Nanoparticle seeded short-wavelength discharge lamps

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Methods, systems and apparatus for using nanoparticle seeded short-wavelength discharge generator sources discharge sources, for use with X-ray, XUV and EUV light emissions. Applications can include EUV lithography. Additional embodiments can use the generator sources for Hollow Cathode Plasma Discharge (HCPD) lamps, and dense plasma focus (DPF) devices and other sources. Target streams of gases such as Xe and nanoparticles such as tin, copper, or lithium can be heated with laser type sources to emit nano-droplets therefrom.
DISBURSING STREAM OF MICRO-TARGETS

FOCUS LIGHT SOURCE

HEAT MICRO-TARGET

GENERATE NANO-DROPLETS
FIG. 3A

FIG. 3B
1

NANOPARTICLE SEeded
SHORT-WAVELENGTH DISCHARGE LAMPS

This invention claims the benefit of U.S. Provisional Patent Application Ser. No. 60/517,523 filed Nov. 5, 2003, and this invention is a Continuation-In-Part of U.S. application Ser. No. 10/822,658 filed Oct. 19, 2001, now U.S. Pat. No. 6,865,255, which is a continuation-in-part of U.S. application Ser. No. 09/881,620 filed Jun. 14, 2001, now U.S. Pat. No. 6,831,963 that further claims the benefit of U.S. Provisional application No. 60/242,102 filed Oct. 20, 2000, and which is a Continuation-In-Part of U.S. application Ser. No. 09/685,291 filed Oct. 10, 2000, now U.S. Pat. No. 6,377,651 that further claims the benefit of U.S. Provisional Application No. 60/158,723 filed Oct. 11, 1999, and this invention is a Continuation-In-Part of U.S. application Ser. No. 10/795,814 filed Mar. 8, 2004, now U.S. Pat. No. 6,862,339.

FIELD OF THE INVENTION

This invention relates to discharge sources, in particular, to methods, systems and devices for nanoparticle seeded short-wavelength discharge sources for X-Ray, XUV and EUV emission that can be used in applications such as lithography, and as hollow cathode plasma discharge (HCPD) lamps, dense plasma focus (DPF) sources and other sources.

BACKGROUND AND PRIOR ART

Pulsed electric discharges are well known sources of short-wavelength light, having applications in regions of the electromagnetic spectrum from the ultra-violet (UV, wavelength \( \lambda < 300 \text{ nm} \)) to the x-ray range (\( \lambda < 1 \text{ nm} \)). However, there is a need for stable, long-life light sources in the EUV region of the spectrum, \( \lambda = 10 \text{ to } 50 \text{ nm} \), particularly for EUV lithography (EUVL).

EUVL is expected to succeed Deep UV lithography technology for the production of silicon-based computer chips, at and beyond the 35 nm node. This technology is expected to take over fabrication in the 2007-2009 timeframe. The stepper machines that print these chips are expected to cost $20-40 M each, and, in this timeframe, anticipated sales of 200-300 units/year are expected, providing the three major stepper manufacturing companies, ASML (Netherlands & USA), Nikon and Canon (Japan), with a new $100 B/year market. The light sources for these steppers, are currently required to provide greater than 100 W of “clean power” and can account for up to 20% of this total market. A source of sufficient power is identified as the principal problem area in the ITRS (SEMATECH) Roadmap for the development of EUVL. The roadmap has been modified periodically over the years to take into account the required increase in wafer throughput, larger (300 mm) wafers, and higher Cost of Ownership (CoO), and the power of the source demanded has progressively increased. Currently the total required emitted power within a solid angle of 2\( \pi \), from a source of <1 mm in size within a 2% bandwidth at a wavelength of 13.5 nm, is 400 to 1000 W. This large amount of power is the major challenge for companies developing the light sources.

There are two primary types of light sources being developed, those that depend on electrical discharge plasma, and those that use a laser-plasma source. Both approaches operate at frequencies in excess of 5 kHz, with pulse-to-pulse stability of approximately 1%. They are also required to be capable of long term operation (up time >95%), and ‘clean’ operation. By ‘clean’ operation we mean ‘debris-free’ or protected from the effects of particulate emission and plasma ions emanating from the source.

