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(71) Applicant: **ASML NETHERLANDS B.V.** [NL/NL]; P.O. Box 324, 5500 AH Veldhoven (NL).

(72) Inventors: **AUSSEMS, Damien, Uriël, Boaz**; P.O. Box 324, 5500 AH Veldhoven (NL). **HUANG, Zhuangxiong**; P.O. Box 324, 5500 AH Veldhoven (NL). **O'GORMAN, Colm**; P.O. Box 324, 5500 AH Veldhoven (NL). **GOOSSENS, Tim, Cornelis**; P.O. Box 324, 5500 AH

Veldhoven (NL). **HAVERMANS, Peter**; P.O. Box 324, 5500 AH Veldhoven (NL). **OESTERHOLT, Rene**; P.O. Box 324, 5500 AH Veldhoven (NL). **LIU, Fei**; P.O. Box 324, 5500 AH Veldhoven (NL).

(74) Agent: **KRUK, Arno**; P.O. Box 324, 5500 AH Veldhoven (NL).

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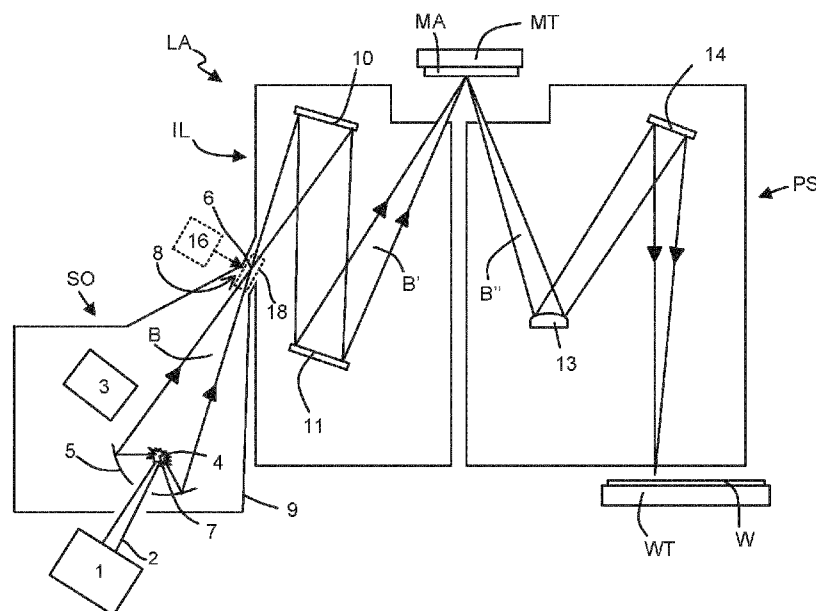


FIG. 1

(57) Abstract: A radiation system comprises a radiation source (SO) and a plasma generator (16). The radiation source comprises: a housing (9) provided with an exit aperture (8); and a radiation generator operable to generate output radiation in the housing and to direct at least a portion of the output radiation through the exit aperture. The plasma generator is operable to produce a plasma (18) which extends at least partially across the at least a portion of the output radiation directed through the exit aperture.

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Radiation System

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application number 19156096.0 which was filed on 8th February 2019 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to a radiation system comprising a radiation source. The radiation source may, for example, be an extreme ultraviolet (EUV) laser produced plasma (LPP) source. In particular, it relates to a radiation system provided with a mechanism for at least partially filtering out one or more spectral components and/or particulate debris. The radiation system may find application in the field of lithography.

BACKGROUND

[0003] A lithographic apparatus is a machine constructed to apply a desired pattern onto a substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). A lithographic apparatus may, for example, project a pattern at a patterning device (e.g., a mask) onto a layer of radiation-sensitive material (resist) provided on a substrate.

[0004] To project a pattern on a substrate a lithographic apparatus may use electromagnetic radiation. The wavelength of this radiation determines the minimum size of features which can be formed on the substrate. A lithographic apparatus, which uses extreme ultraviolet (EUV) radiation, having a wavelength within the range 4-20 nm, for example 6.7 nm or 13.5 nm, may be used to form smaller features on a substrate than a lithographic apparatus which uses, for example, radiation with a wavelength of 193 nm.

[0005] A lithographic system may comprise a radiation source that is operable to produce a radiation beam and a lithographic apparatus that is operable to receive said radiation beam and to use it to form an image (for example a diffraction limited image) of a patterning device on a substrate. One known type of radiation source that is used in the field of EUV lithography, is an LPP radiation source.

[0006] It may be desirable to provide a new radiation system, and associated methods for operation, that at least partially addresses one or more problems associated with prior art arrangements, whether identified herein or otherwise.

SUMMARY

[0007] According to a first aspect of the invention there is provided a system comprising: a radiation source comprising: a housing provided with an exit aperture; and a radiation generator operable to generate output radiation in the housing and to direct at least a portion of the output radiation

through the exit aperture; and a plasma generator operable to produce a plasma which extends at least partially across the at least a portion of the output radiation directed through the exit aperture.

[0008] The output radiation may comprise extreme ultraviolet (EUV) radiation. The system according to the first aspect of the invention is advantageous, as now discussed.

5 [0009] The system may form part of a lithography system. It may be desirable for the radiation output by the radiation source to have a desired wavelength and bandwidth. For example, it may be desirable for the radiation output by the radiation source to comprise EUV radiation. Furthermore, it may be desirable to suppress any out-of-band radiation which has a wavelength outside of a desired bandwidth.

10 [0010] Since the plasma produced by the plasma generator extends at least partially across the at least a portion of the output radiation directed through the exit aperture, at least a portion of the output radiation that is directed through the exit aperture will be incident on the plasma. The plasma generator may be configured such that the plasma filters out at least some out-of-band radiation. In this way, the plasma may be configured to increase a spectral purity of radiation output by the radiation source.

15 [0011] For EUV lithography apparatus that use a laser produced plasma (LPP) source to produce EUV radiation, it is known to use spectral purity filters downstream of the LPP source (for example downstream of an intermediate focus of the LPP source) to filter out out-of-band radiation, however these filters were found not to be able to survive due to the high power density and non-homogeneity of the light. Advantageously, since the system according to the first aspect of the invention uses a plasma as a filter, there is no such damage threshold issue.

20 [0012] Furthermore, plasma is only transparent to radiation with a frequency that is higher than the plasma frequency, which in turn is dependent on the plasma electron density and the effective mass of the electrons in the plasma. The plasma frequency is proportional to the square root of the ratio of the plasma electron density to the effective mass of the electrons in the plasma. Therefore, by adjusting
25 these parameters of the plasma, the system according to the first aspect of the invention can be provided with an adjustable spectral filter.

[0013] Additionally or alternatively, the plasma may be arranged to intercept particles that may be present within the housing (and which may, for example, be produced as a by-product of the generation of the output radiation).

30 [0014] The radiation generator may be operable to produce a laser produced plasma (LPP).

[0015] The radiation generator may comprise: a target generator operable to produce a target comprising target material at a plasma formation region, the plasma formation region arranged to receive laser radiation for illuminating the target material to thereby generate a second plasma that emits the output radiation; and an optical element arranged to direct at least a portion of the output radiation
35 towards the exit aperture.

[0016] Such an LPP radiation source may comprise a number of sources of out-of-band radiation. For example, the output radiation emitted by the second plasma may comprise components of undesired

out-of-band radiation. In addition, a portion of the laser radiation used to generate the second plasma may be scattered towards the exit aperture. Furthermore, it will be appreciated that the housing of the radiation source may be maintained at a relatively high temperature (for example in excess of a melting point of the target material, which may comprise tin). Components of the radiation source which are maintained at such elevated temperatures will emit infrared radiation part of which may be directed towards the exit aperture.

