Title: DROPLET GENERATOR FOR LITHOGRAPHIC APPARATUS, EUV SOURCE AND LITHOGRAPHIC APPARATUS

Abstract: Disclosed is an electro-actuable element for a droplet generator, comprising a plurality of electro-actuable segments spaced apart radially so as to define a channel therebetween. The electro-actuable element may comprise a clamping assembly for clamping the electro-actuable element to a capillary without adhesive. The clamping assembly may comprise an inner wedge member and an outer wedge member. The inner wedge member may comprise a central channel for receiving the electro-actuable element and capillary and be locatable inside the outer wedge member to clamp the electro-actuable element to the capillary.
CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 16151421.1 which was filed on 15 January 2015 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to a lithographic apparatus and a specifically for a droplet generator for an EUV source within a 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):

$$CD = k_1 \times \frac{\lambda}{NA}$$  \hspace{1cm} (1)

where $\lambda$ 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 $\lambda$, by increasing the numerical aperture NA or by decreasing the value of $k_1$.

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. 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 plasma sources, or sources based on synchrotron radiation provided by an electron storage ring.

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 example, by directing a laser beam at a fuel, such as particles of a suitable material (e.g. liquid 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 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.

A proposed LPP radiation source generates a continuous stream of fuel droplets. The radiation source comprises a droplet generator for directing fuel droplets toward a plasma formation location. The droplet generator may comprise a glass capillary surrounded by a piezo actuator which generates an acoustic wave in the fuel. The acoustic wave modulates the jet of fuel to form droplets at a distance (the coalescence distance) from the nozzle. The piezo actuator may be attached to the glass capillary using an adhesive (e.g., an epoxy). However, modulation performance of such a droplet generator can degrade in a matter of days.

SUMMARY
It would be desirable to provide an improved droplet generator design, and in particular an improved method of coupling an actuator (e.g. piezo actuator) to a capillary.
The invention relates to an EUV radiation source comprising a droplet generator configured to generate droplets of fuel directed towards a plasma generation location; and also comprising a laser system configured to direct laser radiation at a specific one of the droplets at the plasma formation location to generate a plasma generating EUV radiation. The droplet generator comprises a capillary in which, in use, the fuel flows in a direction of a longitudinal axis of the capillary, and an actuator configured to modulate a pressure inside the capillary. The actuator comprises a plurality of electro-actuable segments spaced apart angularly around the capillary, and a clamping assembly for clamping the electro-actuable segments to the capillary. The clamping assembly comprises an inner wedge member and an outer wedge member. The inner wedge member has a central channel for accommodating the electro-actuable segments positioned around the capillary. The inner wedge member is located inside the outer wedge member to clamp the electro-actuable segments to the capillary.

The invention also relates to a droplet generator configured for use in such an EUV radiation source, and to a lithographic apparatus comprising such an EUV radiation source.

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**

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;
Figure 3 schematically depicts a droplet generator of a radiation source configured to direct a stream of fuel droplets along a trajectory towards a plasma formation location;

Figure 4 schematically depicts an actuator according to an embodiment of the invention, usable in a droplet generator of a radiation source;

Figure 5 schematically depicts an actuator and clamping assembly according to an embodiment of the invention, usable in a droplet generator of a radiation source;

Figure 6 schematically depicts (a) an inner wedge member and (b) an outer wedge member of the clamping assembly of Figure 5; and

Figure 7 schematically depicts (a) a detail of the droplet generator of Figure 3 and (b) an equivalent detail of a droplet generator according to an embodiment of the invention.

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

Figure 1 schematically depicts a lithographic apparatus 100 including a source collector 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
- 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.
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.

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.

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.

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 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.

The projection system, like 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, 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 vacuum wall and vacuum pumps.

