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- (71) **Applicant:** ASML NETHERLANDS B.V. [NL/NL]; P.O. Box 324, NL-5500 AH Veldhoven (NL).
- (72) **Inventors:** MESTROM, Wilbert; Minister Bongaertsstraat 7, NL-6042 CJ Roermond (NL). LABETSKI, Dzmitry; Alberdingk Thijmstraat 19, NL-3532 VL Utrecht (NL). SWINKELS, Gerardus; Generaal Coenderslaan 27, NL-5623 LT Eindhoven (NL).
- (74) **Agent:** SIEM, Max Yoe Shé; P.O. Box 324, P.O. Box 324, NL-5500 AH Veldhoven (NL).
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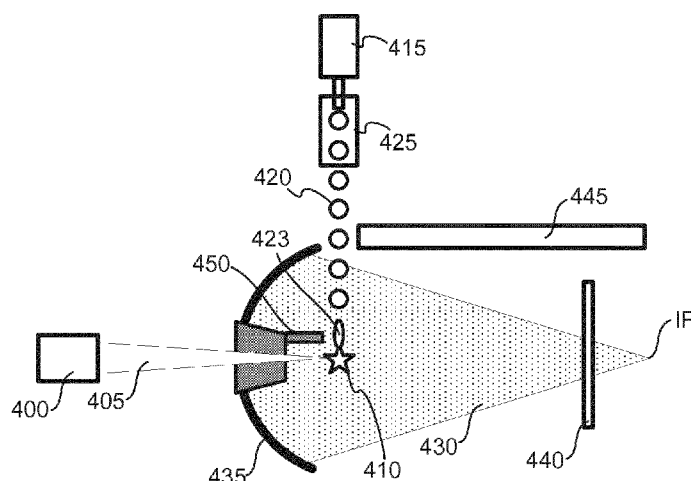


Fig. 4

(57) **Abstract:** Disclosed is a radiation source configured to generate a beam of EUV radiation by excitation of a fuel. The radiation source comprises a gas stream generation module which preconditions a droplet of the fuel by application of a high velocity gas stream to the droplet. Also disclosed is a lithographic apparatus comprising such a radiation source.

POWER SOURCE FOR A LITHOGRAPHIC APPARATUS, AND LITHOGRAPHIC
APPARATUS COMPRISING SUCH A POWER SOURCE

CROSS-REFERENCE TO RELATED APPLICATIONS

- 5 [0001] This application claims the benefit of US provisional application 61/736,365, which was filed on 12 December 2012, and which is incorporated herein in its entirety by reference.

FIELD

- 10 [0002] The present invention relates to a power source for a lithographic apparatus, and associated lithographic apparatus.

BACKGROUND

- [0003] A lithographic apparatus is a machine that applies a desired pattern onto a substrate, usually onto a target portion of the substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In that instance, a patterning device, which is alternatively referred to as a mask or a reticle, may be used to generate a circuit pattern to be formed on an individual layer of the IC. This pattern can be transferred onto a target portion (e.g. comprising part of, one, or several dies) on a substrate (e.g. a silicon wafer). Transfer of the pattern is typically via imaging onto a layer of radiation-sensitive material (resist) provided on the substrate. In general, a single substrate will contain a network of adjacent target portions that are successively patterned.

- [0004] Lithography is widely recognized as one of the key steps in the manufacture of ICs and other devices and/or structures. However, as the dimensions of features made using lithography become smaller, lithography is becoming a more critical factor for enabling miniature IC or other devices and/or structures to be manufactured.

A theoretical estimate of the limits of pattern printing can be given by the Rayleigh criterion for resolution as shown in equation (1):

$$CD = k_1 * \frac{\lambda}{NA} \quad (1)$$

- 30 where λ is the wavelength of the radiation used, NA is the numerical aperture of the projection system used to print the pattern, k_1 is a process dependent adjustment factor, also called the Rayleigh constant, and CD is the feature size (or critical dimension) of the printed feature. It follows from equation (1) that reduction of the minimum printable size of features

can be obtained in three ways: by shortening the exposure wavelength λ , by increasing the numerical aperture NA or by decreasing the value of k1.

[0005] In order to shorten the exposure wavelength and, thus, reduce the minimum printable size, it has been proposed to use an extreme ultraviolet (EUV) radiation source.

5 EUV radiation is electromagnetic radiation having a wavelength within the range of 5-20 nm, for example within the range of 13-14 nm. It has further been proposed that EUV radiation with a wavelength of less than 10 nm could be used, for example within the range of 5-10 nm such as 6.7 nm or 6.8 nm. Such radiation is termed extreme ultraviolet radiation or soft x-ray radiation. Possible sources include, for example, laser-produced plasma sources, discharge
10 plasma sources, or sources based on synchrotron radiation provided by an electron storage ring.

[0006] EUV radiation may be produced using a plasma. A radiation system for producing EUV radiation may include a laser for exciting a fuel to provide the plasma, and a source collector apparatus for containing the plasma. The plasma may be created, for
15 example, by directing a laser beam at a fuel, such as particles of a suitable material (e.g. tin), or a stream of a suitable gas or vapor, such as Xe gas or Li vapor. The resulting plasma emits output radiation, e.g., EUV radiation, which is collected using a radiation collector. The radiation collector may be a mirrored normal incidence radiation collector, which receives the radiation and focuses the radiation into a beam. The source collector apparatus may include
20 an enclosing structure or chamber arranged to provide a vacuum environment to support the plasma. Such a radiation system is typically termed a laser produced plasma (LPP) source.

[0007] In LPP sources it is preferable to precondition the droplet in order to increase its surface area prior to excitation by the main laser. This is typically done by using a laser pre-pulse.

SUMMARY

[0008] It is desirable to provide an alternative to using a laser pre-pulse in droplet preconditioning.

The invention in a first aspect provides a radiation source configured to generate a beam of
30 EUV radiation by excitation of a fuel, said radiation source comprising a gas stream generation module being operable to precondition a droplet of the fuel by application of a high velocity gas stream to the droplet, such that it deforms or breaks-up the droplet.

[0009] The invention in a further aspect provides for a lithographic apparatus, comprising a radiation source of the first aspect, configured to generate a beam of EUV radiation.

[0010] Further features and advantages of the invention, as well as the structure and operation of various embodiments of the invention, are described in detail below with reference to the accompanying drawings. It is noted that the invention is not limited to the specific embodiments described herein. Such embodiments are presented herein for illustrative purposes only. Additional embodiments will be apparent to persons skilled in the relevant art(s) based on the teachings contained herein.

BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

[0011] The accompanying drawings, which are incorporated herein and form part of the specification, illustrate the present invention and, together with the description, further serve to explain the principles of the invention and to enable a person skilled in the relevant art(s) to make and use the invention. Embodiments of the invention are described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 depicts schematically a lithographic apparatus having reflective projection optics;

Figure 2 is a more detailed view of the apparatus of Figure 1; and

Figure 3 schematically depicts an alternative source arrangement to that depicted in Figure 2;

Figure 4 schematically depicts a source arrangement according to an embodiment of the invention;

Figure 5 schematically depicts an alternative source arrangement according to an embodiment of the invention;

Figure 6 schematically depicts a further alternative source arrangement according to an embodiment of the invention;

Figure 7 schematically depicts a nozzle usable to emit a gas stream in any of the source arrangements according to embodiments of the invention; and

Figure 8 schematically depicts a dual nozzle arrangement usable to emit gas streams in any of the source arrangements according to embodiments of the invention.

