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GAS LASER DEVICE AND ELECTRONIC DEVICE MANUFACTURING METHOD

Abstract

A gas laser device is for discharging and exciting a laser gas passing through a discharge space between first and second discharge electrodes and includes a plate supporting the first discharge electrode, a guide member arranged on the plate and guiding the laser gas to the discharge space, a dielectric pipe arranged between the guide member and the first discharge electrode, a first path including the guide member and causing a part of the laser gas to flow therein as a branched flow, a second path including the dielectric pipe and the plate and causing the branched flow flowing out from the first path to flow therethrough, and a third path including the dielectric pipe and the first discharge electrode and guiding the branched flow flowing out from the second path to upstream of the laser gas with respect to the discharge space.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS
[0001] The present application claims the benefit of Japanese Patent Application No. 2024-021951, filed on Feb. 16, 2024, the entire contents of which are hereby incorporated by reference.
BACKGROUND
1. Technical Field
[0002] The present disclosure relates to a gas laser device, and an electronic device manufacturing method.
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 device for exposure, a KrF excimer laser device for outputting laser light having a wavelength of about 248 nm and an ArF excimer laser device for outputting laser light having a wavelength of about 193 nm are used.
[0004] The KrF excimer laser device and the ArF excimer laser device each have a large spectral line width of about 350 to 400 μm in natural oscillation light. Therefore, when a projection lens is formed of a material that transmits ultraviolet rays such as KrF laser light and ArF laser light, there is a case in which chromatic aberration occurs. As a result, the resolution may decrease. Then, a spectral line width of laser light output from the gas laser device needs to be narrowed to the extent that the chromatic aberration can be ignored. For this purpose, there is a case in which a line narrowing module (LNM) including a line narrowing element (etalon, grating, and the like) is provided in a laser resonator of the gas laser device to narrow a spectral line width. In the following, a gas laser device with a narrowed spectral line width is referred to as a line narrowing gas laser device.
LIST OF DOCUMENTS
Patent Documents
[0005] Patent Document 1: Japanese Patent No. 2714357 [0006] Patent Document 2: U.S. Pat. No. 6,529,538
SUMMARY
[0007] A gas laser device, according to an aspect of the present disclosure, for discharging and exciting a laser gas passing through a discharge space between a first discharge electrode and a second discharge electrode includes a plate supporting the first discharge electrode; a guide member arranged on the plate and configured to guide the laser gas to the discharge space; a dielectric pipe arranged between the guide member and the first discharge electrode as being spaced apart from each of the plate and the first discharge electrode; a first path configured as including the guide member, and causing a part of the laser gas to flow therein as a branched flow; a second path configured as including the dielectric pipe and the plate, and causing the branched flow flowing out from the first path to flow therethrough; and a third path configured as including the dielectric pipe and the first discharge electrode, and guiding the branched flow flowing out from the second path to upstream of the laser gas with respect to the discharge space.
[0008] An electronic device manufacturing method according to an aspect of the present disclosure includes generating laser light using a gas laser device, outputting the laser light to an exposure apparatus, and exposing a photosensitive substrate to the laser light in the exposure apparatus to

manufacture an electronic device. Here, the gas laser device is a gas laser device for discharging and exciting a laser gas passing through a discharge space between a first discharge electrode and a second discharge electrode and includes a plate supporting the first discharge electrode; a guide member arranged on the plate and configured to guide the laser gas to the discharge space; a dielectric pipe arranged between the guide member and the first discharge electrode as being spaced apart from each of the plate and the first discharge electrode; a first path configured as including the guide member, and causing a part of the laser gas to flow therein as a branched flow; a second path configured as including the dielectric pipe and the plate, and causing the branched flow flowing out from the first path to flow therethrough; and a third path configured as including the dielectric pipe and the first discharge electrode, and guiding the branched flow flowing out from the second path to upstream of the laser gas with respect to the discharge space.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0009] Embodiments of the present disclosure will be described below merely as examples with reference to the accompanying drawings.
[0010] FIG. **1** is a side view schematically showing the configuration of a gas laser device according to a comparative example.
[0011] FIG. **2** is a sectional view schematically showing the configuration of the gas laser device according to the comparative example.
[0012] FIG. **3** is a sectional view showing in detail the configuration of the vicinity of a main electrode in a laser chamber.
[0013] FIG. **4** is a diagram showing an example of an ideal flow velocity distribution of a laser gas passing through a discharge space.
[0014] FIG. **5** is a timing chart showing operation of the gas laser device.
[0015] FIG. **6** is a view showing an example of a simulation result of a flow of the laser gas.
[0016] FIG. **7** is a diagram showing an example of the flow velocity distribution of the laser gas passing through a discharge space in a case in which missing occurs.
[0017] FIG. **8** is a sectional view showing in detail the configuration of the vicinity of the main electrode in the laser chamber according to a first embodiment.
[0018] FIG. **9** is an enlarged view of the vicinity of a dielectric pipe.
[0019] FIG. **10** is a plan view of a part including an anode electrode and the dielectric pipe viewed from the discharge space.
[0020] FIG. **11** is a view showing an example of a simulation result of the flow of the laser gas in the first embodiment.
[0021] FIG. **12** is a diagram showing an example of the flow velocity distribution of the laser gas passing through the discharge space in the first embodiment.
[0022] FIG. **13** is a timing chart showing operation of the gas laser device according to the first embodiment.
[0023] FIG. **14** is a view showing in detail the configuration of the vicinity of the main electrode in the laser chamber according to a second embodiment.
[0024] FIG. **15** is a plan view of the part including the anode electrode and the dielectric pipe viewed from the discharge space.
[0025] FIG. **16** is a view showing an example of a simulation result of the flow of the laser gas in the second embodiment.
[0026] FIG. **17** is a diagram schematically showing a configuration example of an exposure apparatus.
DESCRIPTION OF EMBODIMENTS

Contents

[0040] 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 the contents of the present disclosure. Also, all configurations and operation described in the embodiment are not necessarily essential as configurations and operation of the present disclosure. Here, the same components are denoted by the same reference numeral, and duplicate description thereof is omitted.

