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(54) **METHOD AND APPARATUS FOR GENERATING X-RAY OR EUV RADIATION**

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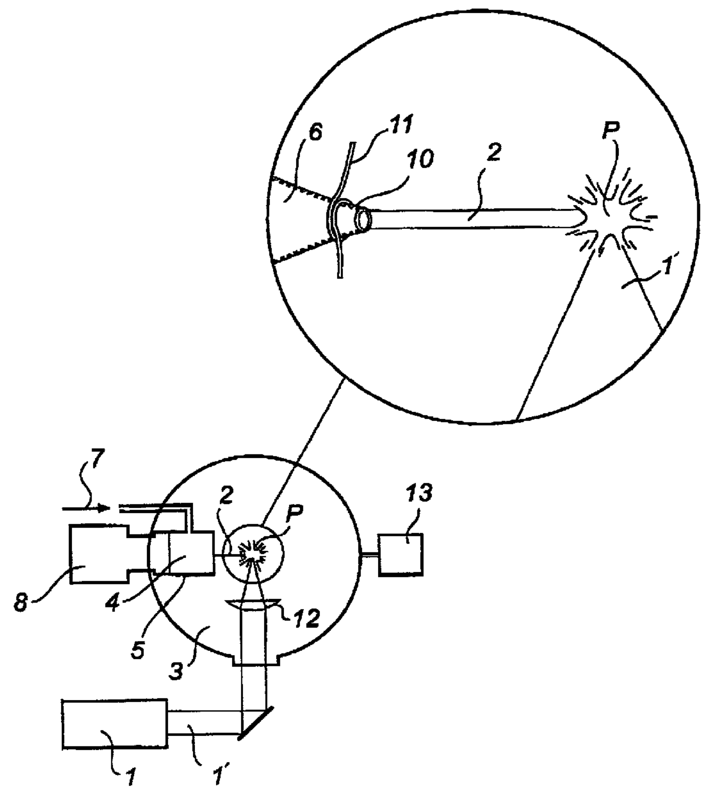
(57) **ABSTRACT**

A method and an apparatus is designed to produce X-ray or EUV radiation for use in lithography, microscopy, materials science, or medical diagnostics. The radiation is produced by urging a substance through an outlet **(6)** to generate a microscopic jet **(2)** in a direction from the outlet **(6)**, and by directing at least one energy beam **(1')** onto the jet **(2)**, wherein the energy beam **(1')** interacts with the jet **(2)** to produce the X-ray or EUV radiation. The temperature of the outlet **(6)** is controlled to increase the directional stability of the jet **(2)**. The thus-achieved directional stability of the jet **(2)** provides for reduced pulse-to-pulse fluctuations of the produced radiation, improved spatial stability of the radiation source, as well as high average power since the energy beam **(1')** can be tightly focused on the jet **(2)**, even at a comparatively large distance from the jet-generating outlet **(6)**. The large distance provides for low erosion of the outlet **(6)**, even when using a high-power energy beam **(1')**.



