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(54) Title: LITHOGRAPHIC SYSTEM AND METHOD

(57) Abstract: A system for securing a particle to a pellicle membrane for subsequent use in a lithographic apparatus, the system comprising a particle securement device configured to secure the particle to the pellicle membrane. The particle securement device is configured to direct the electron beam or the radiation beam such that the electron beam or the radiation beam passes through the pellicle membrane before being incident on the particle.



Lithographic system and method

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 18197443.7 which was filed on September 28, 2018 and EP application 18199853.5 which was filed on October 11, 2018 and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to a system and method of securing a particle to a pellicle membrane such that, when used in a lithographic apparatus, the particle does not detach from the pellicle membrane and thereby cannot reach a reticle of the lithographic apparatus.

BACKGROUND

[0003] A lithographic apparatus is a machine constructed to apply a desired pattern onto a substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). A lithographic apparatus may, for example, project a pattern at a patterning device (e.g., a reticle or mask) onto a layer of radiation-sensitive material (resist) provided on a substrate.

[0004] To project a pattern on a substrate a lithographic apparatus may use electromagnetic radiation. The wavelength of this radiation determines the minimum size of features which can be formed on the substrate. Typical wavelengths currently in use are 365 nm, 248 nm, 193 nm and 13.5 nm. A lithographic apparatus, which uses extreme ultraviolet (EUV) radiation, having a wavelength within a range of 4 nm to 20 nm, for example 6.7 nm or 13.5 nm, may be used to form smaller features on a substrate than a lithographic apparatus which uses, for example, radiation with a wavelength of 193 nm.

[0005] Some lithographic apparatus (e.g. EUV and DUV lithographic apparatus) comprise a pellicle membrane which is attached to the reticle. The pellicle membrane is a thin (e.g. a thickness of less than about 70 nm) transmissive film which is spaced a few mm (e.g. about 5 mm) away from the pattern of the reticle. A particle which is received on the pellicle membrane is in the far field with respect to the pattern of the reticle, and consequently does not have a significant impact upon the quality of image which is projected by the lithographic apparatus on to a substrate. If the pellicle membrane were not present then the particle would lie on the pattern of the reticle and would obscure a portion of the pattern thereby preventing the pattern from being projected correctly on to the substrate. The pellicle membrane thus plays an important role in preventing particles from adversely affecting the projection of a pattern on to a substrate by the lithographic apparatus.

[0006] Before the pellicle is attached to the reticle for use in a lithographic apparatus, the pellicle membrane may become dirty. That is, particles may be incident on the pellicle membrane before the pellicle membrane is used in a lithographic apparatus. Activities including transporting the pellicle membrane, packaging the pellicle membrane and mounting the pellicle membrane to a reticle may result in particles being incident upon the pellicle membrane. It has been found that some particles that are present on the pellicle membrane detach and travel from the pellicle membrane to the reticle during a lithographic exposure, and thereby negatively affect the pattern projected onto the substrate.

[0007] Currently, pellicles that are found to be too dirty for use are discarded. Known methods of dealing with the problem of a dirty pellicle involve cleaning the pellicle e.g. using vibrations, plasma, wet cleaning, etc. However, the known methods risk breaking the pellicle because the pellicle is a very thin film and is prone to being damaged easily. Some known methods of cleaning a dirty pellicle membrane involve applying heat to try to avoid introducing cracks to the pellicle membrane during cleaning. However, the application of heat may also contribute to a weakening of the pellicle, thereby reducing the operational lifetime of the pellicle membrane.

[0008] It is desirable to provide, for example, a system and method which obviates, or mitigates, one or more problems of the prior art, whether identified herein or elsewhere.

SUMMARY

[0009] According to a first aspect of the invention there is provided a system for securing a particle to a pellicle membrane for subsequent use in a lithographic apparatus, the system comprising a particle securement device configured to secure the particle to the pellicle membrane.

[0010] Particles may be incident on the pellicle membrane before the pellicle membrane is used in a lithographic apparatus. During a lithographic exposure, some of the particles on the pellicle membrane may travel from the pellicle membrane to the reticle. These particles may then be imaged onto the substrate during the lithographic exposure, and thereby negatively affect a quality of the lithographic exposure. The system for securing the particle to the pellicle membrane advantageously prevents the particle from travelling to the reticle, and thereby prevents the particle from negatively affecting the lithographic exposure.

[0011] The particle securement device may be configured to irremovably secure the particle to the pellicle membrane. The particle may be secured to the pellicle membrane for the entire duration of an operational lifetime of the pellicle membrane.

[0012] The particle securement device may be configured to secure the particle to a reticle-facing surface of the pellicle membrane.

[0013] The particle securement device may be configured to provide a material to the pellicle membrane for securing the particle to the pellicle membrane.

[00014] The material provided by the particle securement device to the pellicle membrane may have a size in a plane of the pellicle membrane of less than about 10 μm on the pellicle membrane. The material provided by the particle securement device to the pellicle membrane may have a size in a plane of the pellicle membrane of about 10 μm or less on the pellicle membrane.

5 [00015] The material provided by the particle securement device to the pellicle membrane may have a thickness of less than about 100 nm on the pellicle membrane. The material provided by the particle securement device to the pellicle membrane may have a thickness of about 100 nm or less on the pellicle membrane.

10 [00016] If the material provided to the pellicle membrane is too thick and/or has too great a size in a plane of the pellicle membrane (e.g. length, diameter, major axis, etc. depending on the shape of the deposited material) then there is a risk of the material itself being at least partially imaged onto a substrate during a lithographic exposure, thereby negatively affecting the lithographic exposure. By limiting the size and/o thickness of the material on the pellicle membrane, the material and the particle are advantageously kept in the far field with respect to the pattern of the reticle to avoid negatively affecting the quality of image which is projected by the lithographic apparatus on to the substrate.

15 [00017] The material provided by the particle securement device may comprise at least one of molybdenum Mo, ruthenium Ru, zirconium Zr, boron B, cerium Ce, silicon Si, samarium Sm, praseodymium Pr, europium Eu, scandium Sc, promethium Pm, yttrium Y and rubidium Rb.

20 [00018] The material provided by the particle securement device may comprise at least one of carbon, oxygen, nitrogen and hydrogen.

[00019] The material provided by the particle securement device may comprise at least one of a metal carbonyl and a metal cyclopentadienyl.

[00020] The material provided by the particle securement device may comprise at least one of camphor, menthol, naphthalene and biphenyl.

25 [00021] The particle securement device may be configured to provide an electron beam or a radiation beam to the pellicle membrane for securing the particle to the pellicle membrane.

[00022] The electron beam or the radiation beam may be configured to induce an interaction between the material and the pellicle membrane and/or the particle and thereby secure the particle to the pellicle membrane.

30 [00023] The interaction may produce and/or enhance attractive forces acting between the deposited material and the particle and/or the pellicle membrane and may, for example, include covalent bonds, metal bonds, polar bonds, Hydrogen-bonds, Van der Waals forces, etc.

35 [00024] The particle securement device may be configured to direct the electron beam or the radiation beam such that the electron beam or the radiation beam passes through the pellicle membrane before being incident on the particle.

[00025] The electron beam or the radiation beam may form a beam spot on the pellicle membrane that has a diameter of more than about 0.1 μm . The electron beam or the radiation beam may form a beam spot on the pellicle membrane that has a diameter of less than about 5 μm . Providing an electron beam or a radiation beam having these diameters may advantageously enable better management of thermal effects acting on the pellicle membrane. Providing an electron beam or a radiation beam having these diameters may advantageously reduce an extent of a scanning motion of the electron beam or the radiation beam across the pellicle membrane.

[00026] The particle securement device may be configured to direct the electron beam or the radiation beam to form a beam spot on the particle on the pellicle membrane. An outer boundary of the beam spot may be less than about 5 μm from the particle. The outer boundary of the beam spot may be less than about 1 μm from the particle.

[00027] The particle securement device may be configured to direct the electron beam to form a beam spot on an area of the pellicle membrane that includes the particle. The electron beam may have an energy of between about 100 V and about 100 kV.

[00028] The pellicle membrane may be mounted to a reticle during use of the particle securement device. The electron beam may have an energy of between about 0.5 keV and about 5 keV.

[00029] The system may further comprise a support configured to hold the reticle and a material delivery system configured to provide the material in a gap situated between the reticle and the pellicle.

[00030] The system may further comprise a particle locator configured to determine the location of the particle on the pellicle membrane.

[00031] The particle locator may be configured to generate a signal indicative of the location of the particle and provide the signal to the particle securement device. The particle securement device may be configured to use the signal to provide the material and/or the electron beam or the radiation beam to the location of the particle on the pellicle membrane. The electron beam or the radiation beam may be configured to irradiate only a portion of the pellicle membrane corresponding to the location of the particle. The irradiated portion of the pellicle membrane may have a diameter of less than about 5 μm , e.g. about 1 μm .

[00032] The particle locator may be configured to use the electron beam or the radiation beam to determine the location of the particle on the pellicle membrane.

[00033] The particle locator may be configured to detect secondary electrons and/or back-scattered electrons produced by the electron beam or the radiation beam interacting with the pellicle membrane and/or the particle.

[00034] The particle locator may comprise an optical measurement system configured to determine the location of the particle on the pellicle membrane. The optical measurement system may comprise a radiation source for scattering radiation from the particle and a radiation detector for detecting radiation scattered by the particle.

[00035] The particle locator may comprise at least one of a bright field imaging device, a dark field imaging device, an atomic force microscope and capacitive particle detection means.

[00036] The particle locator may be configured to locate particles having a diameter of between about 0.1 μm and about 5 μm .