Both laser plasmas and discharge plasmas can produce high velocity particulate emission or ‘projectiles’ that will damage the expensive, precision-coated EUV collection mirrors that are in direct line-of-sight of the source. In laser plasmas, this particulate debris can originate from solid target sources, or close-proximity nozzles used to inject gaseous targets. In discharge sources, the debris originates from the electrodes or from insulative materials close by. The plasma ions are, of course, inherent to the plasma itself. They need to be stopped from sputtering (ablating) the collection mirrors. Several techniques have been devised to stop the sputtering, including Repeller Field approach disclosed in U.S. Pat. No. 6,377,651 issued to Richardson, et al. on Apr. 23, 2002, which is incorporated by reference.

Companies developing discharge plasmas (DP) include Philips (Hollow-Cathode Plasma Discharge), Xtreme Technologies (IIC Z-pinch), Cymer (Dense Plasma Focus), Plex LLC (star discharge), Gygaphoton (capillary discharge pinch plasma). Most of these companies are focusing their R&D activities on Xeon-based plasmas. Although the use of Xeon mitigates the debris problem to some extent, the principal drawback is its low conversion efficiency into in-band, 13.5 nm EUV light. Both DP and LP sources have been limited to conversion efficiencies (CE) of 0.5 to 0.7%. The highest known CE is 0.95%. Moreover, there are now solid, atomic physics, reason to believe that the CE of Xeon will not improve much beyond these values.

These low CE’s have adverse implications for both discharge plasma and laser plasma sources. For the laser plasma it means the use of a laser system having a power in excess 40 kW, beyond known technical capabilities and possibly prohibitively expensive. For discharge plasma sources, the low CE poses extreme problems with heat removal from the source and very large electrical power requirements, approaching 1 MW.

One approach for laser plasma sources uses microscopic, mass-limited, spherical targets composed of several materials including a small amount of tin. Tin is a metal and can, in principal pose a more serious debris problem as an EUV source. However, it has the advantage that much higher CE’s are possible. CE’s of 1-2% have been demonstrated and there is reason to believe higher values are possible.

The possible advantages of introducing tin into the discharge region of the source have been recognized and cursory tests completed. Use of electrodes made of tin-containing material, or using some method (thermal evaporation, or electron-beam heating) to introduce a tin vapor into the discharge has been disclosed. It is believed that the results have been disappointing for one or more reasons including, creation of large amounts of debris, instabilities in the discharge, and difficulties foreseen in scaling to the required powers. These difficulties originate from the inability to inject into the discharge a precisely known quantity of tin atoms, the minimum quantity that is required for the discharge to radiate 13.5 nm light efficiently.

The present invention advances the art by inclusion of method, apparatus and system that generates a cloud of nanodroplets for use as an X-ray, XUV, EUV, and EUV lithography light source and as a seed for a hollow cathode plasma discharge (HCPD) and dense plasma focus (DPF) source. The principle is the rapid transformation of a micro-target of mixed materials into a cloud of nano-droplets or nanoparticles. Incorporation of the nanoparticle generator into a plasma discharge light source, converts the plasma into a
n nanoparticle dominated plasma that produces a short-wavelength light and improves efficiency.

SUMMARY OF THE INVENTION

The first objective of the present invention is to provide a method, apparatus and system for generating a cloud of nanodroplets or nanoparticles from the rapid transformation of a microparticle mixed materials.

The second objective of the present invention is to provide a method, apparatus and system for generating a cloud of nanodroplets or nanoparticles for use as an X-ray light source.

The third objective of the present invention is to provide a method, apparatus and system for generating a cloud of nanodroplets or nanoparticles for use as an EUV light source.

The fourth objective of this invention is to provide a method, apparatus and system for generating a cloud of nanodroplets or nanoparticles for use as an EUV light source.

The fifth objective of the present invention is to provide a method, apparatus and system for generating a cloud of nanodroplets or nanoparticles for use in EUV lithography.

