical system PL.

$$Ppp = (2 \times \lambda/Pr)/NAo \qquad (1)$$

$$Lpc = (\sqrt{2} \times \lambda/Pr)/NAo \qquad (2)$$

[0101] The ± first-order diffracted beams generated through the nine apertures 61-69 of the aperture stop 54a and the phase grating of the measurement reticle TR pass through thirty six (= 4 × 9) pupil partial regions 61a-69a in the effective region PLpe of the pupil PLp of the projection optical system PL, as shown in Fig. 20, and they are emitted each from the projection optical system PL. An array pattern of the thirty six pupil partial regions 61a-69a is obtained by convolution between the array pattern of the nine apertures 61-69 of the aperture stop 54a shown in Fig. 17 and the array pattern of the four pupil partial regions 60a where the ± first-order diffracted beams generated from one beam pass through the pupil PLp of the projection optical system PL as shown in Fig. 19.

[0102] As described below, in order to avoid overlapping of the ± third-order diffracted beams excluded from the measurement with the ± first-order diffracted beams of measurement targets on the pupil PLp of the projection optical system PL, the thirty six pupil partial regions 61a-69a are assumed to be arrayed so that the X-directional space and Y-directional space between the four pupil partial regions corresponding to one beam and the four pupil partial regions adjacent thereto corresponding to another beam in Fig. 20 become equal to half of the pitch Ppp of the four pupil partial regions (i.e., Ppp/2). In this case, the distance between the center of the four pupil partial regions and the center of the four pupil partial regions adjacent thereto (i.e., the distance optically corresponding to the pitch Ppi of the apertures) is the value of 3/2 times the pitch Ppp of the four pupil partial regions.

[0103] The ± first-order diffracted beams through the thirty six pupil partial regions 61a-69a and the projection optical system PL travel through the measurement aperture 13f of the measuring unit 13 to enter the objective optical system 13a. The ± first-order diffracted beams through the objective optical system 13a are detected by the photoelectric detector 13b on the detection surface 13ba arranged on the pupil plane 13p. As a consequence, thirty six circular light incident regions (not shown) discretely distributed in the same manner as the array pattern of the thirty six pupil partial regions 61a-69a on the pupil PLp of the projection optical system PL, are also formed on the detection surface 13ba.

[0104] It is assumed below for simplicity of description that the intensities of the thirty six ± first-order diffracted beams generated through the phase grating of the measurement reticle TR are identical to each other and that a ratio of respective intensities of the thirty six ± first-order diffracted beams at the image plane PLi of the projection optical system PL is coincident with a ratio of respective intensities of the thirty six ± first-order diffracted beams detected on the detection surface 13ba of the measuring unit 13. In other words, the measuring unit 13 is assumed to be able to accurately measure the mutual intensity ratio of the thirty six ± first-order diffracted beams at the image plane PLi of the projection optical system PL, without being affected by the pupil transmittance distribution of the objective optical system 13a or the like.

[0105] In this case, the measuring apparatus 10' simultaneously supplies the nine beams as many as the apertures 61-69 to the predetermined position on the phase grating of the measurement reticle TR, using the aperture stop 54a with the nine apertures 61-69 arrayed according to the required distribution, and measures the intensities of the totally thirty six ± first-order diffracted beams generated from the respective beams, by the measuring unit 13. The measuring apparatus 10' determines the relative ratio of pupil transmittances in the thirty six pupil partial regions 61a-69a distributed across the entire pupil effective region PLpe of the projection optical system PL, based on the measured values, and collectively measures the pupil transmittance distribution of the projection optical system PL about the thirty six pupil partial regions 61a-69a eventually.

[0106] As a consequence, we can obtain the relative information of pupil transmittances among the thirty six pupil partial regions distributed across the entire pupil effective region PL20pe of the projection optical system PL, and directly obtain the two-dimensional pupil transmittance distribution of the projection optical system PL as a functional distribution, for example, by the Zernike fitting process for the distribution of relative values of these discrete pupil transmittances. As described above, the measuring apparatus 10' of the second embodiment does not need to perform the step movement of the aperture stop 54a and requires only one measurement by the measuring unit 13, and therefore it is able to accurately and quickly measure the pupil transmittance distribution of the projection optical system PL on an as-needed basis in the state in which it is mounted on the exposure apparatus.

[0107] As described above, since the measuring apparatus 10' of the second embodiment uses the measurement reticle TR with the phase grating in which the two types of phase regions 11c, 11d are arranged so as to form the check flag pattern, the intensities of the ± first-order diffracted light components as measurement targets out of the diffracted beams generated through the phase grating of the measurement reticle TR are identical to each other. As a result, the photoelectric detector 13b of the measuring unit 13 is able to accurately detect each of the diffracted light components, using a relatively narrow dynamic range, and therefore to accurately measure the pupil transmittance distribution of the projection optical system PL. Since the measuring apparatus uses the measurement reticle TR with the phase grating in which the two types of phase regions 11c and 11d with the phase difference of π are alternately arranged, the zero-order light to be excluded from the measurement is prevented from being generated and affecting the measurement of intensities of ± first-order diffracted light components, and therefore the measuring apparatus is able to accurately detect each of the components.

[0108] Furthermore, there is no need for changing the posture of the measurement reticle TR or for replacing it with another measurement reticle having a different property, and the measuring apparatus is able to collectively measure the pupil transmittance distribution of the projection optical system PL or to quickly measure it with a very low load, by simply mounting the aperture stop 54a with the plurality of apertures 61-69 stationarily in the illumination optical path. In other words, the measuring apparatus is able to quickly measure the pupil transmittance distribution of the projection optical system PL with a very low load, based on the single measurement result by the measuring unit 13, in the state in which the measurement reticle TR and the aperture stop 54a are stationarily set.

[0109] In the measuring apparatus 10' of the second embodiment, it is important that the thirty six pupil partial regions 61a-69a be separated from each other in order to accurately measure the intensities of the respective diffracted light components and that the size of the pupil partial regions 61a-69a (and, therefore, the size of the apertures 61-69) be controlled at some small level in order to accurately measure the pupil transmittance distribution. Namely, the center-center distance between the pupil partial regions 61a-69a optically corresponding to the apertures 61-69 of the aperture stop 54a does not have to be set excessively large, and therefore the pitch Pr of the phase regions 11c and 11d in the phase grating of the measurement reticle TR does not have to be set excessively small, which eventually facilitates manufacture of the measurement reticle TR.

[0110] In the exposure apparatus of the second embodiment, the controller CR changes the illumination condition for illuminating the pattern on the mask M, based on the measurement result of the pupil transmittance distribution of the projection optical system PL measured by the measuring apparatus 10' (or by the measuring method with the measuring apparatus 10'), to perform desired exposure. Specifically, the controller CR refers to the measurement result of the pupil transmittance distribution and supplies such a control signal as to improve the contrast of the pattern image formed through the projection optical system PL, for example, to the beam shape varying unit 52 including the spatial light modulator 52a, to change the illuminance distribution in the illumination region formed on the pattern surface of the mask M and/or the pupil luminance distribution on the illumination pupil ILp by the action of the spatial light modulator 52a and others.

[0111]Furthermore, the exposure apparatus of the second embodiment is also able to improve the contrast of the pattern image formed through the projection optical system PL, using the mask M with a pattern created based on the measurement result of the pupil transmittance distribution of the projection optical system PL measured by the measuring apparatus 10', instead of the change of the illuminance distribution and/or the pupil luminance distribution, or in addition to the change of the illuminance distribution and/or the pupil luminance distribution. The exposure apparatus of the second embodiment may also be configured so as to let the controller CR as an information processing unit execute the measuring method with the measuring apparatus 10', for example, in accordance with a predetermined program.

[0112] In the measuring apparatus 10' of the second embodiment, the ± third-order diffracted beams, ± fifth-order diffracted beams, etc. are also generated through the phase grating of the measurement reticle TR as in the case of the measuring apparatus 10 in the first embodiment. In this case, the measuring apparatus may be arranged as follows: the ± third-order diffracted beams, ± fifth-order diffracted beams, etc. are excluded from the measurement, the ± fifth-order diffracted beams (and higher-order diffracted beams) with the intensity extremely smaller than that of the ± first-order diffracted beams of measurement targets are ignored, and the ± third-order diffracted beams are set so as not to overlap with the ± first-order diffracted beams on the pupil PLp of the projection optical system PL. A technique for setting the ± third-order diffracted beams so as not to overlap with the ± first-order diffracted beams in the pupil effective region PLpe of the projection optical system PL in the second embodiment will be described below.

[0113] When attention is focused on one beam incident to the measurement reticle TR, the ± third-order diffracted beams to be excluded from the measurement, out of the diffracted beams generated through the phase grating of the measurement reticle TR pass through twelve pupil partial regions 60e on the pupil PLp of the projection optical system PL, as shown in Fig. 21, and are emitted each from the projection optical system PL. The twelve pupil partial regions 60e are circular as the four pupil partial regions 60a associated with the ± first-order diffracted beams are, and have the same size. Respective centers of the twelve pupil partial regions 60e are located at positions of corners of a square defined by four sides extending in the X-direction and Y-direction with the point 60c as a center, and at positions of points where each side is trisected.

[0114] The center-center distance between two X-directionally or Y-directionally adjacent regions among the twelve pupil partial regions 60e is equal to the pitch Ppp being the center-center distance between two X-directionally or Y-directionally adjacent regions among the four pupil partial regions 60a. Each of the sides of the square obtained by connecting the respective centers of the twelve pupil partial regions 60e has a length equal to three times the side of the square formed by connecting the respective centers of the four pupil partial regions 60a (= 3 × Ppp).

[0115] Therefore, the ± third-order diffracted beams generated through the two Y-directionally adjacent apertures 64, 65 in the aperture stop 54a and the phase grating of the measurement reticle TR pass through twenty four (= 12 × 2) pupil partial regions 64e, 65e on the pupil PLp of the projection optical system PL, as shown in Fig. 22, and they are emitted each from the projection optical system PL. Fig. 22 is depicted without illustration of the pupil partial regions corresponding to the ± first-order diffracted beams and ± third-order diffracted beams generated through the other apertures 61-63, 66-69 and the phase grating of the measurement reticle TR, for clarity of the drawing.

[0116] With reference to Fig. 22, however, since the thirty six pupil partial regions 61a-69a corresponding to the ± first-order diffracted beams of measurement targets are set so as to exhibit the array pattern shown in Fig. 20, it is readily presumed that the ± third-order diffracted beams are most unlikely to overlap with the ± first-order diffracted beams on the pupil PLp of the projection optical system PL. Now, let us consider a condition to be satisfied when the thirty six pupil partial regions 61a-69a corresponding to the ± first-order diffracted beams exhibit the array pattern shown in Fig. 20, with reference to Figs. 19 to 22.

[0117] The pitch Ppp of the pupil partial regions (60a; 61a-69a) corresponding to the ± first-order diffracted beams is represented by aforementioned Eq (1). The distance Ppe between the center of the four pupil partial regions (e.g., 64a) and the center of the four pupil partial regions adjacent thereto (e.g., 65a), i.e., the distance Ppe optically corresponding to the pitch Ppi of the apertures 61-69 on the pupil PLp of the projection optical system PL is equal to the value of 3/2 times the pitch Ppp ($= 3 \times (\lambda/Pr)/NAo$). On the other hand, the distance Ppe is also represented by Eq (3) below, using the pitch Ppi of the apertures 61-69 and the radius Ra of the pupil effective region PLpe of the projection optical system PL.

$$Ppe = Ppi/Ra \qquad (3)$$

[0118] Therefore, when the relation in Eq (4) below is satisfied, the thirty six pupil partial regions 61a-69a corresponding to the ± first-order diffracted beams of measurement targets exhibit the array pattern as shown in Fig. 20 and the ± third-order diffracted beams become most unlikely to overlap with the ± first-order diffracted beams on the pupil PLp of the projection optical system PL. In practice, when the measuring apparatus is set so as to satisfy the relation represented by Eq (4), it becomes able to perform high-accuracy measurement of the pupil transmittance distribution without being affected by the ± third-order diffracted beams.

$$Ppi/Ra = 3 \times (\lambda/Pr)/NAo \qquad (4)$$

[0119] In the description about the above-described second embodiment, the beams as many as the apertures are simultaneously supplied to the predetermined position on the phase grating of the measurement reticle TR, using the aperture stop 54a with the plurality of apertures arranged according to the required distribution, and the pupil transmittance distribution of the projection optical system PL is collectively measured based on the ± first-order diffracted beams generated from the respective beams. However, without having to be limited to this, it is also possible to adopt a configuration wherein by action of a mirror array as the spatial light modulator 52a, the apertures of the aperture stop 54a each are successively illuminated to successively supply the beams through the respective apertures to the predetermined position on the phase grating of the measurement reticle TR and wherein the pupil transmittance distribution of the projection optical system PL is measured based on the ± first-order diffracted beams successively generated from the respective beams. Furthermore, it is also possible to adopt a technique of simultaneously or successively forming the localized beams corresponding to the respective apertures by action of the mirror array, without installation of the aperture stop 54a.

[0120] In the description about the above-described second embodiment, it is assumed that the measuring unit 13 can accurately measure the mutual intensity ratio of the ± first-order diffracted beams, without being affected by the pupil transmittance distribution of the objective optical system 13a. However, if the influence of the pupil transmittance distribution of the objective optical system 13a is not negligibly small, the aforementioned technique described in association with the first embodiment may be applied to detect the error of the measurement result due to the pupil transmittance distribution of the objective optical system 13a of the measuring unit 13 and calibrate the measurement result of the pupil transmittance distribution of the projection optical system PL therewith. Furthermore, the measuring unit 13 can be replaced by the PDI/LDI type measuring unit 13A or by the measuring unit 13B making use of the shearing interferometer.

