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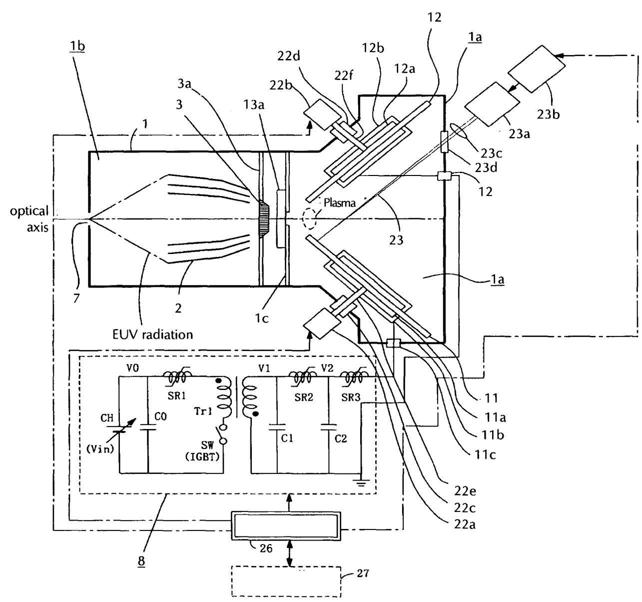
(54) **Extreme ultraviolet light source device**

(57) The invention relates to an extreme ultraviolet light source device, comprising a pair of discharge electrodes (11, 12) arranged oppositely to each other, a pulsed power supply means (8) supplying pulsed power to said discharge electrodes (11, 12), a raw material supply means (11b, 12b) supplying a liquid or solid raw material for the emission of extreme ultraviolet radiation to said discharge electrodes (11, 12) and onto these electrodes (11, 12), and an energy beam radiating means (23a) radiating a focused energy beam (23) towards said raw material (11a) having been supplied onto said discharge electrodes (11, 12) to gasify said raw material (11a) and to start a discharge between said pair of electrodes (11, 12).The surface of said raw material (11a) is arranged at a position shifted from the focal point (P) of the energy beam (23) towards the irradiation entrance side of the energy beam (23).

Fig. 2



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Description

[0001] The present invention relates to an extreme ultraviolet light source device generating extreme ultraviolet radiation from a plasma formed by means of a discharge, and in particular relates to an extreme ultraviolet light source device which gasifies a high temperature plasma raw material for the generation of extreme ultraviolet radiation by radiating an energy beam towards the material, which has been supplied to discharge electrodes, and generates extreme ultraviolet radiation from the plasma formed by means of a discharge from the raw material after the gasification.

[0002] With the downsizing and high integration of semiconductor integrated circuits, an improvement of the resolution is desired from lithography tools used for their manufacture. To comply with this desire, a shortening of the wavelength of the light source for the exposure is promoted, and for the light sources for the exposure of semiconductors of the next generation following excimer lasers, extreme ultraviolet light source devices (in the following also referred to as EUV light source devices) which emit extreme ultraviolet radiation (in the following also referred to as EUV (extreme ultraviolet) radiation) with a wavelength of 13 to 14 nm, and in particular a wavelength of 13.5 nm, are developed.

[0003] With regard to EUV light source devices, several methods for the generation of EUV radiation are known, and one of these is a method which generates a high temperature plasma by heating and exciting an EUV radiation species and extracts the EUV radiation emitted from this plasma. One kind of EUV light source device employing such a method is the DPP (discharge produced plasma) type EUV light source device. The DPP type light source device uses the EUV radiation from a high temperature plasma formed by a current drive. For the radiation species emitting EUV radiation with a strong irradiance with a wavelength of 13.5 nm, that is, the high temperature plasma raw material for the EUV generation in the EUV light source device, attention is turned to Li (lithium) ions and Sn (tin) ions.

[0004] The following is a simple explanation of the mechanism of the EUV radiation on the basis of the DPP method. With the DPP method, for example in the interior of a discharge container, in which electrodes are arranged, an atmosphere of a gaseous high temperature plasma raw material is provided, a discharge is generated between the electrodes in this atmosphere and an initial plasma is formed. The ion density in the initial plasma amounts to, for example, 10^{16} cm^{-3}, while the electron temperature is, for example, at most 1 eV.

[0005] By means of the effect of the self-magnetic field of the direct current flowing between the electrodes because of the discharge, the above mentioned initial plasma is condensed. Thereby, the density of the initial plasma becomes high and the plasma temperature increases abruptly. In the following, this effect is referred to as pinch effect. By means of the heating by the pinch effect, the ion density of the plasma having reached a high temperature reaches 10^{17} to 10^{20} cm^{-3}, while the electron temperature reaches approximately 20 to 30 eV. From this high temperature plasma, EUV radiation is emitted.

[0006] Regarding the DPP method, in recent years a method has been disclosed in JP-A-2007-505460 and corresponding US 2004/0183038 A1, wherein solid or liquid Sn or Li o r the like having been supplied to electrode surfaces generating a discharge is gasified by means of an irradiation with an energy beam such as a laser beam and then a high temperature plasma is generated by means of a discharge.

[0007] In the following, the case of the energy beam being a laser beam is explained. This mentioned method is referred to as LAGDPP (laser assisted gas discharge produced plasma).

[0008] In the following, the EUV light source device shown in JP-A-2007-505460 and corresponding US 2004/0183038 A1 is explained. FIG. 9 is a sectional view of an EUV light source device shown in this document.

[0009] Disc-shaped electrodes 114 and 116 are arranged in a discharge space 112 adjusted to a defined pressure. The electrodes are separated by a defined spacing and rotated with rotary shafts 146. A raw material 124 for a high temperature plasma emitting EUV radiation with a wavelength of 13.5 nm is provided. The high temperature plasma raw material 124 is a heated molten metal and is accommodated in containers 126. The temperature of the molten metal 124 is regulated by temperature regulation means 130 provided in the containers 126.

[0010] The electrodes 114, 116 are arranged such that a part is immersed into the container 126 accommodating the molten metal 124. The liquid molten metal 124, which got onto the surfaces of the electrodes 114, 116, is transported to the discharge space by means of the rotation of the electrodes 114, 116. A laser 120 from a laser source omitted in the drawing is radiated towards this molten metal 124 (that is, is radiated towards the molten metal 124 present on the surfaces of the electrodes 114, 116 separated by a defined spacing). The molten metal 124 irradiated by the laser 124 gasifies. When the molten metal 124 has been gasified by the irradiation with the laser 120, a pulse discharge is started in a region 112 by applying pulsed power to the electrodes 114, 116, and a plasma 122 is formed. When this plasma 122 is heated and excited by means of the large current flowing at the time of the discharge and the plasma reaches a high temperature, EUV radiation is emitted from this high temperature plasma. The EUV radiation is extracted at the upper side of the drawing.

[0011] That means, with the LAGDPP method stated in the above mentioned patent literature example a laser beam is radiated towards a solid or liquid target (high temperature plasma raw material), the raw material is gasified and a gaseous high temperature plasma raw material atmosphere (initial plasma) is formed. Similar to the DPP method, the ion density in this initial plasma amounts to, for example, 10^{16} cm^{-3}, while the electron temperature is, for example, at most 1 eV. Then, the ion density of the plasma having reached a high temperature by means of a discharge current-driven heating reaches 10^{17} to 10^{20} cm^{-3}, while the electron temperature reaches approximately 20 to 30 eV, and from this high temperature plasma, EUV radiation is emitted. That is, for the discharge current-driven heating in the LAGDPP method stated in JP-A-2007-505460 and corresponding US 2004/0183038 A1, the pinch effect is used as in the DPP method.

[0012] A capacitor bank 148 corresponding to a current source is connected electrically to the molten metal 124 accommodated in the containers 126 via insulating feed lines 150. As the molten metal is electrically conducting, electric energy is supplied from the capacitor bank 148 to the electrodes 114, 116 partly immersed into the molten metal 124 via the molten metal 124.

[0013] According to the present method, it becomes easy to gasify Sn or Li, which are solid at normal temperatures, in the vicinity of the discharge region generating the discharge. Thus, as it is possible to supply gasified Sn or Li effectively to the discharge region, it becomes possible to effectively extract EUV radiation with a wavelength of 13.5 nm after the discharge.

[0014] The rotation of the electrodes in the EUV light source device stated in JP-A-2007-505460 and corresponding US 2004/0183038 A1 has the following benefits. It is possible to always supply fresh solid or liquid high temperature plasma raw material being the high temperature plasma raw material seeding the EUV generation to the discharge region. As the positions irradiated by the laser and the positions generating high temperature plasma (the positions of the discharge parts) on the electrode surfaces continuously change, the thermal load on the electrodes decreases and wear can be prevented.

[0015] But the configuration of the device shown in JP-A-2007-505460 and corresponding US 2004/0183038 A1 has the following problems. In the above stated EUV light source device, as mentioned above the raw material on the electrode surfaces is gasified, a discharge is started between the electrodes, and a plasma is formed. But to implement an effective formation of EUV radiation, the density of the gas of the gasified plasma raw material (for example tin) supplied to the discharge region has to be high to a certain degree. This is because, as mentioned before, the ion density of the high temperature plasma emitting EUV radiation is 10^{17} to 10^{20} cm^{-3}, and approximately 10^{16} cm^{-3} are necessary for the ion density of the initial plasma before the pinching of this high temperature plasma. That is, although a discharge is started, no EUV radiation with a wavelength of 13.5 nm is generated from the plasma formed by the discharge if the gas density of the plasma raw material supplied to the discharge region is lower than 10^{16} cm^{-3}.

[0016] In the EUV light source device of JP-A-2007-505460 and corresponding US 2004/0183038 A1, the gas of the plasma raw material is supplied between both electrodes (to the discharge space) by radiating a laser beam towards the liquid or solid raw material applied onto the electrode surfaces. But the raw material gasified by means of the laser irradiation expands three-dimensionally in the space between both electrodes. Therefore, it is difficult to control the density of the gas of the plasma raw material supplied to the discharge region, and the gas density at the time the expanded raw material gas reaches the opposing electrodes and the discharge is started becomes low and is not always suitable for EUV radiation.

