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(54) **EXPOSURE SYSTEM AND METHOD OF MANUFACTURING ELECTRONIC DEVICE**

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(57) **ABSTRACT**

An exposure system includes an illumination optical system configured to illuminate a photomask with a pulse laser beam including a plurality of center wavelengths, and a projection optical system configured to illuminate a photosensitive substrate with the pulse laser beam that has passed through the photomask and to project an image of the photomask. A position of a first pupil that is a pupil of the illumination optical system is shifted from a reference position in a conjugate relationship with a second pupil that is a pupil of the projection optical system in a direction of reducing, by a magnification telecentric error, deviation of an imaging position due to lateral chromatic aberration on the photosensitive substrate.

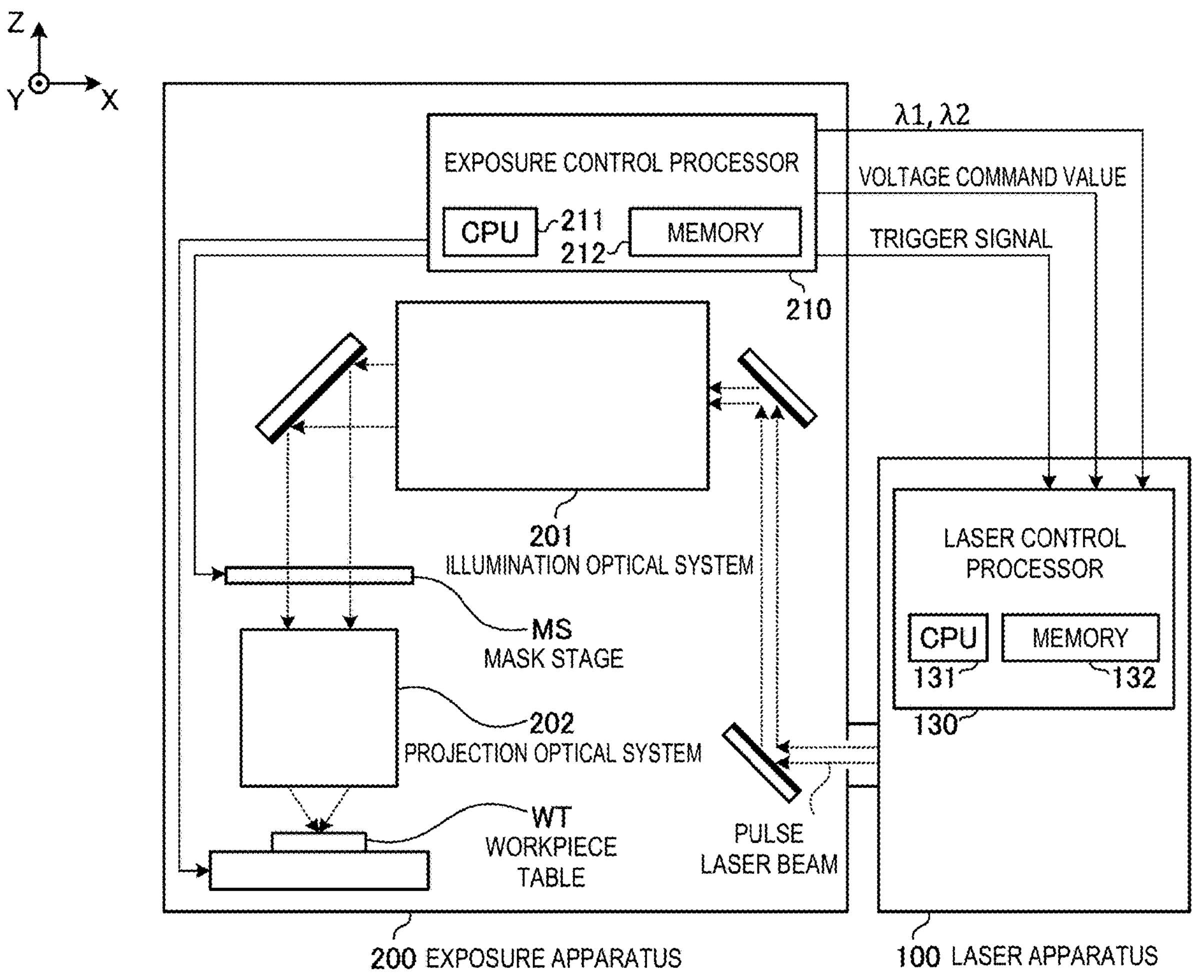


Fig. 1

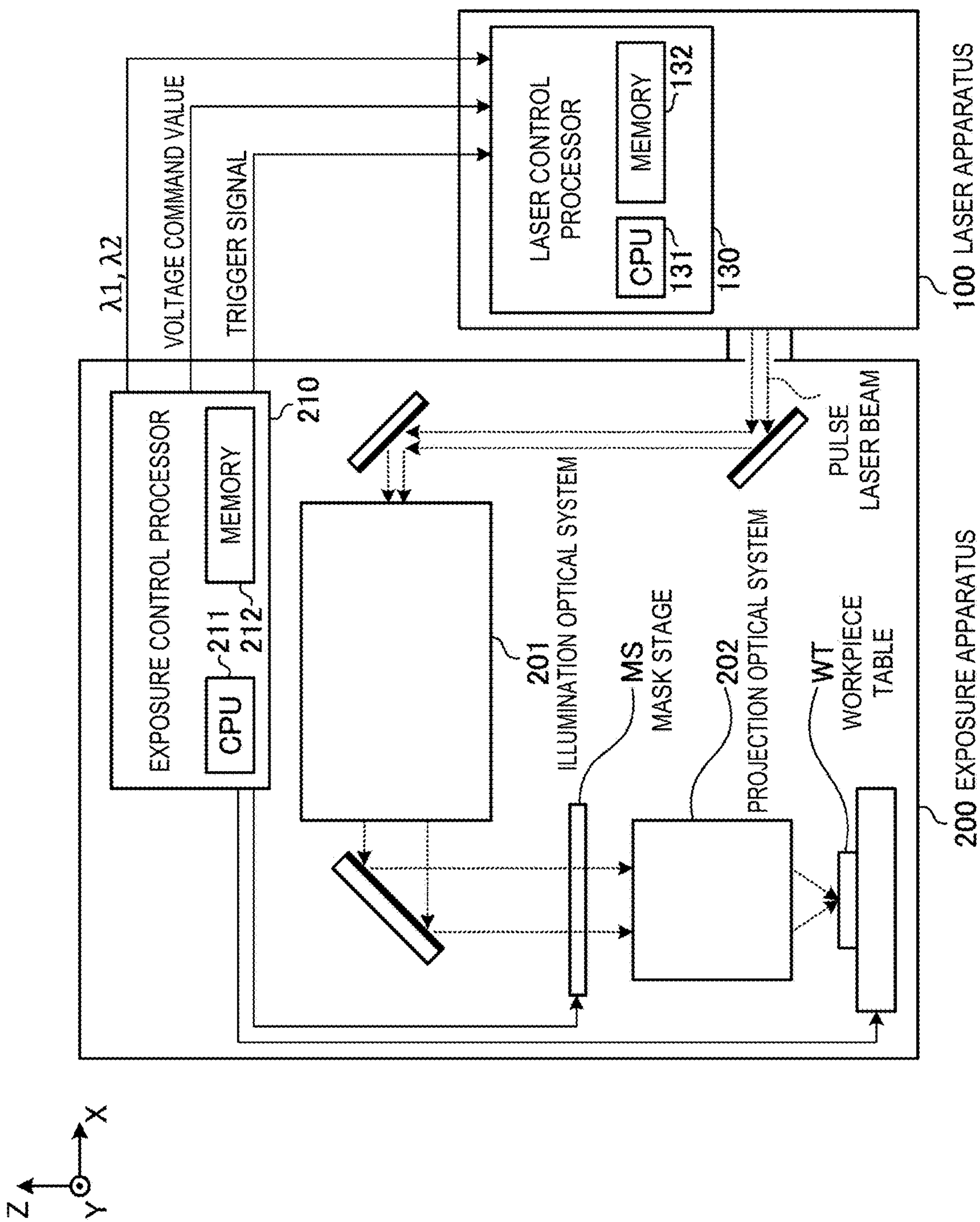
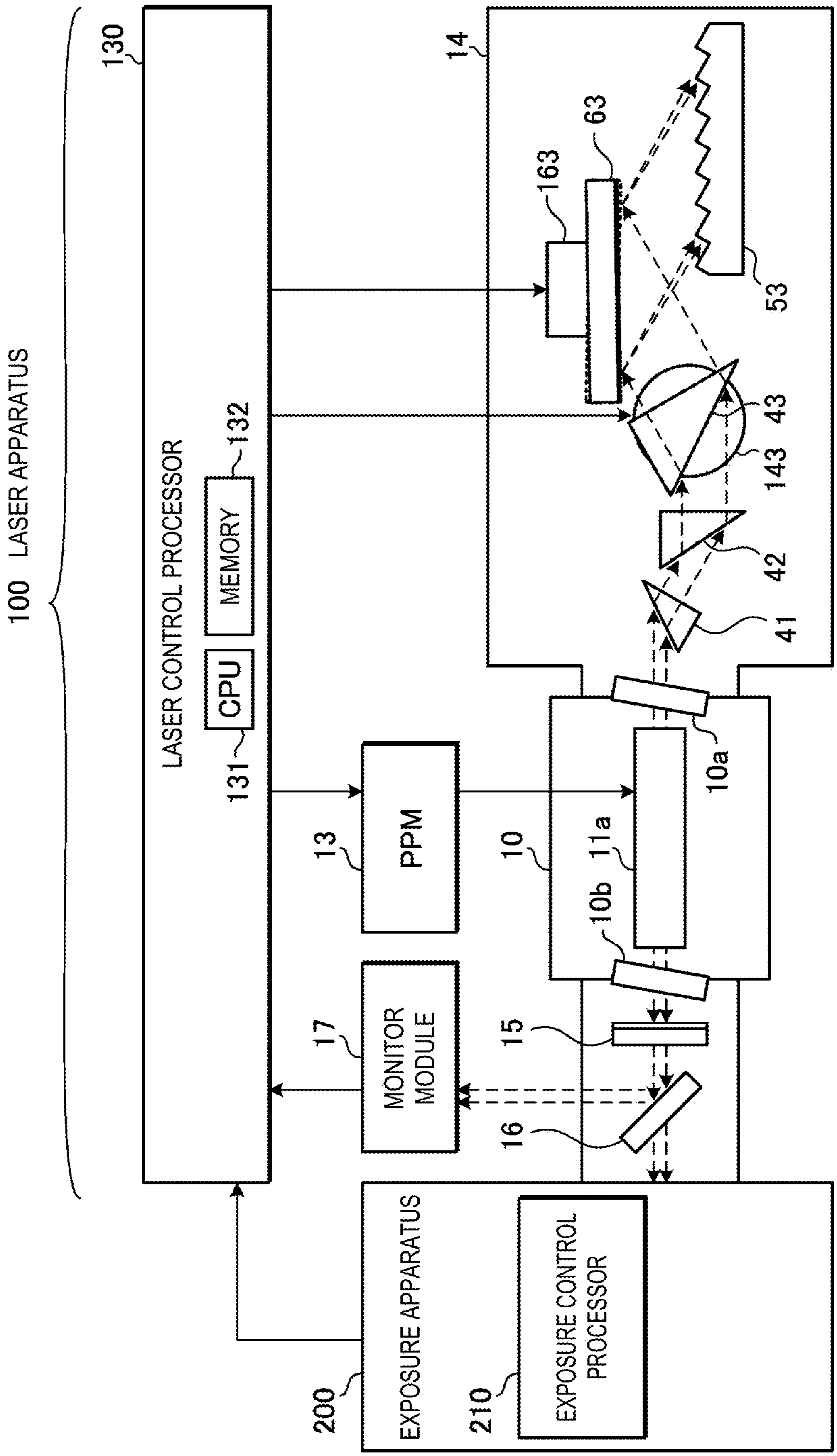

λ1, λ2
VOLTAGE COMMAND VALUE
TRIGGER SIGNAL
LASER CONTROL PROCESSOR
CPU
131
MEMORY
132
130
100 LASER APPARATUS
EXPOSURE CONTROL PROCESSOR
CPU
211
MEMORY
212
210
PULSE LASER BEAM
201 ILLUMINATION OPTICAL SYSTEM
MS MASK STAGE
202 PROJECTION OPTICAL SYSTEM
WT WORKPIECE TABLE
200 EXPOSURE APPARATUS
X
Y
Z

Fig. 2


100 LASER APPARATUS
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LASER CONTROL PROCESSOR
131
CPU
MEMORY
132
14
163
63
53
43
143
42
41
13
PPM
10
11a
10a
10b
17
MONITOR MODULE
15
16
200
EXPOSURE APPARATUS
210
EXPOSURE CONTROL PROCESSOR

Fig. 3

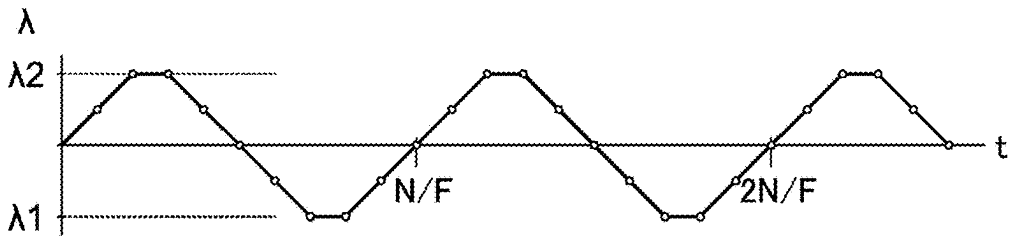


Fig. 4

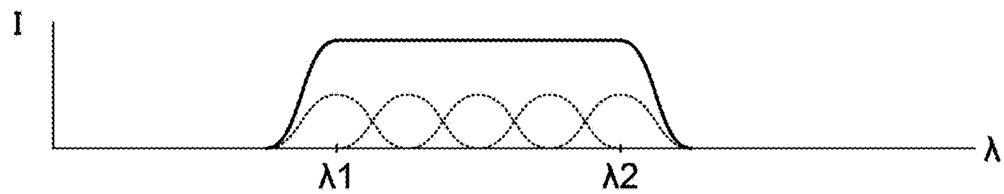


Fig. 5

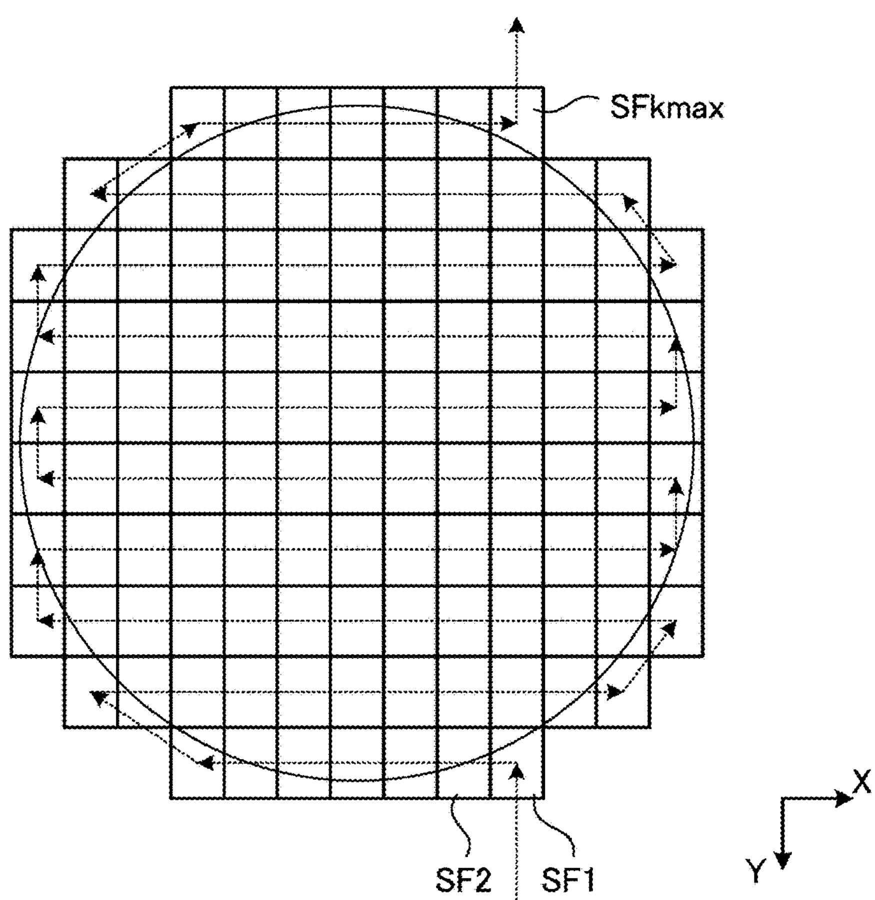
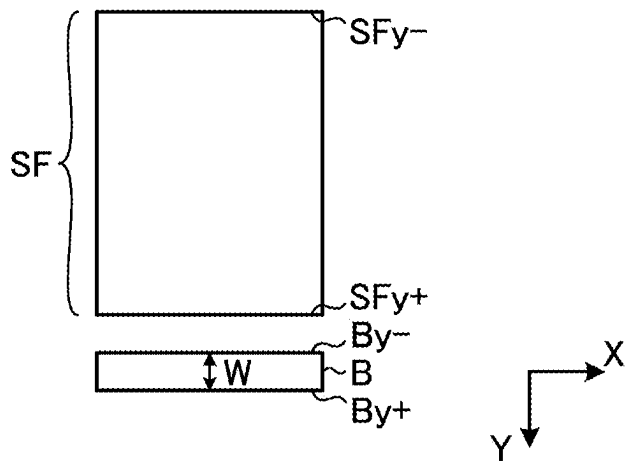


Fig. 6



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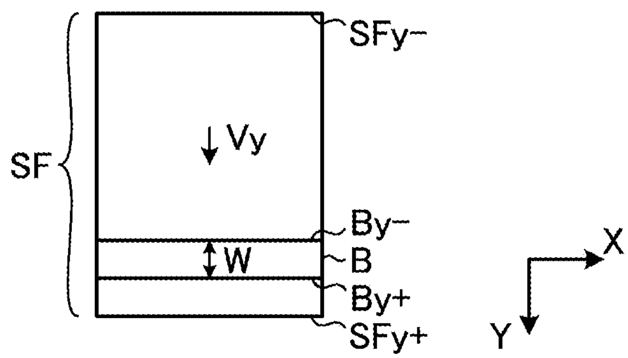