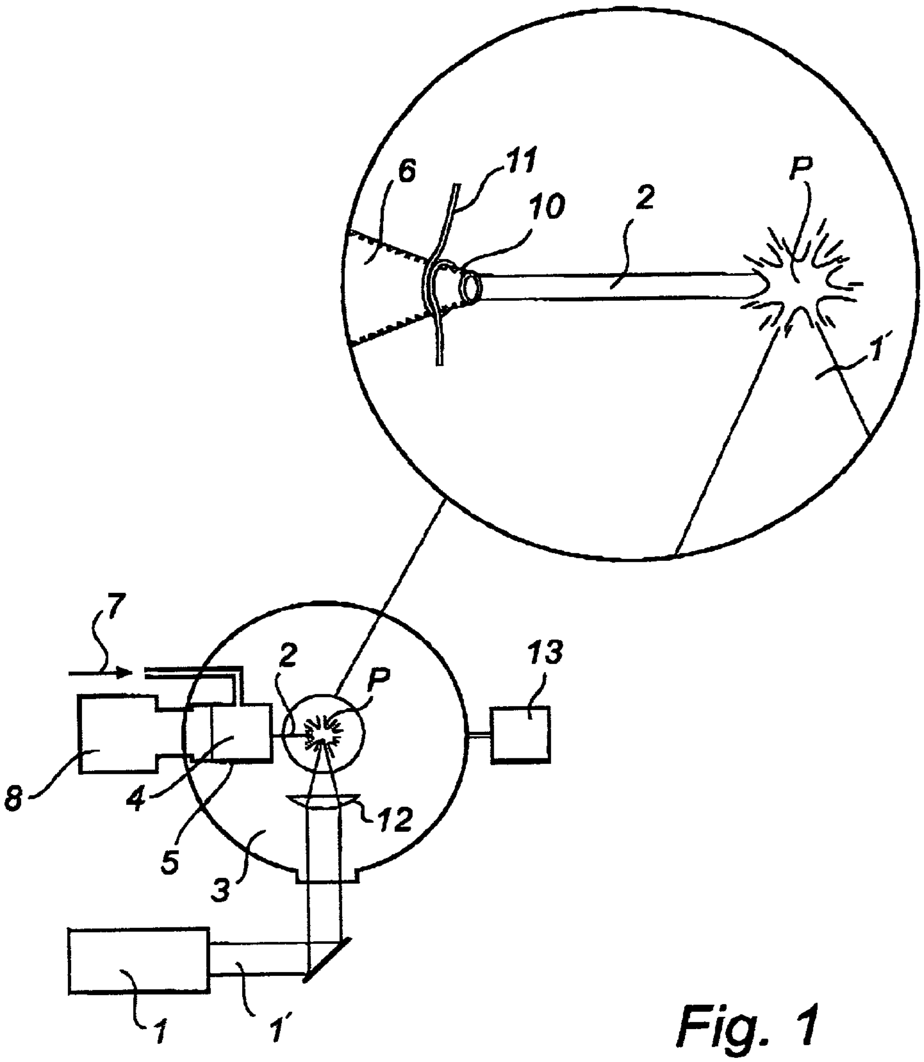
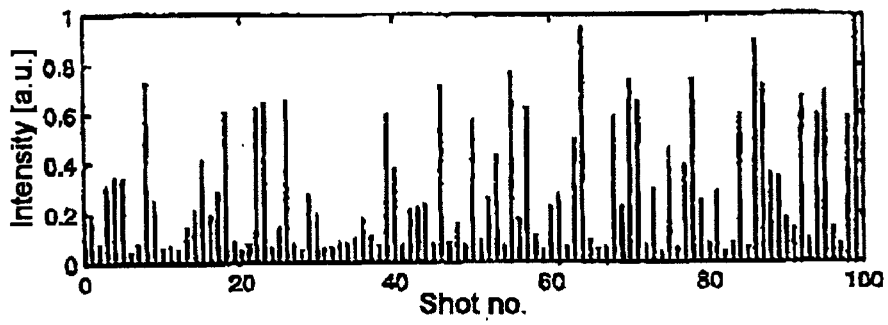


Fig. 1


Intensity [a.u.]
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0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
Shot no.

Fig. 2

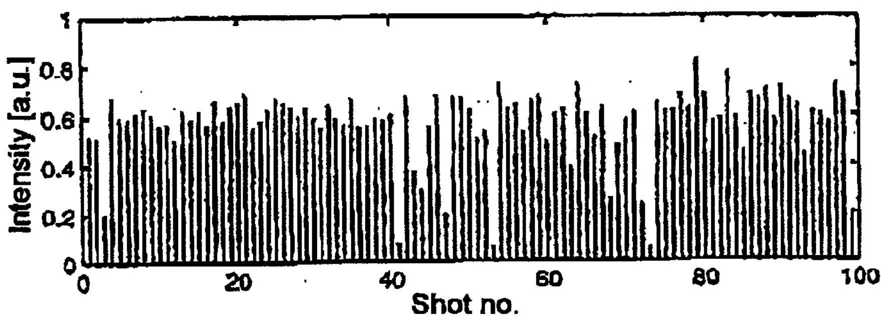
Intensity [a.u.]
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
Shot no.

