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Smith

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(54) **LASER-DRIVEN LIGHT SOURCE**

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(73) Assignee: **Energetiq Technology, Inc.**, Woburn, MA (US)

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Related U.S. Application Data

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(51) **Int. Cl.**

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G01J 3/10	(2006.01)
G21G 4/00	(2006.01)
H01J 61/28	(2006.01)

(52) **U.S. Cl.** .... **250/493.1**; 250/504 R; 315/111.21; 315/111.71; 315/111.91; 313/231.31; 313/231.41; 313/231.71

(58) **Field of Classification Search** .... 250/423 R, 250/423 P, 424, 426, 494.1, 493.1, 504 R, 250/504 H; 315/111.21, 111.71, 111.91; 313/231.31, 231.41, 231.61, 231.71, 631, 313/632, 633

See application file for complete search history.

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Primary Examiner—Bernard E Souw
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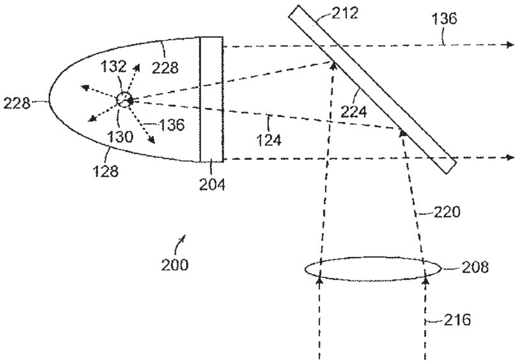
(57) **ABSTRACT**

An apparatus for producing light includes a chamber and an ignition source that ionizes a gas within the chamber. The apparatus also includes at least one laser that provides energy to the ionized gas within the chamber to produce a high brightness light. The laser can provide a substantially continuous amount of energy to the ionized gas to generate a substantially continuous high brightness light.

43 Claims, 8 Drawing Sheets



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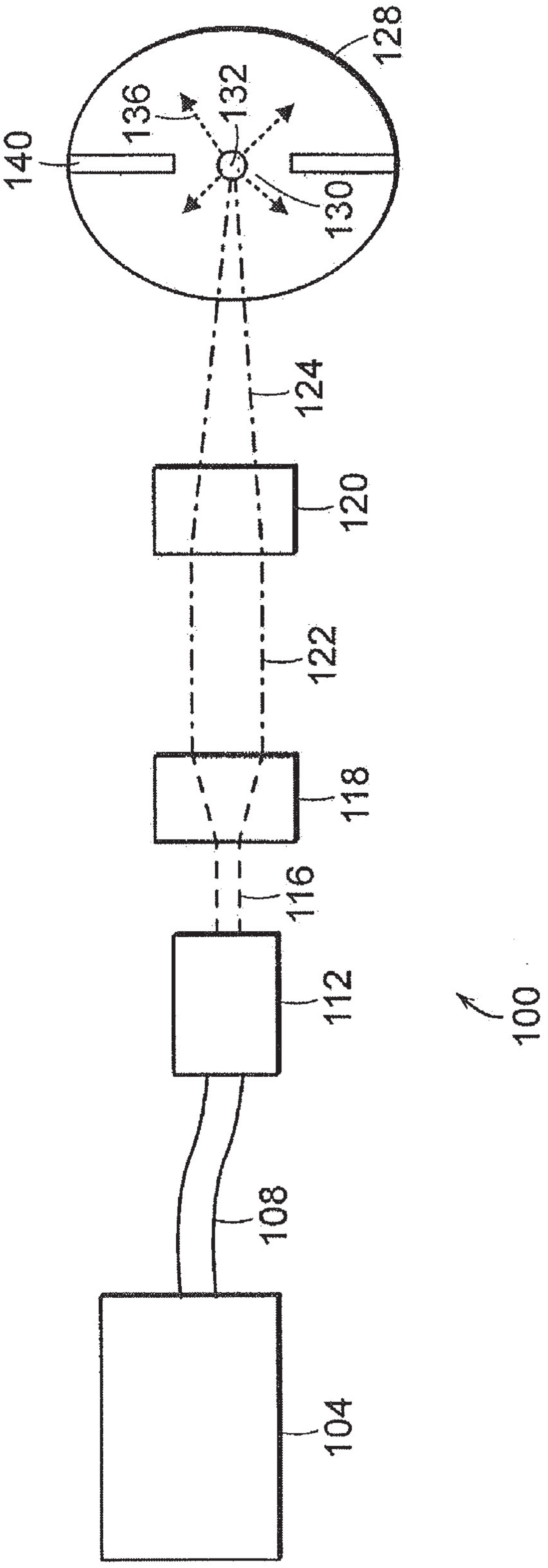

FIG. 1

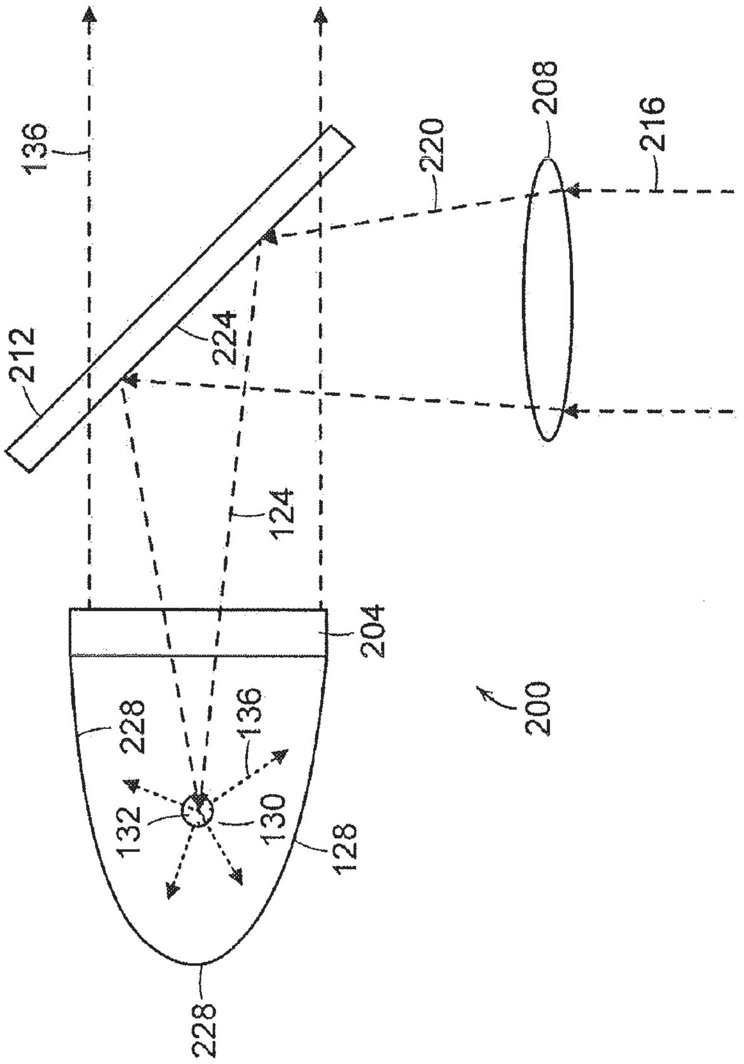

FIG. 2

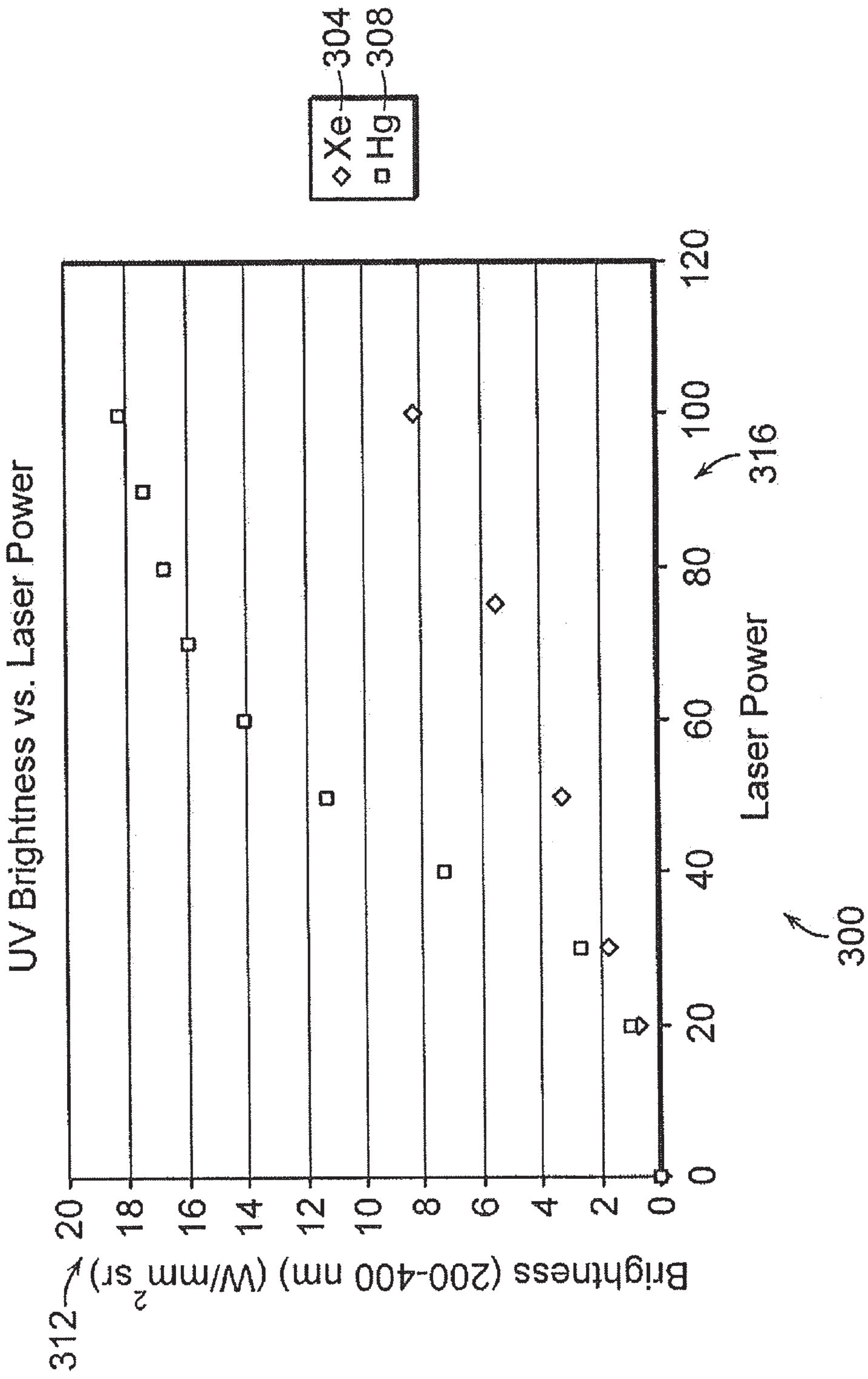
UV Brightness vs. Laser Power
Brightness (200-400 nm) (W/mm^{2}sr)
312
20
18
16
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
Laser Power
316
300
◇ Xe
□ Hg
304
308