1. Comparative Example

[0041] First, a comparative example of the present disclosure will be described. 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.

1.1 Configuration

[0042] The configuration of a gas laser device **2** according to the comparative example will be described using FIGS. **1** and **2**. FIG. **1** schematically shows the configuration of the gas laser device **2**. FIG. **2** is a sectional view of the gas laser device **2** shown in FIG. **1** viewed from a Z direction. The gas laser device **2** is a discharge-excitation-type gas laser device that discharges and excites a laser gas, and is, for example, an excimer laser device.

[0043] In FIG. **1**, the travel direction of pulse laser light PL output from the gas laser device **2** is defined as the Z direction. A discharge direction to be described later is defined as a Y direction. A direction orthogonal to the Z direction and the Y direction is defined as an X direction. Here, the pulse laser light PL is an example of the “laser light” according to the technology of the present disclosure.

[0044] In FIG. **1**, the gas laser device **2** includes a laser chamber **10**, a charger **11**, a pulse power module (PPM) **12**, a pulse energy measurement unit **13**, a processor **14**, a pressure sensor **17**, and a laser resonator. The laser resonator is configured of a line narrowing module **15** and an output coupling mirror **16**.

[0045] The laser chamber **10** is, for example, a metal container made of aluminum metal plated with nickel on the surface thereof. As shown in FIGS. **1** and **2**, a main electrode **20**, a ground plate **21**, wirings **22**, a fan **23**, a heat exchanger **24**, an insulating guide **28**, a conductive guide **29**, and a preionization electrode **30** are provided in the laser chamber **10**. The preionization electrode **30** includes a preionization outer electrode **31**, a dielectric pipe **32**, and a preionization inner electrode **33**.

[0046] A laser gas containing fluorine as a laser medium is enclosed in the laser chamber **10**. The laser gas includes, for example, argon, krypton, xenon, or the like as a rare gas, neon, helium, or the like as a buffer gas, and fluorine, chlorine, or the like as a halogen gas.

[0047] Further, an opening is formed in the laser chamber **10**. An electrically insulating plate **26** in which a feedthrough **25** is embedded is attached to the laser chamber **10** via an O-ring (not shown) so as to close the opening. The PPM **12** is arranged on the electrically insulating plate **26**. The laser chamber **10** is grounded.

[0048] The PPM **12** includes a charging capacitor (not shown) and is connected to the main electrode **20** via the feedthrough **25**. The PPM **12** includes a switch SW for causing discharge to occur at the main electrode **20**. The charger **11** is connected to the charging capacitor of the PPM **12**. Hereinafter, the discharge occurring at the main electrode **20** is referred to as main discharge.

[0049] The main electrode **20** includes a cathode electrode **20***a* and an anode electrode **20***b*. The cathode electrode **20***a* and the anode electrode **20***b* are arranged in the laser chamber **10** so that discharge surfaces of the both face each other. The space between the discharge surface of the cathode electrode **20***a* and the discharge surface of the anode electrode **20***b* is referred to as a discharge space **27**. The cathode electrode **20***a* is supported by the electrically insulating plate **26** on a surface opposite to the discharge surface thereof, and is connected to the feedthrough **25**. The anode electrode **20***b* is supported by the ground plate **21** on a surface opposite to the discharge surface thereof. The anode electrode **20***b* is an example of the "first discharge electrode" according to the technology of the present disclosure. The cathode electrode **20***a* is an example of the "second discharge electrode" according to the technology of the present disclosure. The ground plate **21** is an example of the "plate" according to the technology of the present disclosure.

[0050] The ground plate **21** is connected to the laser chamber **10** via the wirings **22**. The laser chamber **10** is grounded. Therefore, the ground plate **21** is grounded via the wirings **22**. An end part of the ground plate **21** in the Z direction is fixed to the laser chamber **10**.

[0051] The fan **23** is a cross flow fan for circulating the laser gas in the laser chamber **10**, and is arranged on the opposite side of the discharge space **27** with respect to the ground plate **21**. A motor **23***a* for rotationally driving the fan **23** is connected to the laser chamber **10**.

[0052] The laser gas blown out from the fan **23** flows into the discharge space **27**. The flow direction of the laser gas flowing into the discharge space **27** is substantially parallel to the X direction. The laser gas flowing out **27** from the discharge space **27** can be sucked into the fan **23** via the heat exchanger **24**. The heat exchanger **24** changes the temperature of the laser gas by performing heat exchange between a refrigerant supplied to the inside of the heat exchanger **24** and the laser gas.

[0053] The insulating guide **28** is arranged on a surface of the electrically insulating plate **26** facing the discharge space **27** so as to sandwich the cathode electrode **20***a*. The insulating guide **28** is formed in a shape to guide the flow of the laser gas so that the laser gas from the fan **23** efficiently flows between the cathode electrode **20***a* and the anode electrode **20***b*. The insulating guide **28** and the electrically insulating plate **26** are made of, for example, ceramics such as alumina (Al.sub.2O.sub.3) having low reactivity with the fluorine gas.

[0054] The conductive guide **29** is arranged on a surface of the ground plate **21** facing the discharge space **27** so as to sandwich the anode electrode **20***b*. Similarly to the insulating guide **28**, the conductive guide **29** is formed in a shape to guide the flow of the laser gas so that the laser gas from the fan **23** efficiently flows between the cathode electrode **20***a* and the anode electrode **20***b*. The conductive guide **29** is made of, for example, a porous nickel metal having low reactivity with the fluorine gas.