5 [00037] The system may further comprise a first compartment for holding the material in a non-gaseous state. The system may further comprise a second compartment for holding the material in a gaseous state. The system may further comprise a third compartment for transmitting the electron beam or the radiation beam to the pellicle membrane.

10 [00038] The first compartment may comprise a semi-permeable barrier for preventing the non-gaseous material from reaching the pellicle membrane.

[00039] The pellicle membrane may form at least part of the second compartment.

[00040] The particle securement device may comprise a channel between the first compartment and the second compartment. The particle securement device may comprise a channel between the second compartment and the third compartment. The channel may be configured to transmit gas and thereby
15 enable pumping and/or venting of the compartments.

[00041] The second compartment may be held at a pressure of between about 0.001 Pa and about 1 Pa.

[00042] The third compartment may comprise a vacuum environment (e.g. having a pressure of less than about 10^{-5} Pa). The third compartment may comprise a low pressure (e.g. a pressure of more than about 10^{-5} Pa and less than about 0.1 Pa) gaseous environment (e.g. including at least one of H_2 , H_2O , O_2). Degradation of the pellicle membrane may be caused by, for example, electron beam irradiation which may contribute to changes of a surface stress of the pellicle membrane, oxidation and/or reduction of the pellicle membrane, etc. The vacuum environment and/or the low pressure gaseous environment may advantageously reduce the extent of unwanted deposition of material on the pellicle membrane
20 (e.g. on a non-reticle facing surface of the pellicle membrane). The vacuum environment and/or the low pressure gaseous environment may advantageously reduce degradation of the pellicle membrane, e.g. by providing an opposing force that at least partially counters the change of the surface stress of the pellicle membrane.

[00043] The particle securement device may, for example, be configured to maintain a pressure difference of less than about 1 Pa between different sides of the pellicle membrane.
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[00044] The particle securement device may comprise an electrical grounding connected to the pellicle membrane. Electrically grounding the pellicle membrane may advantageously reduce electrical charging of the pellicle membrane by the electron beam.

[00045] The system may further comprise a housing configured to house the pellicle membrane in
35 a clean environment (e.g. a clean environment having an ISO class of 2 or better).

[00046] The system may further comprise a pellicle membrane transfer device configured to mount the pellicle membrane to a reticle held in the clean environment after the particle securement device has secured the particle to the pellicle membrane.

[00047] According to a second aspect of the invention, there is provided a method comprising
5 securing a particle to a pellicle membrane.

[00048] The method may further comprise irremovably securing the particle to the pellicle membrane.

[00049] The method may further comprise securing the particle to a reticle-facing surface of the pellicle membrane.

10 [00050] The method may further comprise providing a material to the pellicle membrane to secure the particle to the pellicle membrane.

[00051] The method may further comprise providing the material to the pellicle membrane such that the material has a size of less than about 10 μm on the pellicle membrane.

[00052] The method may further comprise providing the material to the pellicle membrane such
15 that the material has a thickness of less than about 100 nm on the pellicle membrane.

[00053] The method may further comprise providing an electron beam or a radiation beam to the pellicle membrane to secure the material and the particle to the pellicle membrane.

[00054] The method may further comprise directing the electron beam or the radiation beam to the pellicle membrane to form a beam spot having a diameter of greater than about 0.1 μm on the pellicle
20 membrane. The method may further comprise directing the electron beam or the radiation beam to the pellicle membrane to form a beam spot having a diameter of less than about 5 μm on the pellicle membrane.

[00055] The diameter of the electron beam or the radiation beam may be selected in at least partial dependence on a size of the particle that is to be secured to the pellicle membrane. For example, the
25 location of the particle on the pellicle membrane may be determined using the electron beam. Once the location of the particle on the pellicle membrane has been determined, the diameter of the electron beam or the radiation beam may be changed (e.g. decreased to about 100 nm) and the electron beam or the radiation beam may be used to secure the particle to the pellicle membrane.

[00056] The method may further comprise using the electron beam or the radiation beam to induce
30 an interaction between the material and/or the pellicle membrane or the particle and thereby secure the particle to the pellicle membrane.

[00057] The method may further comprise directing the electron beam or the radiation beam such that the electron beam or the radiation beam passes through the pellicle membrane before being incident on the particle.

[00058] The method may further comprise securing the particle to the pellicle whilst the pellicle is mounted to a reticle, and wherein the electron beam is provided with an energy of between about 0.5 keV and about 5 keV.

5 [00059] The method may further comprise providing the material in a gap situated between the reticle and the pellicle.

[00060] The method may further comprise determining the location of the particle on the pellicle membrane.

10 [00061] The method may further comprise locating particles having a diameter of greater than about 0.1 μm . The method may further comprise locating particles having a diameter of less than about 5 μm .

15 [00062] The method may comprise providing the electron beam or the radiation beam to the pellicle membrane through a compartment comprising a vacuum environment (e.g. a pressure of less than about 10^{-5} Pa). Alternatively, the method may further comprise providing the electron beam or the radiation beam to the pellicle membrane through a compartment having a low pressure (e.g. a pressure of more than about 10^{-5} Pa and less than about 0.1 Pa) gaseous environment (e.g. including at least one of H_2 , H_2O , O_2). Degradation of the pellicle membrane may be caused by, for example, electron beam irradiation which may contribute to changes of a surface stress of the pellicle membrane, oxidation and/or reduction of the pellicle membrane, etc. The vacuum environment and/or the low pressure gaseous environment may advantageously reduce the extent of unwanted deposition of material on the pellicle membrane (e.g. on a non-reticle facing surface of the pellicle membrane). The vacuum environment and/or the low pressure gaseous environment may advantageously reduce degradation of the pellicle membrane, e.g. by providing an opposing force that at least partially counters the change of the surface stress of the pellicle membrane.

20 [00063] The method may further comprise keeping the pellicle membrane in a clean environment after the particle has been secured to the pellicle membrane. The method may further comprise mounting the pellicle membrane to a reticle in the clean environment after the particle has been secured to the pellicle membrane.

25 [00064] According to a third aspect of the invention, there is provided a method of projecting a patterned beam of radiation onto a substrate, the patterned beam of radiation passing through a pellicle membrane before being incident on the substrate, wherein a particle has been secured to the pellicle membrane using the method of the second aspect of the invention.

30 [00065] According to a fourth aspect of the invention, there is provided a pellicle membrane comprising a particle that has been secured to the pellicle membrane using the method of the second aspect of the invention.

[00066] According to a fifth aspect of the invention, the invention concerns the use of the system according to the first aspect for securing a particle to a pellicle membrane for subsequent use in a lithographic apparatus.

[00067] Any portions of any of the aspects of the invention may be combined in any way.

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BRIEF DESCRIPTION OF THE DRAWINGS

[00068] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 schematically depicts a lithographic system comprising a radiation source, a lithographic apparatus and a pellicle according to an embodiment of the invention;
- Figure 2 schematically depicts a system for securing a particle to a pellicle membrane according to an embodiment of the invention;
- Figure 3 schematically depicts a magnified view of a pellicle membrane comprising a particle that has been secured to the pellicle membrane according to an embodiment of the invention; and,
- Figure 4 schematically depicts a system for securing a particle to a pellicle membrane that is mounted to a reticle according to an embodiment of the invention.

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DETAILED DESCRIPTION

[00069] Figure 1 shows a lithographic system comprising a radiation source SO, a lithographic apparatus LA and a pellicle 20 according to an embodiment of the invention. The radiation source SO is configured to generate an EUV radiation beam B and to supply the EUV radiation beam B to the lithographic apparatus LA. The lithographic apparatus LA comprises an illumination system IL, a support structure MT configured to support a patterning device MA (e.g., a mask), a projection system PS and a substrate table WT configured to support a substrate W.

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[00070] The illumination system IL is configured to condition the EUV radiation beam B before the EUV radiation beam B is incident upon the patterning device MA. Thereto, the illumination system IL may include a faceted field mirror device 10 and a faceted pupil mirror device 11. The faceted field mirror device 10 and faceted pupil mirror device 11 together provide the EUV radiation beam B with a desired cross-sectional shape and a desired intensity distribution. The illumination system IL may include other mirrors or devices in addition to, or instead of, the faceted field mirror device 10 and faceted pupil mirror device 11.

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[00071] After being thus conditioned, the EUV radiation beam B interacts with the patterning device MA. As a result of this interaction, a patterned EUV radiation beam B' is generated. The projection system PS is configured to project the patterned EUV radiation beam B' onto the substrate W. For that purpose, the projection system PS may comprise a plurality of mirrors 13,14 which are configured to project the patterned EUV radiation beam B' onto the substrate W held by the substrate

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table WT. The projection system PS may apply a reduction factor to the patterned EUV radiation beam B', thus forming an image with features that are smaller than corresponding features on the patterning device MA. For example, a reduction factor of 4 or 8 may be applied. Although the projection system PS is illustrated as having only two mirrors 13, 14 in Figure 1, the projection system PS may include a different number of mirrors (e.g. six or eight mirrors).

[00072] The substrate W may include previously formed patterns. Where this is the case, the lithographic apparatus LA aligns the image, formed by the patterned EUV radiation beam B', with a pattern previously formed on the substrate W.

[00073] A relative vacuum, i.e. a small amount of gas (e.g. hydrogen) at a pressure well below atmospheric pressure, may be provided in the radiation source SO, in the illumination system IL, and/or in the projection system PS.

[00074] The radiation source SO may be a laser produced plasma (LPP) source, a discharge produced plasma (DPP) source, a free electron laser (FEL) or any other radiation source that is capable of generating EUV radiation.

