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Gasdynamically-Controlled Droplets as the Target in a Laser-Plasma Extreme Ultraviolet Light Source

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(54) **GASDYNAMICALLY-CONTROLLED DROPLETS AS THE TARGET IN A LASER-PLASMA EXTREME ULTRAVIOLET LIGHT SOURCE**

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(52) **U.S. Cl.** **378/119**; 378/143
(58) **Field of Search** .... 378/119, 143, 378/122; 250/493.1, 504 R

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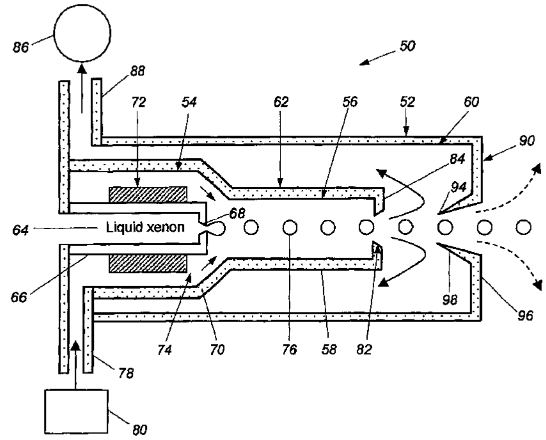
(57) **ABSTRACT**

A target material delivery system in the form of a nozzle **(50)** for an EUV radiation source **(10)**. The nozzle **(50)** includes a target material supply line **(66)** having an orifice **(68)** through which droplets **(76)** of a liquid target material **(64)** are emitted, where the droplets **(76)** have a predetermined size, speed and spacing therebetween. The droplets **(76)** are mixed with a carrier gas **(74)** in a mixing chamber **(54)** enclosing the target material chamber **(60)** and the mixture of the droplets **(76)** and the carrier gas **(74)** enter a drift tube **(56)** from the mixing chamber **(54)**. The droplets **(76)** are emitted into an accelerator chamber **(124)** from the drift tube **(56)** where the speed of the droplets **(76)** is increased to control the spacing therebetween. A vapor extractor **(90)** can be mounted to the accelerator chamber **(124)** or the drift tube **(56)** to remove the carrier gas **(74)** and target material vapor, which would otherwise adversely affect the EUV radiation generation.