[0121] In the description about the above-described second embodiment, it is assumed that the pupil transmittance ratio in the four pupil partial regions corresponding to one beam and the pupil transmittance ratio in the four pupil partial regions corresponding to another beam are measured under the same condition. However, where this assumption does not hold, the ratio of the pupil transmittances in the pupil partial regions 64a and the pupil transmittances in the pupil partial regions 65a cannot be accurately determined, for example, even if the pupil transmittance ratio in the four pupil partial regions 64a and the pupil transmittance ratio in the other four pupil partial regions 65a can be accurately determined.

[0122] In this case, before or after the measurement carried out in the setting of the aperture stop 54a as shown in Fig. 17, the measurement is carried out, for example, in a state in which the aperture stop 54a is shifted by Ppi/3 in the + X-direction and by Ppi/3 in the + Y-direction. As a result, the ± first-order diffracted beams generated through the aperture 64 of the aperture stop 54a and the phase grating of the measurement reticle TR pass through four pupil partial regions 64m1, 64m2, 64m3, and 64m4 on the pupil PLp of the projection optical system PL, as shown in Fig. 23, and they are emitted each from the projection optical system PL. At this time, the four pupil partial regions 64m1-64m4 are located at positions with the shift of Ppe/3 in the + X-direction and the shift of Ppe/3 in the + Y-direction from the four pupil partial regions 64a on the pupil PLp of the projection optical system PL.

[0123] As a result, the pupil partial region 64m1 is in an inclusion region 64r including the four pupil partial regions 64a corresponding to one beam and the pupil partial region 64m2 is in an inclusion region 65r including the four pupil partial regions 65a corresponding to another beam. In this manner, we can obtain a ratio of the pupil transmittance in the pupil partial region 64m1 and the pupil transmittance in the pupil partial region 64m2, for example, and supplement the relative ratio information of the pupil transmittance distribution about the pupil partial regions 64a and 65a on the basis of the pupil transmittance ratio thus obtained. Fig. 23 is depicted without illustration of the pupil partial regions corresponding to the ± first-order diffracted beams generated through the other apertures 61-63, 65-69 of the aperture stop 54a and the phase grating of the measurement reticle TR, for clarity of the drawing.

However, as seen with reference to Fig. 23, it is readily presumed that the relative ratio information of the pupil transmittance distribution can be supplemented about the pupil partial regions 61a-69a.

[0124] In the description about the above-described second embodiment, since the embodiment is applied to the exposure apparatus using the transmission type mask M, the transmission type measurement reticle TR is used in place of the transmission type mask M. However, for example, in the case of the exposure apparatus using a reflection type mask, a reflection type measurement reticle will be used in place of the reflection type mask. In the foregoing second embodiment, as in the case of the first embodiment, a variety of forms can be contemplated as to the specific configuration of the phase grating of the measurement reticle, the specific configuration of the measuring unit, the number, shape, size, and position of the localized beams formed on the illumination pupil, and so on.

[0125] The foregoing second embodiment showed the projection optical system used in the exposure apparatus, as an optical system to be examined, but the optical system to be examined can be any optical system as long as it is an imaging optical system. If the optical system to be examined is a non-imaging optical system, e.g., a Fourier transform optical system, the measurement result of the pupil transmittance distribution of the non-imaging optical system can be obtained in such a manner that an imaging optical system is configured by combining the optical system to be examined, with a Fourier transform optical system having a known pupil transmittance distribution and that the pupil transmittance distribution of the optical system to be combined is subtracted from the measurement result of the pupil transmittance distribution of the imaging optical system.

[0126] In the aforementioned embodiment, the mask can be replaced with a variable pattern forming device which forms a predetermined pattern on the basis of predetermined electronic data. Use of such a variable pattern forming device can minimize influence on synchronization accuracy even if the pattern surface is set vertical. The variable pattern forming device applicable herein can be, for example, a DMD (Digital Micromirror Device) including a plurality of reflective elements driven based on predetermined electronic data. The exposure apparatus with the DMD is disclosed, for example, in Patent Documents 9 an 10 above. Besides the reflective spatial light modulators of the non-emission type like the DMD, it is also possible to apply a transmissive spatial light modulator or a self-emission type image display device. The teachings of Patent Document 10 above are incorporated herein by reference.

[0127] The exposure apparatus of the foregoing embodiment is manufactured by assembling various sub-systems containing their respective components as set forth in the scope of claims in the present application, so as to maintain predetermined mechanical accuracy, electrical accuracy, and optical accuracy. For ensuring these various accuracies, the following adjustments are carried out before and after the assembling: adjustment for achieving the optical accuracy for various optical systems; adjustment for achieving the mechanical accuracy for various mechanical systems; adjustment for achieving the electrical accuracy for various electrical systems. The assembling steps from the various sub-systems into the exposure apparatus include mechanical connections, wire connections of electric circuits, pipe connections of pneumatic circuits, etc. between the various sub-systems. It is needless to mention that there are assembling steps of the individual sub-systems, before the assembling steps from the various sub-systems into the exposure apparatus. After completion of the assembling steps from the various sub-systems into the exposure apparatus, overall adjustment is carried out to ensure various accuracies as the entire exposure apparatus. The manufacture of exposure apparatus may be performed in a clean room in which the temperature, cleanliness, etc. are controlled.

[0128] The following will describe a device manufacturing method using the exposure apparatus according to the above-described embodiment. Fig. 24 is a flowchart showing manufacturing steps of semiconductor devices. As shown in Fig. 24, the manufacturing steps of semiconductor devices include depositing a metal film on a wafer W to become a substrate of semiconductor devices (step S40) and applying a photoresist as a photosensitive material onto the deposited metal film (step S42). The subsequent steps include transferring a pattern formed on a mask (reticle) M, into each shot area on the wafer W, using the projection exposure apparatus of the above embodiment (step S44: exposure step), and developing the wafer W after completion of the transfer, i.e., developing the photoresist on which the pattern has been transferred (step S46: development step).

[0129] Thereafter, using the resist pattern made on the surface of the wafer W in step S46, as a mask, processing such as etching is carried out on the surface of the wafer W (step S48: processing step). The resist pattern herein is a photoresist layer in which depressions and projections are formed in a shape corresponding to the pattern transferred by the projection exposure apparatus of the above embodiment and which the depressions penetrate throughout. Step S48 is to process the surface of the wafer W through this resist pattern. The processing carried out in step S48 includes, for example, at least either etching of the surface of the wafer W or deposition of a metal film or the like. In step S44, the projection exposure apparatus of the above embodiment performs the transfer of the pattern onto the wafer W coated with the photoresist, as a photosensitive substrate or plate P.

[0130] Fig. 25 is a flowchart showing manufacturing steps of a liquid crystal device such as a liquid crystal display device. As shown in Fig. 25, the manufacturing steps of the liquid crystal device include sequentially performing a pattern forming step (step S50), a color filter forming step (step S52), a cell assembly step (step S54), and a module assembly step (step S56). The pattern forming step of step S50 is to form predetermined patterns such as a circuit pattern and an electrode pattern on a glass substrate coated with a photoresist, as a plate P, using the projection exposure apparatus of the above embodiment. This pattern forming step includes an exposure step of transferring a pattern to a photoresist layer, using the projection exposure apparatus of the above embodiment, a development step of performing development of the plate P on which the pattern has been transferred, i.e., development of the photoresist layer on the glass substrate, to make the photoresist layer in a shape corresponding to the pattern, and a processing step of processing the surface of the glass substrate through the developed photoresist layer.

[0131] The color filter forming step of step S52 is to form a color filter in which a large number of sets of three dots corresponding to R (Red), G (Green), and B (Blue) are arrayed in a matrix pattern, or in which a plurality of filter sets of three stripes of R, G, and B are arrayed in a horizontal scan direction. The cell assembly step of step S54 is to assemble a liquid crystal panel (liquid crystal cell), using the glass substrate on which the predetermined pattern has been formed in step S50, and the color filter formed in step S52. Specifically, a liquid crystal is poured into between the glass substrate and the color filter to form the liquid crystal panel. The module assembly step of step S56 is to attach various components such as electric circuits and backlights for display operation of this liquid crystal panel, to the liquid crystal panel assembled in step S54.

[0132] The embodiments of the present invention are not limited just to the application to the exposure apparatus for manufacture of semiconductor devices, but can also be widely applied, for example, to the exposure apparatus for display devices such as liquid crystal display devices or plasma displays formed with rectangular glass plates, and the exposure apparatus for manufacture of various devices such as imaging devices (CCDs and others), micro machines, thin-film magnetic heads, and DNA chips. Furthermore, the embodiments of the present invention are also applicable to the exposure step (exposure apparatus) for manufacture of masks (photomasks, reticles, etc.) on which mask patterns of various devices are formed, by the photolithography process.

[0133] The aforementioned embodiment used the ArF excimer laser light (the wavelength: 193 nm) or the KrF excimer laser light (the wavelength: 248 nm) as the exposure light, but the exposure light does not have to be limited to these: the present invention can also be embodied by applying any other appropriate laser light source, e.g., an F_2 laser light source for supplying the laser light at the wavelength of 157 nm, to the embodiments of the present invention.

[0134] In the foregoing embodiment, it is also possible to apply a technique of filling the space in the optical path between the projection optical system and the photosensitive substrate with a medium having the refractive index larger than 1.1 (typically, a liquid), which is so called a liquid immersion method. In this case, it is possible to adopt one of the following techniques as the technique of filling the space in the optical path between the projection optical system and the photosensitive substrate with the liquid: the technique of locally filling the space with the liquid as disclosed in Patent Document 11 above; the technique of moving a stage holding the substrate to be exposed, in a liquid bath as disclosed in Patent Document 12 above; the technique of forming a liquid bath of a predetermined depth on a stage and holding the substrate therein as disclosed in Patent Document 13 above, and so on. The teachings of Patent Documents 11 to 13 above are incorporated herein by reference. In the aforementioned embodiments, it is also possible to apply the so-called polarization illumination method as disclosed in Patent Documents 14 and 15 above. The teachings of Patent Documents 14 and 15 are incorporated herein by reference.

CLAIMS

1. A measuring method of measuring a pupil transmittance distribution of an optical system to be examined, comprising the steps of:

supplying a first beam to a predetermined position on a first surface in an optical Fourier transform relation with a pupil of the optical system to be examined;

diffracting the first beam by imparting a first phase value to light passing through a first phase region on the first surface and imparting a second phase value different from the first phase value to light passing through a second phase region adjacent to the first phase region;

letting a + first-order diffracted beam of the first beam pass through a first pupil partial region in an effective region of the pupil and letting a − first-order diffracted beam of the first beam pass through a second pupil partial region apart from the first pupil partial region in the effective region, the + first-order diffracted beam of the first beam being generated through diffraction of the first beam, the − first-order diffracted beam of the first beam being generated through diffraction of the first beam;

measuring an intensity of the + first-order diffracted beam of the first beam and an intensity of the − first-order diffracted beam of the first beam, the + first-order diffracted beam of the first beam having traveled via the first pupil partial region and the optical system to be examined, the − first-order diffracted beam of the first beam having traveled via the second pupil partial region and the optical system to be examined; and

determining a ratio of a pupil transmittance in the first pupil partial region and a pupil transmittance in the second pupil partial region, based on a measured value of the intensity of the + first-order diffracted beam of the first beam and a measured value of the intensity of the − first-order diffracted beam of the first beam.

2. The measuring method according to claim 1, wherein the first and second phase regions are alternately arranged on the first surface, and

wherein the second phase value is different by π from the first phase value.

3. The measuring method according to claim 1 or 2, wherein said step of supplying the first beam comprises making an oblique beam inclined relative to an optical axis of the optical system to be examined, incident as the first beam to the predetermined position.

4. The measuring method according to any one of claims 1 to 3, further comprising the steps of:

supplying a second beam to the predetermined position on the first surface;

diffracting the second beam by imparting the first phase value to light passing through the first phase region on the first surface and imparting the second phase value to light passing through the second phase region; and

letting a + first-order diffracted beam of the second beam pass through a third pupil partial region apart from the first and second pupil partial regions in the effective region and letting a − first-order diffracted beam of the second beam pass through a fourth pupil partial region apart from the first to third pupil partial regions in the effective region, the + first-order diffracted beam of the second beam being generated through diffraction of the second beam, the − first-order diffracted beam of the second beam being generated through diffraction of the second beam.

5. The measuring method according to claim 4, wherein the first beam and the second beam are incident simultaneously to the predetermined position.

6. The measuring method according to claim 5, wherein the first beam and the second beam are incident simultaneously to the predetermined position so that ± third-order diffracted beams of the first beam pass through pupil partial regions apart from the first to fourth pupil partial regions on the pupil, the ± third-order diffracted beams of the first beam being generated through diffraction of the first beam.

7. The measuring method according to claim 5 or 6, further comprising the steps of:

making a third beam incident to the predetermined position, before or after incidence of the first and second beams; and

letting a + first-order diffracted beam of the third beam pass through a fifth pupil partial region in a first inclusion region including the first and second pupil partial regions in the effective region and letting a − first-order diffracted beam pass through a sixth pupil partial region in a second inclusion region including the third and fourth pupil partial regions in the effective region, the + first-order diffracted beam of the third beam being generated through diffraction of the third beam, the − first-order diffracted beam of the third beam being generated through diffraction of the third beam.