FIG. 3

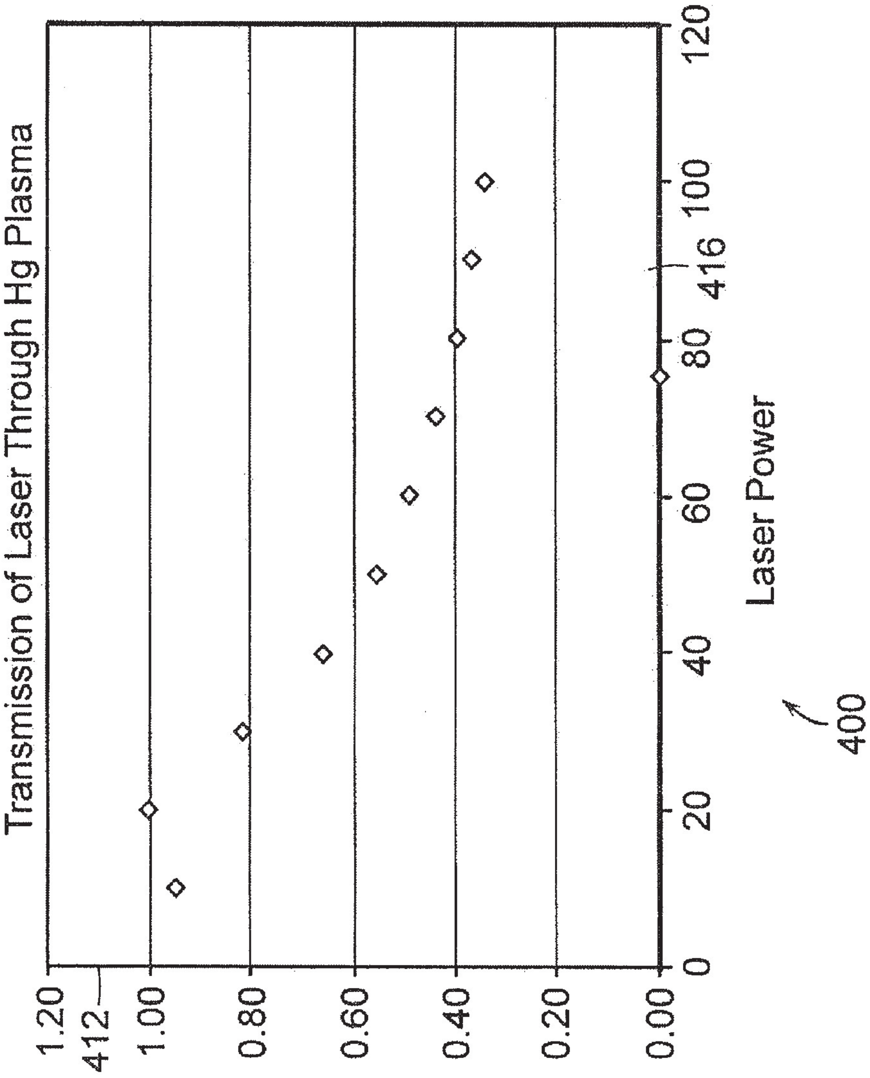
Transmission of Laser Through Hg Plasma
1.20
1.00
0.80
0.60
0.40
0.20
0.00
412
0
20
40
60
80
100
120
416
Laser Power
400