39 Claims, 3 Drawing Sheets



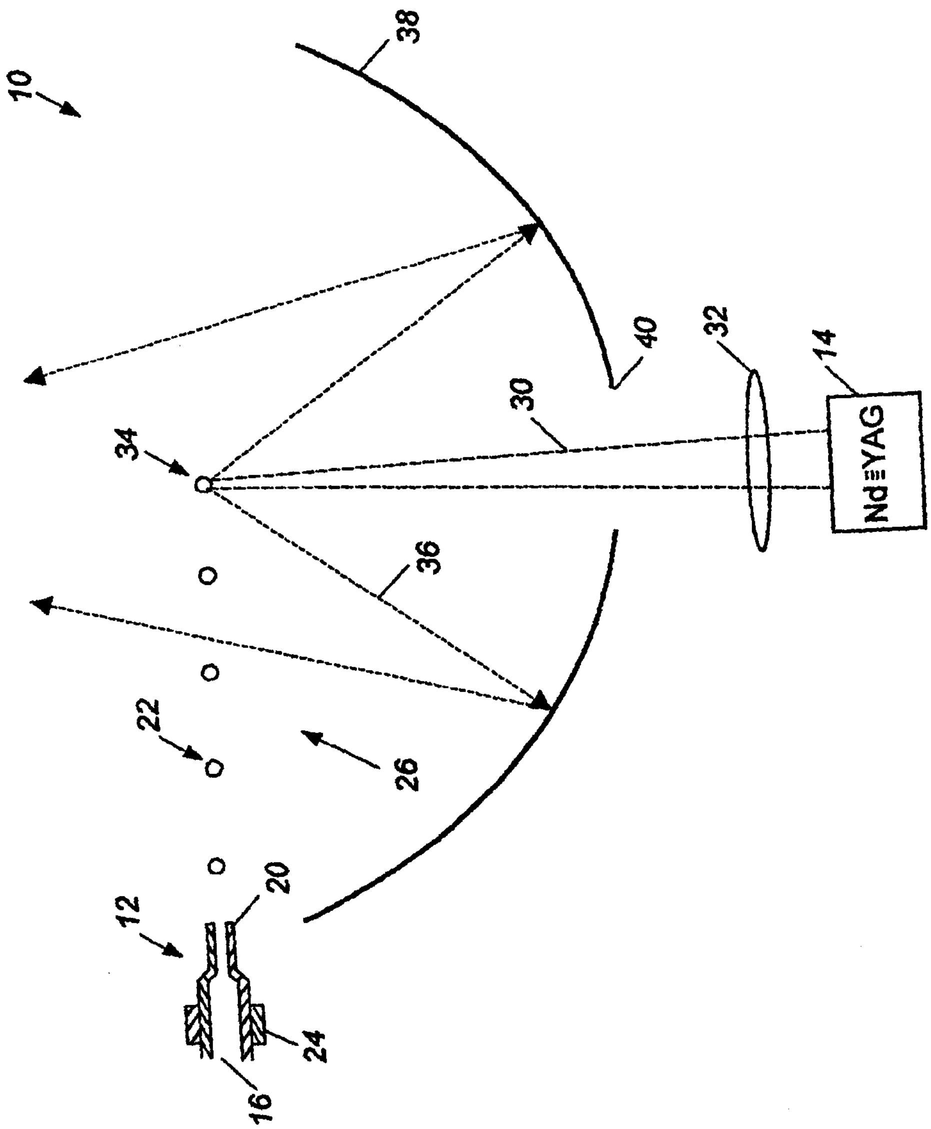
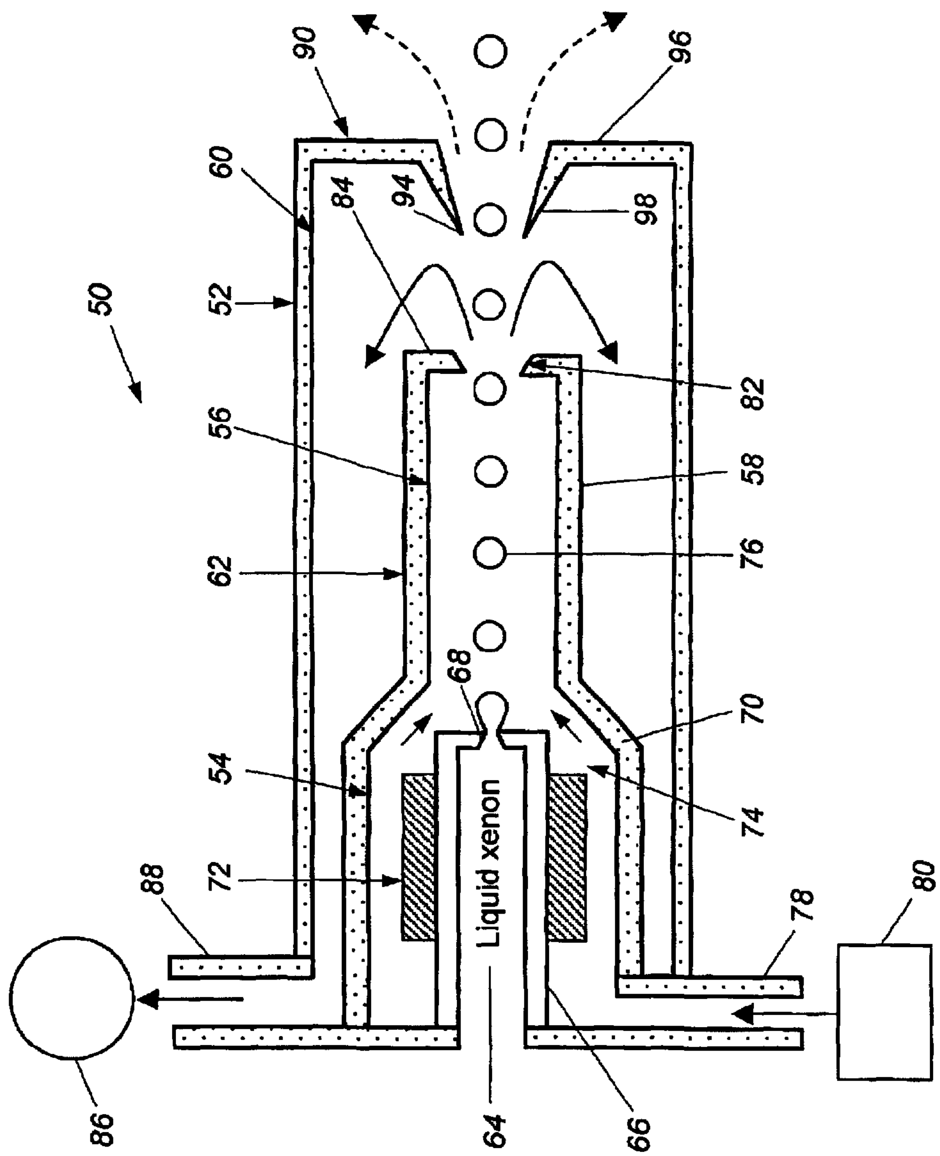