[0012] The features and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In

the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

5 **[0013]** Figure 1 schematically depicts a lithographic apparatus 100 including a source module SO according to one embodiment of the invention. The apparatus comprises:

- an illumination system (illuminator) IL configured to condition a radiation beam B (e.g. EUV radiation).

- a support structure (e.g. a mask table) MT constructed to support a patterning device (e.g. a mask or a reticle) MA and connected to a first positioner PM configured to accurately position the patterning device;

- a substrate table (e.g. a wafer table) WT constructed to hold a substrate (e.g. a resist-coated wafer) W and connected to a second positioner PW configured to accurately position the substrate; and

- 15 - a projection system (e.g. a reflective projection system) PS configured to project a pattern imparted to the radiation beam B by patterning device MA onto a target portion C (e.g. comprising one or more dies) of the substrate W.

20 **[0014]** The illumination system may include various types of optical components, such as refractive, reflective, magnetic, electromagnetic, electrostatic or other types of optical components, or any combination thereof, for directing, shaping, or controlling radiation.

25 **[0015]** The support structure MT holds the patterning device MA in a manner that depends on the orientation of the patterning device, the design of the lithographic apparatus, and other conditions, such as for example whether or not the patterning device is held in a vacuum environment. The support structure can use mechanical, vacuum, electrostatic or other clamping techniques to hold the patterning device. The support structure may be a frame or a table, for example, which may be fixed or movable as required. The support structure may ensure that the patterning device is at a desired position, for example with respect to the projection system.

30 **[0016]** The term “patterning device” should be broadly interpreted as referring to any device that can be used to impart a radiation beam with a pattern in its cross-section such as to create a pattern in a target portion of the substrate. The pattern imparted to the radiation beam may correspond to a particular functional layer in a device being created in the target portion, such as an integrated circuit.

[0017] The patterning device may be transmissive or reflective. Examples of patterning devices include masks, programmable mirror arrays, and programmable LCD panels. Masks are well known in lithography, and include mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types. An
5 example of a programmable mirror array employs a matrix arrangement of small mirrors, each of which can be individually tilted so as to reflect an incoming radiation beam in different directions. The tilted mirrors impart a pattern in a radiation beam which is reflected by the mirror matrix.

[0018] The projection system, like the illumination system, may include various types
10 of optical components, such as refractive, reflective, magnetic, electromagnetic, electrostatic or other types of optical components, or any combination thereof, as appropriate for the exposure radiation being used, or for other factors such as the use of a vacuum. It may be desired to use a vacuum for EUV radiation since other gases may absorb too much radiation. A vacuum environment may therefore be provided to the whole beam path with the aid of a
15 vacuum wall and vacuum pumps.

[0019] As here depicted, the apparatus is of a reflective type (e.g. employing a reflective mask).

[0020] The lithographic apparatus may be of a type having two (dual stage) or more substrate tables (and/or two or more mask tables). In such "multiple stage" machines the
20 additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while one or more other tables are being used for exposure.

[0021] Referring to Figure 1, the illuminator IL receives an extreme ultra violet radiation beam from the source module SO. Methods to produce EUV light include, but are not necessarily limited to, converting a material into a plasma state that has at least one
25 element, e.g., xenon, lithium or tin, with one or more emission lines in the EUV range. In one such method, often termed laser produced plasma ("LPP") the required plasma can be produced by irradiating a fuel, such as a droplet, stream or cluster of material having the required line-emitting element, with a laser beam. The source module SO may be part of an EUV radiation system including a laser, not shown in Figure 1, for providing the laser beam
30 exciting the fuel. The resulting plasma emits output radiation, e.g., EUV radiation, which is collected using a radiation collector, disposed in the source module. The laser and the source module may be separate entities, for example when a CO₂ laser is used to provide the laser beam for fuel excitation.

[0022] In such cases, the laser is not considered to form part of the lithographic apparatus and the radiation beam is passed from the laser to the source module with the aid of a beam delivery system comprising, for example, suitable directing mirrors and/or a beam expander. In other cases the source may be an integral part of the source module, for example
5 when the source is a discharge produced plasma EUV generator, often termed as a DPP source.

[0023] The illuminator IL may comprise an adjuster for adjusting the angular intensity distribution of the radiation beam. Generally, at least the outer and/or inner radial extent (commonly referred to as σ -outer and σ -inner, respectively) of the intensity
10 distribution in a pupil plane of the illuminator can be adjusted. In addition, the illuminator IL may comprise various other components, such as faceted field and pupil mirror devices. The illuminator may be used to condition the radiation beam, to have a desired uniformity and intensity distribution in its cross-section.

[0024] The radiation beam B is incident on the patterning device (e.g., mask) MA,
15 which is held on the support structure (e.g., mask table) MT, and is patterned by the patterning device. After being reflected from the patterning device (e.g. mask) MA, the radiation beam B passes through the projection system PS, which focuses the beam onto a target portion C of the substrate W. With the aid of the second positioner PW and position sensor PS2 (e.g. an interferometric device, linear encoder or capacitive sensor), the substrate
20 table WT can be moved accurately, e.g. so as to position different target portions C in the path of the radiation beam B. Similarly, the first positioner PM and another position sensor PS1 can be used to accurately position the patterning device (e.g. mask) MA with respect to the path of the radiation beam B. Patterning device (e.g. mask) MA and substrate W may be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2.

[0025] The depicted apparatus could be used in at least one of the following modes:

1. In step mode, the support structure (e.g. mask table) MT and the substrate table WT are kept essentially stationary, while an entire pattern imparted to the radiation beam is projected onto a target portion C at one time (i.e. a single static exposure). The substrate table
25 WT is then shifted in the X and/or Y direction so that a different target portion C can be
30 exposed.

2. In scan mode, the support structure (e.g. mask table) MT and the substrate table WT are scanned synchronously while a pattern imparted to the radiation beam is projected onto a target portion C (i.e. a single dynamic exposure). The velocity and direction of the substrate

table WT relative to the support structure (e.g. mask table) MT may be determined by the (de-)magnification and image reversal characteristics of the projection system PS.

3. In another mode, the support structure (e.g. mask table) MT is kept essentially stationary holding a programmable patterning device, and the substrate table WT is moved or scanned while a pattern imparted to the radiation beam is projected onto a target portion C. In this mode, generally a pulsed radiation source is employed and the programmable patterning device is updated as required after each movement of the substrate table WT or in between successive radiation pulses during a scan. This mode of operation can be readily applied to maskless lithography that utilizes programmable patterning device, such as a programmable mirror array of a type as referred to above.

[0026] Combinations and/or variations on the above described modes of use or entirely different modes of use may also be employed.

[0027] Figure 2 shows an embodiment of the lithographic apparatus in more detail, including a radiation system 42, the illumination system IL, and the projection system PS.

The radiation system 42 as shown in Figure 2 is of the type that uses a laser-produced plasma as a radiation source. EUV radiation may be produced by a gas or vapor, for example Xe gas, Li vapor or Sn vapor in which a very hot plasma is created to emit radiation in the EUV range of the electromagnetic spectrum. The very hot plasma is created by causing an at least partially ionized plasma by, for example, optical excitation using CO₂ laser light. Partial pressures of, for example, 10 Pa of Xe, Li, Sn vapor or any other suitable gas or vapor may be required for efficient generation of the radiation. In an embodiment, Sn is used to create the plasma in order to emit the radiation in the EUV range.

[0028] The radiation system 42 embodies the function of source SO in the apparatus of Figure 1. Radiation system 42 comprises a source chamber 47, in this embodiment not only substantially enclosing a source of EUV radiation, but also collector 50 which, in the example of Figure 2, is a normal-incidence collector, for instance a multi-layer mirror.