[0017] The present invention was made with regard to the above circumstances. The object of the present invention is to provide an EUV light source device being able to render the density of the high temperature plasma raw material at the time of the discharge between the electrodes as high as possible.

[0018] The present inventors have found out, as a result of eager researches, that if the surface of the target is arranged at a position shifted from the focal point of the energy beam (laser beam) towards the irradiation entrance side of the energy beam, that is, the surface of the raw material is arranged at a position shifted from the focal point of the energy beam towards the irradiation entrance side of the energy beam, it is possible to generate an initial plasma with a low free expansion. Thereby, the density of the high temperature plasma raw material (gas) at the time the discharge is generated between the electrodes can be maintained in a high state.

[0019] Based on the above statements, the present invention solves the above mentioned problems as follows. In an extreme ultraviolet light source device comprising a pair of discharge electrodes arranged oppositely to each other, a pulsed power supply means supplying pulsed power to said discharge electrodes, a raw material supply means supplying a liquid or solid raw material for the emission of extreme ultraviolet radiation to said discharge electrodes and onto these electrodes, and an energy beam radiating means radiating a focused energy beam towards said raw material having been supplied onto said discharge electrodes to gasify said raw material and to start a discharge between said pair of electrodes, the surface of said raw material is arranged at a position shifted from the focal point of the energy beam towards the irradiation entrance side of the energy beam.

[0020] By means of arranging the focal point of the energy beam to gasify the raw material for the emission of extreme ultraviolet radiation more to the rear than the surface of the raw material, that is, arranging the surface of the raw material at a position shifted from the focal point of the energy beam towards the irradiation entrance side of the energy beam in the present invention, the plasma generated by the energy beam can be rendered such that the free expansion is lower than previously. Therefore, the density of the gas of the plasma raw material in the discharge region can be maintained in a high state, that is, in a state suitable for the generation of extreme ultraviolet radiation.

[0021] The invention will be further explained with reference to the enclosed drawings. In the drawings, which schematically explain preferred embodiments of the invention, like parts are denoted with like reference numbers. In the drawings:

FIG. 1 is a front view showing the configuration of an extreme ultraviolet radiation (EUV) light source device of an embodiment of the present invention.

FIG. 2 is a top view showing the configuration of the extreme ultraviolet radiation (EUV) light source device of Fig. 1.

FIG. 3 is a view showing an enlarged view of the part of the electrodes in FIG. 2 at which the laser beam is focused.

FIG. 4 is a flow chart showing the operation of the embodiment of the present invention.

FIG. 5 is a timing chart to explain the operation of the embodiment of the present invention.

FIG. 6 is a diagram explaining the state of the plasma generated between the electrodes.

FIG. 7 is a diagram to explain an experimental example of the present invention.

FIG. 8 is a diagram showing the state of the plasma being the result of the experiment.

FIG. 9 is a sectional view of a conventional EUV light source device.

[0022] In FIG. 1 and Fig. 2, the configuration (a sectional view) of an extreme ultraviolet radiation (EUV) light source device of an embodiment of the present invention is shown. FIG. 1 is a front view of the EUV light source device of the present embodiment, and the EUV radiation is extracted from the left side in this drawing. FIG. 2 is a top view of the EUV light source device of the present embodiment.

[0023] The EUV light source device shown in FIG. 1 and FIG. 2 has a chamber 1 being a discharge container. The chamber 1 is separated by a separating wall 1 c generally into two spaces. In one space the discharge part is arranged. The discharge part is the heating and exciting means heating and exciting the high temperature plasma raw material which contains the EUV radiation species. The discharge part is made up from a pair of electrodes 11, 12 etc.

[0024] In the other space, an EUV collecting mirror 2 collecting the EUV radiation emitted from the high temperature plasma formed by heating and exciting the high temperature plasma raw material and leading it from an EUV extraction part 7 provided in the chamber 1 to an irradiation optics system of a lithography tool not shown in the drawing, and a debris trap to suppress the movement of debris formed as a result of the plasma forming by the discharge to the EUV radiation collecting part are arranged. As shown in FIG 1. and FIG. 2, in the present embodiment the debris trap is made up from a gas curtain 13b and a foil trap 3.

[0025] In the following, the space in which the discharge part is arranged will be called the discharge space 1a, while the space in which the EUV collecting mirror 2 is arranged will be called the collecting space 1 b. A vacuum pumping device 4 is coupled with the discharge space 1a, while a vacuum pumping device 5 is coupled with the collecting space 1 b. The foil trap 3 is supported, for example, by means of a separating wall 3a for the foil trap support in the collecting space 1b of the chamber 1. That is, in the example shown in FIG. 1 and FIG. 2, the collecting space 1b is divided by the separating wall 3a for the foil trap support into two spaces.

[0026] In FIG. 1 and FIG. 2 the discharge part is shown lager than the EUV collecting part to facilitate the understanding, but the actual dimensional relationship is not as shown in FIG. 1 and FIG. 2. Actually, the EUV collecting part is larger than the discharge part. That means the collecting space 1b is larger than the discharge space 1 a.

Configuration of each part of the EUV light source device of the present embodiment

[0027] In the following, each part of the EUV light source device of the present embodiment is explained in detail.

Discharge part

[0028] The discharge part comprises a first discharge electrode 11 being a disc-shaped element made from metal and a second discharge electrode 12 also being a disc-shaped element made from metal. The first and second discharge electrodes 11, 12 consist of, for example, a metal with a high melting point such as tungsten, molybdenum or tantalum and are arranged such that they oppose each other with a defined spacing. One of the two discharge electrodes 11, 12 is the ground-side electrode, while the other is the high-voltage-side electrode.

[0029] The surfaces of both discharge electrodes 11, 12 may be arranged in the same plane, but to facilitate the power generation, these surfaces are preferably arranged, as shown in FIG. 2, such that the edge portions of the peripheral parts, at which the electric field is concentrated at the time of the energy application, oppose each other with the defined spacing. That is, the electrodes are preferably arranged such that the imaginary planes containing the electrode surfaces intersect. The defined spacing mentioned above is the spacing with the shortest separation between the edge portions of the peripheral parts of both electrodes.

[0030] When pulsed power is applied to both electrodes 11, 12 from a pulsed power supply means (pulsed power generator 8), a discharge is started at the edge portions of said peripheral parts. Generally, the major part of the discharge is generated in the region with the shortest separation between the edge portions of the peripheral parts of both electrodes 11, 12. In the following the space between both electrodes, in which the discharge is generated, will be referred to as the discharge region.

[0031] If the edge portions of the peripheral parts of both electrodes 11, 12 are arranged such that they are separated by a defined spacing as stated above, both electrodes 11, 12 are arranged radially, when seen from above as shown in FIG. 2, with the intersection of the imaginary planes containing the surfaces of the first and second discharge electrodes 11, 12 as the center. In FIG. 2, the region with the largest spacing between the edge portions of the peripheral parts of the radially arranged electrodes 11, 12 is established such that it is positioned at a side opposite to the EUV collecting mirror 2 described later with the intersection of the above mentioned imaginary planes as the center.

[0032] The EUV light source device of the present embodiment employs a high temperature plasma gasified by irradiation with a laser beam as the raw material and utilizes the EUV radiation from the high temperature plasma formed by current drive by an electrical discharge. The means to heat and excite the high temperature plasma raw material is the large current from the discharge generated between the pair of electrodes 11, 12. Thus, the electrodes 11, 12 are subjected to a large thermal load in connection with the discharge. And as the high temperature plasma is generated in the vicinity of the discharge electrodes, the discharge electrodes 11, 12 are also subjected to a thermal load from this plasma. By means of these thermal loads, the electrodes are gradually worn and metal debris is generated.

[0033] When the EUV light source device is used as the light source device of an exposure device, the EUV radiation emitted from the high temperature plasma is collected by the EUV collecting mirror 2 and this collected EUV radiation is emitted to the exposure device. The metal debris damages the EUV collecting mirror 2 and deteriorates the EUV radiation reflection rate of the EUV collecting mirror 2.

[0034] Because of the gradual wear of the electrodes 11, 12 the electrode shape changes. Therefore, the discharge generated between the pair of electrodes 11, 12 becomes gradually unstable, and as a result, also the generation of EUV radiation becomes unstable. If the EUV light source device is used as the light source of a mass production type semiconductor exposure device, it is necessary to suppress the above mentioned wear of the electrodes and to extend the durability of the electrodes as long as possible.

[0035] To comply with this necessity, the EUV light source device shown in FIGs. 1 and 2 is configured such that the first electrode 11 and the second electrode 12 are disc-shaped and these electrodes are rotated at least at the time of the discharge. That is, by rotating the first and second electrodes 11, 12, the position of the electrodes, at which the pulse discharge occurs, changes with every pulse. Therefore, the thermal load suffered by the first and second electrodes 11, 12 becomes low, the speed of wear of the electrodes 11, 12 is reduced, and a long durability of the electrodes becomes possible. In the following, the first electrode 11 will be referred to as the first rotary electrode, and the second electrode 12 will be referred to as the second rotary electrode.

[0036] Concretely, a rotary shaft 22e of a first motor 22a and a rotary shaft 22f of a second motor 22b are mounted at the center part of the disc-shaped first rotary electrode 11 and second rotary electrode 12 respectively. The first motor 22a and the second motor 22b rotate the first rotary electrode 11 and the second rotary electrode 12 by rotating these rotary shafts 22e, 22f. There is no particular limitation with regard to the direction of the rotation. The rotary shafts 22e, 22f are, for example, inserted into the chamber 1 via mechanical seals 22c, 22d. The mechanical seals 22c, 22d permit the rotation of the rotary shafts while maintaining the reduced-pressure atmosphere in the chamber 1.