8. The measuring method according to any one of claims 1 to 7, wherein the first and second phase regions comprise the first phase regions of a rectangular shape and the second phase regions of a rectangular shape arranged in a checkered pattern.

9. A measuring method of measuring a pupil transmittance distribution of an optical system to be examined, comprising the steps of:

supplying a first beam inclined relative to an optical axis of the optical system to be examined, to a predetermined position on a first surface in an optical Fourier transform relation with a pupil of the optical system to be examined;

diffracting the first beam;

letting a + first-order diffracted beam of the first beam pass through a first pupil partial region in an effective region of the pupil and letting a − first-order diffracted beam of the first beam pass through a second pupil partial region apart from the first pupil partial region in the effective region, the + first-order diffracted beam of the first beam being generated through diffraction of the first beam, the − first-order diffracted beam of the first beam being generated through diffraction of the first beam;

measuring an intensity of the + first-order diffracted beam of the first beam and an intensity of the − first-order diffracted beam of the first beam, the + first-order diffracted beam of the first beam having traveled via the first pupil partial region and the optical system to be examined and an intensity of the − first-order diffracted beam of the first beam having traveled via the second pupil partial region and the optical system to be examined; and

determining a ratio of a pupil transmittance in the first pupil partial region and a pupil transmittance in the second pupil partial region, based on a measured value of the intensity of the + first-order diffracted beam of the first beam and a measured value of the intensity of the − first-order diffracted beam of the first beam.

10. The measuring method according to claim 9, wherein said step of diffracting the first beam comprises imparting a first phase value to light passing through a first phase region on the first surface and imparting a second phase value different from the first phase value to light passing through a second phase region adjacent to the first phase region, thereby diffracting the first beam.

11. The measuring method according to claim 10, wherein the first and second phase regions are alternately arranged on the first surface, and

wherein the second phase value is different by π from the first phase value.

12. The measuring method according to claim 10 or 11, further comprising the steps of:

supplying a second beam to the predetermined position on the first surface;

diffracting the second beam by imparting the first phase value to light passing through the first phase region on the first surface and imparting the second phase value to light passing through the second phase region; and

letting a + first-order diffracted beam of the second beam pass through a third pupil partial region apart from the first and second pupil partial regions in the effective region and letting a − first-order diffracted beam of the second beam pass through a fourth pupil partial region apart from the first to third pupil partial regions in the effective region, the + first-order diffracted beam of the second beam being generated through diffraction of the second beam, the − first-order diffracted beam of the second beam being generated through diffraction of the second beam.

13. The measuring method according to claim 12, wherein the first beam and the second beam are incident simultaneously to the predetermined position.

14. The measuring method according to claim 13, wherein the first beam and the second beam are incident simultaneously to the predetermined position so that ± third-order diffracted beams of the first beam pass through pupil partial regions apart from the first to fourth pupil partial regions on the pupil, the ± third-order diffracted beams of the first beam being generated through diffraction of the first beam.

15. The measuring method according to claim 13 or 14, further comprising the steps of:

making a third beam incident to the predetermined position, before or after incidence of the first and second beams; and

letting a + first-order diffracted beam of the third beam pass through a fifth pupil partial region in a first inclusion region including the first and second pupil partial regions in the effective region and letting a − first-order diffracted beam of the third beam pass through a sixth pupil partial region in a second inclusion region including the third and fourth pupil partial regions in the effective region, the + first-order diffracted beam of the third beam being generated through diffraction of the third beam, the − first-order diffracted beam of the third beam being generated through diffraction of the third beam.

16. The measuring method according to any one of claims 11 to 15, wherein the first and second phase regions comprise the first phase regions of a rectangular shape and the second phase regions of a rectangular shape arranged in a checkered pattern.

17. The measuring method according to any one of claims 1 to 16, further comprising the steps of:

supplying a calibration beam through the first surface and the optical system to be examined, to a predetermined position on a second surface optically conjugate with the first surface with respect to the optical system to be examined;

diffracting the calibration beam by imparting a third phase value to light passing through a third phase region on the second surface and imparting a fourth phase value different from the third phase value to light passing through a fourth phase region adjacent to the third phase region; and

measuring an intensity of a + first-order diffracted beam of the calibration beam and an intensity of a − first-order diffracted beam of the calibration beam, + first-order diffracted beam of the calibration beam being generated through diffraction of the calibration beam, the − first-order diffracted beam of the calibration beam being generated through diffraction of the calibration beam.

18. The measuring method according to claim 17, wherein the calibration beam is not diffracted by the first surface.

19. The measuring method according to claim 17 or 18, further comprising the step of:

letting the + first-order diffracted beam of the first beam and the − first-order diffracted beam of the first beam pass through a measuring optical system, the + first-order diffracted beam of the first beam having traveled via the first pupil partial region and the optical system to be examined, the − first-order diffracted beam of the first beam having traveled via the second pupil partial region and the optical system to be examined, pass through a measuring optical system,

wherein the intensities of the + first-order diffracted beam of the first beam and the − first-order diffracted beam of the first beam are measured after passage through the measuring optical system.

20. The measuring method according to claim 19, wherein the intensity of the + first-order diffracted beam of the calibration beam and the intensity of the − first-order diffracted beam of the calibration beam are measured, the + first-order diffracted beam of the calibration beam having been generated through diffraction of the calibration beam and having traveled through the measuring optical system, the − first-order diffracted beam of the calibration beam having been generated through diffraction of the calibration beam and having traveled through the measuring optical system.

21. The measuring method according to claim 20, wherein the calculation result of the ratio of the pupil transmittances is calibrated using measured values of the intensities of the + first-order diffracted beam and the − first-order diffracted beam of the calibration beam, the + first-order diffracted beam and the − first-order diffracted beam of the calibration beam having been generated through diffraction of the calibration beam and having traveled through the measuring optical system.

22. A program for letting a processing unit execute a measuring method according to any one of claims 1 to 21.

23. A computer readable medium storing a computer program for letting a computer execute a measuring method according to any one of

claims 1 to 21.

24. A controlling method of controlling an exposure apparatus comprising an illumination optical system of illuminating a predetermined pattern, and a projection optical system of forming an image of the predetermined pattern on a photosensitive substrate, comprising the step of:

changing an illumination condition for illumination of the predetermined pattern, based on the measurement result of a pupil transmittance distribution of the projection optical system measured by a measuring method according to any one of claims 1 to 21.

25. The controlling method according to claim 24, wherein the illumination condition is at least one of an illuminance distribution on the first surface by the illumination optical system and a pupil luminance distribution on a pupil of the illumination optical system.

26. An exposure method comprising illuminating a predetermined pattern, and performing exposure to transfer the predetermined pattern onto a photosensitive substrate by a projection optical system, comprising the step of:

changing an illumination condition for illumination of the predetermined pattern, based on the measurement result of a pupil transmittance distribution of the projection optical system measured by a measuring method according to any one of claims 1 to 21.

27. An exposure method comprising illuminating a predetermined pattern, and performing exposure to transfer the predetermined pattern onto a photosensitive substrate by a projection optical system, comprising the step of:

using a pattern produced based on the measurement result of a pupil transmittance distribution of the projection optical system measured by a measuring method according to any one of claims 1 to 21.

28. A device manufacturing method comprising the steps of:

performing exposure to transfer the predetermined pattern onto the photosensitive substrate, using an exposure method according to claim 26 or 27;

developing the photosensitive substrate with the predetermined pattern transferred thereon, and forming a mask layer in a shape corresponding to the predetermined pattern on a surface of the photosensitive substrate; and

processing the surface of the photosensitive substrate through the mask layer.

29. A measuring apparatus for measuring a pupil transmittance distribution of an optical system to be examined, comprising:

a diffraction grating allowed to be mounted on a first surface in an optical Fourier transform relation with a pupil of the optical system to be examined, the diffraction grating diffracting light reaching thereto;

an illumination optical system making an inclined beam relative to an optical axis of the optical system to be examined, incident to a predetermined position on the first surface so that a + first-order diffracted beam of the light passes through a first pupil partial region in an effective region of the pupil and so that a − first-order diffracted beam of the light passes through a second pupil partial region apart from the first pupil partial region in the effective region, the + first-order diffracted beam of the light being generated through the diffraction grating mounted on the first surface, the − first-order diffracted beam of the light being generated through the diffraction grating; and

a measuring unit measuring an intensity of the + first-order diffracted beam of the light and an intensity of the − first-order diffracted beam of the light, the + first-order diffracted beam of the light having traveled via the first pupil partial region and the optical system to be examined, the − first-order diffracted beam of the light having traveled via the second pupil partial region and the optical system to be examined,

wherein a ratio of a pupil transmittance in the first pupil partial region and a pupil transmittance in the second pupil partial region is determined based on a measured value of the intensity of the + first-order diffracted beam of the light and a measured value of the intensity of the − first-order diffracted beam of the light.

30. The measuring apparatus according to claim 29, wherein the illumination optical system comprises a localized beam forming unit, the localized beam forming unit forming at least one localized beam with a light intensity distribution localized at a position apart from an optical axis of the illumination optical system on a first conjugate plane optically conjugate with the pupil.

31. The measuring apparatus according to claim 30, wherein the localized beam forming unit has an aperture stop allowed to be inserted into or retracted from an illumination optical path on the first conjugate plane.

32. The measuring apparatus according to claim 30 or 31, wherein the localized beam forming unit has a spatial light modulator, the spatial light modulator providing an angle distribution to a beam traveling toward

the first conjugate plane, in order to form the light intensity distribution localized at the position apart from the optical axis of the illumination optical system on the first conjugate plane.

33. The measuring apparatus according to claim 32, wherein the spatial light modulator comprises a diffractive optical element or a mirror array.

34. The measuring apparatus according to any one of claims 29 to 33, wherein the diffraction grating comprises a phase type diffraction grating.

35. The measuring apparatus according to claim 34, wherein the phase type diffraction grating has a form in which first phase regions to impart a first phase value to transmitted light and second phase regions to impart a second phase value different by π from the first phase value to transmitted light are alternately arranged.

36. The measuring apparatus according to claim 34, wherein the phase type diffraction grating has a form in which the first phase regions of a rectangular shape and the second phase regions of a rectangular shape are arranged in a checkered pattern.

37. The measuring apparatus according to any one of claims 29 to 36, wherein the measuring unit comprises an objective optical system arranged in an optical path between a second conjugate plane optically conjugate with the pupil and the optical system to be examined, and a photoelectric detector photoelectrically detecting the + first-order diffracted beam and the − first-order diffracted beam of the light, the + first-order diffracted beam of the light having traveled via the first pupil partial region and the objective optical system, the − first-order diffracted

beam of the having traveled via the second pupil partial region and the objective optical system, on the second conjugate plane.

38. The measuring apparatus according to claim 37, further comprising:

a second diffraction grating allowed to be mounted on a second surface in an optical Fourier transform relation with the second conjugate plane in an optical path between the optical system to be examined and the objective optical system.

39. The measuring apparatus according to any one of claims 29 to 36, wherein the measuring unit comprises a photoelectric detector arranged at a position apart from a second surface optically conjugate with the first surface with respect to the optical system to be examined, and photoelectrically detecting the + first-order diffracted beam and the − first-order diffracted beam of the light, the + first-order diffracted beam of the light having traveled via the first pupil partial region, the − first-order diffracted beam of the light having traveled via the second pupil partial region, at the position apart from the second surface.

40. The measuring apparatus according to claim 39, further comprising:

a second diffraction grating allowed to be mounted on the second surface.

41. The measuring apparatus according to claim 38 or 40, wherein the second diffraction grating includes a phase type diffraction grating.

42. The measuring apparatus according to claim 41, wherein the second diffraction grating has a form in which first phase regions to impart a first phase value to transmitted light and second phase regions to

impart a second phase value different by π from the first phase value to transmitted light are alternately arranged.

43. The measuring apparatus according to claim 42, wherein the second diffraction grating has a form in which the first phase regions of a rectangular shape and the second phase regions of a rectangular shape are arranged in a checkered pattern.

44. An exposure apparatus comprising an illumination optical system of illuminating a predetermined pattern, and a projection optical system of forming an image of the predetermined pattern on a photosensitive substrate, comprising:

a control unit controlling the illumination optical system in order to switch an illumination condition of the predetermined pattern, based on the measurement result of a pupil transmittance distribution of the projection optical system measured by a measuring method according to any one of claims 1 to 21.

45. The exposure apparatus according to claim 44, wherein the illumination condition is at least one of an illuminance distribution on the first surface by the illumination optical system and a pupil luminance distribution on a pupil of the illumination optical system.

46. An exposure apparatus comprising an illumination optical system of illuminating a predetermined pattern, and a projection optical system of forming an image of the predetermined pattern on a photosensitive substrate, comprising:

a measuring apparatus, according to any one of claims 29 to 43, of measuring a pupil transmittance distribution of the projection optical system.

47. A device manufacturing method comprising the steps of:

performing exposure to transfer the predetermined pattern onto the photosensitive substrate, using an exposure apparatus according to any one of claims 44 to 46;

developing the photosensitive substrate with the predetermined pattern transferred thereon, and forming a mask layer in a shape corresponding to the predetermined pattern on a surface of the photosensitive substrate; and

processing the surface of the photosensitive substrate through the mask layer.

48. The device manufacturing method according to claim 47, wherein said step of performing the exposure comprises using a pattern created based on the measurement result of a pupil transmittance distribution of the projection optical system.

49. A measurement reticle used in carrying out a measuring method according to any one of claims 1 to 8 and 10 to 16, wherein the first phase region and the second phase region are formed on a surface of the measurement reticle.