[00017] The radiation generator may be arranged to focus at least a portion of the output radiation at an intermediate focus, the intermediate focus being disposed at or proximate to the exit aperture.

[00018] For such embodiments, an arrangement wherein the plasma generator is operable to produce a plasma which extends at least partially across the exit aperture is particularly advantageous, as now discussed. Embodiments wherein the radiation generator is arranged to focus at least a portion of the output radiation at the intermediate focus, the volume of plasma that should be generated at the exit aperture to ensure that the plasma extends across the propagation path of the output radiation may be minimized. In turn, this minimizes the amount of power used by the plasma generator.

[00019] Furthermore, such an arrangement differs from existing EUV radiation sources (for example LPP radiation sources) that are provided with a spectral filter. Such arrangements do not place the spectral filter close to the intermediate focus of the radiation source as the skilled person would recognize that at the intermediate focus the power density is at a maximum and therefore the spectral filter is likely to be damaged.

[00020] By using a plasma as the spectral filter (as generated by the plasma generator), the system according to the first aspect of the invention is able to provide this spectral filter proximate the intermediate focus.

[00021] The plasma generator may be operable to form the plasma from hydrogen gas.

[00022] Alternatively, the plasma may be formed from, for example, an inert gas such as, for example argon. In some embodiments, the plasma may be formed from a mixture of gasses, for example a mixture of hydrogen and argon.

[00023] The plasma is opaque to radiation with a frequency that is lower than the plasma frequency, which in turn is dependent on the plasma electron density and the effective mass of the electrons in the plasma.

[00024] The plasma generator may be operable to form a plasma with an electron density higher than 10^{19} cm^{-3} .

[00025] With such an arrangement, the plasma will be opaque for infrared (IR) radiation, for example radiation having a wavelength of the order of $10 \mu\text{m}$ or greater. In contrast, for EUV radiation, such a plasma will behave like a lossless dielectric and the EUV radiation can propagate through it without damping.

[00026] The plasma generator may be operable to form a plasma with an electron density higher than $6.7 \times 10^{22} \text{ cm}^{-3}$.

[00027] With such an arrangement, the plasma will be opaque for infrared DUV radiation, for example radiation having a wavelength of the order of 130 - 400 nm, or greater.

[00028] The plasma generator may be operable to form a plasma with an electron density less than $6.7 \times 10^{24} \text{ cm}^{-3}$.

5 [00029] With such an arrangement, the plasma will be transparent for EUV radiation having a wavelength of 13.5 nm or less. Conversely, radiation having a wavelength greater than 13.5 nm will damp exponentially with distance into the plasma and, for a sufficiently large plasma, will be blocked.

[00030] It will be appreciated that radiation having a frequency that is lower than the plasma frequency will damp exponentially with distance into the plasma. It will be further appreciated that it
10 is desirable that the plasma be sufficiently large, in a propagation direction of the output radiation, that substantially all of the radiation having a frequency that is lower than the plasma frequency is blocked by the plasma.

[00031] The plasma generator may be operable to form a plasma in a region having an extent in a propagation direction of the output radiation that is greater than 300 μm .

15 [00032] In some embodiments, the plasma may be formed in a region having an extent in a propagation direction of the output radiation that is around 1 cm.

[00033] It will be appreciated that desired dimensions of the plasma in a plane that is perpendicular to the propagation direction of the output radiation may be dependent on the dimensions of the exit aperture. In some embodiments, the exit aperture may have a diameter of the order of 6 mm and the
20 plasma may have dimensions of around 1cm in the plane that is perpendicular to the propagation direction of the output radiation.

[00034] The plasma generator may be operable to generate the plasma using arc discharge.

[00035] Alternatively, any other method for generating plasma may be used, including, for example, arrangements that use any of the following: laser radiation to produce a plasma (i.e. a laser produced
25 plasma); a plasma railgun; a hypervelocity plasma source; a microwave-driven plasma source; or any other compact plasma source.

[00036] It will be appreciated that the plasma generator may be located at or near the exit aperture. For example, the plasma may be formed at the exit aperture. Alternatively, the plasma generator may be located remote from the exit aperture and the plasma may be guided across the propagation direction
30 of the output radiation.

[00037] The plasma generator may be operable to direct the plasma produced by the plasma generator so as to flow at least partially across the exit aperture.

[00038] Advantageously, by providing a flow of plasma across the exit aperture the efficiency of removal of particulate debris can be improved over, for example, a static plasma since the particulate
35 debris can be entrained in the plasma flow and prevented from passing through it and forming part of the output of the radiation source.

[00039] The plasma generator may be operable to direct the plasma produced by the plasma generator so as to flow at least partially through the exit aperture and into the housing.

[00040] Advantageously, by providing a flow of plasma through the exit aperture and into the housing the efficiency of removal of particulate debris can be further improved since the flow of plasma will tend to force particulate debris back into the housing. In this way, the plasma generator may be considered to form part of a dynamic plasma lock.

[00041] The plasma generator may comprise at least one plasma generating unit arranged to generate a plasma and to direct the plasma at least partially across the exit aperture.

[00042] The or each plasma generating unit may comprise: a first electrode and a second electrode; a voltage source operable to apply a voltage across the first electrode and the second electrode; and a gas flow generator operable to generate a gas flow between the first electrode and the second electrode and in a direction at least partially across the exit aperture.

[00043] The voltage source may comprise one or more a high-voltage power supplies. The voltage source may comprise one or more resistors. The voltage source may comprise one or more energy-storage capacitors. The voltage source may comprise one or more power switching devices.

[00044] It will be appreciated that the direction at least partially across the exit aperture may be at least partially transverse to a main direction of the output radiation directed towards the exit aperture. It will be appreciated that the output radiation may be focused at or proximate to the exit aperture and may therefore comprise a convergent or divergent radiation beam. In this context, it will be appreciated that the main direction of the output radiation is intended to mean the average direction of the output radiation (which may be the direction of the chief ray of the output radiation).

[00045] The gas flow generated by the gas flow generator may comprise hydrogen gas. The hydrogen gas may be provided at a pressure of around 1 atmosphere or approximately 1 bar.

[00046] The voltage source may be operable to generate an electric field strength between the first electrode and the second electrode that is sufficient to ionize the gas flow so as to form a plasma flow. The voltage source may be operable to apply an initial large voltage across the first electrode and the second electrode so as to initiate the plasma formation. Once a plasma has been formed, a resistance between the first electrode and the second electrode may drop significantly, and a smaller voltage may be applied across the first electrode and the second electrode so as to sustain the plasma. An initial ignition process for the plasma formation may use an electric field strength of the order of 10 kV/cm. For example, at least initially, the voltage source may be operable to apply a voltage across the first electrode and the second electrode of the order of 10 kV and the first electrode and the second electrode may be separated by a distance of the order of 1 cm. In order to sustain the plasma, the voltage source may be operable to generate an electric field strength of at least 100 V/m between the first electrode and the second electrode.

[00047] The first electrode may be hollow and the second electrode may be provided within the first electrode.

[00048] With such an arrangement, the first electrode may be generally tubular and may form part of a conduit for the gas flow. The second electrode may be generally coaxial with the first electrode. Together, the first electrode and the second electrode may provide a channel, which is generally annular in cross section through which the gas flow can flow between the first electrode and the second electrode.

[00049] The or each plasma generating unit may comprise a nozzle.

[00050] The nozzle may act to focus the plasma into a smaller volume. In turn, this can increase the electron density of plasma at the exit aperture.

[00051] The plasma generator may comprise a plurality of the plasma generating units.