[0037] As shown in FIG. 1, the first rotary electrode 11 and the second rotary electrode 12 are arranged such that a part is immersed into the molten tin 11 a, 12a in the first container 11b and in the second container 12b. This tin 11 a, 12a is the raw material for the high temperature plasma emitting EUV radiation with a wavelength of 13.5 nm and also acts as a current supply metal supplying energy to the first rotary electrode 11 and the second rotary electrode 12.

[0038] The first container 11b and the second container 12b are connected to a pulsed power generator 8 being the pulsed power supply means via insulating power lead-in parts 11c, 12c, which are able to maintain the reduced-pressure atmosphere in the chamber 1. The first and second containers 11 b, 12b and the tin 11 a, 12a are electrically conductive, and as a part of the first rotary electrode 11 and a part of the second rotary electrode 12 are immersed into said tin 11 a, 12a, pulsed power is applied between the first rotary electrode 11 and the second rotary electrode 12 by applying the pulsed power from the pulsed power generator 8 between the first container 11b and the second container 12b.

[0039] A temperature regulating means, the illustration of which is omitted in the drawings, is provided at the first container 11b and at the second container 12b to keep the tin in a molten state.

Raw material supply means

[0040] The first container 11b and the second container 12b are the raw material supply means supplying tin 11 a, 12a being the high temperature plasma raw material to the surfaces of the first rotary electrode 11 and the second rotary electrode 12. As stated above, the first rotary electrode 11 and the second rotary electrode 12 are arranged such that a part (peripheral part) is immersed into the liquid tin accommodated in the above mentioned containers. In the containers 11 b, 12b, the tin 11 a, 12a adheres to the surfaces of the peripheral parts of the electrodes. The tin 11 a, 12a adhered to the electrodes is transported to the discharge region by means of the rotation of the electrodes. The tin 11a transported to the discharge region is irradiated with the laser beam, and by the gasification of the tin 11a a discharge is started.

[0041] By this discharge, the tin 11 a, 12a adhered to the electrode surfaces is consumed, but by means of the immersion into the tin 11 a, 12a in the first container 11b and in the second container 12b because of the rotation, tin 11a, 12a is supplied to the electrode surfaces. In the present embodiment, containers, in which tin as stated above is accommodated, are used as the raw material supply means, but it is also possible to use supply means dripping or pouring molten tin into grooves or holes formed in the electrode surfaces.

Energy beam irradiation means for the gasification of the raw material

[0042] The energy beam irradiation means is provided with a laser source 23a emitting a laser beam 23 and a laser control part 23b controlling the operation of the laser source 23a.

[0043] For the laser source 23a emitting the laser beam 23, for example a CO_2 laser source, a solid-state laser source such as a YAG-laser, a YVO_4-laser or a YLF-laser etc., or an excimer laser source such as an ArF-laser, a KrF laser or a XeCl-laser etc. can be employed.

[0044] In the present embodiment, a laser beam is used for the energy beam irradiating a defined spot of the discharge region, but instead of a laser beam, an ion beam or an electron beam can be used to irradiate the high temperature plasma raw material.

[0045] In FIG. 3, an example for the focusing of the laser beam is shown. This figure is an enlarged view of the electrode part focusing the laser beam of FIG. 2. As shown in this figure, the laser beam 23 from the laser source 21a is radiated towards the high temperature plasma raw material (tin) 11a on the first rotary electrode 11. For the focusing optical system 23c, for example a convex lens is used.

[0046] As shown in this figure, in the present invention the focal point P of the laser beam 23 is arranged more to the rear than the surface of the raw material 11a. In other words, the surface of the raw material is arranged such that it is at a position shifted from the focal point P of laser beam 23 towards the irradiation entrance side.

[0047] By means of radiating the laser beam 23 towards the high temperature plasma raw material (tin) 11a on the rotary electrode 11, the high temperature plasma raw material (tin) 11a is gasified. The gasified tin then reaches the oppositely arranged second rotary discharge electrode 12 and a discharge is started.

[0048] The high temperature raw material gasified by the irradiation with the laser beam 23 expands with the direction being perpendicular to the surface of the high temperature plasma raw material 11a irradiated with the laser beam 23 as the center. Therefore, it is necessary that the laser beam 23 radiates towards that side of the high temperature raw material 11a facing the discharge region in order that the high temperature plasma raw material after the gasification expands in the direction of the opposing electrode.

[0049] A part of the high temperature plasma raw material after the gasification by means of the irradiation with the laser beam 23, which has not contributed to the forming of the high temperature plasma by means of the discharge, or a part of the cluster of the gas in atomic form formed by decomposition as a result of the plasma forming contacts the low temperature part in the EUV light source device and deposits there. Therefore, it is preferred that the laser beam 23 is radiated to the high temperature plasma raw material (tin) 11a such that the high temperature plasma raw material after the gasification does not expand in the direction of the EUV collecting mirror 2. Pulsed power generator

[0050] The pulsed power generator 8 being the pulsed power supply means applies pulsed power with a short pulse width via a magnetic pulse compression circuit consisting of a capacitor and a magnetic switch between the first container 11b and the second container 12b being the load, that is, between the first rotary electrode 11 and the second rotary electrode 12.

[0051] FIG. 1 and FIG. 2 show an example for the configuration of the pulsed power generator. The pulsed power generator 8 of FIG. 1 and FIG. 2 has a two-stage magnetic pulse compression circuit, for which two magnetic switches SR2, SR3 consisting of a saturable inductor are used. The two-stage magnetic pulse compression circuit is made up by means of a capacitor C1, the first magnetic switch SR2, a capacitor C2 and the second magnetic switch SR3. The magnetic switch SR1 is an element for reducing the switching loss at a solid-state switch SW being a semiconductor switching element such as an IGBT, and is also referred to as magnetic assist. The solid-state switch SW is the above mentioned switching means and is referred to in the following as switching means.

[0052] In the following, the configuration and the operation of the circuit are explained with reference to FIG. 1 and FIG. 2. First, the charging voltage of a charger CH is set to a defined value Vin and the main capacitor C0 is charged by the charger CH. At this time, the solid-state switch SW such as an IGBT is off. When the charging of the main capacitor C0 is finished and the solid-state switch SW has become on, the voltage present at both ends of the solid-state switch SW is mainly present at both ends of the magnetic switch SR1. By the time the time integral value of the charge voltage V0 of the main capacitor C0 present at both ends of the magnetic switch SR1 reaches the limiting value specified by the characteristics of the magnetic switch SR1, the magnetic switch SR1 is saturated, the magnetic switch switches on and a current flows in a loop consisting of the main capacitor C0, the magnetic switch SR1, the primary side of a step-up transformer Tr1 and the solid-state switch SW. At the same time, a current flows in a loop consisting of the secondary side of the step-up transformer Tr1 and the capacitor C1 and the electric charge stored in the main capacitor C0 transits and is charged into the capacitor C1.

[0053] Subsequently, by the time the time integral value of the voltage V1 in the capacitor C1 reaches the limiting value specified by the characteristics of the magnetic switch SR2, the magnetic switch SR2 is saturated, the magnetic switch switches on, a current flows in a loop consisting of the capacitor C1, the magnetic switch SR2 and the capacitor C2 and the electric charge stored in the capacitor C1 transits and is charged into the capacitor C2. Then, by the time the time integral value of the voltage V2 in the capacitor C2 reaches the limiting value specified by the characteristics of the magnetic switch SR3, the magnetic switch SR3 is saturated, the magnetic switch switches on and a high voltage pulse is applied between the first container 11b and the second container 12, that is, between the first rotary electrode 11 and the second rotary electrode 12.

[0054] By means of setting the inductance of the capacity transition circuit of each stage consisting of the magnetic switch SR2, SR3 and the capacitor C1, C2 such that it becomes lower while transiting to the posterior stage, a pulse compressing operation is performed such that the pulse width of the current pulse flowing in each stage becomes sequentially narrower and a strong discharge with a short pulse can be effected between the first rotary electrode 11 and the second rotary electrode 12. Also the input power to the plasma becomes large.

EUV radiation collecting part

[0055] The EUV radiation emitted by the discharge part is collected by a grazing-incidence type EUV collecting mirror 2 provided in the EUV radiation collecting part and is led from an EUV radiation extraction part 7 provided in the chamber 1 to an irradiation optics system of an exposure device not shown in the drawings.

[0056] This grazing-incidence EUV collecting mirror 2 is, in general, configured such that a plurality of thin concave mirrors is arranged in a nested state with high density. The shape of the reflecting surface of each concave mirror is, for example, the shape of an ellipsoid of revolution, the shape of a paraboloid of revolution or the shape of a Wolter type mirror; each concave mirror has the shape of a body of revolution. A Wolter type shape is a concave shape in which the light incidence surface consists of, sequentially from the light incidence side, a hyperboloid of revolution surface and an ellipsoid of revolution surface or a hyperboloid of revolution surface and a paraboloid of revolution surface.

[0057] The basic material of each above mentioned concave mirror is, for example, nickel (Ni) or the like. As EUV radiation with an extremely short wavelength is reflected, the reflecting surface of the concave mirror is configured as an extremely smooth surface. The reflecting material is a metal film such as, for example, ruthenium (Ru), molybdenum (Mo) or rhodium (Rh). It is coated onto the reflecting surface of each concave mirror. By means of this configuration, the EUV collecting mirror is able to excellently reflect and collect EUV radiation with a grazing incidence angle of 0 ° to 25 °.

Debris trap

[0058] Between the discharge part and the EUV radiation collecting part mentioned above, a debris trap catching debris such as metal powder generated by a high-temperature-plasma-caused sputtering of the peripheral parts of the first and second rotary electrodes 11, 12 contacting the high temperature plasma after the discharge by the high temperature plasma or debris caused by Sn or Li etc. being the EUV radiation species in the high temperature plasma raw material is arranged to prevent damage of the EUV collecting mirror 2.