[00075] As previously discussed, particles may be incident on the pellicle membrane before the pellicle membrane is used in a lithographic apparatus. During a lithographic exposure, some of the particles may travel from the pellicle membrane to the reticle, and thereby negatively affect a quality of the lithographic exposure.

[00076] Figure 2 schematically depicts a system 22 for securing a particle 24 to a pellicle membrane 20 according to an embodiment of the invention. The system 22 at least partially prepares the pellicle membrane 20 for subsequent use in a lithographic apparatus (e.g. the lithographic apparatus of Figure 1). The pellicle membrane 20 is mounted to a frame 23 comprising studs 25. The pellicle membrane 20 and the frame 23 may be referred to as a pellicle assembly. The pellicle assembly is configured to be removably mounted on a reticle MA. In the example of Figure 2, the pellicle assembly is mounted on a base 29 of the system 22. Methods and systems of mounting the pellicle assembly to the reticle MA and/or another surface (such as the base 29) are discussed in international patent application WO/2016079051 which is incorporated in its entirety herein by reference. The system 22 comprises a particle securement device 26 configured to secure the particle 24 to the pellicle membrane 20. The particle 24 may be described as a contaminant particle. The particle securement device 26 may be configured to secure the particle 24 to the pellicle membrane 20 such that the particle 24 does not detach from the pellicle membrane 20 during lithographic exposures. The particle securement device 26 may be configured to irremovably secure the particle 24 to the pellicle membrane 20. That is, the particle securement device 26 may secure the particle 24 to the pellicle membrane 20 such that the particle 24 is secured to the pellicle membrane 20 throughout the operational lifetime of the pellicle membrane.

[00077] The particle securement device 26 may be configured to secure the particle 24 to a reticle-facing surface 21 of the pellicle membrane 20. Particles present on the reticle-facing surface 21 of the pellicle membrane 20 may have a greater risk of travelling from the pellicle membrane 20 to the reticle MA during a lithographic exposure compared to particles present on an opposite side 19 of the pellicle membrane 20. This is at least partially because there is a shorter distance to travel between the reticle-facing surface 21 of the pellicle membrane 20 and the reticle MA compared to the distance between the opposing surface 19 of the pellicle membrane 20 and the reticle MA. Securing the particle 24 to the reticle-facing surface 21 of the pellicle membrane 20 thereby advantageously prevents these particles 24 from negatively affecting a lithographic exposure.

[00078] The particle securement device 26 may be configured to provide a material 28 to the pellicle membrane 20 for securing the particle 24 to the pellicle membrane 20. The material 28 may be provided around the particle 24 so as to form a cap that traps and thereby secures the particle 24 to the pellicle membrane 20. Alternatively or additionally, the material 28 may be provided between the particle 24 and the pellicle membrane 20 and act as an adhesive layer between the particle 24 and the pellicle membrane 20. The material 28 may act to increase attractive forces acting between the particle 24 and the pellicle membrane 20 such that the particle 24 becomes secured to the pellicle membrane 20. The material 28 may additionally or alternatively act to introduce new attractive forces acting between the particle 24 and the pellicle membrane 20 such that the particle 24 becomes secured to the pellicle membrane 20. These attractive forces are described in greater detail below with respect to Figure 3.

[00079] The material 28, once provided to the pellicle membrane 20, should not be large enough to negatively affect a lithographic exposure involving the pellicle membrane 20. That is, if the material 28 deposited on the pellicle membrane 20 is too thick and/or has too great a size in a plane of the pellicle membrane 20 (e.g. length, diameter, major axis, etc. depending on the shape of the deposited material) then there is a risk of the material 28 itself being at least partially imaged onto a substrate during a lithographic exposure, thereby negatively affecting the lithographic exposure. The material 28, along with the particle 24, should be kept in the far field with respect to the pattern of the reticle to avoid negatively affecting the quality of image which is projected by the lithographic apparatus on to the substrate. The material 28 provided by the particle securement device 26 to the pellicle membrane 20 may have a size in a plane of the pellicle membrane 20 of less than about 10 μm on the pellicle membrane 10. The material 28 provided by the particle securement device 26 to the pellicle membrane 20 may have a size in a plane of the pellicle membrane 20 of less than about 1 μm . If the thickness of the material 28 provided on the pellicle membrane 20 is too great then the material 28 may no longer be in the far field with respect to the pattern of the reticle MA and thereby negatively affect a quality of the image that is projected on to the substrate. The material 28 provided by the particle securement device 26 to the pellicle membrane 20 may have a thickness of less than about 100 nm on the pellicle

membrane 20. The material 28 provided by the particle securement device 26 to the pellicle membrane 20 may have a thickness of less than about 10 nm on the pellicle membrane 20.

[00080] It will be appreciated that Figure 2 is merely a schematic representation of an embodiment of the invention, and that the relative sizes of features thereof (e.g. the size of the particle 24, the material and the pellicle membrane 20) have been adjusted for the purposes of illustrating the invention.

[00081] The material 28 provided by the particle securement device 26 may comprise one or more materials that are suitable for use when exposed to EUV radiation. For example, the material 28 may comprise at least one of molybdenum Mo, ruthenium Ru, zirconium Zr, boron B, cerium Ce, silicon Si, samarium Sm, praseodymium Pr, europium Eu, scandium Sc, promethium Pm, yttrium Y and rubidium Rb. The material 28 may comprise one or more materials that are suitable for use in the presence of hydrogen plasma that may be generated by the EUV radiation. For example, the material 28 provided by the particle securement device 26 may comprise at least one of carbon, oxygen, nitrogen and hydrogen. Even if said materials are partially etched by hydrogen plasma, they have a reduced risk of leaving any contamination (e.g. molecular contamination) on the pellicle membrane 20 and/or reticle MA. The material 28 provided by the particle securement device 26 may comprise at least one of a metal carbonyl (e.g. $\text{Mo}(\text{CO})_6$ or $\text{Ru}_3(\text{CO})_{12}$) and a metal cyclopentadienyl (e.g. $\text{Ru}(\text{C}_5\text{H}_5)_2$). The material 28 provided by the particle securement device 26 may comprise at least one of camphor, menthol, naphthalene and biphenyl.

[00082] The particle securement device 26 may be configured to provide an electron beam or a radiation beam 30 to the pellicle membrane 20 for securing the material 28 and the particle 24 to the pellicle membrane 20. The electron beam or the radiation beam 30 may be configured to induce an interaction between the material 28 and the pellicle membrane 20 and/or the particle 24 and thereby secure the particle 24 to the pellicle membrane 20.

[00083] For example, the pellicle securement device 26 may use the electron beam 30 in combination with the material 28 to perform electron beam-induced deposition to secure the particle 24 to the pellicle membrane 20. Electron beam-induced deposition is discussed in greater detail below in relation to Figure 3. The electron beam 30 may have an energy of greater than about 200 eV. The electron beam 30 may have an energy of less than about 100 keV. The electron beam 30 may have an energy in the range of about 1 keV to about 50 keV. The electron beam 30 may have an energy in the range of about 10 keV to about 30 keV.

[00084] As another example, the pellicle securement device 26 may use the radiation beam 30 in combination with the material 28 to perform radiation beam-induced deposition to secure the particle 24 to the pellicle membrane 20. The radiation beam 30 may have a wavelength of greater than about 100 nm. The radiation beam 30 may have a wavelength of less than about 200 nm.

[00085] The particle securement device 26 may be configured to direct the electron beam or the radiation beam 30 to form a beam spot 27 on the pellicle membrane 20. The beam spot 27 may, for

example, have a diameter that is greater than about 0.1 μm . The beam spot 27 may, for example, have a diameter that is less than about 5 μm on the pellicle membrane 20.

[00086] The particle securement device 26 may be configured to direct the electron beam or the radiation beam 30 to form a beam spot 27 on the particle 24 on the pellicle membrane 20. An outer boundary 31a, 31b of the beam spot 27 may be less than about 5 μm from the particle 24 in a plane of the pellicle membrane 20. The outer boundary 31a, 31b of the beam spot 27 may be less than about 1 μm from the particle 24 in a plane of the pellicle membrane 20.

[00087] The system 22 may further comprise a particle locator 32 configured to determine the location of the particle 24 on the pellicle membrane 20. In the example embodiment shown in Figure 2, part of the pellicle securement device 26 acts as the particle locator 32. The particle locator 32 may be configured to use the electron beam or the radiation beam 30 to determine the location of the particle 24 on the pellicle membrane. That is, the electron beam or radiation beam 30 that is used to secure the particle 24 to the pellicle membrane 20 may also be used to locate the particle 24 on the pellicle membrane 20.

[00088] The particle locator 32 may be configured to generate a signal indicative of the location of the particle 24. The particle locator 32 may provide the signal to the particle securement device 26. The particle securement device 26 may be configured to use the signal to provide the material 28 to the location of the particle 24 on the pellicle membrane 20. The particle securement device 26 may be configured to use the signal to provide the electron beam or the radiation beam 30 to the location of the particle 24 on the pellicle membrane 20. For example, the particle locator 32 may comprise a scanning electron microscope that uses the electron beam 30 to determine the location of the particle 24 on the pellicle membrane 20. The scanning electron microscope may be used to perform a fine scan to determine the location of the particle 24 on the pellicle membrane 20 to a desired accuracy. The accuracy of the scanning electron microscope may be selected in at least partial dependence on the size of the particle and/or the size of the intended deposition of material on the pellicle membrane. The accuracy of the scanning electron microscope may be selected in at least partial dependence on the greater value chosen from the size of the particle and the size of the intended deposition on the pellicle membrane. For example, the scanning electron microscope may have an accuracy of greater than about 10 μm , e.g. at least 1 μm .

[00089] The particle locator 32 may be configured to detect secondary electrons and/or back-scattered electrons (not shown) that are produced by the electron beam or the radiation beam 30 interacting with the pellicle membrane 20 and/or the particle 24.

