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Richardson et al.

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[45] **Date of Patent: Oct. 17, 1995**

[54] **WATER LASER PLASMA X-RAY POINT SOURCE AND APPARATUS**

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[73] Assignee: **University of Central Florida**, Orlando, Fla.

[21] Appl. No.: **222,608**

[22] Filed: **Apr. 1, 1994**

[51] **Int. Cl.**[6] **H05G 2/00**
[52] **U.S. Cl.** **378/119**; 378/143
[58] **Field of Search** 378/119, 124, 378/143

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[57] **ABSTRACT**

A high repetition-rate laser plasma target source system and lithography system is disclosed. The target source system comprises in a preferred embodiment a liquid tank source and freezer which freezes microscopic particles into crystal shapes which are projected by a nozzle jet from a high repetition rate liquid-droplet injector into the path of a flashing laser beam, which results in producing soft x-rays of approximately 13 nm. Uncollected and unshot target crystals are collected and reliquified by a heater source in order to be recycled back to the liquid tank source. Optionally an auxiliary source and detector system can be used to allow for instantaneous triggering of the laser beam. The target source system can be incorporated into well known EUV lithography systems for the production of wafer chips.

16 Claims, 5 Drawing Sheets

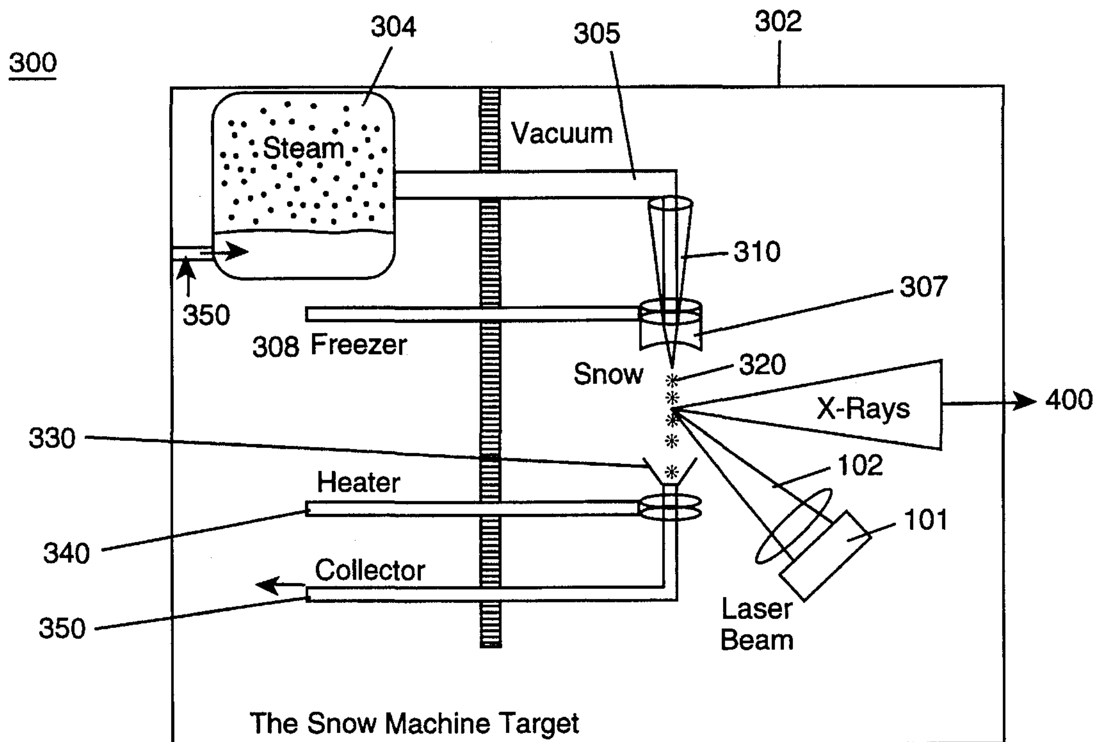
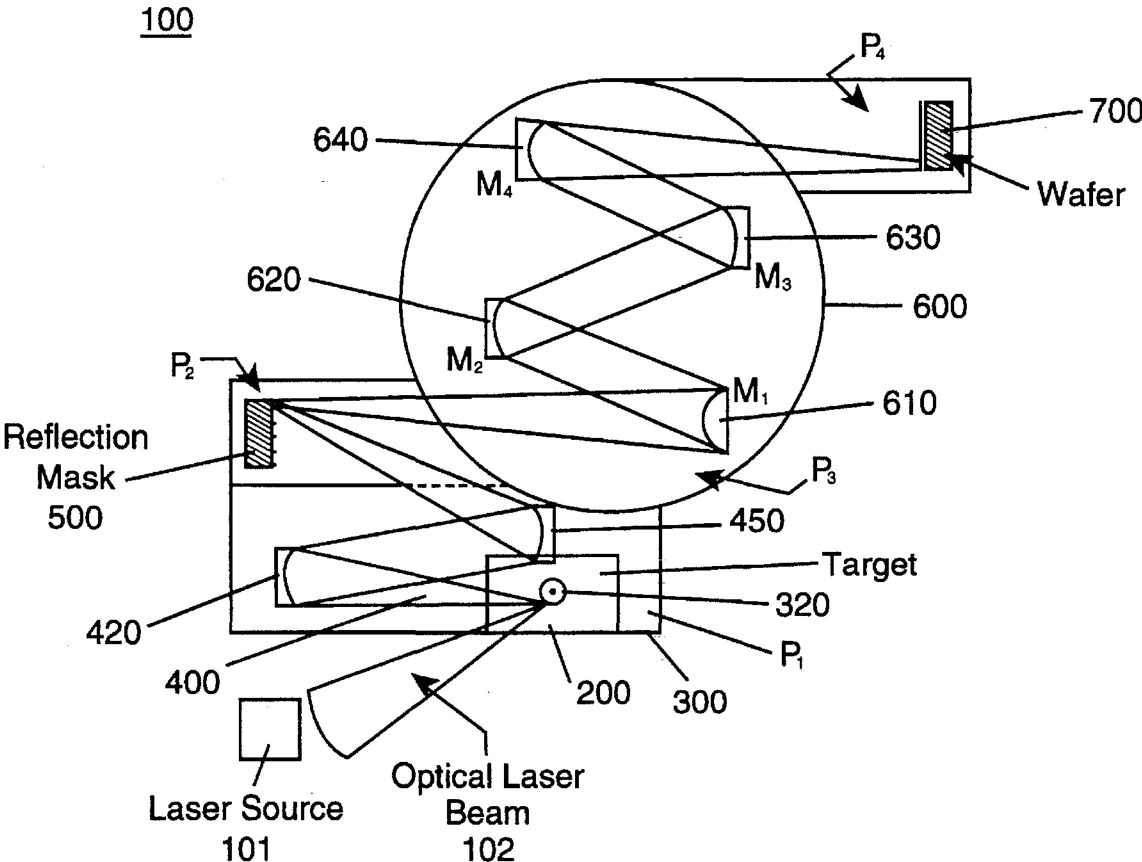