[0059] As mentioned above, the debris trap in the EUV light source device of the present embodiment shown in FIG. 1 and FIG. 2 comprises the gas curtain 13b and the foil trap 3. The gas curtain 13b consists of a gas supplied from a gas supply unit 13 via a nozzle 13a into the chamber 1. In FIG. 1, the configuration of the gas curtain is shown. The nozzle 13a has a rectangular shape, and the opening from which the gas is ejected has the shape of an elongated rectangle. When gas is supplied from the gas supply unit 13 to the nozzle 13a, sheet-shaped gas is ejected from the opening of the nozzle 13a and a gas curtain 13b is formed. The gas curtain 13b alters the direction of movement of the debris and prevents the arrival of debris at the EUV collecting mirror 2. Regarding the gas used for the gas curtain 13b, gas with a high transmittance for EUV radiation is desired, and for example a rare gas such as helium (He) or argon (Ar) or the like or hydrogen (H_2) is used.

[0060] Then, between the gas curtain 13a and the EUV collecting mirror 2 the foil trap 3 is provided. In order to not block the EUV radiation emitted from the high temperature plasma, the foil trap 3 is composed of a plurality of plates arranged radially in the high temperature plasma forming region and an annular support supporting these plates. When such a foil trap 3 is arranged between the gas curtain 13a and the EUV collecting mirror 2, the pressure between the high density high temperature plasma and the foil trap 3 increases. When the pressure increases, the gas density of the gas curtain being present there increases and the number of collisions between the gas atoms and the debris increases. As the debris repeats the collisions, the motion energy decreases. Therefore, the energy at the time of a collision of the debris with the EUV collecting mirror 2 is reduced, because of which it is possible to reduce damages of the EUV collecting mirror 2.

[0061] It is also possible to connect a gas supply unit 14 with the collecting space 1b side of the chamber 1 and to introduce a buffer gas unrelated to the emission of the EUV radiation. The buffer gas supplied from the gas supply unit 14 passes through the foil trap 3 from the EUV collecting mirror 2 side, passes through the space between the separating wall 3a for the foil trap support and the separating wall 1c and is discharged from the vacuum pumping device 4. By the generation of such a gas flow, it is possible to prevent that debris which could not be caught at the foil trap 3 flows to the EUV collecting mirror 2 side and to reduce damages of the EUV collecting mirror 2 by the debris.

[0062] It is also possible to supply a halogen gas such as chlorine (Cl_2) or hydrogen radicals in addition to the buffer gas from the gas supply unit 14 into the collecting space. These gases act as a cleaning gas which reacts with the debris having not been removed by the debris trap and being deposited on the EUV collecting mirror 2 and removes this debris. Thus, it is possible to suppress the decrease of the functionality corresponding to a decrease of the reflection rate of the EUV collecting mirror 2 because of debris deposition.

Separating wall

[0063] The pressure of the discharge space 1a is set such that the discharge for heating and exciting the high temperature plasma raw material gasified by the laser beam irradiation is generated favorably, and it is necessary to maintain this pressure at a vacuum atmosphere below a certain degree. Regarding the collecting space on the other hand, it is necessary to maintain a defined pressure at the debris trap part because it is necessary to reduce the motion energy of debris by the debris trap.

[0064] In FIG. 1 and FIG. 2, a certain gas is flowed from the gas curtain 13b, a certain pressure is maintained at the foil trap 3 and the motion energy of debris is reduced. In order to do this, the collecting space 1b must, as a result, be maintained at a reduced pressure atmosphere with a pressure of some 100 Pa. In the EUV light source device of the present invention a separating wall 1 c dividing the interior of the chamber 1 into a discharge space 1a and a collecting space 1b is provided. In this separating wall 1 c, an opening connecting both spaces spatially is provided. As the opening acts as a pressure resistance, it is possible to maintain the discharge space 1a at some Pa and the collecting space 1b at a suitable pressure, when the discharge space 1a is evacuated by the vacuum pumping device 4 and the collecting space 1b is evacuated by the vacuum pumping device 5, by taking into account the gas flow from the gas curtain 13b, the size of the opening and the evacuation performances of the vacuum pumping devices 4, 5.

Operation of the extreme ultraviolet radiation (EUV) light source device of the present embodiment

[0065] When the EUV light source device of the present embodiment is used as a light source for exposure, it operates e.g. as follows. FIG. 4 is a flow chart showing the operation of the present embodiment, and FIG. 5 is a timing chart to explain the method of the EUV generation. In the following, the operation of the present embodiment is explained by FIG. 4 and FIG. 5.

[0066] The controller 26 of the EUV light source device stores the time data Δt shown in FIG. 5. Here, Δt is the period from the time (moment Td) a trigger signal is inputted into the switch SW (for example an IGBT) being the switching means of the pulsed power supply means (pulsed power generator 8) until the switch SW reaches the on state and the voltage of the capacitor C2 reaches a threshold value Vp. The threshold value Vp is a voltage value in the case that the value of the discharge current flowing at the time of the generation of the discharge becomes higher than a threshold value Ip. Then, the threshold value Ip is the lower limit of the discharge current necessary for the production of a high temperature plasma emitting EUV radiation with the desired intensity. In general, the rise of the voltage wave form between the discharge electrodes is quick when the voltage V applied to the discharge electrodes 11, 12 is large. Thus, the above mentioned Δt depends on the voltage V applied to the discharge electrodes 11, 12. The controller 26 of the EUV light source device stores the relations between the voltage V and the period Δt determined in experiments conducted beforehand as a table.

[0067] First, a standby instruction is sent from the controller 26 of the EUV light source device to the vacuum pumping device 5, the vacuum pumping device 4, the gas supply unit 13, the gas supply unit 14, the first motor 22a and the second motor 22b (S101 in FIG. 4). The vacuum pumping device 5, the vacuum pumping device 4 and the gas supply unit 13 and the gas supply unit 14, having received the standby instruction, start their operations. That is, the vacuum pumping device 4 is operated and the interior of the discharge space becomes a vacuum atmosphere. Together with the operation of the vacuum pumping device 5 the gas supply unit 13 is operated and the gas curtain 13b is formed and the gas supply unit 14 is operated and the buffer gas and the cleaning gas are supplied into the collecting space 1 b. As a result, the collecting space 1b reaches a defined pressure. The first motor 22a and the second motor 22b are operated and the first rotary electrode 11 and the second rotary electrode 12 rotate. In the following, the above mentioned operating states will be referred to collectively as the standby state (S102 in FIG. 4.).

[0068] The controller 26 of the EUV light source device sends a standby completion signal to the controller 27 of the exposure device (S103 in FIG. 4). The controller 26 of the EUV light source device receives a radiation emission instruction from the controller 27 of the exposure device, which has received the standby completion signal. When the intensity of the EUV radiation is controlled at the exposure device, this radiation emission instruction contains also intensity data for the EUV radiation (S104 in FIG. 4).

[0069] The controller 26 of the EUV light source device sends a charge control signal to the charger CH of the pulsed power generator 8. The charge control signal consists, for example, of a charge start timing data signal. If, as mentioned above, intensity data for the EUV radiation are contained in the radiation emission instruction from the controller 27 of the exposure device, also a data signal regarding the charge voltage for the main capacitor C0 is contained in said charge control signal. For example the relations between intensities of the EUV radiation and the charge voltages for the main capacitor C0 are determined beforehand by experiments and a table storing the correlations between both is prepared. The controller 26 of the EUV light source device stores this table and retrieves the data regarding the charge voltage for the main capacitor C0 from the table on the basis of the intensity data for the EUV radiation contained in the radiation emission instruction sent from the controller 27 of the exposure device. On the basis of the retrieved charge voltage data, the controller 26 of the EUV light source device then sends a charge control signal containing data regarding the charge voltage for the main capacitor C0 to the charger CH of the pulsed power generator 8 (S105 in FIG. 4). The charger CH performs the charging of the capacitor C0 as mentioned above (S106 in FIG. 4).

[0070] The controller 26 of the EUV light source device calculates the timing for outputting the main trigger signal to the switch SW (IGBT) of the pulsed power generator 8 and the timing for outputting the trigger signal to the laser controller 23b controlling the operation of the laser source 23a on the basis of the beforehand stored time Δtd (S107 in FIG. 4). It is also possible to employ the moment Td at which the main trigger signal is inputted into the switching means of the pulsed power supply means (pulsed power generator 8) and the switch SW (IGBT) is switched on on as a basis and to set the time T1 at which the laser is radiated beforehand in the controller 26. The controller 26 outputs the main trigger signal to the switch SW (IGBT) at the moment Td and the switch SW is switched on (S108 in FIG. 4, S201 in FIG. 5). When the switch SW is switched on, the voltage between the first rotary electrode 11 and the second rotary electrode 12 rises, and after the period Δt the voltage of the capacitor C2 reaches the threshold value Vp (S202 in FIG. 5). As mentioned above, the threshold value Vp is a voltage value in the case that the value of the discharge current flowing at the time of the generation of the discharge becomes higher than a threshold value Ip, and the threshold value Ip is the lower limit of the discharge current necessary for the production of a high temperature plasma emitting EUV radiation with the desired intensity. At the moment T1 at/after the moment the voltage of the capacitor C2 has reached the threshold value Vp ($T1 \geq Td + \Delta td$) a trigger signal is sent to the laser controller 23b and the laser beam 23 irradiates the high temperature plasma raw material on the surface of the first electrode 11 (S109 in FIG. 4, S203 in FIG. 5).

[0071] The laser beam 23 is radiated to the high temperature plasma raw material on the discharge electrodes 11, 12 and the high temperature plasma raw material is gasified. As the focal point of the laser beam 23 is arranged more to the rear than the surface of the high temperature plasma raw material (the surface of the high temperature plasma raw material is arranged at a position shifted from the focal point of the laser beam 23 towards the irradiation entrance side) as mentioned above, the gasified high temperature plasma raw material reaches the opposing second electrode in a state in which a free expansion with the direction perpendicular to the high temperature plasma raw material surface irradiated by the laser beam 23 as the center is suppressed, and at this time T3 the discharge between the pair of electrodes is started and a discharge current flows (S110 in FIG. 4, S204 in FIG. 5).