[00090] The particle locator 32 may comprise a separate device for locating the particle on the pellicle membrane 20. The particle locator 32 may, for example, comprise an optical measurement system a bright field imaging device, a dark field imaging device, an atomic force microscope and capacitive particle detection means. A system for securing the particle to the pellicle membrane

comprising a particle locator with an optical measurement system is discussed below in relation to Figure 4.

[00091] It has been found that particles having a diameter of between about 0.1 μm and about 5 μm have been found to travel from the pellicle membrane to the reticle during a lithographic exposure. These particles tend to be metallic particles (e.g. ruthenium particles) and/or ceramic particles (e.g. Al_2O_3 and/or SiO_2). The particle locator 32 may be configured to locate particles 24 having a diameter of between about 0.1 μm and about 5 μm . The particle locator 32 may be configured to locate metallic particles and/or ceramic particles. The particle locator 32 may be configured to locate any one of a ruthenium particle, an Al_2O_3 particle and an SiO_2 particle.

[00092] The system 22 may further comprise a first compartment 34 for holding the material 28 in a non-gaseous state 35 and a second compartment 36 for holding the material 28 in a gaseous state 37. The first compartment 34 may be situated within a base 29 of the system 22. The base 29 may be configured to electrically ground the pellicle frame 23. The pellicle frame 23 may be mounted to the base 29 via studs 25 (e.g. the same studs 25 used to mount the frame 23 to the reticle MA). The non-gaseous material 35 may be a solid or a liquid. Liquid material held in the first compartment 34 may, for example, have a concentration of between about 1 gcm^{-3} and about 10 gcm^{-3} .

[00093] Using a material 35 that is solid at room may be preferred due to improved ease of handling and deposition. The first compartment 34 may comprise a semi-permeable barrier 40 for preventing the non-gaseous material 35 from reaching the pellicle membrane 20. That is, the material may leave the first compartment 34 when the material is in a gaseous state 37. However, the semi-permeable barrier 40 acts to prevent non-gaseous matter 35 from entering the second chamber 36 (e.g. via spitting and/or boiling), thereby reducing the risk of damaging the pellicle membrane 20.

The pellicle membrane 20 may form at least part of the second compartment 36. The second compartment 36 may prevent the material 28 (whether gaseous or non-gaseous) from exiting the second compartment 36 and interfering with the electron beam or the radiation beam 30. The second compartment 36 may not be completely sealed. For example, one or more gaps or channels (not shown) may exist in or around the studs 25 of the frame 23 to allow pumping and/or ventilation of the second compartment 36. When the second compartment 36 is not completely sealed the escape of some material to a third compartment 39 may occur. However, the one or more gaps may be sufficiently small that any material that leaks from the second compartment 36 to the third compartment 39 is removed from the third compartment 39 by pumps that create and maintain a vacuum environment in the third compartment 39. The third compartment 39 is the compartment through which the electron beam or the radiation beam is transmitted to the pellicle membrane 20. The second compartment 36 may be held at a pressure of greater than about 0.001 Pa. The second compartment 36 may be held at a pressure of less than about 1 Pa.

[00094] The particle securement device 26 may be configured to direct the electron beam or the radiation beam 30 such that the electron beam or the radiation beam 30 passes through the pellicle membrane 20 before being incident on the particle 24. This advantageously allows a relatively high partial pressure (e.g. between about 100 Pa and about 10^{-3} Pa) to exist in the first compartment 34 which enables the non-gaseous material 35 to become gaseous 37 and travel into the second compartment 36 for deposition on the particle 24. This also advantageously allows a vacuum environment (e.g. a pressure of less than about 10^{-5} Pa) to be maintained in the third compartment 39 such that the electron beam or radiation beam 30 can operate without being interrupted by matter. The pellicle membrane 20 may be capable of withstanding pressures of up to about 100 Pa. Thus, the pressure difference between the third compartment 39 and the second compartment 36 is not great enough to damage the pellicle membrane 20. The particle securement device 26 may be configured to maintain a pressure difference of less than about 1 Pa between different sides of the pellicle membrane 20.

[00095] The second compartment 36 may be connected to the third compartment 39 via a channel. The channel may be configured transmit gas and thereby enable pumping and/or venting of the second compartment 36.

[00096] The third compartment 39 may comprise a gaseous environment having a pressure of more than about 10^{-5} Pa and less than about 0.1 Pa. The third compartment may comprise at least one of H_2 , H_2O , and O_2 in gaseous form.

[00097] The particle securement device 26 may comprise an electrical grounding (not shown) such as, for example, an electrically conducting wire connected to the pellicle membrane 20.

[00098] The system 22 may further comprise a housing 42 configured to house the pellicle membrane 20 in a clean environment 44. The clean environment 44 in the housing 42 may, for example, have an ISO class of 2 or better. The clean environment 44 may comprise a vacuum. Alternatively, the clean environment 44 may comprise a clean gas such as argon, nitrogen, clean air, extreme clean air, etc.

[00099] The system 22 may further comprise a pellicle membrane transfer device 46 configured to mount the pellicle membrane 20 to a reticle MA held in the clean environment 44 after the particle securement device 26 has secured the particle 24 to the pellicle membrane 20. The pellicle membrane transfer device 46 may be configured to move the pellicle assembly (i.e. the pellicle membrane 20 and the frame 23) from the base 29 and mount the pellicle assembly on the reticle MA.

[00100] Figure 3 schematically depicts a magnified view of a pellicle membrane 20 comprising a particle 24 that has been secured to the pellicle membrane 20 according to an embodiment of the invention. Figure 3 shows the material 37, 50, 52 provided by the particle securement device (not shown) to the pellicle membrane 20 in three different forms which are differentiated using different hatching. Gaseous material 37 is represented by cross-hatching, adsorbed material 50 is represented by

horizontal hatching and deposited material 52 is represented by vertical hatching. The three different forms of material 37, 50, 52 correspond to different stages in the particle securement process. The gaseous material 37 is provided by the first compartment (not shown) to the second compartment (not shown) through the semi-permeable membrane (not shown). The gaseous material 37 may be incident upon the pellicle membrane 20 and the particle 24 and become adsorbed on the pellicle membrane 20 and/or the particle 24. An electron beam or a radiation beam 30 may be provided to the location of the particle 24 on the pellicle membrane 20. The electron beam or radiation beam 30 may act to induce an interaction between the adsorbed material 50 and the pellicle membrane 20 and/or the particle 24 and thereby secure the particle 24 to the pellicle membrane 20. The electron beam or radiation beam 30 may act to induce dissociation of adsorbed material 37 on the particle 24 and/or the pellicle membrane 20. The dissociated material (i.e. the deposited material 52) may introduce and/or increase attractive forces acting between the particle 24 and the pellicle membrane 20 and thereby secure the particle 24 to the pellicle membrane 20. The attractive forces acting between the deposited material 52 and the particle 24 and/or the pellicle membrane 20 may, for example, include covalent bonds, metal bonds, polar bonds, Hydrogen-bonds, , Van der Waals forces, etc. A particle 24 secured by the deposited material 52 (e.g. buried by between about 10 nm and about 100 nm of deposited material) may be secured to the pellicle membrane 20 with a force that is between about 10 and 100 times stronger than if the particle 24 was not secured to the pellicle membrane 20. This force reduces the risk of the particle 24 detaching from the pellicle membrane 20 and travelling towards the reticle (not shown) during a lithographic exposure.

[000101] At least part of the electron beam 30 may be partially scattered and/or may be partially stopped by the pellicle membrane 20. At least part of the electron beam 30 may transmit through the pellicle membrane 20 and be incident on the particle 24. At least part 56 of the electron beam 30 may transmit through the particle 24.

[000102] The electron beam 30 may have an energy in the range of about 10 keV to about 30 keV. The pellicle membrane 20 may absorb less than about 10% of the energy of the electron beam 30. The energy of the electron beam 30 absorbed by the pellicle membrane 20 may generate an avalanche of scattered electrons within the pellicle membrane 20 that are capable of inducing dissociation of adsorbed material 50, thereby forming deposited material 52 that acts to secure the particle 24 to the pellicle membrane 20.

[000103] A deposition rate of the material 52 may be between about $0.01 \mu\text{m}^3$ per nA*minute and about $0.1 \mu\text{m}^3$ per nA*minute. For example, a deposit of material 52 having an area in the plane of the pellicle membrane 20 of about $1 \mu\text{m}^2$ and a thickness of between about 10 nm and about 100 nm may be formed on the pellicle membrane 20 in less than a minute using an electron beam 30 having a current of about 1 nA. The deposition rate may be at least partially limited by an electron flux of the electron

beam 30. This means that lower pressures may be used in the second compartment (not shown) because the deposition rate may not be pressure-limited.

[000104] The power of the electron beam 30 that is dissipated within the pellicle membrane 20 may be about 1 W cm^{-2} . This power may be within a radiative cooling limit of the pellicle membrane 20, thus the pellicle membrane 20 may not be damaged by the electron beam 30. An electron beam 30 having a lower current may be preferable for increasing adsorption of the material 50 within the electron beam 30 that is incident on the pellicle membrane 20.

[000105] It will be appreciated that Figure 3 is merely a schematic representation of an embodiment of the invention, and that the relative sizes of features thereof (e.g. the size of the particle 24, the material 37, 50, 52 and the pellicle membrane 20) have been adjusted for the purposes of illustrating the invention.

[000106] Figure 4 schematically depicts a system 60 for securing a particle 24 to a pellicle membrane 20 that is mounted to a reticle MA according to an embodiment of the invention. The pellicle membrane 20 is mounted to a frame 23 comprising studs 25. The pellicle membrane 20 and the frame 23 may be referred to as a pellicle assembly. The pellicle assembly is configured to be removably mounted on the reticle MA.