Figure 1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Liquid xenon

Figure 2

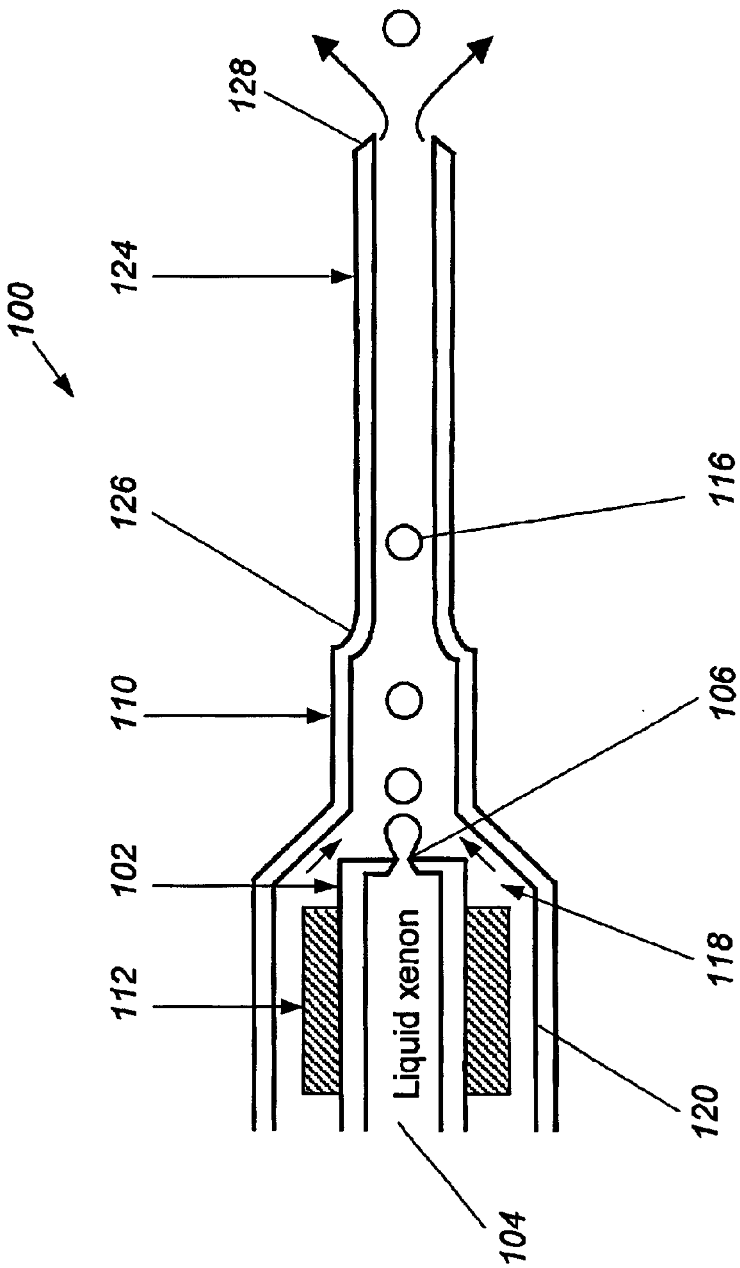

Figure 3

GASDYNAMICALLY-CONTROLLED DROPLETS AS THE TARGET IN A LASER-PLASMA EXTREME ULTRAVIOLET LIGHT SOURCE

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to a laser-plasma, extreme ultraviolet (EUV) radiation source and, more particularly, to a laser-plasma EUV radiation source having a target material delivery system that employs a droplet generator in combination with one or more of a drift tube, accelerator chamber and vapor extractor to provide tightly-controlled target droplets.