50. The measurement reticle according to claim 49, wherein the first phase region and the second phase region are formed on a surface of an optically transparent substrate.

51. An aperture stop used in carrying out a measuring method according to any one of claims 9 to 16, comprising:

an aperture forming a light intensity distribution localized at a position apart from an optical axis of an illumination optical system on a first conjugate plane optically conjugate with the pupil in an optical path of the illumination optical system for supplying the first beam, the aperture being formed at the position apart from the optical axis.

52. A spatial light modulator used in carrying out a measuring method according to any one of claims 9 to 16, wherein for forming a light intensity distribution localized at a position apart from an optical axis of an illumination optical system on a first conjugate plane optically conjugate with the pupil in an optical path of the illumination optical system for supplying the first beam, an angle distribution is provided to a beam traveling toward the first conjugate plane.

53. The spatial light modulator according to claim 52, comprising a diffractive optical element or a mirror array.

54. A controlling method of a spatial light modulator used in carrying out a measuring method according to any one of claims 9 to 16, wherein for forming a light intensity distribution localized at a position apart from an optical axis of an illumination optical system on a first conjugate plane optically conjugate with the pupil in an optical path of the illumination optical system for supplying the first beam, the spatial light modulator is controlled so as to provide an angle distribution to a beam traveling toward the first conjugate plane.

55. A program for letting a processing unit execute a controlling method according to claim 54.

56. A computer readable medium storing a computer program for letting a computer execute a controlling method according to claim 54.

Fig.1

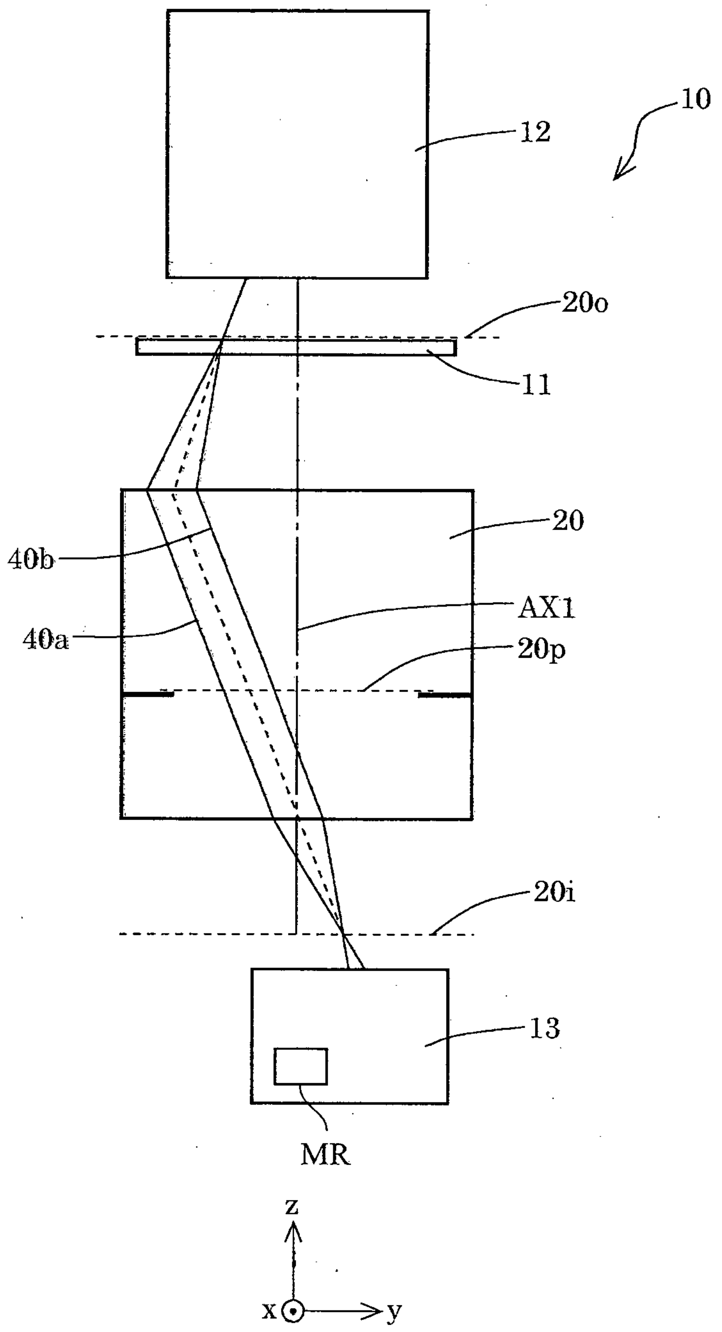


Fig.2

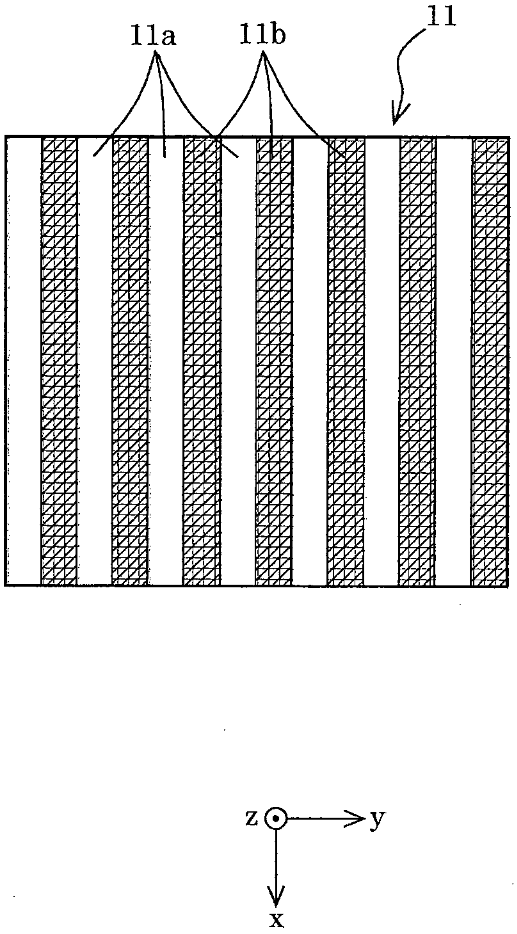


Fig.3

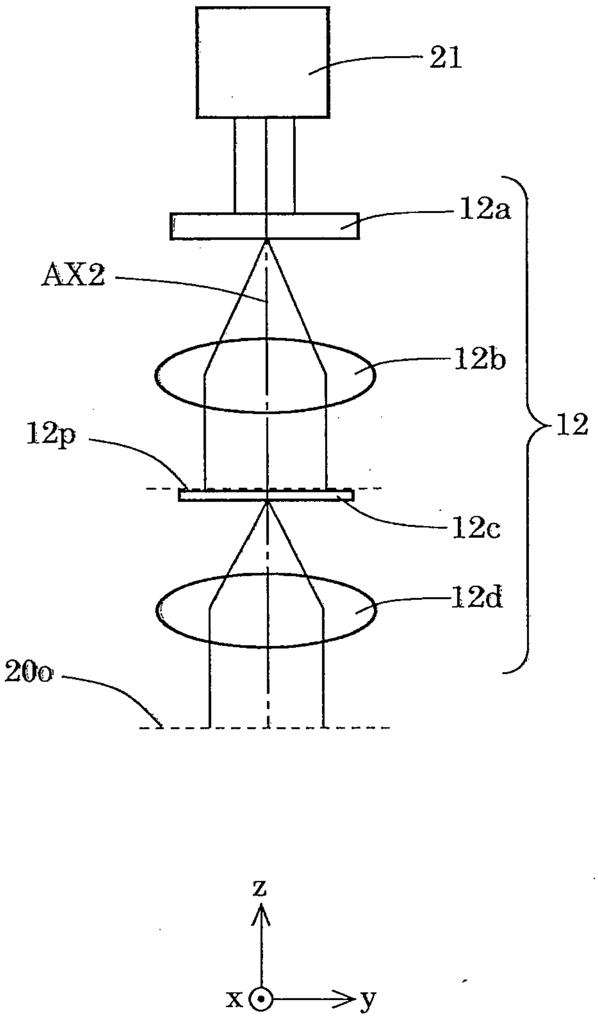
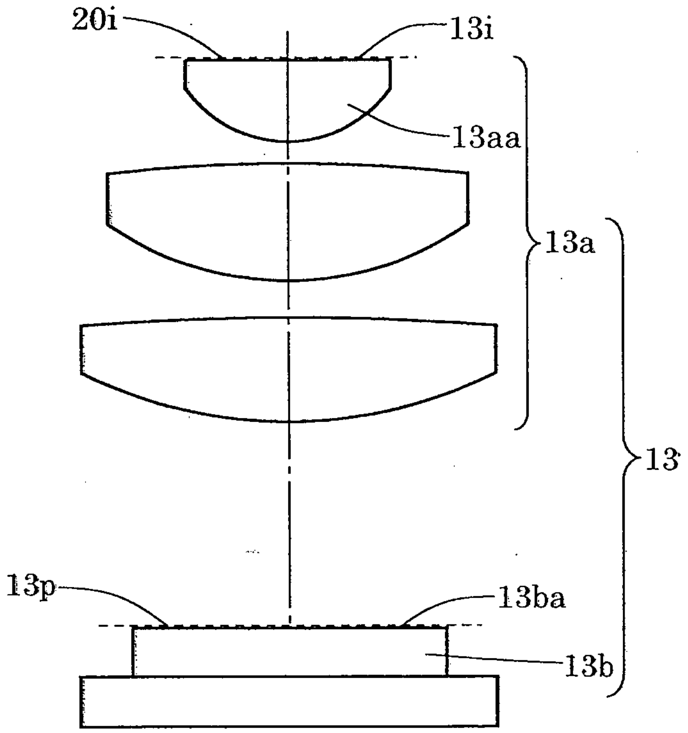