[000107] The system 60 may further comprise a housing 42 configured to house the pellicle membrane 20 in a clean environment 44. The clean environment 44 may comprise a vacuum. Alternatively, the clean environment 44 may comprise a clean gas such as argon, nitrogen, clean air, extreme clean air, etc.

[000108] To reduce or prevent the deposition of material 28 on the reticle MA an energy of the electron beam or the radiation beam (not shown) is reduced compared to the embodiments of the invention shown in Figure 2 and Figure 3. The electron beam may, for example, have an energy of greater than about 0.5 keV. The electron beam 30 may, for example, have an energy of less than about 5 keV. The reduced energy of the electron beam may increase the number of electrons that are stopped by the particle 24 and/or the pellicle membrane 20, thereby reducing the number of electrons reaching the reticle MA.

[000109] The electron beam or radiation beam may be provided with a desired numerical aperture to reduce the electron flux or radiation flux reaching the reticle MA. For example, in the case of an electron beam, the electron flux at the reticle MA may be between about 100 and about 1000 times lower than the electron flux incident on the pellicle membrane 20.

[000110] The deposition of material 28 may be proportional to the electron flux of the electron beam. Thus, deposition of the material 28 at the reticle MA may be reduced or prevented entirely. For example, in the time it takes to deposit a layer of material proximate the particle 24 having an area of about $1 \mu\text{m}^2$ and a thickness of about $10 \text{ nm} \times (1 \mu\text{m})$, a layer of material having an area of about $10 \mu\text{m}^2$

and a thickness of about 0.1 nm may be deposited on the reticle MA. A deposition of this size may not affect a quality of the image of the reticle pattern formed on a substrate during a lithographic exposure.

[000111] The system 60 may comprise a support 70 configured to hold the reticle MA and a material delivery system 72 configured to provide the material 28 in a gap 74 situated between the reticle MA and the pellicle membrane 20. The system 60 may further comprise a first compartment 34 for holding the material 28 in a non-gaseous state 35 and a second compartment 36 for holding the material 28 in a gaseous state 37. The first compartment 34 may comprise a semi-permeable barrier 40 for preventing the non-gaseous material 35 from reaching the pellicle membrane 20.

[000112] In the example of Figure 4, the system 60 comprises an optical measurement system 80. The optical measurement system 80 is configured to determine the location of the particle 24 on the pellicle membrane 20. The optical measurement system 80 may comprise a radiation source 82 for scattering radiation 84 from the particle 24 and a radiation detector 86 for detecting radiation scattered 88 by the particle 24. The location of the particle 24 determined by the optical measurement system 80 may be referenced to, for example, an edge or corner of the pellicle frame 90 and/or an edge or corner of the pellicle membrane 92 and/or an a surface of the support 94. The electron beam or the radiation beam of the pellicle securement device 26 for may use the same position referencing system.

[000113] The optical measurement system 80 may be configured to perform a coarse search for the particle 24. Once a coarse location of the particle 24 has been determined by the optical measurement system 80 the electron beam or the radiation beam (not shown) of the particle securement device 26 may be used to perform a fine search for the particle 24 at the coarse location of the particle 24.

[000114] In any of the embodiments, the supply of material 28 by the pellicle securement device 26 may be adjustable and/or time-dependent.

[000115] 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. Possible other applications include 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.

[000116] Although specific reference may be made in this text to embodiments of the invention in the context of a lithographic apparatus, embodiments of the invention may be used in other apparatus. Embodiments of the invention may form part of a mask inspection apparatus, a metrology apparatus, or any apparatus that measures or processes an object such as a wafer (or other substrate) or mask (or other patterning device). These apparatus may be generally referred to as lithographic tools. Such a lithographic tool may use vacuum conditions or ambient (non-vacuum) conditions.

[000117] Where the context allows, embodiments of the invention may be implemented in hardware, firmware, software, or any combination thereof. Embodiments of the invention may also be implemented as instructions stored on a machine-readable medium, which may be read and executed

by one or more processors. A machine-readable medium may include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computing device). For example, a machine-readable medium may include read only memory (ROM); random access memory (RAM); magnetic storage media; optical storage media; flash memory devices; electrical, optical, acoustical or other forms of propagated signals (e.g. carrier waves, infrared signals, digital signals, etc.), and others. Further, firmware, software, routines, instructions may be described herein as performing certain actions. However, it should be appreciated that such descriptions are merely for convenience and that such actions in fact result from computing devices, processors, controllers, or other devices executing the firmware, software, routines, instructions, etc. and in doing that may cause actuators or other devices to interact with the physical world.

[000118] Embodiments of the several aspects of the invention may be worded in accordance with one or more of the next following clauses:

1] A system for securing a particle to a pellicle membrane for subsequent use in a lithographic apparatus, the system comprising a particle securement device configured to secure the particle to the pellicle membrane.

2] The system of clause 1, wherein the particle securement device is configured to irremovably secure the particle to the pellicle membrane.

3] The system of clause 1 or clause 2, wherein the particle securement device is configured to secure the particle to a reticle-facing surface of the pellicle membrane.

4] The system of any of clauses 1 to 3, wherein the particle securement device is configured to provide a material to the pellicle membrane for securing the particle to the pellicle membrane.

5] The system of clause 4, wherein the material provided by the particle securement device to the pellicle membrane has a size in a plane of the pellicle membrane of less than about 10 μm .

6] The system of clause 4 or clause 5, wherein the material provided by the particle securement device to the pellicle membrane has a thickness of less than about 100 nm on the pellicle membrane.

7] The system of any of clauses 4 to 6, wherein the material provided by the particle securement device comprises at least one of molybdenum Mo, ruthenium Ru, zirconium Zr, boron B, cerium Ce, silicon Si, samarium Sm, praseodymium Pr, europium Eu, scandium Sc, promethium Pm, yttrium Y and rubidium Rb.

8] The system of any of clauses 4 to 7, wherein the material provided by the particle securement device comprises at least one of carbon, oxygen, nitrogen and hydrogen.

9] The system of any of clauses 4 to 8, wherein the material provided by the particle securement device comprises at least one of a metal carbonyl and a metal cyclopentadienyl.

10] The system of any of clauses 4 to 9, wherein the material provided by the particle securement device comprises at least one of camphor, menthol, naphthalene and biphenyl.

11] The system of any preceding clause, wherein the particle securement device is configured to provide an electron beam or a radiation beam to the pellicle membrane for securing the particle to the pellicle membrane.

12] The system of clause 11, wherein the electron beam or the radiation beam is configured to induce an interaction between the material and the pellicle membrane and/or the particle and thereby secure the particle to the pellicle membrane.

13] The system of clause 11 or clause 12, wherein the particle securement device is configured to direct the electron beam or the radiation beam such that the electron beam or the radiation beam passes through the pellicle membrane before being incident on the particle.

14] The system of any of clauses 11 to 13, wherein the particle securement device is configured to direct the electron beam or the radiation beam to form a beam spot having a diameter of between about 0.1 μm and about 5 μm on the pellicle membrane.

15] The system of any of clauses 11 to 14, wherein the particle securement device is configured to direct the electron beam or the radiation beam to form a beam spot on the particle on the pellicle membrane, and wherein an outer boundary of the beam spot is less than about 5 μm from the particle, and optionally wherein the outer boundary of the beam spot is less than about 1 μm from the particle.

16] The system of any of clauses 11 to 14, wherein the particle securement device is configured to direct the electron beam to form a beam spot on an area of the pellicle membrane that includes the particle, and wherein the electron beam has an energy of between about 100 V and about 100 kV.

17] The system of any of clauses 11 to 15, wherein the pellicle membrane is mounted to a reticle during use of the particle securement device and wherein the electron beam has an energy of between about 0.5 keV and about 5 keV.

18] The system of clause 17, further comprising a support configured to hold the reticle and a material delivery system configured to provide the material in a gap situated between the reticle and the pellicle.

19] The system of any preceding clause, further comprising a particle locator configured to determine the location of the particle on the pellicle membrane.

20] The system of clause 19, wherein the particle locator is configured to generate a signal indicative of the location of the particle and provide the signal to the particle securement device, and wherein the particle securement device is configured to use the signal to provide the material and/or the electron beam or the radiation beam to the location of the particle on the pellicle membrane.

21] The system of clause 19 or clause 20, wherein the particle locator is configured to use the electron beam or the radiation beam to determine the location of the particle on the pellicle membrane.

22] The system of clause 21, wherein the particle locator is configured to detect secondary electrons and/or back-scattered electrons produced by the electron beam or the radiation beam interacting with the pellicle membrane and/or the particle.

23] The system of any of clauses 19 to 22, wherein the particle locator comprises an optical measurement system configured to determine the location of the particle on the pellicle membrane, the optical measurement system comprising a radiation source for scattering radiation from the particle and a radiation detector for detecting radiation scattered by the particle.

5 24] The system of any of clauses 19 to 23, wherein the particle locator comprises at least one of a bright field imaging device, a dark field imaging device, an atomic force microscope and capacitive particle detection means.

25] The system of any of clauses 19 to 24, wherein the particle locator is configured to locate particles having a diameter of between about 0.1 μm and about 5 μm .

10 26] The system of any of clauses 4 to 25, further comprising a first compartment for holding the material in a non-gaseous state and a second compartment for holding the material in a gaseous state and a third compartment for transmitting the electron beam or the radiation beam to the pellicle membrane.

15 27] The system of clause 26, wherein the first compartment comprises a semi-permeable barrier for preventing the non-gaseous material from reaching the pellicle membrane.