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 substrates (and/or two or more mask tables). In such "multiple stage" machines the 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 collector 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 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 collector module SO may be part of an EUV radiation system including a laser, not shown in Figure 1, for providing the laser beam exciting the fuel. The resulting plasma emits output radiation, e.g., EUV radiation, which is collected using a radiation collector, disposed in the source collector module. The laser and the source collector 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 collector 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 collector module, for example 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 distribution in a pupil plane of the illuminator can be adjusted. In addition, the illuminator IL may comprise various other components, such as facetted 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, 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 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 PI, P2.

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 WT is then shifted in the X and/or Y direction so that a different target portion C can be 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.

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

Figure 2 shows the apparatus 100 in more detail, including the source collector module SO, the illumination system IL, and the projection system PS. The source collector module SO is constructed and arranged such that a vacuum environment can be maintained in an enclosing structure 220 of the source collector module SO. The systems IL and PS are likewise contained within vacuum environments of their own. An EUV radiation emitting plasma 2 may be formed by a laser produced LPP plasma source. The function of source
collector module SO is to deliver EUV radiation beam 20 from the plasma 2 such that it is focused in a virtual source point. The virtual source point is commonly referred to as the intermediate focus (IF), and the source collector module is arranged such that the intermediate focus IF is located at or near an aperture 221 in the enclosing structure 220. The virtual source point IF is an image of the radiation emitting plasma 2.

From the aperture 221 at the intermediate focus IF, the radiation traverses the illumination system IL, which in this example includes a faceted field mirror device 22 and a facetted pupil mirror device 24. These devices form a so-called "fly's eye" illuminator, which is arranged to provide a desired angular distribution of the radiation beam 21, at the patterning device MA, as well as a desired uniformity of radiation intensity at the patterning device MA. Upon reflection of the beam 21 at the patterning device MA, held by the support structure (mask table) MT, a patterned beam 26 is formed and the patterned beam 26 is imaged by the projection system PS via reflective elements 28, 30 onto a substrate W held by the wafer stage or substrate table WT. To expose a target portion C on substrate W, pulses of radiation are generated on substrate table WT and masked table MT perform synchronized movements 266, 268 to scan the pattern on patterning device MA through the slit of illumination.

Each system IL and PS is arranged within its own vacuum or near-vacuum environment, defined by enclosing structures similar to enclosing structure 220. More elements than shown may generally be present in illumination system IL and projection system PS. Further, there may be more mirrors present than those shown in the Figures. For example there may be one to six additional reflective elements present in the illumination system IL and/or the projection system PS, besides those shown in Figure 2.

Considering source collector module SO in more detail, laser energy source comprising laser 223 is arranged to deposit laser energy 224 into a fuel, such as xenon (Xe), tin (Sn) or lithium (Li), creating the highly ionized plasma 2 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 is emitted from the plasma, collected by a near-normal incidence collector and focused on the aperture 221. The plasma 2 and the aperture 221 are located at first and second focal points of collector CO, respectively.

Although the collector 3 shown in Figure 2 is a single curved mirror, the collector may take other forms. For example, the collector may be a Schwarzschild collector having two radiation collecting surfaces. In an embodiment, the collector may be a grazing
incidence collector which comprises a plurality of substantially cylindrical reflectors nested within one another.

To deliver the fuel, which for example is liquid tin, a droplet generator 226 is arranged within the enclosure 220, arranged to fire a high frequency stream 228 of droplets towards the desired location of plasma 2. In operation, laser energy 224 is delivered in a synchronism with the operation of droplet generator 226, to deliver impulses of radiation to turn each fuel droplet into plasma 2. The frequency of delivery of droplets may be several kilohertz, for example 50 kHz. In practice, laser energy 224 is delivered in at least two pulses: a pre pulse with limited energy is delivered to the droplet before it reaches the plasma location, in order to vaporize the fuel material into a small cloud and/or to modify a shape of the droplet, and then a main pulse of laser energy 224 is delivered to the cloud or the droplet with its modified shape at the desired location, to generate the plasma 2. A trap 230 is provided on the opposite side of the enclosing structure 220, to capture fuel that is not, for whatever reason, turned into plasma.