Fig.4



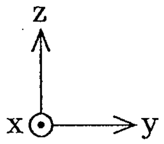


Fig.5

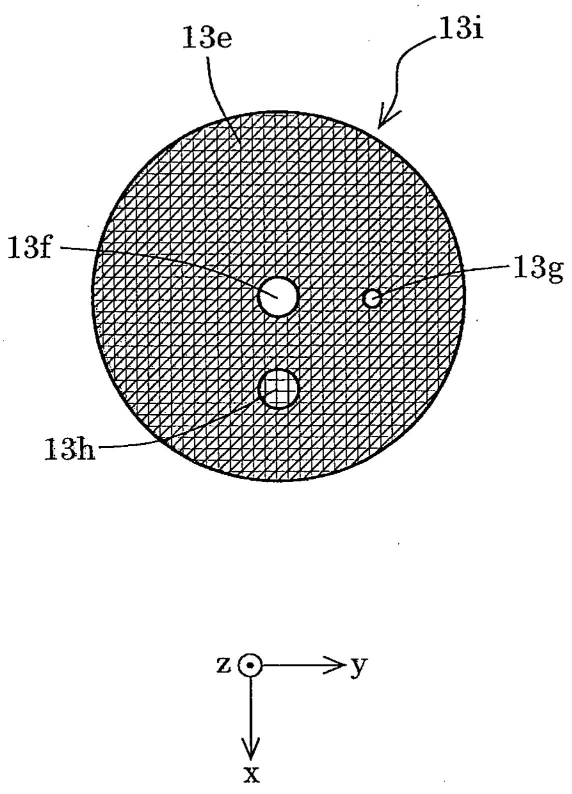


Fig.6

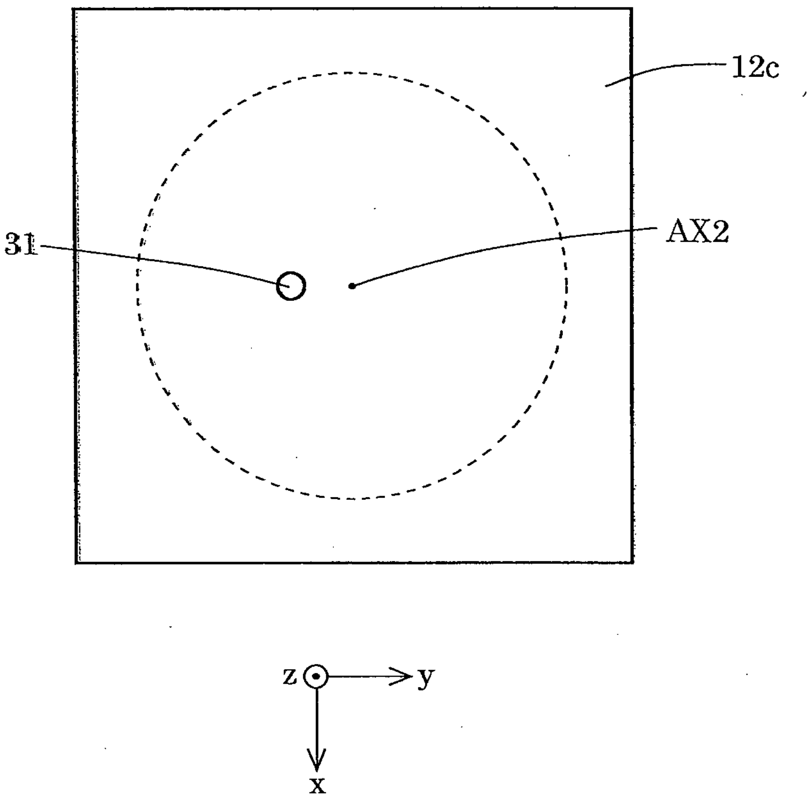


Fig.7

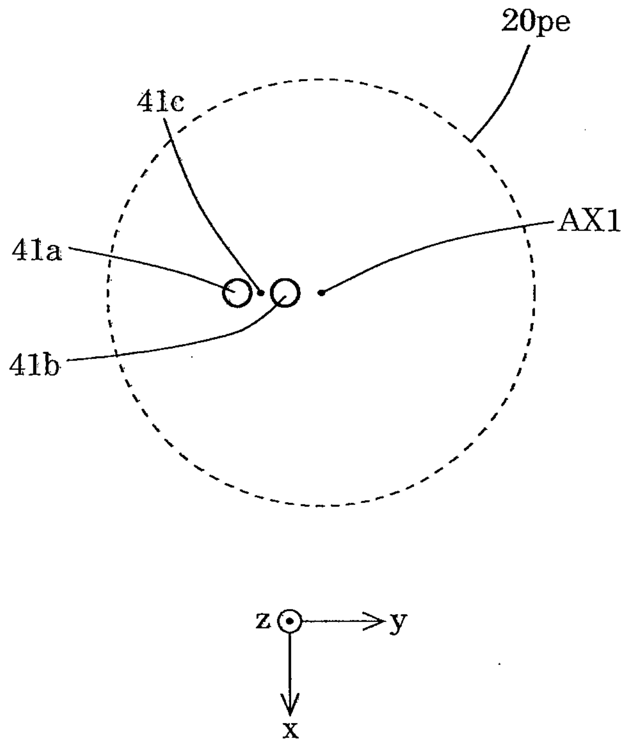


Fig.8

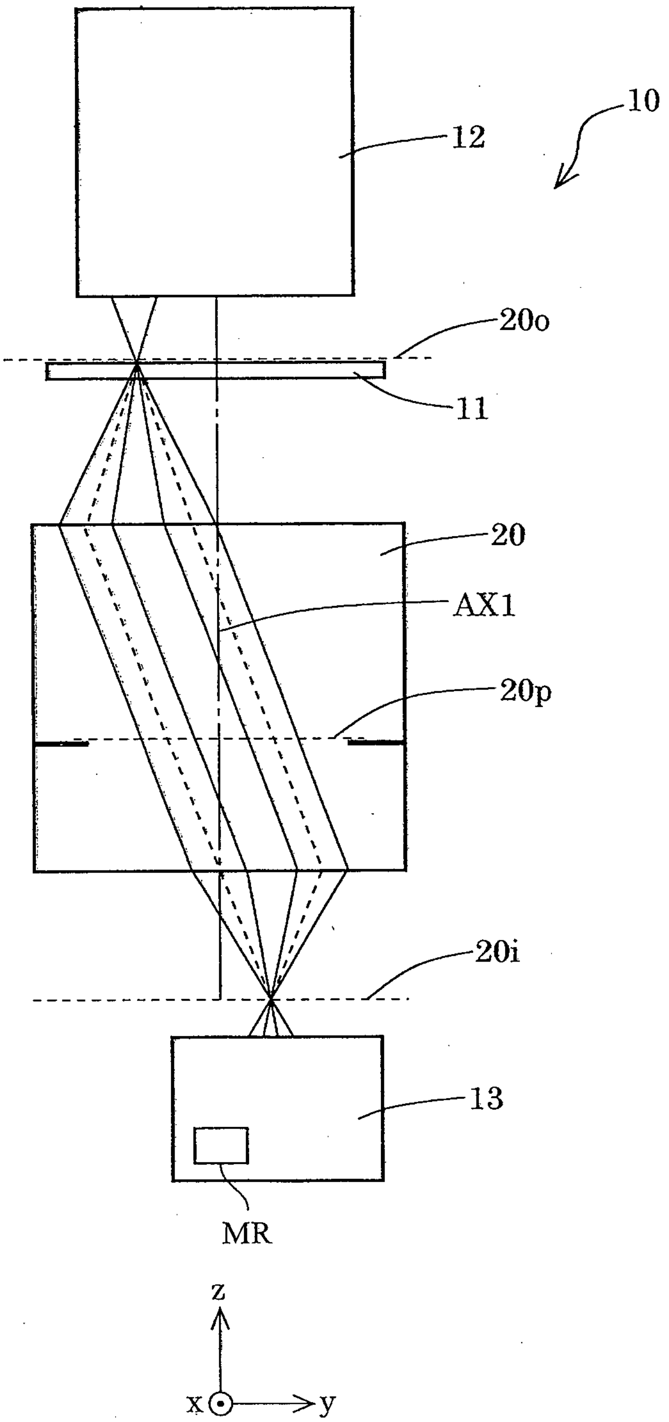


Fig.9

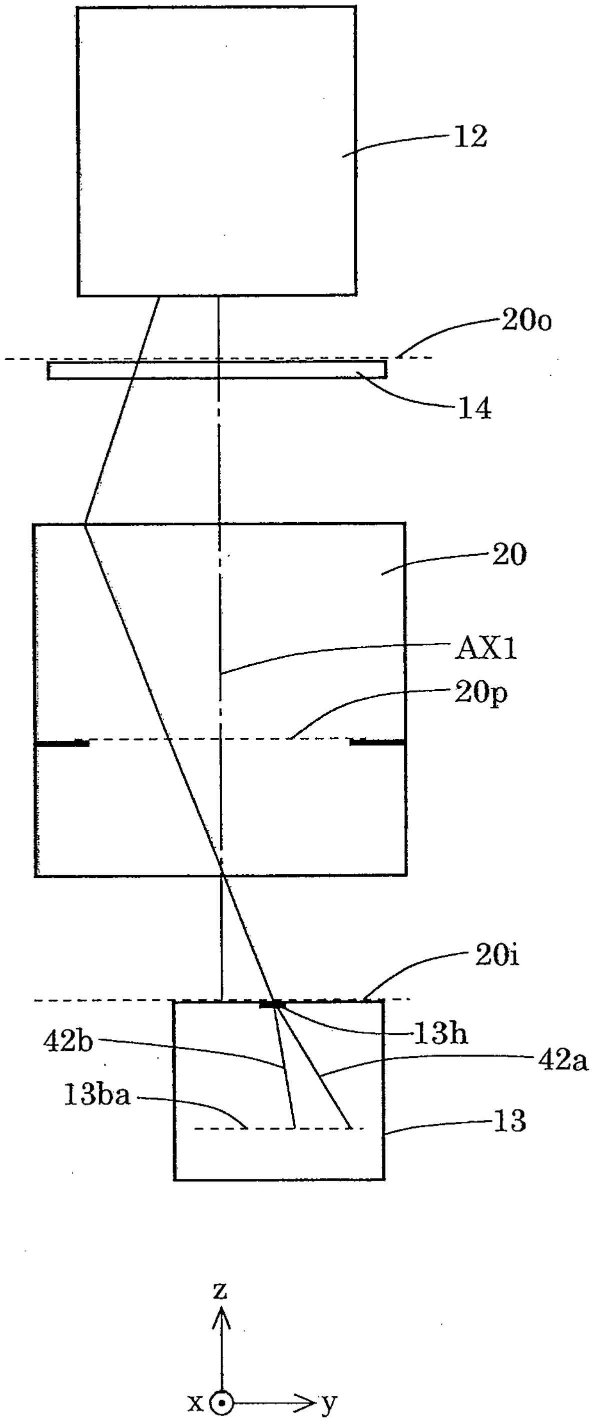
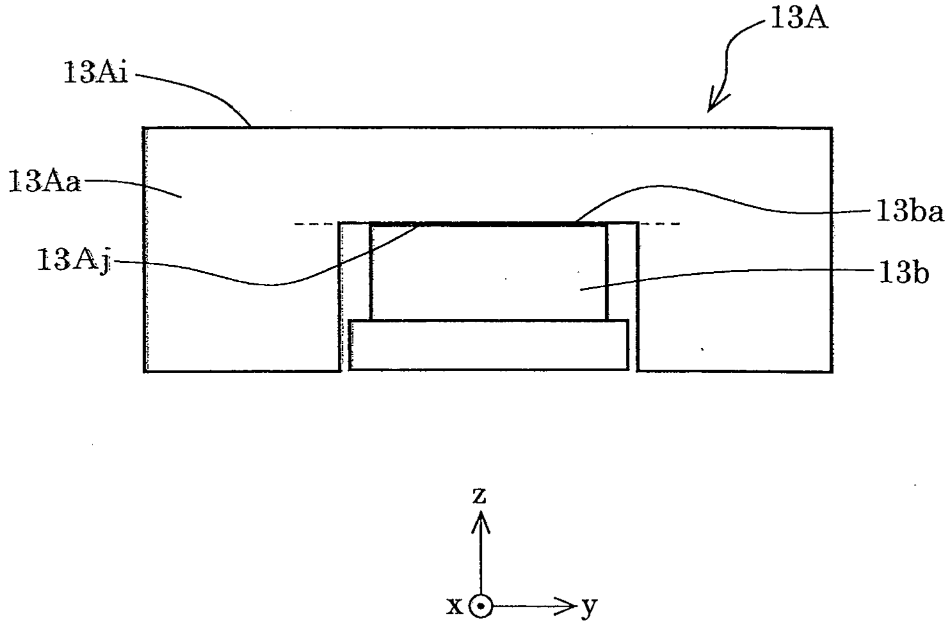


Fig.10



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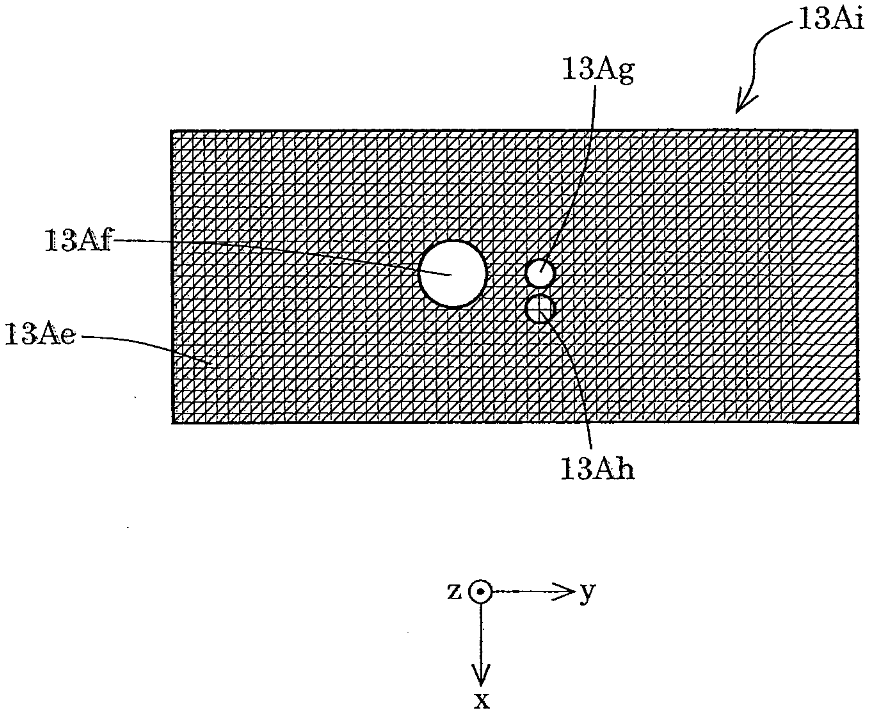