2. Discussion of the Related Art

Microelectronic integrated circuits are typically patterned on a substrate by a photolithography process, well known to those skilled in the art, where the circuit elements are defined by a light beam propagating through a mask. As the state of the art of the photolithography process and integrated circuit architecture becomes more developed, the circuit elements become smaller and more closely spaced together. As the circuit elements become smaller, it is necessary to employ photolithography light sources that generate light beams having shorter wavelengths and higher frequencies. In other words, the resolution of the photolithography process increases as the wavelength of the light source decreases to allow smaller integrated circuit elements to be defined. The current state of the art for photolithography light sources generate light in the extreme ultraviolet (EUV) or soft x-ray wavelengths (131–14 nm).

U.S. Pat. No. 6,324,256, entitled "Liquid Sprays as a Target for a Laser-Plasma Extreme Ultraviolet Light Source," and assigned to the assignee of this application, discloses a laser-plasma, EUV radiation source for a photolithography system that employs a liquid, such as xenon, as the target material for generating the laser plasma. A xenon target material provides the desirable EUV wavelengths, and the resulting evaporated xenon gas is chemically inert and is easily pumped out by the source vacuum system. Other liquids and gases, such as argon and krypton, and combinations of liquids and gases, are also available for the laser target material to generate EUV radiation.

The EUV radiation source employs a source nozzle that generates a stream of target droplets. The droplet stream is created by forcing a liquid target material through an orifice (50–100 microns diameter), and perturbing the flow by voltage pulses from an excitation source, such as a piezoelectric transducer, attached to a nozzle delivery tube. Typically, the droplets are produced at a rate (10–100 kHz) defined by the Rayleigh instability break-up frequency of a continuous flow stream for the particular orifice diameter.

To meet the EUV power and dose control requirements for next generation commercial semiconductors manufactured using EUV photolithography, the laser beam source must be pulsed at a high rate, typically 5–10 kHz. It therefore becomes necessary to supply high-density droplet targets having a quick recovery of the droplet stream between laser pulses, such that all laser pulses interact with target droplets under optimum conditions. This requires a droplet generator which produces droplets with precisely controlled size, speed and trajectory.

Various techniques have been investigated in the art for delivering liquid or solid xenon to the target location at the desirable delivery rate and having the desirable recovery time. These techniques include condensing supersonic jets, liquid sprays, continuous liquid streams and liquid/frozen droplets. As an example of this last technique, commercial droplet generators, such as inkjet printer heads, have been investigated for generating liquid droplets of different sizes that can be used in EUV sources.

The use of known droplet generators for providing a low temperature, high-volatility, low surface tension, low-viscosity fluid, such as liquid xenon, in combination with the need to inject the droplets into a vacuum provides significant design concerns. For example, because the target material is a gas at room temperature and pressure, the material must be cooled to form the liquid. Thus, it is important to prevent the liquid droplets from immediately flash boiling and disintegrating as they are emitted from the nozzle into the source vacuum. Also, because the cooled liquid droplets that do not immediately flash boil will evaporate and freeze as they travel through the source environment, the source parameters must be tightly controlled to insure the resulting size and consistency of the droplets at the target location is correct. Additionally, the speed, spacing and frequency of production of the droplets must be controlled.

SUMMARY OF THE INVENTION

In accordance with the teachings of the present invention, a target material delivery system, or nozzle, for an EUV radiation source is disclosed. The nozzle includes a target material chamber having an orifice through which droplets of a liquid target material are emitted. The size of the orifice and the droplet generation frequency is provided so that the droplets have a predetermined size, speed and spacing therebetween. In one embodiment, the droplets emitted from the target chamber are mixed with a carrier gas and the mixture of the droplets and carrier gas is directed into a drift tube. The carrier gas provides a pressure in the drift tube above the pressure of the source vacuum chamber to prevent the droplets from flash boiling and disintegrating. The drift tube allows the droplets to evaporate and freeze as they travel to become the desired size and consistency for EUV generation.

In one embodiment, the droplets are directed through an accelerator chamber from the drift tube where the speed of the droplets is increased to control the spacing therebetween. A vapor extractor can be provided relative to an exit end of the drift tube or accelerator chamber that separates the carrier gas and the vapor resulting from droplet evaporation so that these by-products are not significantly present at the laser focus area, and therefore do not absorb the EUV radiation that is generated.