The droplet generator 226 comprises a reservoir 201 which contains the fuel liquid and a nozzle 202. The nozzle 202 is configured to eject droplets of the fuel liquid towards the plasma 2 formation location. The droplets of fuel liquid may be ejected from the nozzle 202 by a combination of pressure within the reservoir 201 and a vibration applied to the nozzle by a piezoelectric actuator (not shown).

As the skilled person will know, reference axes X, Y and Z may be defined for measuring the geometry and behavior of the apparatus, its various components, and the radiation beams 20, 21, 26. At each part of the apparatus, a local reference frame of X, Y and Z axes may be defined. The Z axis broadly coincides with the direction 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, the X axis coincides broadly with the direction of fuel stream 228, while the Y axis is orthogonal to that, pointing out of the page as indicated in Figure 2. 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.

Numerous additional components critical to operation of the source collector module and the lithographic apparatus as a whole are 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 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.

[0036] Figure 3 depicts the droplet generator 226 in more detail. The droplet generator comprises a capillary 261 between reservoir 201 and nozzle 202. An actuator 262 (for example a piezo actuator) surrounds a part of the capillary 261. The actuator 262 is connected to a controller 263. The controller 263 controls the actuator 262 according to a driving frequency.

[0037] The fuel (molten material from which droplets of molten material are formed) is disposed inside the capillary 261. The fuel 264 passes through the nozzle 202 so as to form droplets of fuel. The capillary extends longitudinally in the droplet direction 250. The capillary 261 is connected via a stiff housing 265 to the reservoir 201 for holding the fuel. In an embodiment the stiff housing 265 is impermeable by the fuel. For example, in an embodiment the stiff housing 265 is molten-tin tight.

[0038] When the fuel 264 passes through the nozzle 202, it breaks up into droplets. Compared to the way that the jet of fuel 264 naturally breaks up (so-called Rayleigh breakup), it is desirable to produce larger droplets of fuel separated by a greater distance from each other.

[0039] Droplets are generated out of a very small nozzle 202 (possibly 3-5 μm in diameter) at the end of the capillary 261. The actuator controls a pressure inside the capillary 261. The capillary 261 is, for example, surrounded by an actuator 262 (e.g., a tight fitting piezo tube). The actuator 262 is driven by the controller 263, e.g. an arbitrary waveform generator, with a signal that at least contains the high frequency to break up the jet and the low frequency to control the coalescence behavior. A certain amount of molten fuel is stored in a reservoir 201, e.g. heated vessel, and forced to flow towards the nozzle 202 through a filter 269. The flow rate is maintained by a gas pressure above the fluid level in the reservoir 201.

[0040] Droplet generator 226, as with droplet generators according to embodiments of this disclosure, may produce droplets using a method called low frequency modulated continuous jet. With this method a continuous jet is decomposed in small droplets by a high frequency close to the Rayleigh frequency. These droplets, however, because of the low frequency modulation, will have slightly different velocities. In course of their flight high
speed droplets overtake low speed droplets and coalesce into larger droplets spaced at a large distance. The large distance helps to avoid the plasma influencing the trajectory of the droplets. In order to keep the collector clean from condensing fuel, high energy ions and high speed fuel fragments, directed hydrogen gas flows transport these contaminants away. The amount of tin used is a compromise between EUV power generated and contamination of the inside of the source, especially parts in the optical path, such as the collector.