[0055] A laser gas supply device **18***a* and a laser gas exhaust device **18***b* are connected to the laser chamber **10**. The laser gas supply device **18***a* includes a valve and a flow rate control valve, and is connected to a gas cylinder accommodating the laser gas. The laser gas exhaust device **18***b* includes a valve and an exhaust pump.

[0056] At an end part of the laser chamber **10**, each of the windows **10***a*, **10***b* for outputting light generated in the laser chamber **10** to the outside is provided. The laser chamber **10** is arranged such that the optical path of the optical resonator passes through the discharge space **27** and the windows **10***a*, **10***b*.

[0057] The line narrowing module **15** includes a prism **15***a* and a grating **15***b*. The prism **15***a* transmits the light output from the laser chamber **10** through the window **10***a* toward the grating **15***b* while expanding the beam width of the light.

[0058] The grating **15***b* is arranged in the Littrow arrangement in which the incident angle and the diffraction angle are the same. The grating **15***b* is a wavelength selection element that selectively extracts light having a wavelength near a particular wavelength in accordance with the diffraction angle. The spectral width of the light returning from the grating **15***b* to the laser chamber **10** via the prism **15***a* is line-narrowed.

[0059] The output coupling mirror **16** transmits a part of the light output from the laser chamber **10** through the window **10***b*, and reflects the other part back into the laser chamber **10**. The surface of the output coupling mirror **16** is coated with a partial reflection film.

[0060] Light output from the laser chamber **10** reciprocates between the line narrowing module **15** and the output coupling mirror **16**, and is amplified each time the light passes through the discharge space **27**. A part of the amplified light is output as the pulse laser light PL via the output coupling mirror **16**.

[0061] The pulse energy measurement unit **13** is arranged on the optical path of the pulse laser light PL output via the output coupling mirror **16**. The pulse energy measurement unit **13** includes a beam splitter **13***a*, a light concentrating optical system **13***b*, and an optical sensor **13***c*.

[0062] The beam splitter **13***a* transmits the pulse laser light PL with a high transmittance and reflects a part of the pulse laser light PL toward the light concentrating optical system **13***b*. The light concentrating optical system **13***b* concentrates the light reflected by the beam splitter **13***a* on a light receiving surface of the optical sensor **13***c*. The optical sensor **13***c* measures the pulse energy of the light concentrated on the light receiving surface, and outputs the measurement value to the processor **14**.

[0063] The pressure sensor **17** detects the gas pressure in the laser chamber **10**, and outputs the detection value to the processor **14**. The processor **14** determines the gas pressure of the laser gas in the laser chamber **10** based on the detection value of the gas pressure and the charge voltage of the charger **11**.

[0064] The charger **11** is a high voltage power source that supplies the charge voltage to the charging capacitor included in the PPM **12**. The switch SW of the PPM **12** is controlled by the processor **14**. When the switch SW is turned ON from OFF, the PPM **12** generates a high voltage pulse from the electric energy held in the charging capacitor and applies the high voltage pulse to the main electrode **20**.

[0065] The processor **14** is a processing device that transmits and receives various signals to and from an exposure apparatus controller **110** provided in an exposure apparatus **100**. For example, the exposure apparatus controller **110** transmits, to the processor **14**, a target pulse energy of the pulse laser light PL to be output to the exposure apparatus **100**, an oscillation trigger signal, and the like.

[0066] The processor **14** generally controls operation of each component of the gas laser device **2** based on various signals transmitted from the exposure apparatus controller **110**, the measurement value of the pulse energy, the detection value of the gas pressure, and the like.

[0067] The processor **14** functions as a controller of the gas laser device **2**. For example, the processor **14** is a processing device including a storage device in which a control program is stored and a central processing unit (CPU) that executes the control program. The processor **14** is specifically configured or programmed to perform various processes included in the present disclosure. The storage device is a non-transitory computer-readable storage medium, and includes, for example, a memory that is a main storage device and a storage that is an auxiliary storage device. Here, the storage device may be a semiconductor memory, a hard disk drive (HDD) device, a solid state drive (SSD) device, or a combination thereof.

[0068] FIG. **3** shows in detail the configuration of the vicinity of the main electrode **20** in the laser chamber **10**. In the following description, the upstream side refers to a side, with respect to the discharge space **27**, from which the laser gas flows into the discharge space **27**. The downstream side refers to a side, with respect to the discharge space **27**, to which the laser gas flows out from the discharge space **27**.

[0069] The preionization outer electrode **31** is arranged between the anode electrode **20***b* and the dielectric pipe **32**, and is held in contact with a side surface of a holding member **34** made of metal. The holding member **34** is fixed to an upstream side surface of the anode electrode **20***b*. The preionization inner electrode **33** is arranged in the dielectric pipe **32**, and the preionization outer electrode **31** is in contact with the outside of the dielectric pipe **32**.

[0070] The insulating guide **28** is arranged so as to cover the upstream and downstream side surfaces of the cathode electrode **20***a*. The surface of the insulating guide **28** is inclined so as to be