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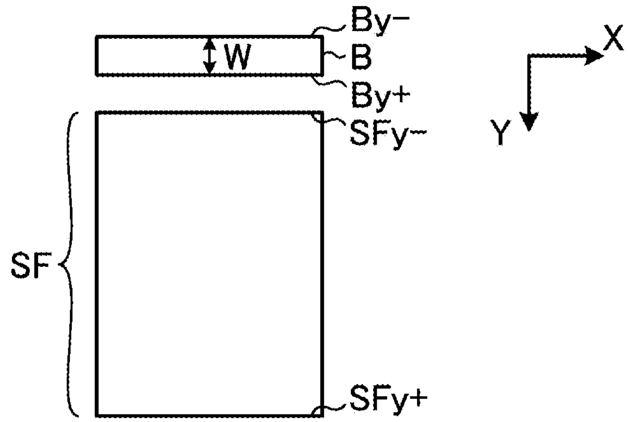
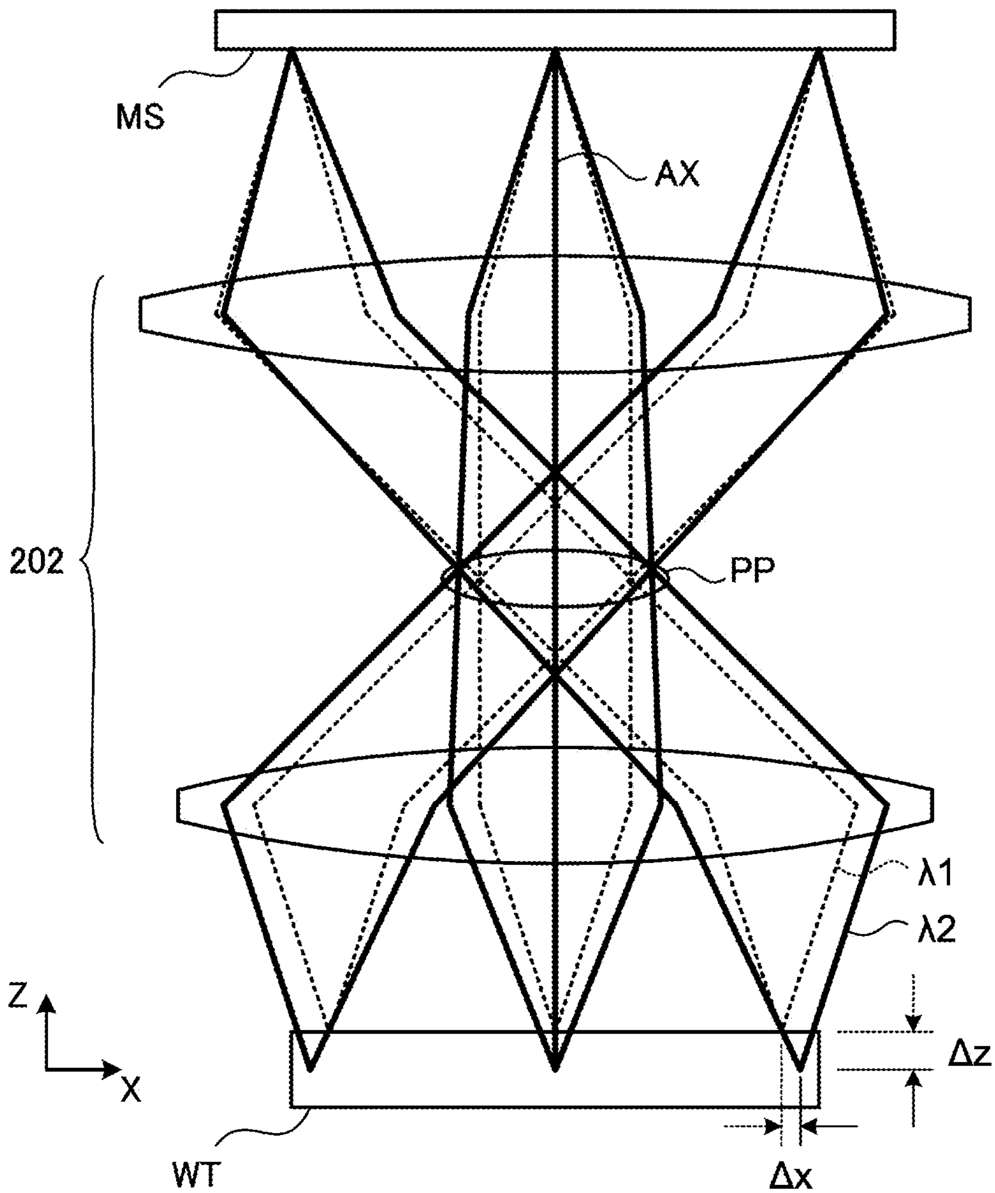


Fig. 9



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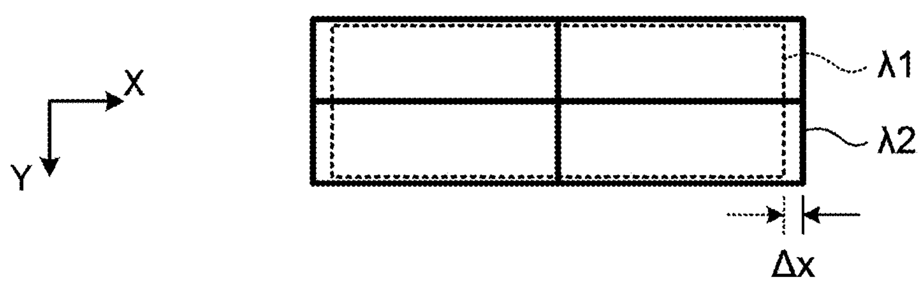
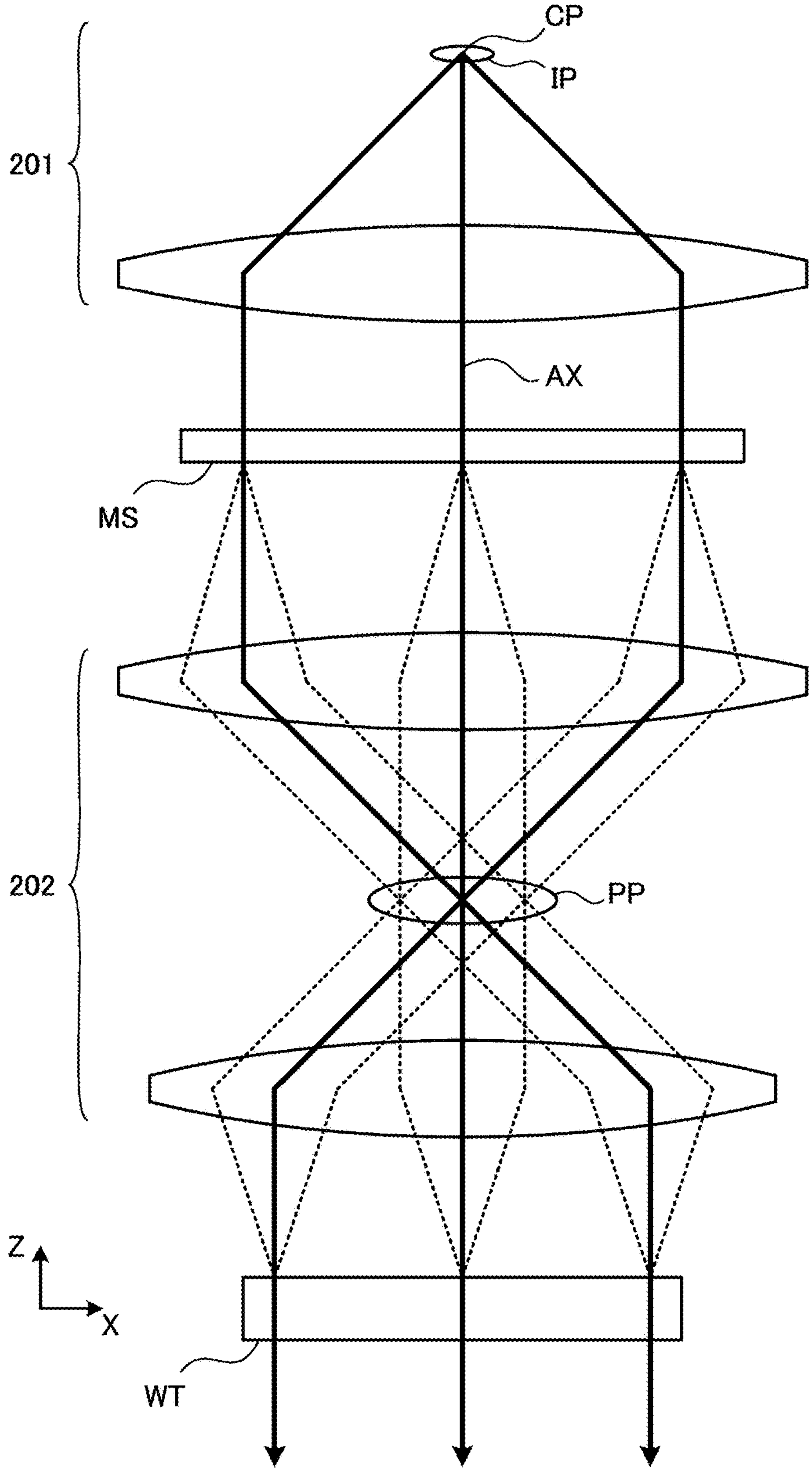


Fig. 11



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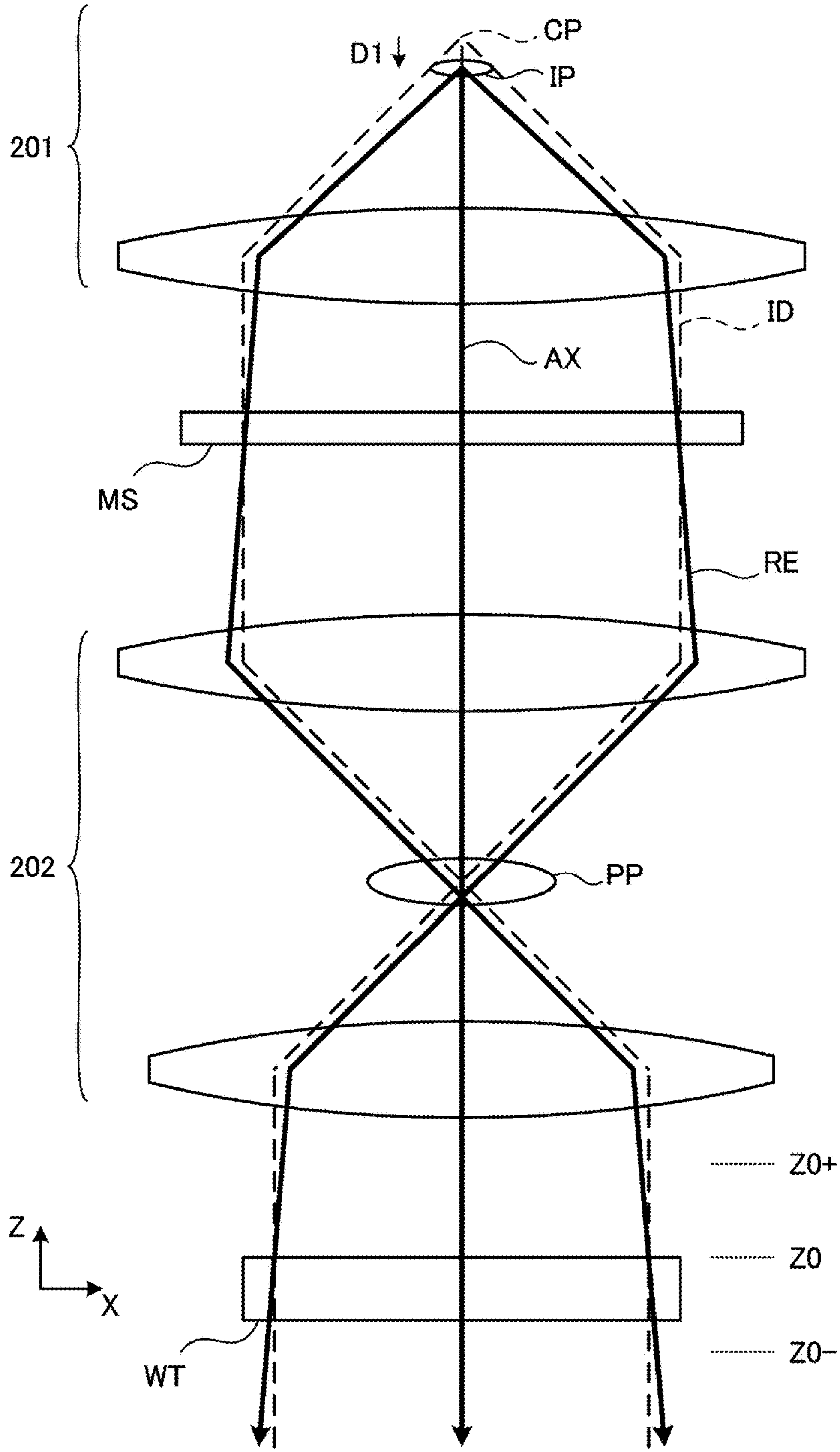

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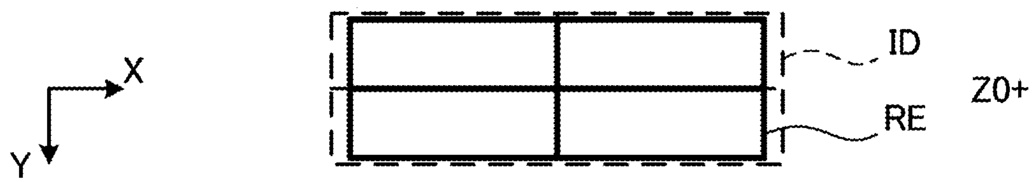
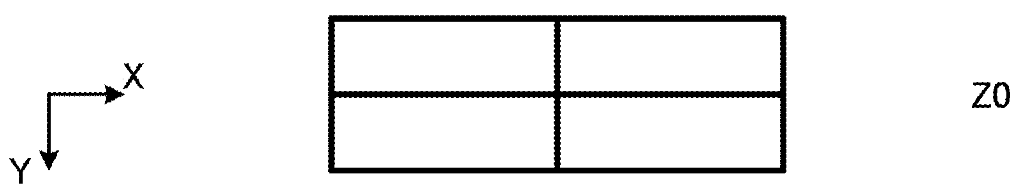


Fig. 14



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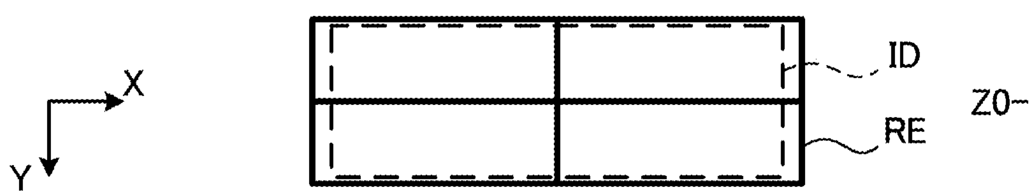


Fig. 16

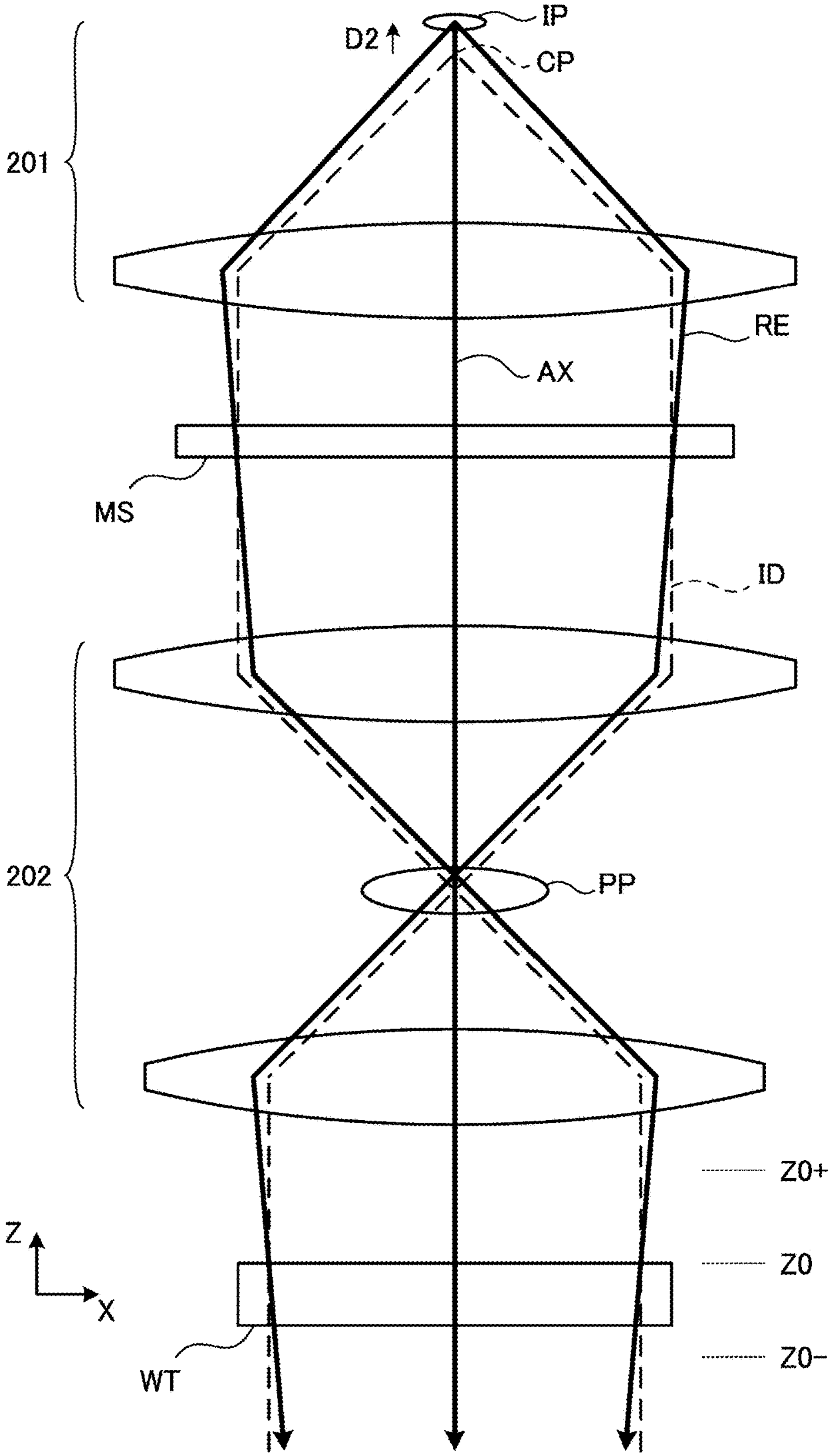
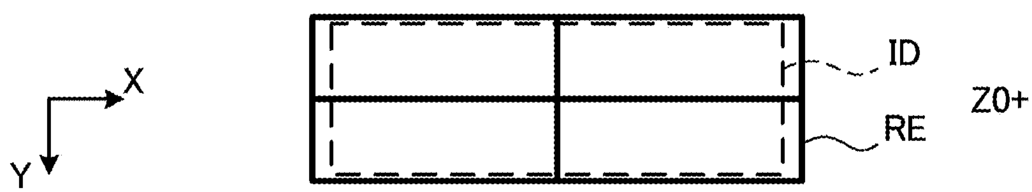