Additional objects, advantages and features of the present invention will become apparent from the following description and appended claims, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a plan view of a laser-plasma, extreme ultraviolet radiation source;

FIG. **2** is a cross-sectional view of a target material delivery system herein referred to as a nozzle for a laser-plasma, extreme ultraviolet radiation source including a drift tube and a vapor extractor, according to the invention; and

FIG. **3** is a cross-sectional view of a nozzle for a laser-plasma, extreme ultraviolet radiation source including a drift tube and an accelerator chamber, according to the invention.

DISCUSSION OF THE EMBODIMENTS

The following discussion of the embodiments of the invention directed to controlling the target droplets in a laser-plasma, extreme ultraviolet radiation source is merely exemplary in nature, and is in no way intended to limit the invention, or it's applications or uses.

FIG. **1** is a plan view of an EUV radiation source **10** including a nozzle **12** and a laser beam source **14**. A liquid **16**, such as liquid xenon, flows through the nozzle **12** from a suitable source (not shown). The liquid **16** is forced under pressure through an exit orifice **20** of the nozzle **12** where it is formed into a stream **26** of liquid droplets **22** directed to a target location **34**. A piezoelectric transducer **24** positioned on the nozzle **12** perturbs the flow of liquid **16** to generate the droplets **22**. The droplets **22** are emitted from the nozzle as liquid droplets, but as the droplets **22** travel from the nozzle **12** to the target location **34** in the vacuum environment, they partially evaporate and freeze.

A laser beam **30** from the source **14** is focused by focusing optics **32** onto the droplet **22** at the target location **34**, where the source **14** is pulsed relative to the rate of the droplets **22** as they reach the target location **34**. The energy of the laser beam **30** vaporizes the droplet **22** and generates a plasma that radiates EUV radiation **36**. The EUV radiation **36** is collected by collector optics **38** and is directed to the circuit (not shown) being patterned. The collector optics **38** can have any suitable shape for the purposes of collecting and directing the radiation **36**. In this design, the laser beam **30** propagates through an opening **40** in the collector optics **38**, however, other orientations are known. The plasma generation process is performed in a vacuum.

FIG. **2** is a cross-sectional view of a target material delivery system in the form of a nozzle **50**, according to the invention, applicable to be used as the nozzle **12** in the source **10**. The nozzle **50** includes an outer cylindrical housing **52** defining an outer vapor extraction chamber **60** and an inner cylindrical housing **62** coaxial with the housing **52**, as shown. The housing **62** includes an outer wall **58** defining a mixing chamber **54** and a drift tube **56** connected thereto. A cylindrical target material supply line **66** is positioned within and coaxial to the mixing chamber **54** through which the target material **64**, here liquid xenon, is transferred under pressure from a suitable source (not shown). The supply line **66** includes an orifice **68** proximate a tapered shoulder region **70** in the wall **58** connecting the mixing chamber **54** to the drift tube **56**, as shown.

A piezoelectric transducer **72** is provided external to and in contact with the supply line **66**, and agitates the chamber **66** so that target droplets **76** are emitted from the orifice **68** into the drift tube **56**. The size of the orifice **68** and the frequency of the piezoelectric agitation are selected to generate the target droplets **76** of a predetermined size. Typically, the piezoelectric transducer **72** is pulsed at a frequency that is related to the Rayleigh break-up frequency of the liquid xenon for a particular diameter of the orifice **68** to provide a continuous flow stream, so that the droplets **76** have the desired size at the target location **34**.

A gas delivery pipe **78** is connected to the mixing chamber **54** and directs a carrier gas, such as helium or argon, from a carrier gas source **80** to the mixing chamber **54**. Other carrier gases can also be used as would be appreciated by those skilled in the art. The carrier gas is relatively transparent to the laser beam **30** and may be cooled so as to aid in the freezing of the droplets **76**. The carrier gas source **80** includes one or more canisters (not shown) holding the carrier gases or, alternatively, a pump from a closed-loop gas recirculation system. The source **80** may include a valve (not shown) that selectively controls which gas, or what mixture of the gases, is admitted to the mixing chamber **54** for mixing with the droplets **76** and a heat exchanger for temperature control. The carrier gas provides a pressure in the drift tube **56** above the pressure of the vacuum chamber in which the nozzle **50** is positioned. The pressure, volume and flow rate of the carrier gas would application specific to provide the desired pressure.