Fig. 1



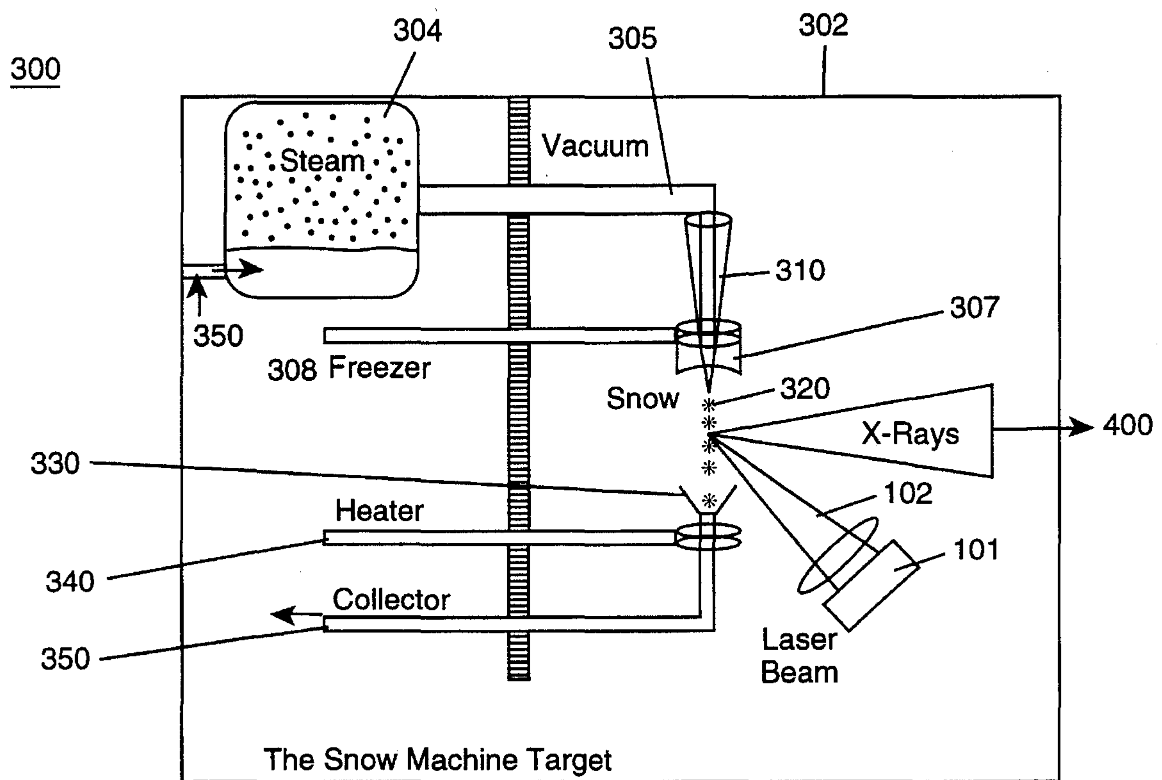


Fig. 2

