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OUTPUT MIRROR FOR ULTRAVIOLET LASER BEAM, ULTRAVIOLET LASER APPARATUS, AND ELECTRONIC DEVICE MANUFACTURING METHOD

Abstract

An output mirror for an ultraviolet laser beam includes a plate-shaped sapphire substrate, at least a part of one main surface of the sapphire substrate is a partial reflective surface that is exposed, reflects a part of the ultraviolet laser beam, and transmits another part of the ultraviolet laser beam, and the other main surface of the sapphire substrate is provided with a reflection suppressing structure configured to suppress reflection of the ultraviolet laser beam.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of Japanese Patent Application No. 2024-24647, filed on Feb. 21, 2024, the entire contents of which are hereby incorporated by reference.

BACKGROUND

1. Technical Field

[0002] The present disclosure relates to an output mirror for an ultraviolet laser beam, an ultraviolet laser apparatus, and an electronic device manufacturing method.

2. Related Art

[0003] In recent years, improvement in resolution has been desired for semiconductor exposure apparatuses with miniaturization and high integration of semiconductor integrated circuits. For this purpose, exposure light sources that output light having shorter wavelengths have been developed. For example, as gas laser apparatuses for exposure, a KrF excimer laser apparatus that outputs a laser beam having a wavelength of about 248.0 nm and an ArF excimer laser apparatus that outputs a laser beam having a wavelength of about 193.4 nm are used.

[0004] Spectral line widths of self-oscillation light of the KrF excimer laser apparatus and the ArF excimer laser apparatus are as wide as 350 μm to 400 μm. Therefore, when a projection lens is configured of a material that transmits ultraviolet light such as a KrF laser beam and an ArF laser beam, chromatic aberration may occur. As a result, the resolution may decrease. Thus, a spectral line width of a laser beam output from a gas laser apparatus needs to be narrowed to the extent that the chromatic aberration can be ignored. Therefore, a line narrowing module (LNM) including a line narrowing element (etalon, grating, or the like) may be included inside a laser resonator of the gas laser apparatus in order to narrow the spectral line width. In the following, a gas laser apparatus with a narrowed spectral line width will be referred to as a line narrowed gas laser apparatus.

LIST OF DOCUMENTS

Patent Documents

[0005] Patent Document 1: U.S. Pat. No. 6,642,989 [0006] Patent Document 2: U.S. Pat. No. 5,507,175 [0007] Patent Document 3: U.S. Pat. No. 7,756,189 [0008] Patent Document 4: U.S. Pat. No. 11,784,452

SUMMARY

[0009] An aspect of the present disclosure is an output mirror for an ultraviolet laser beam including a plate-shaped sapphire substrate, at least a part of one main surface of the sapphire substrate may be a partial reflective surface that is exposed, reflects a part of the ultraviolet laser beam, and transmits another part of the ultraviolet laser beam, and the other main surface of the sapphire substrate may be provided with a reflection suppressing structure configured to suppress reflection of the ultraviolet laser beam.

[0010] Moreover, another aspect of the present disclosure is an ultraviolet laser apparatus including an amplifier configured to amplify an ultraviolet laser beam, the amplifier may include an output mirror for the ultraviolet laser beam, the output mirror may include a plate-shaped sapphire substrate, at least a part of one main surface of the output mirror may be a partial reflective surface from which the sapphire substrate is exposed, the partial reflective surface reflecting a part of the ultraviolet laser beam and transmitting another part of the ultraviolet laser beam, and the other main surface of the output mirror may be provided with a reflection suppressing structure configured to suppress reflection of the ultraviolet laser beam.

[0011] Furthermore, yet another aspect of the present disclosure is an electronic device manufacturing method that may include: generating an ultraviolet laser beam with an ultraviolet laser apparatus including an output mirror for the ultraviolet laser beam, the output mirror including a plate-shaped sapphire substrate, at least a part of one main surface of the output mirror being a partial reflective surface from which the sapphire substrate is exposed, the partial reflective surface reflecting a part of the ultraviolet laser beam and transmitting another part of the ultraviolet laser beam, the other main surface of the output mirror being provided with a reflection suppressing structure configured to suppress reflection of the ultraviolet laser beam; outputting the ultraviolet laser beam to an exposure apparatus; and exposing a photosensitive substrate to the ultraviolet laser beam within the exposure apparatus to manufacture an electronic device.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0012] Some embodiments of the present disclosure will be described below merely as examples with reference to the accompanying drawings.
[0013] FIG. **1** is a schematic diagram illustrating an overall schematic configuration example of an electronic device manufacturing apparatus.
[0014] FIG. **2** is a schematic diagram illustrating an overall schematic configuration example of an ultraviolet laser apparatus of a comparative example.
[0015] FIG. **3** is a schematic diagram illustrating a schematic configuration example of an output mirror included in the ultraviolet laser apparatus of the comparative example.
[0016] FIG. **4** is a schematic diagram illustrating a schematic configuration example of an output mirror of the first embodiment.
[0017] FIG. **5** is a graph illustrating a relationship between a substrate refractive index and a surface reflectance due to Fresnel reflection.
[0018] FIG. **6** is a schematic diagram illustrating disposition of an output mirror in a first modification of the first embodiment.
[0019] FIG. **7** is a schematic diagram illustrating disposition of an output mirror in a second modification of the first embodiment.
[0020] FIG. **8** is a schematic diagram illustrating disposition of an output mirror in a third modification of the first embodiment.
[0021] FIG. **9** is a schematic diagram illustrating a positional relationship between an output mirror and a window of a chamber device in a fourth modification of the first embodiment.
[0022] FIG. **10** is a schematic diagram of a case where a moth eye structure is included as a reflection suppressing structure of an output mirror in an ultraviolet laser apparatus according to a second embodiment.
[0023] FIG. **11** is an explanatory diagram of the moth eye structure.
[0024] FIG. **12** is a schematic diagram illustrating a schematic configuration example of a part of an amplifier included in an ultraviolet laser apparatus of a third embodiment.
[0025] FIG. **13** is a graph illustrating incident angle dependence of a reflectance of Fresnel reflection.
DESCRIPTION OF EMBODIMENTS
[0026] 1. Description of electronic device manufacturing apparatus used in electronic device exposure process [0027] 2. Description of ultraviolet laser apparatus of comparative example [0028] 2.1 Configuration [0029] 2.2 Operation [0030] 2.3 Problem [0031] 3. Description of ultraviolet laser apparatus of first embodiment [0032] 3.1 Configuration [0033] 3.2 Operation [0034] 3.3 Effect and advantage [0035] 3.4 Description of first modification [0036] 3.5 Description of second modification [0037] 3.6 Description of third modification [0038] 3.7 Description of fourth modification [0039] 4. Description of ultraviolet laser apparatus of second embodiment [0040] 4.1 Configuration [0041] 4.2 Effect and advantage [0042] 5. Description of ultraviolet laser apparatus of third embodiment [0043] 5.1 Configuration [0044] 5.2 Operation [0045] 5.3 Effect