Fig. 17



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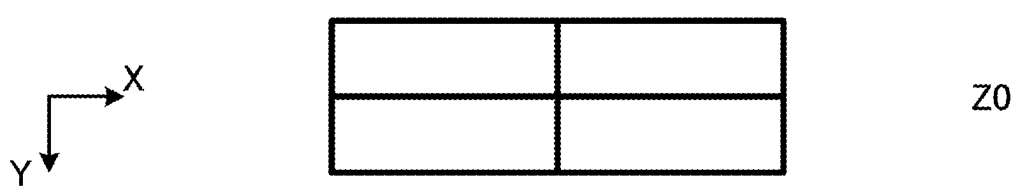

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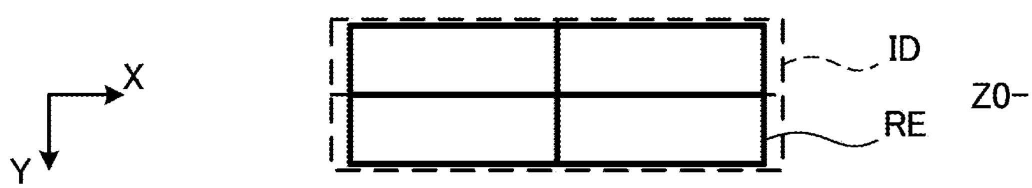

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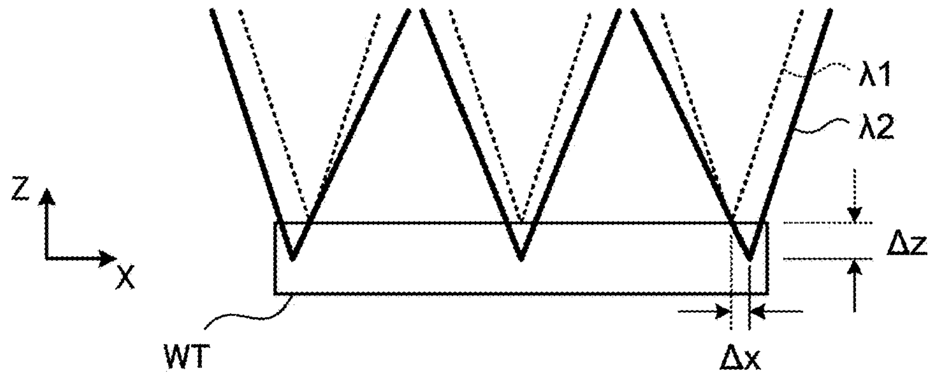

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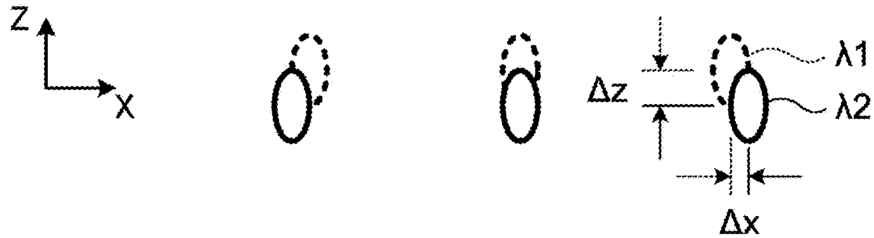

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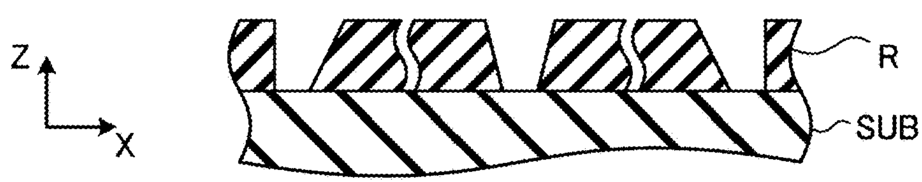

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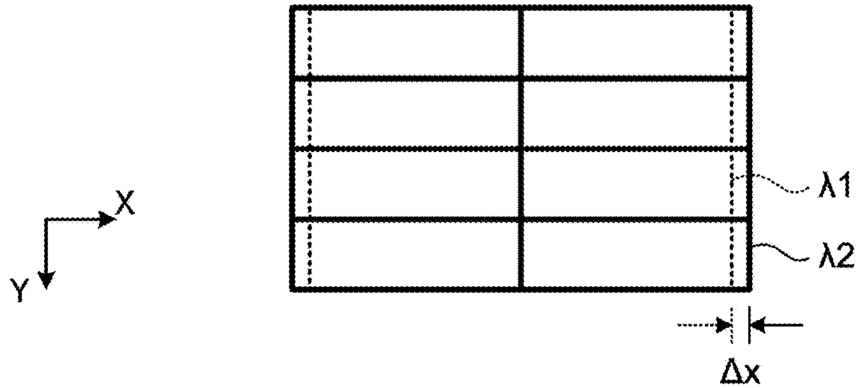

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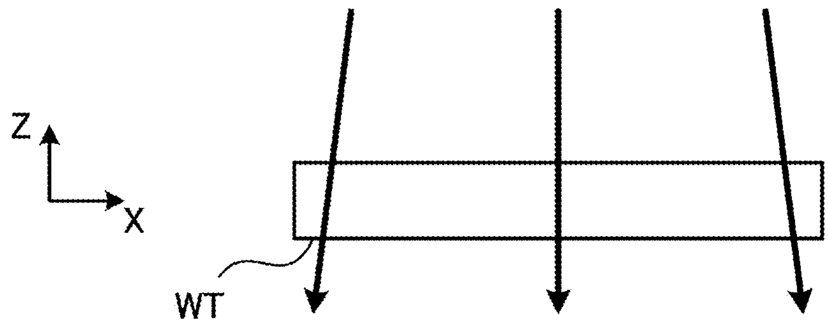

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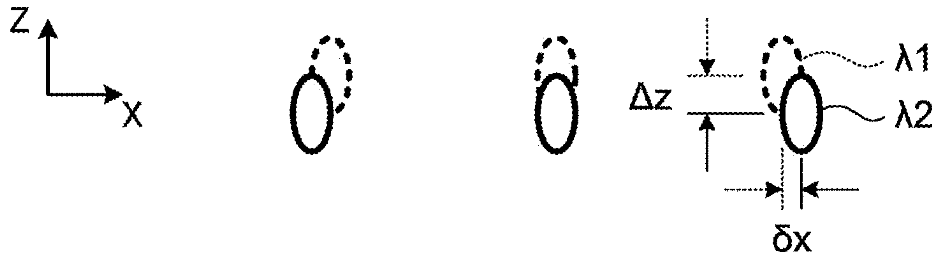

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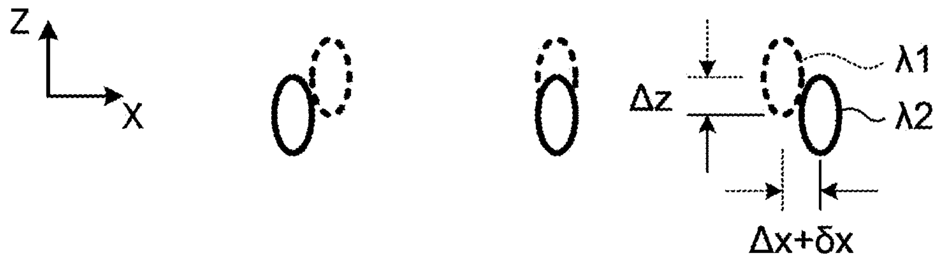

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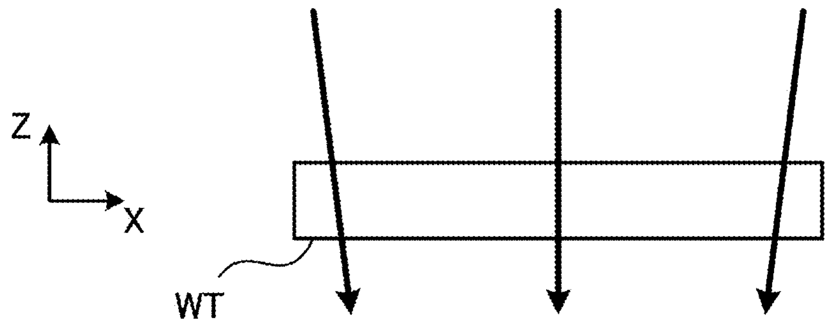

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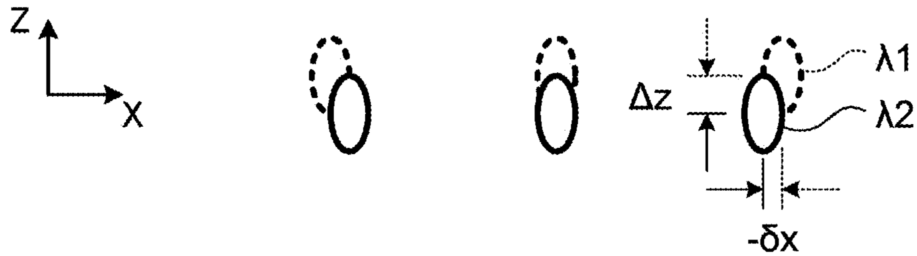

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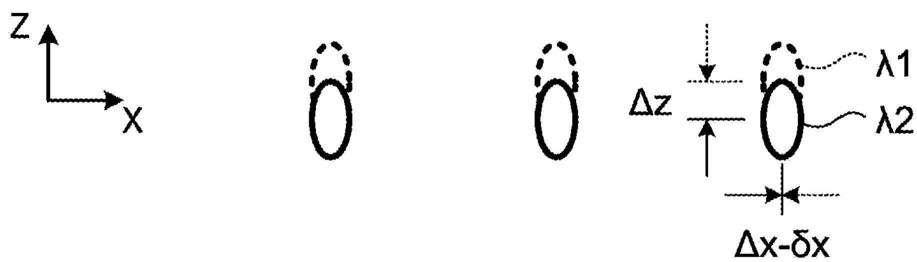


Fig. 30

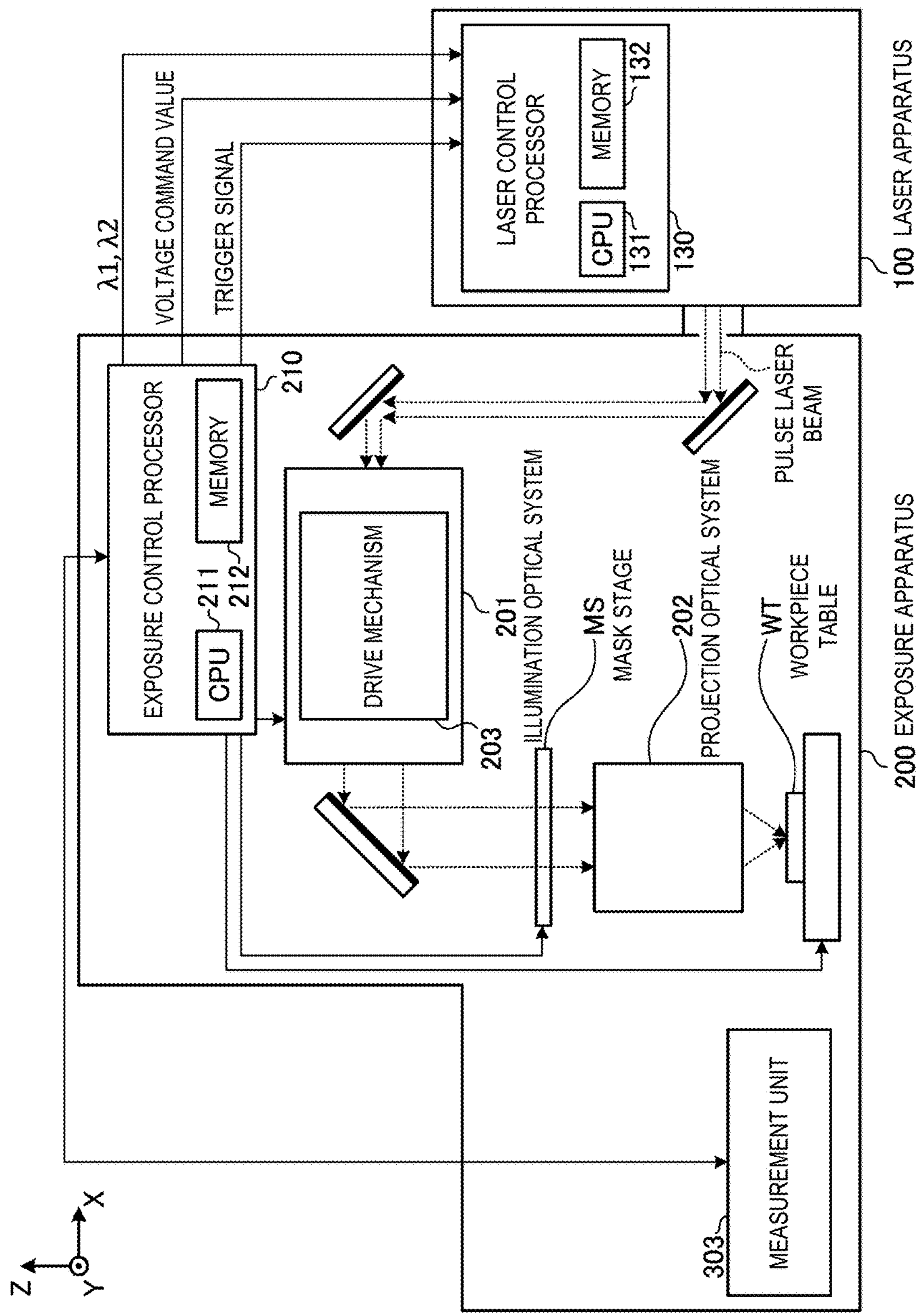

λ1, λ2
VOLTAGE COMMAND VALUE
TRIGGER SIGNAL
LASER CONTROL PROCESSOR
CPU
131
MEMORY
132
130
100 LASER APPARATUS
EXPOSURE CONTROL PROCESSOR
CPU
211
MEMORY
212
210
DRIVE MECHANISM
203
201
ILLUMINATION OPTICAL SYSTEM
MS
MASK STAGE
202
PROJECTION OPTICAL SYSTEM
WT
WORKPIECE TABLE
PULSE LASER BEAM
200 EXPOSURE APPARATUS
MEASUREMENT UNIT
303
X
Y
Z