28] The system of clause 26 or clause 27, wherein the pellicle membrane forms at least part of the second compartment.

20 29] The system of any of clauses 26 to 28, wherein the second compartment is connected to the third compartment via a channel, and wherein the channel is configured to allow pumping and/or venting of the second compartment

30] The system of any of clauses 26 to 29, wherein the second compartment is held at a pressure of between about 0.001 Pa and about 1 Pa.

31] The system of any of clauses 26 to 30, wherein the third compartment comprises a vacuum environment having a pressure of less than about 10^{-5} Pa.

25 32] The system of any of clauses 26 to 30, wherein the third compartment comprises a gaseous environment having a pressure of more than about 10^{-5} Pa and less than about 0.1 Pa.

33] The system of clause 32, wherein the third compartment comprises at least one of H_2 , H_2O , and O_2 .

30 34] The system of any preceding clause, wherein the particle securement device is configured to maintain a pressure difference of less than about 1 Pa between different sides of the pellicle membrane.

35] The system of any preceding clause, wherein the particle securement device comprises an electrical grounding connected to the pellicle membrane.

36] The system of any preceding clause, further comprising a housing configured to house the pellicle membrane in a clean environment.

37] The system of clause 36, further comprising a pellicle membrane transfer device configured to mount the pellicle membrane to a reticle held in the clean environment after the particle securement device has secured the particle to the pellicle membrane.

38] A method comprising securing a particle to a pellicle membrane.

5 39] The method of clause 38, further comprising irremovably securing the particle to the pellicle membrane.

40] The method of clause 38 or clause 39, further comprising securing the particle to a reticle-facing surface of the pellicle membrane.

10 41] The method of any of clauses 38 to 40, further comprising providing a material to the pellicle membrane to secure the particle to the pellicle membrane.

42] The method of clause 41, further comprising providing the material to the pellicle membrane such that the material has a size in a plane of the pellicle membrane of less than about 10 μm .

43] The method of clause 41 or clause 42, further comprising providing the material to the pellicle membrane such that the material has a thickness of less than about 100 nm on the pellicle membrane.

15 44] The method of any of clauses 41 to 43, further comprising providing an electron beam or a radiation beam to the pellicle membrane to secure the material and the particle to the pellicle membrane.

45] The method of clause 44, further comprising directing the electron beam or the radiation beam to the pellicle membrane to form a beam spot having a diameter of between about 0.1 μm and about 5 μm on the pellicle membrane.

20 46] The method of clause 44 or clause 45, further comprising using the electron beam or the radiation beam to induce an interaction between the material and/or the pellicle membrane or the particle and thereby secure the particle to the pellicle membrane.

25 47] The method of any of clauses 44 to 46, further comprising directing the electron beam or the radiation beam such that the electron beam or the radiation beam passes through the pellicle membrane before being incident on the particle.

48] The method of any of clauses 44 to 47, further comprising securing the particle to the pellicle membrane whilst the pellicle membrane is mounted to a reticle, and wherein the electron beam is provided with an energy of between about 0.5 keV and about 5 keV.

30 49] The method of clause 48, further comprising providing the material in a gap situated between the reticle and the pellicle.

50] The method of any of clauses 38 to 49, further comprising determining the location of the particle on the pellicle membrane.

51] The method of clause 50, further comprising locating particles having a diameter of between about 0.1 μm and about 5 μm on the pellicle membrane.

52] The method of any of clauses 44 to 51, further comprising providing the electron beam or the radiation beam to the pellicle membrane through a compartment comprising a vacuum environment having a pressure of less than about 10^{-5} Pa.

53] The method of any of clauses 44 to 52, further comprising providing the electron beam or the radiation beam to the pellicle membrane through a compartment comprising a gaseous environment having a pressure of more than about 10^{-5} Pa and less than about 0.1 Pa.

54] The method of clause 53, further comprising providing the compartment with at least one of H_2 , H_2O , and O_2 .

55] The method of any of clauses 38 to 54, further comprising keeping the pellicle membrane in a clean environment after the particle has been secured to the pellicle membrane.

56] A method of projecting a patterned beam of radiation onto a substrate, the patterned beam of radiation passing through a pellicle membrane before being incident on the substrate, wherein a particle has been secured to the pellicle membrane using the method of any of clauses 38 to 55.

57] A pellicle membrane comprising a particle that has been secured to the pellicle membrane using the method of any of clauses 38 to 55.

58] Use of the system according to any of clauses 1-37 for securing a particle to a pellicle membrane for subsequent use in a lithographic apparatus.

[000119] 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. A system for securing a particle to a pellicle membrane for subsequent use in a lithographic apparatus, the system comprising a particle securement device configured to secure the particle to the pellicle membrane.

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2. The system of claim 1, wherein the particle securement device is configured to irremovably secure the particle to the pellicle membrane.

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3. The system of claim 1 or claim 2, wherein the particle securement device is configured to secure the particle to a reticle-facing surface of the pellicle membrane.

4. The system of any of claims 1 to 3, wherein the particle securement device is configured to provide a material to the pellicle membrane for securing the particle to the pellicle membrane.

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5. The system of claim 4, wherein the material provided by the particle securement device to the pellicle membrane has a size in a plane of the pellicle membrane of less than about 10 μm .

6. The system of claim 4 or claim 5, wherein the material provided by the particle securement device to the pellicle membrane has a thickness of less than about 100 nm on the pellicle membrane.

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7. The system of any of claims 4 to 6, wherein the material provided by the particle securement device comprises at least one of molybdenum Mo, ruthenium Ru, zirconium Zr, boron B, cerium Ce, silicon Si, samarium Sm, praseodymium Pr, europium Eu, scandium Sc, promethium Pm, yttrium Y and rubidium Rb.

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8. The system of any of claims 4 to 7, wherein the material provided by the particle securement device comprises at least one of carbon, oxygen, nitrogen and hydrogen.

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9. The system of any of claims 4 to 8, wherein the material provided by the particle securement device comprises at least one of a metal carbonyl and a metal cyclopentadienyl.

10. The system of any of claims 4 to 9, wherein the material provided by the particle securement device comprises at least one of camphor, menthol, naphthalene and biphenyl.

11. The system of any preceding claim, wherein the particle securement device is configured to provide an electron beam or a radiation beam to the pellicle membrane for securing the particle to the pellicle membrane.

5 12. The system of claim 11, wherein the electron beam or the radiation beam is configured to induce an interaction between the material and the pellicle membrane and/or the particle and thereby secure the particle to the pellicle membrane.

10 13. The system of claim 11 or claim 12, wherein the particle securement device is configured to direct the electron beam or the radiation beam such that the electron beam or the radiation beam passes through the pellicle membrane before being incident on the particle.

14. The system of any of claims 11 to 13, wherein the particle securement device is configured to direct the electron beam or the radiation beam to form a beam spot having a diameter of between about 0.1 μm and about 5 μm on the pellicle membrane.

15. The system of any of claims 11 to 14, wherein the particle securement device is configured to direct the electron beam or the radiation beam to form a beam spot on the particle on the pellicle membrane, and wherein an outer boundary of the beam spot is less than about 5 μm from the particle, and optionally wherein the outer boundary of the beam spot is less than about 1 μm from the particle.

16. The system of any of claims 11 to 14, wherein the particle securement device is configured to direct the electron beam to form a beam spot on an area of the pellicle membrane that includes the particle, and wherein the electron beam has an energy of between about 100 V and about 100 kV.

17. The system of any of claims 11 to 15, wherein the pellicle membrane is mounted to a reticle during use of the particle securement device and wherein the electron beam has an energy of between about 0.5 keV and about 5 keV.

18. The system of claim 17, further comprising a support configured to hold the reticle and a material delivery system configured to provide the material in a gap situated between the reticle and the pellicle.

19. The system of any preceding claim, further comprising a particle locator configured to determine the location of the particle on the pellicle membrane.

20. The system of claim 19, wherein the particle locator is configured to generate a signal indicative of the location of the particle and provide the signal to the particle securement device, and wherein the particle securement device is configured to use the signal to provide the material and/or the electron beam or the radiation beam to the location of the particle on the pellicle membrane.

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21. The system of claim 19 or claim 20, wherein the particle locator is configured to use the electron beam or the radiation beam to determine the location of the particle on the pellicle membrane.

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22. The system of claim 21, wherein the particle locator is configured to detect secondary electrons and/or back-scattered electrons produced by the electron beam or the radiation beam interacting with the pellicle membrane and/or the particle.

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23. The system of any of claims 19 to 22, wherein the particle locator comprises an optical measurement system configured to determine the location of the particle on the pellicle membrane, the optical measurement system comprising a radiation source for scattering radiation from the particle and a radiation detector for detecting radiation scattered by the particle.

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24. The system of any of claims 19 to 23, wherein the particle locator comprises at least one of a bright field imaging device, a dark field imaging device, an atomic force microscope and capacitive particle detection means.

25. The system of any of claims 19 to 24, wherein the particle locator is configured to locate particles having a diameter of between about 0.1 μm and about 5 μm .

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26. The system of any of claims 4 to 25, further comprising a first compartment for holding the material in a non-gaseous state and a second compartment for holding the material in a gaseous state and a third compartment for transmitting the electron beam or the radiation beam to the pellicle membrane.

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27. The system of claim 26, wherein the first compartment comprises a semi-permeable barrier for preventing the non-gaseous material from reaching the pellicle membrane.

28. The system of claim 26 or claim 27, wherein the pellicle membrane forms at least part of the second compartment.

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29. The system of any of claims 26 to 28, wherein the second compartment is connected to the third compartment via a channel, and wherein the channel is configured to allow pumping and/or venting of the second compartment

30. The system of any of claims 26 to 29, wherein the second compartment is held at a pressure of between about 0.001 Pa and about 1 Pa.