[0029] As part of an LPP radiation source, a laser system 61 (described in more detail below) is constructed and arranged to provide a laser beam 63 which is delivered by a beam delivering system 65 through an aperture 67 provided in the collector 50. Also, the radiation system includes a target material 69, such as Sn or Xe, which is supplied by target material supply 71. The beam delivering system 65, in this embodiment, is arranged to establish a beam path focused substantially upon a desired plasma formation position 73.

[0030] In operation, the target material 69, which may also be referred to as fuel, is supplied by the target material supply 71 in the form of droplets. When such a droplet of the

target material 69 reaches the plasma formation position 73, the laser beam 63 impinges on the droplet and an EUV radiation-emitting plasma forms inside the source chamber 47. In the case of a pulsed laser, this involves timing the pulse of laser radiation to coincide with the passage of the droplet through the position 73. As mentioned, the fuel may be for example
5 xenon (Xe), tin (Sn) or lithium (Li). These create a highly ionized plasma with electron temperatures of several 10's of eV. Higher energy EUV radiation may be generated with other fuel materials, for example Tb and Gd. The energetic radiation generated during de-excitation and recombination of these ions includes the wanted EUV radiation which is emitted from the plasma at position 73. The plasma formation position 73 and the aperture 52
10 are located at first and second focal points of collector 50, respectively and the EUV radiation is focused by the normal-incidence collector 50 onto the intermediate focus point IF.

[0031] The beam of radiation emanating from the source chamber 47 traverses the illumination system IL via so-called normal incidence reflectors 53, 54, as indicated in Figure 2 by the radiation beam 56. The normal incidence reflectors direct the beam 56 onto a
15 patterning device (e.g. reticle or mask) positioned on a support (e.g. reticle or mask table) MT. A patterned beam 57 is formed, which is imaged by projection system PS via reflective elements 58, 59 onto a substrate carried by wafer stage or substrate table WT. More elements than shown may generally be present in illumination system IL and projection system PS. For example there may be one, two, three, four or even more reflective elements present than
20 the two elements 58 and 59 shown in Figure 2. Radiation collectors similar to radiation collector 50 are known from the prior art.

[0032] As the skilled reader will know, reference axes X, Y and Z may be defined for measuring and describing the geometry and behavior of the apparatus, its various components, and the radiation beams 55, 56, 57. At each part of the apparatus, a local
25 reference frame of X, Y and Z axes may be defined. The Z axis broadly coincides with the direction of optical axis O at a given point in the system, and is generally normal to the plane of a patterning device (reticle) MA and normal to the plane of substrate W. In the source collector module 42, the X axis coincides broadly with the direction of fuel stream (69, described below), while the Y axis is orthogonal to that, pointing out of the page as indicated
30 in Figure 3. On the other hand, in the vicinity of the support structure MT that holds the reticle MA, the X axis is generally transverse to a scanning direction aligned with the Y axis. For convenience, in this area of the schematic diagram Figure 2, the X axis points out of the page, again as marked. These designations are conventional in the art and will be adopted

herein for convenience. In principle, any reference frame can be chosen to describe the apparatus and its behavior.

[0033] In addition to the wanted EUV radiation, the plasma produces other wavelengths of radiation, for example in the visible, UV and DUV range. There is also IR radiation present from the laser beam 63. The non-EUV wavelengths are not wanted in the illumination system IL and projection system PS and various measures may be deployed to block the non-EUV radiation. As schematically depicted in Figure 2, a transmissive SPF may be applied upstream of virtual source point IF. Alternatively or in addition to such a filter, filtering functions can be integrated into other optics. For example a diffractive filter can be integrated in collector 50 and/or mirrors 53, 54 etc., by provision of a grating structure tuned to divert the longer, IR radiation away from the virtual source point IF. Filters for IR, DUV and other unwanted wavelengths may thus be provided at one or more locations along the paths of beams 55, 56, 57, within source module (radiation system 42), the illumination system IL and/or projection system PS.

[0034] Figure 3 shows an alternative LPP source arrangement which may be used in place of that illustrated in Figure 2. A main difference is that the main pulse laser beam is directed onto the fuel droplet from the direction of the intermediate focus point IF, such that the collected EUV radiation is that which is emitted generally in the direction from which the main laser pulse was received. Figure 3 shows the main laser 30 emitting a main pulse beam 31 delivered to a plasma generation site 32 via at least one optical element (such as a lens or folding mirror) 33. The EUV radiation 34 is collected by a grazing incidence collector 35 such as those used in discharge produced plasma (DPP) sources. Also shown is a debris trap 36, which may comprise one or more stationary foil traps and/or a rotating foil trap.

[0035] To deliver the fuel, which for example is liquid tin, a droplet generator or target material supply 71 is arranged within the source chamber 47, to fire a stream of droplets towards the plasma formation position 73. In operation, laser beam 63 may be delivered in synchronization with the operation of target material supply 71, to deliver impulses of radiation to turn each fuel droplet into a plasma. The frequency of delivery of droplets may be several kilohertz, or even several tens or hundreds of kilohertz. Typically, in present arrangements, a laser beam 63 may be delivered by a laser system 61 in at least two pulses: a pre pulse PP with limited energy is delivered to the droplet before it reaches the plasma location, in order to deform (change geometry) or vaporize the fuel material into a preferably pancake or cigar like shape or a small cloud (preconditioning the droplet), and then a main pulse MP of laser energy is delivered to the cloud at the desired location, to

generate the plasma. In a typical example, the diameter of the plasma is about 2-3 mm. A trap 72 is provided on the opposite side of the enclosing structure 47, to capture fuel that is not, for whatever reason, turned into plasma.

[0036] Laser system 61 may be for example the MOPA (Master Oscillator Power Amplifier) type. Such a laser system 61 includes a “master” laser or “seed” laser, followed by a power amplifier system PA, for firing a main pulse of laser energy towards an expanded droplet cloud. A beam delivery system 24 is provided to deliver the laser energy 63 into the source chamber 47. Laser system 61, target material supply 71 and other components can be controlled by a controller (not shown separately). The controller performs many control functions, and has sensor inputs and control outputs for various elements of the system. Sensors may be located in and around the elements of radiation system 42, and optionally elsewhere in the lithographic apparatus.

[0037] Figure 4 shows an alternative source arrangement in which the preconditioning of a fuel droplet is not performed by use of a pre-pulse laser. Instead, it has been determined that preconditioning of the fuel droplet may be performed by application of a gas shock wave or continuous high velocity gas stream to the tin droplet; i.e. exposing that fuel droplet to a high speed gas stream, possibly in a sudden manner.

[0038] Shown in Figure 4 is a laser system 400 (not necessarily part of the source) which directs laser beam 405 at plasma formation site 410 so as to generate EUV radiation. Also shown is a fuel droplet generator 415 which emits fuel droplets 420 through droplet shroud 425, the shroud protecting the droplets from gas flows in the source during droplet formation. EUV radiation 430 emitted from plasma formation site 410 is collected by collector 435 and focused at the intermediate focus IF. Obscuration 440 is provided primarily to prevent unused CO₂ laser light entering the projection optics. In addition it acts to block particles travelling directly from the plasma to the scanner. Also shown is part of the source vessel wall 445.

[0039] In this embodiment the fuel droplets 420 are preconditioned by application of a gas shock wave or continuous high velocity gas stream. In the example of Figure 4, this gas shock wave or continuous high velocity gas stream is applied via a gas stream supply unit 450, the output of which is shown here located in the vicinity of the centre of the collector 435. As a result, the gas shock wave or continuous high velocity gas stream is applied and propagates in the same direction as (and parallel to) the propagation direction of laser beam 405, and hits the droplet 420 in a direction perpendicular to the droplet's 420 trajectory. As a result, preconditioned fuel droplet 423 is formed.