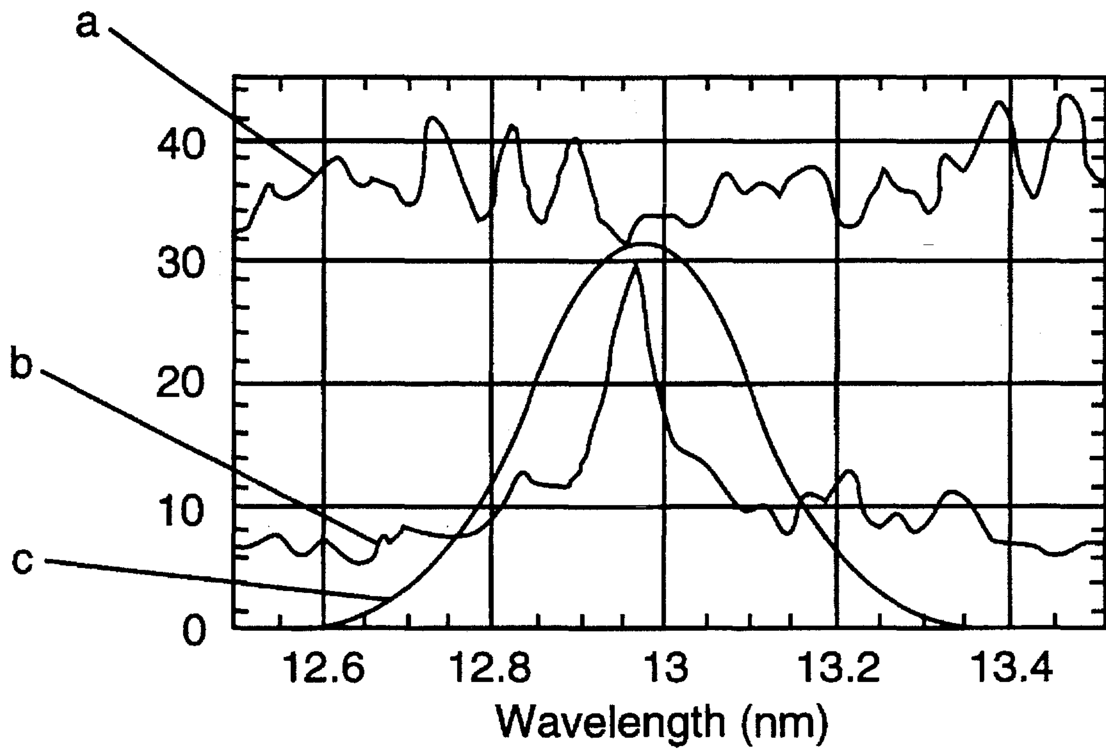


Fig. 3