Because the pressure in the drift tube **56** and the temperature of the material **64** are low, the droplets **76** begin to evaporate and freeze, which creates a vapor pressure. The combination of the vapor pressure and the carrier gas pressure prevents the droplets **76** from flash boiling, and thus disintegrating. In certain applications, the carrier gas may not be needed because the vapor pressure alone may be enough to prevent the droplets **76** from flash boiling.

The carrier gas and target material mixture flows through the drift tube **56** for a long enough period of time to allow the droplets **76** to evaporatively cool and freeze to the desired size and consistency for the EUV source application. The length of the drift tube **56** is optimized for different target materials and applications. For xenon, drift tube lengths of 10–20 cm appear to be desirable. The droplets **76** are emitted from the drift tube **56** through an opening **82** in an end plate **84** of the drift tube **56** into the chamber **60**, and have a desirable speed, spacing and size.

The carrier gas and evaporation material are generally unwanted by-products in the target location **34** because they may absorb the EUV radiation decreasing the EUV production efficiency. To remove these materials from the droplet stream, a vapor extractor **90** is provided, according to the invention. The vapor extractor **90** is mounted, in any desirable manner, to the housing **52** opposite the chamber **60**, as shown. The extractor **90** includes an end plate **96** including a conical portion **98** defining an opening **94**. The conical portion **98** may, alternatively, be replaced by a nozzle or orifice of some other shape to create the opening **94**. The opening **94** is aligned with the droplets **76** so that the droplets **76** exit the nozzle **50** through the opening **94**. The vapor extractor **90** prevents the majority of the evaporation material and carrier gas mixture from continuing along with the droplet stream because it is collected in the vapor extraction chamber **60**. A pump **86** pumps the extracted carrier gas and the evaporation material out of the chamber **60** through a pipe **88**.

FIG. **3** is a cross-sectional view of a nozzle **100** also applicable to be used as the nozzle **12** in the source **10**, according to another embodiment of the present invention. The nozzle **100** includes a target material chamber **102** directing a liquid target material **104** through an orifice **106** into a drift tube **110**. As above, the nozzle **100** includes a piezoelectric vibrator **112** that agitates the target material to generate target droplets **116** of a predetermined diameter exiting the orifice **106**. The droplets **116** are mixed with a carrier gas **118** from a carrier gas chamber **120** as the droplets **116** enter the drift tube **110**. The droplets and carrier gas mixture propagate through the drift tube **110** where the droplets **116** partially evaporate and freeze. The carrier gas provides a pressure that prevents the droplets **116** from immediately flash boiling before they have had an opportunity to freeze. The drift tube **110** allows the droplets **116** to partially or wholly freeze so that they will not breakup during acceleration through the nozzle **100**.

In certain designs, the spacing between the droplets **116** may not be correct as they exit the orifice **106** as set by the continuous break-up frequency. To increase the spacing between the droplets **116**, the droplet and carrier gas mixture enters an accelerator section **124** connected to the drift tube **110**. A narrowed shoulder region **126** between the drift tube **110** and the accelerator section **124** causes the target material and gas mixture to accelerate through the accelerator section **124**. The increase in speed causes the distance between the droplets **116** in the mixture to increase. The length of the accelerator section **124** is also application specific, and is selected for a particular target material speed and size. The diameter of the accelerator section **124** is determined based on the diameter of the droplets **116** so that the section **124** is just wide enough to allow the droplets **116** to pass and be accelerated by the carrier gas pressure.

The droplets **116** exit the accelerator section **124** through an exit orifice **128**. The droplets **116** are directed to the target location **34**, where they are vaporized by the laser beam **30** to generate the plasma, as discussed above.

The nozzle **100** does not employ a vapor extractor in this embodiment, but such an extractor could be optionally added. In certain designs and applications, the carrier gas and evaporation material can be removed by the source chamber pump. Also, in some applications, the evaporation material and carrier gas may not significantly adversely affect the EUV radiation generation process.

The foregoing discussion discloses and describes merely exemplary embodiments of the present invention. One skilled in the art will readily recognize from such discussion and from the accompanying drawings and claims, that various changes, modifications and variations can be made therein without departing from the spirit and scope of the invention as defined in the following claims.