[0040] Figure 5 shows a variation on the arrangement of Figure 4, but with the gas stream supply unit 450' positioned on the opposite side of the plasma formation site 410 compared to the Figure 4 arrangement. As a result, the gas shock wave or continuous high velocity gas stream is applied and propagates in the same axial direction as (and anti-parallel to) the propagation direction of laser beam 405, and hits the droplet 420 in a direction perpendicular to the droplet's 420 trajectory. As a result, preconditioned fuel droplet 423' is formed.

[0041] As the gas stream supply unit 450' is located in the EUV radiation 430 cone region, between the plasma formation site 410 and intermediate focus IF, any adverse effect on EUV output by blocking of the EUV radiation by gas stream supply unit 450' should be minimized. An EUV source apparatus typically comprises an obscuration 440 primarily for blocking the laser light 405 from entering the projection optics. This does mean however that some EUV radiation is blocked by this obscuration 440. Positioning the gas stream supply unit 450' within the shadow of this obscuration 440 would mean that it would not block any additional EUV radiation, and that the only EUV radiation blocked by gas stream supply unit 450' (or at least most of it) would have been blocked by the obscuration 440 in any case.

[0042] Figure 6 shows a further variation on the arrangement of Figure 4, but with the gas stream supply unit 450'' positioned in the region of the fuel supply. In this specific embodiment the gas stream supply unit 450'' (or at least the nozzle thereof) is integral with the droplet shroud 425. As a result, the gas shock wave or continuous high velocity gas stream is applied and propagates in a direction perpendicular to the propagation direction of laser beam 405, and hits the droplet 420 in the same direction as the droplet's 420 trajectory. As a result, preconditioned fuel droplet 423'' is formed.

[0043] The gas stream supply unit 450, 450' 450'' should emit gas at high speed (close to the speed of sound, sub-sonic or supersonic) so as to have sufficient energy to properly precondition the target droplet. Flow properties are preferably kept 'laminar' and not turbulent. This is so that the flow is better directed towards an interaction region and does not create additional disturbance to the droplet 420 or the preconditioned droplet 423, 423', 423'' as this will have a detrimental effect as position accuracy of the target, which is important for EUV production. Similarly, it is preferable to emit as little gas as possible during the preconditioning so as not to interfere with other functions that gas has to fulfill within the EUV source. Hydrogen gas is typically already used within the source, and therefore may be used as the gas species emitted by the gas stream supply unit. Other gases may be used

instead, such as (for example) the inert (group 18) gases; the gasses should be selected based on their EUV absorption characteristics.

[0044] The gas stream supply unit 450 may comprise a directional shock tube directed at the preconditioning area. The gas stream supply unit 450 may emit the gas in a pulsed (as opposed to continuous) manner. To do this, a piezoelectric transducer may be used to pinch the gas stream as required so as to create a pulsed gas stream from a continuous supply. Other techniques are also possible, for example a fast magnetic valve or an accurate chopping mechanism could also be used. The gas speed may be tunable to so as to obtain different preconditioning effects e.g. droplet shape and/or how it changes over time, or to obtain end target of a particular size.

[0045] The gas stream supply unit 450 may have a gas supply nozzle which:

- (a) May have different exit cross-sections (rectangular, circular, etc.)
- (b) May be a simple pipe or orifice with a given cross-section or a nozzle (e.g. naval nozzle or some other nozzle shape) optimal for generation of the gas stream field.

(c) May be a driven (low pressure part) of a shock tube which generates a gas stream of given strength in pulses.

[0046] It should be appreciated that the arrangements of Figures 4 to 6 have different advantages and effects due to the direction in which the gas stream or shock wave is applied to the droplet. Other considerations include (amongst other things) the speed of the shock wave and the length of time it is applied.

[0047] The effect of a shock wave or continuous high velocity gas stream upon a droplet is actually very different depending upon the Weber number (We) of the gas flow and the Ohnesorge number (Oh) of the droplet material. For a particular material (i.e. a particular Oh), whether the droplet deforms or actually breaks-up depends upon the Weber number. The article "Near-Limit Drop Deformation and Secondary Breakup" (International Journal of Multiphase Flow, Vol. 18, No. 5, pp. 635-652, 1992) shows a deformation map and the break-up regimes as function of We and Oh numbers.

[0048] Preconditioning of a droplet may comprise applying a high velocity gas stream or gas shock wave to induce deformation, or applying a high velocity gas stream or gas shock wave to induce break-up, and either technique is included within the scope of this disclosure. It has been determined that, for a low viscosity liquid (e.g. $Oh \ll 1$) such as liquid tin, droplet deformation begins at $We > 1$, and droplet break-up occurs at $We > 10$. To increase EUV generation the cross-sectional area and/or effective total surface area should be increased, and this can be achieved using both techniques. Deformation requires synchronization of laser

pulses with droplet deformation, but is more controllable and repeatable. Break-up requires high Weber number/Gas flow speeds or resonance action of the gas stream, but results in increased surface area compared to a deformed droplet.

[0049] Preconditioning in the droplet deformation regime tends to flatten the droplet into a more flattened circular or “pancake” shape if the shock wave or continuous high velocity gas stream is applied in a perpendicular direction to that which the droplet travels (as in the case of Figures 4 and 5). If applied in the same direction as that which the droplet travels an elongated ellipsoid or “cigar” shape is obtained.

[0050] The Weber number We_g is defined as:

$$We_g = \frac{d_0 \rho_g U^2}{\sigma} ;$$

where U_g is the gas velocity, ρ_g is the gas density, d_0 is the initial droplet diameter and σ is the droplet surface tension. For an example arrangement using hydrogen gas having a density ρ_g corresponding to a temperature of 300K and pressure of 1 bar, and where $U=1200$ m/s, $d_0=30\mu\text{m}$ (within the typical performance range of the LPP droplet generator) and $\sigma=0.544$ N/m (typical surface tension of Sn at its melting point); the Weber number will be 6.47. This is high enough to operate in droplet deformation regime (oscillatory or non-oscillatory). By increasing droplet diameter (using improved droplet generators) and/or gas density and/or velocity; higher values of Weber number can be reached, such that the droplet can be brought into the break-up regime.

[0051] Droplet deformation and/or break-up takes time. As a consequence, the high velocity gas stream or shock wave should act on a droplet for a length of time sufficient to precondition the droplet in the manner desired. As the droplet is moving during this time, the gas stream should act upon the droplet over a determined distance. The characteristic time of deformation t_{ch} can be estimated using the following equation:

$$t_{ch} = \frac{d_0 \sqrt{\frac{\rho_l}{\rho_g}}}{U}$$

where U is the gas velocity, ρ_g is the gas density, ρ_l is the droplet density and d_0 is the initial droplet diameter.

[0052] For an example arrangement using hydrogen gas having a density ρ_g corresponding to a temperature of 300K and pressure of 1 bar, and where $U=1200$ m/s, $d_0=30\mu\text{m}$ and $\rho_l=7000$ kg/m³, the characteristic time may be calculated to be 7.3μs. The time t_b to break-up droplets is about a factor 5 larger than the characteristic time for materials

having small Oh numbers. For a known deformation time, the characteristic length L_{ch} along which the gas stream should act on the droplet can be estimated, assuming a certain droplet velocity. The current droplet generator produces droplets with velocity in the range 50-100 m/s, so the characteristic length of the gas stream cross-section will be in the range 0.37-0.73 mm.