Fig. 3

METHOD AND APPARATUS FOR GENERATING X-RAY OR EUV RADIATION

TECHNICAL FIELD

[0001] The present invention generally relates to a method and an apparatus for generating X-ray or EUV radiation, i.e. radiation in the wavelength region of approximately 0.01-100 nm. The generated radiation can be used in any application requiring X-ray or EUV radiation, for example lithography, microscopy, materials science, or medical diagnostics.

BACKGROUND ART

[0002] EUV and X-ray sources of high intensity are applied in many fields, for instance surface physics, materials testing, crystal analysis, atomic physics, medical diagnostics, lithography and microscopy. Conventional X-ray sources, in which an electron beam is brought to impinge on an anode, generate a relatively low X-ray intensity. Large facilities, such as synchrotron light sources, produce a high average power. However, there are many applications that require compact, small-scale systems which produce a relatively high average power. Compact and more inexpensive systems yield better accessibility to the applied user and thus are of potentially greater value to science and society. An example of an application of particular industrial importance is future narrow-line-width lithography systems.

[0003] Ever since the 1960s, the size of the structures that constitute the basis of integrated electronic circuits has decreased continuously. The advantage thereof is faster and more complicated circuits needing less power. At present, photolithography is used to industrially produce such circuits having a line width of about 0.18 μm with projected extension towards 0.10-0.13 μm. In order to further reduce the line width, other methods will probably be necessary, of which EUV projection lithography is a very interesting candidate and X-ray lithography may become interesting for certain technological niches. In EUV projection lithography, use is made of a reducing extreme ultraviolet (EUV) objective system in the wavelength range around 10-20 nm ("EUV Lithography—The Successor to Optical Lithography?" by Bjorkholm, published in Intel Technology Journal Q3'98). Proximity X-ray lithography, employing a contact copy scheme, is carried out in the wavelength range around 1 nm (see for instance the article "X-ray Lithography" by Maldonado, published in J. Electronic Materials 19, p. 699, 1990).

[0004] Laser plasmas are attractive table-top X-ray and EUV sources due to their high brightness, high spatial stability and, potentially, high-repetition rate However, with conventional bulk or tape targets, the operating time is limited, especially when high-repetition-rate lasers are used, since fresh target material cannot be supplied at a sufficient rate. Furthermore, such conventional targets produce debris which may destroy or coat sensitive components such as X-ray optics or EUV multilayer mirrors positioned close to the plasma. Several methods have been designed to eliminate the effect of debris, i.e., preventing the already produced debris from reaching the sensitive components. As an alternative, the amount of debris actually produced can be limited by replacing conventional solid targets with for example gas targets, gas-cluster targets, liquid-droplet targets, or liquid-jet targets.

[0005] Targets in the form of microscopic liquid droplets, such as disclosed in the article "Droplet target for low-debris laser-plasma soft X-ray generation" by Rymell and Hertz, published in Opt. Commun. 103, p. 105, 1993, are attractive low-debris, high-density targets potentially capable of high repetition-rate laser-plasma operation with high-brightness emission. Such droplets are generated by stimulated breakup of a liquid jet which is formed at a nozzle in a low-pressure chamber. However, the hydrodynamic properties of certain fluids result in unstable drop formation. Furthermore, the operation of the laser must be carefully synchronized with the droplet formation. Another problem may arise in the use of liquid substances with rapid evaporation, namely that the jet freezes immediately upon generation so that drops cannot be formed. Such substances primarily include media that are in a gaseous state at normal pressure and temperature and that are cooled to a liquid state for generation of the droplet targets. To ensure droplet formation, it is necessary to provide a suitable gas atmosphere in the low-pressure chamber, or to raise the temperature of the jet above its freezing temperature by means of an electric heater provided around the jet, such as disclosed in the article "Apparatus for producing uniform solid spheres of hydrogen" by Foster et al., published in Rev. Sci. Instrum. 6, pp 625-631, 1977.