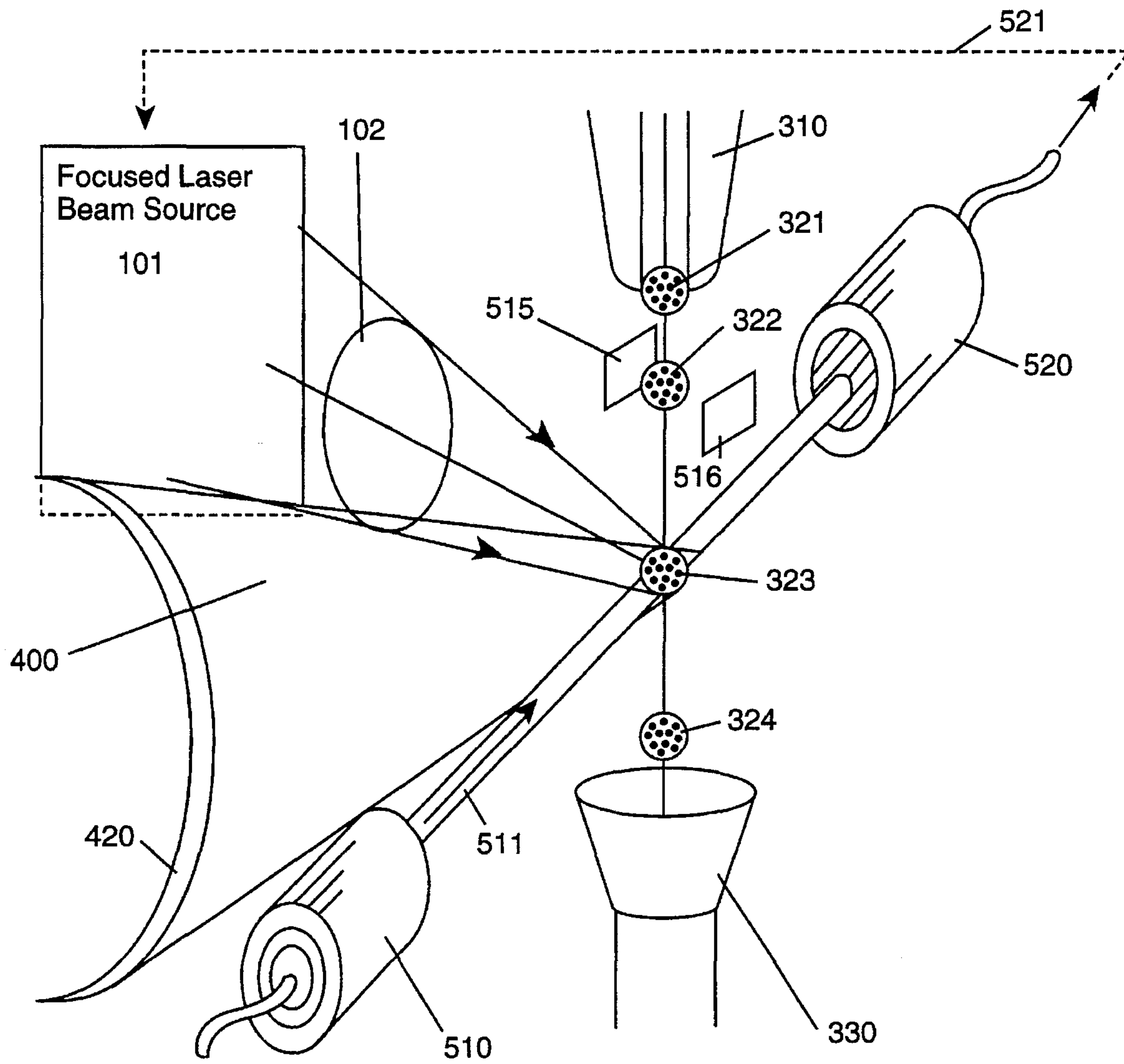
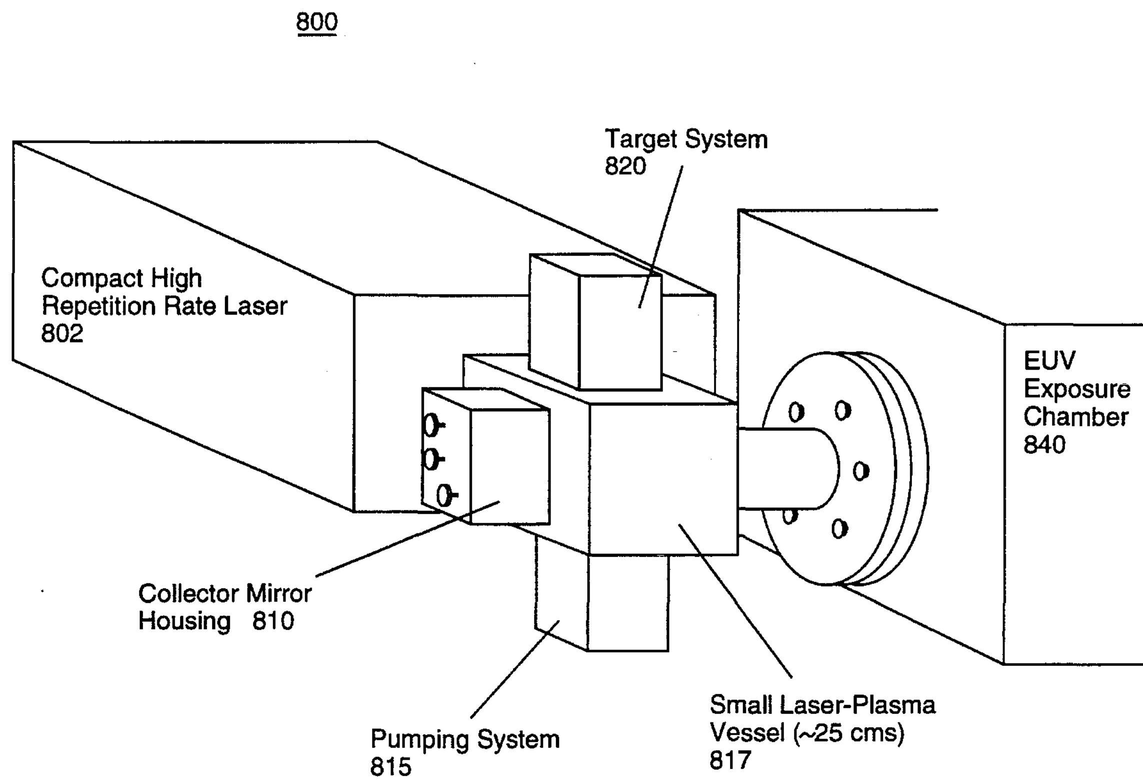