[0053] It can be shown that the ratio of the maximum diameter of the preconditioned droplet $d_{c,max}$ and the initial droplet diameter d_0 is:

$$\frac{d_{c,max}}{d_0} = 0.19\sqrt{We_g} + 1$$

[0054] Consequently the maximum diameter of the preconditioned droplet scales with the Weber number. For a Weber number of 6.47 as per the previous example, the maximum deformation diameter $d_{c,max}$ is a factor 1.5 larger than initial droplet diameter d_0 , and therefore the droplet cross-sectional surface area increase is:

$$\frac{d_{c,max}^2}{d_0^2} = 2.2$$

[0055] In embodiments where the gas stream is supplied in a direction perpendicular to droplet trajectory (for example, the arrangements shown in Figures 4 and 5), the gas stream supply unit should apply the gas stream to the droplet over a distance L_{ch} , in order to apply the shock wave or continuous high velocity gas stream for sufficient time to deform the droplet. Figure 7 shows a rectangular nozzle 700 which may be used to supply the shock wave to the droplet 420. The nozzle 700 has height h (along droplet trajectory) and width w . In a specific example, height h is similar to the characteristic length L_{ch} required for droplet deformation. Consequently the nozzle height may be in the range 0.37-0.73 mm, or more generally 0.1-1.0 mm. The nozzle width w should preferably be much larger than droplet diameter. Where the droplet diameter is in the region of 30 μm , the width w may be in the range 150-300 μm . Assuming that the nozzle 700 operates in a regime of pressure 1 bar and temperature 300 K, the gas flow through the nozzle 700 will be in the region of $(0.6-2.3) \cdot 10^{-5}$ kg/s or 4-15 slm, which is a small fraction of the total flow supplied to the LPP source (typical values are in the range from 100 to 300 slm).

[0056] Figure 8 shows an arrangement where more than one (here two) gas stream supply units 700a, 700b are provided within a single source. Such an arrangement can be used in place of the gas stream supply unit 450, 450' 450'' in either of Figures 4, 5 and 6 and

is generally applicable to all the concepts disclosed herein. Such an arrangement may be used to control droplet and fragment trajectory.

[0057] Alternatively or in addition, such an arrangement may be used operate in resonance with droplet deformation. After passing the first shock wave or high velocity gas stream, the droplet tends to return to a spherical (end) shape because this (from an energy point of view) is the optimum shape. However, before this happens, the droplet shape / geometry will oscillate, at a particular frequency (eigen-frequency). By applying further gas injections at preferred droplet geometries during its oscillation (multiple injection stages are required), particularly in resonance with the eigen-frequency, the deformation effect is enhanced.

[0058] In Figure 8, the first gas stream supply unit 700a deforms the droplet 710, while changing its trajectory. The second gas stream supply unit 700b acts on the deformed droplet, straightening the droplet's trajectory relative to its initial trajectory. In addition after the first gas stream supply unit 700a deforms the droplet 710, it begins to oscillate as described. Application of one or more further streams 700b causes resonance in the deformed droplet, breaking it up to form droplet cloud 720. Units 700a and 700b may comprise two (or more) nozzles of a single gas supply unit.

[0059] The concepts disclosed herein are equally applicable to LPP source arrangements of the type shown in Figure 3. In such a source, gas stream supply units may be positioned in any suitable location, including in the vicinity of the droplet generator (not shown on the Figure) as with Figure 6, or anywhere in the same plane as the plasma formation position 32, or to the side of this plane opposite the collector, or in the vicinity of optical element 33. As disclosed, the preconditioning shock wave or continuous high velocity gas stream may be applied perpendicular to the droplet trajectory, or in the same or opposite direction as the droplet trajectory. It should also be appreciated that these specific arrangements are for illustration only, and the relative propagation direction of the shock wave or continuous high velocity gas stream, propagation direction of the laser and of the droplet trajectory may vary from any of the arrangements shown, for all embodiments described.

[0060] Any of the gas supply systems disclosed herein may have temperature control in addition to pressure control, so that gas stream emitted from the nozzle may be controlled, for example it may be raised up to a few thousand degrees Kelvin.

[0061] Numerous additional components may be present in a typical apparatus, though not illustrated here. These include arrangements for reducing or mitigating the effects

of contamination within the enclosed vacuum, for example to prevent deposits of fuel material damaging or impairing the performance of collector 50 and other optics. Other features present but not described in detail are all the sensors, controllers and actuators involved in controlling of the various components and sub-systems of the lithographic apparatus.

[0062] The present invention may be summarized by one or more of the following clauses:

Clause 1. A radiation source configured to generate a beam of EUV radiation by excitation of a fuel, said radiation source comprising a gas stream generation module being operable to precondition a droplet of the fuel by application of a high velocity gas stream to the droplet.

Clause 2. A radiation source according to clause 1 wherein said high velocity gas stream applies a shock wave to the droplet.

Clause 3. A radiation source according to clause 2 wherein said gas stream generation module is operable to emit the gas stream at sonic or supersonic speed in order to apply said shock wave.

Clause 4. A radiation source according to clause 2 or 3 wherein said gas stream generation module is operable to emit said gas stream in the form of a pulse.

Clause 5. A radiation source according to clause 1 wherein said gas stream generation module is operable to apply the gas stream at sub-sonic speed in order precondition the droplet.

Clause 6. A radiation source according to clause 1 wherein the gas stream generation module is operable to emit the gas stream in the form of a continuous high velocity gas stream.

Clause 7. A radiation source according to any preceding clause, wherein the gas stream generation module is operable to emit the high velocity gas stream such that it deforms the droplet.

Clause 8. A radiation source according to any of the clauses 1 to 6 wherein the gas stream generation module is operable to emit the high velocity gas stream such that it breaks-up the droplet.

Clause 9. A radiation source according to any preceding clause, wherein the gas stream generation module is operable to apply the high velocity gas stream to the droplet over a distance sufficient to deform and/or break-up the droplet.

Clause 10. A radiation source according to clause 9 wherein a gas stream outlet of the gas stream generation module comprises a nozzle having a dimension, parallel with the droplet's trajectory, that is approximately the same or similar to said distance sufficient to deform and/or break-up the droplet.

5 Clause 11. A radiation source according to any preceding clause, wherein the gas stream generation module is operable to emit said high velocity gas stream to the droplet in the same direction as the droplet's trajectory.

Clause 12. A radiation source according to any of the clauses 1 to 10, wherein the gas stream generation module is operable to emit said high velocity gas stream to the droplet in a
10 direction perpendicular to the droplet's trajectory.

Clause 13. A radiation source according to any preceding clause, wherein the fuel is excited by laser radiation to generate said beam of EUV radiation and the radiation source comprises an obscuration to prevent laser radiation exiting the source with the beam of EUV radiation, and wherein said gas stream generation module, or an outlet thereof, is located in
15 the shadow of the obscuration, such that it blocks little or no further EUV radiation, other than that which would be blocked by the obscuration in the absence of the gas stream generation module.

Clause 14. A radiation source according to any preceding clause, wherein each fuel droplet has an Ohnesorge number smaller than 1 and the Weber number at the interface of the
20 gas stream and each droplet is larger than 1.

Clause 15. A radiation source according to any preceding clause, further comprising a droplet generator for generating the each fuel droplet, said droplet generator comprising a shroud to protect each droplet from gas flows within the source during droplet formation, wherein said gas stream generation module, or an outlet thereof, is integral with the shroud.