[00052] Each plasma generating unit may be operable to provide a flow of plasma, from a different direction, that at least partially traverses the exit aperture. Together, all of these plasma flows may combine to form a plasma which extends at least partially across the exit aperture and which has a greater electron density than any of the individual plasma flows.

[00053] The plasma generator may be provided with one or more adjustable parameters. One or more properties of the plasma may be controllable by controlling said one or more adjustable parameters.

[00054] The one or more adjustable parameters may, for example, comprise the voltage across the first electrode and the second electrode that may be applied by the voltage source. Additionally or alternatively, the one or more adjustable parameters may, for example, comprise a pressure or the gas flow generated by the gas flow generator.

[00055] The output radiation generated by the radiation generator may be pulsed, the plasma produced by the plasma generator may be pulsed. The radiation generator and the plasma generator may be synchronized such that the plasma is present as each pulse of the output radiation propagates through a region wherein the plasma is formed. For example, the radiation generator and the plasma generator may be synchronized such that the plasma is present as each pulse of the output radiation propagates through the exit aperture.

[00056] According to a second aspect of the invention there is provided a lithographic system comprising: a system according to the first aspect of the invention; and a lithographic apparatus operable to receive output radiation from the radiation source and to form an image of a patterning device on a substrate using said output radiation.

[00057] The lithographic system according to the second aspect of the invention may incorporate any features of the system according to the first aspect of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[00058] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 depicts a lithographic system comprising a lithographic apparatus and a radiation source;

- Figure 2 depicts in cross section an embodiment of a plasma generating unit that may form part of a plasma generator that may form part of the lithographic system shown in Figure 1;

5 - Figure 3A shows, in cross section and in a plane which contains an optical axis of the radiation source, a first embodiment of a plasma generator comprising a plurality of plasma generating units as shown in Figure 2, also shown is a portion of an enclosing structure of the radiation source shown in Figure 1;

10 - Figure 3B shows, in cross section and in a plane which is perpendicular to the optical axis of the radiation source, the first embodiment of a plasma generator as shown in Figure 3A; and

- Figure 4 shows, in cross section and in a plane which contains an optical axis of the radiation source, a second embodiment of a plasma generator comprising a plurality of plasma generating units as shown in Figure 2, also shown is a portion of an enclosing structure of the radiation source shown in Figure 1.

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DETAILED DESCRIPTION

[00059] Figure 1 shows a lithographic system according to an embodiment of the present invention comprising a radiation source SO and a lithographic apparatus LA. The radiation source SO is configured to generate an EUV radiation beam B and to supply the EUV radiation beam B to the lithographic apparatus LA. The lithographic apparatus LA comprises an illumination system IL, a support structure MT configured to support a patterning device MA (e.g., a mask), a projection system PS and a substrate table WT configured to support a substrate W.

20 [00060] The illumination system IL is configured to condition the EUV radiation beam B before the EUV radiation beam B is incident upon the patterning device MA. Thereto, the illumination system IL may include a faceted field mirror device 10 and a faceted pupil mirror device 11. The faceted field mirror device 10 and faceted pupil mirror device 11 receive the EUV radiation beam B and, together, the faceted field mirror device 10 and faceted pupil mirror device 11 are arranged to provide an EUV radiation beam B' with a desired cross-sectional shape and a desired intensity distribution. The illumination system IL may include other mirrors or devices in addition to, or instead of, the faceted field mirror device 10 and faceted pupil mirror device 11.

30 [00061] After being thus conditioned, the EUV radiation beam B' interacts with the patterning device MA. As a result of this interaction a patterned EUV radiation beam B'' is generated. The projection system PS is configured to project the patterned EUV radiation beam B'' onto the substrate W. For that purpose, the projection system PS may comprise a plurality of mirrors 13,14 which are configured to project the patterned EUV radiation beam B'' onto the substrate W held by the substrate table WT. The projection system PS may apply a reduction factor to the patterned EUV radiation beam B'' thus forming an image with features that are smaller than corresponding features on the patterning

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device MA. For example, a reduction factor of 4 or 8 may be applied. Although the projection system PS is illustrated as having only two mirrors 13, 14 in Figure 1, the projection system PS may include a different number of mirrors (e.g., six or eight mirrors).

[00062] The substrate W may include previously formed patterns. Where this is the case, the lithographic apparatus LA aligns the image, formed by the patterned EUV radiation beam B', with a pattern previously formed on the substrate W.

[00063] A relative vacuum, i.e. a small amount of gas (e.g. hydrogen) at a pressure well below atmospheric pressure, may be provided in the radiation source SO, in the illumination system IL, and/or in the projection system PS.

[00064] The radiation source SO shown in Figure 1 is, for example, of a type which may be referred to as a laser produced plasma (LPP) source. A laser system 1, which may, for example, include a CO₂ laser, is arranged to deposit energy via a laser beam 2 into a fuel, such as tin (Sn) which is provided from, e.g., a fuel emitter 3. The laser beam 2 may be referred to as the laser radiation 2. Although tin is referred to in the following description, any suitable fuel may be used. This fuel may, for example, be in liquid form, and may, for example, be a metal or alloy. The fuel emitter 3 may comprise a nozzle configured to direct tin, e.g. in the form of droplets, along a trajectory towards a plasma formation region 4. Therefore the fuel emitter 3 may be considered to be a target generator operable to produce a target (for example a tin droplet) comprising target material (for example tin) at the plasma formation region 4. The laser beam 2 is incident upon the tin at the plasma formation region 4. The fuel emitter 3 may be operable to produce a plurality of targets (for example a stream of tin droplets) at the plasma formation region 4. The laser beam 2 may be pulsed, for example with each pulse being incident on a different one of the plurality of targets (e.g. tin droplets) at the plasma formation region 4. The deposition of laser energy into the tin creates a tin plasma 7 at the plasma formation region 4. Radiation, including EUV radiation, is emitted from the plasma 7 during de-excitation and recombination of electrons with ions of the plasma.

[00065] The laser radiation 2 may have any suitable wavelength. In some embodiments, the laser radiation 2 has a wavelength of around 10 µm, which may be produced by a CO₂ laser. In some embodiments, the laser radiation 2 has a wavelength of around 1 µm, which may be produced by a YAG (yttrium aluminium garnet) based laser.

[00066] The EUV radiation from the plasma is collected and focused by a collector 5. Collector 5 comprises, for example, a near-normal incidence radiation collector 5 (sometimes referred to more generally as a normal-incidence radiation collector). The collector 5 may have a multilayer mirror structure which is arranged to reflect EUV radiation (e.g., EUV radiation having a desired wavelength such as 13.5 nm). The collector 5 may have an ellipsoidal configuration, having two focal points. A first one of the focal points may be at the plasma formation region 4, and a second one of the focal points may be at an intermediate focus 6, as discussed below.

[00067] The collector 5 may be considered to be an optical element that is arranged to focus at least a portion of the radiation generated by the plasma 7 at the intermediate focus 6.

[00068] The laser system 1 may be spatially separated from the radiation source SO. Where this is the case, the laser beam 2 may be passed from the laser system 1 to the radiation source SO with the aid of a beam delivery system (not shown) comprising, for example, suitable directing mirrors and/or a beam expander, and/or other optics.

[00069] Radiation that is reflected by the collector 5 forms the EUV radiation beam B. The EUV radiation beam B is focused at intermediate focus 6 to form an image at the intermediate focus 6 of the plasma present at the plasma formation region 4. The image at the intermediate focus 6 acts as a virtual radiation source for the illumination system IL. The radiation source SO is arranged such that the intermediate focus 6 is located at or proximate to an opening 8 in an enclosing structure 9 of the radiation source SO. The opening 8 in the enclosing structure 9 may be referred to as an exit aperture 8 and the enclosing structure 9 may be referred to as a housing 9 provided with the exit aperture 8. The collector 5 may be considered to be an optical element arranged to direct at least a portion of the output radiation (i.e. EUV radiation beam B) towards the opening 8.