FIG. 4

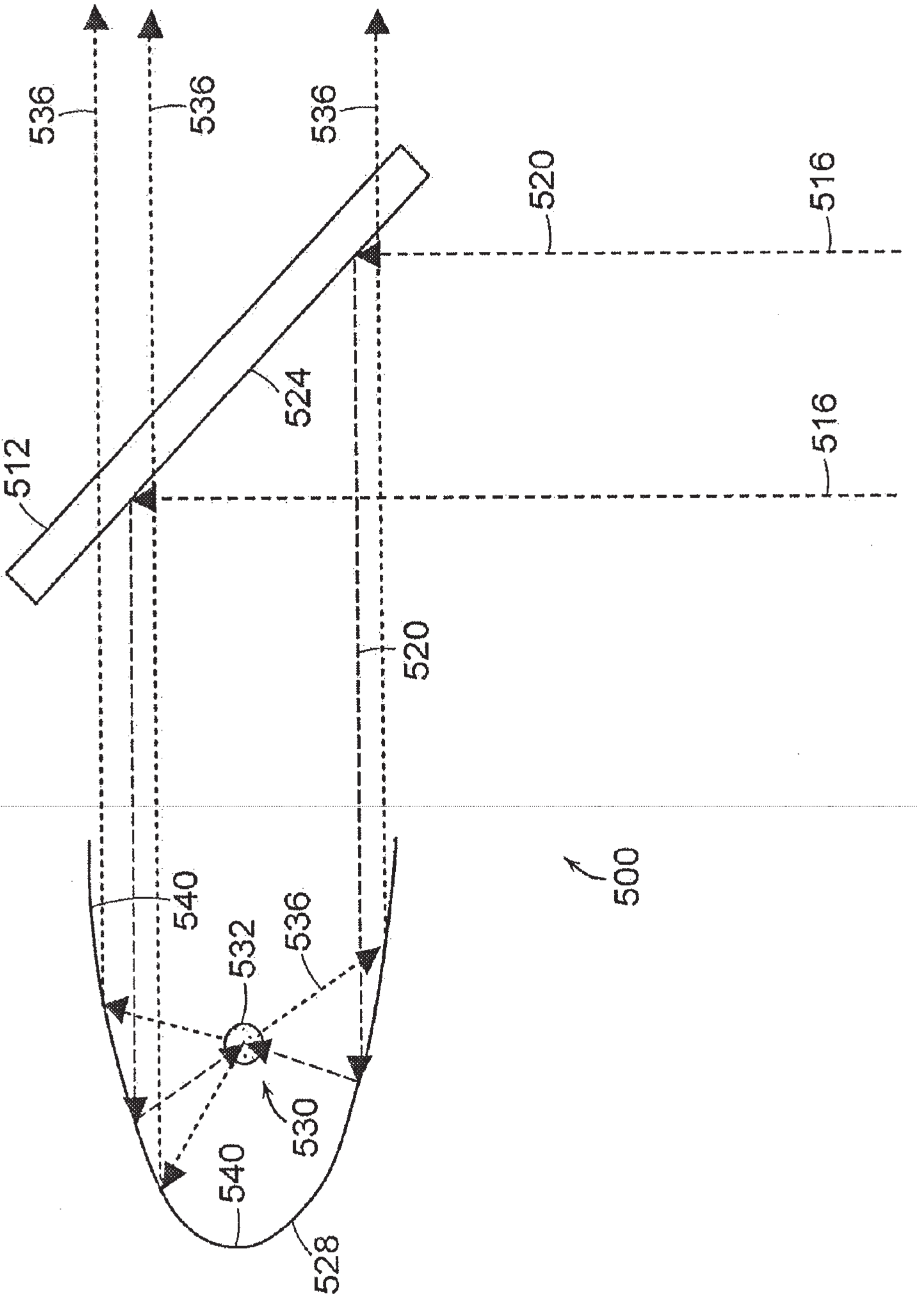

FIG. 5

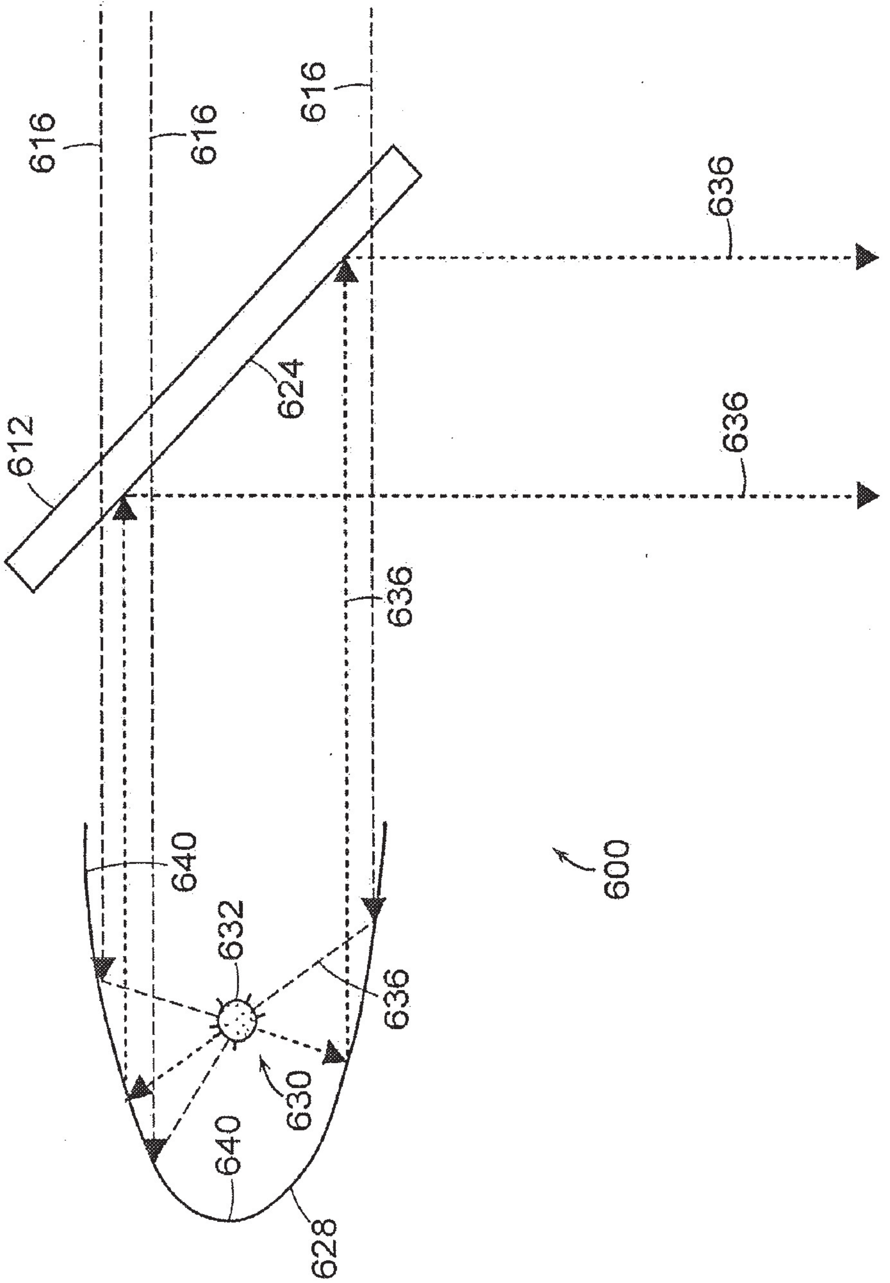

FIG. 6

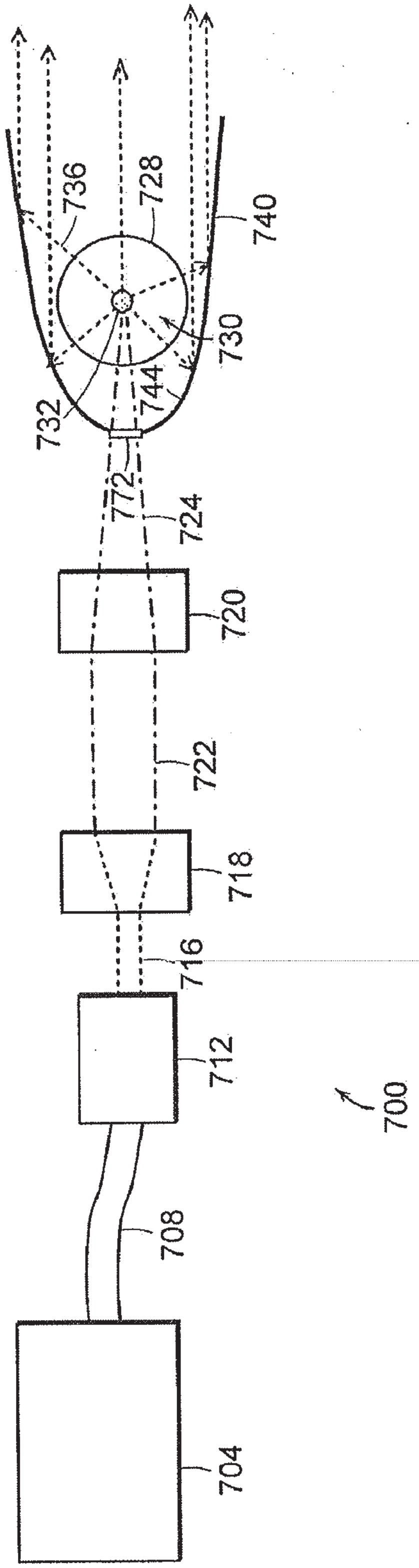

FIG. 7

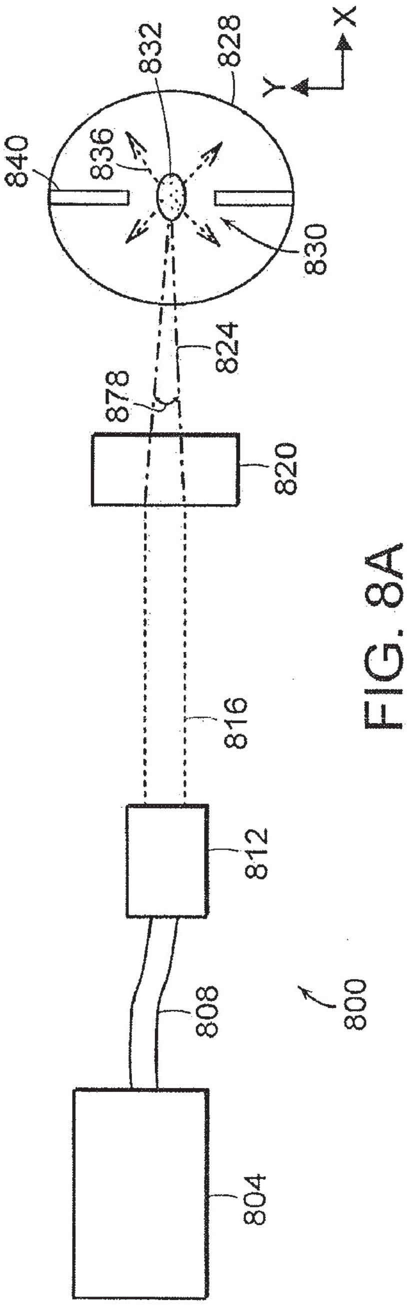
804
808
812
816
820
878
824
828
832
836
840
830
Y
X
800

FIG. 8A

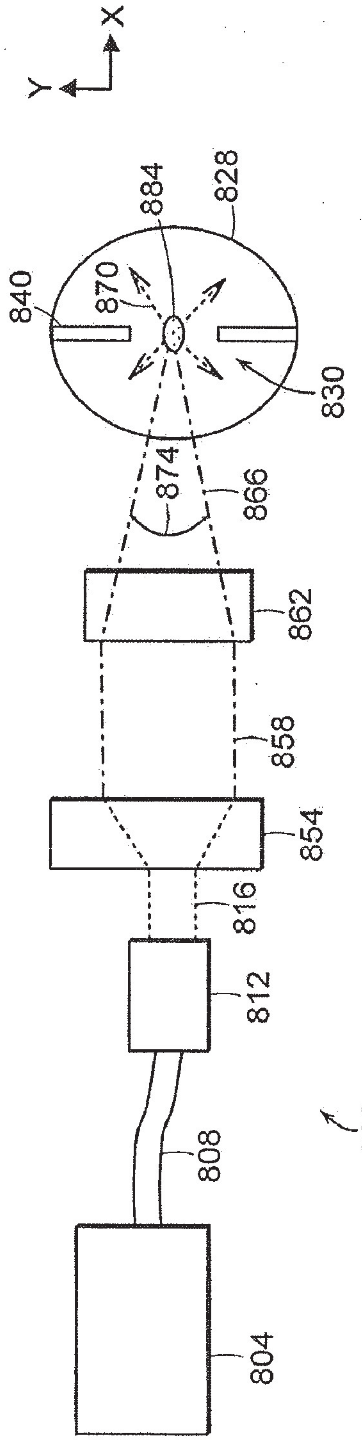
804
808
812
816
854
858
862
866
874
828
884
870
840
830
Y
X
800

FIG. 8B

LASER-DRIVEN LIGHT SOURCE

RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Ser. No. 11/395,523, filed on Mar. 31, 2006, now U.S. Pat. No. 7,435,982, the entire disclosure of which is incorporated by reference herein.

FIELD OF THE INVENTION

The invention relates to methods and apparatus for providing a laser-driven light source.

BACKGROUND OF THE INVENTION

High brightness light sources can be used in a variety of applications. For example, a high brightness light source can be used for inspection, testing or measuring properties associated with semiconductor wafers or materials used in the fabrication of wafers (e.g., reticles and photomasks). The electromagnetic energy produced by high brightness lights sources can, alternatively, be used as a source of illumination in a lithography system used in the fabrication of wafers, a microscopy systems, or a photoresist curing system. The parameters (e.g., wavelength, power level and brightness) of the light vary depending upon the application.

The state of the art in, for example, wafer inspection systems involves the use of xenon or mercury arc lamps to produce light. The arc lamps include an anode and cathode that are used to excite xenon or mercury gas located in a chamber of the lamp. An electrical discharge is generated between the anode and cathode to provide power to the excited (e.g., ionized) gas to sustain the light emitted by the ionized gas during operation of the light source. During operation, the anode and cathode become very hot due to electrical discharge delivered to the ionized gas located between the anode and cathode. As a result, the anode and/or cathode are prone to wear and may emit particles that can contaminate the light source or result in failure of the light source. Also, these arc lamps do not provide sufficient brightness for some applications, especially in the ultraviolet spectrum. Further, the position of the arc can be unstable in these lamps.

Accordingly, a need therefore exists for improved high brightness light sources. A need also exists for improved high brightness light sources that do not rely on an electrical discharge to maintain a plasma that generates a high brightness light.

SUMMARY OF THE INVENTION

The present invention features a light source for generating a high brightness light.

The invention, in one aspect, features a light source having a chamber. The light source also includes an ignition source for ionizing a gas within the chamber. The light source also includes at least one laser for providing energy to the ionized gas within the chamber to produce a high brightness light.

In some embodiments, the at least one laser is a plurality of lasers directed at a region from which the high brightness light originates. In some embodiments, the light source also includes at least one optical element for modifying a property of the laser energy provided to the ionized gas. The optical element can be, for example, a lens (e.g., an aplanatic lens, an achromatic lens, a single element lens, and a fresnel lens) or mirror (e.g., a coated mirror, a dielectric coated mirror, a narrow band mirror, and an ultraviolet transparent infrared reflecting mirror). In some embodiments, the optical element is one or more fiber optic elements for directing the laser energy to the gas.

The chamber can include an ultraviolet transparent region. The chamber or a window in the chamber can include a material selected from the group consisting of quartz, Suprasil® quartz (Heraeus Quartz America, LLC, Buford, Ga.), sapphire, MgF_2, diamond, and CaF_2. In some embodiments, the chamber is a sealed chamber. In some embodiments, the chamber is capable of being actively pumped. In some embodiments, the chamber includes a dielectric material (e.g., quartz). The chamber can be, for example, a glass bulb. In some embodiments, the chamber is an ultraviolet transparent dielectric chamber.

The gas can be one or more of a noble gas, Xe, Ar, Ne, Kr, He, D_2, H_2, O_2, F_2, a metal halide, a halogen, Hg, Cd, Zn, Sn, Ga, Fe, Li, Na, an excimer forming gas, air, a vapor, a metal oxide, an aerosol, a flowing media, or a recycled media. The gas can be produced by a pulsed laser beam that impacts a target (e.g., a solid or liquid) in the chamber. The target can be a pool or film of metal. In some embodiments, the target is capable of moving. For example, the target may be a liquid that is directed to a region from which the high brightness light originates.

In some embodiments, the at least one laser is multiple diode lasers coupled into a fiber optic element. In some embodiments, the at least one laser includes a pulse or continuous wave laser. In some embodiments, the at least one laser is an IR laser, a diode laser, a fiber laser, an ytterbium laser, a CO_2 laser, a YAG laser, or a gas discharge laser. In some embodiments, the at least one laser emits at least one wavelength of electromagnetic energy that is strongly absorbed by the ionized medium.