Fig. 4

Fig. 5



WATER LASER PLASMA X-RAY POINT SOURCE AND APPARATUS

This invention relates to lasers, and in particular to an ice water target source for laser plasma soft-x-ray or EUV projection lithography.

BACKGROUND AND PRIOR ART

For soft x-ray or EUV projection lithography there is a need for a high repetition-rate laser plasma source that can radiate at a specific wavelength of approximately 13 nm in the EUV part of the spectrum and capable of operating at approximately 1200 Hz. This type of source should comprise a compact high repetition-rate laser and a renewable target system capable of operating for prolonged periods of time. For a production line facility, there would need to be uninterrupted system operation for periods of approximately 3 months. That is, uninterrupted operation for some 10^9 shots. To make the irradiation system cost effective, current system cost scenarios indicate the unit shot material cost must be in the vicinity of $\$10^{-6}$ per shot. Target sources for laser plasma soft-x-ray projection lithography have encompassed several systems such as tape driven targets and solid targets and frozen gases which all have inherent problems.

U.S. Pat. No. 5,151,928 to Hirose discloses a system which uses film type tapes as a target source. However, tape driven targets are limited mass targets that are difficult to construct, prone to breakage and produce low velocity debris that can damage the other components such as the mirrors in the laser output system. Furthermore, using and replacing the tapes is generally cumbersome and costly.

Solid targets also have many problems. Known solid target sources include rotating solid wheels of Sn or tin, or copper or gold. These sources inherently can produce various ballistic particles types that can emanate from the plasma in various directions. When using tin as the target, the interaction of the laser light with the plasma, causes highly stripped, energetic ions to be formed by collision ionization. These ions can stream ballistically from the plasma region with velocities of between 10^6 and 10^7 centimeters per second. Furthermore, after the interaction of the plasma and the tin target, hot clumps or clusters of target material are boiled off of the target. These material has been determined to be another form of debris particles that can have velocities in the range of 200 to 2500 centimeters per second. The sizes of these particles range from less than 1 to greater than 200 micrometers. These larger particles can cause cold particle cratering on many of the components used to construct visible and x-ray optical components such as the mirrors and are capable of puncturing thin-film x-ray filters. All of these debris size particles can degrade the surface quality or the operating performance by overcoating the optical elements in the laser output system. Likewise, other solid targets besides tin can produce similar debris type particles.

Frozen gasses such as Krypton, Xenon, and Argon have also been tried as laser source targets, and also have problems. Besides the exorbitant cost required for containment costs, these gasses are also quite expensive and would be difficult to have a continuous high repetition rate that would cost significantly greater than $\$10^{-6}$. Moreover, all previous embodiments of frozen gas targets have envisaged massive (continuous) large-mass pellets targets which produce particulate debris.

SUMMARY OF THE INVENTION

The first objective of the present invention is to provide an inexpensive, continuously sequencing target system as a laser plasma x-ray source.

The second object of this invention is to provide a target system that produces nondamaging debris for a laser plasma x-ray source.

The third object of this invention is to provide a laser plasma target source capable of producing x-rays in the region of 13 nm within a narrow bandwidth.

The fourth object of this invention is to provide a laser plasma target source that can operate at a frequency of approximately 1000 Hz to 100 kHz.

The fifth object of this invention is to provide a laser plasma target source that can operate continuously.

The sixth object of this invention is to generate a narrow band EUV radiation source.