[00070] The fuel emitter 3 and the plasma formation region 4 arranged to receive the laser beam 2 for illuminating the target material may together be considered to form a radiation generator operable to generate output radiation in the enclosing structure 9 and to direct at least a portion of that output radiation (i.e. EUV radiation beam B) through the opening 8. The collector 5 may also be considered to form part of the radiation generator.

[00071] Although Figure 1 depicts the radiation source SO as a laser produced plasma (LPP) source, any suitable source such as a discharge produced plasma (DPP) source or a free electron laser (FEL) may be used to generate EUV radiation.

[00072] As schematically indicated in Figure 1, the lithographic system further comprises a plasma generator 16 operable to produce a plasma 18 which extends at least partially across the opening 8 of the radiation source SO. Such an arrangement is advantageous, as now discussed. The radiation source SO and the plasma generator 16 may be considered to provide a system, which may be referred to as a radiation system. It will be appreciated that the laser system 1 and/or the beam delivery system (when provided) may be considered to form part of the radiation system.

[00073] It will be appreciated that the radiation system may form part of a lithography system, as shown in Figure 1, or may be used for some other purpose. It may be desirable for the radiation output by the radiation source SO to have a desired wavelength and bandwidth. For example, to accurately control the lithographic process, it may be desirable for the radiation output by the radiation source SO to comprise EUV radiation only. Furthermore, it may be desirable to suppress any out-of-band radiation which has a wavelength outside of a desired bandwidth.

[00074] Since the plasma 18 produced by the plasma generator 16 extends at least partially across the opening 8, at least a portion of the radiation that is directed through the opening 8 will be incident

on the plasma 18. The plasma generator 16 may be configured such that the plasma filters out at least some out-of-band radiation. In this way, the plasma may be configured to increase a spectral purity of radiation output by the radiation source.

[00075] For EUV lithography apparatus that use an LPP source to produce EUV radiation, it is known to use spectral purity filters downstream of the LPP source (for example downstream of an intermediate focus 6 of the LPP source) to filter out out-of-band radiation. However these filters have been found not to be able to survive due to the high power density and non-homogeneity of the light. Advantageously, since the radiation source SO uses a plasma 18 as a filter, there is no such damage threshold issue.

[00076] The LPP radiation source SO of the type shown in Figure 1 may comprise a number of sources of out-of-band radiation. For example, the output radiation emitted by the radiation generating plasma 7 may comprise components of undesired out-of-band radiation (for example DUV radiation). In addition, a portion of the laser radiation 2 used to generate the radiation generating plasma 7 may be scattered towards the opening 8. Such scattering may be facilitated, for example, by tin droplets and tin debris, which may reflect such laser radiation 2 efficiently.

[00077] Furthermore, it will be appreciated that the enclosing structure 9 of the radiation source SO may be maintained at a relatively high temperature (for example in excess of a melting point of tin). Components of the radiation source SO which are maintained at such elevated temperatures will emit infrared radiation part of which may be directed towards the opening 8.

[00078] The inventors of the present invention have realised that the plasma 18 may be arranged so as to filter out at least some of these sources of out-of-band radiation. The plasma is only transparent to radiation with a frequency that is higher than the plasma frequency, which in turn is dependent on the plasma electron density and the effective mass of the electrons in the plasma. The plasma frequency, ω_p , is given by:

$$\omega_p = \left(\frac{e^2 n}{\epsilon_0 m_e} \right)^{1/2} \quad (1)$$

where e is the charge of the electron, n is the plasma electron density, ϵ_0 is the permittivity of free space and m_e is the effective mass of the electrons in the plasma. Therefore, the plasma frequency is proportional to the square root of the ratio of the plasma electron density to the effective mass of the electrons in the plasma. Therefore, by adjusting these parameters of the plasma, the radiation source according to the first aspect of the invention can be provided with an adjustable spectral filter. In practice, the effective mass of the electrons in the plasma may be relatively constant and the main control parameter that can be used to influence the plasma frequency may be the plasma electron density.

[00079] The plasma 18 is opaque to radiation with a frequency that is lower than the plasma frequency.

[00080] In some embodiments, the plasma generator 16 is operable to form a plasma 18 with an electron density higher than a threshold electron density value. This ensures that the plasma is opaque to radiation with frequencies that are below a corresponding threshold frequency value (said corresponding threshold frequency value can be found from the threshold electron density value using equation (1)).

[00081] In some embodiments, the plasma generator 16 is operable to form a plasma 18 with an electron density higher than 10^{19} cm^{-3} . With such an arrangement, the plasma will be opaque for infrared (IR) radiation, for example radiation having a wavelength of the order of $10 \text{ }\mu\text{m}$ or greater. In at least some embodiments, the laser radiation 2 has a wavelength of around $10 \text{ }\mu\text{m}$ and therefore, for such embodiments, forming a plasma 18 with an electron density higher than 10^{19} cm^{-3} will prevent (or at least reduce) the amount of stray laser radiation that is received by the lithographic apparatus LA. In contrast, for radiation with larger frequencies (for example EUV radiation), such a plasma 18 will behave like a lossless dielectric and the EUV radiation can propagate through it without damping.

[00082] In some embodiments, the plasma generator 16 may be operable to form a plasma 18 with an electron density higher than 10^{21} cm^{-3} . With such an arrangement, the plasma will be opaque for infrared (IR) radiation, for example radiation having a wavelength of the order of $1 \text{ }\mu\text{m}$ or greater. In at least some embodiments, the laser radiation 2 has a wavelength of around $1 \text{ }\mu\text{m}$ and therefore, for such embodiments, forming a plasma 18 with an electron density higher than 10^{21} cm^{-3} will prevent (or at least reduce) the amount of stray laser radiation that is received by the lithographic apparatus LA. In addition, such embodiments that are able to generate a plasma 18 with an electron density higher than 10^{21} cm^{-3} (such that the plasma 18 is opaque for infrared radiation) will prevent (or at least reduce) the amount of infrared radiation emitted by components of the radiation source SO that is received by the lithographic apparatus LA.

[00083] In some embodiments, the plasma generator 16 may be operable to form a plasma 18 with an electron density higher than $6.7 \times 10^{22} \text{ cm}^{-3}$. With such an arrangement, the plasma will also be opaque for deep ultraviolet (DUV) radiation, for example radiation having a wavelength of the order of $130 - 400 \text{ nm}$, or greater.

[00084] In some embodiments, the plasma generator 16 may be operable to form a plasma 18 with an electron density lower than $6.7 \times 10^{24} \text{ cm}^{-3}$. With such an arrangement, the plasma will remain transparent for EUV radiation, for example radiation having a wavelength of 13.5 nm or less (while the plasma 18 will block radiation having a wavelength of greater than 13.5 nm).

[00085] It will be appreciated that radiation having a frequency that is lower than the plasma frequency cannot propagate through the plasma 18. Rather, in the plasma 18 radiation having a frequency that is lower than the plasma frequency will be damped exponentially (that is the amplitude of the radiation will decrease exponentially with distance into the plasma 18). Such radiation may be referred to as evanescent or cut off. It will be further appreciated that it is desirable that the plasma 18 be sufficiently large, in a propagation direction of the output radiation, that substantially all of the

radiation having a frequency that is lower than the plasma frequency is blocked by the plasma 18, such that no energy from such radiation is transmitted through the plasma 18. Radiation having a frequency that is lower than the plasma frequency will damp exponentially within a characteristic depth, L , given by:

$$L = \frac{1}{\text{Im}k} = \frac{1}{(\omega/c) \sqrt{\omega_p^2/\omega^2 - 1}} \quad (2)$$

5 where ω is the frequency of the radiation propagating into the plasma 18.