and advantage

[0046] Hereinafter, embodiments of the present disclosure will be described in detail with reference to the drawings. The embodiments described below illustrate some examples of the present disclosure and do not limit the content of the present disclosure. Also, all configurations and operations described in the embodiments are not necessarily essential as configurations and operations of the present disclosure. Note that the same components will be denoted by the same reference signs, and repeated description will be omitted.

1. Description of Electronic Device Manufacturing Apparatus Used in Electronic Device Exposure Process

[0047] FIG. **1** is a schematic diagram illustrating an overall schematic configuration example of an electronic device manufacturing apparatus used in an electronic device exposure process. As illustrated in FIG. **1**, the manufacturing apparatus used in the exposure process includes an ultraviolet laser apparatus **100** and an exposure apparatus **200**. The exposure apparatus **200** includes an illumination optical system **210** including a plurality of mirrors **211**, **212**, and **213** and a projection optical system **220**. The illumination optical system **210** illuminates a reticle pattern on a reticle stage RT with a laser beam that is incident from the ultraviolet laser apparatus **100**. The projection optical system **220** performs reduction projection of the laser beam transmitted through the reticle and forms an image on an unillustrated workpiece disposed on a workpiece table WT. The workpiece is a photosensitive substrate such as a semiconductor wafer to which a photoresist is applied. The exposure apparatus **200** synchronously translates the reticle stage RT and the workpiece table WT to expose the workpiece to a laser beam reflecting the reticle pattern. A device pattern is transferred onto the semiconductor wafer through the exposure process as described above to thereby manufacture a semiconductor device, which is an electronic device.

2. Description of Ultraviolet Laser Apparatus of Comparative Example

2.1 Configuration

[0048] An ultraviolet laser apparatus of a comparative example will be described. Note that 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.

[0049] FIG. **2** is a schematic diagram illustrating an overall configuration example of an ultraviolet laser apparatus **100** of the present example. The ultraviolet laser apparatus **100** is, for example, an ArF excimer laser apparatus using mixed gas including argon (Ar), fluorine (F.sub.2), and neon (Ne). The ultraviolet laser apparatus **100** outputs a laser beam L having a center wavelength of about 193.4 nm. Note that in the specification, the term “laser beam” means an ultraviolet laser beam. The ultraviolet laser apparatus **100** may be a gas laser apparatus other than the ArF excimer laser apparatus, and may be, for example, a KrF excimer laser apparatus using KrF gas including krypton (Kr) and fluorine (F.sub.2). In this case, the ultraviolet laser apparatus **100** emits a pulsed laser beam having a center wavelength of about 248 nm. ArF gas or KrF gas, which is a laser medium, may be referred to as laser gas. Therefore, the ultraviolet laser beam may be an ArF laser beam having a center wavelength of about 193.4 nm or a KrF laser beam having a center wavelength of 248 nm.

[0050] The ultraviolet laser apparatus **100** of the present example includes, as main components, a housing **110**, a laser oscillator **130** that is a master oscillator disposed in an internal space of the housing **110**, a light transmission unit **141**, an amplifier **160** that is a power oscillator, a detection unit **153**, a display unit **180**, and a processor **190**.

[0051] The laser oscillator **130** includes, as main components, a chamber device CH**1**, a charger **41**, a pulse power module **43**, a line narrowing module **60**, and an output mirror **70**.

[0052] FIG. **2** illustrates an internal configuration of the chamber device CH**1** seen from a direction substantially perpendicular to a traveling direction of the laser beam L. The chamber device CH**1** includes, as main components, a housing **30**, a pair of windows **31***a* and **31***b*, a pair of electrodes **32***a* and **32***b*, an insulating unit **33**, a feedthrough **34**, and an electrode holder unit **36**.

[0053] The housing **30** encloses the laser gas in the internal space. The internal space is a space in which light is generated by excitation of the laser medium in the laser gas. This light travels to the windows **31***a* and **31***b*.

[0054] The window **31***a* is disposed on a front-side wall surface of the housing **30** in the traveling direction of the laser beam L from the ultraviolet laser apparatus **100** to the exposure apparatus **200**, and the window **31***b* is disposed on a rear-side wall surface of the housing **30** in the traveling direction. The windows **31***a* and **31***b* are made of, for example, calcium fluoride substrates, and the inner and outer surfaces of the housing **30** at the windows **31***a* and **31***b* are planar. Note that it is only necessary for the windows **31***a* and **31***b* to be able to transmit the laser beam L and the windows **31***a* and **31***b* are not limited to the calcium fluoride substrates.

[0055] The electrodes **32***a* and **32***b* are disposed to face each other in the internal space of the housing **30**, and a longitudinal direction of the electrodes **32***a* and **32***b* follows a traveling direction of light generated by a high voltage applied between the electrode **32***a* and the electrode **32***b*. A discharge space between the electrode **32***a* and the electrode **32***b* in the housing **30** is sandwiched between the window **31***a* and the window **31***b*. The electrodes **32***a* and **32***b* are discharge electrodes for exciting the laser medium by glow discharge. In the present example, the electrode **32***a* is a cathode, and the electrode **32***b* is an anode.

[0056] The electrode **32***a* is supported by the insulating unit **33**. The insulating unit **33** blocks an opening formed in the housing **30**. The insulating unit **33** includes an insulator. In addition, the feedthrough **34** made of a conductive member is disposed in the insulating unit **33**. The feedthrough **34** applies a voltage supplied from the pulse power module **43** to the electrode **32***a*. The electrode **32***b* is supported by the electrode holder unit **36** and is electrically connected to the electrode holder unit **36** having a ground potential.