What is claimed is:

1. A target material delivery system, in the form of a nozzle, for an extreme ultraviolet radiation source comprising:

a target material supply line including an orifice, said target material chamber line configured to emit a stream of droplets of a target material from the orifice;

a mixing chamber enclosing the target chamber, said mixing chamber configured to receive the stream of droplets and a carrier gas;

a drift chamber coupled to the mixing chamber and configured to receive the droplet and carrier gas mixture, said drift chamber configured to prevent the droplets from flash boiling and to allow the droplets to freeze;

an accelerator chamber coupled to the drift chamber and configured to receive the droplet and carrier gas mixture, said accelerator chamber including an exit opening opposite the drift chamber through which the droplet stream exits the nozzle, said accelerator chamber configured to cause the speed of the droplets to increase; and

an extractor mounted to the accelerator chamber proximate the exit opening, said extractor configured to remove a substantial portion of the carrier gas and target material vapor from the droplet and carrier gas mixture.

2. The system according to claim **1** wherein the target material supply line, the mixing chamber, the drift chamber and the accelerator chamber are cylindrical.

3. The system according to claim **2** wherein the drift chamber has a smaller diameter than the mixing chamber and the accelerator chamber has a smaller diameter than the drift chamber.

4. The system according to claim **1** further comprising a carrier gas source, said carrier gas source being in fluid communication with the mixing chamber through a valve.

5. The system according to claim **1** wherein the extractor is coupled to a vapor extractor chamber enclosing the drift chamber, wherein the carrier gas and the target material vapor extracted by the extractor from the mixture is collected in the vapor extractor chamber.

6. The system according to claim **5** further comprising a vapor pump, said vapor pump being coupled to the vapor extractor chamber and configured to remove the extracted carrier gas and target material vapor therein.

7. The system according to claim **1** wherein the extractor includes a conical section aligned with the stream of droplets and the exit opening.

8. The system according to claim **1** further comprising a piezoelectric transducer in contact with the target material supply line, said piezoelectric transducer configured to agitate the target material supply line to generate the stream of droplets.

9. The system according to claim **1** wherein the target material is liquid xenon.

10. A nozzle for an extreme ultraviolet radiation source comprising:

a target material chamber including an orifice, said target material chamber configured to emit a stream of droplets of a target material from the orifice; and

a drift chamber aligned with the orifice and configured to receive the stream of droplets, said drift chamber being of a predetermined length so as to allow the droplets to freeze as they propagate through the drift chamber, said drift chamber including a drift chamber opening opposite the target material chamber through which the droplets exit the drift chamber.

11. The nozzle according to claim **10** wherein the drift chamber includes a carrier gas opening configured to receive a carrier gas, said carrier gas mixing with the stream of droplets in the drift chamber, said carrier gas, in combination with vapor from the droplets, providing a pressure within the drift chamber so as to prevent the droplets from flash boiling.

12. The nozzle according to claim **11** wherein the carrier gas is introduced into the drift chamber through a mixing chamber that encloses the target material chamber in a coaxial manner, said drift chamber being in fluid communication with the mixing chamber.

13. The nozzle according to claim **12** wherein the target material chamber, the mixing chamber and the drift chamber are cylindrical.

14. The nozzle according to claim **10** further comprising a vapor extractor including a vapor extractor opening aligned with the target material chamber orifice and the drift chamber opening, said vapor extractor configured to extract vapor from the stream of droplets resulting from partial evaporation of the droplets.

15. The nozzle according to claim **14** wherein the vapor extractor includes a conical portion aligned with the drift chamber opening.

16. The nozzle according to claim **14** further comprising a vapor extractor chamber, said vapor extractor chamber configured to collect vapor extracted by the vapor extractor, said vapor extractor chamber enclosing the drift chamber.

17. The nozzle according to claim **16** further comprising a vapor pump, said vapor pump being coupled to the vapor extractor chamber and configured to remove the extracted vapor collected therein.

18. The nozzle according to claim **10** further comprising an accelerator chamber coupled to the drift chamber and configured to receive the stream of droplets therefrom, said accelerator chamber including an accelerator chamber exit opening opposite the drift chamber through which the droplet stream exits the nozzle, said accelerator chamber configured to cause the speed of the droplets to increase.

19. The nozzle according to claim **18** wherein the drift tube and the accelerator chamber are cylindrical, where the accelerator chamber has a smaller diameter than the drift chamber.