The ignition source can be or can include electrodes, an ultraviolet ignition source, a capacitive ignition source, an inductive ignition source, an RF ignition source, a microwave ignition source, a flash lamp, a pulsed laser, or a pulsed lamp. The ignition source can be a continuous wave (CW) or pulsed laser impinging on a solid or liquid target in the chamber. The ignition source can be external or internal to the chamber.

The light source can include at least one optical element for modifying a property of electromagnetic radiation emitted by the ionized gas. The optical element can be, for example, one or more mirrors or lenses. In some embodiments, the optical element is configured to deliver the electromagnetic radiation emitted by the ionized gas to a tool (e.g., a wafer inspection tool, a microscope, a metrology tool, a lithography tool, or an endoscopic tool).

The invention, in another aspect, relates to a method for producing light. The method involves ionizing with an ignition source a gas within a chamber. The method also involves providing laser energy to the ionized gas in the chamber to produce a high brightness light.

In some embodiments, the method also involves directing the laser energy through at least one optical element for modifying a property of the laser energy provided to the ionized gas. In some embodiments, the method also involves actively pumping the chamber. The ionizable medium can be a moving target. In some embodiments, the method also involves directing the high brightness light through at least one optical element to modify a property of the light. In some embodiments, the method also involves delivering the high brightness light emitted by the ionized medium to a tool (e.g., a wafer inspection tool, a microscope, a metrology tool, a lithography tool, or an endoscopic tool).

In another aspect, the invention features a light source. The lights source includes a chamber and an ignition source for ionizing an ionizable medium within the chamber. The light source also includes at least one laser for providing substantially continuous energy to the ionized medium within the chamber to produce a high brightness light.

In some embodiments, the at least one laser is a continuous wave laser or a high pulse rate laser. In some embodiments, the at least one laser is a high pulse rate laser that provides pulses of energy to the ionized medium so the high brightness light is substantially continuous. In some embodiments, the magnitude of the high brightness light does not vary by more than about 90% during operation. In some embodiments, the at least one laser provides energy substantially continuously to minimize cooling of the ionized medium when energy is not provided to the ionized medium.

In some embodiments, the light source can include at least one optical element (e.g., a lens or mirror) for modifying a property of the laser energy provided to the ionized medium. The optical element can be, for example, an aplanatic lens, an achromatic lens, a single element lens, a fresnel lens, a coated mirror, a dielectric coated mirror, a narrow band mirror, or an ultraviolet transparent infrared reflecting mirror. In some embodiments, the optical element is one or more fiber optic elements for directing the laser energy to the ionizable medium.

In some embodiments, the chamber includes an ultraviolet transparent region. In some embodiments, the chamber or a window in the chamber includes a quartz material, suprasil quartz material, sapphire material, MgF_2 material, diamond material, or CaF_2 material. In some embodiments, the chamber is a sealed chamber. The chamber can be capable of being actively pumped. In some embodiments, the chamber includes a dielectric material (e.g., quartz). In some embodiments, the chamber is a glass bulb. In some embodiments, the chamber is an ultraviolet transparent dielectric chamber.

The ionizable medium can be a solid, liquid or gas. The ionizable medium can include one or more of a noble gas, Xe, Ar, Ne, Kr, He, D_2, H_2, O_2, F_2, a metal halide, a halogen, Hg, Cd, Zn, Sn, Ga, Fe, Li, Na, an excimer forming gas, air, a vapor, a metal oxide, an aerosol, a flowing media, a recycled media, or an evaporating target. In some embodiments, the ionizable medium is a target in the chamber and the ignition source is a pulsed laser that provides a pulsed laser beam that strikes the target. The target can be a pool or film of metal. In some embodiments, the target is capable of moving.

In some embodiments, the at least one laser is multiple diode lasers coupled into a fiber optic element. The at least one laser can emit at least one wavelength of electromagnetic energy that is strongly absorbed by the ionized medium.

The ignition source can be or can include electrodes, an ultraviolet ignition source, a capacitive ignition source, an inductive ignition source, an RF ignition source, a microwave ignition source, a flash lamp, a pulsed laser, or a pulsed lamp. The ignition source can be external or internal to the chamber.

In some embodiments, the light source includes at least one optical element (e.g., a mirror or lens) for modifying a property of electromagnetic radiation emitted by the ionized medium. The optical element can be configured to deliver the electromagnetic radiation emitted by the ionized medium to a tool (e.g., a wafer inspection tool, a microscope, a metrology tool, a lithography tool, or an endoscopic tool).

The invention, in another aspect relates to a method for producing light. The method involves ionizing with an ignition source an ionizable medium within a chamber. The method also involves providing substantially continuous laser energy to the ionized medium in the chamber to produce a high brightness light.

In some embodiments, the method also involves directing the laser energy through at least one optical element for modifying a property of the laser energy provided to the ionizable medium. The method also can involve actively pumping the chamber. In some embodiments, the ionizable medium is a moving target. The ionizable medium can include a solid, liquid or gas. In some embodiments, the method also involves directing the high brightness light through at least one optical element to modify a property of the light. In some embodiments, the method also involves delivering the high brightness light emitted by the ionized medium to a tool.

The invention, in another aspect, features a light source having a chamber. The light source includes a first ignition means for ionizing an ionizable medium within the chamber. The light source also includes a means for providing substantially continuous laser energy to the ionized medium within the chamber.

The invention, in another aspect, features a light source having a chamber that includes a reflective surface. The light source also includes an ignition source for ionizing a gas within the chamber. The light source also includes a reflector that at least substantially reflects a first set of predefined wavelengths of electromagnetic energy directed toward the reflector and at least substantially allows a second set of predefined wavelengths of electromagnetic energy to pass through the reflector. The light source also includes at least one laser (e.g., a continuous-wave fiber laser) external to the chamber for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light. A continuous-wave laser emits radiation continuously or substantially continuously rather than in short bursts, as in a pulsed laser.

In some embodiments, at least one laser directs a first set of wavelengths of electromagnetic energy through the reflector toward the reflective surface (e.g., inner surface) of the chamber and the reflective surface directs at least a portion of the first set of wavelengths of electromagnetic energy toward the plasma. In some embodiments, at least a portion of the high brightness light is directed toward the reflective surface of the chamber, is reflected toward the reflector, and is reflected by the reflector toward a tool. In some embodiments, at least one laser directs a first set of wavelengths of electromagnetic energy toward the reflector, the reflector reflects at least a portion of the first wavelengths of electromagnetic energy towards the reflective surface of the chamber, and the reflective surface directs a portion of the first set of wavelengths of electromagnetic energy toward the plasma.

In some embodiments, at least a portion of the high brightness light is directed toward the reflective surface of the chamber, is reflected toward the reflector, and passes through the reflector toward an output of the light source. In some embodiments, the light source comprises a microscope, ultraviolet microscope, wafer inspection system, reticle inspection system or lithography system spaced relative to the output of the light source to receive the high brightness light. In some embodiments, a portion of the high brightness light is directed toward the reflective surface of the chamber, is reflected toward the reflector, and electromagnetic energy comprising the second set of predefined wavelengths of electromagnetic energy passes through the reflector.

The chamber of the light source can include a window. In some embodiments, the chamber is a sealed chamber. In some embodiments, the reflective surface of the chamber comprises a curved shape, parabolic shape, elliptical shape, spherical shape or aspherical shape. In some embodiments, the chamber has a reflective inner surface. In some embodiments, a coating or film is located on the outside of the chamber to produce the reflective surface. In some embodiments, a coating or film is located on the inside of the chamber to produce the reflective surface. In some embodiments, the reflective surface is a structure or optical element that is distinct from the inner surface of the chamber.

The light source can include an optical element disposed along a path the electromagnetic energy from the laser travels. In some embodiments, the optical element is adapted to provide electromagnetic energy from the laser to the plasma over a large solid angle. In some embodiments, the reflective surface of the chamber is adapted to provide electromagnetic energy from the laser to the plasma over a large solid angle. In some embodiments, the reflective surface of the chamber is adapted to collect the high brightness light generated by the plasma over a large solid angle. In some embodiments, one or more of the reflective surface, reflector and the window include (e.g., are coated or include) a material to filter predefined wavelengths (e.g., infrared wavelengths of electromagnetic energy) of electromagnetic energy.

The invention, in another aspect, features a light source that includes a chamber that has a reflective surface. The light source also includes an ignition source for ionizing a gas within the chamber. The light source also includes at least one laser external to the chamber for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light. The light source also includes a reflector positioned along a path that the electromagnetic energy travels from the at least one laser to the reflective surface of the chamber.

In some embodiments, the reflector is adapted to at least substantially reflect a first set of predefined wavelengths of electromagnetic energy directed toward the reflector and at least substantially allow a second set of predefined wavelengths of electromagnetic energy to pass through the reflector.

The invention, in another aspect, relates to a method for producing light. The method involves ionizing with an ignition source a gas within a chamber that has a reflective surface. The method also involves providing laser energy to the ionized gas in the chamber to produce a plasma that generates a high brightness light.

In some embodiments, the method involves directing the laser energy comprising a first set of wavelengths of electromagnetic energy through a reflector toward the reflective surface of the chamber, the reflective surface reflecting at least a portion of the first set of wavelengths of electromagnetic energy toward the plasma. In some embodiments, the method involves directing at least a portion of the high brightness light toward the reflective surface of the chamber which is reflected toward the reflector and is reflected by the reflector toward a tool.

In some embodiments, the method involves directing the laser energy comprising a first set of wavelengths of electromagnetic energy toward the reflector, the reflector reflects at least a portion of the first wavelengths of electromagnetic energy toward the reflective surface of the chamber, the reflective surface directs a portion of the first set of wavelengths of electromagnetic energy toward the plasma. In some embodiments, the method involves directing a portion of the high brightness light toward the reflective surface of the chamber which is reflected toward the reflector and, electromagnetic energy comprising the second set of predefined wavelengths of electromagnetic energy passes through the reflector.

The method can involve directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a large solid angle. In some embodiments, the method involves directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a solid angle of approximately 0.012 steradians. In some embodiments, the method involves directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a solid angle of approximately 0.048 steradians. In some embodiments, the method involves directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a solid angle of greater than about 2π (about 6.28) steradians. In some embodiments, the reflective surface of the chamber is adapted to provide the laser energy to the plasma over a large solid angle. In some embodiments, the reflective surface of the chamber is adapted to collect the high brightness light generated by the plasma over a large solid angle.

The invention, in another aspect, relates to a method for producing light. The method involves ionizing with an ignition source a gas within a chamber that has a reflective surface. The method also involves directing electromagnetic energy from a laser toward a reflector that at least substantially reflects a first set of wavelengths of electromagnetic energy toward the ionized gas in the chamber to produce a plasma that generates a high brightness light.