[0057] The charger **41** is a DC power supply device that charges an unillustrated capacitor, which is provided inside the pulse power module **43**, with a predetermined voltage. The charger **41** is disposed outside the housing **30** and is connected to the pulse power module **43**. The pulse power module **43** includes an unillustrated switch controlled by the processor **190**. The pulse power module **43** is a voltage application circuit that, when a switch is turned from OFF to ON by the control, boosts the voltage applied from the charger **41** to generate a pulsed high voltage and applies the high voltage to the electrodes **32***a* and **32***b*. When the high voltage is applied, discharge occurs between the electrode **32***a* and the electrode **32***b*. The laser medium inside the housing **30** is excited by energy of the discharge. When the excited laser gas transitions to a ground level, light is emitted, and the emitted light passes through the windows **31***a* and **31***b* and is output to the outside of the housing **30**. The windows **31***a* and **31***b* are inclined to form a Brewster angle with respect to the traveling direction of the laser beam L such that reflection of P-polarized light of the laser beam L is suppressed, and in the present example, the windows **31***a* and **31***b* are inclined with respect to a direction perpendicular to the traveling direction of the laser beam L and the direction in which the electrodes **32***a* and **32***b* face each other. Therefore, the laser beam L exiting the chamber device CH**1** includes first linearly polarized light, a polarization direction of which is perpendicular to the direction in which the electrodes **32***a* and **32***b* face each other, and linearly polarized light, a polarization direction of which differs from the polarization direction of the first linearly polarized light, is reduced from the laser beam L. In other words, the windows **31***a* and **31***b* also serve as polarizers that are inclined with respect to the polarization direction of the first linearly polarized light and reduces the linearly polarized light in the polarization direction that differs from the polarization direction of the first linearly polarized light from the laser beam L.

[0058] Note that in the specification and claims, the term “perpendicular” refers to a state in which the angle formed is equal to or greater than 89 degrees and equal to or less than 91 degrees, and the term “parallel” refers to a state in which the angle formed is within 1 degree.

[0059] The line narrowing module **60** includes a housing **65**, a prism **61** disposed in an internal space of the housing **65**, a grating **63**, and an unillustrated rotation stage. An opening is formed in the housing **65**, and the housing **65** is connected to a rear side of the housing **30** via the opening.

[0060] The prism **61** expands a beam width of light exiting the window **31***b* and causes the light to be incident on the grating **63**. Furthermore, the prism **61** reduces a beam width of reflected light from the grating **63** and returns the light to the internal space of the housing **30** via the window **31***b*. The prism **61** is supported by the rotation stage and is rotated by the rotation stage. The rotation of the prism **61** can change an incident angle of the light with respect to the grating **63**, and a wavelength of the light returning from the grating **63** to the housing **30** via the prism **61** can be selected. Although FIG. **2** illustrates an example in which one prism **61** is disposed, two or more prisms may be disposed.

[0061] A surface of the grating **63** is made of a material having a high reflectance, and a large number of grooves are provided at predetermined intervals in the surface. The grating **63** is a dispersive optical element. The cross-sectional shape of each groove is, for example, a right-angled triangle. Light that is incident on the grating **63** from the prism **61** is reflected by these grooves and is diffracted in a direction in accordance with a wavelength of the light. The grating **63** is disposed in Littrow arrangement such that the incident angle of the light that is incident on the grating **63** from the prism **61** coincides with a diffraction angle of the diffracted light having a desired wavelength. Thus, light having a desired wavelength is returned to the housing **30** via the prism **61**.

[0062] The output mirror **70** faces the window **31***a*, transmits a part of the laser beam L exiting the window **31***a*, reflects and returns the other part of the laser beam L to the internal space of the housing **30** via the window **31***a*. The output mirror **70** is fixed to an unillustrated holder and is disposed in an internal space of the housing **110**.

[0063] A Fabry-Perot-type resonator is formed by the grating **63** and the output mirror **70** between which the housing **30** is sandwiched, and the housing **30** is disposed on an optical path of the resonator. Therefore, the resonator resonates light between the output mirror **70** and the grating **63** sandwiching the chamber device CH**1**.

[0064] The light transmission unit **141** includes, as main components, high reflective mirrors **141***b* and **141***c*. Each of the high reflective mirrors **141***b* and **141***c* is fixed to an unillustrated holder with the inclination angle thereof adjusted, and is disposed in the internal space of the housing **110**. The high reflective mirrors **141***b* and **141***c* highly reflect the laser beam L. The high reflective mirrors **141***b* and **141***c* are disposed on the optical path of the laser beam L from the output mirror **70**. The laser beam L is reflected by the high reflective mirrors **141***b* and **141***c* and is then incident on the amplifier **160**.

[0065] The amplifier **160** amplifies energy of the laser beam L output from the laser oscillator **130**. A basic configuration of the amplifier **160** includes, as main components, a chamber device CH**2**, a charger **341**, a rear mirror **380**, and an output mirror **400**, which are components substantially similar to those of the laser oscillator **130**. Note that the same components as those of the laser oscillator **130** will be denoted by the same reference signs, and detailed description thereof will be omitted unless otherwise specified.

[0066] The electrodes **32***a* and **32***b* generate discharge for amplifying the laser beam L from the laser oscillator **130**. The direction in which the electrodes **32***a* and **32***b* face each other is a direction perpendicular to the polarization direction of the first linearly polarized light in the laser beam L from the laser oscillator **130**. The windows **31***a* and **31***b* are inclined with respect to the polarization direction of the first linearly polarized light such that the first linearly polarized light in the laser beam L is incident as P-polarized light and an incident angle θ of the laser beam L becomes the Brewster angle. Therefore, the laser beam L exiting the chamber device CH**2** includes the first linearly polarized light, and linearly polarized light in a polarization direction that differs from the polarization direction of the first linearly polarized light is reduced from the laser beam L.

[0067] Note that the amplifier **160** is different from the laser oscillator **130** in that the amplifier **160** does not include the line narrowing module **60** and includes the rear mirror **380**.