[0072] The discharge is generated between the edge portions of the peripheral parts of the first rotary electrode 11 and the second rotary electrode 12, and a plasma is formed. When the plasma is heated and excited by the pulsed large current flowing in the plasma and reaches a high temperature state, an EUV radiation with a wavelength of 13.5 nm is emitted from this high temperature plasma. Because of the magnetic pressure of the discharge, the raw material gasified by the laser irradiation is condensed without expanding and a plasma with a small diameter and a high density is formed. Thus, EUV radiation with a high conversion efficiency is emitted (S111 in FIG. 4, S205 in FIG. 5).

[0073] Following the end of the first EUV emission, the operation returns to step S104 in FIG. 4 and waits for the radiation emission instruction from the exposure device.

[0074] FIG. 6 is a diagram explaining the state of the plasma generated between the electrodes. In this figure, the surfaces of a pair of vertically opposing discharge electrodes are shown and it is illustrated how the state of the plasma between the electrodes changes over time. FIG. 6(a) pertains to the state of the art case in which the focal point of the laser beam is at the surface of the raw material, while FIG. 6(b) pertains to the present invention in which the focal point of the laser beam is arranged more to the rear than the surface of the raw material (the surface of the raw material is arranged more to the irradiation entrance side than the focal point of the laser beam).

[0075] Regarding FIG. 6(a) pertaining to the state of the art, when a laser beam irradiation of the high temperature plasma raw material (tin) on the electrode is performed the raw material gas formed by the laser beam irradiation reaches the opposing electrode while expanding three-dimensionally, a bridge is formed between the electrodes and the discharge starts when the current starts to flow. The raw material gas is condensed by the magnetic force together with the increase of the discharge current and a pinch plasma is formed. EUV radiation is emitted from this pinch plasma. But as the raw material gas also expands in the lateral direction while advancing to the opposing electrode until the start of the discharge, it is largely expanded at the starting point of the discharge and the gas density has become low. Therefore the pinch effect is bad and the achieved ion density and electron temperature do not reach values at which an EUV emission with a high conversion efficiency is obtained.

[0076] When, by contrast, in FIG. 6(b) a laser beam is radiated towards the high temperature plasma raw material (tin) of the electrode, the generated raw material gas does not expand in the lateral direction but expands in an elongated state towards the opposing electrode. When the raw material gas has reached the opposing electrode, a bridge is formed between the electrodes, the current has started to flow and the discharge has been started, the three-dimensional expansion of the raw material gas is low and thus the gas density is high. When the raw material gas is condensed and heated by the magnetic force together with the increase of the discharge current, the pinch efficiency becomes high and the achieved ion density and the electron temperature reach values at which an EUV emission with a high conversion efficiency is obtained.

[0077] FIG. 7 is a diagram to explain an experimental example of the present invention. As shown in FIG. 7, in the experiment a laser beam with a wavelength (λ) of 532 nm (double waves of a YAG laser beam of 1.06 μm), a pulsed power of 60 mJ, a pulse width of 10 ns and a diameter (D) of 10 mm radiated from a laser source 30 was focused to 100 μm by a lens 31 with a focal length (f) of 600 mm. Then, the surface of a tin (Sn) plate 33 with a thickness (t) of 3 mm was arranged as shown in FIG. 7(a), (b) and (c) at, before and after, respectively, the focal point of the laser beam and the shape of the generated plasma was recorded with a CCD camera.

[0078] FIG. 8(a) shows the shape of the plasma for the case of an arrangement of the surface of the tin plate 33 at a position 7 mm before the focal point of the laser beam, FIG. 8(b) shows that for the case of an arrangement at the focal point, and FIG. 8(c) shows that for the case of an arrangement at a position 7 mm behind the focal point. The laser beam was radiated from the upper side in each drawing and is shown with dotted lines. The hatched portions in the figures are regions in which the density of the generated plasma is high. In the case (a) of the arrangement of the surface of the tin plate 7 mm before the focal point the plasma generated by the irradiation with the laser beam converges towards the direction from which the laser beam is radiated (the upper side in the drawing), and the region with a high plasma density has an elongated extension.

[0079] When the radiation of an energy beam (a laser beam) towards the high temperature plasma raw material on one electrode of the pair of electrodes is supposed, a bridge is formed between the electrodes when the gasified high temperature plasma raw material reaches the other electrode and a discharge is started. When the region with a high plasma density has an elongated extension such as in FIG. 8(a), the region with a high plasma density can reach the opposing electrode in the state of a suppressed self expansion. Therefore, the discharge is started in a state in which the gas of the high temperature plasma raw material has maintained a high density. Therefore the pinch efficiency at the time the raw material gas is condensed and heated by the magnetic force together with the increase of the discharge current after the start of the discharge increases and the achieved ion density and electron temperature reach values at which an EUV emission with a high conversion efficiency is obtained and it is possible to obtain intense EUV radiation.

[0080] In the cases of (b), in which the surface of the tin plate is arranged at the focal point, and (c), in which it is arranged behind the focal point, on the contrary, the region with a high plasma density has a round shape, which shows that the region with a high plasma density expands freely. Therefore, the plasma density is low at the time the gasified raw material reaches the opposing electrode, and even if this plasma is condensed, an ion density and electron temperature suitable to obtain EUV radiation with a high conversion efficiency are not achieved.

Claims

1. An extreme ultraviolet light source device, comprising

- a pair of discharge electrodes (11, 12) arranged oppositely to each other,
- a pulsed power supply means (8) supplying pulsed power to said discharge electrodes (11, 12),
- a raw material supply means (11 b, 12b) supplying a liquid or solid raw material for the emission of extreme ultraviolet radiation to said discharge electrodes (11, 12) and onto these electrodes (11, 12), and
- an energy beam radiating means (23a) radiating a focused energy beam (23) towards said raw material (11 a) having been supplied onto said discharge electrodes (11, 12) to gasify said raw material (11 a) and to start a discharge between said pair of electrodes (11, 12),

characterized in that the surface of said raw material (11a) is arranged at a position shifted from the focal point (P) of the energy beam (23) towards the irradiation entrance side of the energy beam (23).

2. An extreme ultraviolet light source device as claimed in claim 1, wherein the energy beam radiating means

(23a) is a laser.

3. An extreme ultraviolet light source device as claimed in claim 2, wherein the laser (23a) is a CO_2 laser, an excimer laser, a YAG laser, a YVO_4 laser or a YLF laser.

Fig. 1

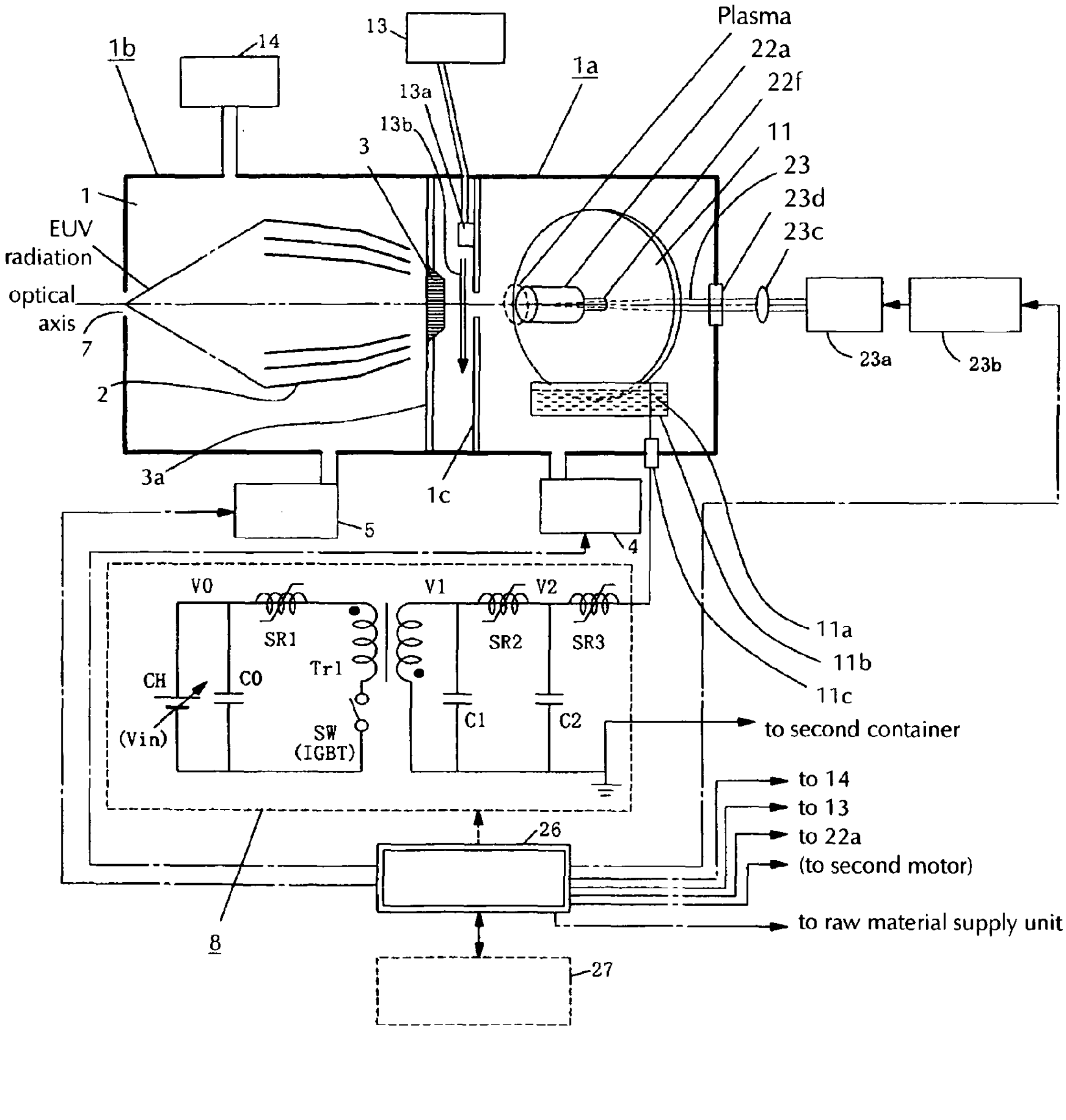

1b
14
13
13a
13b
3
1a
Plasma
22a
22f
11
23
23d
23c
1
EUV
radiation
optical
axis
7
2
3a
1c
5
4
23a
23b
V0
SR1
Tr1
CH
C0
(Vin)
SW
(IGBT)
V1
V2
SR2
SR3
C1
C2
11a
11b
11c
to second container
to 14
to 13
to 22a
(to second motor)
to raw material supply unit
26
8
27