25 Clause 16. A radiation source according to any preceding clause, further comprising a collector for collecting the EUV radiation generated, said collector being centred on an axis which includes the point at which each fuel droplet is excited to generate the EUV radiation, wherein said gas stream generation module or an outlet thereof, is located adjacent said axis.

Clause 17. A radiation source according to clause 16, wherein the gas stream generation
30 module is operable to emit the high velocity gas stream in a direction parallel or anti-parallel to said axis.

Clause 18. A radiation source according to clause 16, wherein the gas stream generation module comprises a heating unit operable to raise the temperature of the gas emitted as the high velocity gas stream.

Clause 19. A radiation source according to clause 18, wherein the heating unit operable to raise the temperature of the gas to a temperature in the order of magnitude of 1000K.

Clause 20. A radiation source according to any preceding clause, wherein said radiation source comprises a plurality of gas stream generation modules, or outlets thereof, each one
5 being operable to apply the high velocity gas stream to the droplet at different points along the droplet's trajectory.

Clause 21. A radiation source according to any preceding clause, wherein the gas stream generation module comprises a shock tube in order to generate the high velocity gas stream.

Clause 22. A lithographic apparatus, comprising a radiation source according to any
10 preceding clause, configured to generate a beam of EUV radiation.

Clause 23. A lithographic apparatus according to clause 22, comprising a laser unit for generating a laser beam operable to excite said fuel in order to generate the beam of EUV radiation.

[0063] While the concepts disclosed herein have been described specifically in
15 combination with LPP sources, they are also applicable to other types of sources, such as DPP sources, should it be desirable to precondition the fuel in such DPP sources. Although specific reference may be made in this text to the use of lithographic apparatus in the manufacture of ICs, it should be understood that the lithographic apparatus described herein may have other applications, such as the manufacture of integrated optical systems, guidance
20 and detection patterns for magnetic domain memories, flat-panel displays, liquid-crystal displays (LCDs), thin-film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms "wafer" or "die" herein may be considered as synonymous with the more general terms "substrate" or "target portion", respectively. The substrate referred to herein may be processed, before or after exposure, in
25 for example a track (a tool that typically applies a layer of resist to a substrate and develops the exposed resist), a metrology tool and/or an inspection tool. Where applicable, the disclosure herein may be applied to such and other substrate processing tools. Further, the substrate may be processed more than once, for example in order to create a multi-layer IC, so that the term substrate used herein may also refer to a substrate that already contains
30 multiple processed layers.

[0064] The term "lens", where the context allows, may refer to any one or combination of various types of optical components, including refractive, reflective, magnetic, electromagnetic and electrostatic optical components.

[0065] While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The descriptions above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the art that modifications may be made to the invention as described without
5 departing from the scope of the claims set out below.

CLAIMS

1. A radiation source configured to generate a beam of EUV radiation by excitation of a fuel, said radiation source comprising a gas stream generation module being operable to precondition a droplet of the fuel by application of a high velocity gas stream to the droplet, such that it deforms or breaks-up the droplet.
2. A radiation source as claimed in claim 1 wherein said high velocity gas stream applies a shock wave to the droplet.
3. A radiation source as claimed in claim 2 wherein said gas stream generation module is operable to emit the gas stream at sonic or supersonic speed in order to apply said shock wave.
4. A radiation source as claimed in any preceding claim wherein the gas stream generation module is operable to apply the high velocity gas stream to the droplet over a distance sufficient to deform and/or break-up the droplet.
5. A radiation source as claimed in claim 4 wherein a gas stream outlet of the gas stream generation module comprises a nozzle having a dimension, parallel with the droplet's trajectory, that is approximately the same or similar to said distance sufficient to deform and/or break-up the droplet.
6. A radiation source as claimed in any preceding claim wherein the gas stream generation module is operable to emit said high velocity gas stream to the droplet in the same direction as the droplet's trajectory or in a direction perpendicular to the droplet's trajectory.
7. A radiation source as claimed in any preceding claim wherein the fuel is excited by laser radiation to generate said beam of EUV radiation, the radiation source being configured to apply said laser radiation onto the droplet of the fuel when in a deformed state.
8. A radiation source as claimed in any preceding claim wherein the fuel is excited by laser radiation to generate said beam of EUV radiation and the radiation source comprises an obscuration to prevent laser radiation exiting the source with the beam of EUV radiation, and

wherein said gas stream generation module, or an outlet thereof, is located in the shadow of the obscuration, such that it blocks little or no further EUV radiation, other than that which would be blocked by the obscuration in the absence of the gas stream generation module.

5 9. A radiation source as claimed in any preceding claim wherein each fuel droplet has an Ohnesorge number smaller than 1 and the Weber number at the interface of the gas stream and each droplet is larger than 1.

10 10. A radiation source as claimed in any preceding claim further comprising a droplet generator for generating the each fuel droplet, said droplet generator comprising a shroud to protect each droplet from gas flows within the source during droplet formation, wherein said gas stream generation module, or an outlet thereof, is integral with the shroud.

15 11. A radiation source as claimed in any preceding claim further comprising a collector for collecting the EUV radiation generated, said collector being centered on an axis which includes the point at which each fuel droplet is excited to generate the EUV radiation, wherein said gas stream generation module or an outlet thereof, is located adjacent said axis.

20 12. A radiation source as claimed in claim 16 wherein the gas stream generation module comprises a heating unit operable to raise the temperature of the gas emitted as the high velocity gas stream.

25 13. A radiation source as claimed in any preceding claim wherein said radiation source comprises a plurality of gas stream generation modules, or outlets thereof, each one being operable to apply the high velocity gas stream to the droplet at different points along the droplet's trajectory.

30 14. A lithographic apparatus, comprising a radiation source as claimed in any preceding claim, configured to generate a beam of EUV radiation.

15. A lithographic apparatus as claimed in claim 14 comprising a laser unit for generating a laser beam operable to excite said fuel in order to generate the beam of EUV radiation, the laser unit being operable to excite the droplet of the fuel when in a deformed or broken-up state.

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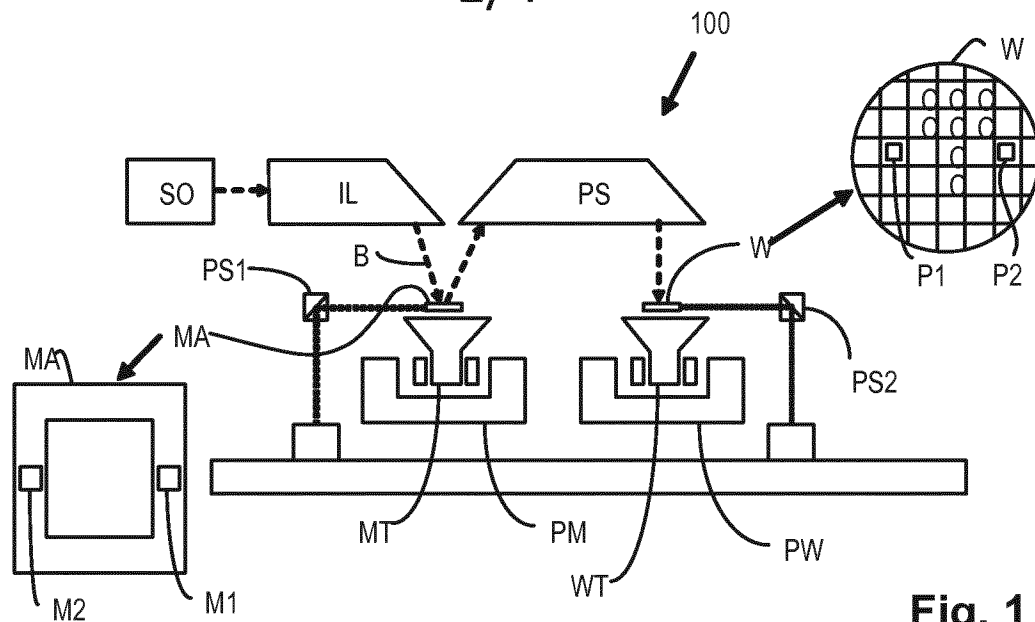