In some embodiments, the electromagnetic energy from the laser first is reflected by the reflector toward the reflective surface of the chamber. In some embodiments, the electromagnetic energy directed toward the reflective surface of the chamber is reflected toward the plasma. In some embodiments, a portion of the high brightness light is directed toward the reflective surface of the chamber, reflected toward the reflector and passes through the reflector.

In some embodiments, the electromagnetic energy from the laser first passes through the reflector and travels toward the reflective surface of the chamber. In some embodiments, the electromagnetic energy directed toward the reflective surface of the chamber is reflected toward the plasma. In some embodiments, a portion of the high brightness light is directed toward the reflective surface of the chamber, reflected toward the reflector and reflected by the reflector.

The invention, in another aspect, features a light source that includes a chamber having a reflective surface. The light source also includes a means for ionizing a gas within the chamber. The light source also includes a means for at least substantially reflecting a first set of predefined wavelengths of electromagnetic energy directed toward the reflector and at least substantially allowing a second set of predefined wavelengths of electromagnetic energy to pass through the reflector. The light source also includes a means for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light.

The invention, in another aspect, features a light source that includes a sealed chamber. The light source also includes an ignition source for ionizing a gas within the chamber. The light source also includes at least one laser external to the sealed chamber for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light. The light source also includes a curved reflective surface disposed external to the sealed chamber to receive at leas a portion of the high brightness light emitted by the sealed chamber and reflect the high brightness light toward an output of the light source.

In some embodiments, the light source includes an optical element disposed along a path the electromagnetic energy from the laser travels. In some embodiments, the sealed chamber includes a support element that locates the sealed chamber relative to the curved reflective surface. In some embodiments, the sealed chamber is a quartz bulb. In some embodiments, the light source includes a second curved reflective surface disposed internal or external to the sealed chamber to receive at least a portion of the laser electromagnetic energy and focus the electromagnetic energy on the plasma that generates the high brightness light.

The invention, in another aspect, features a light source that includes a sealed chamber and an ignition source for ionizing a gas within the chamber. The light source also includes at least one laser external to the sealed chamber for providing electromagnetic energy. The light source also includes a curved reflective surface to receive and reflect at least a portion of the electromagnetic energy toward the ionized gas within the chamber to produce a plasma that generates a high brightness light, the curved reflective surface also receives at least a portion of the high brightness light emitted by the plasma and reflects the high brightness light toward an output of the light source.

In some embodiments, the curved reflective surface focuses the electromagnetic energy on a region in the chamber where the plasma is located. In some embodiments, the curved reflective surface is located within the chamber. In some embodiments, the curved reflective surface is located external to the chamber. In some embodiments, the high brightness light is ultraviolet light, includes ultraviolet light or is substantially ultraviolet light.

The foregoing and other objects, aspects, features, and advantages of the invention will become more apparent from the following description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, feature and advantages of the invention, as well as the invention itself, will be more fully understood from the following illustrative description, when read together with the accompanying drawings which are not necessarily to scale.

FIG. **1** is a schematic block diagram of a light source, according to an illustrative embodiment of the invention.

FIG. **2** is a schematic block diagram of a portion of a light source, according to an illustrative embodiment of the invention.

FIG. **3** is a graphical representation of UV brightness as a function of the laser power provided to a plasma, using a light source according to the invention.

FIG. **4** is a graphical representation of the transmission of laser energy through a plasma generated from mercury, using a light source according to the invention.

FIG. **5** is a schematic block diagram of a light source, according to an illustrative embodiment of the invention.

FIG. **6** is a schematic block diagram of a light source, according to an illustrative embodiment of the invention.

FIG. **7** is a schematic block diagram of a light source, according to an illustrative embodiment of the invention.

FIG. **8**A is a schematic block diagram of a light source in which electromagnetic energy from a laser is provided to a plasma over a first solid angle, according to an illustrative embodiment of the invention.

FIG. **8**B is a schematic block diagram of the light source of FIG. **8**A in which the electromagnetic energy from the laser is provided to the plasma over a larger solid angle, according to an illustrative embodiment of the invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

FIG. **1** is a schematic block diagram of a light source **100** for generating light, that embodies the invention. The light source **100** includes a chamber **128** that contains an ionizable medium (not shown). The light source **100** provides energy to a region **130** of the chamber **128** having the ionizable medium which creates a plasma **132**. The plasma **132** generates and emits a high brightness light **136** that originates from the plasma **132**. The light source **100** also includes at least one laser source **104** that generates a laser beam that is provided to the plasma **132** located in the chamber **128** to initiate and/or sustain the high brightness light **136**.

In some embodiments, it is desirable for at least one wavelength of electromagnetic energy generated by the laser source **104** to be strongly absorbed by the ionizable medium in order to maximize the efficiency of the transfer of energy from the laser source **104** to the ionizable medium.

In some embodiments, it is desirable for the plasma **132** to be small in size in order to achieve a high brightness light source. Brightness is the power radiated by a source of light per unit surface area into a unit solid angle. The brightness of the light produced by a light source determines the ability of a system (e.g., a metrology tool) or an operator to see or measure things (e.g., features on the surface of a wafer) with adequate resolution. It is also desirable for the laser source **104** to drive and/or sustain the plasma with a high power laser beam.

Generating a plasma **132** that is small in size and providing the plasma **132** with a high power laser beam leads simultaneously to a high brightness light **136**. The light source **100** produces a high brightness light **136** because most of the power introduced by the laser source **104** is then radiated from a small volume, high temperature plasma **132**. The plasma **132** temperature will rise due to heating by the laser beam until balanced by radiation and other processes. The high temperatures that are achieved in the laser sustained plasma **132** yield increased radiation at shorter wavelengths of electromagnetic energy, for example, ultraviolet energy. In one experiment, temperatures between about 10,000 K and about 20,000 K have been observed. The radiation of the plasma **132**, in a general sense, is distributed over the electromagnetic spectrum according to Planck's radiation law. The wavelength of maximum radiation is inversely proportional to the temperature of a black body according to Wien's displacement law. While the laser sustained plasma is not a black body, it behaves similarly and as such, the highest brightness in the ultraviolet range at around 300 mm wavelength is expected for laser sustained plasmas having a temperature of between about 10,000 K and about 15,000 K. Most conventional arc lamps are, however, unable to operate at these temperatures.

It is therefore desirable in some embodiments of the invention to maintain the temperature of the plasma **132** during operation of the light source **100** to ensure that a sufficiently bright light **136** is generated and that the light emitted is substantially continuous during operation.

In this embodiment, the laser source **104** is a diode laser that outputs a laser beam via a fiberoptic element **108**. The fiber optic element **108** provides the laser beam to a collimator **112** that aids in conditioning the output of the diode laser by aiding in making laser beam rays **116** substantially parallel to each other. The collimator **112** then directs the laser beam **116** to a beam expander **118**. The beam expander **118** expands the size of the laser beam **116** to produce laser beam **122**. The beam expander **118** also directs the laser beam **122** to an optical lens **120**. The optical lens **120** is configured to focus the laser beam **122** to produce a smaller diameter laser beam **124** that is directed to the region **130** of the chamber **128** where the plasma **132** exists (or where it is desirable for the plasma **132** to be generated and sustained).

In this embodiment, the light source **100** also includes an ignition source **140** depicted as two electrodes (e.g., an anode and cathode located in the chamber **128**). The ignition source **140** generates an electrical discharge in the chamber **128** (e.g., the region **130** of the chamber **128**) to ignite the ionizable medium. The laser then provides laser energy to the ionized medium to sustain or create the plasma **132** which generates the high brightness light **136**. The light **136** generated by the light source **100** is then directed out of the chamber to, for example, a wafer inspection system (not shown).

Alternative laser sources are contemplated according to illustrative embodiments of the invention. In some embodiments, neither the collimator **112**, the beam expander **118**, or the lens **120** may be required. In some embodiments, additional or alternative optical elements can be used. The laser source can be, for example, an infrared (IR) laser source, a diode laser source, a fiber laser source, an ytterbium laser source, a CO_2 laser source, a YAG laser source, or a gas discharge laser source. In some embodiments, the laser source **104** is a pulse laser source (e.g., a high pulse rate laser source) or a continuous wave laser source. Fiber lasers use laser diodes to pump a special doped fiber which then lases to produce the output (i.e., a laser beam). In some embodiments, multiple lasers (e.g., diode lasers) are coupled to one or more fiber optic elements (e.g., the fiber optic element **108**). Diode lasers take light from one, or usually many, diodes and directs the light down a fiber to the output. In some embodiments, fiber laser sources and direct semiconductor laser sources are desirable for use as the laser source **104** because they are relatively low in cost, have a small form factor or package size, and are relatively high in efficiency.

Efficient, cost effective, high power lasers (e.g., fiber lasers and direct diode lasers) are recently available in the NIR (near infrared) wavelength range from about 700 nm to about 2000 nm. Energy in this wavelength range is more easily transmitted through certain materials (e.g., glass, quartz and sapphire) that are more commonly used to manufacture bulbs, windows and chambers. It is therefore more practical now to produce light sources that operate using lasers in the 700 nm to 2000 nm range than has previously been possible.

In some embodiments, the laser source **104** is a high pulse rate laser source that provides substantially continuous laser energy to the light source **100** sufficient to produce the high brightness light **136**. In some embodiments, the emitted high brightness light **136** is substantially continuous where, for example, magnitude (e.g. brightness or power) of the high brightness light does not vary by more than about 90% during operation. In some embodiments, the ratio of the peak power of the laser energy delivered to the plasma to the average power of the laser energy delivered to the plasma is approximately 2-3. In some embodiments, the substantially continuous energy provided to the plasma **132** is sufficient to minimize cooling of the ionized medium to maintain a desirable brightness of the emitted light **136**.

In this embodiment, the light source **100** includes a plurality of optical elements (e.g., a beam expander **118**, a lens **120**, and fiber optic element **108**) to modify properties (e.g., diameter and orientation) of the laser beam delivered to the chamber **132**. Various properties of the laser beam can be modified with one or more optical elements (e.g., mirrors or lenses). For example, one or more optical elements can be used to modify the portions of, or the entire laser beam diameter, direction, divergence, convergence, and orientation. In some embodiments, optical elements modify the wavelength of the laser beam and/or filter out certain wavelengths of electromagnetic energy in the laser beam.

Lenses that can be used in various embodiments of the invention include, aplanatic lenses, achromatic lenses, single element lenses, and fresnel lenses. Mirrors that can be used in various embodiments of the invention include, coated mirrors, dielectric coated mirrors, narrow band mirrors, and ultraviolet transparent infrared reflecting mirrors. By way of example, ultraviolet transparent infrared reflecting mirrors are used in some embodiments of the invention where it is desirable to filter out infrared energy from a laser beam while permitting ultraviolet energy to pass through the mirror to be delivered to a tool (e.g., a wafer inspection tool, a microscope, a lithography tool or an endoscopic tool).