A controller 263 controls the actuator 262 so as to control the size and separation of the droplets of fuel. In an embodiment the controller controls the actuator 262 according to a signal having at least two frequencies. A first frequency is used to control the droplet generator 226 to produce relatively small droplets of fuel. This first frequency may be in the region of MHz. The second frequency is a lower frequency in the kHz range. The second frequency of the signal may be used to vary the speed of the droplets as they exit the nozzle 202 of the droplet generator 226. The purpose of varying the speeds of the droplets is to control the droplets such that they coalesce with each other so as to form larger droplets of fuel, spaced at a corresponding larger distance. Note that, as an alternative to applying a low frequency modulation, an amplitude modulation may be considered as well. The capillary of the droplet generator may be configured to comprise a Helmholtz resonator, as explained in WO2014/082811, herein incorporated by reference. The coalescence behavior may be further enhanced by adding harmonics in between the driving frequency and the Rayleigh frequency.

In this respect a block wave with adjustable duty may be used to obtain shorter coalescence lengths.

Fuel droplets may be approximately spherical, with a diameter about 30μm, usually less than the minimal dimension of the waist of the focused laser beam, being 60-450 μm. Droplets may be generated at frequencies between 40 to 320 kHz and fly towards the plasma formation location with velocities between 40 to 120 m/s, or even faster (up to 500 m/s). Desirably, the inter-droplet spacing is larger than about 1 mm (e.g., between 1 mm and 3 mm). The coalescence process may comprise between 100 to 226 droplets coalescing to form each of the larger droplets.

Actuator 262 is typically attached to the capillary 261, and therefore acoustically coupled to the fuel contained therein, using an adhesive such as an epoxy adhesive. While this achieves acceptable performance in the short term, modulation performance degradation can be seen to occur over a few days, when it would be desirable not to see such degradation over timescales of years. It is believed that a principal cause of the performance degradation may be delamination of the adhesive layer between actuator 262...
and capillary 261, which results in acoustic decoupling of the actuator 262 from the capillary 261 and its contents. The reasons for this delamination are not completely understood. However it is believed that thermo-mechanical stress may be a cause. This thermo-mechanical stress is as a consequence of the different thermal expansion coefficients of the actuator (approx. 2 ppm/K), the quartz capillary (approx. 0.3 ppm/K) and the epoxy adhesive (approx. 45 ppm/K). The adhesive is cured at about 150°C and the operational temperature of the nozzle is about 260°C. Another potential issue is the large tolerance in the thickness of the adhesive layer (which may be between 0 and 30µm). This is as a result of the tolerances of the capillary outer diameter and the actuator inner diameter, and also the actuator inner roughness. A thin adhesive layer has more strain and can delaminate by shear forces.

0044] Figure 4 illustrates a segmented electro-actuable element or actuator 400, e.g. a piezo actuator, according to a first embodiment. The segmented actuator 400 comprises a plurality of electro-actuable segments 410. In an embodiment the segmented actuator 400 comprises three or more segments 410. In the specific example illustrated, the segmented actuator 400 comprises four segments 410. The actuator 410 may be angularly (i.e., tangentially, as opposed to "axially" and to "radially" in a cylindrical coordinate system) segmented into segments 410, with each segment extending longitudinally along part of the capillary.

0045] Segmented actuator 400 may be used with a capillary, such as capillary 261 of Figure 3. As such, segmented actuator 400 may replace actuator 262 of droplet generator 226. In an embodiment, segmented actuator 400 may be coupled to a capillary of a droplet generator using an adhesive, such that each segment 410 is glued to the capillary. As before, the adhesive may be an epoxy adhesive.

0046] Using a segmented actuator 400 reduces the radial tolerances between the capillary and the segments of the segmented actuator 400.

0047] In another embodiment, it is proposed to couple a segmented actuator, such as segmented actuator 400, to a glass (quartz) capillary without using an adhesive. In such an embodiment, it is proposed to mechanically clamp the segmented actuator 400 to the capillary. Mechanically clamping with an appropriate radial preload provides a good acoustic coupling between segmented actuator 400 and the capillary contents (fuel), with a long lifetime performance.