[00086] For example, for embodiments wherein the plasma generator 16 is operable to form a plasma 18 with an electron density higher than 10^{19} cm^{-3} , the characteristic depth for infrared radiation (having a wavelength of around $10 \text{ }\mu\text{m}$) will be approximately $100 \text{ }\mu\text{m}$. It will be appreciated that the characteristic depth is the distance of plasma that would damp the radiation amplitude by a factor or
10 $1/e$. In some embodiments, the plasma generator 16 is operable to form a plasma 18 in a region having an electron density higher than 10^{19} cm^{-3} and having an extent in a propagation direction of the EUV radiation beam B that is greater than $300 \text{ }\mu\text{m}$. With such an arrangement around 95% of the infrared radiation would be filtered out by the plasma. It may be desirable to form a plasma 18 in a region having an extent in a propagation direction of the EUV radiation beam B that is around 1 cm or more.

15 [00087] It will be appreciated that desired dimensions of the plasma 18 in a plane that is perpendicular to the propagation direction of the EUV radiation beam B may be dependent on the dimensions of the opening 8. In some embodiments, the opening 8 may have a diameter of the order of 6 mm and the plasma may have dimensions of around 1 cm in the plane that is perpendicular to the propagation direction of the output radiation.

20 [00088] As discussed above, the plasma 18 may act as a spectral filter. Additionally or alternatively, the plasma 18 may be arranged to intercept particles that may be present within the enclosing structure 9 (and which may, for example, be produced as a by-product of the generation of the output radiation).

[00089] In the embodiment shown in Figure 1, the plasma generator 16 is operable to produce a plasma 18 which extends at least partially across the opening 8. In alternative embodiments, the plasma
25 generator 16 may be operable to produce a plasma 18 at another position within the lithographic system (preferably downstream of the radiation source SO and upstream of the optics within the lithographic apparatus LA). However, an arrangement wherein the plasma generator 16 is operable to produce a plasma 18 which extends at least partially across the opening 8 is particularly advantageous, as now discussed. As discussed above, the collector 5 is arranged to focus at least a portion of the output radiation B at the intermediate focus 6 (which is proximate the opening 8). For such embodiments, by
30 generating the plasma 18 so as to at least partially extend across the opening 8, the volume of plasma 18 that should be generated to ensure that the plasma 18 extends across the propagation path of the output radiation B may be minimized. In turn, this minimizes the amount of power used by the plasma generator 16.

[00090] Furthermore, such an arrangement differs from existing EUV radiation sources (for example LPP radiation sources) that are provided with a spectral filter. Such arrangements do not place the spectral filter close to the intermediate focus 6 of the radiation source SO as the skilled person would recognize that at the intermediate focus 6 the power density is at a maximum and therefore the spectral filter is likely to be damaged. However, by using a plasma 18 as the spectral filter (as generated by the plasma generator 16), the radiation system (comprising the radiation source SO and the plasma generator 16) is able to provide this spectral filter functionality proximate the intermediate focus 6.

[00091] The plasma generator 16 may be operable to form the plasma from any gas. Said gas may comprise, for example, hydrogen gas. Additionally or alternatively, the gas may comprise, for example, an inert gas such as, for example argon.

[00092] In some embodiments, the plasma generator 16 may be operable to generate the plasma 18 using arc discharge. Alternatively, any other method for generating plasma may be used, including, for example, arrangements that use any of the following: laser radiation to produce a plasma (i.e. a laser produced plasma); a plasma railgun; a hypervelocity plasma source; a microwave-driven plasma source; or any other compact plasma source.

[00093] It will be appreciated that the plasma generator 16 may be located at or near the opening 8. For example, the plasma 18 may be formed at the opening 8. Alternatively, the plasma generator 16 may be located remote from the opening 8 and the plasma 18 may be guided across the propagation direction of the output radiation B.

[00094] In some embodiments, the plasma generator 16 may be operable to direct the plasma 18 produced by the plasma generator 16 so as to flow at least partially across the opening 8. Advantageously, by providing a flow of plasma 18 across the opening 8 the efficiency of removal of particulate debris can be improved over, for example, a static plasma since the particulate debris can be entrained in the plasma flow and prevented from passing through it and forming part of the output of the radiation source SO.

[00095] In some embodiments, the plasma generator 16 may comprise at least one plasma generating unit arranged to generate a plasma 18 and to direct the plasma 18 at least partially across the path of the output radiation beam B. For example, one or more plasma generating units may be arranged to direct a flow of plasma 18 at least partially across the opening 8. An embodiment of a plasma generating unit 20 that may form part of the plasma generator 16 is shown schematically, and in cross section, in Figure 2.

[00096] The plasma generating unit 20 comprises: a first electrode 22, a second electrode 24, a voltage source 26 and a gas flow generator 28. The first electrode 22 is hollow having a central bore. The second electrode 24 is provided within the bore of the hollow first electrode 22.

[00097] The voltage source 26 is operable to apply a voltage across the first electrode 22 and the second electrode 24. As shown schematically in Figure 2, this is achieved via two connecting wires 32, 34 which connect the voltage source 26 to the first and second electrodes 22, 24 respectively. As will

be appreciated by the skilled person, the voltage source 26 may comprise any combination of the following: one or more a high-voltage power supplies; one or more resistors; one or more energy-storage capacitors; and one or more power switching devices.

[00098] The gas flow generator 28 is operable to generate a gas flow 36 between the first electrode 22 and the second electrode 24. The gas flow 36 generated by the gas flow generator 28 may comprise hydrogen gas. The hydrogen gas may be provided at a pressure of around 1 atmosphere or approximately 1 bar.

[00099] The voltage source 26 is operable to generate an electric field strength between the first electrode 22 and the second electrode 24 that is sufficient to ionize the gas flow 36 so as to form a plasma flow 38. The voltage source 26 may be operable to apply an initial large voltage across the first electrode 22 and the second electrode 24 so as to initiate the plasma 18 formation. Once a plasma 18 has been formed, a resistance between the first electrode 22 and the second electrode 24 drops significantly, and a smaller voltage may be applied across the first electrode 22 and the second electrode 24 so as to sustain the plasma 18. An initial ignition process for the plasma 18 formation may use an electric field strength of the order of 10 kV/cm. For example, at least initially, the voltage source 26 may be operable to apply a voltage across the first electrode 22 and the second electrode 24 of the order of 10 kV and the first electrode 22 and the second electrode 24 may be separated by a distance of the order of 1 cm. In order to sustain the plasma 18, the voltage source 26 may be operable to generate an electric field strength of at least 100 V/m between the first electrode 22 and the second electrode 24.

[00100] In the arrangement shown in Figure 2, the first electrode 22 is generally tubular and may form part of a conduit for the gas flow 36 from the gas flow generator 28. The second electrode 24 is generally coaxial with the first electrode 22. Together, the first electrode 22 and the second electrode 24 define a channel 30, which is generally annular in cross section through which the gas flow 36 can flow between the first electrode 22 and the second electrode 24.

[00101] Although the first electrode 22 is generally tubular, it is provided with a generally frustoconical portion at an end of the first electrode 22 which is distal the gas flow generator 28. The frustoconical portion acts as a nozzle. The nozzle acts to focus the plasma flow 38 into a smaller volume. In turn, this can increase the electron density of the plasma flow 38 (which may be directed at least partially across the opening 8).