[0068] The rear mirror **380** is provided between the high reflective mirror **141***c* and the window

31*b* and face each of the high reflective mirror **141***c* and the window **31***b*. The rear mirror **380** transmits the laser beam L from the laser oscillator **130** toward a discharge space between the electrodes **32***a* and **32***b*, and reflects a part of the laser beam L amplified by the electrode **32***a* and **32***b* and exiting the chamber device CH**2** toward the discharge space between the electrodes **32***a* and **32***b*.
[0069] The output mirror **400** is disposed on a side opposite to the side of the rear mirror **380** relative to the chamber device CH**2**. The output mirror **400** reflects a part of the laser beam L from the chamber device CH**2** and transmits the other part of the laser beam L. A surface of the output mirror **400** on the side of the chamber device CH**2** is coated with a partial reflective film having a predetermined reflectance. Furthermore, a surface of the output mirror **400** on the side opposite to the chamber device CH **2** is coated with a non-reflective film having a reflectance of approximately zero.
[0070] FIG. **3** is a schematic diagram illustrating a schematic configuration example of the output mirror **400** included in the ultraviolet laser apparatus **100** of the comparative example. The output mirror **400** may be disc-shaped. The surface of the output mirror **400** on the side of the chamber device CH**2** and the surface on the opposite side may be flat. The output mirror **400** includes a plate-shaped substrate **410**. One main surface **411** of the substrate **410** is provided with a partial reflective film **420** having a reflectance of 10% to 20%, and the other main surface is provided with a reflection suppressing film **430** having a reflectance of approximately 0%. The substrate **410** is made of, for example, CaF.sub.2, MgF.sub.2, or synthetic quartz. The partial reflective film **420** and the reflection suppressing film **430** have structures formed of dielectric multilayer films in which high refractive index material layers and low refractive index material layers are alternately laminated. By adjusting the thicknesses of the high refractive index material layers and the low refractive index material layers, desired reflectance of the partial reflective film **420** and the reflection suppressing film **430** is attained. Examples of the material of the high refractive index material layer include dielectric materials such as LaF.sub.3 and GdF.sub.3, and examples of the material of the low refractive index material layer include a dielectric material such as MgF.sub.2.
[0071] The detection unit **153** includes, as main components, a beam splitter **153***b* and an optical sensor **153***c*.
[0072] The beam splitter **153***b* is disposed on the optical path of the laser beam L transmitted through the output mirror **400**. The beam splitter **153***b* transmits the laser beam L transmitted through the output mirror **400** toward an exit window **173** with a higher transmittance, and reflects a part of the laser beam L toward a light receiving surface of the optical sensor **153***c*.
[0073] The optical sensor **153***c* measures pulsed energy of the laser beam L that is incident on the light receiving surface of the optical sensor **153***c*. The optical sensor **153***c* is electrically connected to the processor **190** and outputs a signal indicative of the measured pulsed energy to the processor **190**. The processor **190** controls a voltage to be applied to the electrodes **32***a* and **32***b* of the laser oscillator **130** and/or the amplifier **160** on the basis of the signal.
[0074] The exit window **173** is provided on a side opposite to the output mirror **400** with reference to the beam splitter **153***b* of the detection unit **153**. The exit window **173** is provided on a wall of the housing **110**. Light transmitted through the beam splitter **153***b* exits the emission window **173** toward the exposure apparatus **200** outside the housing **110**. The laser beam L is, for example, a pulsed laser beam having a center wavelength of 193.4 nm.
[0075] The display unit **180** is a monitor that displays a state of control performed by the processor **190** on the basis of a signal from the processor **190**. The display unit **180** may be disposed outside the housing **110**.
[0076] The processor **190** of the present disclosure is a processing device including a storage device that stores a control program and a central processing unit (CPU) that executes the control program. The processor **190** is specifically configured or programmed to perform various kinds of processing included in the present disclosure. The processor **190** controls the entire ultraviolet laser

apparatus **100**. The processor **190** is electrically connected to an unillustrated exposure processor of the exposure apparatus **200**, and transmits and receives various signals to and from the exposure processor.

2.2 Operation

[0077] Next, an operation of the ultraviolet laser apparatus **100** of the comparative example will be described.

[0078] When the ultraviolet laser apparatus **100** emits the laser beam L, the processor **190** receives a signal indicating target energy Et and a light emission trigger signal from the unillustrated exposure processor of the exposure apparatus **200**. The target energy Et is a target value of energy of the laser beam L used in the exposure process. The processor **190** sets a predetermined charge voltage in the charger **341** such that energy E becomes the target energy Et, and turns ON the switch of the pulse power module **43** in synchronization with the light emission trigger signal. In this manner, the pulse power module **43** generates a pulsed high voltage from electric energy held in the charger **41**, and the high voltage is applied between the electrode **32***a* and the electrode **32***b*. When the high voltage is applied, discharge occurs between the electrode **32***a* and the electrode **32***b*, and the laser medium contained in the laser gas between the electrode **32***a* and the electrode **32***b* is brought into an excited state and emits light when the laser medium returns to the ground state. The emitted light resonates between the grating **63** and the output mirror **70** and is amplified every time the light passes through the discharge space in the internal space of the housing **30**, and laser oscillation occurs. The laser beam L includes first linearly polarized light, and linearly polarized light in a polarization direction that differs from the polarization direction of the first linearly polarized light is reduced from the laser beam L when the laser beam L is transmitted through the windows **31***a* and **31***b*. A part of the laser beam L is transmitted through the output mirror **70**, is reflected by the high reflective mirrors **141***b* and **141***c*, and travels into the amplifier **160**. In the amplifier **160**, the laser beam L is transmitted through the rear mirror **380** and the window **31***b* and travels into the housing **30** of the chamber device CH**2**.

[0079] The processor **190** turns ON the switch of the pulse power module **43** of the amplifier **160** such that discharge occurs when the laser beam L from the laser oscillator **130** travels into the discharge space in the housing **30** of the amplifier **160**. In other words, the processor **190** controls the pulse power module **43** such that a high voltage is applied to the electrodes **32***a* and **32***b* of the amplifier **160** after elapse of a predetermined delay time with respect to the timing at which the switch of the pulse power module **43** is turned ON.