31. The system of any of claims 26 to 30, wherein the third compartment comprises a vacuum environment having a pressure of less than about 10^{-5} Pa.

32. The system of any of claims 26 to 30, wherein the third compartment comprises a gaseous environment having a pressure of more than about 10^{-5} Pa and less than about 0.1 Pa.

33. The system of claim 32, wherein the third compartment comprises at least one of H_2 , H_2O , and O_2 .

34. The system of any preceding claim, wherein the particle securement device is configured to maintain a pressure difference of less than about 1 Pa between different sides of the pellicle membrane.

35. The system of any preceding claim, wherein the particle securement device comprises an electrical grounding connected to the pellicle membrane.

36. The system of any preceding claim, further comprising a housing configured to house the pellicle membrane in a clean environment.

37. The system of claim 36, further comprising a pellicle membrane transfer device configured to mount the pellicle membrane to a reticle held in the clean environment after the particle securement device has secured the particle to the pellicle membrane.

38. A method comprising securing a particle to a pellicle membrane.

39. The method of claim 38, further comprising irremovably securing the particle to the pellicle membrane.

40. The method of claim 38 or claim 39, further comprising securing the particle to a reticle-facing surface of the pellicle membrane.

41. The method of any of claims 38 to 40, further comprising providing a material to the pellicle membrane to secure the particle to the pellicle membrane.

5 42. The method of claim 41, further comprising providing the material to the pellicle membrane such that the material has a size in a plane of the pellicle membrane of less than about 10 μm .

43. The method of claim 41 or claim 42, further comprising providing the material to the pellicle membrane such that the material has a thickness of less than about 100 nm on the pellicle membrane.

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44. The method of any of claims 41 to 43, further comprising providing an electron beam or a radiation beam to the pellicle membrane to secure the material and the particle to the pellicle membrane.

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45. The method of claim 44, further comprising directing the electron beam or the radiation beam to the pellicle membrane to form a beam spot having a diameter of between about 0.1 μm and about 5 μm on the pellicle membrane.

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46. The method of claim 44 or claim 45, further comprising using the electron beam or the radiation beam to induce an interaction between the material and/or the pellicle membrane or the particle and thereby secure the particle to the pellicle membrane.

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47. The method of any of claims 44 to 46, further comprising directing the electron beam or the radiation beam such that the electron beam or the radiation beam passes through the pellicle membrane before being incident on the particle.

48. The method of any of claims 44 to 47, further comprising securing the particle to the pellicle membrane whilst the pellicle membrane is mounted to a reticle, and wherein the electron beam is provided with an energy of between about 0.5 keV and about 5 keV.

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49. The method of claim 48, further comprising providing the material in a gap situated between the reticle and the pellicle.

50. The method of any of claims 38 to 49, further comprising determining the location of the particle on the pellicle membrane.

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51. The method of claim 50, further comprising locating particles having a diameter of between about 0.1 μm and about 5 μm on the pellicle membrane.

52. The method of any of claims 44 to 51, further comprising providing the electron beam or the radiation beam to the pellicle membrane through a compartment comprising a vacuum environment having a pressure of less than about 10^{-5} Pa.

53. The method of any of claims 44 to 52, further comprising providing the electron beam or the radiation beam to the pellicle membrane through a compartment comprising a gaseous environment having a pressure of more than about 10^{-5} Pa and less than about 0.1 Pa.

54. The method of claim 53, further comprising providing the compartment with at least one of H_2 , H_2O , and O_2 .

55. The method of any of claims 38 to 54, further comprising keeping the pellicle membrane in a clean environment after the particle has been secured to the pellicle membrane.

56. A method of projecting a patterned beam of radiation onto a substrate, the patterned beam of radiation passing through a pellicle membrane before being incident on the substrate, wherein a particle has been secured to the pellicle membrane using the method of any of claims 38 to 55.

57. A pellicle membrane comprising a particle that has been secured to the pellicle membrane using the method of any of claims 38 to 55.

58. Use of the system according to any of claims 1-37 for securing a particle to a pellicle membrane for subsequent use in a lithographic apparatus.