[00102] The plasma generator 16 shown in Figure 1 may comprise a plurality of plasma generating units 20 generally of the form shown in Figure 2 and described above. Embodiments of such plasma generators 16 are now described with reference to Figures 3A to 4.

[00103] A first embodiment of a plasma generator 16 comprising a plurality of plasma generating units 20 is shown in Figures 3A and 3B.

[00104] Figure 3A shows, in cross section, a portion of the enclosing structure 9 of the radiation source SO proximate to the opening 8 in a plane which contains an optical axis 40 of the radiation source SO. In Figures 3A and 3B the optical axis 40 of the radiation source SO is the z-direction. It

will be appreciated that the optical axis 40 of the radiation source SO may coincide with a main direction of the output radiation B, which may be the average direction of the output radiation B (which may be the direction of the chief ray of the output radiation B). Figure 3B shows, in cross section, the opening 8 of the radiation source SO in a plane which is perpendicular to the optical axis 40 of the radiation source SO.

[000105] As can be seen in Figure 3B, in the embodiment shown in Figures 3A and 3B, the plasma generator 16 comprises three plasma generating units 20 distributed around the opening 8 and three plasma exits 42 distributed around the opening 8. Each of the plasma generating units 20 is arranged to direct the plasma flow 38 generated thereby across the opening 8. Each of the plasma exits 42 is disposed opposite a different one of the plasma generating units 20 and is arranged to receive the plasma flow 38 generated thereby once it has propagated across the opening 8.

[000106] Each plasma generating unit 20 is operable to provide a flow of plasma 38, from a different direction, that at least partially traverses the opening 8. Together, all of these plasma flows 38 combine to form a plasma 18 which extends at least partially across the opening 8 and which has a greater electron density than any of the individual plasma flows 36.

[000107] Although the example shown in Figure 3A and 3B comprises three plasma generating units 20 and three corresponding plasma exits 42, it will be appreciated that in alternative embodiments more or fewer plasma generating units 20 may be provided. Generally, a plasma exit 42 may be provided on an opposite side of the opening 8 to each of the plasma generating units 20.

[000108] A second embodiment of a plasma generator 16 comprising a plurality of plasma generating units 20 is shown in Figure 4.

[000109] Figure 4 shows, in cross section, a portion of the enclosing structure 9 of the radiation source SO proximate to the opening 8 in a plane which contains an optical axis 40 of the radiation source SO. In Figure 4 the optical axis 40 of the radiation source SO is the z-direction. It will be appreciated that the optical axis 40 of the radiation source SO may coincide with a main direction of the output radiation B, which may be the average direction of the output radiation B (which may be the direction of the chief ray of the output radiation B).

[000110] In this embodiment, as shown in Figure 4, the plasma generator 16 comprises six plasma generating units 20 distributed around the opening 8. Although the example shown in Figure 4 comprises six plasma generating units 20, it will be appreciated that in alternative embodiments more or fewer plasma generating units 20 may be provided. It will be further appreciated that the plasma generating units 20 may be distributed substantially evenly around the opening 8.

[000111] Each of the plasma generating units 20 is arranged to direct the plasma flow 38 generated by that plasma generating unit 20 partially across the opening 8. In addition, as can be seen in Figure 4, each of plasma generating units 20 is arranged to direct the plasma flow 38 generated thereby so as to flow at least partially through the opening 8 and into the enclosing structure 9 of the radiation source SO.

[000112] Each plasma generating unit 20 is operable to provide a flow of plasma 38, from a different direction, that at least partially traverses the opening 8. Together, all of these plasma flows 38 combine to form a plasma 18 which extends at least partially across the opening 8 and which has a greater electron density than any of the individual plasma flows 36.

5 [000113] Advantageously, by providing a flow of plasma through the opening 8 and into the enclosing structure 9 of the radiation source SO the efficiency of removal of particulate debris can be further improved since the flow of plasma 18 will tend to force particulate debris back into the enclosing structure 9. Therefore, this particulate debris is (at least partially) prevented from going through the opening 8 and reaching optics in the lithographic apparatus LA. In this way, the plasma generator 16
10 may be considered to form part of a dynamic plasma lock.

[000114] In some embodiments, the plasma generator 16 is provided with one or more adjustable parameters and one or more properties of the plasma 18 can be controlled by controlling said one or more adjustable parameters. The one or more adjustable parameters may, for example, comprise the voltage across the first electrode 22 and the second electrode 24 that may be applied by the voltage
15 source 26 of one or more of the plasma generating units 20. Additionally or alternatively, the one or more adjustable parameters may, for example, comprise a pressure or the gas flow 36 generated by the gas flow generator 28 of one or more of the plasma generating units 20.

[000115] In some embodiments, the output radiation B generated by the radiation source SO is pulsed. For such embodiments, the plasma 18 produced by the plasma generator 16 may be pulsed.
20 Furthermore the radiation source SO and the plasma generator 16 may be synchronized such that the plasma 18 is present as each pulse of the output radiation propagates through the opening 8.

[000116] Although specific reference may be made in this text to the use of lithographic apparatus in the manufacture of ICs, it should be understood that the lithographic apparatus described herein may have other applications. Possible other applications include the manufacture of integrated optical
25 systems, guidance and detection patterns for magnetic domain memories, flat-panel displays, liquid-crystal displays (LCDs), thin-film magnetic heads, etc.

[000117] Although specific reference may be made in this text to embodiments of the invention in the context of a lithographic apparatus, embodiments of the invention may be used in other apparatus. Embodiments of the invention may form part of a mask inspection apparatus, a metrology apparatus,
30 or any apparatus that measures or processes an object such as a wafer (or other substrate) or mask (or other patterning device). These apparatus may be generally referred to as lithographic tools. Such a lithographic tool may use vacuum conditions or ambient (non-vacuum) conditions.

[000118] Where the context allows, embodiments of the invention may be implemented in hardware, firmware, software, or any combination thereof. Embodiments of the invention may also be
35 implemented as instructions stored on a machine-readable medium, which may be read and executed by one or more processors. A machine-readable medium may include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computing device). For example, a

machine-readable medium may include read only memory (ROM); random access memory (RAM); magnetic storage media; optical storage media; flash memory devices; electrical, optical, acoustical or other forms of propagated signals (e.g. carrier waves, infrared signals, digital signals, etc.), and others. Further, firmware, software, routines, instructions may be described herein as performing certain actions. However, it should be appreciated that such descriptions are merely for convenience and that such actions in fact result from computing devices, processors, controllers, or other devices executing the firmware, software, routines, instructions, etc. and in doing that may cause actuators or other devices to interact with the physical world.

[000119] While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The descriptions above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the art that modifications may be made to the invention as described without departing from the scope of the claims set out below.

CLAIMS:

1. A system comprising:
a radiation source comprising:
5 a housing provided with an exit aperture; and
a radiation generator operable to generate output radiation in the housing and
to direct at least a portion of the output radiation through the exit aperture; and
a plasma generator operable to produce a plasma which extends at least
partially across the at least a portion of the output radiation directed through the exit
10 aperture.
2. The system of claim 1 wherein the radiation generator comprises:
a target generator operable to produce a target comprising target material at a plasma formation
region, the plasma formation region arranged to receive laser radiation for illuminating the target
15 material to thereby generate a second plasma that emits the output radiation; and
an optical element arranged to direct at least a portion of the output radiation towards the exit
aperture.
3. The system of claim 1 or claim 2 wherein the radiation generator is arranged to focus at least a
20 portion of the output radiation at an intermediate focus, the intermediate focus being disposed at or
proximate to the exit aperture.
4. The system of any preceding claim wherein the plasma generator is operable to form the plasma
from hydrogen gas.
25
5. The system of any preceding claim wherein the plasma generator is operable to form a plasma
with an electron density higher than 10^{19} cm^{-3} .
6. The system of any preceding claim wherein the plasma generator is operable to form a plasma
30 with an electron density higher than $6.7 \times 10^{22} \text{ cm}^{-3}$.
7. The system of any preceding claim wherein the plasma generator is operable to form a plasma
with an electron density less than $6.7 \times 10^{24} \text{ cm}^{-3}$.
- 35 8. The system of any preceding claim wherein the plasma generator is operable to form a plasma
in a region having an extent in a propagation direction of the output radiation that is greater than 300
 μm .