[0080] In this manner, the laser beam L that is incident on the amplifier **160** is amplified by the amplifier **160**. In addition, the laser beam L traveling into the internal space of the housing **30** travels to the output mirror **400** via the window **31***a* as described above, and a part of the laser beam L is reflected by the partial reflective film **420** of the output mirror **400**. The laser beam L reflected by the output mirror **400** travels into the internal space of the housing **30** via the window **31***a*, is amplified, and exits the window **31***b*. The light exiting the window **31***b* is reflected by the rear mirror **380** and travels into internal space of the housing **30** via the window **31***b*. In this manner, the laser beam L having a predetermined wavelength reciprocates between the rear mirror **380** and the output mirror **400**. The laser beam L includes the first linearly polarized light, and the linearly polarized light in the polarization direction that differs from the polarization direction of the first linearly polarized light is reduced from the laser beam L when the laser beam L is transmitted through the windows **31***a* and **31***b*. Furthermore, the laser beam L is amplified every time the laser beam L passes through the discharge space inside the housing **30**.

[0081] The other part of the laser beam L amplified by the chamber device CH**2** and exiting the window **31***a* is transmitted through the output mirror **400** and travels to the beam splitter **153***b*.

[0082] A part of the laser beam L traveling to the beam splitter **153***b* is transmitted through the beam splitter **153***b* and travels to the exit window **173**, and the other part is reflected by the beam splitter **153***b* and travels to the optical sensor **153***c*.

[0083] The optical sensor **153***c* measures the energy E of the received laser beam L. The optical sensor **153***c* outputs a signal indicating the measured energy E to the processor **190**. The processor **190** feedback-controls a charge voltage of the charger **341** such that a difference ΔE between the energy E and the target energy Et falls within an allowable range. At this time, the processor **190** may close an unillustrated shutter disposed in front of the exit window **173** until the difference ΔE falls within the allowable range such that the laser beam L is not incident on the exposure apparatus **200**.

2.3 Problem

[0084] With an increase in throughput of the exposure apparatus **200**, there is an increasing demand for an increase in output of the ultraviolet laser apparatus **100** which is a light source. The ultraviolet laser beam L transmitted through the output mirror **400** of the amplifier **160** is light after amplification and thus has a high energy density. Therefore, when the output of the light source is increased, deterioration of the dielectric multilayer film constituting the partial reflective film **420** may be accelerated. Therefore, there is a demand for a more durable output mirror that can withstand the demand for an increase in output.

[0085] In the following embodiments, a highly durable output mirror and a highly durable ultraviolet laser apparatus will be exemplified.

3. Description of Ultraviolet Laser Apparatus of First Embodiment

[0086] An output mirror **400** and an ultraviolet laser apparatus **100** of the present embodiment will be described. Note that the same components as those described above will be denoted by the same reference signs, and repeated description thereof will be omitted unless particularly explained.

3.1 Configuration

[0087] The ultraviolet laser apparatus **100** of the present embodiment is different from the ultraviolet laser apparatus **100** of the comparative example only in the configuration of the output mirror **400**. Therefore, description of the entire configuration of the ultraviolet laser apparatus **100** will be omitted.

[0088] FIG. **4** is a schematic diagram illustrating the output mirror **400** according to the present embodiment. In the present embodiment, a substrate **410** of the output mirror **400** is a sapphire substrate made of a sapphire crystal. Hereinafter, the substrate **410** will be described as a sapphire substrate **410**. At least a part of one main surface **411** of the sapphire substrate **410** is exposed. In other words, at least a part of the one main surface **411** is a non-coated surface on which a layer or the like made of a material different from that of the sapphire substrate **410** is not provided. The one main surface **411** is a partial reflective surface **401** that reflects a part of an ultraviolet laser beam L and transmits the other part of the ultraviolet laser beam L. Note that although an example in which the entire one main surface **411** is exposed is illustrated in the example of FIG. **4**, it is only necessary for a part of the one main surface **411** that is the partial reflective surface **401** to be exposed and the other part of the one main surface **411** may be coated.

[0089] An ultraviolet light transmittance of the sapphire crystals constituting the sapphire substrate **410** may not be sufficiently high as compared with CaF.sub.2 which is one of materials of the substrate **410** used in the output mirror **400** of the comparative example in the current situation. Therefore, although the thickness of the sapphire substrate **410** is preferably as thin as possible, it is also necessary to maintain strength and surface precision. From these viewpoints, the thickness of the sapphire substrate **410** is preferably equal to or greater than 1 mm and equal to or less than 7 mm, and is more preferably equal to or greater than 1 mm and equal to or less than 5 mm.

[0090] FIG. **5** is a graph illustrating a relationship between a substrate refractive index and a surface reflectance due to Fresnel reflection. The sapphire crystals have an ordinary refractive index of 1.929 and an extraordinary refractive index of 1.917 for ultraviolet light having a wavelength of 193 nm. As illustrated by a dotted line in FIG. **5**, it can be seen that the reflectance of Fresnel reflection on the one main surface **411** of the sapphire substrate **410** is approximately 10% for the ultraviolet light having a wavelength of 193 nm. Therefore, the reflectance of the partial reflective surface **401** in the configuration in which the one main surface **411** of the sapphire substrate **410** is exposed is approximately 10% for the ultraviolet light having a wavelength of 193 nm. Therefore, when the ultraviolet laser apparatus **100** is an ArF excimer laser apparatus, the reflectance of the partial reflective surface **401** of the output mirror **400** is approximately 10%.

[0091] In addition, the ordinary refractive index of the sapphire crystals for ultraviolet light having a wavelength of 248 nm is 1.8467. As illustrated by the one-dotted dashed line in FIG. **5**, the reflectance of Fresnel reflectance on the one main surface **411** of the sapphire substrate **410** for the ultraviolet light having a wavelength of 248 nm is approximately 98. Therefore, the reflectance of the partial reflective surface **401** in the configuration in which the one main surface **411** of the sapphire substrate **410** is exposed is approximately 9% for the ultraviolet light having a wavelength of 248 nm. Therefore, when the ultraviolet laser apparatus **100** is a KrF excimer laser apparatus, the reflectance of the partial reflective surface **401** of the output mirror **400** is approximately 9%.