Fig. 31

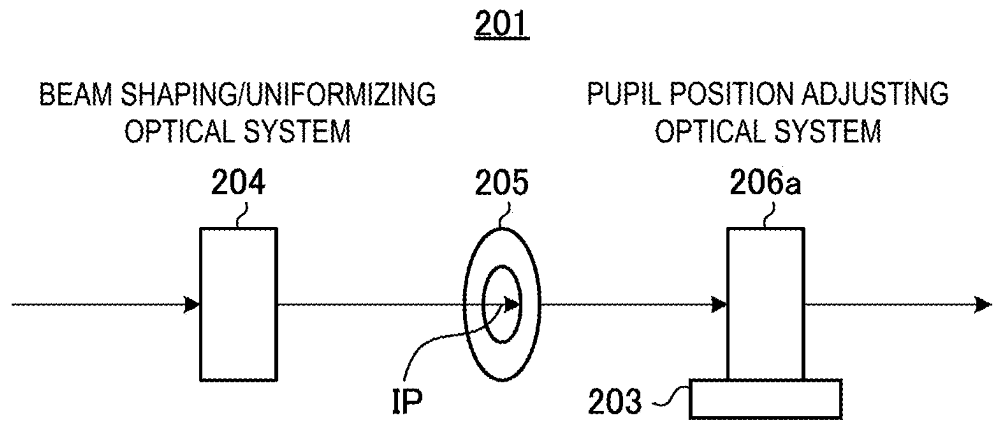


Fig. 32

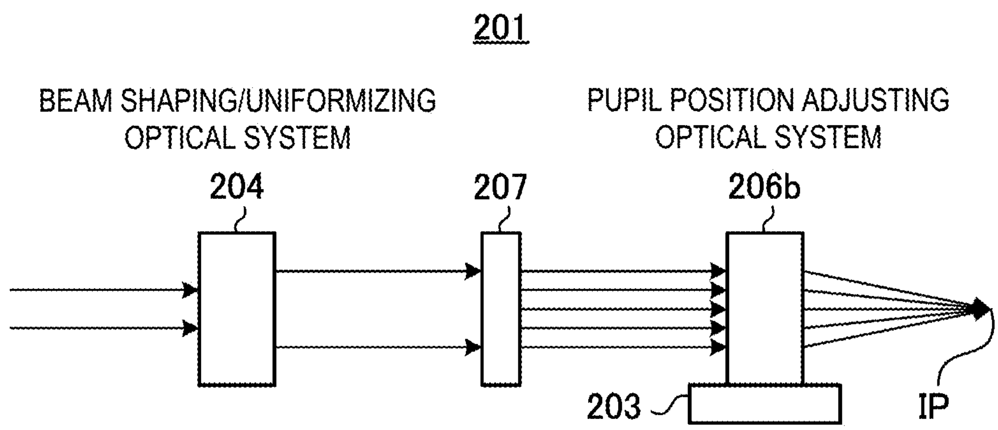


Fig. 33

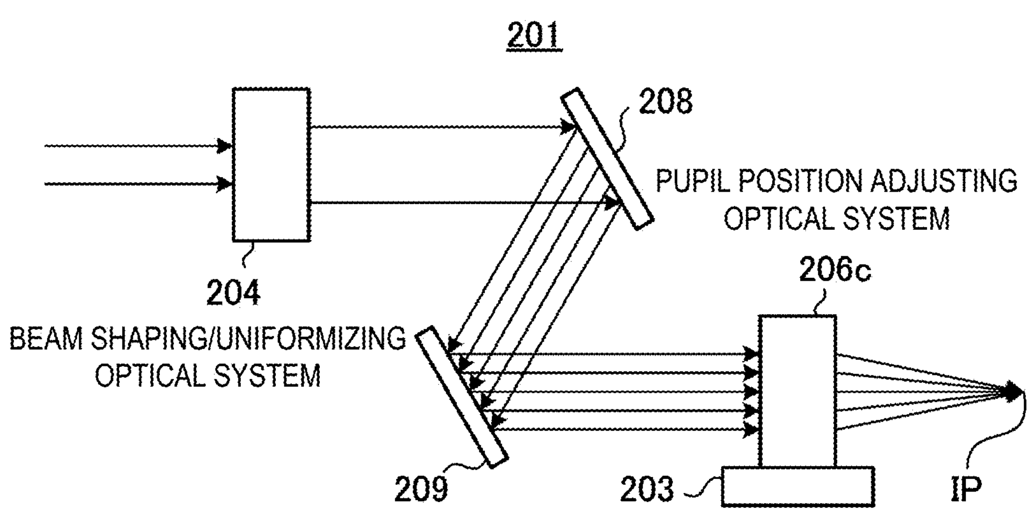


Fig. 34

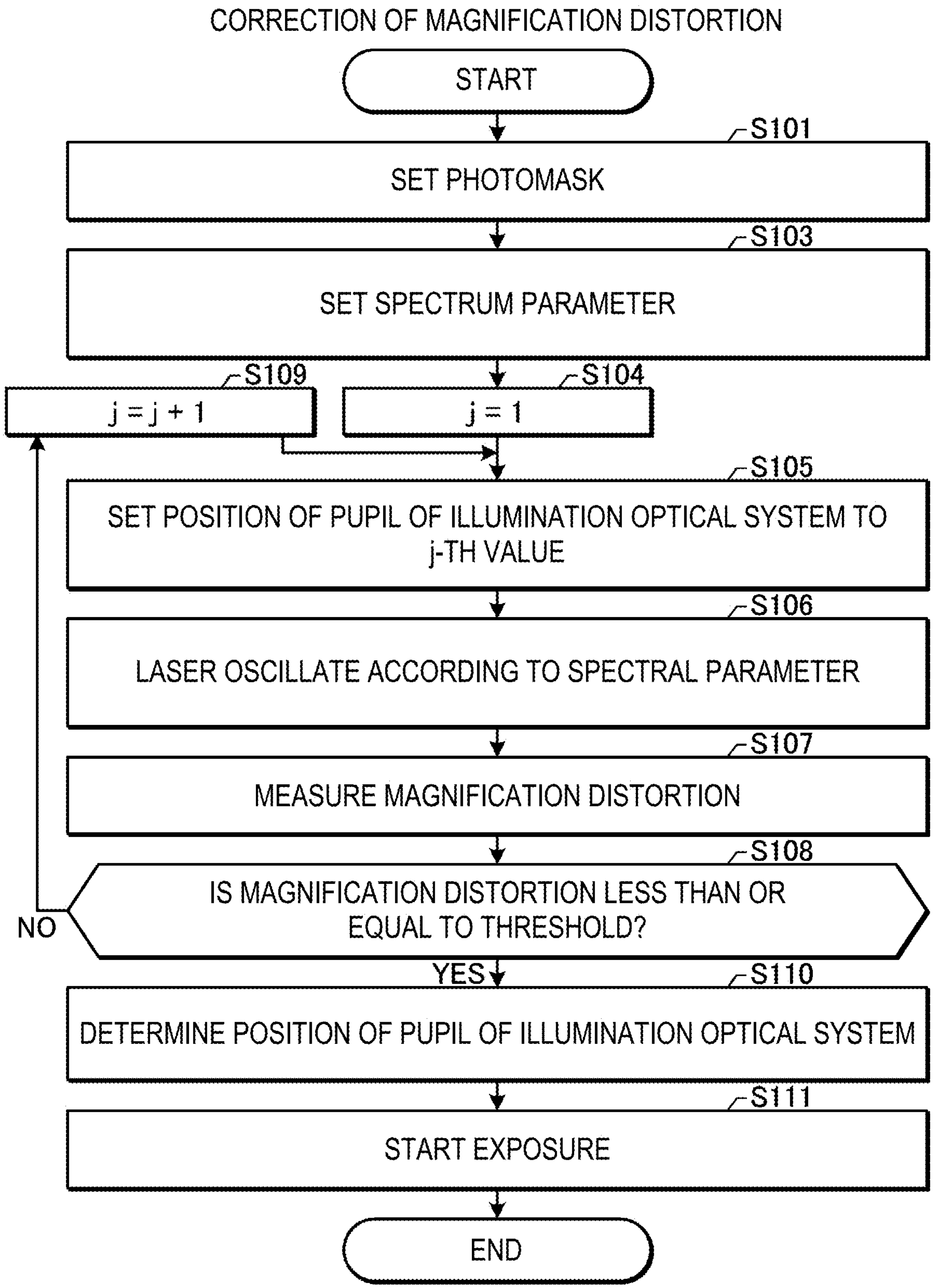

CORRECTION OF MAGNIFICATION DISTORTION
START
S101
SET PHOTOMASK
S103
SET SPECTRUM PARAMETER
S109
j = j + 1
S104
j = 1
S105
SET POSITION OF PUPIL OF ILLUMINATION OPTICAL SYSTEM TO j-TH VALUE
S106
LASER OSCILLATE ACCORDING TO SPECTRAL PARAMETER
S107
MEASURE MAGNIFICATION DISTORTION
S108
IS MAGNIFICATION DISTORTION LESS THAN OR EQUAL TO THRESHOLD?
NO
YES
S110
DETERMINE POSITION OF PUPIL OF ILLUMINATION OPTICAL SYSTEM
S111
START EXPOSURE
END

Fig. 35

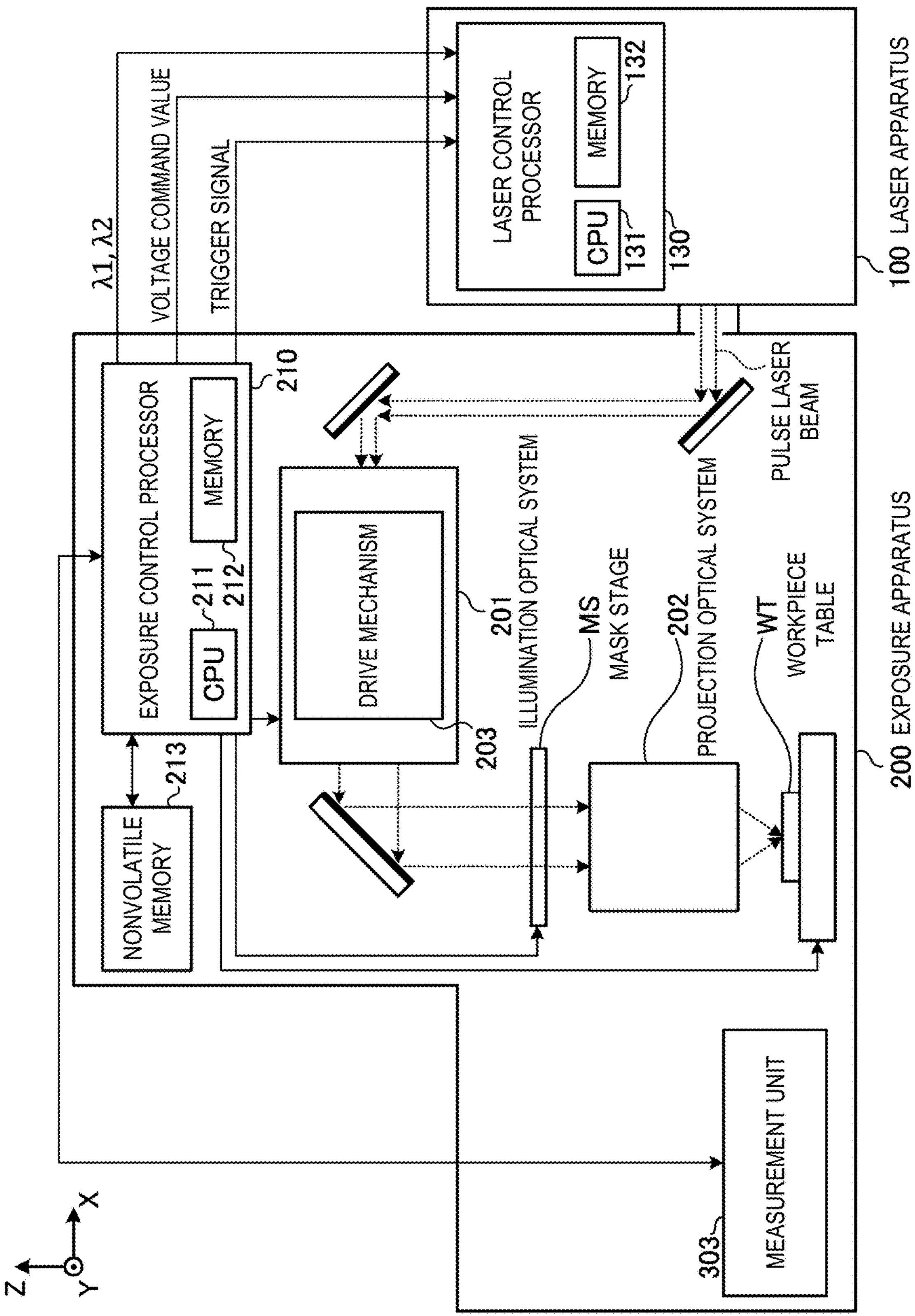

λ1, λ2
VOLTAGE COMMAND VALUE
TRIGGER SIGNAL
LASER CONTROL PROCESSOR
CPU
131
MEMORY
132
130
100 LASER APPARATUS
EXPOSURE CONTROL PROCESSOR
CPU
211
MEMORY
212
210
PULSE LASER BEAM
DRIVE MECHANISM
203
201
ILLUMINATION OPTICAL SYSTEM
MS
MASK STAGE
202
PROJECTION OPTICAL SYSTEM
WT
WORKPIECE TABLE
NONVOLATILE MEMORY
213
200 EXPOSURE APPARATUS
MEASUREMENT UNIT
303
X
Y
Z

Fig. 36

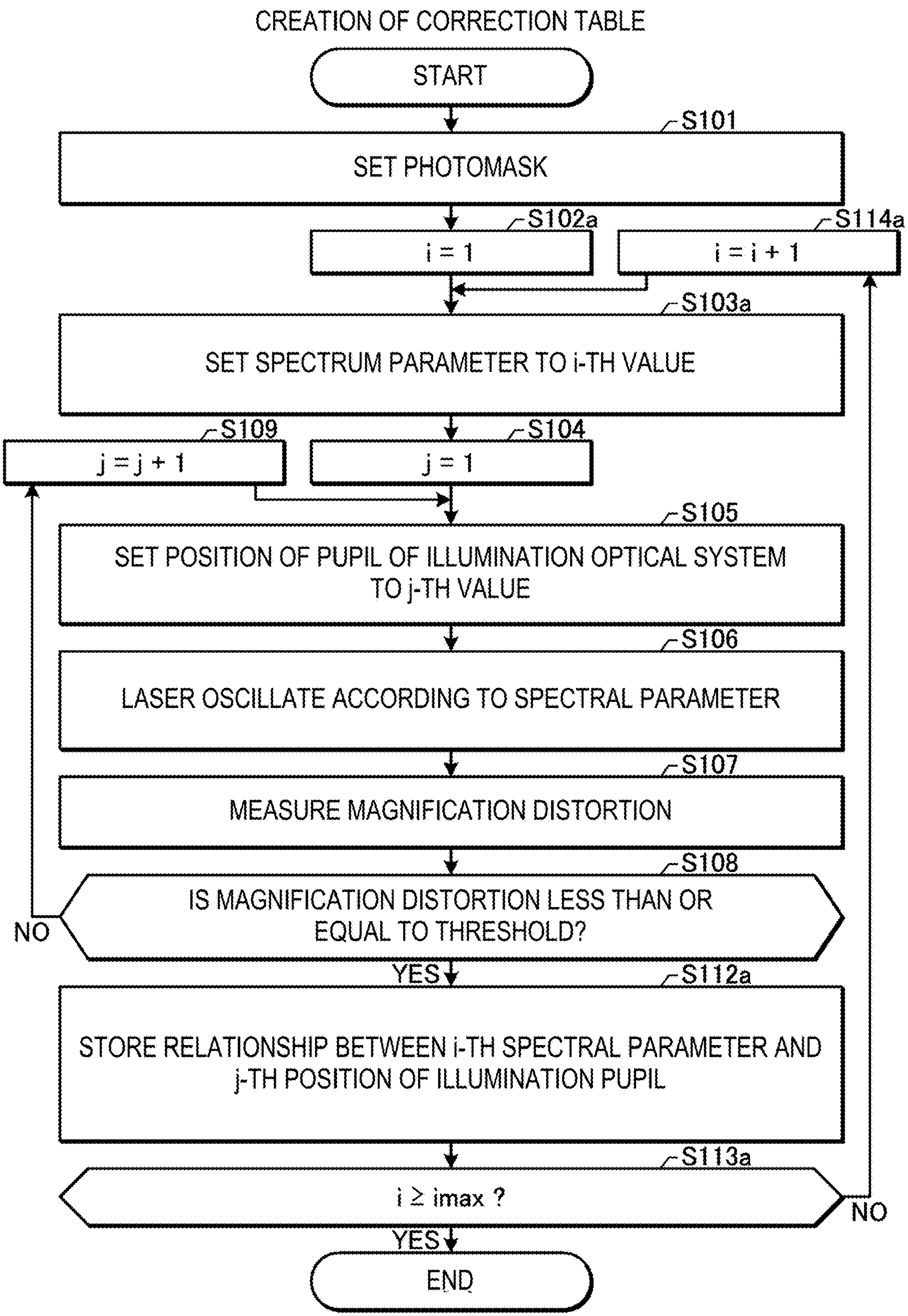

CREATION OF CORRECTION TABLE
START
S101
SET PHOTOMASK
S102a
i = 1
S114a
i = i + 1
S103a
SET SPECTRUM PARAMETER TO i-TH VALUE
S109
j = j + 1
S104
j = 1
S105
SET POSITION OF PUPIL OF ILLUMINATION OPTICAL SYSTEM TO j-TH VALUE
S106
LASER OSCILLATE ACCORDING TO SPECTRAL PARAMETER
S107
MEASURE MAGNIFICATION DISTORTION
S108
IS MAGNIFICATION DISTORTION LESS THAN OR EQUAL TO THRESHOLD?
NO
YES
S112a
STORE RELATIONSHIP BETWEEN i-TH SPECTRAL PARAMETER AND j-TH POSITION OF ILLUMINATION PUPIL
S113a
i ≥ imax ?
NO
YES
END