9. The system of any preceding claim wherein the plasma generator is operable to generate the plasma using arc discharge.

10. The system of any preceding claim wherein the plasma generator is operable to direct the plasma produced by the plasma generator so as to flow at least partially across the exit aperture.

11. The system of any preceding claim wherein the plasma generator is operable to direct the plasma produced by the plasma generator so as to flow at least partially through the exit aperture and into the housing.

12. The system of any preceding claim wherein the plasma generator comprises at least one plasma generating unit arranged to generate a plasma and to direct the plasma at least partially across the exit aperture.

13. The system of claim 12 wherein, the or each plasma generating unit comprises:
a first electrode and a second electrode;
a voltage source operable to apply a voltage across the first electrode and the second electrode;
and
a gas flow generator operable to generate a gas flow between the first electrode and the second electrode and in a direction at least partially across the exit aperture.

14. The system of claim 13 wherein the first electrode is hollow and the second electrode is provided within the first electrode.

15. The system of claim 13 or claim 14 wherein the or each plasma generating unit comprises a nozzle.

16. The system of any one of claims 12 to 15 wherein the plasma generator comprises a plurality of the plasma generating units.

17. The system of any preceding claim wherein the plasma generator is provided with one or more adjustable parameters and wherein one or more properties of the plasma can be controlled by controlling said one or more adjustable parameters.

18. The system of any preceding claim wherein the output radiation generated by the radiation generator is pulsed, the plasma produced by the plasma generator is pulsed and wherein the radiation

generator and the plasma generator are synchronized such that the plasma is present as each pulse of the output radiation propagates through a region wherein the plasma is formed.

19. A lithographic system comprising:
- 5 a system of any preceding claim; and
- a lithographic apparatus operable to receive output radiation from the radiation source and to form an image of a patterning device on a substrate using said output radiation.