[0006] As an alternative, as known from U.S. Pat. No. 6,002,744, which is incorporated herein by reference, the laser radiation is instead focused on a spatially continuous portion of a jet which is generated by urging a liquid substance through an outlet or nozzle. This liquid-jet approach alleviates the need for temporal synchronization of the laser with the generation of the target, while keeping the production of debris equally low as from droplet targets. Furthermore, liquid substances having unsuitable hydrodynamic properties for droplet formation can be used in this approach. Another advantage over the droplet-target approach is that the spatially continuous portion of the jet can be allowed to freeze. Such a liquid-jet laser-plasma source has been further demonstrated in the article "Cryogenic liquid-jet target for debris-free laser-plasma soft x-ray generation" by Berglund et al, published in Rev. Sci. Instrum. 69, p. 2361, 1998, and the article "Liquid-jet target laser-plasma sources for EUV and X-ray lithography" by Rymell et al, published in Microelectronic Engineering 46, p. 453, 1999, by using liquid nitrogen and xenon, respectively, as target material. In these cases, a high-density target is formed as a spatially continuous portion of the jet, wherein the spatially continuous portion can be in a liquid or a frozen state. Such laser-plasma sources have the advantage of being high-brightness, low-debris sources capable of continuous high-repetition-rate operation, and the plasma can be produced far from the outlet orifice, thereby limiting plasma-induced erosion of the outlet. Such erosion may be a source of damaging debris. Further, by producing the plasma far from the outlet, self-absorption of the generated radiation can be minimized. This is due to the fact that the temperature around the jet decreases with the distance from the outlet, resulting in a correspondingly decreasing evaporation rate. Thus, the local gas atmosphere around the jet also decreases with the distance from the outlet.

[0007] However, many substances, and in particular liquid substances formed by cooling normally gaseous substances, yield a jet that experiences stochastic changes in its direction from the jet-generating outlet. Typically the change in direction can be as large as about ±1° and occurs a few times per minute to a few times per second. This in turn results in a spatial instability at the focus of the laser beam, i.e. at the desired area of beam-jet-interaction, which should be as far away from the outlet orifice as possible for the reasons given above. The spatial instability leads to high pulse-to-pulse fluctuations in the emitted X-ray and EUV radiation flux and spatial instability of the radiating plasma. Furthermore, the average power is significantly lowered.

SUMMARY OF THE INVENTION

[0008] It is therefore an object of the present invention to provide a method and an apparatus for stable and uncomplicated generation of X-ray or EUV radiation. More specifically, the invention should provide for low pulse-to-pulse fluctuations in the generated X-ray or EUV radiation flux, low erosion of the jet-generating outlet, as well as low self-absorption of the generated radiation.

[0009] It is also an object to provide an apparatus for generating X-ray or EUV radiation that is compact, inexpensive, generates radiation at a relatively high average power and has a minimum production of debris.

[0010] A further object is to provide a method and an apparatus which produces X-ray or EUV radiation which is suitable for EUV projection lithography and proximity lithography.

[0011] One more object of the invention is to permit use of the method and the apparatus in microscopy, materials science, biomedical and medical diagnostics.

[0012] These and other objects, which will be apparent from the following specification, are wholly or partially achieved by the method and the apparatus according to the independent claims. The dependent claims define preferred embodiments.