0048] Figure 5 illustrates (in cross-section) a mechanically clamped segmented actuator 400, clamped to a capillary 420. The segmented actuator 400 is clamped to the
capillary 420 with a clamping assembly, which is formed by an inner wedge member 430 and an outer wedge member 440. Figure 6 shows (a) the inner wedge member 430 and (b) the outer wedge member 440 as separate elements. The inner wedge member 430 and the outer wedge 440 may be made from, e.g., Invar. As known, Invar is a nickel-iron alloy and has a coefficient of thermal expansion that is low for the intended purpose. The clamping assembly and actuator may be taken apart and reassembled non-destructively.

[0049] Inner wedge member 430 and outer wedge member 440 each have complementary conical wedge profiles, such that the inner wedge member 430 has a conical wedge profile on its outer surface which complements (e.g., is of opposite surface slope) the inner surface of outer wedge member 440. The inner wedge member 430 is placed around the segmented actuator 400, and the outer wedge member 440 is placed over the inner wedge member 430, thereby clamping the segmented actuator 400 to the capillary 420. The wedge angle of the inner wedge member 430 and outer wedge member 440 should be such that the wedge members are self-braking, and therefore will not loosen. By way of example, a wedge angle of 5 degrees or smaller, or 3 degrees (as depicted in Figure 5) or smaller, is self-braking for a coefficient of friction between the wedges of 0.05 and higher. A minimum coefficient of friction may be obtained by using clean parts within a high vacuum without lubrication. No adhesive or bolts are required.

[0050] The inner wedge member 430 may be made radially compliant. This can best be seen in Figure 6(a), where longitudinal slits 450 are provided along most of the length of the inner wedge member 430. These longitudinal slits 450 allow the inner wedge member 430 to be radially compressed onto the segmented actuator 400 by the outer wedge member 440.

[0051] The wedge members 430, 440 may be axially preloaded with a particular force to provide a constant and reproducible radial preload to the segmented actuator 400. Grooves 460 may be provided on the outer surface of outer wedge member 440 to facilitate this preloading (which may be performed using a torque wrench, possibly with dedicated tooling). To provide a constant and reproducible coefficient of friction, the complementary surfaces of wedge members 430, 440 may be coated. For example, the outer surface of the inner wedge member 430 may be coated with Ni (nickel) of nominal thickness of e.g., 5 µm with a tolerance of 2 µm, and the outer wedge member 440 may be coated with NiP-ptfe with a nominal thickness of, e.g., 10 µm with a tolerance of 2 µm. The clamping assembly and actuator may be taken apart and reassembled non-destructively.
In an embodiment, a soft metal coating may be added to the capillary, such that the soft metal lies between the capillary 420 and the segmented actuator 400 when assembled. The soft metal coating removes air inclusions between the capillary 420 and the segmented actuator 400 caused by surface roughness and tolerances. As such, this soft metal coating may be sufficiently soft so as to deform under the clamping pressure. This soft metal coating will improve the acoustic coupling from the actuator to the capillary contents (fuel). The soft metal coating may be made of, e.g., PdAg and have a thickness of, e.g., 10-15 μm.

Optionally, this soft metal coating on the capillary 420 may also be used as the inner electrode for the segmented actuator 400. Such an arrangement is shown in schematic cross-section in Figure 7(b) (the clamping assembly is not shown for clarity). For comparison, an equivalent detail of the Figure 3 arrangement is shown in Figure 7(a). Figure 7(a) shows the capillary 261 (in part), the actuator 262, outer electrode 270, inner electrode 280 and adhesive (epoxy) layer 290.

Figure 7(b) shows capillary 420 (in part), the segmented actuator 400, outer electrode 470 and the capillary coating/inner electrode 480. The capillary coating/inner electrode surrounds the capillary and therefore is in contact with all segments of the segmented actuator 400. There is no adhesive layer in this embodiment, as it utilises mechanical clamping as described above. In this way, the inner electrode 480 can be connected at a point next to the actuator 400 on the capillary, rather than on the outer surface of the segmented actuator 400. This frees up space along the segmented actuator's outer surface and means that the clamping assembly (wedge members 430, 440) can be clamped along a greater proportion of the actuator's length, improving the clamping. In another embodiment, not illustrated, the inner wedge member 430/clamping assembly can double as the outer electrode (again it contacts each segment of the segmented actuator 400), thereby allowing clamping along the full length of the segmented actuator 400.