closer to the electrically insulating plate **26** as the distance from the cathode electrode **20***a* increases.
[0071] The conductive guide **29** includes a first guide member **29***a*, a second guide member **29***b*, and a third guide member **29***c*. The first guide member **29***a* and the third guide member **29***c* are arranged upstream of the anode electrode **20***b*. The second guide member **29***b* is arranged downstream of the anode electrode **20***b*. The first guide member **29***a* is an example of the "guide member" according to the technology of the present disclosure.
[0072] The first guide member **29***a* is arranged on the ground plate **21** so as to guide the laser gas to the discharge space **27**. The dielectric pipe **32** is arranged between the first guide member **29***a* and the anode electrode **20***b* so as to be spaced apart from each of the ground plate **21** and the anode electrode **20***b*. The second guide member **29***b* is arranged on the ground plate **21** downstream of the anode electrode **20***b* so as to cover the downstream side surface of the anode electrode **20***b*.
[0073] The third guide member **29***c* is arranged between the dielectric pipe **32** and the anode electrode **20***b* so as to cover the upstream side surface of the anode electrode **20***b* and to guide the laser gas to the discharge space **27**. The third guide member **29***c* is close to the dielectric pipe **32**.
[0074] The surface of the conductive guide **29** is inclined as a whole so as to be closer to the ground plate **21** as the distance from the anode electrode **20***b* increases.
[0075] Each of the upstream and downstream side surfaces of the cathode electrode **20***a* in the vicinity of the discharge surface thereof are not covered with the insulating guide **28**, and the cathode electrode **20***a* protrudes from the surface of the insulating guide **28** toward the anode electrode **20***b*. Thus, the discharge surface of the cathode electrode **20***a* is spaced apart from the surface of the insulating guide **28**.
[0076] Each of the upstream and downstream side surfaces of the anode electrode **20***b* in the vicinity of the discharge surface thereof are not covered with the conductive guide **29**, and the anode electrode **20***b* protrudes from the surface of the conductive guide **29** toward the cathode electrode **20***a*. Thus, the discharge surface of the anode electrode **20***b* is spaced apart from the surface of the conductive guide **29**.
1.2 Operation
[0077] Next, operation of the gas laser device **2** according to the comparative example will be described. First, the processor **14** controls the laser gas supply device **18***a* to supply the laser gas into the laser chamber **10**, and drives the motor **23***a* to rotate the fan **23**. As a result, as indicated by arrows in FIG. **2**, the laser gas filled in the laser chamber **10** circulates.
[0078] The processor **14** receives the target pulse energy and the oscillation trigger signal from the exposure apparatus controller **110**. Here, the oscillation trigger signal is a signal for instructing the gas laser device **2** to output one pulse of the pulse laser light PL.
[0079] The processor **14** sets the charge voltage corresponding to the target pulse energy in the charger **11**. The processor **14** operates the switch SW of the PPM **12** in synchronization with the oscillation trigger signal.
[0080] When the switch SW of the PPM **12** is turned ON from OFF, a voltage is applied to each between the preionization inner electrode **33** and the preionization outer electrode **31** of the preionization electrode **30** and between the cathode electrode **20***a* and the anode electrode **20***b*. As a result, corona discharge occurs at the preionization electrode **30**, and ultraviolet (UV) light is generated. When the laser gas in the discharge space **27** is irradiated with the UV light, the laser gas is preionized.
[0081] Thereafter, when the voltage between the cathode electrode **20***a* and the anode electrode **20***b* reaches a breakdown voltage, main discharge occurs in the discharge space **27**. When the discharge direction of the main discharge is defined as a direction in which electrons flow, the discharge direction is the direction from the cathode electrode **20***a* toward the anode electrode **20***b*. When the main discharge occurs, the laser gas in the discharge space **27** is excited to emit light.
[0082] The light emitted from the laser gas is reflected by the line narrowing module **15** and the

output coupling mirror **16** and reciprocates in the laser resonator, thereby performing laser oscillation. The light line-narrowed by the line narrowing module **15** is output from the output coupling mirror **16** as the pulse laser light PL.
[0083] A part of the pulse laser light PL output from the output coupling mirror **16** enters the pulse energy measurement unit **13**. The pulse energy measurement unit **13** measures the pulse energy of the entering pulse laser light PL, and outputs the measurement value to the processor **14**.
[0084] The processor **14** calculates a difference ΔE between the measurement value of the pulse energy and the target pulse energy. The processor **14** performs feedback control on the charge voltage based on the difference ΔE so that the measurement value of the pulse energy becomes the target pulse energy.
[0085] When the charge voltage is higher than a maximum value of an allowable range, the processor **14** controls the laser gas supply device **18***a* to supply the laser gas into the laser chamber **10** until a predetermined pressure is reached. Further, when the charge voltage is lower than a minimum value of the allowable range, the processor **14** controls the laser gas exhaust device **18***b* to exhaust the laser gas from the laser chamber **10** until a predetermined pressure is reached.
[0086] FIG. **4** shows an example of an ideal flow velocity distribution of the laser gas passing through the discharge space **27**. In FIG. **4**, P1 represents the position of the discharge surface of the cathode electrode **20***a* in the Y direction, and P2 represents the position of the discharge surface of the anode electrode **20***b* in the Y direction. Further, P3 represents the center position of the discharge space **27** in the Y direction. A solid line represents the flow velocity distribution of the laser gas, and a broken line represents an average flow velocity calculated from the flow velocity distribution of the laser gas. The same applies to FIGS. **7** and **12** described later.
[0087] A discharge product is generated in the discharge space **27** by the main discharge. Since the discharge product has conductivity, if the discharge product stays in the discharge space **27**, arc discharge caused by the discharge product may occur. However, the laser gas is rectified by the surface of the insulating guide **28** and the surface of the conductive guide **29**, and passes through the discharge space **27** ideally with a flow velocity distribution as shown in FIG. **4**. The discharge product generated in the discharge space **27** moves downstream and is removed by the laser gas, so that occurrence of the arc discharge caused by the discharge product is suppressed.
1.3 Problem
[0088] FIG. **5** is a timing chart showing an example of operation of the gas laser device **2**. When the exposure apparatus **100** exposes a semiconductor wafer, exposure is performed by a so-called "burst output" in which the pulse laser light PL is output from the gas laser device **2** at a predetermined repetition frequency. Here, for example, in a period in which the semiconductor wafer is moved, the semiconductor wafer is exchanged, a mask is exchanged, or the like in the exposure apparatus **100**, the exposure with the pulse laser light PL is paused. That is, in the exposure using the gas laser device **2**, a burst output period TB in which the burst output is performed and a burst pause period TR in which the burst output is paused are repeated.
[0089] When the above-described arc discharge occurs during the burst output period TB, the laser gas is not sufficiently excited during the arc discharge, so that a so-called "missing" in which the pulse laser light PL is not output occurs. In the gas laser device **2** according to the comparative example, when the discharge product in the discharge space **27** is removed by the flow of the laser gas as described above, it is considered that missing is suppressed. However, as shown in FIG. **5**, the applicant of the present invention has confirmed that there is a case in which missing during the burst output period TB occurs in the gas laser device **2** according to the comparative embodiment.
[0090] Therefore, the applicant performed a simulation on the flow of the laser gas to presume the cause of occurrence of missing. FIG. **6** shows an example of a simulation result of the flow of the laser gas. The flow of the laser gas includes a "main flow" that is a laminar flow that travels along the surfaces of the insulating guide **28** and the conductive guide **29** at high speed in the X direction without being separated at the discharge surfaces of the cathode electrode **20***a* and the anode