Fig.12

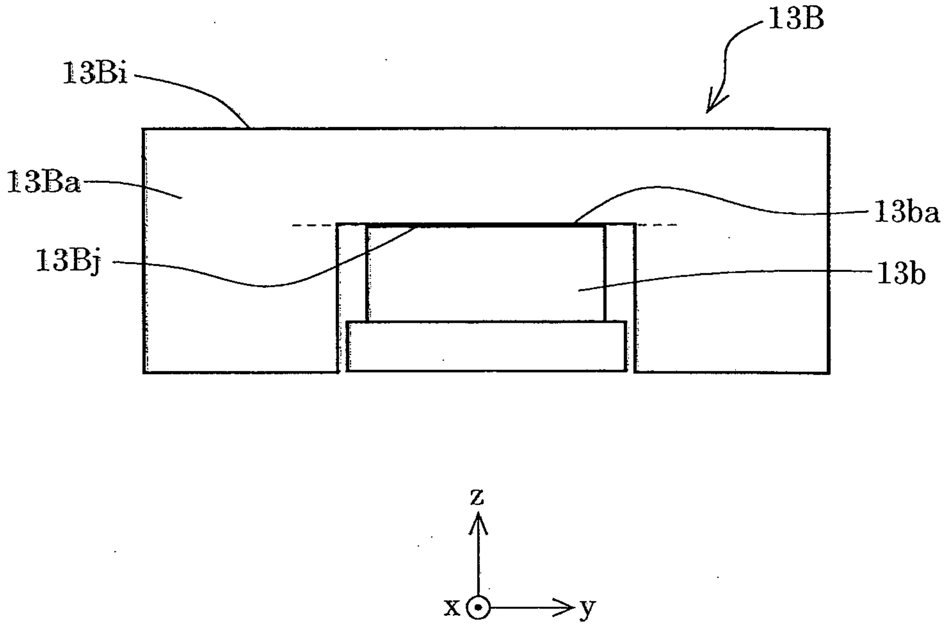


Fig.13

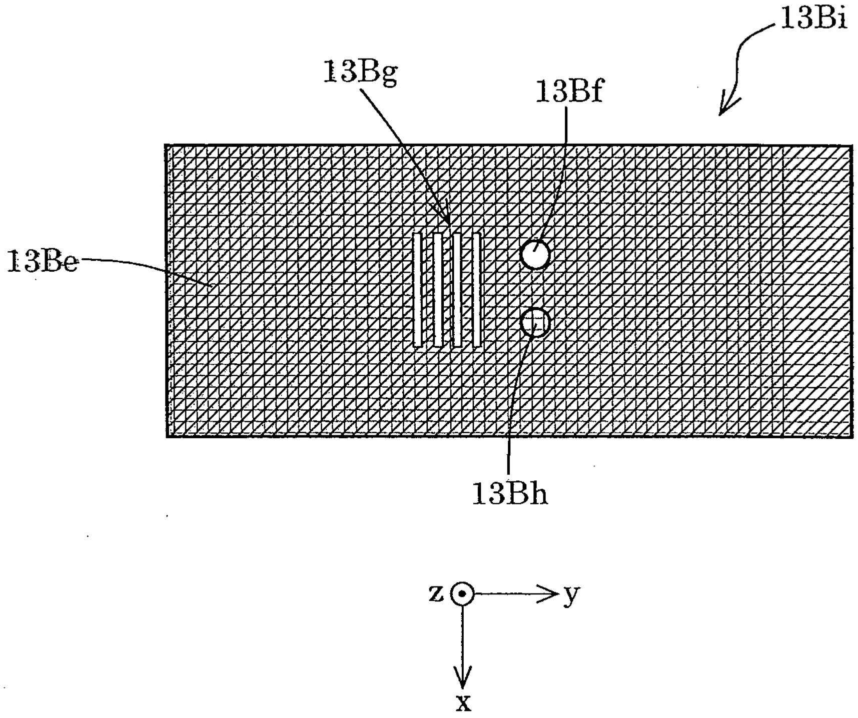
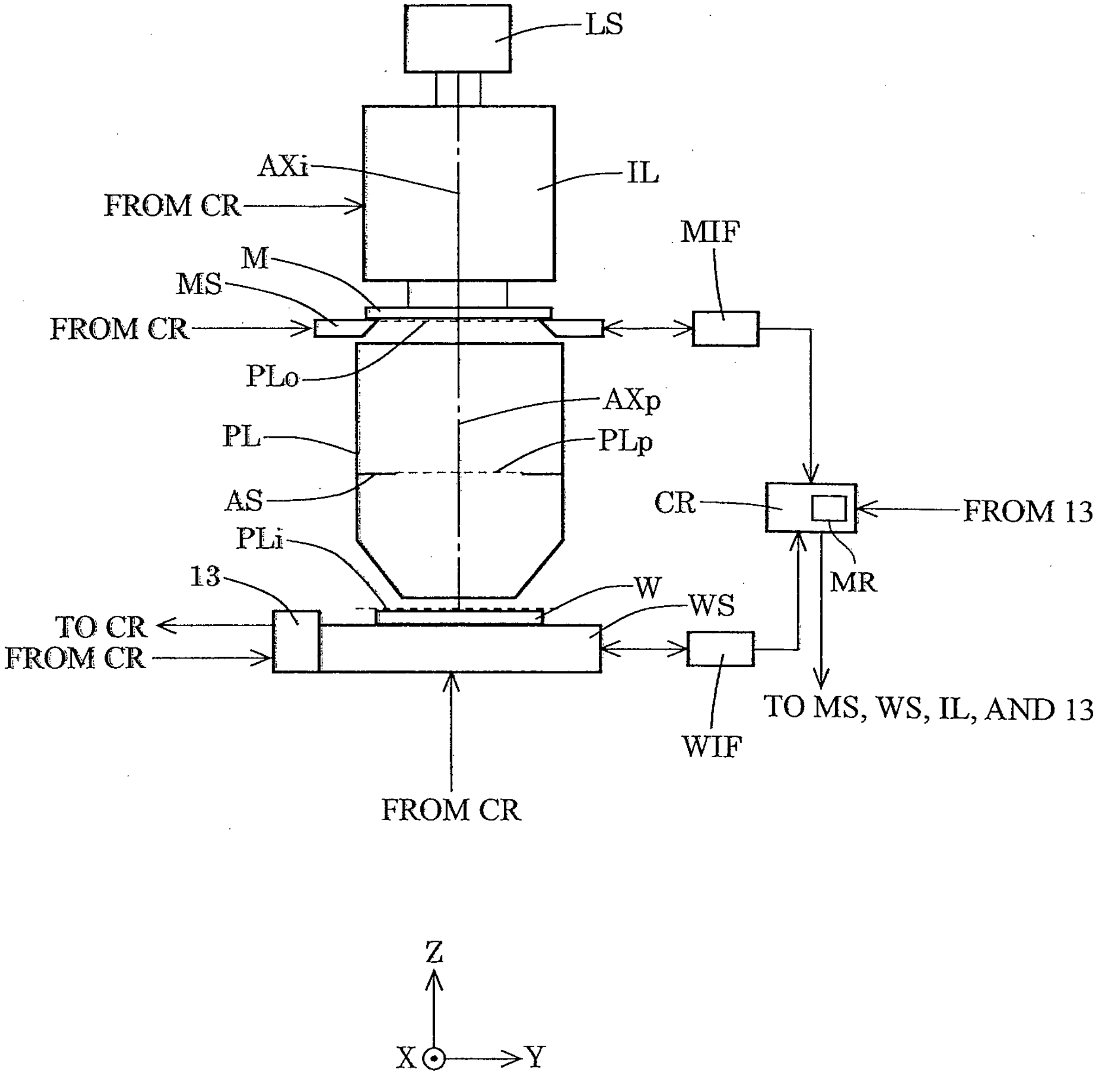


Fig.14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MIF
M
MS
FROM CR
PLo
AXp
PL
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AS
CR
FROM 13
PLi
MR
13
W
WS
TO CR
FROM CR
TO MS, WS, IL, AND 13
WIF
FROM CR
Z
X
Y

Fig.15

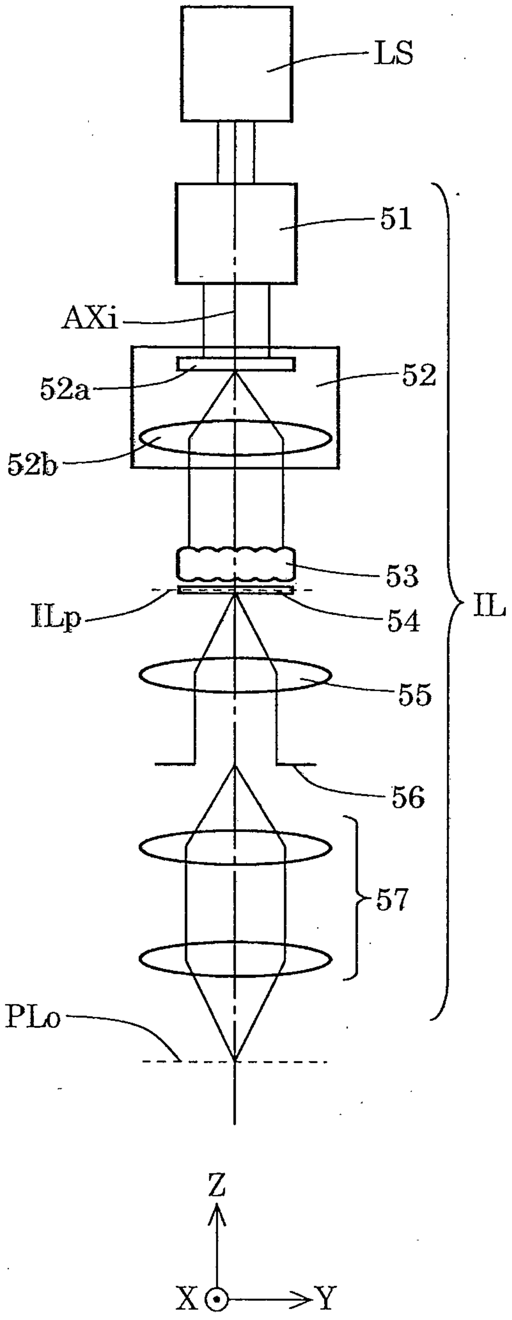
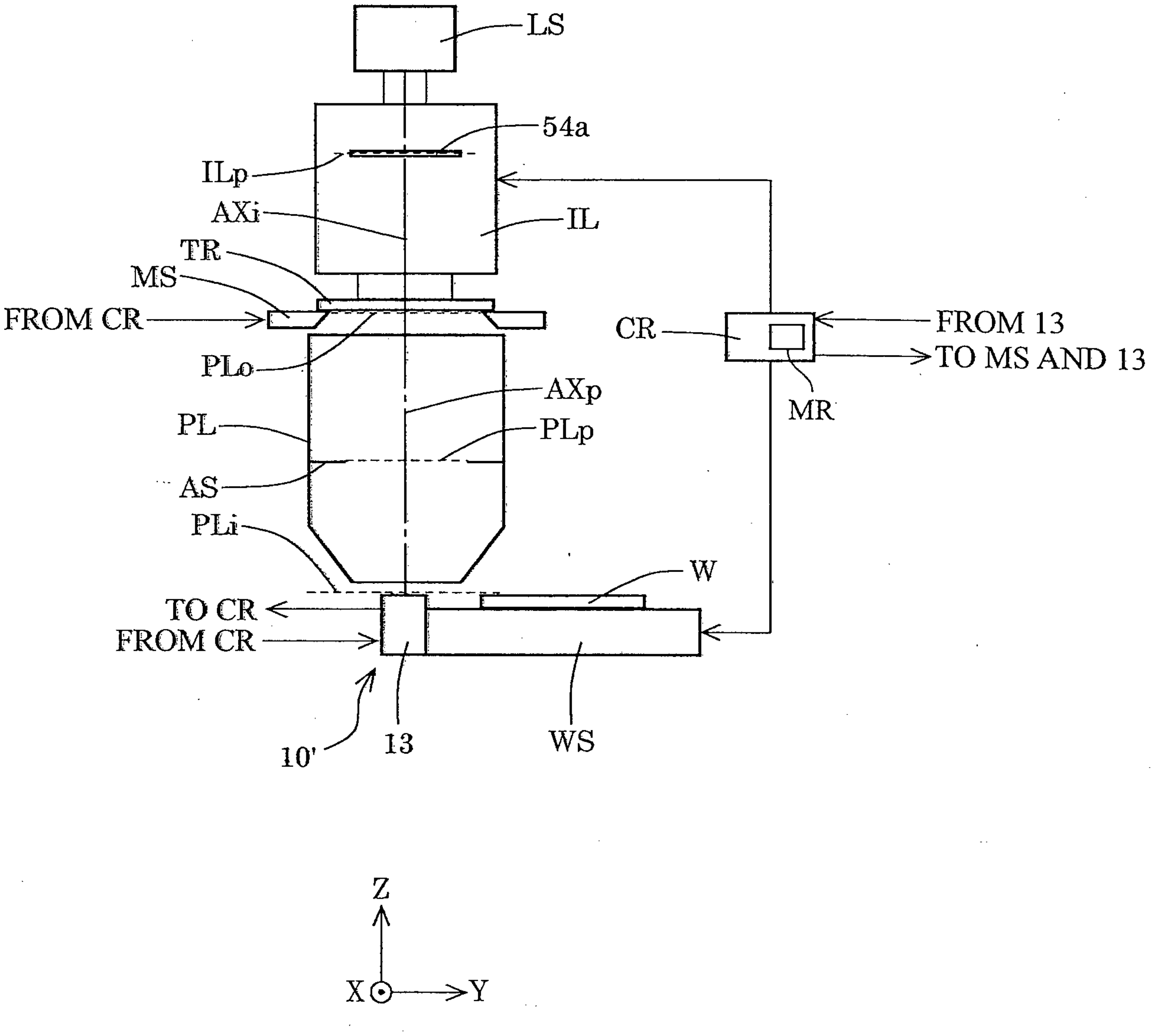


Fig.16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ILp
AXi
IL
TR
MS
FROM CR
CR
FROM 13
TO MS AND 13
MR
PLo
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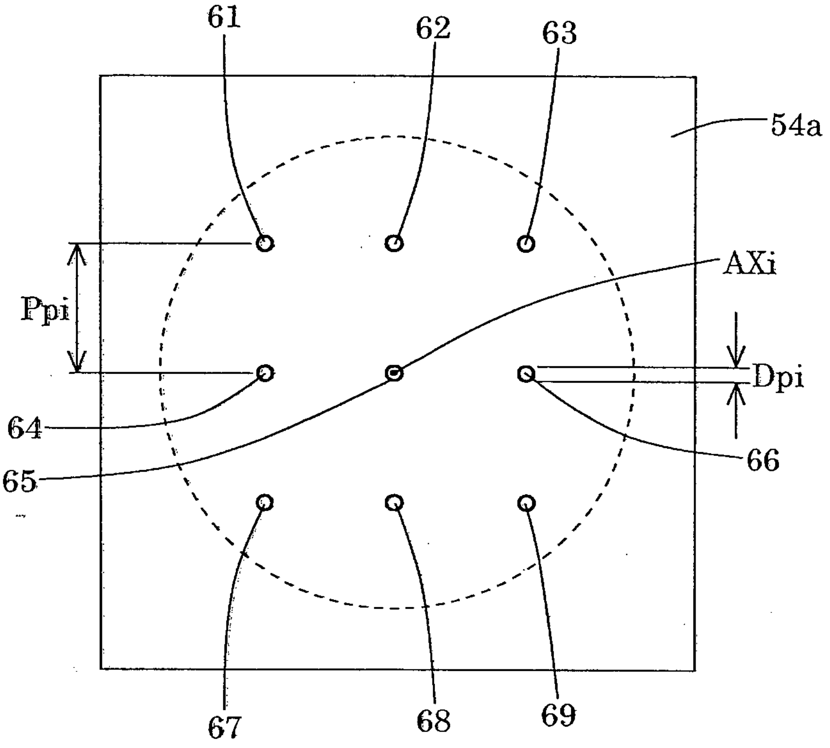
PL
PLp
AS
PLi
W
TO CR
FROM CR
10'
13
WS
Z
X
Y