Fig. 1

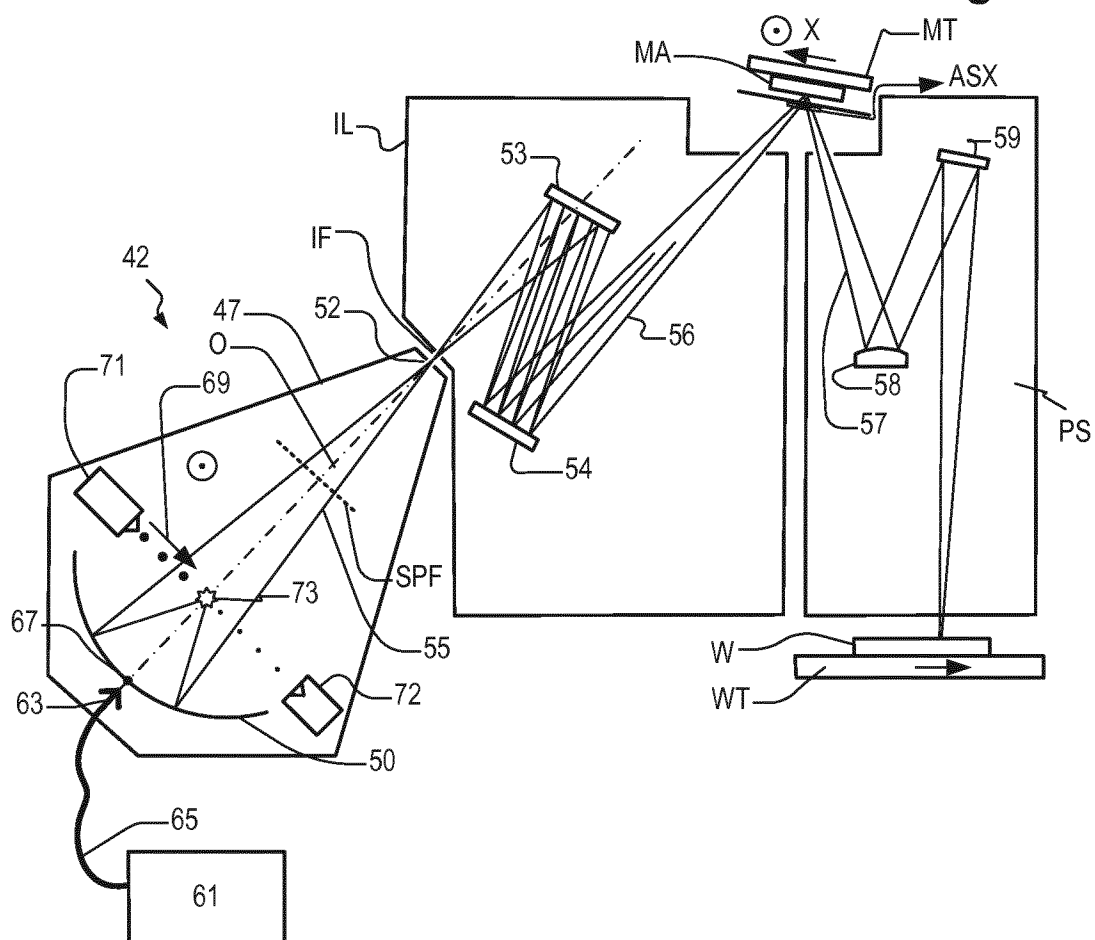


Fig. 2

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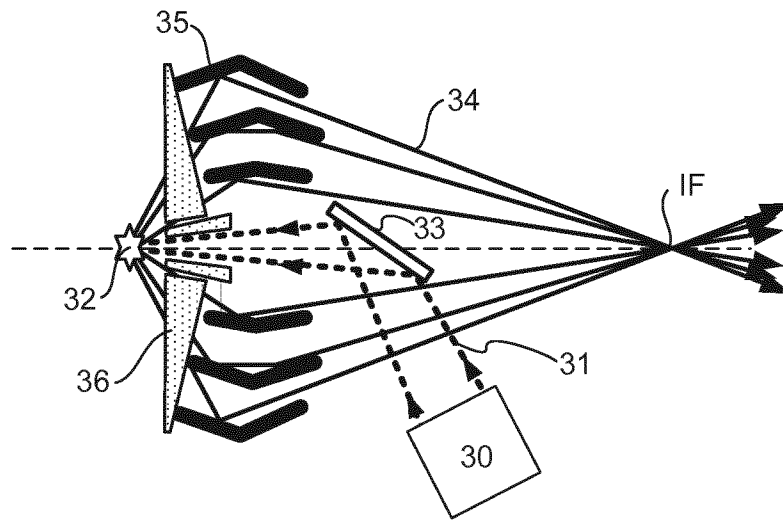