[0013] It has been found that controlling the temperature of the outlet, normally heating the same, has the effect of considerably improving the directional stability of the generated jet. Thus, the invention allows for low pulse-to-pulse fluctuations in the generated X-ray or EUV radiation flux, increased average power, as well as increased spatial stability of the radiating beam-jet-interaction area. The directionally stable jet also allows for a large distance between the outlet and the beam-jet-interaction area, thereby minimizing both erosion of the outlet and self-absorption of the generated radiation. A "large distance" in this context is typically at least a few millimeters. In view of the large distance made possible by the invention, the power of the energy beam might be increased without causing undesired heating of the target generator. Thus, the invention allows for a higher X-ray and EUV flux. Further, the invention allows for use of several new substances and, thus, for stable generation of radiation in new wavelength ranges.

[0014] These advantages are obtained while retaining many of the advantages of the prior art technologies, as discussed by way of introduction, for example a great reduction of debris, excellent geometric access, a possibility of long-term operation without interruption by providing new target material continuously through the jet, a possibility of using lasers of high repetition rates, which increases the average power of the generated X-ray or EUV radiation.

[0015] The inventive control of the temperature of the outlet should preferably be effected with minimum influence on the temperature of the substance inside the jet-generating outlet, since such influence might cause boiling or a modification of the hydrodynamic properties of the substance, which potentially might lead to instabilities in the generation of the jet, for example potentially undesired spray formation.

[0016] According to one preferred embodiment, the temperature of the outlet is controlled by means of ohmic heating, for example by applying a voltage to an electrically conducting resistive wire arranged around and preferably in contact with the outlet, or by applying the voltage to a portion of the outlet itself. This embodiment is advantageous in its simplicity and ruggedness. By means of thin wires or evaporated electrodes it is possible to localize the generated heat close to the outlet opening.

[0017] According to another preferred embodiment, the temperature of the outlet is controlled by directing radiation energy, for example laser radiation or microwaves, onto the outlet which is heated by absorption of this radiation energy. This embodiment provides for non-intrusive heating of the outlet, in that no new material needs to be mechanically introduced at the outlet, and can be precisely controlled to heat only the outlet opening, if desired. Preferably, the outlet is treated for enhanced and/or more localized absorption of the radiation energy, for example by providing an absorbing or conducting arrangement, such as a coating or an antenna, on the outlet.

[0018] Without committing oneself to a theory, it is assumed that the results regarding the improved directional stability of the generated jet can be explained by the following model. When the substance leaves the outlet, the thus-formed jet, as well as any liquid wetting the outlet, undergoes evaporative cooling. This results in the outlet being cooled, leading to uncontrolled deposition of frozen material on, or close to, the outlet orifice. Such frozen material could induce the stochastic directional instability described above. Heating of the outlet is believed to minimize such deposition of frozen material.

[0019] According to a further preferred embodiment of the invention, the jet leaves the outlet in a condensed, i.e. liquid or frozen, state. This allows for collimated transport of target material far from the outlet. To form such a jet of condensed matter, it is preferred to urge a substance in a liquid state through the jet-forming outlet. The substance used in the invention could be a medium which is in a liquid state both at room temperature and the temperature prevailing at the generation of the jet. This medium could also be a solution comprising solids and a suitable carrier fluid. In a particularly preferred embodiment, however, the substance is a medium which is in a gaseous state at room temperature, but which is cooled to a liquid state before being urged through the outlet to form the jet. This type of medium can, by means of the invention, be used in an uncomplicated way for stable generation of X-ray or EUV radiation at previously unaccessible wavelengths. By using an inert gas, in particular a noble gas, the damages caused by debris can be reduced significantly.

[0020] It should be noted, however, that the jet can be in any suitable state (gaseous, liquid, or solid) when interacting with the energy beam.

[0021] According to one embodiment of the invention, the energy beam is directed onto a spatially continuous portion of the jet. This can be achieved, for instance, by generating a spatially completely continuous jet, and by directing the energy beam onto the actual jet before it spontaneously breaks up into droplets or a spray. Alternatively, it is conceivable to generate a pulsed or semicontinuous jet consisting of separate, spatially continuous portions each having a length that significantly exceeds the diameter. In both cases, the jet might be frozen due to evaporative cooling before interacting with the energy beam.

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