The sixth objective of the present invention is to provide a method, apparatus and system for generating a cloud of nanodroplets or nanoparticles as a seed for a Hollow Cathode Plasma Discharge (HCPD) source.

The seventh objective of the present invention is to provide a method, apparatus and system for generating a cloud of nano-droplets or nanoparticles as a seed for a dense plasma focus (DFP) source.

The method, apparatus and system of the present invention generates a cloud of nano-droplets for use as an X-ray, EUV, EUV, and EUV lithography light source and as a seed for a hollow cathode plasma discharge (HCPD), Star discharge (SD) and dense plasma focus (DFP) source, and other sources. The principle is the rapid transformation of a micro-target of mixed materials into a cloud of nano-droplets or nanoparticles. The micro-target includes at least two materials, an evaporant and a nanoparticle material.

The method, apparatus and system includes a dispenser for dispensing a target stream of microparticles, a light source and a focus lens for focusing the light source on the target stream.

The target stream of dispersed microparticles, or micro-droplets, are arranged to pass through the focus of the lens that focuses the light source onto the target stream. The energy absorbed from the light source heats the material of the microparticle, generating nano-droplets. Incorporation of the nanoparticle generator into a plasma discharge light source, converts the plasma into a nanoparticle dominated plasma that produces a short-wavelength light and improves efficiency. With the integration of the novel nanoparticle generator, these discharge lamps would work the same way they do now with a gaseous medium, with the exception that the gaseous medium would be modified, and seeded with a known number of nanoparticles of elements.

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

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1A illustrates a dispenser for dispensing a steady stream of microparticles or micro-droplets.

FIG. 1B illustrates a dispersed micro-particle passing through the focus of a lens that focuses the output of a pulsed laser onto the microparticle.

FIG. 1C illustrates the microparticle of FIG. 1B superheated above vaporization of the evaporant material.

FIG. 1D illustrates the nanoparticles or nano-droplets diffusing outward.

FIG. 2 is a flow diagram of a method of generating nanoparticles.

FIG. 3A illustrates the primary components of a preferred embodiment of the nanoparticle generator.

FIG. 3B illustrates another embodiment of the primary components of the nanoparticle generator.

FIG. 4A illustrates a hollow cathode plasma discharge (HCPD) lamp.

FIGS. 4B and 4C illustrate integration of the nanoparticle generator of the present invention as a seed for a hollow cathode plasma discharge (HCPD) lamp.

FIG. 5A illustrates a dense plasma focus (DFP) source.

FIG. 5B illustrates integration of the nanoparticle generator as a seed for dense plasma focus (DFP) source.

FIG. 6A illustrates another dense plasma focus (DFP) source.

FIG. 6B shows another embodiment of the nanoparticle generator as a seed for a dense plasma focus (DFP) source.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Before explaining the disclosed embodiment of the present invention in detail it is to be understood that the invention is not limited in its applications 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.

The present method, apparatus and system generates a cloud of nano-droplets for use as an X-ray, EUV, EUV, and EUV lithography light source and as a seed for a hollow cathode plasma discharge (HCPD) and dense plasma focus (DFP) source, Star Plasma Device or any other electrical discharge plasma source. The principle is the rapid transformation of a micro-target of mixed materials into a cloud of nano-droplets or nanoparticles. The micro-target includes at least two materials that are categorized as either an evaporant or a nanoparticle material (NPM). Typical NPM’s might be any metal, particularly metals with low melting points (such as Copper, Zinc, Lead, Tin, Silver, Antimony, Gold, Aluminum Lithium, etc) or a non metal with a relatively high melting point. A list of some possible NPM’s is included in Table 1.