[0092] A reflection suppressing structure **402** that suppresses reflection of the ultraviolet laser beam L is provided on the other main surface **412** of the sapphire substrate **410** opposing the one main surface **411**. In the present embodiment, the reflection suppressing structure **402** has a configuration that is similar to that of the reflection suppressing film **430** of the comparative example, and has a structure including a dielectric multilayer film.

[0093] The output mirror **400** is disposed such that the partial reflective surface **401** faces a side of a chamber device CH**2** and the reflection suppressing structure **402** faces a side of an exit window **173** such that the partial reflective surface **401** is perpendicular to the ultraviolet laser beam L exiting the chamber device CH**2**.

3.2 Operation

[0094] As described above, since the reflectance of the partial reflective surface **401**, which is the exposed one main surface **411** of the sapphire substrate **410**, is approximately 10% for the ultraviolet light having a wavelength of 193 nm, a part of the ultraviolet laser beam L that is incident on the output mirror **400** is reflected by the partial reflective surface **401** and the other part thereof is transmitted therethrough when the ultraviolet laser beam L exits the ultraviolet laser apparatus **100**. Then, an amplifier **160** amplifies and outputs the ultraviolet laser beam L similarly to the ultraviolet laser apparatus **100** of the comparative example.

3.3 Effect and Advantage

[0095] The output mirror **400** of the present embodiment includes the plate-shaped sapphire substrate **410**, and at least a part of the one main surface **411** of the sapphire substrate **410** is the partial reflective surface **401** that is exposed, reflects a part of the ultraviolet laser beam L, and transmits the other part of the ultraviolet laser beam L, and the other main surface **412** of the sapphire substrate **410** is provided with the reflection suppressing structure **402** that suppresses reflection of the ultraviolet laser beam L. In this manner, since the multilayer film is not formed on the partial reflective surface **401** in the output mirror **400** of the present embodiment, no deterioration of the multilayer film occurs, and high durability can be achieved with respect to the high-output ultraviolet laser beam L with a high energy density. In addition, the ultraviolet laser apparatus **100** including the output mirror **400** of the present embodiment can have high durability.

3.4 Description of First Modification

[0096] A first modification of the ultraviolet laser apparatus **100** of the first embodiment will be described. Note that the same components as those described above will be denoted by the same reference signs, and repeated description thereof will be omitted unless specifically explained.

[0097] As described above, since the output mirror **400** includes the sapphire substrate **410** and the sapphire crystal that is the material of the substrate **410** is a birefringent material, influences of birefringence can be reduced by appropriately selecting a crystal orientation and a direction of polarization of incident light.

[0098] FIG. **6** is a schematic diagram illustrating disposition of the output mirror **400** in the present modification. As illustrated in FIG. **6**, the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is oriented in a direction perpendicular to the plane of the paper in this modification. Therefore, the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is parallel to the partial reflective surface **401** that is the one main surface. Furthermore, in the present modification, the polarization direction of the ultraviolet laser beam L exiting the chamber device CH**2** of the amplifier **160** is oriented in an H direction. In other words, the output mirror **400** is disposed such that the polarization direction of the ultraviolet laser beam L that is incident on the output mirror **400** is parallel to the c axis of the sapphire crystal that is the material of the sapphire substrate **410**. Note that the optical axis of the ultraviolet laser beam L and the partial reflective surface **401** of the output mirror **400** are perpendicular to each other. This disposition of the output mirror **400** can reduce the influences of birefringence due to the sapphire substrate **410**.

3.5 Description of Second Modification

[0099] A second modification of the ultraviolet laser apparatus **100** of the first embodiment will be described. Note that the same components as those described above will be denoted by the same reference signs, and repeated description thereof will be omitted unless specifically explained.

[0100] FIG. **7** is a schematic diagram illustrating disposition of the output mirror **400** in the present modification. As illustrated in FIG. **7**, the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is oriented in a direction parallel to a V direction in the present modification. Therefore, the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is parallel to the partial reflective surface **401** that is the one main surface. In addition, the polarization direction of the ultraviolet laser beam L exiting the chamber device CH**2** of the amplifier **160** in the present modification is also similar to that in the first modification. In other words, the output mirror **400** is disposed such that the polarization direction of the ultraviolet laser beam L that is incident on the output mirror **400** is perpendicular to the c axis of the sapphire crystal that is the material of the sapphire substrate **410**. Note that the optical axis of the ultraviolet laser beam L and the partial reflective surface **401** of the output mirror **400** are perpendicular to each other. This disposition of the output mirror **400** can reduce the influences of birefringence due to the sapphire substrate **410**.

3.6 Description of Third Modification

[0101] A third modification of the ultraviolet laser apparatus **100** of the first embodiment will be described. Note that the same components as those described above will be denoted by the same reference signs, and repeated description thereof will be omitted unless specifically explained.

[0102] FIG. **8** is a schematic diagram illustrating disposition of the output mirror **400** in the present modification. As illustrated in FIG. **8**, the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is oriented in a direction parallel to a Z direction in the present modification. In other words, the output mirror **400** is disposed such that the optical axis of the ultraviolet laser beam L that is incident on the output mirror **400** is parallel to the c axis of the sapphire crystal that is the material of the sapphire substrate **410**. Therefore, the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is perpendicular to the partial reflective surface **401** that is the one main surface. Note that the optical axis of the ultraviolet laser beam L and the partial reflective surface **401** of the output mirror **400** are perpendicular to each other. This disposition of the output mirror **400** can reduce the influences of birefringence due to the sapphire substrate **410**.

3.7 Description of Fourth Modification

[0103] A fourth modification of the ultraviolet laser apparatus **100** of the first embodiment will be described. Note that the same components as those described above will be denoted by the same reference signs, and repeated description thereof will be omitted unless specifically explained.