electrode **20**_b_. The laminar flow refers to a state in which a fluid flows regularly in a certain direction. In FIG. **6**, M1 to M5 represent a plurality of components included in the main flow. The same applies to FIGS. **11** and **16** described later.

[0091] In addition to the main flow, the flow of the laser gas includes "stagnation" occurring downstream of each of the cathode electrode **20**_a_ and the anode electrode **20**_b_. Stagnation includes a turbulent flow occurring by separation of the laser gas at the discharge surfaces of the cathode electrode **20**_a_ and the anode electrode **20**_b_, and the laser gas separated from the main flow by the turbulent flow. Further, stagnation includes the laser gas that travels along the surfaces of the insulating guide **28** and the conductive guide **29** at low speed in the X direction and stays between the main flow and the surfaces. The distribution of stagnation is presumed to be the cause of the occurrence of missing.

[0092] Stagnation stays while including a flow in a direction opposite to the direction of the main flow, and causes a part of the main flow after passing through the discharge space **27** to transition to stagnation. Therefore, it is presumed that stagnation is a factor that lowers the flow velocity by giving a flow path resistance to the main flow. Hereinafter, stagnation occurring in a cathode-side space between the surface of the insulating guide **28** and the main flow is referred to as "cathode-side stagnation." Further, stagnation occurring in an anode-side space between the surface of the conductive guide **29** and the main flow is referred to as "anode-side stagnation."

[0093] It is presumed that the laser gas having passed through the discharge space **27** flows in a state of being biased toward the second guide member **29**_b_ while receiving a force in the −Y direction by a suction action due to rotation of the fan **23**. Therefore, it is presumed that the cathode-side stagnation and the anode-side stagnation are asymmetric.

[0094] Specifically, the cathode-side stagnation occurring at the discharge surface of the cathode electrode **20**_a_ is successively fed into the cathode-side space. The cathode-side stagnation becomes enlarged while taking in a part of the main flow. As a result, the main flow component M1 travels while being decelerated by receiving a large flow path resistance from the cathode-side stagnation without re-adhering to the insulating guide **28**. Further, it is presumed that the deceleration of the main flow component M1 causes a chain deceleration of the main flow components M2 to M4. Re-adhering refers to a phenomenon in which a fluid flowing along a wall surface separates from the wall surface and then flows again along the wall surface as a laminar flow.

[0095] The anode-side stagnation occurring at the anode electrode **20**_b_ is successively fed into the anode-side space as well, but since the laser gas flows while receiving a force in the −Y direction, the occurring anode-side stagnation immediately re-adheres, so that enlargement is suppressed. Owing to that enlargement of the anode-side stagnation is suppressed, the main flow component M5 re-adheres to the conductive guide **29**, and the flow path resistance is reduced. As a result, since the flow velocity of the main flow component M5 increases, it is presumed that the main flow having passed through the discharge space **27** flows in a state of being biased toward the conductive guide **29** as a whole.

[0096] FIG. **7** shows an example of the flow velocity distribution of the laser gas passing through the discharge space **27** in the case in which missing occurs. When missing occurs, there occurs a decrease in the flow velocity in the vicinity of the position P1 of the discharge surface of the cathode electrode **20**_a_ and a decrease in the average flow velocity due to the decrease. It is presumed that, as a result, a removing rate of the discharge product decreases and the arc discharge occurs, thereby causing missing.

[0097] In order to increase the removing rate of the discharge product, it is conceivable to increase the number of revolutions of the fan **23** to increase the flow rate of the laser gas. However, when the number of revolutions of the fan **23** is increased, various problems arise such as an increase in power consumption, difficulty in controlling the fan **23**, unevenness in the flow velocity due to an increase in vibration of the fan **23**, and breakage of the fan **23**.

[0098] Although it is also conceivable to decrease the number of revolutions of the fan **23** to suppress enlargement of the cathode-side stagnation, the removing rate of the discharge product decreases when the number of revolutions of the fan **23** is decreased. Further, in this case, it is not possible to perform burst output operation at a high repetition frequency.

[0099] Therefore, an object of the present disclosure is to provide a gas laser device and an electronic device manufacturing method that enable burst output without missing.

2. First Embodiment

2.1 Configuration

[0100] The gas laser device **2** according to a first embodiment of the present disclosure has a configuration similar to that of the gas laser device **2** according to the comparative example except that the configuration in the laser chamber **10** is different.