In a preferred embodiment, the target source system comprises a liquid tank source and freezer means which freezes microscopic particles into crystal shaped droplets which are projected by a nozzle jet on a high repetition rate liquid-droplet injector into the path of a flashing laser beam, which results in producing soft x-rays of approximately 13 nm. Uncollected and unshot target crystals are collected and reliquified by a heater source in order to be recycled back to the liquid tank source. Optionally an auxiliary source and detector system can be used to allow for instantaneous triggering of the laser beam.

Further objects and advantages of this invention will be apparent from the following detailed description of a presently preferred embodiment which is illustrated schematically in the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** illustrates an overview of an EUV Lithography system that uses the water laser x-ray plasma source.

FIG. **2** shows a preferred embodiment of the apparatus used as the laser target source in FIG. **1**.

FIG. **3** shows comparative x-ray spectroscopic data from laser plasma targets.

FIG. **4** illustrates a modification for the embodiment of FIG. **2**.

FIG. **5** shows exterior containers used for housing the components of FIG. **1**.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Before explaining the disclosed embodiment of the present invention in detail it is to be understood that the invention is not limited in its application to the details of the particular arrangement shown since the invention is capable of other embodiments. Also, the terminology used herein is for the purpose of description and not of limitation.

FIG. **1** illustrates an overview of an EUV Lithography system **100** that uses the water laser x-ray plasma source **300** which will be discussed later in reference to FIG. **2**. The components of the EUV Lithography system **100** will now be discussed. The laser beam source **101** used to irradiate the EUV target can be a high repetition rate Nd:Yag or KrF examer laser. **200** indicates the vacuum enclosure for the laser plasma target. Element **300** refers to the apparatus that continuously creates replenishable target material **320** for each laser shot, such as ice droplets. Element **420** is a first

EUV collector mirror which can be spherical in overall shape or have a spherical surface. The surface of this mirror can be coated with special multilayer structures to provide high reflectivity at near-normal incidence at selected EUV wavelengths such as 7 nm, 13 nm, and so on. Element **450** is a second multilayered coated EUV collector mirror. Although not shown, alternatively a third or more multilayered coated EUV collector mirrors can be incorporated in the FIG. **1** system. **500** refers to a specially fabricated mask structure having reflecting surfaces comprising a structure pattern to be imaged onto the wafer **700**. Elements **610, 620, 630** and **640** refer to various other spherical reflective components well known to be used in an optical system of high precision that arc capable of imaging reflection mask **500** to wafer **700**. Elements **6 10, 620, 630** and **640** can further be coated with multilayer EUV normal incidence coatings for preselected wavelengths to be used in the system. Enclosure **600** denotes a separate vacuum enclosure for housing components **610, 620, 630** and **640** of the imaging system. Alternatively, enclosure **600** can contain a low background gas such as He. Finally element **700** is a lithographic wafer comprising an EUV sensitive resist on a semiconductor substrate.

In operation an optical laser beam **102** is emitted from source **101** striking target **320**. Radiation **400** in the form of x-rays from the laser plasma source generated from target **300** are collected at mirror **420** and subsequently focussed via mirrors **450** onto mask **500** which subsequently reflects a preselected pattern via mirrors **610** to **640** to wafer **700**.

FIG. **2** shows a preferred embodiment of the apparatus **300** used to create the continuously replenishable target material used as the laser target **320** in FIG. **1**. A source supply of basic laser target material such as a pressurized water tank **304** can supply water to injector **310** either as a continuous stream of water under pressure, or as a vapor or steam that is subsequently frozen by freezer means **308**. The components of apparatus **300** can be housed in a vacuum enclosure **302**. Means **308** freezes the steam from tube **305** into frozen pellets **320** of ice crystals or snow. These frozen pellets of ice can be formed by passing the droplets through a single metallic tube **307** that has been thermo-electrically cooled or chilled by liquid Nitrogen having an approximate temperature of minus 77 degrees centigrade. Alternatively, element **307** can comprise concentric metallic tubes where the area between the inner and outer tubes includes cold liquid helium of approximately minus 260 degrees centigrade. An additional freezing technique can be accomplished by the inherent freezing that can take place within the vacuum chamber **302**. In the latter technique small droplets of water injected into a vacuum will freeze due to rapid evaporation from the surface of the droplet. Under this technique approximately 10% of the mass of a 100 ngm water droplet will be lost to evaporation before the droplet freezes.