[0104] FIG. **9** is a schematic diagram illustrating a positional relationship between the output mirror **400** and the window **31***a* of the chamber device CH**2** in the present modification. In the present modification, the window **31***a* that is provided in the chamber device CH**2** and from which the ultraviolet laser beam L exits is disposed to be inclined such that an angle θ formed between a normal line N of a main surface of the window **31***a* and the optical axis of the ultraviolet laser beam L forms a Brewster angle. An inclination axis S of the window **31***a* is a rotational axis when the main surface of the window **31***a* is inclined to form the Brewster angle as described above from a state perpendicular to the optical axis of the ultraviolet laser beam L, and is parallel to the V axis as illustrated in FIG. **9**. Therefore, the inclination axis S is perpendicular to the optical axis of the ultraviolet laser beam L that is incident on the output mirror **400**. Furthermore, as illustrated in FIG. **9**, the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is oriented in a direction parallel to the H direction in this modification. In other words, in the present modification, the output mirror **400** is arranged such that the c axis of the sapphire crystal that is the material of the sapphire substrate **410** is perpendicular to the inclination axis S of the window **31***a* provided in the chamber device CH**2** and a propagation direction of the ultraviolet laser beam L. This disposition of the output mirror **400** can reduce window reflected light of the ultraviolet laser beam L exiting the chamber device CH**2** and the influences of birefringence due to the sapphire substrate **410**.

4. Description of Ultraviolet Laser Apparatus of Second Embodiment

[0105] Next, an output mirror **400** of a second embodiment will be described. Note that the same components as those described above will be denoted by the same reference signs, and repeated description thereof will be omitted unless specifically explained.

4.1 Configuration

[0106] FIG. **10** is a schematic diagram illustrating the output mirror **400** in the present embodiment similarly to FIG. **4**. The output mirror **400** of the present embodiment is different from the output mirror **400** of the first embodiment in a moth eye structure in which the reflection suppressing structure **402** is provided on the other main surface **412** of the sapphire substrate **410**.

[0107] FIG. **11** is a schematic diagram illustrating the moth eye structure. The moth eye structure includes a large number of protrusion-shaped structures **415** aligned at regular intervals, and a pitch size P of the structures **415** is smaller than a wavelength of an ultraviolet laser beam L. In other words, when the wavelength of the ultraviolet laser beam L generated by the ultraviolet laser apparatus **100** of the present embodiment is 193 nm, the pitch size P of the structures **415** is smaller than 193 nm.

[0108] The protrusion-shaped structures **415** are, for example, conical. However, the shape of the structures **415** is not limited to a cone and may be a spindle shape or a pyramid. In addition, it is preferable that the height of the structures **415** be larger than the pitch size P. Note that methods of forming the moth eye structure on the other main surface **412** of the sapphire substrate **410** can include, for example, dry etching.

4.2 Effect and Advantage

[0109] In the present embodiment, the output mirror **400** can realize the incident surface and the exit surface of the ultraviolet laser beam L without using the dielectric multilayer film. Therefore, the output mirror **400** of the present embodiment can be more durable for the high-output ultraviolet laser beam L, and the ultraviolet laser apparatus **100** including the output mirror **400** of the present embodiment can be more durable.

[0110] Note that the application of the reflection suppressing function achieved by the moth eye structure is not limited to the output mirror **400**, and the reflection suppressing function may be used for other optical elements of the ultraviolet laser apparatus **100**.

5. Description of Ultraviolet Laser Apparatus of Third Embodiment

[0111] Next, an ultraviolet laser apparatus **100** of a third embodiment will be described. Note that the same components as those described above will be denoted by the same reference signs, and repeated description thereof will be omitted unless specifically explained.

5.1 Configuration

[0112] FIG. **12** is a schematic diagram illustrating a schematic configuration example of a part of an amplifier **160** included in the ultraviolet laser apparatus **100** of the present embodiment. In the ultraviolet laser apparatus **100** of the present embodiment, the amplifier **160** includes a ring-type resonator. Note that the ultraviolet laser apparatus **100** may be, for example, any of an ArF excimer laser apparatus and a KrF excimer laser apparatus.

[0113] In the present embodiment, the amplifier **160** amplifies energy of an ultraviolet laser beam L. The amplifier **160** of the present embodiment is different from the amplifier **160** of the first embodiment in that the amplifier **160** of the present embodiment includes high reflective mirrors **605**, **610**, and **615**.

[0114] In the present embodiment, the output mirror **400** is disposed at a position that is inclined by 45° with respect to the optical axis of the ultraviolet laser beam L exiting a chamber device CH**2** and faces the window **31***a* of the chamber device CH**2**. The high reflective mirror **605** is disposed to be aligned with the output mirror **400** at a position facing the window **31***a* of the chamber device CH**2** to form an angle of 90° with the output mirror **400**. The high reflective mirror **610** is disposed at a position facing the window **31***b* with an inclination of 45° with respect to the ultraviolet laser beam L exiting the chamber device CH**2** on the side opposite to the output mirror **400** with the chamber device CH**2** sandwiched therebetween. The high reflective mirror **615** is disposed to be aligned with the high reflective mirror **610** at a position facing the window **31***b* of the chamber device CH**2** to form an angle of 90° with the high reflective mirror **610**.

[0115] Note that the configuration of the output mirror **400** is similar to that of the output mirror **400** of the ultraviolet laser apparatus **100** in the first embodiment, the modifications of the first embodiment, or the second embodiment.

5.2 Operation

[0116] The ultraviolet laser beam L from a laser oscillator **130** is incident from a main surface **412** on which a reflection suppressing structure **402** is provided, and is transmitted through the output mirror **400**. The ultraviolet laser beam L transmitted through the output mirror **400** is reflected by the high reflective mirror **605** to pass between the electrode **32***a* and the electrode **32***b* from the window **31***a*. The ultraviolet laser beam L that has passed through the inside of the chamber device CH**2** and has been amplified exits the window **31***b*, is reflected by the high reflective mirror **610** and the high reflective mirror **615**, passes again between the electrode **32***a* and the electrode **32***b* of the chamber device CH**2** from the window **31***b* to be amplified, and then exits the window **31***a*. Thereafter, the ultraviolet laser beam L is incident on the output mirror **400**. Since the output mirror **400** is disposed to be inclined by 45° with respect to a traveling direction of the ultraviolet laser beam L exiting the chamber device CH**2**, the ultraviolet laser beam L is incident from the side of the partial reflective surface **401** of the output mirror **400** at an incident angle of 45°. A part of the ultraviolet laser beam L that has been incident on the output mirror **400** is reflected by the partial reflective surface **401** of the output mirror **400**, is incident on and reflected by the high reflective mirror **605**, is incident on the chamber device CH**2** again, and is then amplified. The other part of the ultraviolet laser beam L that has been incident on the output mirror **400** is transmitted through the output mirror **400** and exits the amplifier **160**.