TABLE 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting point (°C)</th>
<th>Latent Heat of Fusion (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium</td>
<td>181</td>
<td>432</td>
</tr>
<tr>
<td>Aluminum</td>
<td>660</td>
<td>396</td>
</tr>
<tr>
<td>Antimony</td>
<td>630</td>
<td>165</td>
</tr>
<tr>
<td>Arsenic</td>
<td>613-817</td>
<td>370</td>
</tr>
<tr>
<td>Astatine</td>
<td>302</td>
<td>114</td>
</tr>
<tr>
<td>Barium</td>
<td>725</td>
<td>56</td>
</tr>
<tr>
<td>Bismuth</td>
<td>271</td>
<td>52</td>
</tr>
<tr>
<td>Cadmium</td>
<td>321</td>
<td>54</td>
</tr>
<tr>
<td>Calcium</td>
<td>840</td>
<td>216</td>
</tr>
<tr>
<td>Cerium</td>
<td>799</td>
<td>66</td>
</tr>
<tr>
<td>Cesium</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>Copper</td>
<td>1083</td>
<td>206</td>
</tr>
<tr>
<td>Gallium</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>Germanium</td>
<td>937</td>
<td>459</td>
</tr>
<tr>
<td>Gold</td>
<td>1064</td>
<td>63</td>
</tr>
</tbody>
</table>

FIG. 6C illustrates the nanoparticles or nano-droplets as a seed for a dense plasma focus (DFP) source.

FIG. 6D illustrates the nanoparticles or nano-droplets and the dense plasma focus (DPF) source.

Further embodiments of the present invention are illustrated schematically in the accompanying drawings.
For instance, for an approximately type of dispenser that produces microparticles having the two micro Joule of laser energy, is required for super-heating the micro-target. The laser required to convert the microparticles into nanoparticles is not required to be sophisticated. A mall, diode-pumped Nd:YAG laser with a fiber optic output producing a few millijoules of energy is sufficient. The fiber optic coupler, as a focusing element, and a burst of pulsed laser energy transmitted from a source, such as an optical fiber. The droplet dispenser consists of a droplet dispenser as a focusing element, and a burst of pulsed laser energy transmitted from a source, such as an optical fiber. The droplet dispenser consists of a system that generates a high speed stream of micro-droplets of materials, initially in a liquid form. As previously discussed, the microparticles include a nanoparticle material and an evaporant. The evaporant material is above the melting point, then the atoms of this microparticle material will coalesce into clusters or small aerosols, nanoparticles, while the vapors of the evaporant material will be driven off as gases as shown in FIG. IC. In step 26 of FIG. 2, the exploding evaporant will tend to blow the NPM nanoparticles outward, away from the focus as shown in FIG. 1D.

Control of the irradiation conditions (laser pulse energy, pulse duration, wavelength, focal spot size), the particle conditions (size, material composition), and the exposure chamber environment, provides control over the size and size-distribution of the nanoparticles created. The size of the resultant nanoparticle may be determined by commonly known techniques such as simple witness plate detection techniques.

In FIG. 3A, the nanoparticle generation system consists of a droplet dispenser for dispensing microparticles, a lens as a focusing element, and a burst of pulsed laser energy transmitted from a source, such as an X-ray, EUV or EUV light sources. A discharge lamp is a leading candidate as an approximately 13.5 nm light source for EUV lithography. X-ray, EUV or EUV emitting discharge lamps currently use a gas as the initial plasma medium. The spectral characteristics of the light source are therefore limited to the spectral characteristics that can be afforded those gases that can be used in the discharge. This limits the accessibility of specific wavelengths which would result in improved efficiency. For example, the EUVL requires a very bright light at approximately 13.5 nm with an approximately 2% bandwidth (approximately 0.27 nm).

Xenon is one gas that provides emission at this wavelength in a discharge plasma. The emission primarily comes from excited states of $Xe^{13+}$. However, the efficiency of light generation at this wavelength in Xenon is extremely small, approximately 0.7%. Were the wavelength to be approximately 11.0 nm, the preferred wavelength for Xenon, the efficiency would be ten times higher. This is a general problem with high power short-wavelength light sources. The limited number of atomic gases in the Mendeleevs Table allow only a small number of discrete wavelengths to be generated with good efficiency. The method, system and
device of the present invention expands the range of selectivity, by increasing the number of materials that can be used in a discharge light source, essentially to include nearly all of the elements in the periodic table.