In this embodiment, the chamber **128** is a sealed chamber initially containing the ionizable medium (e.g., a solid, liquid or gas). In some embodiments, the chamber **128** is instead capable of being actively pumped where one or more gases are introduced into the chamber **128** through a gas inlet (not shown), and gas is capable of exiting the chamber **128** through a gas outlet (not shown). The chamber can be fabricated from or include one or more of, for example, a dielectric material, a quartz material, Suprasil quartz, sapphire, MgF_2, diamond or CaF_2. The type of material may be selected based on, for example, the type of ionizable medium used and/or the wavelengths of light **136** that are desired to be generated and output from the chamber **128**. In some embodiments, a region of the chamber **128** is transparent to, for example, ultraviolet energy. Chambers **128** fabricated using quartz will generally allow wavelengths of electromagnetic energy of as long as about 2 microns to pass through walls of the chamber. Sapphire chamber walls generally allow electromagnetic energy of as long as about 4 microns to pass through the walls.

In some embodiments, it is desirable for the chamber **128** to be a sealed chamber capable of sustaining high pressures and temperatures. For example, in one embodiment, the ionizable medium is mercury vapor. To contain the mercury vapor during operation, the chamber **128** is a sealed quartz bulb capable of sustaining pressures between about 10 to about 200 atmospheres and operating at about 900 degrees centigrade. The quartz bulb also allows for transmission of the ultraviolet light **136** generated by the plasma **132** of the light source **100** through the chamber **128** walls.

Various ionizable media can be used in alternative embodiments of the invention. For example, the ionizable medium can be one or more of a noble gas, Xe, Ar, Ne, Kr, He, D_2, H_2, O_2, F_2, a metal halide, a halogen, Hg, Cd, Zn, Sn, Ga, Fe, Li, Na, an excimer forming gas, air, a vapor, a metal oxide, an aerosol, a flowing media, or a recycled media. In some embodiments, a solid or liquid target (not shown) in the chamber **128** is used to generate an ionizable gas in the chamber **128**. The laser source **104** (or an alternative laser source) can be used to provide energy to the target to generate the ionizable gas. The target can be, for example, a pool or film of metal. In some embodiments, the target is a solid or liquid that moves in the chamber (e.g., in the form of droplets of a liquid that travel through the region **130** of the chamber **128**). In some embodiments, a first ionizable gas is first introduced into the chamber **128** to ignite the plasma **132** and then a separate second ionizable gas is introduced to sustain the plasma **132**. In this embodiment, the first ionizable gas is a gas that is more easily ignited using the ignition source **140** and the second ionizable gas is a gas that produces a particular wavelength of electromagnetic energy.

In this embodiment, the ignition source **140** is a pair of electrodes located in the chamber **128**. In some embodiments, the electrodes are located on the same side of the chamber **128**. A single electrode can be used with, for example, an RF ignition source or a microwave ignition source. In some embodiments, the electrodes available in a conventional arc lamp bulb are the ignition source (e.g., a model USH-200DP quartz bulb manufactured by Ushio (with offices in Cypress, Calif.)). In some embodiments, the electrodes are smaller and/or spaced further apart than the electrodes used in a conventional arc lamp bulb because the electrodes are not required for sustaining the high brightness plasma in the chamber **128**.

Various types and configurations of ignition sources are also contemplated, however, that are within the scope of the present invention. In some embodiments, the ignition source **140** is external to the chamber **128** or partially internal and partially external to the chamber **128**. Alternative types of ignition sources **140** that can be used in the light source **100** include ultraviolet ignition sources, capacitive discharge ignition sources, inductive ignition sources, RF ignition sources, a microwave ignition sources, flash lamps, pulsed lasers, and pulsed lamps. In one embodiment, no ignition source **140** is required and instead the laser source **104** is used to ignite the ionizable medium and to generate the plasma **132** and to sustain the plasma and the high brightness light **136** emitted by the plasma **132**.

In some embodiments, it is desirable to maintain the temperature of the chamber **128** and the contents of the chamber **128** during operation of the light source **100** to ensure that the pressure of gas or vapor within the chamber **128** is maintained at a desired level. In some embodiments, the ignition source **140** can be operated during operation of the light source **100**, where the ignition source **140** provides energy to the plasma **132** in addition to the energy provided by the laser source **104**. In this manner, the ignition source **140** is used to maintain (or maintain at an adequate level) the temperature of the chamber **128** and the contents of the chamber **128**.

In some embodiments, the light source **100** includes at least one optical element (e.g., at least one mirror or lens) for modifying a property of the electromagnetic energy (e.g., the high brightness light **136**) emitted by the plasma **132** (e.g., an ionized gas), similarly as described elsewhere herein.

FIG. **2** is a schematic block diagram of a portion of a light source **200** incorporating principles of the present invention. The light source **200** includes a chamber **128** containing an ionizable gas and has a window **204** that maintains a pressure within the chamber **128** while also allowing electromagnetic energy to enter the chamber **128** and exit the chamber **128**. In this embodiment, the chamber **128** has an ignition source (not shown) that ignites the ionizable gas (e.g., mercury or xenon) to produce a plasma **132**.

A laser source **104** (not shown) provides a laser beam **216** that is directed through a lens **208** to produce laser beam **220**. The lens **208** focuses the laser beam **220** on to a surface **224** of a thin film reflector **212** that reflects the laser beam **220** to produce laser beam **124**. The reflector **212** directs the laser beam **124** on region **130** where the plasma **132** is located. The laser beam **124** provides energy to the plasma **132** to sustain and/or generate a high brightness light **136** that is emitted from the plasma **132** in the region **130** of the chamber **128**.

In this embodiment, the chamber **128** has a paraboloid shape and an inner surface **228** that is reflective. The paraboloid shape and the reflective surface cooperate to reflect a substantial amount of the high brightness light **136** toward and out of the window **204**. In this embodiment, the reflector **212** is transparent to the emitted light **136** (e.g., at least one or more wavelengths of ultraviolet light). In this manner, the emitted light **136** is transmitted out of the chamber **128** and directed to, for example, a metrology tool (not shown). In one embodiment, the emitted light **136** is first directed towards or through additional optical elements before it is directed to a tool.

By way of illustration, an experiment was conducted to generate ultraviolet light using a light source, according to an illustrative embodiment of the invention. A model L6724 quartz bulb manufactured by Hamamatsu (with offices in Bridgewater, N.J.) was used as the chamber of the light source (e.g., the chamber **128** of the light source **100** of FIG. **1**) for experiments using xenon as the ionizable medium in the chamber. A model USH-200DP quartz bulb manufactured by Ushio (with offices in Cypress, Calif.) was used as the chamber of the light source for experiments using mercury as the ionizable medium in the chamber. FIG. **3** illustrates a plot **300** of the UV brightness of a high brightness light produced by a plasma located in the chamber as a function of the laser power (in watts) provided to the plasma. The laser source used in the experiment was a 1.09 micron, 100 watt CW laser. The Y-Axis **312** of the plot **300** is the UV brightness (between about 200 and about 400 mm) in watts/mm^2 steradian (sr). The X-Axis **316** of the plot **300** is the laser beam power in watts provided to the plasma. Curve **304** is the UV brightness of the high brightness light produced by a plasma that was generated using xenon as the ionizable medium in the chamber. The plasma in the experiment using xenon was between about 1 mm and about 2 mm in length and about 0.1 mm in diameter. The length of the plasma was controlled by adjusting the angle of convergence of the laser beam. A larger angle (i.e., larger numerical aperture) leads to a shorter plasma because the converging beam reaches an intensity capable of sustaining the plasma when it is closer to the focal point. Curve **308** is the UV brightness of the high brightness light produced by a plasma that was generated using mercury as the ionizable medium in the chamber. The plasma in the experiment using mercury was about 1 mm in length and about 0.1 mm in diameter.

By way of illustration, another experiment was conducted to generate ultraviolet using a light source according to an illustrative embodiment of the invention. A model USH-200DP quartz bulb manufactured by Ushio (with offices in Cypress, Calif.) was used as the chamber of the light source for experiments using mercury as the ionizable medium in the chamber (e.g., the chamber **128** of the light source **100** of FIG. **1**). The laser source used in the experiment was a 1.09 micron, 100 watt ytterbium doped fiber laser from SPI Lasers PLC (with offices in Los Gatos, Calif.). FIG. **4** illustrates a plot **400** of the transmission of laser energy through a plasma located in the chamber generated from mercury versus the amount of power provided to the plasma in watts. The Y-Axis **412** of the plot **400** is the transmission coefficient in non-dimensional units. The X-Axis **416** of the plot **400** is the laser beam power in watts provided to the plasma. The curve in the plot **400** illustrates absorption lengths of 1 mm were achieved using the laser source. The transmission value of 0.34 observed at 100 watts corresponds to a i/e absorption length of about 1 mm.

FIG. **5** is a schematic block diagram of a portion of a light source **500** incorporating principles of the present invention. The light source **500** includes a chamber **528** that has a reflective surface **540**. The reflective surface **540** can have, for example, a parabolic shape, elliptical shape, curved shape, spherical shape or aspherical shape. In this embodiment, the light source **500** has an ignition source (not shown) that ignites an ionizable gas (e.g., mercury or xenon) in a region **530** within the chamber **528** to produce a plasma **532**.

In some embodiments, the reflective surface **540** can be a reflective inner or outer surface. In some embodiments, a coating or film is located on the inside or outside of the chamber to produce the reflective surface **540**.

A laser source (not shown) provides a laser beam **516** that is directed toward a surface **524** of a reflector **512**. The reflector **512** reflects the laser beam **520** toward the reflective surface **540** of the chamber **528**. The reflective surface **540** reflects the laser beam **520** and directs the laser beam toward the plasma **532**. The laser beam **516** provides energy to the plasma **532** to sustain and/or generate a high brightness light **536** that is emitted from the plasma **532** in the region **530** of the chamber **528**. The high brightness light **536** emitted by the plasma **532** is directed toward the reflective surface **540** of the chamber **528**. At least a portion of the high brightness light **536** is reflected by the reflective surface **540** of the chamber **528** and directed toward the reflector **512**. The reflector **512** is substantially transparent to the high brightness light **536** (e.g., at least one or more wavelengths of ultraviolet light). In this manner, the high brightness light **536** passes through the reflector **512** and is directed to, for example, a metrology tool (not shown). In some embodiments, the high brightness light **536** is first directed towards or through a window or additional optical elements before it is directed to a tool.