5.3 Effect and Advantage

[0117] FIG. **13** is a graph illustrating a relationship between a Fresnel reflectance and an incident angle at a wavelength of 193 nm for each polarization direction. As illustrated in FIG. **13**, when the incident angle is 45°, the Fresnel reflectance is 18.8% with respect to S-polarized light, and the Fresnel reflectance is 3.6% with respect to P-polarized light. Therefore, the output mirror **400** is an output mirror having a reflectance of approximately 19% with respect to the S-polarized light. Similarly to the other embodiments, the output mirror **400** in the present embodiment is not provided with the partial reflective film including the dielectric multilayer film, and the ultraviolet laser apparatus **100** with a high output and high durability can thus be realized.

[0118] Note that the configuration of the amplifier **160** in the embodiments may be applied to a laser oscillator that is a first stage of an ultraviolet laser apparatus based on a multistage amplification system, or may be applied to a plurality of amplifiers. The configuration of the output

mirror **400** may be applied to an output mirror of a single laser oscillator.
[0119] 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. 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” 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 the any thereof and any other than A, B, and C.

Claims

1. An output mirror for an ultraviolet laser beam, the output mirror comprising: a plate-shaped sapphire substrate, at least a part of one main surface of the sapphire substrate being a partial reflective surface that is exposed, reflects a part of the ultraviolet laser beam, and transmits another part of the ultraviolet laser beam, the other main surface of the sapphire substrate being provided with a reflection suppressing structure configured to suppress reflection of the ultraviolet laser beam.
2. The output mirror according to claim 1, wherein the reflection suppressing structure includes a moth eye structure provided on the other main surface of the sapphire substrate.
3. The output mirror according to claim 1, wherein the reflection suppressing structure includes a structure including a dielectric multilayer film.
4. The output mirror according to claim 1, wherein the ultraviolet laser beam is an ArF laser beam or a KrF laser beam.
5. The output mirror according to claim 1, wherein a c axis of a sapphire crystal, which is a material of the sapphire substrate, is parallel to the one main surface.
6. The output mirror according to claim 1, wherein a material of the sapphire substrate is a sapphire crystal, a c axis of the sapphire crystal being perpendicular or parallel to a polarization direction of the ultraviolet laser beam.
7. The output mirror according to claim 1, wherein a material of the sapphire substrate is a sapphire crystal, a c axis of the sapphire crystal being perpendicular to the one main surface.
8. The output mirror according to claim 1, wherein a material of the sapphire substrate is a sapphire crystal, a c axis of the sapphire crystal being parallel to a traveling direction of the ultraviolet laser beam.
9. The output mirror according to claim 1, wherein a material of the sapphire substrate is a sapphire crystal, a c axis of the sapphire crystal being perpendicular to an inclination axis of a window and a traveling direction of the ultraviolet laser beam, the ultraviolet laser beam exiting from the window, the window being provided in a chamber device and being inclined around the inclination axis at a center with respect to an exit direction of the ultraviolet laser beam.
10. The output mirror according to claim 1, wherein the sapphire substrate has a thickness of equal to or greater than 1 mm and equal to or less than 7 mm.
11. The output mirror according to claim 1, wherein the sapphire substrate has a thickness of equal to or greater than 1 mm and equal to or less than 5 mm.
12. An ultraviolet laser apparatus comprising: an amplifier configured to amplify an ultraviolet laser beam, the amplifier including an output mirror for the ultraviolet laser beam, the output mirror including a plate-shaped sapphire substrate, at least a part of one main surface of the output mirror being a partial reflective surface from which the sapphire substrate is exposed, the partial reflective

surface reflecting a part of the ultraviolet laser beam and transmitting another part of the ultraviolet laser beam, the other main surface of the output mirror being provided with a reflection suppressing structure configured to suppress reflection of the ultraviolet laser beam.

13. The ultraviolet laser apparatus according to claim 12, wherein a material of the sapphire substrate is a sapphire crystal and the output mirror is disposed such that a c axis of the sapphire crystal is perpendicular or parallel to a polarization direction of the ultraviolet laser beam.

14. The ultraviolet laser apparatus according to claim 12, wherein a material of the sapphire substrate is a sapphire crystal and the output mirror is disposed such that a c axis of the sapphire crystal is parallel to a traveling direction of the ultraviolet laser beam.

15. The ultraviolet laser apparatus according to claim 12, wherein a material of the sapphire substrate is a sapphire crystal and the output mirror is disposed such that a c axis of the sapphire crystal is perpendicular to an inclination axis of a window and a traveling direction of the ultraviolet laser beam, the ultraviolet laser beam exiting from the window, the window being provided in a chamber device and being inclined around the inclination axis at a center with respect to an exit direction of the ultraviolet laser beam.

16. The ultraviolet laser apparatus according to claim 12, wherein the amplifier is a ring-type resonator.

17. The ultraviolet laser apparatus according to claim 16, wherein the output mirror of the amplifier is disposed to be inclined by 45° with respect to a traveling direction of the ultraviolet laser beam exiting a chamber device included in the amplifier, and the ultraviolet laser beam is incident on the other main surface of the output mirror.

18. An electronic device manufacturing method comprising: generating an ultraviolet laser beam with an ultraviolet laser apparatus including an output mirror for the ultraviolet laser beam, the output mirror including a plate-shaped sapphire substrate, at least a part of one main surface of the output mirror being a partial reflective surface from which the sapphire substrate is exposed, the partial reflective surface reflecting a part of the ultraviolet laser beam and transmitting another part of the ultraviolet laser beam, the other main surface of the output mirror being provided with a reflection suppressing structure configured to suppress reflection of the ultraviolet laser beam; outputting the ultraviolet laser beam to an exposure apparatus; and exposing a photosensitive substrate to the ultraviolet laser beam within the exposure apparatus to manufacture an electronic device.