Fig. 3

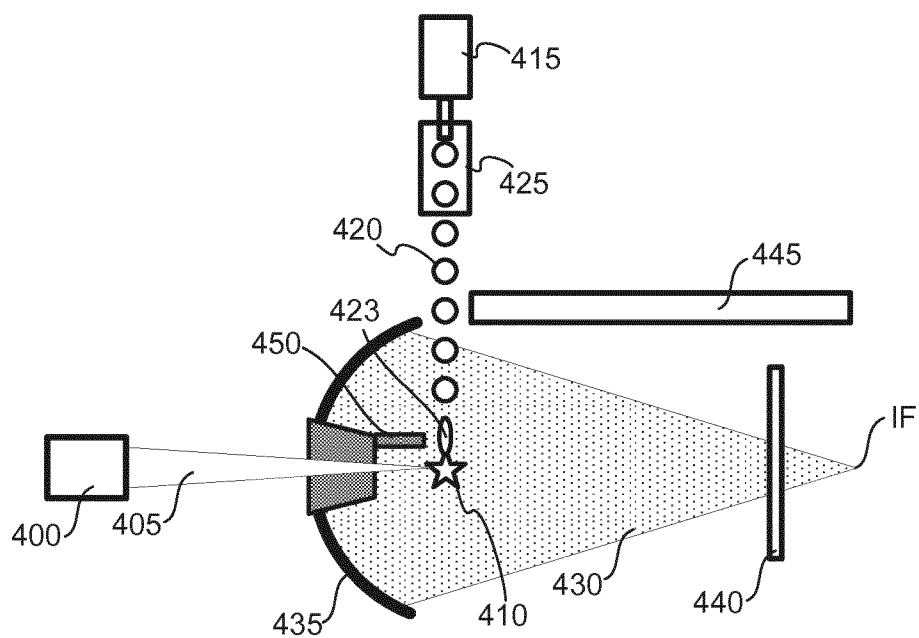


Fig. 4

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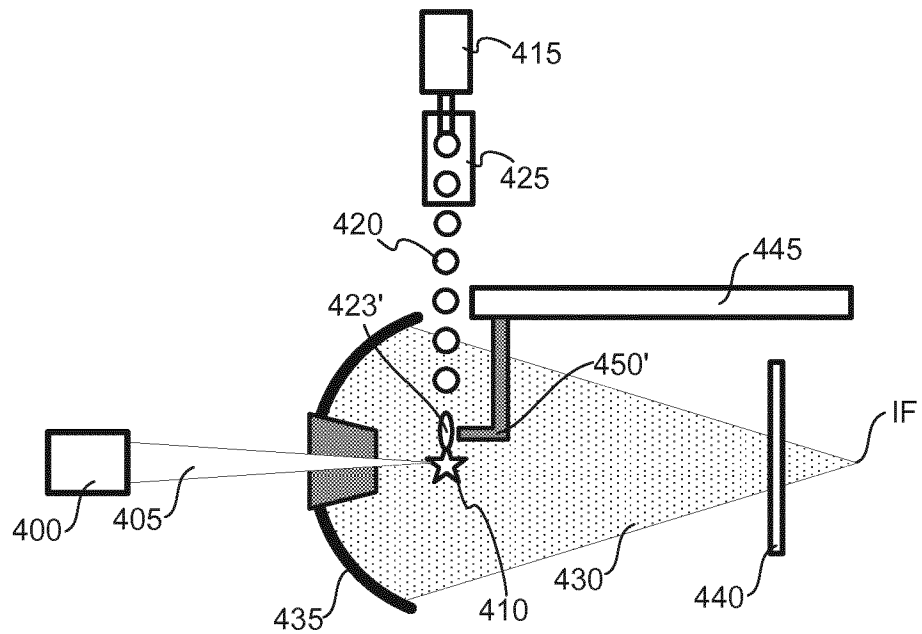


Fig. 5

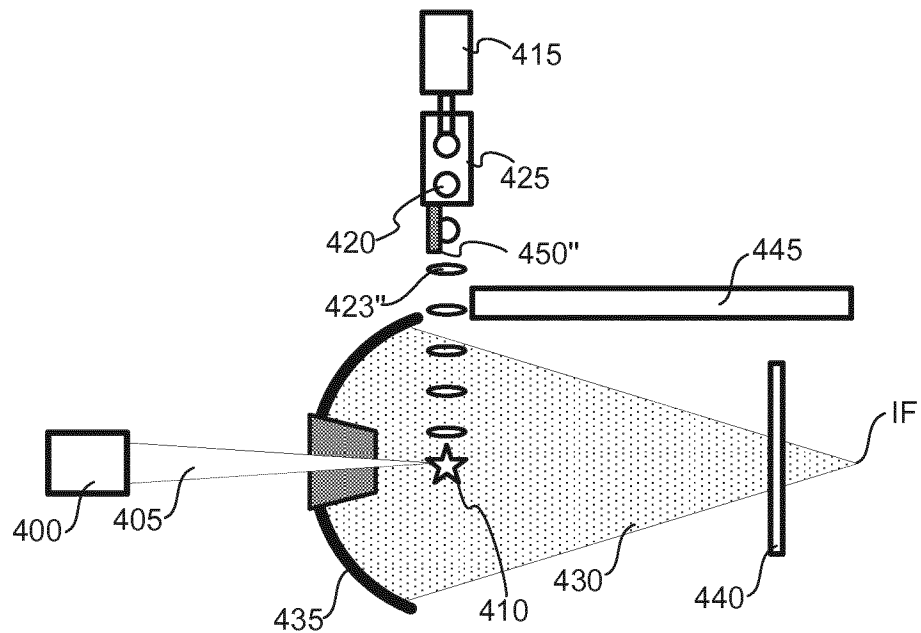


Fig. 6

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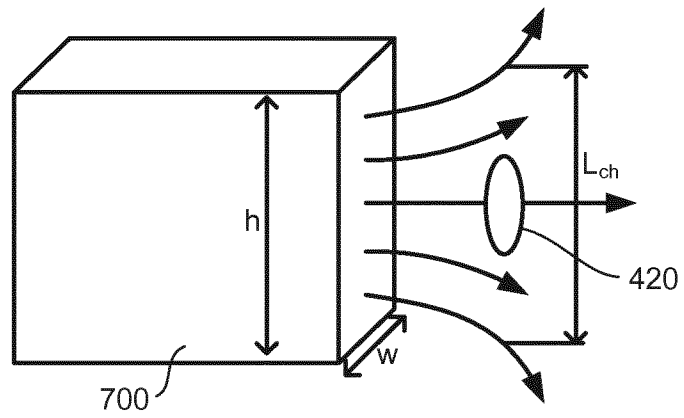


Fig. 7

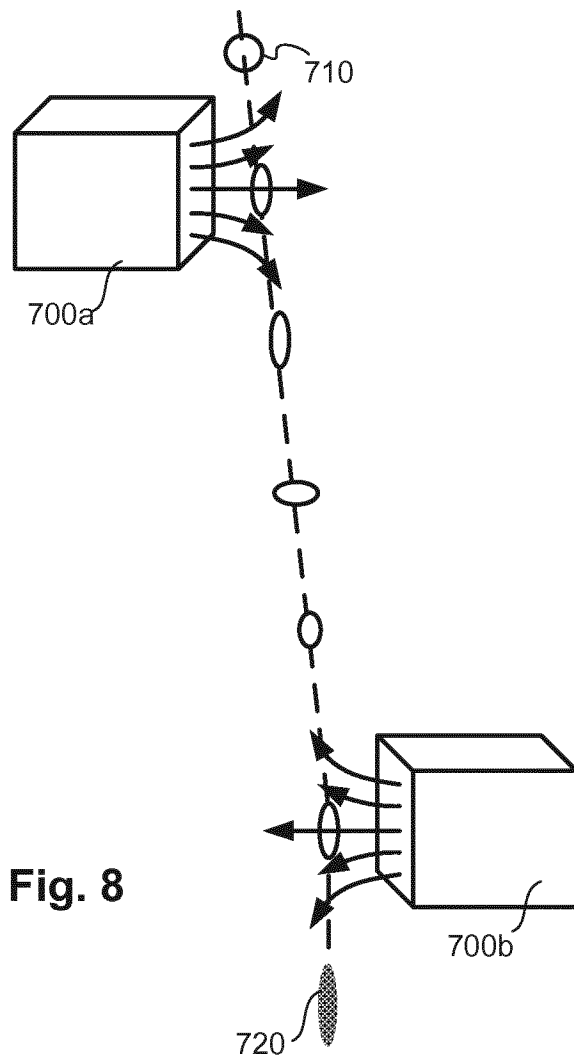


Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/072927

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 H05G2/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G03F H05G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	----- WO 2009/025557 A1 (ASML NETHERLANDS BV [NL]; VAN EMPEL TJARKO ADRIAAN RUDOLF [NL]; BANINE) 26 February 2009 (2009-02-26) paragraph [0037] - paragraph [0049]; figures 2,4,5	1-15
A	----- WO 2011/131431 A1 (ASML NETHERLANDS BV [NL]; LABETSKI DZMITRY [NL]; LOOPSTRA ERIK [NL]; K) 27 October 2011 (2011-10-27) paragraph [0055] - paragraph [0064]; figures 4,5 ----- -/-	1-15



Further documents are listed in the continuation of Box C.



See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search

24 March 2014

Date of mailing of the international search report

22/04/2014

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

van Toledo, Wiebo

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/072927

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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A	----- HSIANG L -P ET AL: "Near-limit drop deformation and secondary breakup", INTERNATIONAL JOURNAL OF MULTIPHASE FLOW UK, vol. 18, no. 5, September 1992 (1992-09), pages 635-652, XP002722153, ISSN: 0301-9322 cited in the application the whole document -----	1,2

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International application No

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