With the integration of the novel nanoparticle generator, these discharge lamps would work the same way they do now with a gaseous medium, with the exception that the gaseous medium would be modified, and seeded with a known number of nanoparticles. For instance, in the case of the approximately 13.5 nm light source for EUVL, discharge light sources would be modified to operate with gases seeded with a predetermined number of Tin nanoparticles. In-band conversion efficiencies of several percent are then possible. Moreover, with an optimized conversion efficiency, the number and size of nanoparticles generated from each droplet can be adjusted so that all nanoparticles of tin (or other materials) are completely ionized, thereby minimizing the associated debris.

The nanoparticle generator is sufficiently small and rugged and can therefore be incorporated in different regions of a conventional plasma discharge design. The configuration and placement of the nanoparticle generator within a particular plasma discharge design depends on a number of factors, including the lamps overall design and operation, thermal considerations, and the plasma environment. It may be advantageous to protect the components of the nanoparticle generator from the effects of electrode debris and plasma erosion.

Incorporation of Nanoparticle Generator in Plasma Discharge Light Sources

While there are many possible designs of discharge plasma light sources that the nanoparticle generator of the present invention can be incorporated into, the nanoparticle generator is described for use with a hollow cathode discharge plasma source and a dense plasma focus source for purpose of illustration and discussion, not of limitation.

Hollow Cathode Discharge Plasma Source

The Hollow Cathode Plasma Discharge (HCPD) lamp design is particularly well suited for improvement with integration of the novel nanoparticle generator. FIGS. 4B and 4C illustrate two examples of integrating the nanoparticle generator with the hollow cathode discharge plasma source. FIG. 40 illustrates a hollow cathode plasma discharge device with a nanoparticle generator. The light source is shown in FIG. 4A. The light source is typically a discharge lamp for EUV light source in Xe gas, or a mixture of inert gases, is typically a few millimeters in length and less than a millimeter in diameter. The DPF device can be seeded incorporating the novel nanoparticle generator in several ways. Two examples of configurations are shown in FIG. 5B and 60. FIG. 6B shows a discharge lamp with two HCPD light sources.

In FIG. 5B, the nanoparticles are seeded from the cathode 630. In both cases the seeded nanoparticles are injected before the collapse of the pinched plasma. The pinched plasma will ionize, heat and excite the nanoparticles to temperatures sufficient for efficient short-wavelength emission. Synchronization of the injected microparticle in the plasma discharge cycle would be achieved in a similar manner as with the HCPD device. The method, apparatus and system of the present invention can be used for as an X-ray, XUV, EUV, and EUV lithography light source and as a seed for a hollow cathode plasma discharge (HCPD) and dense plasma focus (DPF) source. The principle is the rapid transformation of a microparticle of mixed materials into a cloud of nano-droplets or nanoparticles. The microparticle includes at least two materials, an evaporant and a nanoparticle material.

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.

I claim:

1. A method of generating nanoparticles from a single microdroplet, comprising the steps of:
   dispensing a target stream of microdroplets from a source, each microdroplet consisting essentially of an evaporant and a nanoparticle material (NPM), each microdroplet having a diameter of approximately 1 micron to approximately 500 microns; focusing a light source onto each next one of the microdroplets in the target stream; heating the next microdroplet with the light source; and generating nanoparticles from the heated next microdroplet.
   2. The method of claim 1, wherein the nanoparticle material includes: metal.
3. The method of claim 1, wherein the nanoparticle material includes: non-metal.
4. The method of claim 1, wherein the heating step includes:
raising temperature of the target stream above a boiling point of the evaporant and below that of the NPM.
5. The method of claim 4 wherein the rising temperature occurs over a time of approximately picoseconds to approximately microseconds.
6. The method of claim 1, wherein the light source includes a laser.
7. The method of claim 1, wherein microdroplet includes a diameter of approximately 30 microns and energy from the source is approximately 1 mJ (micro joules).
8. The method of claim 1, wherein dispensing the target stream includes dispensing microdroplets at a frequency from approximately 10 kHz to approximately 1 MHz.
9. The method of claim 1, further comprising the step of: applying the method as an X-ray light source.
10. The method of claim 1, further comprising the step of: applying the method as an XUV light source.
11. The method of claim 1, further comprising the step of: applying the method as an EUV light source.
12. The method of claim 1, further comprising the step of: integrating the method with a plasma discharge light source; and
seeding a gas with nanoparticles.
13. The method of claim 12, further comprising the step of: generating an approximately 13.5 nm light source.
14. The method of claim 12, further comprising the step of: seeding a gas in a discharge light source with the nanoparticles.
15. The method of claim 12, wherein the nanoparticles include: tin.
16. The method of claim 12, wherein the gas includes: Xe.
17. The method of claim 12, wherein the gas includes: He.
18. The method of claim 1, further comprising the step of: applying the method as a seed for a Hollow Cathode Plasma Discharge (HCPD) lamp.
19. The method of claim 1, further comprising the step of: applying the method as a seed for a dense plasma focus (DPF) source.
20. A system for generating nanoparticles from single microdroplets comprising:
means for dispensing a target stream of micro droplets from a source, each microdroplet consisting essentially of an evaporant and a nanoparticle material (NPM) each microdroplet having a diameter of approximately 1 micron to approximately 500 microns;
a light source for heating the microdroplets; and
means for focusing the light source on the micro droplets of the target stream, one by one, to generate the nanoparticles.
21. The system of claim 20, further comprising:
a plasma light source; and
means for seeding a gas in the plasma light source with the nanoparticles.
22. The system of claim 20, further comprising:
means for integrating the system as an x-ray light source.
23. The system of claim 20, further comprising:
means for integrating the system as an XUV light source.
24. The system of claim 20, further comprising:
means for integrating the system as an EUV light source.
25. Device for generating nanoparticles from a single microdroplet comprising:
aderenser for discharging a target stream of microdroplets, each microdroplet consisting essentially of an evaporant and a nanoparticle material (NPM), each microdroplet having a diameter of approximately 1 micron to approximately 500 microns;
a light source for heating the target stream; and
a focusing lens for causing the light source on the target stream to generate nanoparticles form the microdroplets.
26. The device of claim 25, wherein the light source comprises a laser.
27. The device of claim 25, wherein the dispenser and the focusing lens are collinear.
28. The device of claim 25, wherein the dispenser and the focusing lens are coaxial.
29. A nanoparticle-seeded short-wavelength discharge source comprising:
a plasma discharge light source;
a device for generating nanoparticles from a stream of microdroplets, each microdroplet consisting essentially of an evaporant and a nanoparticle material (NPM), each microdroplet having a diameter of approximately 1 micron to approximately 500 microns; and
means for seeding a discharge gas with the nanoparticles.
30. The discharge source of claim 29, wherein the discharge gas comprises: He.
31. The discharge source of claim 29, wherein the discharge gas comprises: Xe.
32. The discharge source of claim 29, wherein the nanoparticle generating device comprises:
means for dispensing a target stream of micro droplets from a source, each micro droplet consisting essentially of an evaporant and a nanoparticle material (NPM), each micro droplet having a diameter of approximately 1 micron to approximately 500 microns;
a light source; and
means for focusing the light source on the micro droplets of the target stream, one by one, to generate the nanoparticles.
33. The discharge source of claim 29, wherein the micro droplets includes: at least two basic constituents, nanoparticle material (NPM) and evaporant.
34. The discharge source of claim 29, wherein the discharge light source comprises: an X-ray light source.
35. The discharge source of claim 29, wherein the discharge light source comprises: an XUV light source.
36. The discharge source of claim 29, wherein the discharge light source comprises: an EUV light source.
37. The discharge source of claim 29, wherein the discharge light source comprises: a Hollow Cathode Plasma Discharge (HCPD) lamp.
38. The discharge source of claim 29, wherein the discharge light source comprises: a dense plasma focus (DPF) source.
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