Fig. 37

213a

i	1	2	・・・	imax
SPECTRAL PARAMETER	S1	S2	・・・	Simax
POSITION OF PUPIL OF ILLUMINATION OPTICAL SYSTEM	P1	P2	・・・	Pimax

Fig. 38

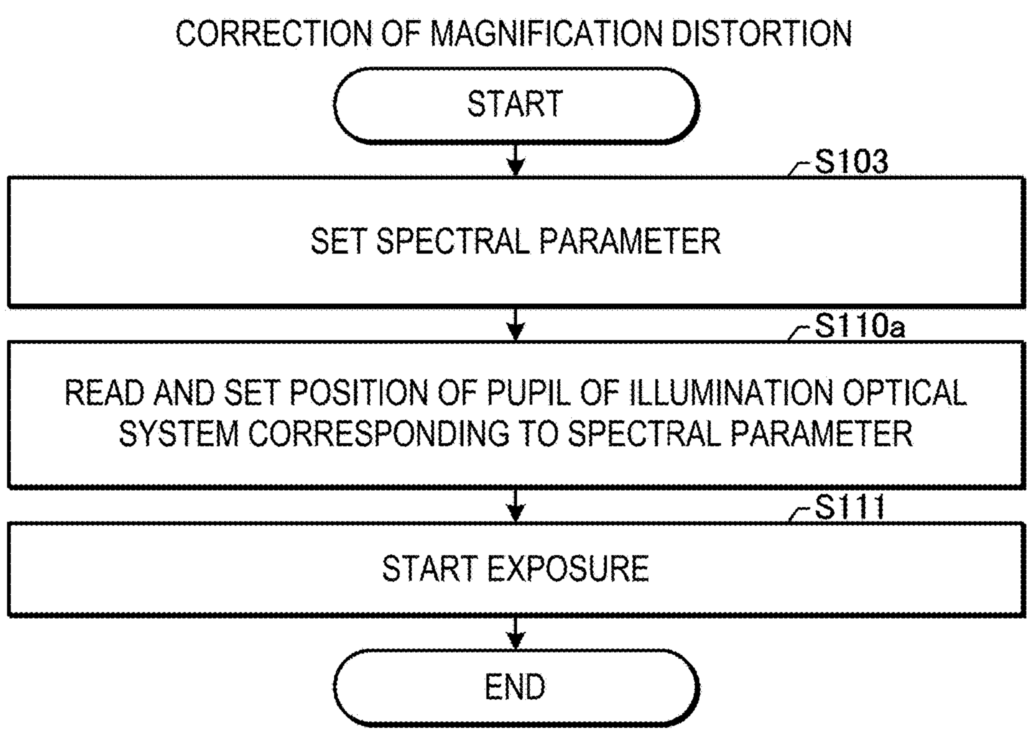


Fig. 39

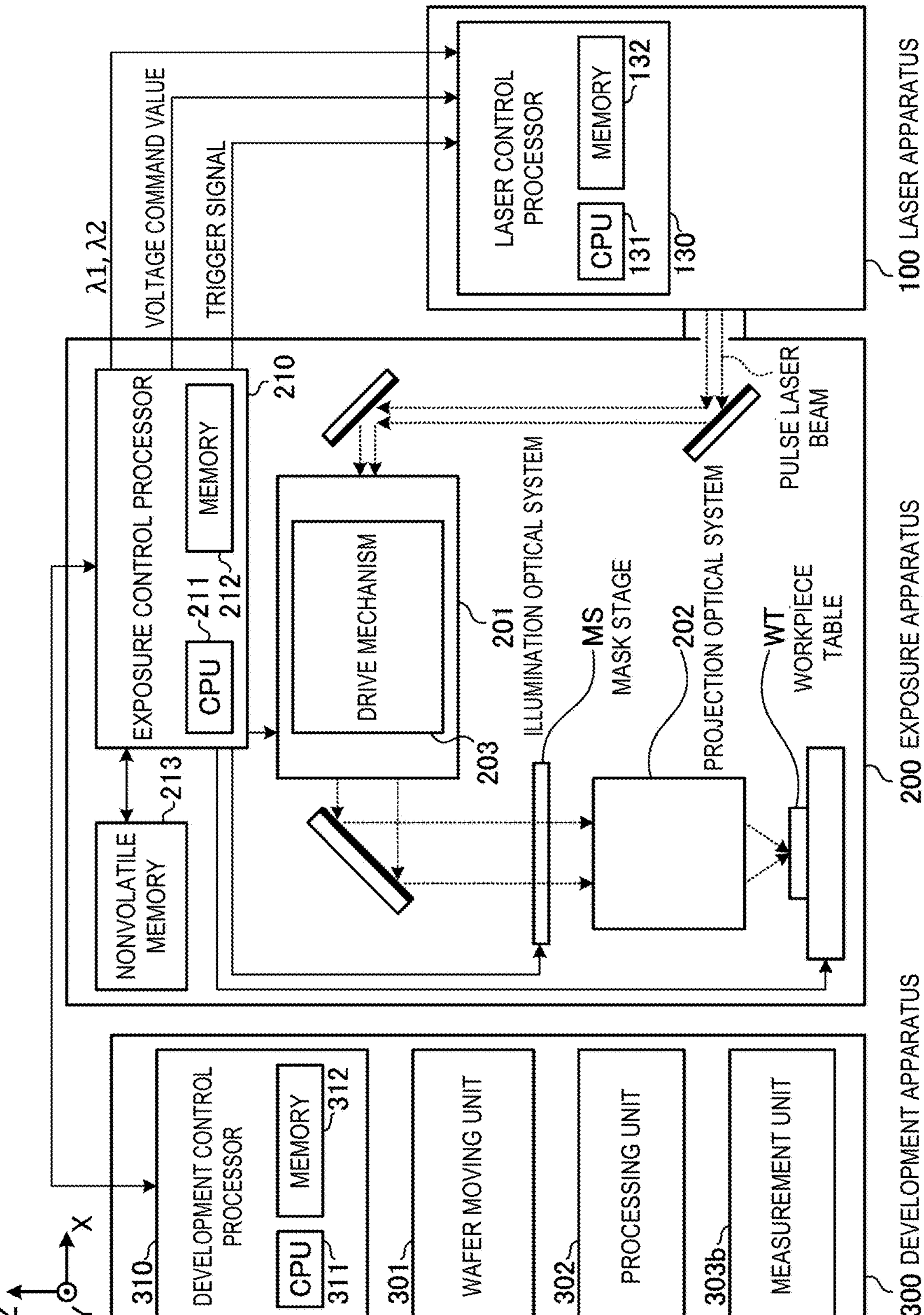
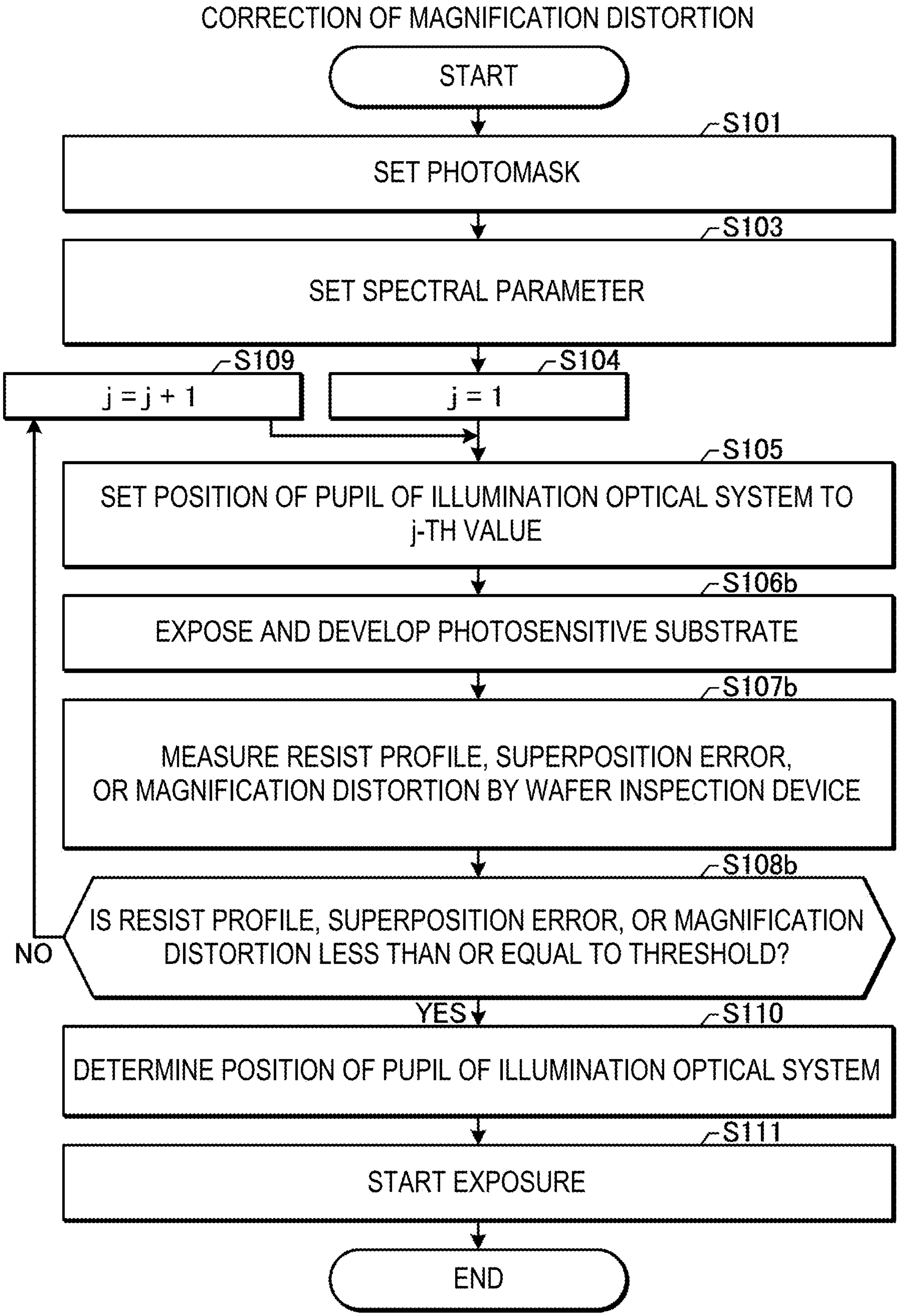

λ1, λ2
VOLTAGE COMMAND VALUE
TRIGGER SIGNAL
LASER CONTROL PROCESSOR
CPU
131
MEMORY
132
130
100 LASER APPARATUS
EXPOSURE CONTROL PROCESSOR
CPU
211
MEMORY
212
210
NONVOLATILE MEMORY
213
DRIVE MECHANISM
203
201
ILLUMINATION OPTICAL SYSTEM
MS
MASK STAGE
202
PROJECTION OPTICAL SYSTEM
WT
WORKPIECE TABLE
PULSE LASER BEAM
200 EXPOSURE APPARATUS
DEVELOPMENT CONTROL PROCESSOR
CPU
311
MEMORY
312
310
WAFER MOVING UNIT
301
PROCESSING UNIT
302
MEASUREMENT UNIT
303b
300 DEVELOPMENT APPARATUS
Z
X
Y

Fig. 40


CORRECTION OF MAGNIFICATION DISTORTION
START
S101
SET PHOTOMASK
S103
SET SPECTRAL PARAMETER
S109
j = j + 1
S104
j = 1
S105
SET POSITION OF PUPIL OF ILLUMINATION OPTICAL SYSTEM TO j-TH VALUE
S106b
EXPOSE AND DEVELOP PHOTOSENSITIVE SUBSTRATE
S107b
MEASURE RESIST PROFILE, SUPERPOSITION ERROR, OR MAGNIFICATION DISTORTION BY WAFER INSPECTION DEVICE
S108b
IS RESIST PROFILE, SUPERPOSITION ERROR, OR MAGNIFICATION DISTORTION LESS THAN OR EQUAL TO THRESHOLD?
NO
YES
S110
DETERMINE POSITION OF PUPIL OF ILLUMINATION OPTICAL SYSTEM
S111
START EXPOSURE
END

EXPOSURE SYSTEM AND METHOD OF MANUFACTURING ELECTRONIC DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a continuation application of International Application No. PCT/JP2022/046927, filed on Dec. 20, 2022, the entire contents of which are hereby incorporated by reference.

BACKGROUND

1. Technical Field

[0002] The present disclosure relates to an exposure system and a method of manufacturing an electronic device.

2. Related Art

[0003] Recently, in a semiconductor exposure apparatus, improvement in resolution has been desired for miniaturization and high integration of semiconductor integrated circuits. For this purpose, an exposure light source that outputs light having a shorter wavelength has been developed. For example, as a gas laser apparatus for exposure, a KrF excimer laser apparatus that outputs a laser beam having a wavelength of about 248 nm and an ArF excimer laser apparatus that outputs a laser beam having a wavelength of about 193 nm are used.

[0004] Spectral linewidths of spontaneous oscillation beams of the KrF excimer laser apparatus and the ArF excimer laser apparatus are as wide as from 350 pm to 400 pm. Therefore, when a projection lens is formed of a material that transmits ultraviolet light such as KrF and ArF laser beams, chromatic aberration may occur. As a result, the resolution may decrease. Thus, the spectral linewidth of the laser beam output from the gas laser apparatus needs to be narrowed to an extent that the chromatic aberration is ignorable. Therefore, in a laser resonator of the gas laser apparatus, a line narrowing module (LNM) including a line narrowing element (such as etalon or grating) may be provided in order to narrow the spectral linewidth. A gas laser apparatus with a narrowed spectral linewidth is referred to as a line narrowing gas laser apparatus.

LIST OF DOCUMENT

Patent Document

[0005] Patent Document 1: International Publication No. WO2021/110343

SUMMARY

[0006] In one aspect of the present disclosure, an exposure system includes an illumination optical system and a projection optical system. The illumination optical system is configured to illuminate a photomask with a pulse laser beam including a plurality of center wavelengths. The projection optical system is configured to illuminate a photosensitive substrate with the pulse laser beam that has passed through the photomask and to project an image of the photomask. A position of a first pupil that is a pupil of the illumination optical system is shifted from a reference position in a conjugate relationship with a second pupil that is a pupil of the projection optical system in a direction of reducing, by a magnification telecentric error, deviation of an imaging position due to lateral chromatic aberration on the photosensitive substrate.

[0007] In one aspect of the present disclosure, a method of manufacturing an electronic device includes exposing, with an exposure system, a photosensitive substrate to a pulse laser beam to manufacture the electronic device. The exposure system includes an illumination optical system configured to illuminate a photomask with the pulse laser beam including a plurality of center wavelengths, and a projection optical system configured to illuminate the photosensitive substrate with the pulse laser beam that has passed through the photomask and to project an image of the photomask, a position of a first pupil that is a pupil of the illumination optical system being shifted from a reference position in a conjugate relationship with a second pupil that is a pupil of the projection optical system in a direction of reducing, by a magnification telecentric error, deviation of an imaging position due to lateral chromatic aberration on the photosensitive substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Some embodiments of the present disclosure will be described below, by way of example only, with reference to the accompanying drawings.

[0009] FIG. **1** schematically illustrates a configuration of an exposure system in a comparative example.

[0010] FIG. **2** schematically illustrates a configuration of a laser apparatus.

[0011] FIG. **3** is a graph illustrating a periodic wavelength change.

[0012] FIG. **4** illustrates an integrated spectrum of a pulse laser beam including a plurality of center wavelengths.

[0013] FIG. **5** illustrates a photosensitive substrate exposed by an exposure apparatus.

[0014] FIG. **6** is a diagram explaining how a position of a scan field of a photosensitive substrate changes with respect to a position of a beam cross section of a pulse laser beam.

[0015] FIG. **7** is a diagram explaining how the position of the scan field of the photosensitive substrate changes with respect to the position of the beam cross section of the pulse laser beam.

[0016] FIG. **8** is a diagram explaining how the position of the scan field of the photosensitive substrate changes with respect to the position of the beam cross section of the pulse laser beam.

[0017] FIG. **9** is a schematic diagram of a projection optical system included in the exposure apparatus.

[0018] FIG. **10** illustrates how an image formed on a photosensitive substrate is deformed by the projection optical system illustrated in FIG. **9**.

[0019] FIG. **11** is a schematic diagram of an optical system including a part of an illumination optical system and a both-side telecentric projection optical system.

[0020] FIG. **12** illustrates a change in a main light beam when a pupil of the illumination optical system is shifted in a direction of an optical axis in the optical system illustrated in FIG. **11**.

[0021] FIG. **13** is a diagram explaining how an image formed on a photosensitive substrate is changed by the optical system illustrated in FIG. **12**.

[0022] FIG. **14** is a diagram explaining how an image formed on the photosensitive substrate is changed by the optical system illustrated in FIG. **12**.

[0023] FIG. **15** is a diagram explaining how an image formed on the photosensitive substrate is changed by the optical system illustrated in FIG. **12**.

[0024] FIG. **16** illustrates a change in the main light beam when the pupil of the illumination optical system is shifted in a direction opposite to that in FIG. **12** in the optical system illustrated in FIG. **11**.

[0025] FIG. **17** is a diagram explaining how an image formed on the photosensitive substrate is changed by the optical system illustrated in FIG. **16**.

[0026] FIG. **18** is a diagram explaining how an image formed on the photosensitive substrate is changed by the optical system illustrated in FIG. **16**.

[0027] FIG. **19** is a diagram explaining how an image formed on the photosensitive substrate is changed by the optical system illustrated in FIG. **16**.

[0028] FIG. **20** is a schematic diagram illustrating a part of a marginal light beam of a pulse laser beam incident on a workpiece table when longitudinal chromatic aberration and lateral chromatic aberration occur.

[0029] FIG. **21** schematically illustrates an imaging region of light of each wavelength of the pulse laser beam illustrated in FIG. **20**.

[0030] FIG. **22** is a sectional view illustrating a resist profile when the photosensitive substrate exposed to the pulse laser beam illustrated in FIG. **20** and FIG. **21** is developed.

[0031] FIG. **23** illustrates deviation of an image on the photosensitive substrate scan-exposed to the pulse laser beam illustrated in FIG. **20** and FIG. **21**.

[0032] FIG. **24** is a schematic diagram illustrating a part of the main light beam of the pulse laser beam incident on the workpiece table when a magnification telecentric error occurs.

[0033] FIG. **25** schematically illustrates an imaging region of light of each wavelength of the pulse laser beam illustrated in FIG. **24**.

[0034] FIG. **26** schematically illustrates an imaging region of light of each wavelength when the lateral chromatic aberration is taken into consideration in the pulse laser beam illustrated in FIG. **24**.

[0035] FIG. **27** is a schematic diagram illustrating a part of the main light beam of the pulse laser beam incident on the workpiece table when the magnification telecentric error occurs in a direction opposite to that in FIG. **24**.

[0036] FIG. **28** schematically illustrates an imaging region of light of each wavelength of the pulse laser beam illustrated in FIG. **27**.

[0037] FIG. **29** schematically illustrates an imaging region of light of each wavelength when the lateral chromatic aberration is taken into consideration in the pulse laser beam illustrated in FIG. **27**.

[0038] FIG. **30** schematically illustrates a configuration of an exposure system according to a first embodiment.

[0039] FIG. **31** conceptually illustrates a first example of an illumination optical system capable of moving a position of a pupil.

[0040] FIG. **32** conceptually illustrates a second example of the illumination optical system capable of moving the position of the pupil.

[0041] FIG. **33** conceptually illustrates a third example of the illumination optical system capable of moving the position of the pupil.

[0042] FIG. **34** is a flowchart illustrating processing of correcting magnification distortion in the first embodiment.

[0043] FIG. **35** schematically illustrates a configuration of an exposure system according to a second embodiment.

[0044] FIG. **36** is a flowchart illustrating processing of creating a correction table in the second embodiment.

[0045] FIG. **37** illustrates an example of the correction table stored in a nonvolatile memory.

[0046] FIG. **38** is a flowchart illustrating processing of correcting magnification distortion in the second embodiment.

[0047] FIG. **39** schematically illustrates a configuration of an exposure system according to a third embodiment.

[0048] FIG. **40** is a flowchart illustrating processing of correcting magnification distortion in the third embodiment.

DESCRIPTION OF EMBODIMENTS

<Contents>

[0082] Hereinafter, embodiments of the present disclosure will be described in detail with reference to the drawings. The embodiments described below show some examples of the present disclosure and do not limit contents of the present disclosure. In addition, all configurations and operations described in the embodiments are not necessarily essential as configurations and operations of the present disclosure. Here, the same components are denoted by the same reference signs, and any redundant description thereof is omitted.

1. Comparative Example

[0083] FIG. **1** schematically illustrates a configuration of an exposure system in a comparative example. The comparative example of the present disclosure is an example recognized by the applicant as known only by the applicant, and is not a publicly known example admitted by the applicant. FIG. **1** illustrates an X axis, a Y axis, and a Z axis perpendicular to each other. The exposure system includes a laser apparatus **100** and an exposure apparatus **200**. In FIG. **1**, the laser apparatus **100** is illustrated in a simplified manner.

[0084] The laser apparatus **100** includes a laser control processor **130**. The laser control processor **130** is a processing device including a memory **132** in which a control program is stored, and a CPU (central processing unit) **131** which executes the control program. The laser control processor **130** is specially configured or programmed to execute various kinds of processing included in the present disclosure. The laser apparatus **100** is configured to output a pulse laser beam toward the exposure apparatus **200**.

1.1 Exposure Apparatus 200

1.1.1 Configuration

[0085] As illustrated in FIG. **1**, the exposure apparatus **200** includes an illumination optical system **201**, a projection optical system **202**, and an exposure control processor **210**. The illumination optical system **201** illuminates an unillustrated photomask disposed on a mask stage MS with the pulse laser beam incoming from the laser apparatus **100**.