Element **310** of FIG. **2** represents a nozzle jet device for projecting crystals into the path of laser beam **102**. High repetition rate liquid-droplet injectors with nozzle jets such as those described in U.S. Pat. Nos. 5,126,755 and 5,142,297 which are incorporated by reference can be utilized to project the frozen water droplets **320**. Although these patents describe specific embodiments of ink jet systems, the laser plasma target system disclosed in this application can utilize any type of ink jet type droplet injectors, so long as the droplet size can be made to approximate 100 ngm in mass. Element **330** signifies a vacuum collector system for absorbing unused or unshot targets. An optional heater system **340** can reliquify unused or unshot targets that can be recycled through collector tube **350**. Unused targets will liquify on contact with the collector **330**. Enhanced liquification can be introduced by heating the collector with an optional heating coil element **340**. A pump within line **350** will suck the unused liquid to reservoir tank **304** or alternatively to a waste site.

The operation of apparatus **300** will now be discussed in reference to FIG. **2**. Source tank **304** creates steam that feeds through line **305** and becomes frozen by freezer means **308**. Alternatively, the vacuum space within chamber **302** can inherently cause the steam to freeze into crystal forms such as those having a snow flake shape. Nozzle jet **310** projects microparticle ice crystals **320** at a rate of up to 100 kHz into the path of flashing laser beam **102** which flashes at a rate of approximately 200 Hz to 100,000 Hz. Collector system **330** which is in the path of crystals **320** collects the unused and unshot target crystals. Heater **340** reliquifies the crystals in order that the crystals can be recycled and pumped through line **350** back to tank source **304**.

FIG. **3** shows comparative x-ray spectroscopic data from laser plasma targets. Two spectra are shown. One is of the typical radiance of an ice target laser plasma compared to the emission of conventional target plasma. Superimposed on the spectra of the conventional target(from a Sn target) is an example of the reflectivity of typical EUV mirrors as a function of EUV radiation wavelength. Line "a" shows a typical radiance pattern along 0 to 13.4 nm that comes from materials such as Sn, An, Cu, W, Xe, or Kr as laser target sources. Line "b" shows the narrow line emission emanating at a wavelength of 13 nm from using an ice target such as the crystal particle droplets **320** shown in FIG. **2**. Line c shows the typical reflectivity function of a Mo/Si multilayer EUV mirror operating at 13 nm. As mentioned in the background section, for soft x-ray or EUV projection lithography there is a need for a high repetition-rate laser plasma source that can radiate at a specific wavelength of approximately 13 nm in the EUV part of the spectrum and capable of operating at approximately 1200 Hz. Thus, using ice crystals as a target source fulfills these needs.

FIG. **3** demonstrates that an ice target can provide approximately the same amount of radiation at 13 nm that can be effectively reflected by Mo/Si multilayer mirrors tuned to a wavelength of 13 nm. It should be noted that the radiation from the conventional target that is outside the reflection curve of the Mo/Si multilayer mirror is absorbed by the mirror. This absorbed energy can give rise to undescribable thermal distortion in the mirror surface and reduction in the reflectivity of the mirror. This points to another inherent advantage of the radiation emitted by the ice target.

FIG. **4** illustrates an auxiliary laser beam particle detection system **510, 511, 515, 5 16, 520, 521** for use with the embodiment **300** of FIG. **2**. Element **102** refers to flashing focussed laser beam. The beam **102** is focussed to intensities on the ice target of 10^{11} to 10^{12} w/cm^2,sufficient to create a plasma having a temperature high enough to ensure the copious production of Li-like oxygen ions. Elements **321** through **324** constitute the path of ice crystal droplets emanating from nozzle jet **310**. Elements **515** and **516** refers to an electrostatic guidance system which causes the ice crystals to have an electrostatic charge. The electrostatic guidance system functions. The first function is an electrostatic charging by a device generating an charge or by a device that generates an miniature electron beam that causes the droplet **322** to be charged. The second function of the system **515, 516** is as an array of charged electrodes which provide a variable electric field that can be manipulated to guide the trajectory of the charged droplets **322** to pass

through the focus volume **323** of the high power laser beam **102**. Electrostatic guidance systems of this type or systems that have these features are commonly incorporated into ink jet systems. Unshot and unused target droplets such as **324** are collected at **330**. Element **420** in FIG. **4** is a high NA collector mirror(shown also in FIG. **1**) made of high reflective multilayer EUV materials (such as Mo/Si) or some other form of efficient EUV light collector. Mirror **420** collects radiation from the source at **323** and passes the radiation via a second mirror **450** onto the reflection mask **500** as shown in FIG. **1**. Items **5 10** and **520** comprise one embodiment of a particle detection system which verifies that the injected frozen droplet is in the focus of the laser beam, and commands the laser to fire. This detection system utilizes a continuous beam **511** from a low power laser **510** that is focussed through the focus volume of the high power pulsed laser beam **102**. A photo detector **520** detects this continuous signal and the moment in time when a droplet **323** passing through the high power laser beam focuses and obscures the continuous laser beam **511**. In operation, the detection of the electrostatic charged ice droplets **323** by particle flight detector **520** will trigger the instantaneous firing of laser **101** to flash beam **102** at ice crystal target **323** which in turn produces X-rays 400. The remaining components work in the same manner and operation as FIG. **2**.