In some embodiments, the light source **500** includes a separate, sealed chamber (e.g., the sealed chamber **728** of FIG. 7) located in the concave region of the chamber **528**. The sealed chamber contains the ionizable gas that is used to create the plasma **532**. In alternative embodiments, the sealed chamber contains the chamber **528**. In some embodiments, the sealed chamber also contains the reflector **512**.

FIG. **6** is a schematic block diagram of a portion of a light source **600** incorporating principles of the present invention. The light source **600** includes a chamber **628** that has a reflective surface **640**. The reflective surface **640** can have, for example, a parabolic shape, elliptical shape, curved shape, spherical shape or aspherical shape. In this embodiment, the light source **600** has an ignition source (not shown) that ignites an ionizable gas (e.g., mercury or xenon) in a region **630** within the chamber **628** to produce a plasma **632**.

A laser source (not shown) provides a laser beam **616** that is directed toward a reflector **612**. The reflector **612** is substantially transparent to the laser beam **616**. The laser beam **616** passes through the reflector **612** and is directed toward the reflective surface **640** of the chamber **628**. The reflective surface **640** reflects the laser beam **616** and directs it toward the plasma **632** in the region **630** of the chamber **628**. The laser beam **616** provides energy to the plasma **632** to sustain and/or generate a high brightness light **636** that is emitted from the plasma **632** in the region **630** of the chamber **628**. The high brightness light **636** emitted by the plasma **632** is directed toward the reflective surface **640** of the chamber **628**. At least a portion of the high brightness light **636** is reflected by the reflective surface **640** of the chamber **628** and directed toward a surface **624** of the reflector **612**. The reflector **612** reflects the high brightness light **636** (e.g., at least one or more wavelengths of ultraviolet light). In this manner, the high brightness light **636** (e.g., visible and/or ultraviolet light) is directed to, for example, a metrology tool (not shown). In some embodiments, the high brightness light **636** is first directed towards or through a window or additional optical elements before it is directed to a tool. In some embodiments, the high brightness light **636** includes ultraviolet light. Ultraviolet light is electromagnetic energy with a wavelength shorter than that of visible light, for instance between about 50 nm and 400 nm.

In some embodiments, the light source **600** includes a separate, sealed chamber (e.g., the sealed chamber **728** of FIG. 7) located in the concave region of the chamber **628**. The sealed chamber contains the ionizable gas that is used to create the plasma **632**. In alternative embodiments, the sealed chamber contains the chamber **628**. In some embodiments, the sealed chamber also contains the reflector **612**.

FIG. **7** is a schematic block diagram of a light source **700** for generating light, that embodies the invention. The light source **700** includes a sealed chamber **728** (e.g., a sealed quartz bulb) that contains an ionizable medium (not shown). The light source **700** provides energy to a region **730** of the chamber **728** having the ionizable medium which creates a plasma **732**. The plasma **732** generates and emits a high brightness light **736** that originates from the plasma **732**. The light source **700** also includes at least one laser source **704** that generates a laser beam that is provided to the plasma **732** located in the chamber **728** to initiate and/or sustain the high brightness light **736**.

In this embodiment, the laser source **704** is a diode laser that outputs a laser beam via a fiberoptic element **708**. The fiber optic element **708** provides the laser beam to a collimator **712** that aids in conditioning the output of the diode laser by aiding in making laser beam rays **716** substantially parallel to each other. The collimator **712** then directs the laser beam **716** to a beam expander **718**. The beam expander **718** expands the size of the laser beam **716** to produce laser beam **722**. The beam expander **718** also directs the laser beam **722** to an optical lens **720**. The optical lens **720** is configured to focus the laser beam **722** to produce a smaller diameter laser beam **724**. The laser beam **724** passes through an aperture or window **772** located in the base **724** of a curved reflective surface **740** and is directed toward the chamber **728**. The chamber **728** is substantially transparent to the laser beam **724**. The laser beam **724** passes through the chamber **728** and toward the region **730** of the chamber **728** where the plasma **732** exists (or where it is desirable for the plasma **732** to be generated by the laser **724** and sustained).

In this embodiment, the ionizable medium is ignited by the laser beam **724**. In alternative embodiments, the light source **700** includes an ignition source (e.g., a pair of electrodes or a source of ultraviolet energy) that, for example, generates an electrical discharge in the chamber **728** (e.g., the region **730** of the chamber **728**) to ignite the ionizable medium. The laser source **704** then provides laser energy to the ionized medium to sustain the plasma **732** which generates the high brightness light **736**. The chamber **728** is substantially transparent to the high brightness light **736** (or to predefined wavelengths of electromagnetic radiation in the high brightness light **736**). The light **736** (e.g., visible and/or ultraviolet light) generated by the light source **700** is then directed out of the chamber **728** toward an inner surface **744** of the reflective surface **740**.

In this embodiment, the light source **700** includes a plurality of optical elements (e.g., a beam expander **718**, a lens **720**, and fiber optic element **708**) to modify properties (e.g., diameter and orientation) of the laser beam delivered to the chamber **732**. Various properties of the laser beam can be modified with one or more optical elements (e.g., mirrors or lenses). For example, one or more optical elements can be used to modify the portions of, or the entire laser beam diameter, direction, divergence, convergence, and orientation. In some embodiments, optical elements modify the wavelength of the laser beam and/or filter out certain wavelengths of electromagnetic energy in the laser beam.

Lenses that can be used in various embodiments of the invention include, aplanatic lenses, achromatic lenses, single element lenses, and fresnel lenses. Mirrors that can be used in various embodiments of the invention include, coated mirrors, dielectric coated mirrors, narrow band mirrors, and ultraviolet transparent infrared reflecting mirrors. By way of example, ultraviolet transparent infrared reflecting mirrors are used in some embodiments of the invention where it is desirable to filter out infrared energy from a laser beam while permitting ultraviolet energy to pass through the mirror to be delivered to a tool (e.g., a wafer inspection tool, a microscope, a lithography tool or an endoscopic tool).

FIGS. **8A** and **8B** are schematic block diagrams of a light source **800** for generating light, that embodies the invention. The light source **800** includes a chamber **828** that contains an ionizable medium (not shown). The light source **800** provides energy to a region **830** of the chamber **828** having the ionizable medium which creates a plasma. The plasma generates and emits a high brightness light that originates from the plasma. The light source **800** also includes at least one laser source **804** that generates a laser beam that is provided to the plasma located in the chamber **828** to initiate and/or sustain the high brightness light.

In some embodiments, it is desirable for the plasma to be small in size in order to achieve a high brightness light source. Brightness is the power radiated by a source of light per unit surface area into a unit solid angle. The brightness of the light produced by a light source determines the ability of a system (e.g., a metrology tool) or an operator to see or measure things (e.g., features on the surface of a wafer) with adequate resolution. It is also desirable for the laser source **804** to drive and/or sustain the plasma with a high power laser beam.

Generating a plasma that is small in size and providing the plasma with a high power laser beam leads simultaneously to a high brightness light. The light source **800** produces a high brightness light because most of the power introduced by the laser source **804** is then radiated from a small volume, high temperature plasma. The plasma temperature will rise due to heating by the laser beam until balanced by radiation and other processes. The high temperatures that are achieved in the laser sustained plasma yield increased radiation at shorter wavelengths of electromagnetic energy, for example, ultraviolet energy. In one experiment, temperatures between about 10,000 K and about 20,000 K have been observed. The radiation of the plasma, in a general sense, is distributed over the electromagnetic spectrum according to Planck's radiation law. The wavelength of maximum radiation is inversely proportional to the temperature of a black body according to Wien's displacement law. While the laser sustained plasma is not a black body, it behaves similarly and as such, the highest brightness in the ultraviolet range at around 300 nm wavelength is expected for laser sustained plasmas having a temperature of between about 10,000 K and about 15,000 K. Conventional arc lamps are, however, unable to operate at these temperatures.

It is desirable in some embodiments of the invention to deliver the laser energy to the plasma in the chamber **828** over a large solid angle in order to achieve a plasma that is small in size. Various methods and optical elements can be used to deliver the laser energy over a large solid angle. In this embodiment of the invention, parameters of a beam expander and optical lens are varied to modify the size of the solid angle over which the laser energy is delivered to the plasma in the chamber **828**.

Referring to FIG. **8A**, the laser source **804** is a diode laser that outputs a laser beam via a fiberoptic element **808**. The fiber optic element **808** provides the laser beam to a collimator **812** that aids in conditioning the output of the diode laser by aiding in making laser beam rays **816** substantially parallel to each other. The collimator **812** directs the laser beam **816** to an optical lens **820**. The optical lens **820** is configured to focus the laser beam **816** to produce a smaller diameter laser beam **824** having a solid angle **878**. The laser beam **824** is directed to the region **830** of the chamber **828** where the plasma **832** exists.

In this embodiment, the light source **800** also includes an ignition source **840** depicted as two electrodes (e.g., an anode and cathode located in the chamber **828**). The ignition source **840** generates an electrical discharge in the chamber **828** (e.g., the region **830** of the chamber **828**) to ignite the ionizable medium. The laser then provides laser energy to the ionized medium to sustain or create the plasma **832** which generates the high brightness light **836**. The light **836** generated by the light source **800** is then directed out of the chamber to, for example, a wafer inspection system (not shown).

FIG. **8B** illustrates an embodiment of the invention in which the laser energy is delivered to the plasma in the chamber **828** over a solid angle **874**. This embodiment of the invention includes a beam expander **854**. The beam expander **854** expands the size of the laser beam **816** to produce laser beam **858**. The beam expander **854** directs the laser beam **858** to an optical lens **862**. The combination of the beam expander **854** and the optical lens **862** produces a laser beam **866** that has a solid angle **874** that is larger than the solid angle **878** of the laser beam **824** of FIG. **8A**. The larger solid angle **874** of FIG. **8B** creates a smaller size plasma **884** than the size of the plasma in FIG. **8A**. In this embodiment, the size of the plasma **884** in FIG. **8B** along the X-axis and Y-axis is smaller than the size of the plasma **832** in FIG. **8A**. In this manner, the light source **800** generates a brighter light **870** in FIG. **8B** as compared with the light **836** in FIG. **8A**.