Embodiments of the segmented actuator (e.g. a segmented piezo actuator) as described above, with or without the clamping assembly also disclosed herein, may be used on any droplet generator which uses a tubular member (e.g., glass/quartz capillary) to deliver the fuel to the nozzle, such that the tubular member passes through the central channel defined by the segments of the segmented actuator. Also disclosed is a droplet generator comprising such a segmented actuator, and optionally comprising a soft metallic coating on the tubular member. Optionally, the soft metallic coating may be used as the inner electrode for the segmented actuator. Optionally, the clamping assembly may be used as the outer electrode for the segmented actuator.
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 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 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 multiple processed layers.

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.

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 departing from the scope of the claims set out below.
CLAIMS

1. An EUV radiation source comprising:
   - a droplet generator configured to generate droplets of fuel directed towards a plasma generation location; and
   - a laser system configured to direct laser radiation at a specific one of the droplets at the plasma formation location to generate a plasma generating EUV radiation;
   wherein:
   - the droplet generator comprises:
     - a capillary in which, in use, the fuel flows in a direction of a longitudinal axis of the capillary; and
     - an actuator configured to modulate a pressure inside the capillary;
   - the actuator comprises:
     - a plurality of electro-actuable segments spaced apart angularly around the capillary; and
   - a clamping assembly for clamping the electro-actuable segments to the capillary; and
   - the clamping assembly comprises an inner wedge member and an outer wedge member, the inner wedge member comprising a central channel for accommodating the electro-actuable segments positioned around the capillary, the inner wedge member being located inside the outer wedge member to clamp the electro-actuable segments to the capillary.

2. The EUV radiation source of claim 1, wherein an outer surface of the inner wedge member has a first conical slope, and an inner surface of the outer wedge member has a second conical slope complementary to the first conical slope.

3. The EUV radiation source of claim 1 or 2, wherein the inner wedge member is radially compressible under a pressure resulting from the clamping of the electro-actuable segments to the capillary.

4. The EUV radiation source of claim 1 or 2, wherein:
   - the inner wedge member is radially compressible; and
the inner wedge has one or more longitudinal slits along most of a length of the inner
wedge member.

5. The EUV radiation source of claim 1, 2, 3 or 4, wherein an outer surface of the inner
wedge member is provided with a first coating, and an inner surface of the outer wedge
member is provided with a second coating configured to provide a reproducible value of a
coefficient of friction between the outer surface and the inner surface.

6. The EUV radiation source of claim 5, wherein:

one of the first coating and the second coating comprises Ni; and

the other one of the first coating and the second coating comprises NiP-pfte.

7. The EUV radiation source of claim 1, 2, 3, 4, 5 or 6, wherein the capillary has a metal
coating configured to deform under a pressure arising from the clamping of the electro-
actuable segments to the capillary.

8. The EUV radiation source of claim 7, wherein the metal coating comprises PdAg.

9. The EUV radiation source of claim 7 or 8, wherein:

the clamping assembly has a first electrode configured for electric connection to the
electro-actuable segments; and

the metal coating forms a second electrode for electric connection to the electro-
actuable segments.

10. A droplet generator configured for use in the EUV radiation source of claim 1, 2, 3, 4, 5,
6, 7, 8 or 9.

11. A lithographic apparatus comprising the EUV radiation source of claim 1, 2, 3, 4, 5, 6, 7,
8 or 9.
Fig. 7
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)
H05G G03F

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Date of the actual completion of the international search: 20 February 2017

Date of mailing of the international search report: 27/02/2017

Authorized officer: Mei xner, Matthi as
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