[0086] The projection optical system **202** illuminates an unillustrated workpiece placed on a workpiece table WT with the pulse laser beam that has passed through the photomask, and projects an image of the photomask. The workpiece is a photosensitive substrate such as a semiconductor wafer on which a resist film is applied.

[0087] The exposure control processor **210** is a processing device including a memory **212** in which a control program is stored and a CPU **211** which executes the control program. The exposure control processor **210** corresponds to a processor in the present disclosure. The exposure control processor **210** is specially configured or programmed to execute various kinds of processing included in the present disclosure. The exposure control processor **210** coordinates control of the exposure apparatus **200**, and transmits and receives various kinds of parameters and various kinds of signals to and from the laser control processor **130**.

1.1.2 Operation

[0088] The exposure control processor **210** transmits various kinds of parameters including a target short wavelength **λ1**, a target long wavelength **λ2**, and a voltage command value, and a trigger signal to the laser control processor **130**. The laser control processor **130** controls the laser apparatus **100** according to these parameters and signal. The target short wavelength **λ1** corresponds to a first wavelength in the present disclosure, and the target long wavelength **λ2** corresponds to a second wavelength in the present disclosure.

[0089] The exposure control processor **210** synchronously translates the mask stage MS and the workpiece table WT in opposite directions. Thus, the workpiece is exposed to the pulse laser beam reflecting a mask pattern of the photomask.

[0090] The mask pattern is transferred to the photosensitive substrate by photolithography as described above. Thereafter, an electronic device can be manufactured through a plurality of processes.

1.2 Laser Apparatus 100

1.2.1 Configuration

[0091] FIG. **2** schematically illustrates a configuration of the laser apparatus **100**. In FIG. **2**, the exposure apparatus **200** is illustrated in a simplified manner. In addition to the laser control processor **130**, the laser apparatus **100** includes a laser chamber **10**, a pulse power module (PPM) **13**, a line narrowing module **14**, an output coupling mirror **15**, and a monitor module **17**. The line narrowing module **14** and the output coupling mirror **15** form an optical resonator.

[0092] The laser chamber **10** is disposed in an optical path of the optical resonator. The laser chamber **10** is provided with windows **10*a*** and **10*b***. The laser chamber **10** includes a discharge electrode **11*a*** and an unillustrated discharge electrode paired with the discharge electrode **11*a*** inside the laser chamber **10**. The laser chamber **10** is filled with a laser gas containing, for example, an argon gas or a krypton gas as a rare gas, a fluorine gas as a halogen gas, and a neon gas as a buffer gas, or the like.

[0093] The pulse power module **13** includes an unillustrated switch, and is connected to an unillustrated charger.

[0094] The line narrowing module **14** includes prisms **41** to **43**, a grating **53**, and a mirror **63**. Details of the line narrowing module **14** will be described later.

[0095] The output coupling mirror **15** is formed of a partial reflective mirror. A beam splitter **16** that transmits a part of the pulse laser beam with a high transmittance and reflects the other part is disposed in an optical path of the pulse laser beam passing through the output coupling mirror **15**. The monitor module **17** is disposed in an optical path of the pulse laser beam reflected by the beam splitter **16**.

1.2.2 Operation

[0096] The laser control processor **130** acquires various kinds of parameters including the target short wavelength **λ1**, the target long wavelength **λ2**, and the voltage command value from the exposure control processor **210**. The laser control processor **130** transmits a control signal to the line narrowing module **14** based on the target short wavelength **λ1** and the target long wavelength **λ2**.

[0097] The laser control processor **130** receives the trigger signal from the exposure control processor **210**. The laser control processor **130** transmits an oscillation trigger signal based on the trigger signal to the pulse power module **13**. The switch included in the pulse power module **13** is turned to an ON state when the oscillation trigger signal is received from the laser control processor **130**. When the switch is turned to the ON state, the pulse power module **13** generates a pulsed high voltage from electric energy charged in the charger, and applies the high voltage to the discharge electrode **11*a***.

[0098] When the high voltage is applied to the discharge electrode **11**_a_, discharge occurs in a discharge space between the discharge electrode **11**_a_ and the unillustrated discharge electrode. By energy of the discharge, the laser gas in the laser chamber **10** is excited and shifts to a high energy level. When the excited laser gas then shifts to a low energy level, light having a wavelength corresponding to the energy level difference is discharged.

[0099] The light generated in the laser chamber **10** is output to an outside of the laser chamber **10** through the windows **10**_a_ and **10**_b_. The light passing through the window **10**_a_ enters the line narrowing module **14**. Of the light that has entered the line narrowing module **14**, light near a desired wavelength is turned back by the line narrowing module **14** and returned to the laser chamber **10**.

[0100] The output coupling mirror **15** transmits a part of the light passing through the window **10**_b_ so that the part of the light exits the output coupling mirror **15**, and reflects the other part back into the laser chamber **10**.

[0101] In this way, the light output from the laser chamber **10** reciprocates between the line narrowing module **14** and the output coupling mirror **15**. The light is amplified every time it passes through the discharge space in the laser chamber **10**. Further, the light is narrowed every time it is turned back by the line narrowing module **14**, and becomes light having a steep wavelength distribution with a part of a range of a selected wavelength by means of the line narrowing module **14** as a center wavelength. The light laser-oscillated and narrowed in this way is output as a pulse laser beam from the output coupling mirror **15**.

[0102] The monitor module **17** measures the center wavelength of the pulse laser beam and transmits a measured wavelength to the laser control processor **130**. The laser control processor **130** feedback-controls the line narrowing module **14** based on the measured wavelength. The pulse laser beam transmitted through the beam splitter **16** enters the exposure apparatus **200**.

1.3 Line Narrowing Module **14**

1.3.1 Configuration

[0103] The prisms **41** to **43** are disposed in an optical path of a light beam passing through the window **10**_a_ in an order from the smallest of the reference numerals of these prisms. The prism **43** is rotatable about an axis perpendicular to a plane of FIG. **2** by a rotating stage **143**.

[0104] The mirror **63** is disposed in an optical path of the light beam transmitted through the prisms **41** to **43**. The mirror **63** is rotatable about an axis perpendicular to the plane of FIG. **2** by a rotating stage **163**. The grating **53** is disposed in an optical path of the light beam reflected by the mirror **63**.

1.3.2 Operation

[0105] Each of the prisms **41** to **43** expands a beam width of the light beam passing through the window **10**_a_ in a plane parallel to the plane of FIG. **2**. The light beam transmitted through the prisms **41** to **43** is reflected by the mirror **63** and incident on the grating **53**.

[0106] The light beam incident on the grating **53** is reflected by a plurality of grooves of the grating **53** and is diffracted in a direction corresponding to the wavelength of the light. The grating **53** is disposed in Littrow arrangement such that an incident angle of the light beam from the mirror **63** onto the grating **53** coincides with a diffracting angle of diffracted light of a desired wavelength.

[0107] The mirror **63** and the prisms **41** to **43** reduce the beam width of the light beam returned from the grating **53** in the plane parallel to the plane of FIG. **2**, and return the light beam to the inside of the laser chamber **10** through the window **10**_a_.

[0108] The laser control processor **130** controls the rotating stages **143** and **163** via an unillustrated driver. In accordance with rotation angles of the rotating stages **143** and **163**, the incident angle of the light beam on the grating **53** changes, and the wavelength selected by the line narrowing module **14** changes.

[0109] The laser control processor **130** controls the rotating stage **163** such that a posture of the mirror **63** periodically changes for each of a plurality of pulses, based on the target short wavelength **λ1** and the target long wavelength **λ2** received from the exposure control processor **210**. Thus, the center wavelength of the pulse laser beam periodically changes between the target short wavelength **λ1** and the target long wavelength **λ2** for each of the pulses. In this way, the laser apparatus **100** outputs the pulse laser beam including a plurality of center wavelengths.

[0110] A focal length in the exposure apparatus **200** depends on the wavelength of the pulse laser beam. Since the pulse laser beam that is laser-oscillated at the multiple wavelengths and enters the exposure apparatus **200** can be imaged at a plurality of different positions in a direction of an optical path axis of the pulse laser beam, a focal depth can be substantially increased. For example, even when a resist film having a large thickness is exposed, imaging performance in a thickness direction of the resist film can be maintained. Alternatively, a resist profile indicating a cross-sectional shape of the developed resist film can be adjusted.

1.4 Periodic Wavelength Change and Integrated Spectrum

[0111] FIG. **3** is a graph illustrating a periodic wavelength change. In FIG. **3**, a horizontal axis represents time t and a vertical axis represents a wavelength λ. Each of small circles illustrated in FIG. **3** indicates the time t when the pulse laser beam is output and the center wavelength at that time.

[0112] In an example illustrated in FIG. **3**, the center wavelength periodically changes between the target short wavelength **λ1** and the target long wavelength **λ2**. A pulse number for one period of the wavelength change is defined as N, and a repetition frequency of the pulse laser beam is defined as F. A period T of the wavelength change is given by an equation below.

$$T=N/F$$

[0113] FIG. **4** illustrates an integrated spectrum of the pulse laser beam including the center wavelengths. The integrated spectrum illustrated in FIG. **4** corresponds to an integrated spectrum for one period of the wavelength change illustrated in FIG. **3**. In FIG. **4**, a horizontal axis represents the wavelength k and a vertical axis represents light intensity I. A dashed line represents a spectrum of the pulse laser beam for each pulse, and each center wavelength coincides with a peak wavelength. By changing the center wavelength in multiple stages between the target short wavelength **λ1** and the target long wavelength **λ2** as illustrated in FIG. **3**, the integrated spectrum illustrated in FIG. **4** can have a flat top shape having substantially uniform light intensity I between the target short wavelength λ1 and the target long wavelength λ2.

1.5 Scan Exposure

[0114] FIG. **5** illustrates a photosensitive substrate exposed by the exposure apparatus **200**. The photosensitive substrate is, for example, a single crystal silicon plate having a substantially disk shape. The photosensitive substrate is exposed for each section of scan fields SF**1**, SF**2**, and others. Each of the scan fields SF**1** and SF**2** corresponds to a region where several semiconductor chips of many semiconductor chips formed on the photosensitive substrate are formed, and a mask pattern of one photomask is transferred by scanning of one time. Numbers included in the signs SF**1** and SF**2** indicate an exposure order. When descriptions are given without specifying the exposure order, the scan field is simply denoted as SF without any number added.

[0115] First, the photosensitive substrate is moved such that the first scan field SF**1** is irradiated with the pulse laser beam, and the first scan field SF**1** is exposed. Next, the photosensitive substrate is moved such that the second scan field SF**2** is irradiated with the pulse laser beam, and the second scan field SF**2** is exposed. The other scan fields SF are also sequentially exposed, and when a last scan field SFkmax is exposed, exposure of the photosensitive substrate ends.

[0116] FIG. **6** to FIG. **8** illustrate how a position of the scan field SF of the photosensitive substrate changes with respect to a position of a beam cross section B of the pulse laser beam. A direction in which the position of the scan field SF changes is defined as a Y axis direction, and a direction perpendicular to the Y axis direction is defined as an X axis direction.

[0117] When one scan field SF is exposed, the pulse laser beam is continuously output at a predetermined repetition frequency. Continuous output of the pulse laser beam at the predetermined repetition frequency is referred to as burst output. When an exposure position is moved from one scan field SF to another scan field SF, output of the pulse laser beam is stopped. Thus, the burst output is repeated multiple times to expose one photosensitive substrate.

[0118] A width in the X axis direction of the scan field SF corresponds to a width in the X axis direction of the beam cross section B of the pulse laser beam at a position of the workpiece table WT (see FIG. **1**). A width in the Y axis direction of the scan field SF is larger than a width W in the Y axis direction of the beam cross section B of the pulse laser beam at the position of the workpiece table WT.

[0119] A procedure of scanning and exposing each scan field SF in the Y axis direction to the pulse laser beam is performed in the order of FIG. **6**, FIG. **7**, and FIG. **8**. First, as illustrated in FIG. **6**, the workpiece table WT is positioned such that an end SFy+ in a +Y direction of the scan field SF is positioned away from a position of an end By—in a −Y direction of the beam cross section B by a predetermined distance in the −Y direction. Then, the workpiece table WT is accelerated in the +Y direction so as to be a velocity Vy before the end SFy+ in the +Y direction of the scan field SF coincides with the position of the end By—in the −Y direction of the beam cross section B. As illustrated in FIG. **7**, the scan field SF is exposed while the workpiece table WT is moved in the +Y direction such that the position of the scan field SF moves uniformly and linearly at the velocity Vy with respect to the position of the beam cross section B. As illustrated in FIG. **8**, when the workpiece table WT is moved until the end SFy− in the −Y direction of the scan field SF passes the position of the end By+ in the +Y direction of the beam cross section B, the scanning of the scan field SF ends.

[0120] In this way, the exposure is performed while the scan field SF moves with respect to the position of the beam cross section B. When the scan field SF is used as a reference, it can be said that the scanning is performed in the −Y direction with the pulse laser beam.

[0121] Required time Ts for the scan field SF to move a distance corresponding to the width W of the beam cross section B of the pulse laser beam at the velocity Vy is as follows.

$$Ts=W/Vy$$

[0122] An irradiation pulse number Ns of the pulse laser beam with which an arbitrary part of the scan field SF is irradiated is the same as a pulse number of the pulse laser beam generated during the required time Ts, and is as follows.

$$Ns=F\cdot Ts$$

[0123] The irradiation pulse number Ns of the pulse laser beam with which an arbitrary part of the scan field SF is irradiated is preferably a multiple of the pulse number N for one period of the wavelength change. As a result, any part of the scan field SF is irradiated with the pulse laser beam of the irradiation pulse number Ns having the same integrated spectrum. This makes it possible to manufacture a high-quality electronic device with little variation in an exposure result depending on an irradiation position.

1.6 Magnification Distortion

[0124] The exposure apparatus **200** transfers a pattern of the photomask to the photosensitive substrate at a prescribed reduction magnification, for example, a size of ¼. However, the size of the pattern transferred to the photosensitive substrate may be larger or smaller than an expected size. This phenomenon can be seen as a deviation of each point in the plane of the photosensitive substrate from its intended position, and this deviation varies depending on a distance from an optical axis, and is therefore referred to as magnification distortion.

[0125] In photolithography, depending on design of the exposure apparatus **200** and a setting of the optical system at the time of exposure, whether enlargement or reduction is caused by the magnification distortion is changed, or a degree of enlargement or reduction is changed. In manufacture of an electronic device, exposure is performed multiple times by different exposure apparatuses **200** or different settings, so that the magnification distortion causes the overlay error between multiple layers.

1.7 Chromatic Aberration

[0126] FIG. **9** is a schematic diagram of the projection optical system **202** included in the exposure apparatus **200**. FIG. **9** illustrates marginal light beams of light having the target short wavelength λ1 and the target long wavelength λ2 from the photomask disposed on the mask stage MS to the photosensitive substrate disposed on the workpiece table WT. With respect to the target short wavelength λ1, the position of the photomask is in a conjugate relationship with the position of the photosensitive substrate, and the pattern of the photomask is transferred to the photosensitive substrate.

[0127] The optical system of the exposure apparatus **200** is designed so that aberration is minimized at a certain design wavelength, for example, at the target short wavelength λ**1**. However, in a case where light having a wavelength different from the design wavelength, the target long wavelength λ**2** for example, is used, a traveling direction of the light is different from that in a case where the light having the design wavelength is used, due to wavelength dependency of a refraction angle. This difference is called chromatic aberration.

[0128] The chromatic aberration has an effect of shifting an image both in a direction of an optical axis AX and in a direction perpendicular to the optical axis AX. A chromatic aberration component that shifts the image in the direction of the optical axis AX is referred to as longitudinal chromatic aberration, and a chromatic aberration component that shifts the image in the direction perpendicular to the optical axis AX is referred to as lateral chromatic aberration. In FIG. **9**, the longitudinal chromatic aberration is indicated by Δz, and the lateral chromatic aberration is indicated by Δx.

1.8 Magnification Chromatic Aberration

[0129] FIG. **10** illustrates how an image formed on the photosensitive substrate is deformed by the projection optical system **202** illustrated in FIG. **9**. A dashed line represents an image by the target short wavelength λ**1**, and a solid line represents an image by the target long wavelength λ**2**. The lateral chromatic aberration Δx may vary depending on a distance of an object point or an image point from the optical axis AX, and may cause the magnification distortion. The magnification distortion caused by the lateral chromatic aberration Δx is referred to as the magnification chromatic aberration.

[0130] When exposure is performed with light including the center wavelengths, since there is a wavelength different from the design wavelength, the magnification chromatic aberration occurs.

1.9 Magnification Telecentric Error

[0131] When a main light beam is parallel to the optical axis AX on an object side or an image side of an imaging optical system, it is said to be telecentric on the object side or the image side. A projection optical system of a modern exposure apparatus is telecentric on both the object side, i.e. a photomask side, and the image side, i.e. a photosensitive substrate side, and this case is said to be both-side telecentric.

[0132] A both-side telecentric optical system has an advantage that, for example, movement of the photosensitive substrate or the photomask in the direction of the optical axis AX does not cause the magnification distortion. In the projection optical system **202** illustrated in FIG. **9**, the position of the photomask and the position of the photosensitive substrate are in the conjugate relationship. The projection optical system **202** illustrated in FIG. **9** is both-side telecentric for the light having the wavelength λ**1**, but may not be both-side telecentric for the light having the wavelength λ**2**.

[0133] A magnification telecentric error will be described with reference to FIG. **11** to FIG. **19**. FIG. **11** is a schematic diagram of an optical system including a part of the illumination optical system **201** and the both-side telecentric projection optical system **202**. In FIG. **11**, the position of the photomask and the position of the photosensitive substrate are in the conjugate relationship. Furthermore, a pupil IP of the illumination optical system **201** is positioned at a conjugate point CP of a pupil PP of the projection optical system **202**. FIG. **11** illustrates an ideal state without a magnification telecentric error. In this case, the size of the image does not change even if the photosensitive substrate moves up and down in the direction of the optical axis AX.