Fig.17



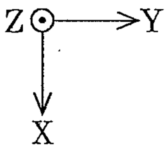


Fig.18

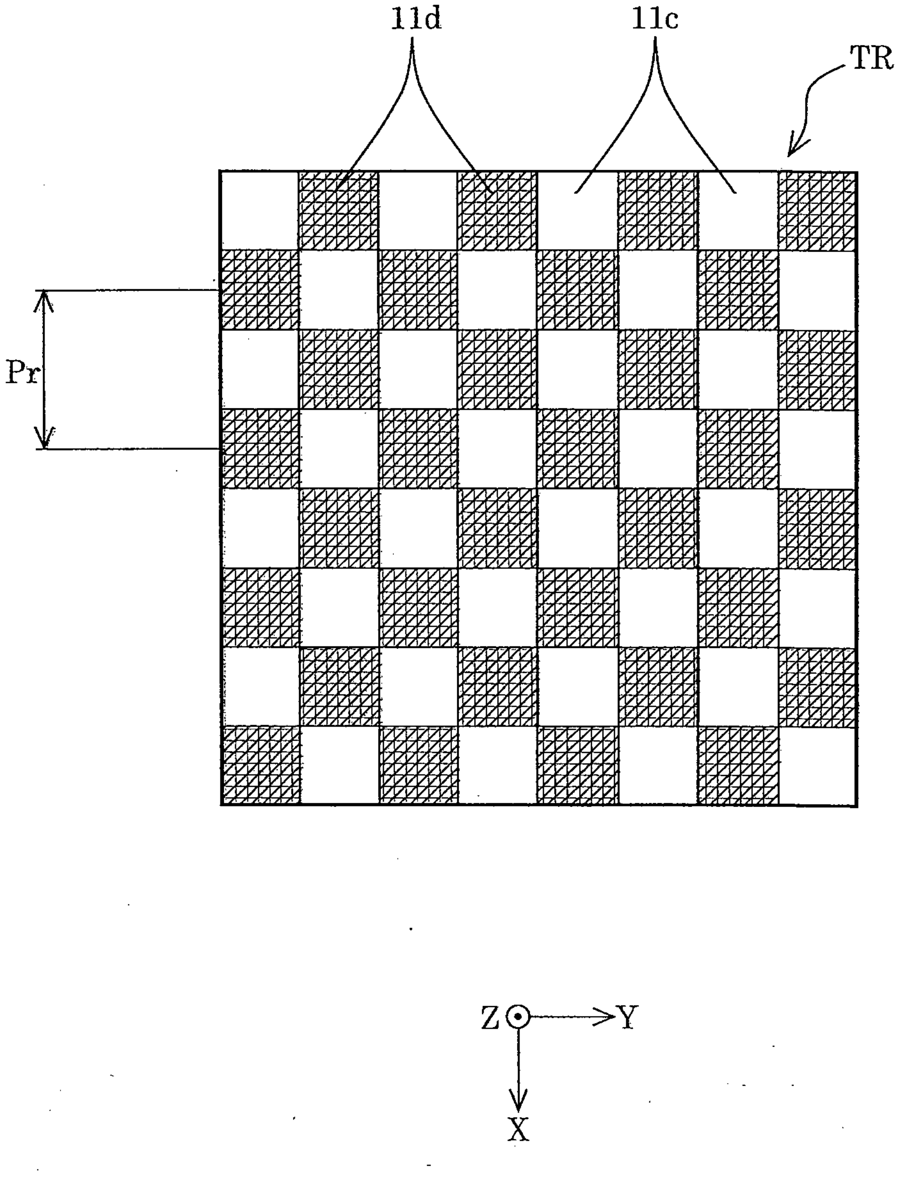


Fig.19

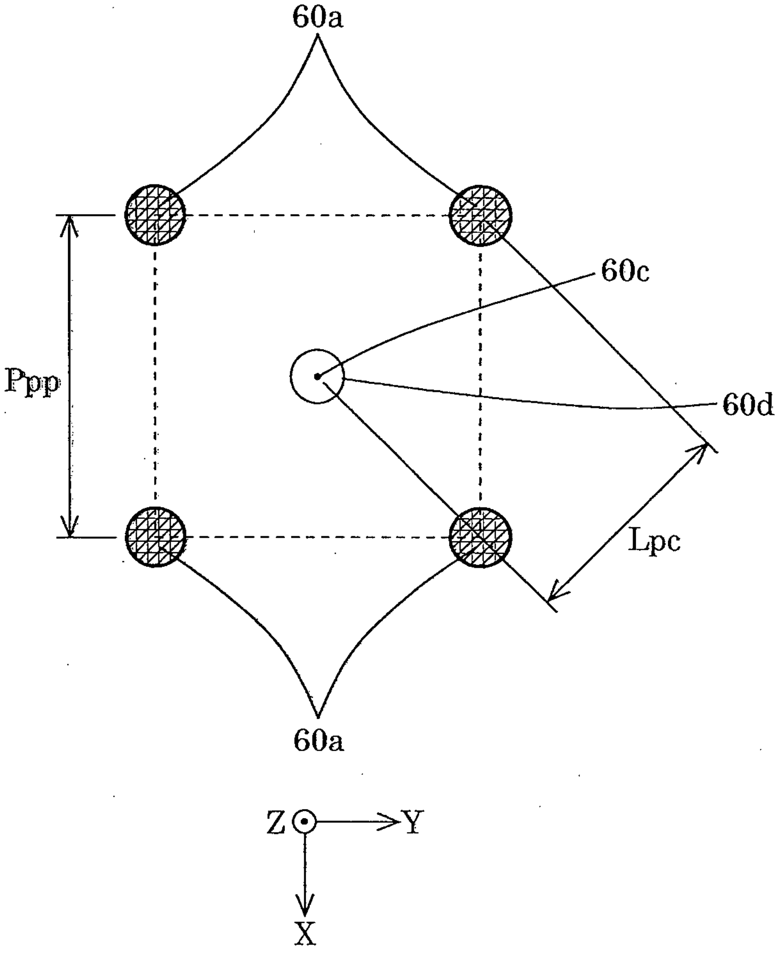
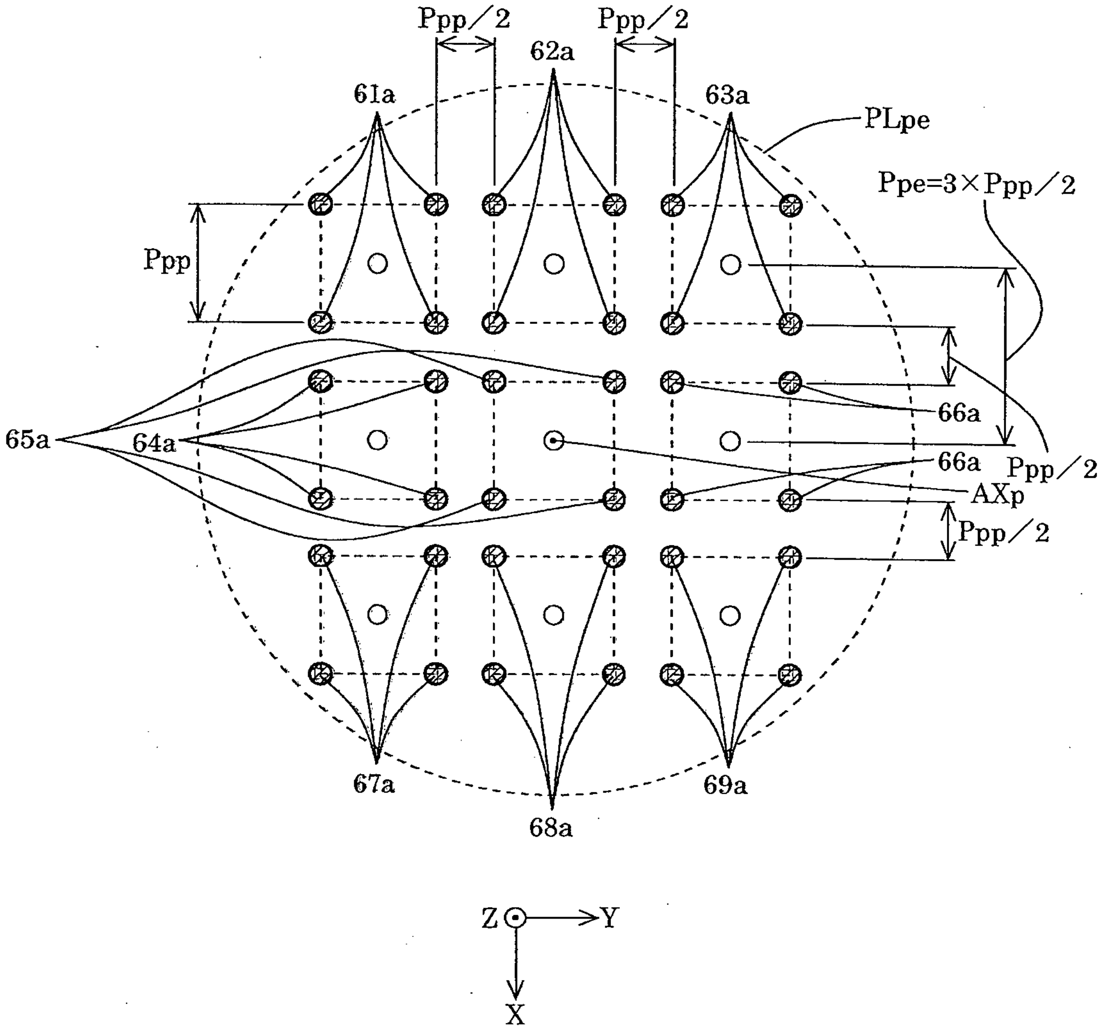


Fig.20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Ppp／2
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61a
63a
PLpe
Ppe=3×Ppp／2
Ppp
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66a
Ppp／2
AXp
Ppp／2
67a
68a
69a
Z
Y
X