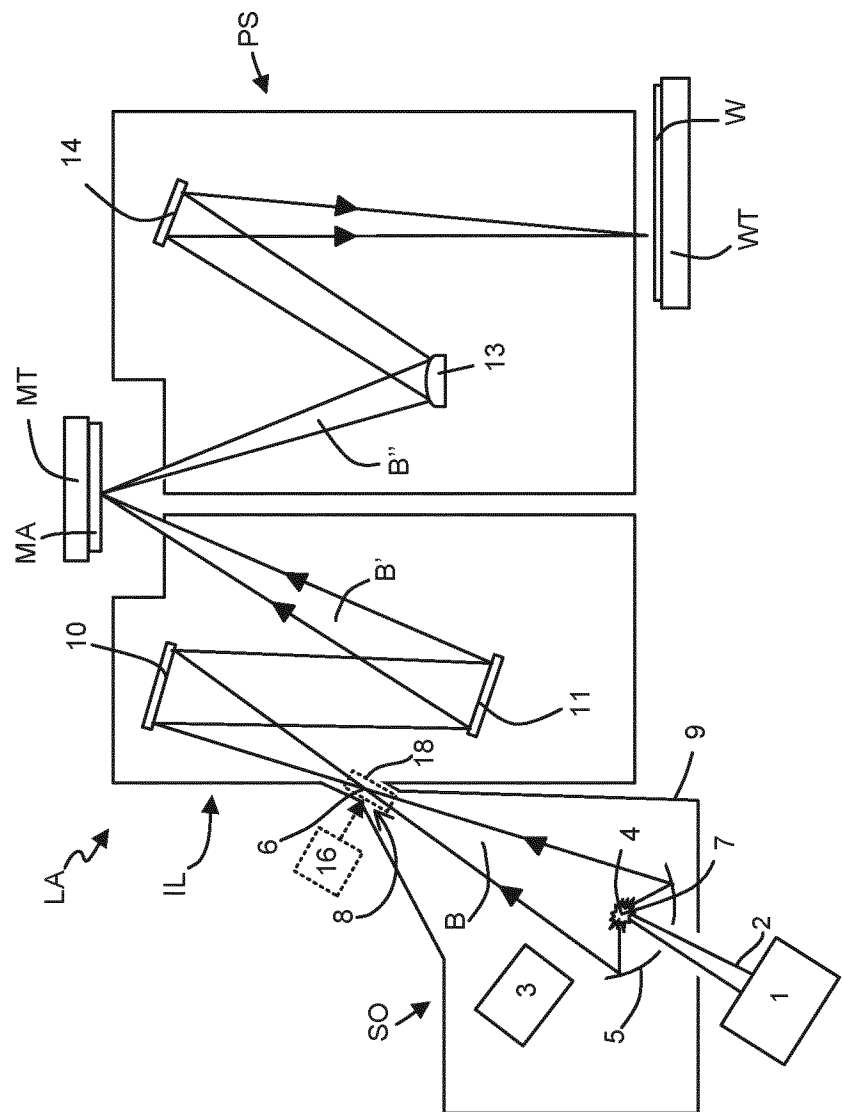


FIG. 1

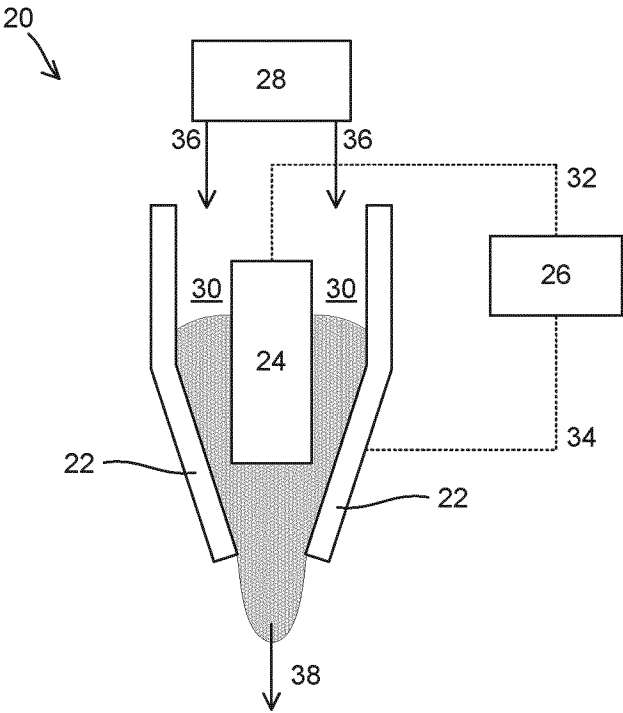


FIG. 2

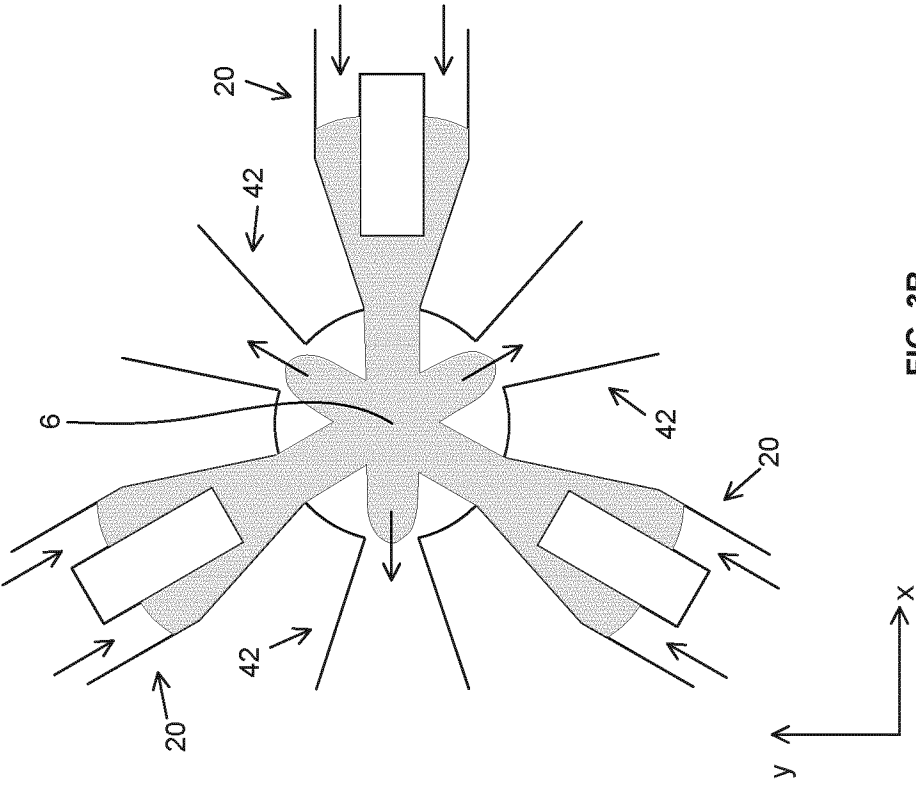


FIG. 3A

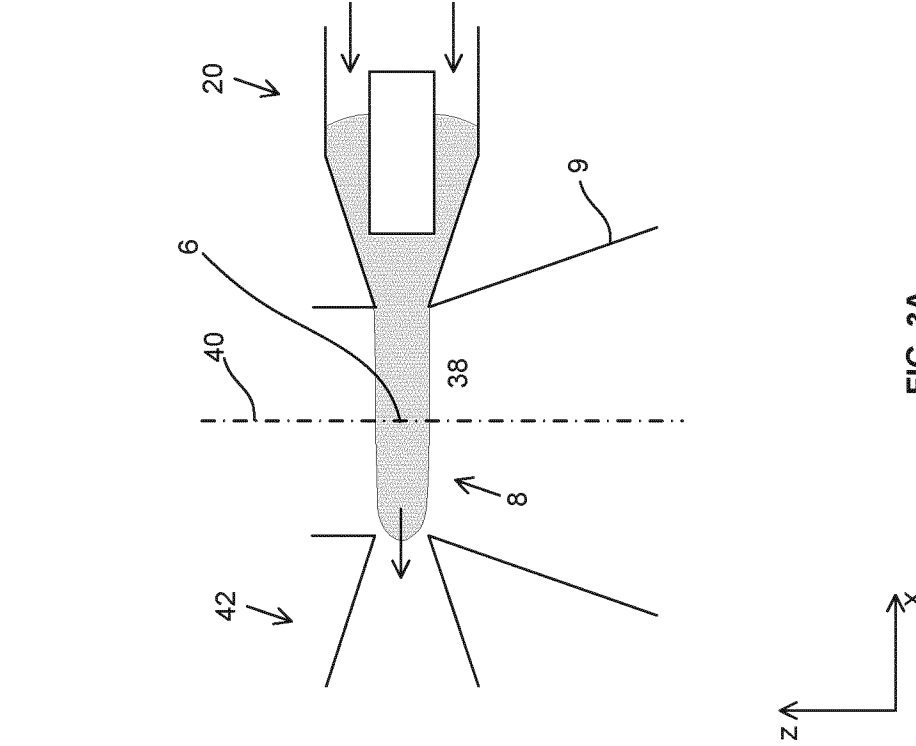
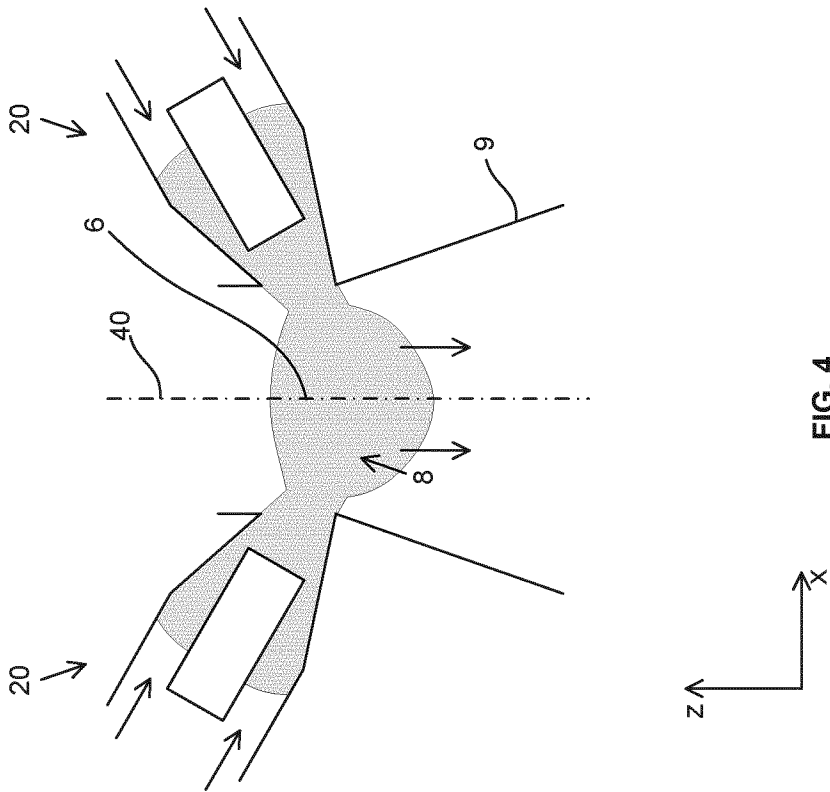


FIG. 3B



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/051709

A. CLASSIFICATION OF SUBJECT MATTER INV. H05G2/00 G21K1/10 G03F7/20 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H05G G21K G03F		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/149260 A1 (GOODWIN FRANCIS [US]) 23 June 2011 (2011-06-23) figures 1,3 paragraphs [0022] - [0037]	1-3,5-7, 10-13, 17,19
X	US 2011/222040 A1 (STEINHOFF JENS ARNO [DE] ET AL) 15 September 2011 (2011-09-15) paragraphs [0071], [0077] - [0081]; figure 8 paragraph [0002]	1-4,18, 19
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 9 April 2020		Date of mailing of the international search report 22/04/2020
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Giovanardi, Chiara

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2020/051709

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PINKOSKI B T ET AL: "X-ray transmission through a plasma window", REVIEW OF SCIENTIFIC INSTRUMENTS, AIP, MELVILLE, NY, US, vol. 72, no. 3, 1 March 2001 (2001-03-01), pages 1677-1679, XP012039026, ISSN: 0034-6748, DOI: 10.1063/1.1344598 the whole document -----	1,7-9, 12-17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2020/051709

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2011149260	A1	23-06-2011	NONE

US 2011222040	A1	15-09-2011	JP 5758153 B2 05-08-2015
		JP 2011192989 A	29-09-2011
		US 2011222040 A1	15-09-2011