[0101] FIG. **8** shows in detail the configuration of the vicinity of the main electrode **20** in the laser chamber **10** according to the first embodiment. The present embodiment differs from the comparative embodiment only in that the third guide member **29***c* shown in FIG. **6** is not provided. That is, in the present embodiment, the conductive guide **29** includes the first guide member **29***a* and the second guide member **29***b*. Accordingly, in the present embodiment, a branched flow path **40** through which a branched flow branched from the main flow of the laser gas flows is formed around the dielectric pipe **32**.

[0102] The branched flow path **40** includes a first path **41**, a second path **42**, and a third path **43**. The first path **41** is configured including the first guide member **29***a*, and a part of the laser gas of the main flow flows therein as the branched flow. The second path **42** is configured including the dielectric pipe **32** and the ground plate **21**, and the branched flow flowing out of the first path **41** flows therethrough. The third path **43** is configured including the dielectric pipe **32** and the anode electrode **20***b*, and guides the branched flow flowing out of the second path **42** to upstream of the discharge space **27**. In the present embodiment, the first path **41** is configured including the first guide member **29***a* and the dielectric pipe **32**.

[0103] Specifically, the first path **41** is a gap between the dielectric pipe **32** and the first guide member **29***a*. The second path **42** is a gap between the dielectric pipe **32** and the ground plate **21**. The third path **43** is a gap between the dielectric pipe **32** and the anode electrode **20***b*. Here, the holding member **34** and a part of the preionization outer electrode **31** are present in the third path **43**.

[0104] The first path **41** has, at an end thereof, an inlet port **41***a* into which a part of the laser gas of the main flow flows. The third path **43** has, at an end thereof, an outlet port **43***a* through which the branched flow flows out toward the main flow. The branched flow flowing in from the inlet port **41***a* flows through the branched flow path **40** in the order of the first path **41**, the second path **42**, and the third path **43**, flows out from the outlet port **43***a*, and merges into the main flow at upstream of the discharge space **27**.

[0105] FIG. **9** is an enlarged view of the vicinity of the dielectric pipe **32**. The front surface of the first guide member **29***a* is a plane parallel to the Z direction and non-parallel to the X direction and the Y direction. E1 is an imaginary plane obtained by extending the front surface of the first guide member **29***a* toward the discharge space **27**. E2 is an imaginary plane parallel to the imaginary plane E1 and in contact with the front surface of the dielectric pipe **32**. F is an outer diameter of the dielectric pipe **32**.

[0106] To cause a part of the laser gas of the main flow to flow into the branched flow path **40**, it is preferable that the dielectric pipe **32** partially protrudes from the imaginary plane E1 toward the main flow. A protrusion amount dtop of the dielectric pipe **32** is defined by the distance between the imaginary plane E1 and the imaginary plane E2. The protrusion amount dtop and the outer diameter F preferably satisfy the relationship of $0<\mathrm{dtop}\leq 0.5\,F$.

[0107] FIG. **10** is a plan view of a part including the anode electrode **20***b* and the dielectric pipe **32** viewed from the discharge space **27**. The discharge surface of the anode electrode **20***b* is a rectangular extending in the Z direction. The first guide member **29***a*, the second guide member

29*b*, the dielectric pipe **32**, and the preionization outer electrode **31** are arranged along the longitudinal direction of the discharge surface of the anode electrode **20***b*.

[0108] The dielectric pipe **32** extends in the Z direction, and both ends thereof are held by a pair of holding members **35**. The pair of holding members **35** are arranged on the ground plate **21**, and form both end faces of the branched flow path **40** in the Z direction. The inlet port **41***a* and the outlet port **43***a* are each rectangular extending in the Z direction.

[0109] The preionization outer electrode **31** includes a contact portion **31***a*, a fixed portion **31***b*, and a plurality of connection portions **31***c*. The contact portion **31***a* extends in the Z direction and is in contact with the dielectric pipe **32**. The fixed portion **31***b* extends in the Z direction and is held by the holding member **34**. Each of the connection portions **31***c* extends in the X direction and is connected between the contact portion **31***a* and the fixed portion **31***b*. The plurality of connection portions **31***c* are arranged at equal intervals in the Z direction. The preionization outer electrode **31** is ladder-shaped as a whole, and spaces between two adjacent connection portions **31***c* are present at the outlet port **43***a* respectively, and the branched flow of the laser gas passes through the spaces.

[0110] When the minimum width of the inlet port **41***a* in a direction perpendicular to the flowing direction of the branched flow is defined as din and the minimum width of the outlet port **43***a* in the direction perpendicular to the flowing direction of the branched flow is defined as dout, it is preferable that the relationship of dout≥din is satisfied. Further, when the distance between the discharge surface of the cathode electrode **20***a* and the discharge surface of the anode electrode **20***b* is defined as D, it is preferable that the relationship of 0.1D≤din≤0.5D is satisfied. In the present embodiment, the minimum width din is the length of the inlet port **41***a* in the X direction, and the minimum width dout is the length of the outlet port **43***a* in the X direction.

2.2 Operation

[0111] The operation of the gas laser device **2** according to the present embodiment is similar to that of the comparative example except that the effect caused by the formation of the branched flow path **40** is different.

[0112] FIG. **11** shows an example of a simulation result of the flow of the laser gas in the first embodiment. As shown in FIG. **11**, in the present embodiment, a part of the main flow component M5 is separated and flows into the branched flow path **40** from the inlet port **41***a*. The branched flow travels through the branched flow path **40** along the surface of the dielectric pipe **32** and reaches the outlet port **43***a*. Here, it is presumed that the principle of the branched flow occurring and traveling through the branched flow path **40** is due to the Coanda effect.

[0113] In the branched flow path **40**, stagnation having a flow component opposite to the travel direction of the branched flow occurs on the side surface of the first guide member **29***a*, the front surface of the ground plate **21**, the side surface of the holding member **34**, and the side surface of the anode electrode **20***b*. Hereinafter, stagnation occurring in the branched flow path **40** is referred to as branched flow stagnation.