[0134] FIG. **12** illustrates a change in the main light beam when the pupil IP of the illumination optical system **201** is shifted in the direction of the optical axis AX in the optical system illustrated in FIG. **11**. The pupil IP of the illumination optical system **201** is shifted in a direction of an arrow D**1** along the optical axis AX of the pulse laser beam from the conjugate point CP with the pupil PP of the projection optical system **202**. As a result, the main light beam changes from an ideal state ID to an actual state RE, and the incident angle with respect to the photosensitive substrate becomes non-perpendicular. At this time, when the photosensitive substrate moves in the direction of the optical axis AX, the size of the image changes. The pupil IP of the illumination optical system **201** corresponds to a first pupil in the present disclosure, the pupil PP of the projection optical system **202** corresponds to a second pupil in the present disclosure, and the position of the conjugate point CP corresponds to a reference position in the present disclosure.

[0135] FIG. **13** to FIG. **15** illustrate how an image formed on the photosensitive substrate is changed by the optical system illustrated in FIG. **12**. A position Z**0** in a Z direction is a best focus position of the projection optical system **202**, and at the position Z**0**, the image formed on the photosensitive substrate does not change before and after the pupil IP is shifted. However, at a position Z**0+** deviating from the position Z**0** in the Z direction, the image changes from the ideal state ID to the actual state RE and becomes smaller, and conversely, at a position Z**0−** deviating from Z**0** in a −Z direction, the image becomes larger.

[0136] FIG. **16** illustrates a change in the main light beam when the pupil IP of the illumination optical system **201** is shifted in a direction opposite to that in FIG. **12** in the optical system illustrated in FIG. **11**. The pupil IP of the illumination optical system **201** is shifted in a direction of an arrow D**2** along the optical axis AX of the pulse laser beam from the conjugate point CP with the pupil PP of the projection optical system **202**.

[0137] FIG. **17** to FIG. **19** illustrate how an image formed on the photosensitive substrate is changed by the optical system illustrated in FIG. **16**. As in FIG. **14**, at the position Z**0**, the image formed on the photosensitive substrate is not deformed before and after the pupil IP is shifted. However, at the position Z**0+** deviating from the position Z**0** in the Z direction, the image changes from the ideal state ID to the actual state RE and becomes larger, and conversely, at the position Z**0−** deviating from Z**0** in the −Z direction, the image becomes smaller.

[0138] As illustrated in FIG. **12** to FIG. **19**, an error caused by enlargement or reduction of an image generated when the photosensitive substrate is shifted from the best focus position is referred to as a magnification telecentric error. Since the traveling direction of the main light beam can be controlled by the position of the pupil IP of the illumination optical system **201**, the magnitude of the magnification telecentric error can be controlled.

1.10 Problem of Comparative Example

[0139] FIG. **20** is a schematic diagram illustrating a part of the marginal light beam of the pulse laser beam incident on the workpiece table WT when the longitudinal chromatic aberration Δz and the lateral chromatic aberration Δx occur. FIG. **20** corresponds to a portion of FIG. **9** extracted. FIG. **20** includes the marginal light beam of the target short wavelength **λ1** and the marginal light beam of the target long wavelength **λ2**, where a tip of each marginal light beam indicates the best focus position of each wavelength.

[0140] FIG. **21** schematically illustrates an imaging region of the light of each wavelength of the pulse laser beam illustrated in FIG. **20**. The image generated by the pulse laser beam does not suddenly disappear even if it is shifted from the best focus position, but gradually decreases in contrast in an imaging region of a certain size, and is not formed when it is out of the imaging region. The imaging region does not have a distinct boundary, but is conveniently illustrated in an elliptical shape. Due to the longitudinal chromatic aberration Δz, for example, the target long wavelength **λ2** forms an image at a position deviating in the −Z direction more than the target short wavelength **λ1**. On the other hand, the lateral chromatic aberration Δx occurs in opposite directions about the optical axis AX, and for example, the target long wavelength **λ2** forms an image at a position deviating outward about the optical axis AX more than the target short wavelength **λ1**.

[0141] FIG. **22** is a sectional view illustrating a resist profile when the photosensitive substrate exposed to the pulse laser beam illustrated in FIG. **20** and FIG. **21** is developed. The photosensitive substrate includes a resist film R formed on a surface of a semiconductor substrate SUB. Since the pulse laser beam illustrated in FIG. **20** and FIG. **21** has the longitudinal chromatic aberration Δz, excellent imaging performance can be obtained over an entire thickness direction of the resist film R even in the resist film R having a large thickness. However, the lateral chromatic aberration Δx occurs in a region away from the optical axis AX of the pulse laser beam, and an imaging position in the X direction differs between the target short wavelength **λ1** and the target long wavelength **λ2**. Therefore, inclination angles of wall surfaces on both sides of a part where the resist film R is removed may be asymmetric.

[0142] FIG. **23** illustrates the deviation of the image on the photosensitive substrate scan-exposed to the pulse laser beam illustrated in FIG. **20** and FIG. **21**. As illustrated in FIG. **23**, the imaging position in the X direction differs between the target short wavelength **λ1** and the target long wavelength **λ2**, and in particular, the deviation becomes remarkable at ends away from the optical axis AX in the X direction and the −X direction. Therefore, even in a case of the resist film R having a small thickness, the image may be shifted or blurred due to the lateral chromatic aberration Δx. In the scan exposure described with reference to FIG. **6** to FIG. **8**, the photosensitive substrate is moved in the Y direction while being irradiated with the pulse laser beam, so that the lateral chromatic aberration in the Y direction is averaged.

[0143] International Publication No. WO2021/110343 discloses that a pattern is shifted in advance according to a position in a photomask, or an assist pattern (sub-resolution assist feature: SRAF) is inserted. However, such a photomask is optimized for a specific spectral parameter, and other photomasks must be designed and produced if the spectral parameter changes even with the exposure of the same pattern. In addition, there may be no sufficient area to dispose the assist pattern around the pattern to be exposed in the photomask. Further, a dimension of the assist pattern has a lower limit on production, and if the dimension of the assist pattern is too large, an effect of the assist pattern may become excessive.

[0144] Embodiments described below relate to suppressing the magnification chromatic aberration by generating a magnification telecentric error −δx to cancel the lateral chromatic aberration Δx when the exposure is performed using multiple wavelengths.

2. Exposure System in which Position of Pupil IP of Illumination Optical System **201** is Shifted

2.1 Principle

[0145] FIG. **24** is a schematic diagram illustrating a part of the main light beam of the pulse laser beam incident on the workpiece table WT when a magnification telecentric error occurs. FIG. **24** corresponds to a portion of FIG. **12** extracted. For convenience of explanation, it is assumed that the lateral chromatic aberration has not occurred or is very small. In this case, the main light beam of the target short wavelength **λ1** and the main light beam of the target long wavelength **λ2** are common to each other.

[0146] FIG. **25** schematically illustrates an imaging region of the light of each wavelength of the pulse laser beam illustrated in FIG. **24**. Due to the longitudinal chromatic aberration Δz, for example, the target long wavelength **λ2** forms an image at a position deviating in the −Z direction more than the target short wavelength **λ1**. On the other hand, even when it is assumed that the lateral chromatic aberration has not occurred or is very small, in a case where the incident angle of the main light beam on the photosensitive substrate is non-perpendicular due to the deviation of the pupil IP of the illumination optical system **201**, a magnification telecentric error δx determined by the longitudinal chromatic aberration Δz and the incident angle occurs between the target short wavelength **λ1** and the target long wavelength **λ2**.

[0147] FIG. **26** schematically illustrates an imaging region of the light of each wavelength when the lateral chromatic aberration Δx is taken into consideration in the pulse laser beam illustrated in FIG. **24**. The imaging region illustrated in FIG. **26** corresponds to a sum of the lateral chromatic aberration Δx illustrated in FIG. **21** and the magnification telecentric error δx illustrated in FIG. **25**. In FIG. **26**, the lateral chromatic aberration Δx and the magnification telecentric error δx act in the same direction to generate large magnification distortion Δx+δx.

[0148] FIG. **27** is a schematic diagram illustrating a part of the main light beam of the pulse laser beam incident on the workpiece table WT when the magnification telecentric error −δx occurs in the direction opposite to that in FIG. **24**. FIG. **27** corresponds to a portion of FIG. **16** extracted. When it is assumed that the lateral chromatic aberration has not occurred or is very small for the convenience of explanation, the main light beam of the target short wavelength **λ1** and the main light beam of the target long wavelength **λ2** are common to each other.

[0149] FIG. **28** schematically illustrates an imaging region of the light of each wavelength of the pulse laser beam illustrated in FIG. **27**. Due to the longitudinal chromatic aberration Δz, for example, the target long wavelength $\lambda 2$ forms an image at a position deviating in the −Z direction more than the target short wavelength $\lambda 1$. On the other hand, even when it is assumed that the lateral chromatic aberration has not occurred or is very small, in the case where the incident angle of the main light beam on the photosensitive substrate is non-perpendicular due to the deviation of the pupil IP of the illumination optical system **201**, the magnification telecentric error $-\delta x$ determined by the longitudinal chromatic aberration Δz and the incident angle occurs between the target short wavelength $\lambda 1$ and the target long wavelength $\lambda 2$. Since the direction of the deviation of the pupil IP of the illumination optical system **201** differs between FIG. **25** and FIG. **28**, the magnification telecentric error δx in FIG. **25** and the magnification telecentric error $-\delta x$ in FIG. **28** occur in the opposite directions.

[0150] FIG. **29** schematically illustrates an imaging region of the light of each wavelength when the lateral chromatic aberration Δx is taken into consideration in the pulse laser beam illustrated in FIG. **27**. The imaging region illustrated in FIG. **29** corresponds to a sum of the lateral chromatic aberration Δx illustrated in FIG. **21** and the magnification telecentric error $-\delta x$ illustrated in FIG. **28**. As illustrated in FIG. **29**, the lateral chromatic aberration Δx and the magnification telecentric error $-\delta x$ are caused to act in the opposite directions to cancel each other, and the deviation of the imaging position due to the lateral chromatic aberration Δx on the photosensitive substrate can be reduced by the magnification telecentric error $-\delta x$. Thus, the magnification distortion is reduced.

2.2 Configuration

[0151] FIG. **30** schematically illustrates a configuration of an exposure system in a first embodiment. In the first embodiment, the exposure apparatus **200** includes a measurement unit **303**, and the illumination optical system **201** includes a drive mechanism **203**.

[0152] The measurement unit **303** includes a stage on which an exposed photosensitive substrate is mounted, and a sensor that observes an exposure state of the photosensitive substrate. The measurement unit **303** drives the stage under control of the exposure control processor **210**, measures a pattern formed on the photosensitive substrate by the sensor, and measures magnification distortion from the pattern. The measurement unit **303** corresponds to a measurement sensor in the present disclosure.

[0153] The drive mechanism **203** includes an actuator that drives at least one optical element included in the illumination optical system **201** in order to adjust the position of the pupil IP of the illumination optical system **201**. As described with reference to FIG. **12** and FIG. **16**, the drive mechanism **203** is configured to adjust the position of the pupil IP of the illumination optical system **201**, along the optical axis AX of the pulse laser beam, both in the direction of the arrow D**1** approaching the pupil PP from the conjugate point CP with the pupil PP of the projection optical system **202** and in the direction of the arrow D**2** away from the pupil PP. The drive mechanism **203** operates under the control of the exposure control processor **210**.

[0154] FIG. **31** conceptually illustrates a first example of the illumination optical system **201** capable of moving the position of the pupil IP. The illumination optical system **201** includes a beam shaping/uniformizing optical system **204**, a mechanical aperture **205**, and a pupil position adjusting optical system **206***a*.

[0155] The beam shaping/uniformizing optical system **204** shapes and uniformizes a pulse laser beam having a substantially rectangular beam cross section and a Gaussian light intensity distribution into a desired beam cross section and a uniform light intensity distribution, for example.

[0156] The mechanical aperture **205** is a mechanical diaphragm and is disposed near the pupil IP. The mechanical aperture **205** corresponds to a mechanical diaphragm in the present disclosure.

[0157] The pupil position adjusting optical system **206***a* irradiates the photomask with the light outcoming from the pupil IP. By moving at least one of optical elements included in the pupil position adjusting optical system **206***a* by the drive mechanism **203**, the position of the pupil IP is moved in the direction of the optical axis AX.

[0158] FIG. **32** conceptually illustrates a second example of the illumination optical system **201** capable of moving the position of the pupil IP. The illumination optical system **201** includes the beam shaping/uniformizing optical system **204**, a diffractive optical element **207**, and a pupil position adjusting optical system **206***b*.

[0159] The diffractive optical element **207** is an optical element that has a large number of recesses and projections on its surface and branches the transmitted light into a plurality of diffracted light beams. The recesses and the projections on the surface of the diffractive optical element **207** are designed to direct the diffracted light beams in respective desired directions. The diffracted light beams outcoming from the diffractive optical element **207** enter the pupil position adjusting optical system **206***b*.

[0160] The pupil position adjusting optical system **206***b* condenses the diffracted light beams on the pupil IP. By moving at least one of the optical elements included in the pupil position adjusting optical system **206***b* by the drive mechanism **203**, a light condensing position, that is, the position of the pupil IP is moved in the direction of the optical axis AX.

[0161] FIG. **33** conceptually illustrates a third example of the illumination optical system **201** capable of moving the position of the pupil IP. The illumination optical system **201** includes the beam shaping/uniformizing optical system **204**, a micromirror array **208**, a mirror **209**, and a pupil position adjusting optical system **206***c*.

[0162] The micromirror array **208** is an optical element that includes a plurality of mirrors with respectively adjustable inclination and branches the light incident on the micromirror array **208** into a plurality of reflected light beams. The inclination of the mirrors included in the micromirror array **208** is adjusted so as to direct the reflected light beams in the respective desired directions. The reflected light beams outcoming from the micromirror array **208** enter the pupil position adjusting optical system **206***c* via the mirror **209**.

[0163] The pupil position adjusting optical system **206***c* condenses the reflected light beams on the pupil IP. By moving at least one of the optical elements included in the pupil position adjusting optical system **206***c* by the drive mechanism **203**, the light condensing position, that is, the position of the pupil IP is moved in the direction of the optical axis AX.

2.3 Operation (Correction of Magnification Distortion)

[0164] FIG. **34** is a flowchart illustrating processing of correcting the magnification distortion in the first embodiment. The exposure control processor **210** corrects the magnification distortion by controlling the drive mechanism **203** so as to reduce the deviation of the imaging position due to the lateral chromatic aberration Δx as follows based on the magnification distortion measured by the measurement unit **303**.

[0165] In S**101**, the exposure control processor **210** controls an unillustrated conveyance device so as to set the photomask on the mask stage MS of the exposure apparatus **200**.

[0166] In S**103**, the exposure control processor **210** sets a spectral parameter of the pulse laser beam including the center wavelengths. The spectral parameter includes, for example, the target short wavelength λ**1** and the target long wavelength λ**2**. Alternatively, the spectral parameter may include the wavelength difference between the target short wavelength λ**1** and the target long wavelength λ**2**. The spectral parameter may further include a pulse number N for one period of the wavelength change.

[0167] In S**104**, the exposure control processor **210** sets a value of a counter j that specifies the position of the pupil IP of the illumination optical system **201** to an initial value of 1.

[0168] In S**105**, the exposure control processor **210** controls the drive mechanism **203** so that the position of the pupil IP of the illumination optical system **201** becomes a j-th value.

[0169] In S**106**, the exposure control processor **210** transmits various kinds of parameters and signals to the laser control processor **130** so as to laser oscillate according to the spectral parameter set in S**103**. Further, the exposure control processor **210** controls the mask stage MS and the workpiece table WT so that an image of the photomask by the pulse laser beam including the center wavelengths is transferred onto the photosensitive substrate and the photosensitive substrate is exposed. Here, the photosensitive substrate to be exposed may be a photosensitive substrate for measurement, which is different from a photosensitive substrate for manufacturing a semiconductor device.

[0170] In S**107**, the exposure control processor **210** controls the measurement unit **303** to measure the magnification distortion from the pattern formed on the exposed photosensitive substrate.

[0171] In S**108**, the exposure control processor **210** determines whether or not the magnification distortion is less than or equal to a threshold. If the magnification distortion exceeds the threshold (S**108**: NO), the exposure control processor **210** advances the processing to S**109**. If the magnification distortion is less than or equal to the threshold (S**108**: YES), the exposure control processor **210** advances the processing to S**110**.

[0172] In S**109**, the exposure control processor **210** adds 1 to the value of the counter j to update j, and then returns the processing to S**105**. An upper limit value may be set for the value of the counter j, and the exposure control processor **210** may end the processing of the present flowchart when j reaches the upper limit value.

[0173] In S**110**, the exposure control processor **210** determines the position of the pupil IP of the illumination optical system **201** to be the j-th value at which the magnification distortion becomes less than or equal to the threshold.

[0174] In S**111**, the exposure control processor **210** disposes the photosensitive substrate for manufacturing a semiconductor device on the workpiece table WT, starts the exposure, and ends the processing of the present flowchart.

2.4 Effect

[0175] According to the first embodiment, the exposure system includes the illumination optical system **201** configured to illuminate the photomask with the pulse laser beam including the target short wavelength λ**1** and the target long wavelength λ**2**, and the projection optical system **202** configured to illuminate the photosensitive substrate with the pulse laser beam that has passed through the photomask and to project an image of the photomask. The position of the pupil IP of the illumination optical system **201** is shifted from the conjugate point CP of the pupil PP of the projection optical system **202** in the direction of the arrow D**2** for reducing, by the magnification telecentric error −δx, the deviation of the imaging position due to the lateral chromatic aberration Δx on the photosensitive substrate.

[0176] Accordingly, since the position of the pupil IP of the illumination optical system **201** is shifted, the deviation of the imaging position due to the lateral chromatic aberration Δx can be reduced by the magnification telecentric error −δx, so that even a thick resist film can be accurately processed. In addition, a degree of freedom in the design of the photomask is higher than in a case where the deviation of the imaging position is reduced by the design of the photomask. Further, when the wavelength difference between the target short wavelength λ**1** and the target long wavelength λ**2** is changed, it is not necessary to redesign the photomask separately according to the wavelength difference, and a common photomask can be used.

[0177] According to the first embodiment, the position of the pupil IP is shifted from the conjugate point CP of the pupil PP along the optical axis AX of the pulse laser beam.

[0178] Accordingly, by shifting the pupil IP in the direction of the optical axis AX, the magnification telecentric error −δx can be generated while suppressing a change in the optical axis AX of the pulse laser beam incident on the photosensitive substrate.

[0179] According to the first embodiment, the exposure system includes the drive mechanism **203** configured to adjust the position of the pupil IP, and the exposure control processor **210** configured to control the drive mechanism **203** so as to reduce the deviation of the imaging position due to the lateral chromatic aberration Δx.