Fig. 2

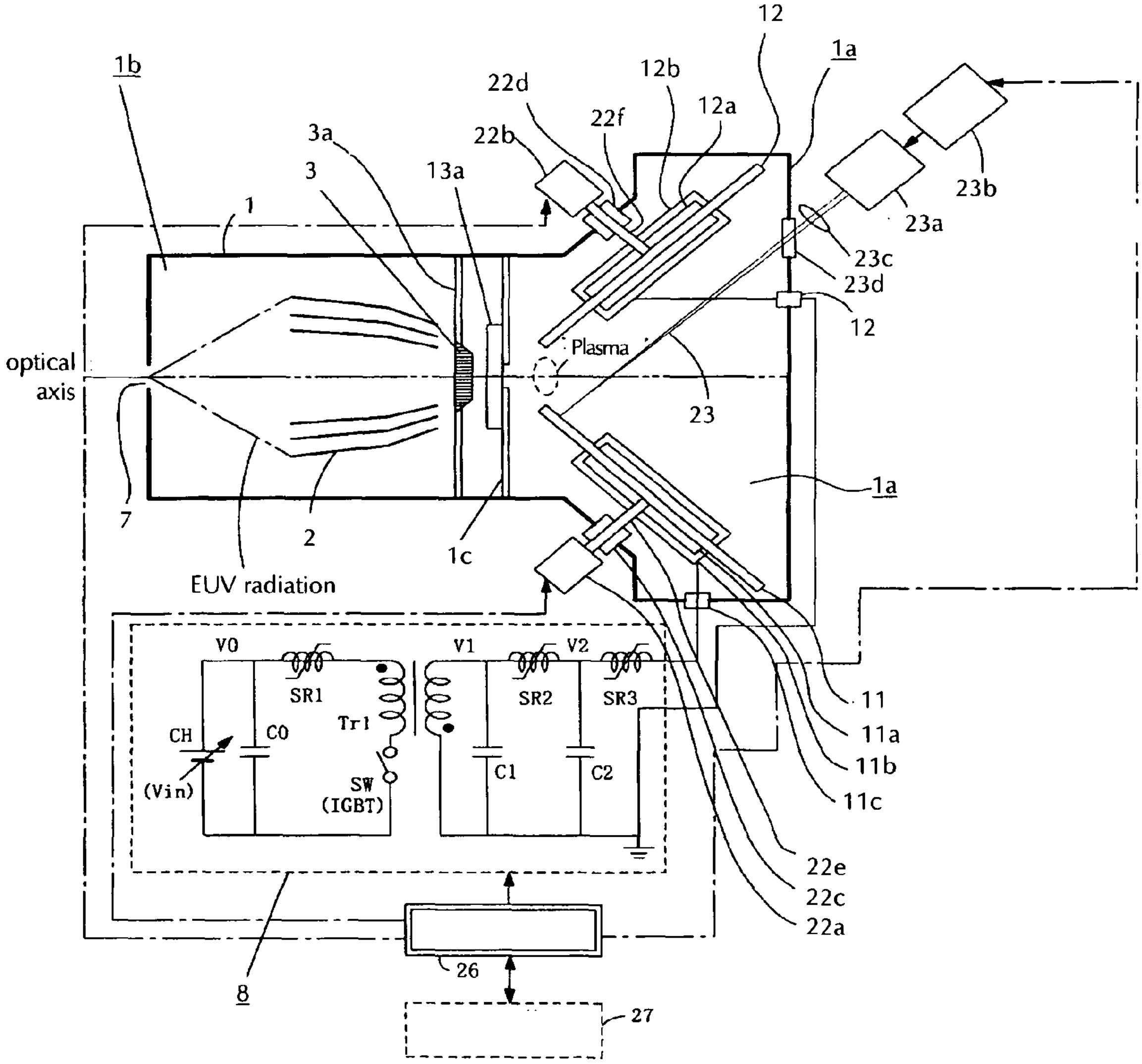

12
1a
1b
12b
22d
12a
22f
3a
22b
3
13a
23b
23a
1
23c
23d
12
optical axis
Plasma
23
1a
7
2
1c
EUV radiation
V0
V1
V2
SR1
SR2
SR3
CH
C0
Tr1
(Vin)
SW
(IGBT)
C1
C2
11
11a
11b
11c
22e
22c
22a
26
8
27