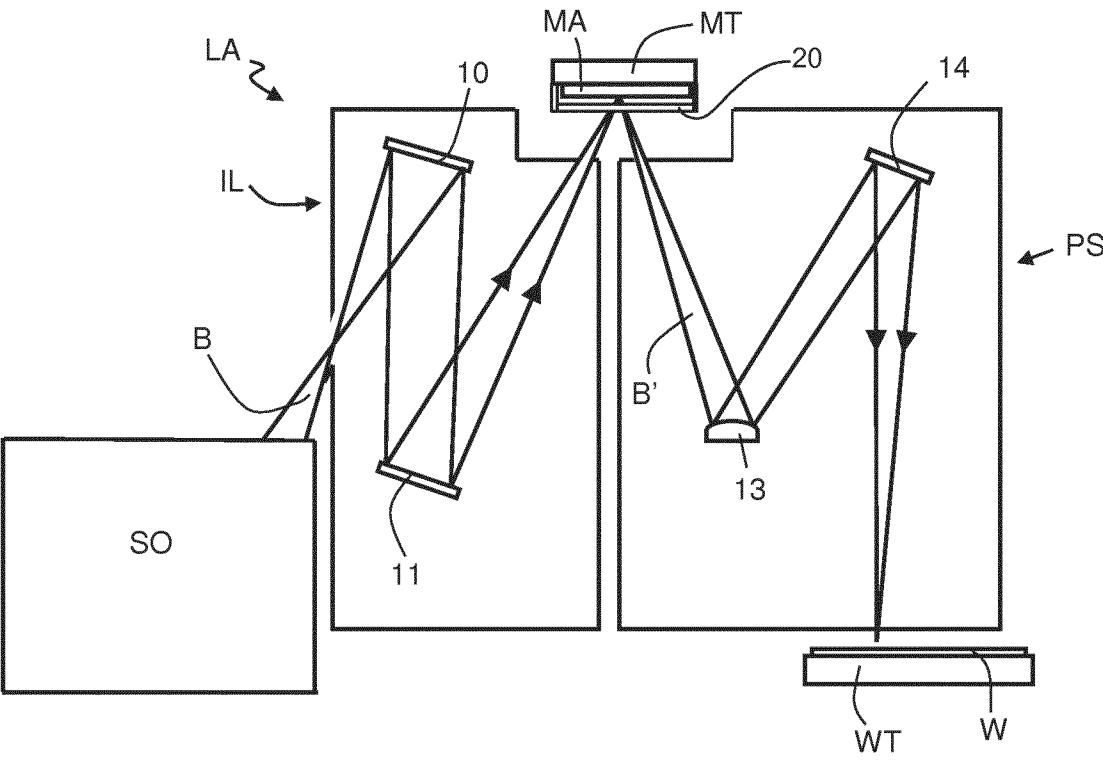


Fig. 1

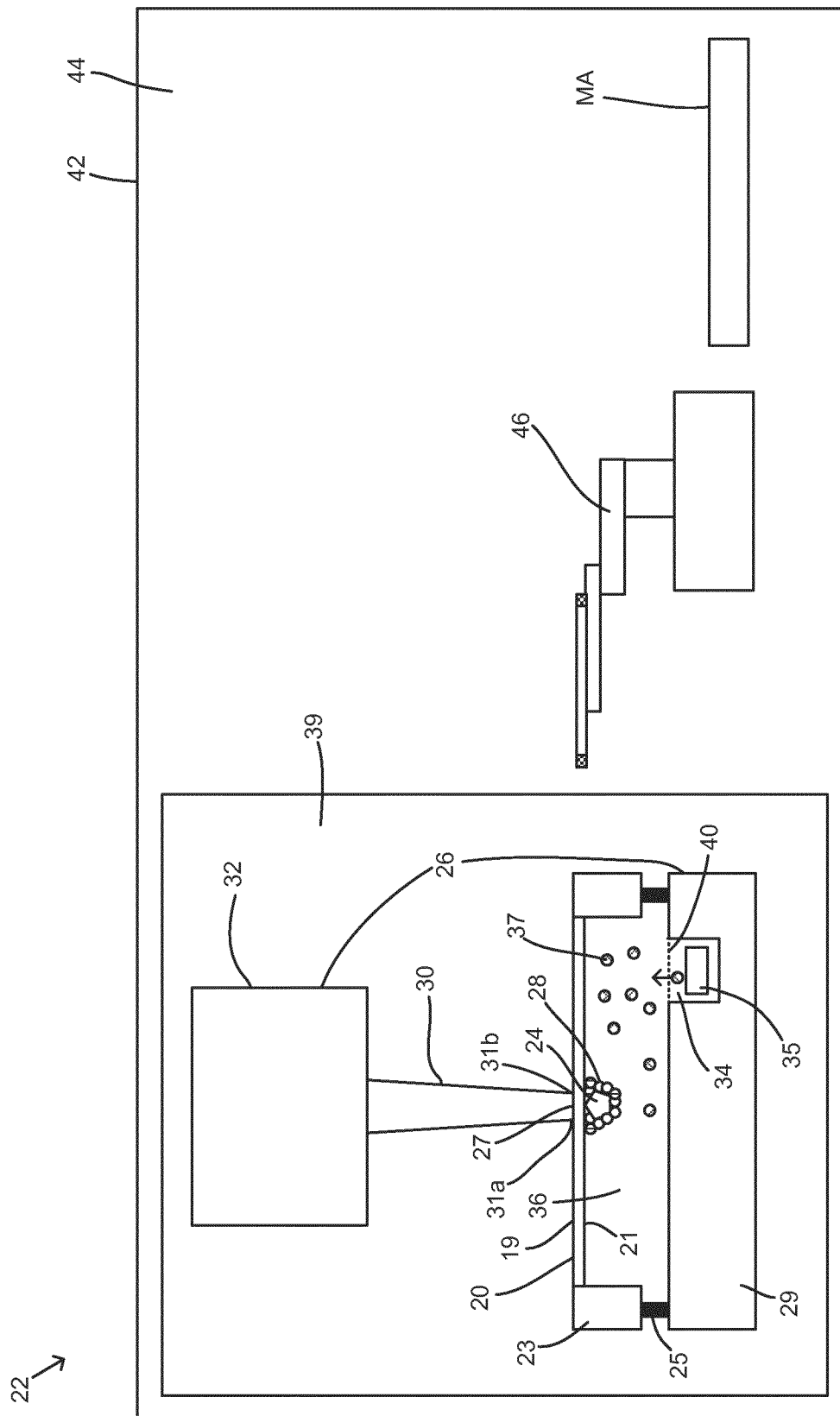


Fig. 2

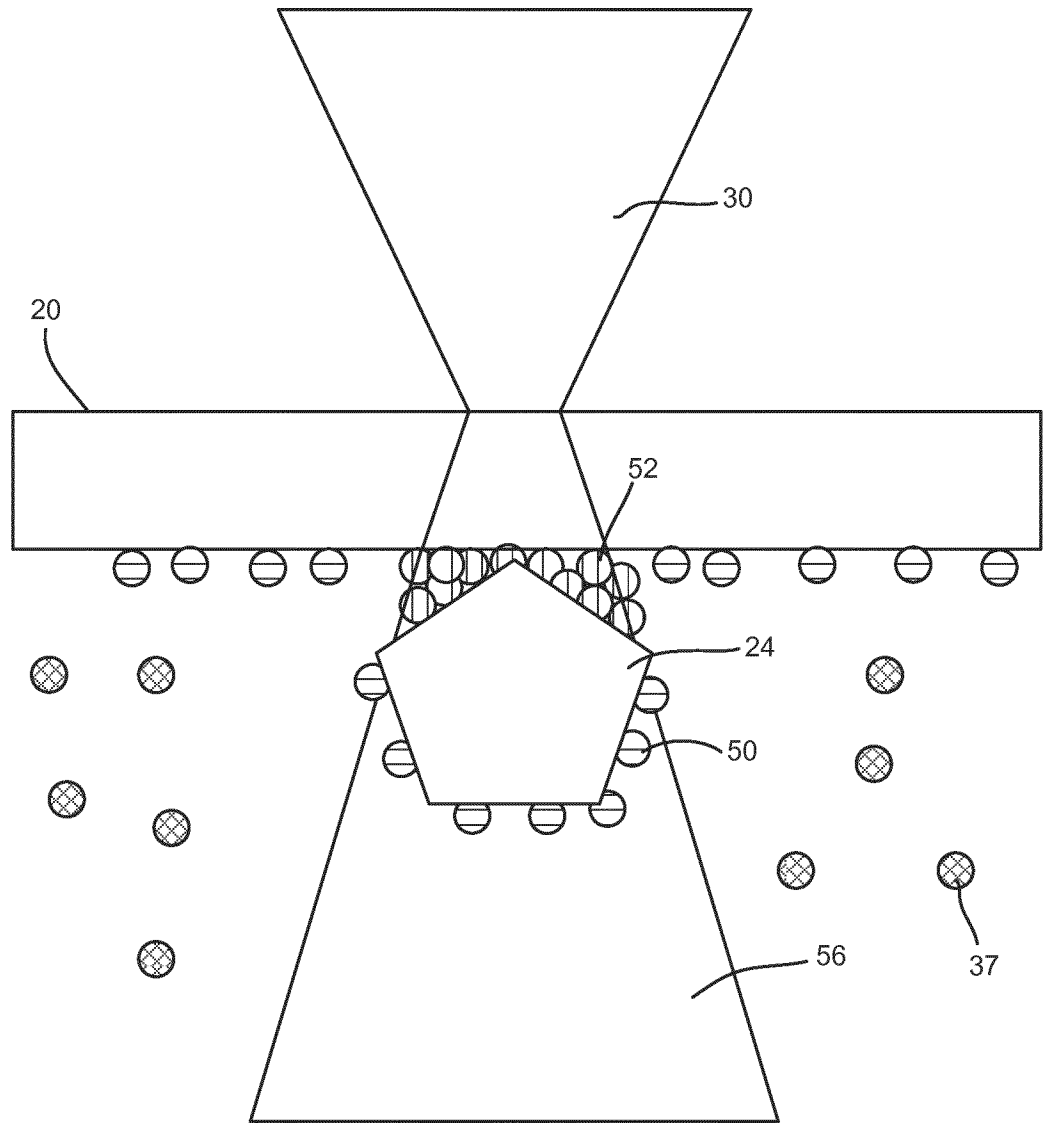


Fig. 3

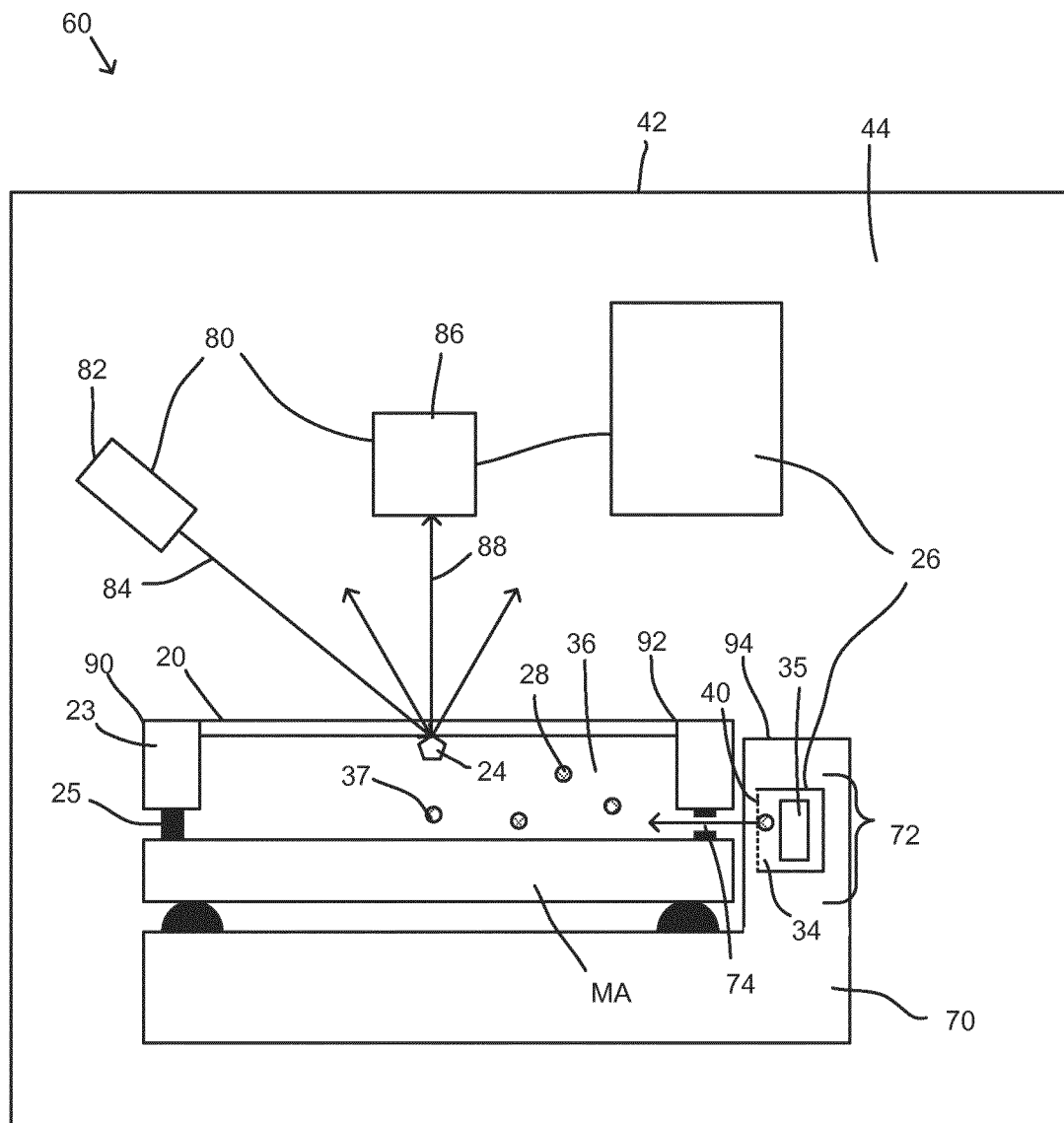


Fig. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/072112

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F1/62 G03F7/20
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

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

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 252 574 A2 (YEN YUNG TSAI [US]) 13 January 1988 (1988-01-13) the whole document	1-4,7,8, 36, 38-41, 55-58
X	US 5 332 604 A (YEN YUNG-TSAI [US]) 26 July 1994 (1994-07-26) column 1, line 10 - column 2, line 23; claims 1,5-7; figures 4,5 column 2, lines 39-61; figure 5 column 4, lines 41-66 column 5, lines 14-17	1-4,8, 38-41, 56-58
A	US 2015/293460 A1 (TAKEHISA KIWAMU [JP] ET AL) 15 October 2015 (2015-10-15) claims 1-12; figures 1-9 ----- -/-	19-25, 50,51

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

30 October 2019

Date of mailing of the international search report

12/11/2019

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INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2019/072112

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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International application No

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