[0114] The branched flow having reached the outlet port **43***a* passes through the ladder-shaped space of the preionization outer electrode **31** and flows out toward the insulating guide **28** located upstream, that is, toward the +Y direction. The branched flow having flown out merges with the main flow component M5 at a position upstream of the discharge space **27**. Thus, the branched flow has kinetic energy that can overcome the branched flow stagnation and merges with the main flow component M5.

[0115] The main flow component M5 after the branched flow merges enters the discharge space **27** in a state of being biased toward the cathode electrode **20***a* than in the comparative example shown in FIG. **6**. At this time, the main flow components M1 to M4 also enter the discharge space **27** in a state of being biased toward the cathode electrode **20***a* by being affected by the main flow component M5 in a chain reaction. Therefore, the main flow enters the discharge space **27** in a state of being biased toward the cathode electrode **20***a* as a whole as compared with the comparative example.

[0116] In summary, according to the present embodiment, first to fourth effects described below can be obtained.
[0117] As a first effect, the branched flow having kinetic energy that can change the position of the main flow occurs. Since the branched flow occurring by the Coanda effect travels through the branched flow path **40** along the surface of the dielectric pipe **32**, the branched flow flows out from the branched flow path **40** without losing much kinetic energy. This first effect occurs at all positions in the Z direction of the branched flow path **40**. As a result, the branched flow having little variation of kinetic energy in the Z direction flows out from the outlet port **43***a*.
[0118] As a second effect, the branched flow oriented toward the +Y direction flows out from the outlet port **43***a*. Since the dielectric pipe **32** is located upstream of the discharge space **27**, the branched flow occurring by the Coanda effect is separated from the dielectric pipe **32** and flows out from the outlet port **43***a* in the +Y direction. Further, since the dielectric pipe **32** extends in the Z direction, the branched flow flows out in the +Y direction from all positions in the Z direction at the outlet port **43***a*.
[0119] As a third effect, the entire main flow is displaced toward the cathode electrode **20***a*. Since the branched flow traveling in the +Y direction merges with the main flow entering the discharge space **27** in the +X direction, the entire main flow enters the discharge space **27** while being displaced toward the cathode electrode **20***a*.
[0120] As a fourth effect, the symmetry between the cathode-side stagnation and the anode-side stagnation is improved. Owing to that the entire main flow enters the discharge space **27** while being displaced toward the cathode electrode **20***a*, re-adhering of the main flow component M1 in the cathode-side space is promoted, and enlargement of the cathode-side stagnation is suppressed. On the other hand, re-adhering of the main flow component M5 is delayed in the anode-side space, so that the anode-side stagnation becomes enlarged. Thus, the symmetry between the cathode-side stagnation and the anode-side stagnation is improved.
[0121] FIG. **12** shows an example of the flow velocity distribution of the laser gas passing through the discharge space **27** in the first embodiment. FIG. **12** shows an ideal flow velocity distribution and average flow velocity thereof in addition to the flow velocity distribution and average flow velocity in the present embodiment. According to FIG. **12**, in the present embodiment, a decrease in the flow velocity appears in the vicinity of the discharge surface position P2 of the anode electrode **20***b*, but the flow velocity approaches an ideal value as it approaches the discharge surface position P1 of the cathode electrode **20***a*.

2.3 Effect

[0122] According to the present embodiment, since the symmetry between the cathode-side stagnation and the anode-side stagnation is improved and the flow velocity distribution of the laser gas passing through the discharge space **27** approaches the ideal flow velocity distribution, removing of the discharge product is improved. As a result, arc discharge is suppressed, and burst output without missing is possible as shown in FIG. **13**.

3. Second Embodiment

3.1 Configuration

[0123] The gas laser device **2** according to a second embodiment of the present disclosure has a configuration similar to that of the gas laser device **2** according to the first embodiment except that the configuration in the laser chamber **10** is different.
[0124] FIG. **14** shows in detail the configuration of the vicinity of the main electrode **20** in the laser chamber **10** according to the second embodiment. The present embodiment differs from the first embodiment only in the configuration of the conductive guide **29**. In the present embodiment, the first guide member **29***a* of the conductive guide **29** is arranged close to the dielectric pipe **32**. Further, the first guide member **29***a* is formed with a through hole **50** extending from the upstream end portion toward the anode electrode **20***b* along the X direction.
[0125] In the present embodiment, the first path **41** of the branched flow path **40** is configured by

the through hole **50**. The inlet port **41***a* into which the branched flow flows is an upstream opening of the through hole **50**. The second path **42** is a gap between the dielectric pipe **32** and the ground plate **21** as in the first embodiment. The third path **43** is a gap between the dielectric pipe **32** and the anode electrode **20***b* as in the first embodiment. Here, the holding member **34** and a part of the preionization outer electrode **31** are present in the third path **43**.

[0126] FIG. **15** is a plan view of a part including the anode electrode **20***b* and the dielectric pipe **32** viewed from the discharge space **27**. The through hole **50** extends in the Z direction. Further, in the present embodiment, the pair of holding members **35** extend from the dielectric pipe **32** to the first guide member **29***a*. Thus, the pair of holding members **35** form both end surfaces of the first path **41** in the Z direction.

[0127] In the present embodiment as well, it is preferable to satisfy the relationship of dout≥din and the relationship of 0.1D≤din≤0.5D. Here, in the present embodiment, since the branched flow flows into the inlet port **41***a* in the X direction, the minimum width din is the length thereof in the Y direction.

3.2 Operation

[0128] The operation of the gas laser device **2** according to the present embodiment is similar to that of the first embodiment except for the difference due to the different configuration of the branched flow path **40**.