20. The nozzle according to claim **10** wherein the target material is liquid xenon.

21. The nozzle according to claim **10** further comprising a piezoelectric transducer in contact with the target material chamber, said piezoelectric transducer configured to agitate the material chamber to generate the stream of droplets.

22. A nozzle for an extreme ultraviolet radiation source comprising:

a target material supply line including an orifice, said target material supply line configured to emit a stream of droplets of a target material from the orifice;

a drift chamber configured to receive the stream of droplets from the target material supply line, said stream of droplets propagating through the drift chamber as the droplets freeze, said stream of droplets exiting the drift chamber through an exit opening; and

a vapor extractor positioned relative to the exit opening in the drift chamber, said vapor extractor configured to remove vapor from the condensation of the droplets.

23. The nozzle according to claim **22** wherein the drift chamber includes a carrier gas opening configured to receive a carrier gas, said carrier gas mixing with the stream of droplets in the drift chamber, said carrier gas, in combination with vapor from the droplets, providing a pressure within the drift chamber so as to prevent the droplets from flash boiling.

24. The nozzle according to claim **23** wherein the carrier gas is introduced into the drift chamber through a mixing chamber surrounding the target material supply line in a coaxial manner, said drift chamber being in fluid communication with the mixing chamber.

25. The nozzle according to claim **22** wherein the vapor extractor includes a conical portion aligned with the exit opening.

26. The nozzle according to claim **22** further comprising a vapor extractor chamber, said vapor extractor chamber configured to collect vapor extracted by the vapor extractor, said vapor extractor chamber enclosing the drift chamber.

27. The nozzle according to claim **26** further comprising a vapor pump, said vapor pump being coupled to the vapor extractor chamber and configured to remove the extracted vapor collected therein.

28. The nozzle according to claim **22** wherein the target material is liquid xenon.

29. The nozzle according to claim **22** further comprising a piezoelectric transducer in contact with the target material supply line, said piezoelectric transducer configured to agitate the target material supply line to generate the stream of droplets.

30. A nozzle for an extreme ultraviolet radiation source comprising:

a target material supply line including an orifice, said target material supply line configured to emit a stream of droplets of a target material from the orifice;

a drift chamber configured to receive the stream of droplets from the target material supply line, said stream of droplets propagating through the drift chamber as the droplets freeze, said stream of droplets exiting the drift chamber through a drift chamber exit opening; and

an accelerator chamber coupled to the drift chamber and configured to receive the stream of droplets therefrom, said accelerator chamber including an accelerator chamber exit opening opposite the drift chamber through which the droplet stream exits the nozzle, said accelerator chamber configured to cause the speed of the droplets to increase.

31. The nozzle according to claim **30** wherein the target material supply line, the drift chamber and the accelerator chamber are cylindrical.

32. The nozzle according to claim **30** wherein the drift chamber includes a carrier gas opening configured to receive a carrier gas, said carrier gas mixing with the stream of droplets in the drift chamber, said carrier gas, in combination with vapor from the droplets, providing a pressure within the drift chamber so as to prevent the droplets from flash boiling.

33. The nozzle according to claim **32** wherein the carrier gas is introduced into the drift chamber through a mixing chamber that encloses the target material supply line in a coaxial manner, said drift tube being in fluid communication with the mixing chamber.

34. The nozzle according to claim **30** further comprising a vapor extractor including a vapor extractor opening aligned with the target material chamber orifice and the drift chamber opening, said vapor extractor configured to extract vapor from the stream of droplets resulting from evaporation of the droplets.

35. The nozzle according to claim **34** wherein the vapor extractor includes a conical portion aligned with the drift chamber opening.

36. The nozzle according to claim **34** further comprising a vapor extractor chamber, said vapor extractor chamber configured to collect vapor extracted by the vapor extractor, said vapor extractor chamber enclosing the drift chamber.

37. The nozzle according to claim **36** further comprising a vapor pump, said vapor pump being coupled to the vapor extractor chamber and configured to remove the extracted vapor collected therein.

38. The nozzle according to claim **30** wherein the target material is liquid xenon.

39. The nozzle according to claim **30** further comprising a piezoelectric transducer in contact with the target material supply line, said piezoelectric transducer configured to agitate the target material supply line to generate the stream of droplets.

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