Fig.21

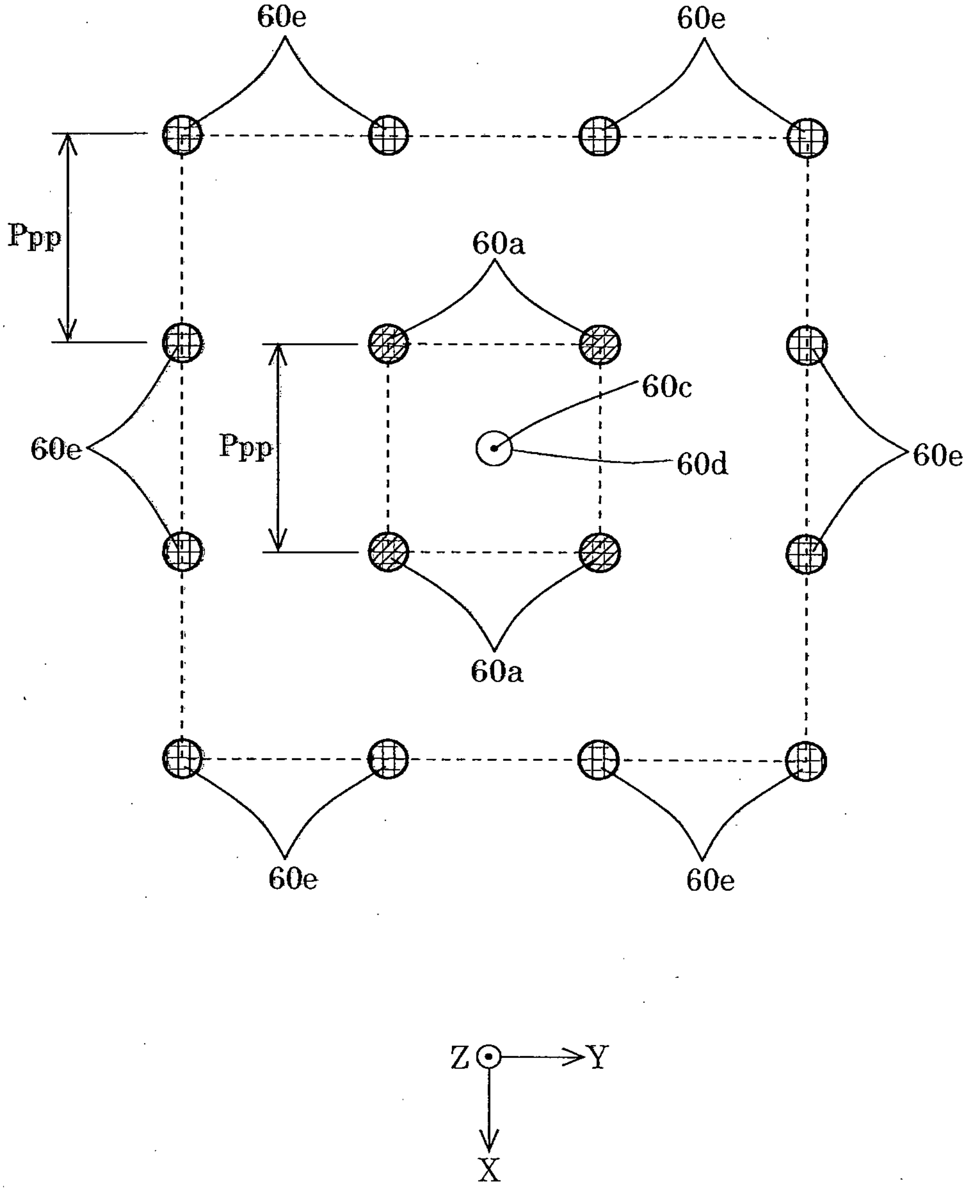
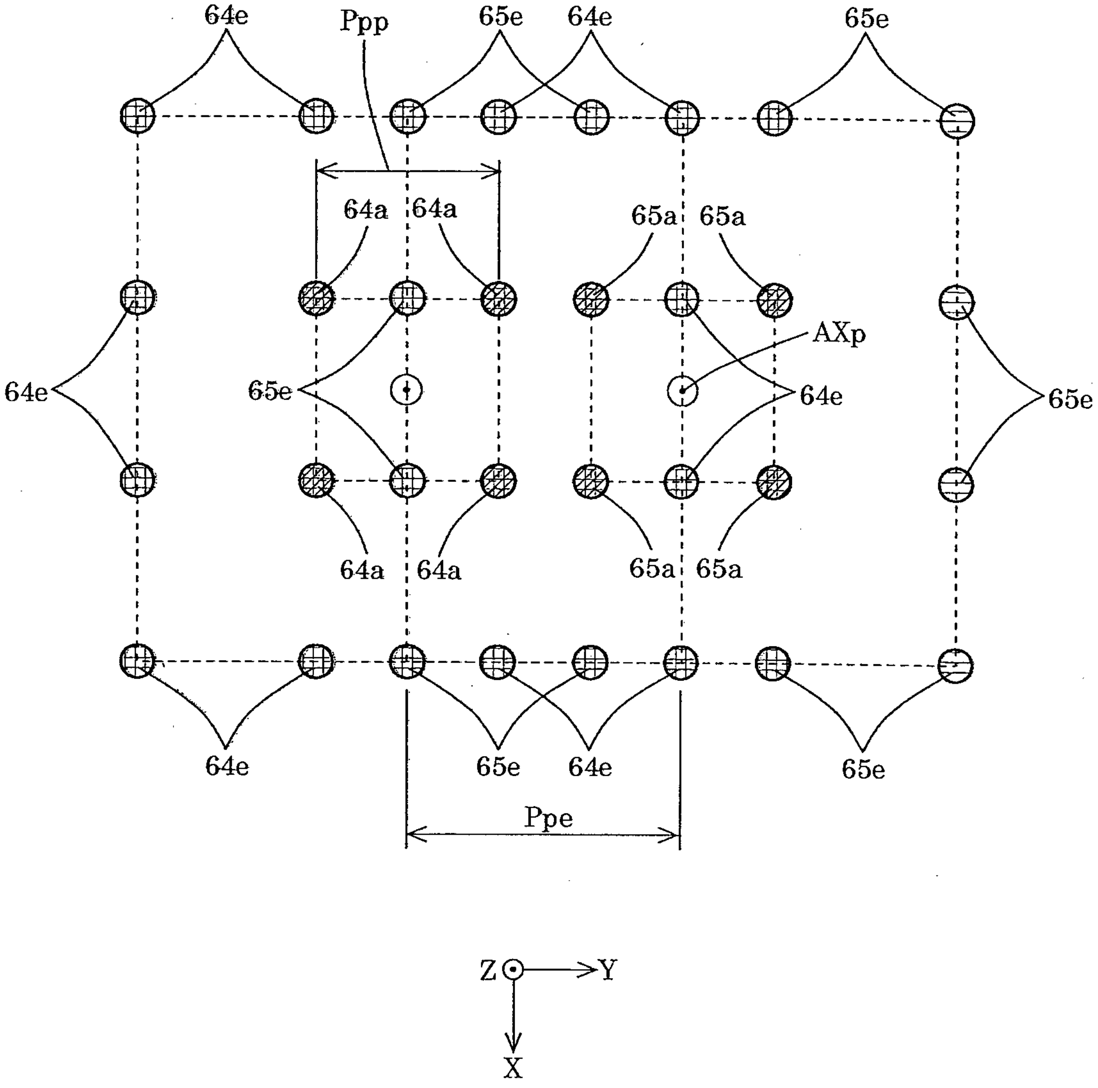


Fig.22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Ppp
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AXp
64e
65e
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Ppe
Z
Y
X

Fig.23

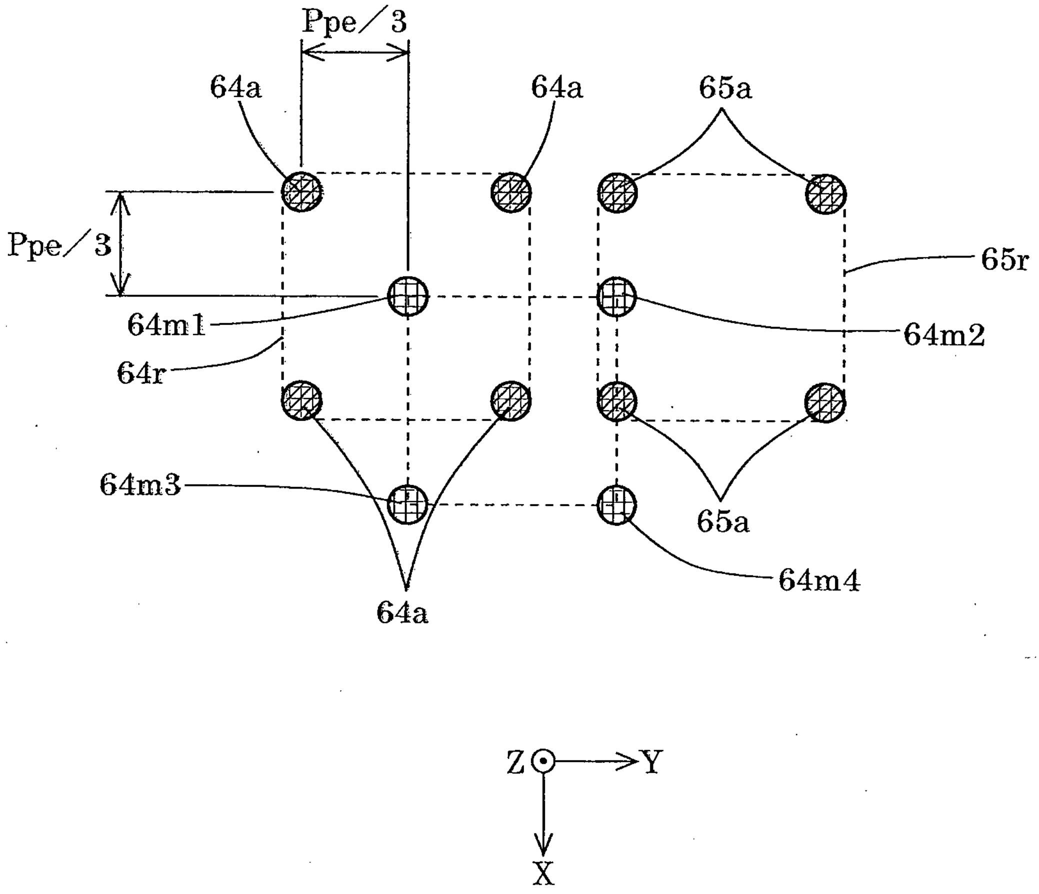


Fig.24

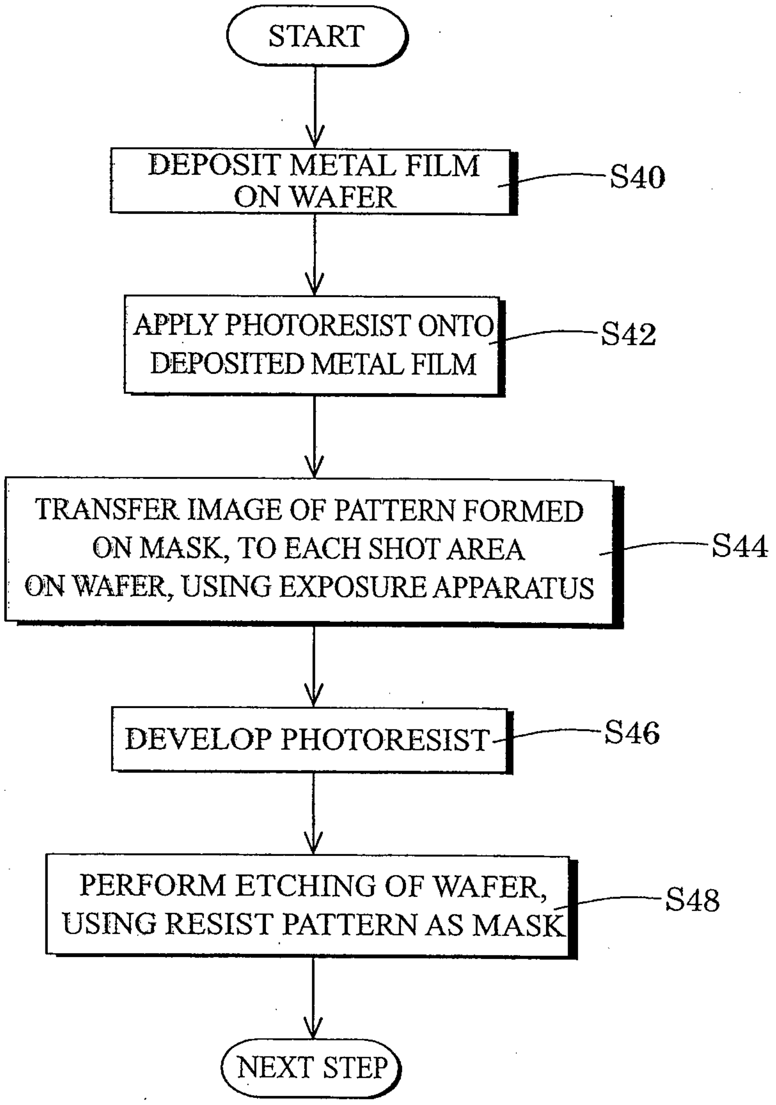
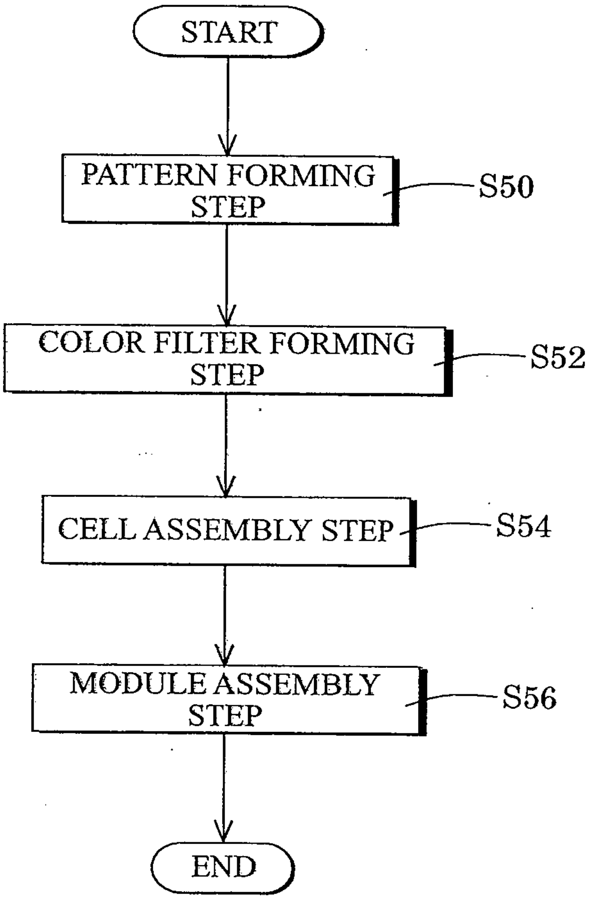

START
DEPOSIT METAL FILM ON WAFER
S40
APPLY PHOTORESIST ONTO DEPOSITED METAL FILM
S42
TRANSFER IMAGE OF PATTERN FORMED ON MASK, TO EACH SHOT AREA ON WAFER, USING EXPOSURE APPARATUS
S44
DEVELOP PHOTORESIST
S46
PERFORM ETCHING OF WAFER, USING RESIST PATTERN AS MASK
S48
NEXT STEP

Fig.25


START
PATTERN FORMING STEP
S50
COLOR FILTER FORMING STEP
S52
CELL ASSEMBLY STEP
S54
MODULE ASSEMBLY STEP
S56
END

INTERNATIONAL SEARCH REPORT

International application No

PCT/JP2011/053588

A. CLASSIFICATION OF SUBJECT MATTER

INV. G03F7/20 G01M11/02

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 H01L G01M G03B G01N

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/180278 A1 (SATO KAZUYA [JP] ET AL) 16 September 2004 (2004-09-16)	1,2,8, 17-28, 44,45, 47-56
Y	paragraphs [0118] - [0130], [0139], [0142]; figures 14-16 -----	3-7, 9-16, 29-43,46
Y	US 2003/133099 A1 (SHIODE YOSHIHIRO [JP]) 17 July 2003 (2003-07-17) paragraphs [0183] - [184,]; figures 32,33 -----	3-7, 9-16, 29-43,46

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

☒ See patent family annex.

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search 4 May 2011	Date of mailing of the international search report 18/05/2011
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Weckesser, Jens

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/JP2011/053588

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2004180278 A1	16-09-2004	NONE	
US 2003133099 A1	17-07-2003	CN 1547681 A	17-11-2004
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		WO 03021352 A1	13-03-2003
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