FIG. **5** shows exterior system **800** used for housing the components of FIG. **1**. The compact high repetition rate laser source **101** can be housed within box **802**. The exterior dimensions of the entire system **800** can fit into a space of approximately 1 m×0.5 m×0.5 m. The total weight of all the components **800** is approximately 50 kgms excluding electric power supplies and cooling systems. The collector mirrors **420** and **450** depicted in FIG. **1** can be housed in collector mirror housing **810** which can be readily removable from the rest of the system for replacement of parts and repairs. Referring to FIG. **5**, pumping system **815** can be incorporated into the system **800** to ensure low pressure operation of approximately 1×10^{-3} torr or less within the chamber **817** as shown in FIG. **3**. Chamber **817** connects all the other components together which allows EUV radiation to be generated. Target system container **820** can house the individual components shown in FIG. **2** EUV exposure vacuum chamber **840** in FIG. **5** can contain reflection mask **500** and collector/imaging optics **600** and wafer **700** of FIG. **1**.

While the invention has been described as an x-ray source for x-ray lithography, the invention is not limited to this use. The invention can be used as an x-ray source for x-ray microscopy, x-ray imaging systems, x-ray spectroscopy, x-ray fluorescence absorption spectroscopy, x-ray diffraction, x-ray protein diffraction studies, and x-ray interferometry.

While the preferred embodiment refers to collecting unshot and unused crystal targets for recycling, optionally the unused droplet targets can be vaporized additionally by laser beams, microwaves or infrared radiation. Alteratively, the unshot droplets can be captured and vaporized by a heated surface.

While the invention has been described, disclosed, illustrated and shown in various terms of certain embodiments or modifications which it has presumed in practice, the scope of the invention is not intended to be, nor should it be deemed to be, limited thereby and such other modifications or embodiments as may be suggested by the teachings herein are particularly reserved especially as they fall within the breadth and scope of the claims here appended.

We claim:

1. A method of producing x-rays from a target source comprising the steps of:

continuously feeding frozen water into a target source;

irradiating the target source with a laser; and

producing x-rays therefrom.

2. The method of producing x-rays of claim **1**, further comprising the step of: removing residual water particles after the step of irradiating.

3. The method of producing x-rays of claim **2**, wherein the step of removing further includes: vaporizing the residual water particles.

4. The method of producing x-rays of claim **2**, wherein the step of removing further includes: heating the residual water particles.

5. The method of producing x-rays of claim **2**, wherein the step of removing further includes: collecting the residual water particles with a vacuum.

6. The method of producing x-rays of claim **1**, wherein the step of feeding further includes; freezing the water particles into ice crystals.

7. The method of producing x-rays of claim **6**, wherein the step of feeding further includes; projecting the frozen particles through a high repetition rate liquid-droplet injector.

8. The method of producing x-rays of claim **6**, wherein the step of producing further includes; producing x-rays of approximately 13 nm.

9. The method of producing x-rays of claim **6**, wherein the step of feeding the target source further includes;

continuously feeding the target source at a frequency of approximately 1000 Hz.

10. The method of producing x-rays of claim **6**, wherein the step of feeding the target source further includes;

continuously feeding the target source in a noninterfering shot sequence approaching 2 X 10^7 targets.

11. The method of producing x-rays of claim **6**, wherein the step of feeding the target source further includes;

continuously feeding the target source in a noninterfering shot sequence exceeding 2 X 10^7 targets.

12. A method of producing 13 nm x-rays comprising the steps of:

forming ice crystals; and

irradiating the frozen ice crystals with a light source.

13. The method of producing 13 nm x-rays of claim **12**, wherein the light source is: a laser.

14. An apparatus for producing x-rays comprising:

a supply of water;

means for freezing the water into crystals;

means for feeding the crystals into a target path;

means for irradiating a laser beam into the target path creating x-rays; and

means for collecting residual crystals.

15. The apparatus for producing x-rays of claim **14**, wherein the means for feeding the crystals further includes: a high repetition rate liquid-droplet injector.

16. The apparatus for producing x-rays of claim **14**, wherein the x-rays:

have an approximate wavelength of 13rim.

* * * * *