[0129] FIG. **16** shows an example of a simulation result of the flow of the laser gas in the second embodiment. As shown in FIG. **16**, even in the case in which the through hole **50** is the first path **41**, the branched flow similar to that in the first embodiment occurs, so that a similar effect as in the first embodiment can be obtained.

3.3 Effect

[0130] According to the present embodiment, similarly to the first embodiment, since the symmetry between the cathode-side stagnation and the anode-side stagnation is improved and the flow velocity distribution of the laser gas passing through the discharge space **27** approaches the ideal flow velocity distribution as in the first embodiment, removing of the discharge product is improved. As a result, arc discharge is suppressed, and burst output without missing is possible.

4. Electronic Device Manufacturing Method

[0131] FIG. **17** schematically shows a configuration example of the exposure apparatus **100**. The exposure apparatus **100** includes an illumination optical system **104** and a projection optical system **106**. For example, the illumination optical system **104** illuminates a reticle pattern of a reticle (not shown) arranged on a reticle stage RT with the pulse laser light PL incident from the gas laser device **2**. The projection optical system **106** causes the pulse laser light PL transmitted through the reticle to be imaged as being reduced and projected on a workpiece (not shown) arranged on a workpiece table WT. The workpiece is a photosensitive substrate such as a semiconductor wafer on which photoresist is applied.

[0132] The exposure apparatus **100** synchronously translates the reticle stage RT and the workpiece table WT to expose the workpiece to the pulse laser light PL reflecting the reticle pattern. After the reticle pattern is transferred onto the semiconductor wafer by the exposure process described above, a semiconductor device can be manufactured through a plurality of processes. The semiconductor device is an example of the "electronic device" in the present disclosure.

[0133] Here, not limited to the manufacturing of an electronic device, the gas laser device **2** may be used for laser processing such as drilling.

[0134] 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.

[0135] The terms used throughout the present specification and the appended claims should be interpreted as non-limiting terms. 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 the any thereof and any other than A, B, and C.

Claims

1. A gas laser device for discharging and exciting a laser gas passing through a discharge space between a first discharge electrode and a second discharge electrode, comprising: a plate supporting the first discharge electrode; a guide member arranged on the plate and configured to guide the laser gas to the discharge space; a dielectric pipe arranged between the guide member and the first discharge electrode as being spaced apart from each of the plate and the first discharge electrode; a first path configured as including the guide member, and causing a part of the laser gas to flow therein as a branched flow; a second path configured as including the dielectric pipe and the plate, and causing the branched flow flowing out from the first path to flow therethrough; and a third path configured as including the dielectric pipe and the first discharge electrode, and guiding the branched flow flowing out from the second path to upstream of the laser gas with respect to the discharge space.
2. The gas laser device according to claim 1, wherein the guide member is arranged as being spaced apart from the dielectric pipe, and the first path is configured as including the guide member and the dielectric pipe.
3. The gas laser device according to claim 2, wherein the dielectric pipe partially protrudes from an imaginary surface obtained by extending a surface of the guide member toward the discharge space.
4. The gas laser device according to claim 3, a relationship of $0<dtop\leq 0.5F$ is satisfied, where dtop is a protrusion amount of the dielectric pipe and F is an outer diameter of the dielectric pipe.
5. The gas laser device according to claim 1, wherein a through hole is formed in the guide member, and the first path in configured by the through hole.
6. The gas laser device according to claim 1, wherein a relationship of $dout\geq din$ is satisfied, where din is a minimum width of an inlet port of the first path in a direction perpendicular to a flowing direction of the branched flow, and dout is a minimum width of an outlet port of the third path in a direction perpendicular to a flowing direction of the branched flow.
7. The gas laser device according to claim 6, wherein a relationship of $0.1D\leq din\leq 0.5D$ is satisfied, where D is a distance between a discharge surface of the first discharge electrode and a discharge surface of the second discharge electrode.
8. The gas laser device according to claim 1, wherein the first discharge electrode is an anode electrode, and the second discharge electrode is a cathode electrode.
9. The gas laser device according to claim 8, further comprising a ladder-shaped preionization outer electrode arranged between the first discharge electrode and the dielectric pipe.
10. The gas laser device according to claim 9, further comprising a preionization inner electrode arranged in the dielectric pipe.
11. The gas laser device according to claim 10, wherein the plate is a ground plate, and the guide member has conductivity.
12. The gas laser device according to claim 11, further comprising a conductive guide including the guide member as a first guide member, wherein the conductive guide includes a second guide member arranged downstream of the first discharge electrode on the plate to cover a side surface of the first discharge electrode.
13. The gas laser device according to claim 12, wherein the first discharge electrode protrudes from a surface of the conductive guide toward the second discharge electrode.

14. The gas laser device according to claim 13, further comprising an insulating guide arranged to cover upstream and downstream side surfaces of the second discharge electrode.
15. The gas laser device according to claim 14, wherein the second discharge electrode protrudes from a surface of the insulating guide toward the first discharge electrode.
16. An electronic device manufacturing method, comprising: generating laser light using a gas laser device; outputting the laser light to an exposure apparatus; and exposing a photosensitive substrate to the laser light in the exposure apparatus to manufacture an electronic device, the gas laser device being a gas laser device for discharging and exciting a laser gas passing through a discharge space between a first discharge electrode and a second discharge electrode and including: a plate supporting the first discharge electrode; a guide member arranged on the plate and configured to guide the laser gas to the discharge space; a dielectric pipe arranged between the guide member and the first discharge electrode as being spaced apart from each of the plate and the first discharge electrode; a first path configured as including the guide member, and causing a part of the laser gas to flow therein as a branched flow; a second path configured as including the dielectric pipe and the plate, and causing the branched flow flowing out from the first path to flow therethrough; and a third path configured as including the dielectric pipe and the first discharge electrode, and guiding the branched flow flowing out from the second path to upstream of the laser gas with respect to the discharge space.