An experiment was conducted in which a beam expander and optical lens were selected to allow operation of the light source as shown in FIGS. **8A** and **8B**. A Hamamatsu L2273 xenon bulb (with offices in Bridgewater, N.J.) was used as the sealed chamber **828**. The plasma was formed in the Hamamatsu L2273 xenon bulb using an SPI continuous-wave (CW) 100 W, 1090 nm fiber laser (sold by SPI Lasers PLC, with offices in Los Gatos, Calif.)). A continuous-wave laser emits radiation continuously or substantially continuously rather than in short bursts, as in a pulsed laser. The fiber laser **804** contains laser diodes which are used to pump a special doped fiber (within the fiber laser **804**, but not shown). The special doped fiber then lases to produce the output of the fiber laser **804**. The output of the fiber laser **804** then travels through the fiberoptic element **808** to the collimeter **812**. The collimeter **812** then outputs the laser beam **816**. The initial laser beam diameter (along the Y-Axis), corresponding to beam **816** in FIG. **8A**, was 5 mm. The laser beam **816** was a Gaussian beam with a 5 mm diameter measured to the

$$\frac{1}{e^2}$$

intensity level. The lens used in the experiment, corresponding to lens **820**, was 30 mm in diameter and had a focal length of 40 mm. This produced a solid angle of illumination of the plasma **832** of approximately 0.012 steradians. The length (along the X-Axis) of the plasma **832** produced in this arrangement was measured to be approximately 2 mm. The diameter of the plasma **832** (along the Y-Axis), was approximately 0.05 mm. The plasma **832** generated a high brightness ultraviolet light **836**.

Referring to FIG. **8**B, a 2× beam expander was used as the beam expander **854**. The beam expander **854** expanded beam **816** from 5 mm in diameter (along the Y-Axis) to 10 mm in diameter, corresponding to beam **858**. Lens **862** in FIG. **8**B was the same as lens **820** in FIG. **8**A. The combination of the beam expander **854** and the optical lens **862** produced a laser beam **866** having a solid angle **874** of illumination of approximately 0.048 steradians. In this experiment, the length of the plasma (along the X-Axis) was measured to be approximately 1 mm and the diameter measured along the Y-Axis remained 0.05 mm. This reduction of plasma length by a factor of 2, due to a change in solid angle of a factor of 4, is expected if the intensity required to sustain the plasma at its boundary is a constant. A decrease in plasma length (along the X-Axis) by a factor of 2 (decrease from 2 mm in FIG. **8**A to 1 mm in FIG. **8**B) resulted in an approximate doubling of the brightness of the radiation emitted by the plasma for a specified laser beam input power because the power absorbed by the plasma is about the same, while the radiating area of the plasma was approximately halved (due to the decrease in length along the X-Axis). This experiment illustrated the ability to make the plasma smaller by increasing the solid angle of the illumination from the laser.

In general, larger solid angles of illumination can be achieved by increasing the laser beam diameter and/or decreasing the focal length of the objective lens. If reflective optics are used for illumination of the plasma, them the solid angle of illumination can become much larger than the experiment described above. For example, in some embodiments, the solid angle of illumination can be greater than about 2π (about 6.28) steradians when the plasma is surrounded by a deep, curved reflecting surface (e.g., a paraboloid or ellipsoid). Based on the concept that a constant intensity of light is required to maintain the plasma at its surface, in one embodiment (using the same bulb and laser power described in the experiment above) we calculated that a solid angle of 5 steradians would produce a plasma with its length equal to its diameter, producing a roughly spherical plasma.

Variations, modifications, and other implementations of what is described herein will occur to those of ordinary skill in the art without departing from the spirit and the scope of the invention as claimed. Accordingly, the invention is to be defined not by the preceding illustrative description but instead by the spirit and scope of the following claims.

What is claimed is:

1. A light source, comprising:

a chamber comprising a reflective surface;

an ignition source for ionizing a gas within the chamber;

a reflector that at least substantially reflects a first set of predefined wavelengths of electromagnetic energy directed toward the reflector and at least substantially allows a second set of predefined wavelengths of electromagnetic energy to pass through the reflector; and

at least one laser external to the chamber for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light.

2. The light source of claim **1**, wherein the at least one laser directs a first set of wavelengths of electromagnetic energy toward the reflector, the reflector reflects at least a portion of the first wavelengths of electromagnetic energy towards the reflective surface of the chamber, and the reflective surface

directs a portion of the first set of wavelengths of electromagnetic energy toward the plasma.

3. The light source of claim **2**, wherein at least a portion of the high brightness light is directed toward the reflective surface of the chamber, is reflected toward the reflector, and passes through the reflector toward an output of the light source.

4. The light source of claim **3**, comprising a microscope, ultraviolet microscope, wafer inspection system, reticle inspection system or lithography system spaced relative to the output of the light source to receive the high brightness light.

5. The light source of claim **4**, wherein a portion of the high brightness light is directed toward the reflective surface of the chamber, is reflected toward the reflector, and electromagnetic energy comprising the second set of predefined wavelengths of electromagnetic energy passes through the reflector.

6. The light source of claim **1**, wherein the chamber comprises a window.

7. The light source of claim **1**, wherein the chamber is a sealed chamber.

8. The light source of claim **1**, wherein the reflective surface of the chamber comprises a curved shape, parabolic shape, elliptical shape, spherical shape or aspherical shape.

9. The light source of claim **1**, comprising an optical element disposed along a path the electromagnetic energy from the laser travels.

10. The light source of claim **9**, wherein the optical element is adapted to provide electromagnetic energy from the laser to the plasma over a large solid angle.

11. The light source of claim **1**, wherein the reflective surface of the chamber is adapted to provide electromagnetic energy from the laser to the plasma over a large solid angle.

12. The light source of claim **1**, wherein the reflective surface of the chamber is adapted to collect the high brightness light generated by the plasma over a large solid angle.

13. The light source of claim **12**, wherein the large solid angle is greater than about 3 steradians.

14. The light source of claim **13**, wherein the large solid angle is about 5 steradians.

15. The light source of claim **6**, wherein one or more of the reflective surface, reflector and the window comprise a material to filter predefined wavelengths of electromagnetic energy.

16. The light source of claim **1**, wherein the laser is a continuous-wave fiber laser.

17. A light source, comprising:

a chamber comprising a reflective surface;

an ignition source for ionizing a gas within the chamber;

at least one laser external to the chamber for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light; and

a reflector positioned along a path that the electromagnetic energy travels from the at least one laser to the reflective surface of the chamber.

18. The light source of claim **17**, wherein the reflector is adapted to at least substantially reflect a first set of predefined wavelengths of electromagnetic energy directed toward the reflector and at least substantially allow a second set of predefined wavelengths of electromagnetic energy to pass through the reflector.

19. A method for producing light, comprising:

ionizing with an ignition source a gas within a chamber comprising a reflective surface; and

providing laser energy to the ionized gas in the chamber to produce a plasma that generates a high brightness light.

20. The method of claim **19**, comprising directing the laser energy comprising a first set of wavelengths of electromagnetic energy toward the reflector, the reflector reflects at least a portion of the first wavelengths of electromagnetic energy toward the reflective surface of the chamber, the reflective surface directs a portion of the first set of wavelengths of electromagnetic energy toward the plasma.

21. The method of claim **20**, comprising directing a portion of the high brightness light toward the reflective surface of the chamber which is reflected toward the reflector and, electromagnetic energy comprising the second set of predefined wavelengths of electromagnetic energy passes through the reflector.

22. The method of claim **19**, comprising directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a large solid angle.

23. The method of claim **19**, wherein the reflective surface of the chamber is adapted to provide the laser energy to the plasma over a large solid angle.

24. The method of claim **19**, wherein the reflective surface of the chamber is adapted to collect the high brightness light generated by the plasma over a large solid angle.

25. The method of claim **19**, comprising directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a solid angle of approximately 0.012 steradians.

26. The method of claim **19**, comprising directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a solid angle of approximately 0.048 steradians.

27. The method of claim **19**, comprising directing the laser energy through an optical element that modifies a property of the laser energy to direct the laser energy toward the plasma over a solid angle of greater than about 2π steradians.

28. A method for producing light, comprising:

ionizing with an ignition source a gas within a chamber comprising a reflective surface; and

directing electromagnetic energy from a laser toward a reflector that at least substantially reflects a first set of wavelengths of electromagnetic energy toward the ionized gas in the chamber to produce a plasma that generates a high brightness light.

29. The method of claim **28**, wherein the electromagnetic energy from the laser first is reflected by the reflector toward the reflective surface of the chamber.

30. The method of claim **29**, wherein the electromagnetic energy directed toward the reflective surface of the chamber is reflected toward the plasma.

31. The method of claim **30**, wherein a portion of the high brightness light is directed toward the reflective surface of the chamber, reflected toward the reflector and passes through the reflector.

32. The method of claim **30**, wherein the electromagnetic energy directed toward the reflective surface of the chamber is reflected toward the plasma.

33. The method of claim **31**, wherein a portion of the high brightness light is directed toward the reflective surface of the chamber, reflected toward the reflector and reflected by the reflector.

34. A light source, comprising:

a chamber comprising a reflective surface;

an ignition source for ionizing a gas within the chamber;

a reflector that at least substantially reflects a first set of predefined wavelengths of electromagnetic energy directed toward the reflector and at least substantially allows a second set of predefined wavelengths of electromagnetic energy to pass through the reflector; and

a means for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light.

35. A light source, comprising:

a sealed chamber;

an ignition source for ionizing a gas within the chamber;

at least one laser external to the sealed chamber for providing electromagnetic energy to the ionized gas within the chamber to produce a plasma that generates a high brightness light; and

a curved reflective surface disposed external to the sealed chamber to receive at least a portion of the high brightness light emitted by the sealed chamber and reflect the high brightness light toward an output of the light source.

36. The light source of claim **35**, comprising an optical element disposed along a path the electromagnetic energy from the laser travels.

37. The light source of claim **35**, wherein the sealed chamber comprises a support element that locates the sealed chamber relative to the curved reflective surface.

38. The light source of claim **35**, comprising a second curved reflective surface disposed internal or external to the sealed chamber to receive at least a portion of the laser electromagnetic energy and focus the electromagnetic energy on the plasma that generates the high brightness light.

39. A light source, comprising:

a sealed chamber;

an ignition source for ionizing a gas within the chamber;

at least one laser external to the sealed chamber for providing electromagnetic energy; and

a curved reflective surface to receive and reflect at least a portion of the electromagnetic energy toward the ionized gas within the chamber to produce a plasma that generates a high brightness light, the curved reflective surface also receives at least a portion of the high brightness light emitted by the plasma and reflects the high brightness light toward an output of the light source.

40. The light source of claim **39**, wherein the curved reflective surface focuses the electromagnetic energy on a region in the chamber where the plasma is located.

41. The light source of claim **39**, wherein the curved reflective surface is located within the chamber.

42. The light source of claim **39**, wherein the curved reflective surface is located external to the chamber.

43. The light source of claim **39**, wherein the high brightness light comprises ultraviolet light.

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