Fig. 3

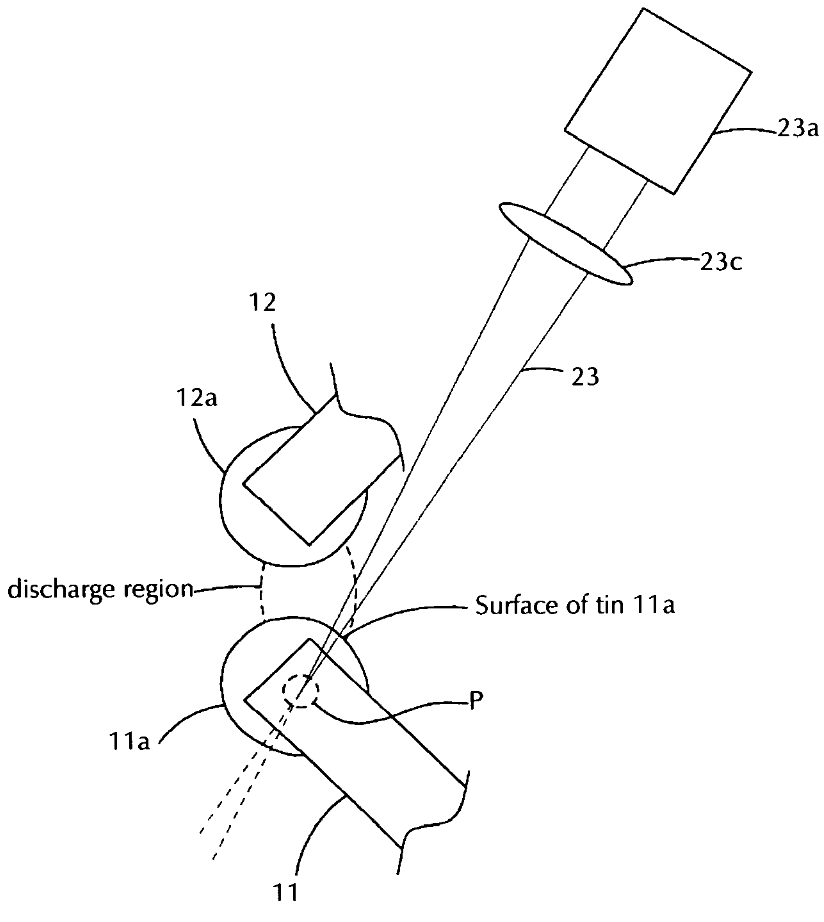


Fig. 4

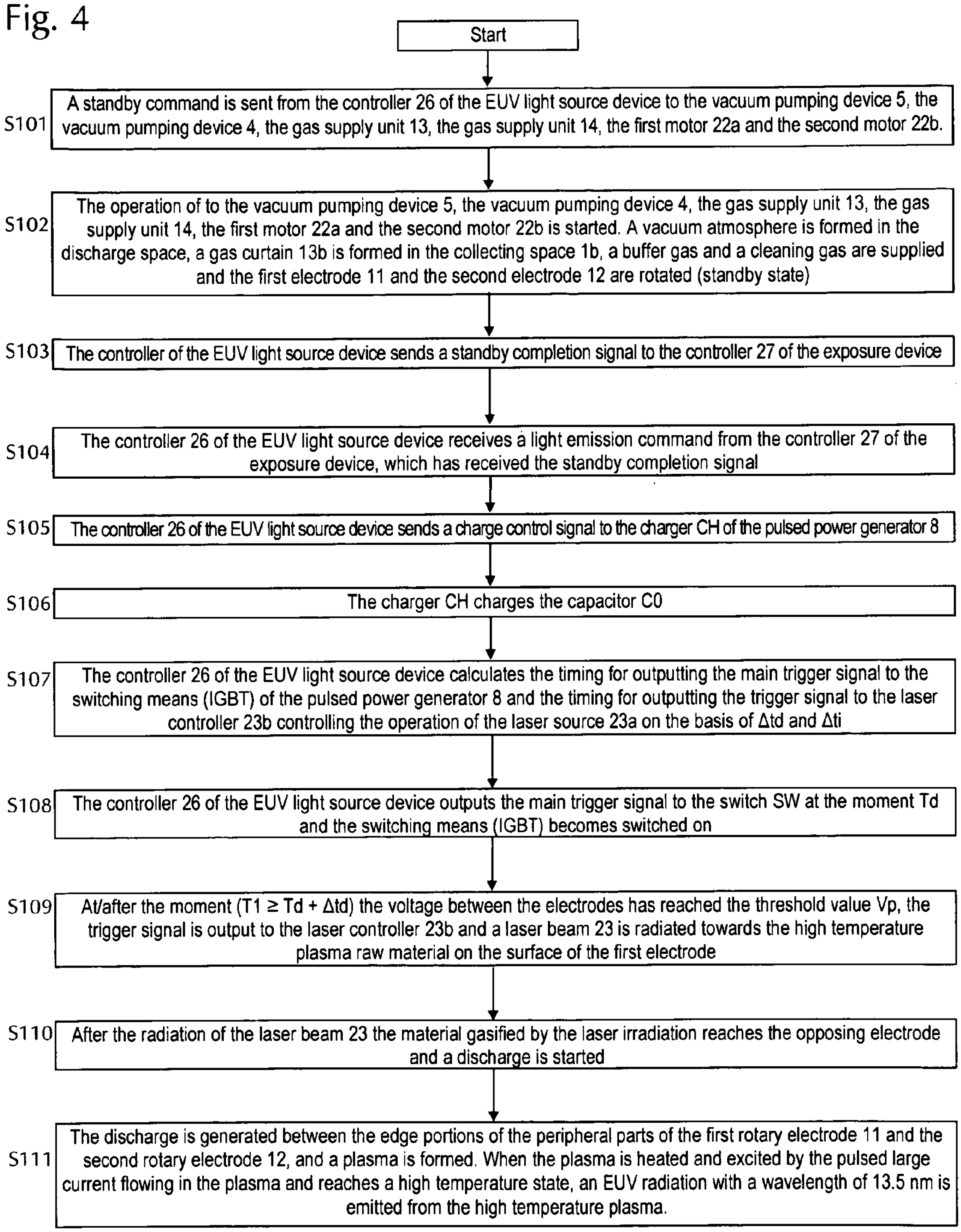

Start
S101
A standby command is sent from the controller 26 of the EUV light source device to the vacuum pumping device 5, the vacuum pumping device 4, the gas supply unit 13, the gas supply unit 14, the first motor 22a and the second motor 22b.
S102
The operation of to the vacuum pumping device 5, the vacuum pumping device 4, the gas supply unit 13, the gas supply unit 14, the first motor 22a and the second motor 22b is started. A vacuum atmosphere is formed in the discharge space, a gas curtain 13b is formed in the collecting space 1b, a buffer gas and a cleaning gas are supplied and the first electrode 11 and the second electrode 12 are rotated (standby state)
S103
The controller of the EUV light source device sends a standby completion signal to the controller 27 of the exposure device
S104
The controller 26 of the EUV light source device receives a light emission command from the controller 27 of the exposure device, which has received the standby completion signal
S105
The controller 26 of the EUV light source device sends a charge control signal to the charger CH of the pulsed power generator 8
S106
The charger CH charges the capacitor C0
S107
The controller 26 of the EUV light source device calculates the timing for outputting the main trigger signal to the switching means (IGBT) of the pulsed power generator 8 and the timing for outputting the trigger signal to the laser controller 23b controlling the operation of the laser source 23a on the basis of Δtd and Δti
S108
The controller 26 of the EUV light source device outputs the main trigger signal to the switch SW at the moment Td and the switching means (IGBT) becomes switched on
S109
At/after the moment (T1 ≥ Td + Δtd) the voltage between the electrodes has reached the threshold value Vp, the trigger signal is output to the laser controller 23b and a laser beam 23 is radiated towards the high temperature plasma raw material on the surface of the first electrode
S110
After the radiation of the laser beam 23 the material gasified by the laser irradiation reaches the opposing electrode and a discharge is started
S111
The discharge is generated between the edge portions of the peripheral parts of the first rotary electrode 11 and the second rotary electrode 12, and a plasma is formed. When the plasma is heated and excited by the pulsed large current flowing in the plasma and reaches a high temperature state, an EUV radiation with a wavelength of 13.5 nm is emitted from the high temperature plasma.

Fig. 5

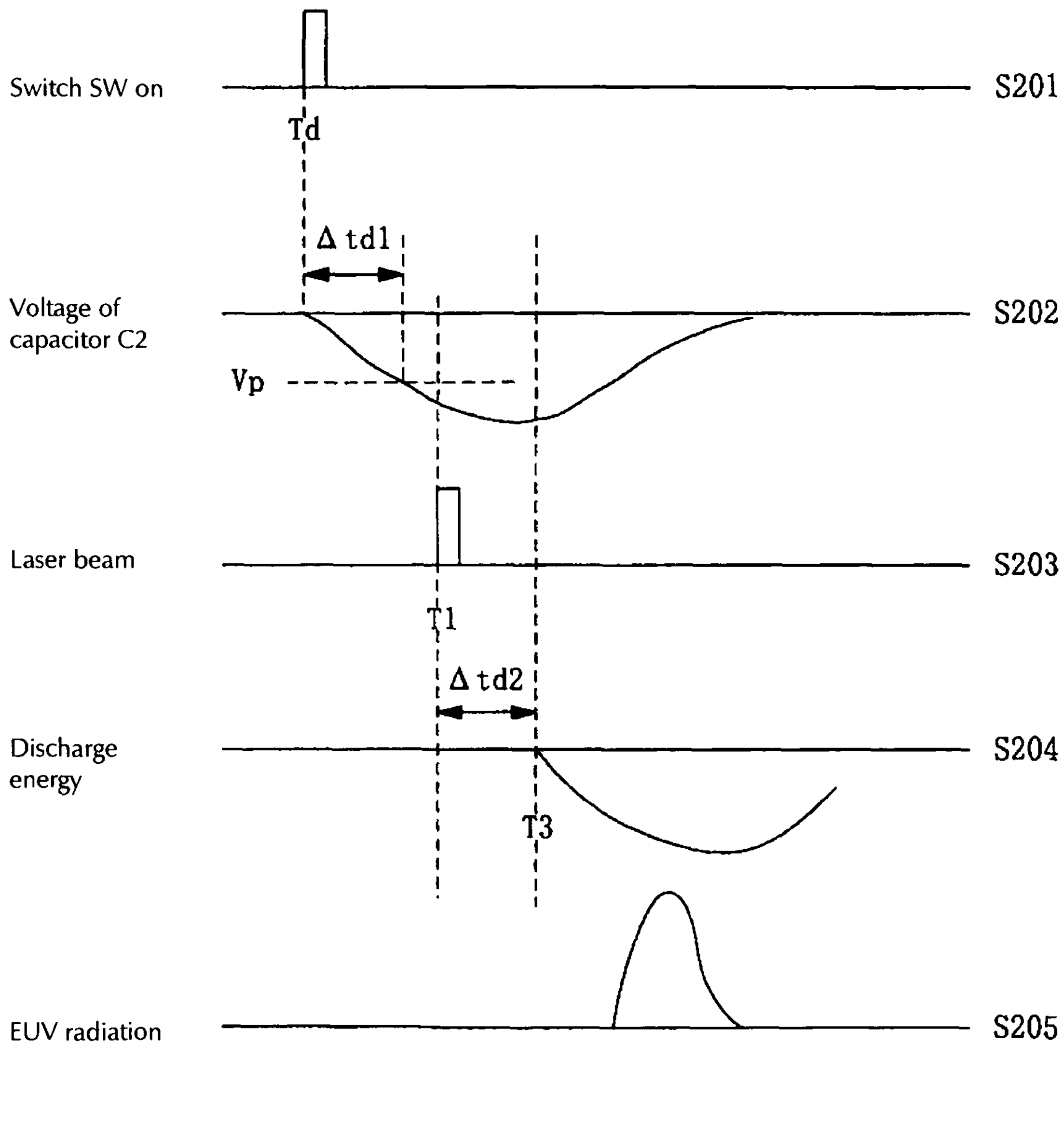
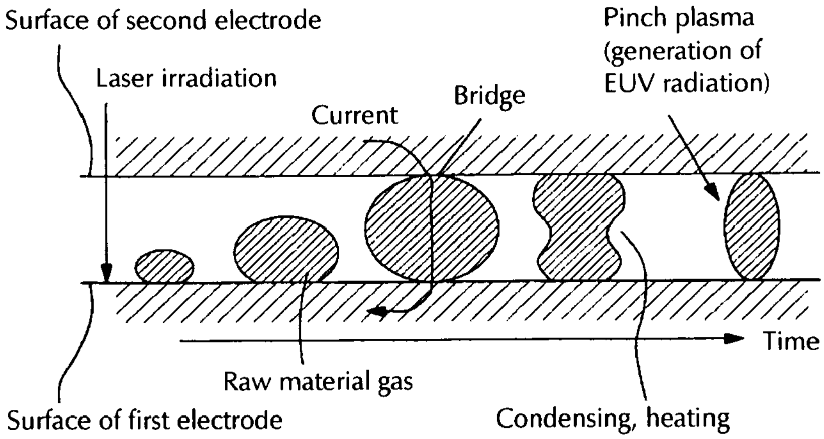
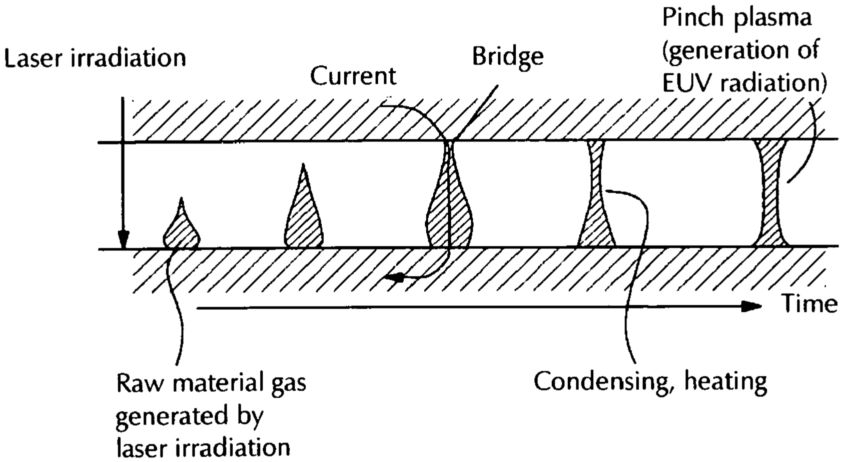