[0180] Accordingly, since the position of the pupil IP can be adjusted by the drive mechanism **203**, the magnification distortion can be suppressed even when the spectral parameter such as the wavelength difference between the target short wavelength λ**1** and the target long wavelength λ**2** is changed.

[0181] According to the first embodiment, the drive mechanism **203** is configured to adjust the position of the pupil IP, along the optical axis AX of the pulse laser beam, both in the direction of the arrow D**1** approaching the pupil PP from the conjugate point CP of the pupil PP and in the direction of the arrow D**2** away from the pupil PP.

[0182] Accordingly, it is possible to select an appropriate moving direction even when the moving direction of the pupil IP for suppressing the magnification distortion is the direction of the arrow D**1** approaching the pupil PP or is the direction of the arrow D**2** away from the pupil PP.

[0183] According to the first embodiment, the exposure system includes the measurement unit **303** configured to measure the pattern formed by projection onto the photosensitive substrate, and the exposure control processor **210** controls the drive mechanism **203** based on a measurement result of the measurement unit **303**.

[0184] Accordingly, the magnification distortion can be accurately suppressed based on the measurement result of the measurement unit **303**.

[0185] According to the first embodiment, the measurement unit **303** measures the magnification distortion of the pattern formed by the projection onto the photosensitive substrate, and the exposure control processor **210** controls the drive mechanism **203** based on the magnification distortion.

[0186] Accordingly, the position of the pupil IP can be adjusted so as to reduce the magnification distortion.

[0187] In other respects, the first embodiment is similar to the comparative example.

3. Exposure System that Determines Position of Pupil IP of Illumination Optical System 201 Based on Spectral Parameter

3.1 Configuration

[0188] FIG. **35** schematically illustrates a configuration of an exposure system in a second embodiment. In the second embodiment, the exposure apparatus **200** includes a nonvolatile memory **213**. The nonvolatile memory **213** stores a correction table **213***a* (see FIG. **37**) in which the spectral parameter is associated with the position of the pupil IP of the illumination optical system **201**. The nonvolatile memory **213** is accessible to the exposure control processor **210**.

3.2 Operation

3.2.1 Creation of Correction Table

[0189] FIG. **36** is a flowchart illustrating processing of creating the correction table **213***a* in the second embodiment. The exposure control processor **210** creates the correction table **213***a* as follows.

[0190] In S**101**, the exposure control processor **210** controls an unillustrated conveyance device so as to set the photomask on the mask stage MS of the exposure apparatus **200**. This is the same as the processing included in the correction of the magnification distortion of the first embodiment.

[0191] In S**102***a*, the exposure control processor **210** sets a value of a counter i that specifies the spectral parameter to an initial value of 1.

[0192] In S**103***a*, the exposure control processor **210** sets the spectral parameter to an i-th value.

[0193] The processing from S**104** to S**109** is the same as the processing included in the correction of the magnification distortion of the first embodiment, and the exposure control processor **210** searches for the position of the pupil IP at which the magnification distortion is less than or equal to the threshold for the given spectral parameter. If the magnification distortion is less than or equal to the threshold (S**108**: YES), the exposure control processor **210** advances the processing to S**112***a*.

[0194] In S**112***a*, the exposure control processor **210** causes a correspondence relationship between an i-th spectral parameter and a j-th position of the pupil IP of the illumination optical system **201** at which the magnification distortion is less than or equal to the threshold to be stored in the correction table **213***a* of the nonvolatile memory **213**, based on the measurement result of the magnification distortion by the measurement unit **303**.

[0195] In S**113***a*, the exposure control processor **210** determines whether or not the value of the counter i has reached a maximum value imax. When the value of the counter i has reached the maximum value imax (S**113***a*: YES), the exposure control processor **210** ends the processing of the present flowchart. When the value of the counter i is smaller than the maximum value imax (S**113***a*: NO), the exposure control processor **210** advances the processing to S**114***a*.

[0196] In S**114***a*, the exposure control processor **210** adds 1 to the value of the counter i to update i, and then returns the processing to S**103***a*.

[0197] FIG. **37** illustrates an example of the correction table **213***a* stored in the nonvolatile memory **213**. The correction table **213***a* is a data table storing spectral parameters S**1** to Simax and positions P**1** to Pimax of the pupil IP of the illumination optical system **201** at which the magnification distortion is less than or equal to the threshold, corresponding to the values 1 to imax of the counter i. The positions P**1** to Pimax of the pupil IP correspond to a control parameter in the present disclosure. A different correction table **213***a* may be created for each photomask.

3.2.2 Correction of Magnification Distortion

[0198] FIG. **38** is a flowchart illustrating processing of correcting the magnification distortion in the second embodiment. The exposure control processor **210** controls the drive mechanism **203** based on the spectral parameter of the pulse laser beam as follows. It is assumed that the photomask is already set on the mask stage MS.

[0199] In S**103**, the exposure control processor **210** sets the spectral parameter of the pulse laser beam. This is the same as the first embodiment.

[0200] In S**110***a*, the exposure control processor **210** sets the position of the pupil IP of the illumination optical system **201** corresponding to the set spectral parameter to the value read from the correction table **213***a*, and controls the drive mechanism **203**.

[0201] In S**111**, the exposure control processor **210** disposes the photosensitive substrate on the workpiece table WT, starts the exposure, and ends the processing of the present flowchart.

[0202] In other respects, the second embodiment is similar to the first embodiment.

3.3 Effect

[0203] According to the second embodiment, the exposure control processor **210** can access the correction table **213***a* in which the wavelength difference between the target short wavelength λ**1** and the target long wavelength λ**2** is associated with the positions P**1** to Pimax of the pupil IP, and reads the position of the pupil IP corresponding to the wavelength difference from the correction table **213***a* to control the drive mechanism **203**.

[0204] Accordingly, since the position of the pupil IP can be read from the correction table **213***a* based on the wavelength difference between the target short wavelength λ**1** and the target long wavelength λ**2**, the drive mechanism **203** can be quickly controlled.

[0205] According to the second embodiment, the exposure control processor **210** controls the drive mechanism **203** based on the spectral parameter of the pulse laser beam. For example, the drive mechanism **203** may be controlled not only using the correction table **213***a* but also using a function of the spectral parameter and the control parameter for the drive mechanism **203**. Accordingly, since the control is performed based on the spectral parameter, a process for controlling the drive mechanism **203** can be simplified.

[0206] According to the second embodiment, the exposure control processor **210** can access the correction table **213***a* in which the spectral parameters S**1** to Simax and the positions P**1** to Pimax of the pupil IP are associated with each other, and reads the position of the pupil IP corresponding to the spectral parameter from the correction table **213***a* to control the drive mechanism **203**.

[0207] Accordingly, since the position of the pupil IP can be read from the correction table **213***a* based on the spectral parameters S**1** to Simax, the drive mechanism **203** can be quickly controlled.

[0208] According to the second embodiment, the exposure system includes the measurement unit **303** configured to measure the pattern formed by the projection onto the photosensitive substrate, and the exposure control processor **210** causes the correspondence relationship between the spectral parameters S**1** to Simax and the positions P**1** to Pimax of the pupil IP to be stored in the correction table **213***a*, based on the measurement result of the measurement unit **303**.

[0209] Accordingly, it is possible to create a highly reliable correction table **213***a* for adjusting the position of the pupil IP based on the measurement result.

[0210] According to the second embodiment, the measurement unit **303** measures the magnification distortion of the pattern formed by the projection onto the photosensitive substrate, and the exposure control processor **210** causes, for each of the spectral parameters S**1** to Simax, the correspondence relationship with the positions P**1** to Pimax of the pupil IP at which the magnification distortion becomes less than or equal to the threshold to be stored in the correction table **213***a*.

[0211] Accordingly, it is possible to create a highly reliable correction table **213***a* for reducing the magnification distortion based on the measurement result of the magnification distortion.

4. Exposure System Including Measurement Unit **303***b* Separate from Exposure Apparatus **200**

4.1 Configuration

[0212] FIG. **39** schematically illustrates a configuration of an exposure system according to a third embodiment. In the third embodiment, the exposure system includes a development apparatus **300** separate from the exposure apparatus **200**. The development apparatus **300** includes a wafer moving unit **301**, a processing unit **302**, a measurement unit **303***b*, and a development control processor **310**.

[0213] The wafer moving unit **301** is a device that transfers the photosensitive substrate to and from the exposure apparatus **200** and moves the photosensitive substrate inside the development apparatus **300**.

[0214] The processing unit **302** is a device that performs application of a resist film on the photosensitive substrate, post-exposure baking (PEB) of the photosensitive substrate exposed in the exposure apparatus **200**, supplying of a developer, cleaning, drying, post-development baking (PDB), and the like.

[0215] The measurement unit **303***b* is a device that measures the pattern formed on the photosensitive substrate by exposure and development. The measurement unit **303***b* may be a cross-sectional inspection SEM that measures a resist profile, a pattern position measurement device that measures the overlay error, or a device that measures the magnification distortion from a planar shape of the resist film. The measurement unit **303***b* corresponds to the measurement sensor in the present disclosure. The measurement unit **303***b* may be provided separately from the development apparatus **300**.

[0216] The development control processor **310** is a processing device including a memory **312** in which a control program is stored and a CPU **311** which executes the control program. The development control processor **310** is specially configured or programmed to execute various kinds of processing included in the present disclosure.

[0217] The exposure apparatus **200** may not include the measurement unit **303** described in the first embodiment.

4.2 Operation (Correction of Magnification Distortion)

[0218] FIG. **40** is a flowchart illustrating processing of correcting the magnification distortion in the third embodiment. As described below, the development control processor **310** develops and measures the photosensitive substrate, the exposure control processor **210** controls the drive mechanism **203** so as to reduce the deviation of the imaging position due to the lateral chromatic aberration Δx based on the measurement result, and thus the magnification distortion is corrected.

[0219] Processing of S**101** to S**105** is the same as that of the first embodiment. In S**106***b*, not only the exposure control processor **210** controls the exposure apparatus **200** to expose the photosensitive substrate, but also the development control processor **310** controls the development apparatus **300** so that the exposed photosensitive substrate is developed by the development apparatus **300**.

[0220] In S**107***b*, the development control processor **310** controls the measurement unit **303***b* to measure the resist profile, the overlay error, or the magnification distortion of the exposed and developed photosensitive substrate. The resist profile is measured as a larger value as the inclination angles of the wall surfaces of the resist film are asymmetric, for example.

[0221] In S**108***b*, the exposure control processor **210** receives the measurement result of the resist profile, the overlay error, or the magnification distortion measured by the measurement unit **303***b* from the development control processor **310**, and determines whether or not the measurement result is less than or equal to a threshold. If the measurement result exceeds the threshold (S**108***b*: NO), the exposure control processor **210** advances the processing to S**109**. If the measurement result is less than or equal to the threshold (S**108***b*: YES), the exposure control processor **210** advances the processing to S**110**. The processing of S**109**, S**110** and S**111** is the same as that of the first embodiment.

[0222] In other respects, the third embodiment is similar to the first embodiment. Alternatively, in a configuration in which the exposure apparatus **200** includes the nonvolatile memory **213** as in the second embodiment, the exposure system may include the measurement unit **303***b* separate from the exposure apparatus **200**.

4.3 Effect

[0223] According to the third embodiment, the exposure system includes the measurement unit **303***b* configured to measure the pattern formed by the projection and development on the photosensitive substrate, and the exposure control processor **210** controls the drive mechanism **203** based on the measurement result of the measurement unit **303***b*.

[0224] Accordingly, product quality can be further improved by measuring the developed pattern and controlling the drive mechanism **203** based on the measurement result.

[0225] According to the third embodiment, the measurement unit **303***b* measures the resist profile of the photosensitive substrate, and the exposure control processor **210** controls the drive mechanism **203** based on the asymmetry of the resist profile.

[0226] Accordingly, since the drive mechanism **203** is controlled based on the asymmetry of the resist profile of the developed photosensitive substrate, it is possible to manufacture a product with reduced asymmetry of the resist profile.

[0227] According to the third embodiment, the measurement unit **303***b* measures the overlay error between multiple layers formed by multiple instances of the projection and the development, and the exposure control processor **210** controls the drive mechanism **203** based on the overlay error.

[0228] Accordingly, since the drive mechanism **203** is controlled based on the overlay error of the developed photosensitive substrate, it is possible to manufacture a product having a small overlay error.

[0229] According to the third embodiment, the measurement unit **303***b* measures the magnification distortion from the planar shape of the resist film included in the photosensitive substrate, and the exposure control processor **210** controls the drive mechanism **203** based on the magnification distortion.

[0230] Accordingly, since the drive mechanism **203** is controlled based on the magnification distortion measured from the planar shape of the resist film of the developed photosensitive substrate, it is possible to manufacture a product having small magnification distortion.

5. Others

[0231] The description above is intended to be illustrative and the present disclosure is not limited thereto. Therefore, it would be obvious to those skilled in the art that various modifications to the embodiments of the present disclosure would be possible without departing from the spirit and the scope of the appended claims. Further, it would be also obvious to those skilled in the art that embodiments of the present disclosure would be appropriately combined.

[0232] The terms used throughout the present specification and the appended claims should be interpreted as non-limiting terms unless clearly described. For example, terms such as "comprise", "include", "have", and "contain" should not be interpreted to be exclusive of other structural elements. Further, indefinite articles "a/an" described in the present specification and the appended claims should be interpreted to mean "at least one" or "one or more." Further, "at least one of A, B, and C" should be interpreted to mean any of A, B, C, A+B, A+C, B+C, and A+B+C as well as to include combinations of any thereof and any other than A, B, and C.

What is claimed is:

1. An exposure system comprising:

an illumination optical system configured to illuminate a photomask with a pulse laser beam including a plurality of center wavelengths; and

a projection optical system configured to illuminate a photosensitive substrate with the pulse laser beam that has passed through the photomask and to project an image of the photomask,

a position of a first pupil that is a pupil of the illumination optical system being shifted from a reference position in a conjugate relationship with a second pupil that is a pupil of the projection optical system in a direction of reducing, by a magnification telecentric error, deviation of an imaging position due to lateral chromatic aberration on the photosensitive substrate.

2. The exposure system according to claim **1**, wherein

the position of the first pupil is shifted from the reference position along an optical axis of the pulse laser beam.

3. The exposure system according to claim **1**, further comprising:

a drive mechanism configured to adjust the position of the first pupil; and

a processor configured to control the drive mechanism to reduce the deviation.

4. The exposure system according to claim **3**, wherein

the drive mechanism is configured to be capable of adjusting the position of the first pupil, along an optical axis of the pulse laser beam, both in a direction approaching the second pupil from the reference position and in a direction away from the second pupil.

5. The exposure system according to claim **3**, wherein

the illumination optical system includes a mechanical diaphragm disposed near the first pupil, and a pupil position adjusting optical system driven by the drive mechanism.

6. The exposure system according to claim **3**, wherein

the illumination optical system includes a diffractive optical element, and a pupil position adjusting optical system configured to condense the pulse laser beam that has passed through the diffractive optical element.

7. The exposure system according to claim **3**, wherein

the illumination optical system includes a micromirror array, and a pupil position adjusting optical system configured to condense the pulse laser beam reflected by the micromirror array.

8. The exposure system according to claim **3**, further comprising

a measurement sensor configured to measure a pattern formed by projection onto the photosensitive substrate, wherein

the processor controls the drive mechanism based on a measurement result of the measurement sensor.

9. The exposure system according to claim **8**, wherein

the measurement sensor measures magnification distortion of the pattern formed by the projection onto the photosensitive substrate, and the processor controls the drive mechanism based on the magnification distortion.

10. The exposure system according to claim **3**, wherein

the center wavelengths include a first wavelength and a second wavelength, and

the processor is capable of accessing a data table in which a wavelength difference between the first wavelength and the second wavelength and a control parameter for the drive mechanism are associated with each other, and reads the control parameter corresponding to the wavelength difference from the data table to control the drive mechanism.

11. The exposure system according to claim **3**, wherein

the processor controls the drive mechanism based on a spectral parameter of the pulse laser beam.

12. The exposure system according to claim **11**, wherein

the processor is capable of accessing a data table in which the spectral parameter and a control parameter for the drive mechanism are associated with each other, and reads the control parameter corresponding to the spectral parameter from the data table to control the drive mechanism.

13. The exposure system according to claim **12**, further comprising

a measurement sensor configured to measure a pattern formed by projection onto the photosensitive substrate, wherein

the processor causes a correspondence relationship between the spectral parameter and the control parameter to be stored in the data table, based on a measurement result of the measurement sensor.

14. The exposure system according to claim **13**, wherein

the measurement sensor measures magnification distortion of the pattern formed by the projection onto the photosensitive substrate, and

the processor causes, for each of a plurality of values of the spectral parameter, the correspondence relationship with the control parameter with which the magnification distortion becomes less than or equal to a threshold to be stored in the data table.

15. The exposure system according to claim **13**, wherein

the measurement sensor measures the pattern formed by projection and development on the photosensitive substrate.

16. The exposure system according to claim **3**, further comprising

a measurement sensor configured to measure a pattern formed by projection and development on the photosensitive substrate, wherein

the processor controls the drive mechanism based on a measurement result of the measurement sensor.

17. The exposure system according to claim **16**, wherein

the measurement sensor measures a resist profile of the photosensitive substrate, and

the processor controls the drive mechanism based on asymmetry of the resist profile.

18. The exposure system according to claim **16**, wherein

the measurement sensor measures an overlay error between multiple layers formed by multiple instances of the projection and the development, and the processor controls the drive mechanism based on the overlay error.

19. The exposure system according to claim **16**, wherein

the measurement sensor measures magnification distortion from a planar shape of a resist film included in the photosensitive substrate, and

the processor controls the drive mechanism based on the magnification distortion.

20. A method of manufacturing an electronic device, comprising

exposing, with an exposure system, a photosensitive substrate to a pulse laser beam to manufacture the electronic device,

the exposure system including

an illumination optical system configured to illuminate a photomask with the pulse laser beam including a plurality of center wavelengths, and

a projection optical system configured to illuminate the photosensitive substrate with the pulse laser beam that has passed through the photomask and to project an image of the photomask,

a position of a first pupil that is a pupil of the illumination optical system being shifted from a reference position in a conjugate relationship with a second pupil that is a pupil of the projection optical system in a direction of reducing, by a magnification telecentric error, deviation of an imaging position due to lateral chromatic aberration on the photosensitive substrate.

* * * * *