Switch SW on
S201
Td
Δ td1
Voltage of capacitor C2
S202
Vp
Laser beam
S203
T1
Δ td2
Discharge energy
S204
T3
EUV radiation
S205

Fig. 6


Surface of second electrode
Laser irradiation
Current
Bridge
Pinch plasma
(generation of
EUV radiation)
Time
Raw material gas
Surface of first electrode
Condensing, heating


Laser irradiation
Current
Bridge
Pinch plasma
(generation of
EUV radiation)
Time
Raw material gas
generated by
laser irradiation
Condensing, heating

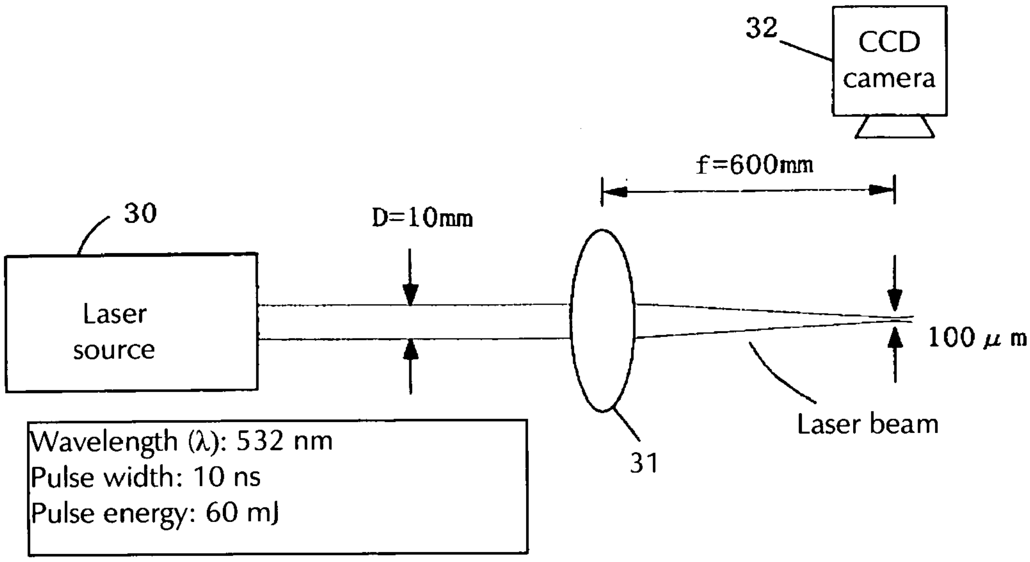


Fig. 7(a)

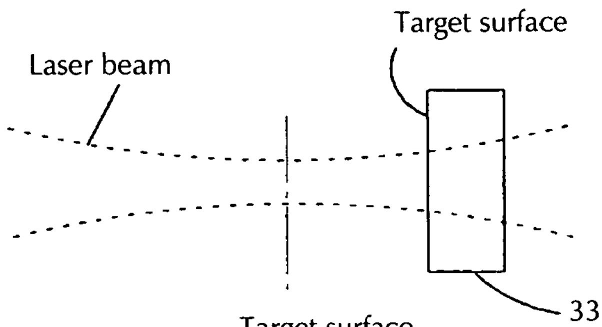


Fig. 7(b)

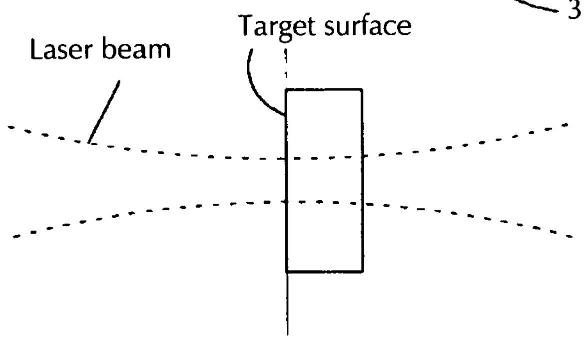
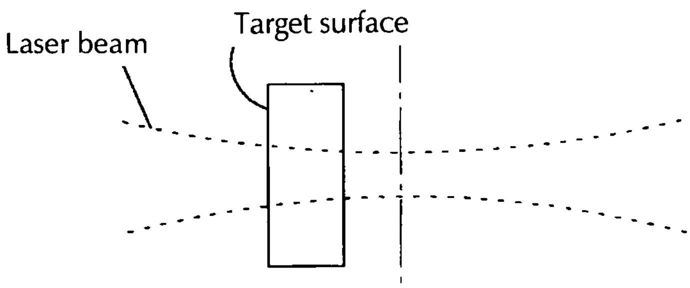
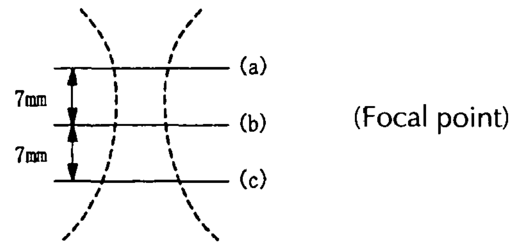


Fig. 7(c)





Target: Sn plate (t = 3 mm)
Laser light pulse energy: 60 mJ
Wavelength (λ): 532 nm
Pulse width: 10 ns

Fig. 8(a)

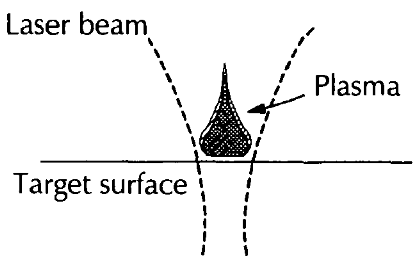
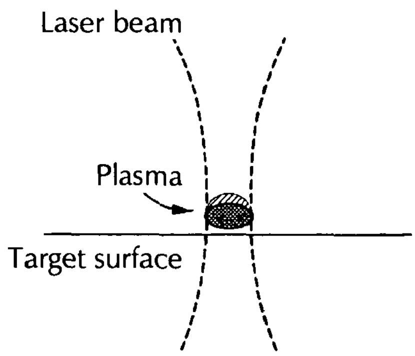


Fig. 8(b)



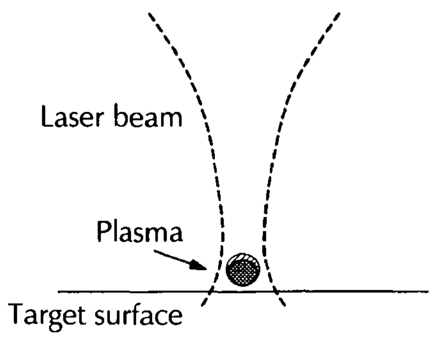
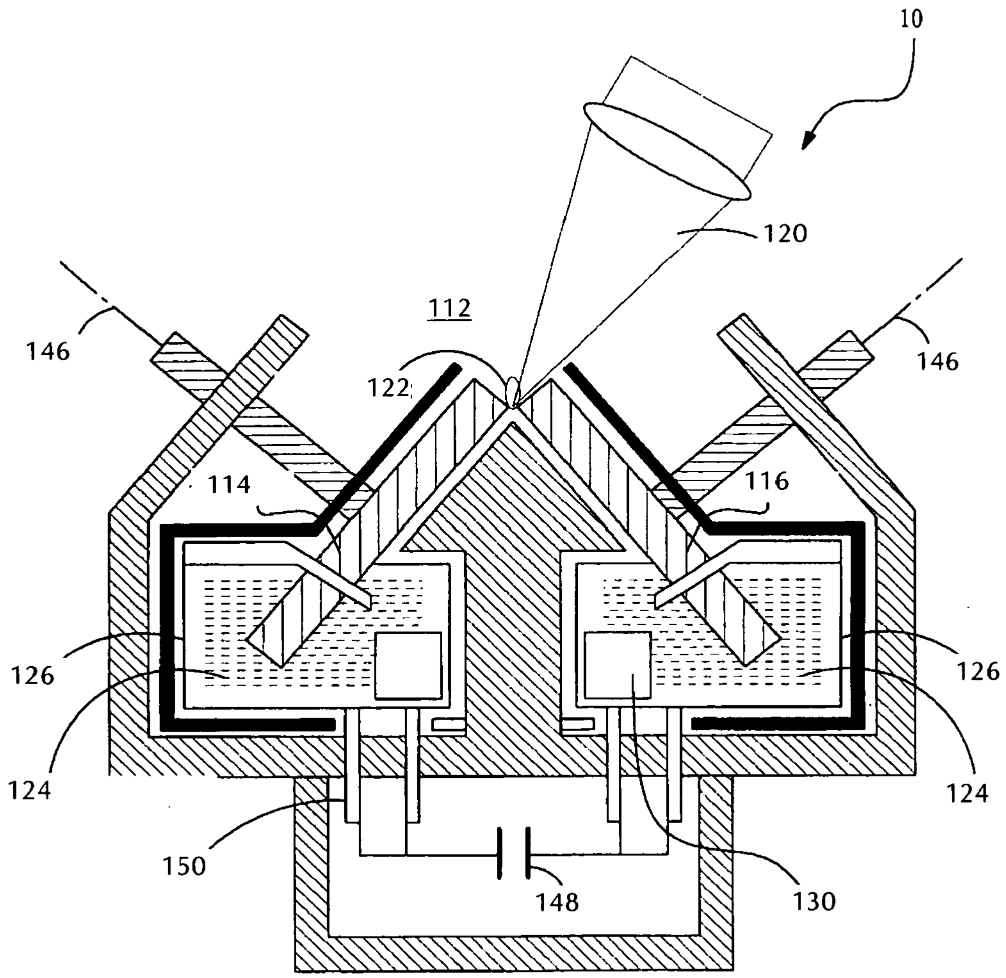


Fig. 8(c)

Fig. 9 (Prior Art)



REFERENCES CITED IN THE DESCRIPTION

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- US 20040183038 A1 **[0006] [0008] [0011] [0014] [0015] [0016]**