



(51) International Patent Classification:

G02B 5/18 (2006.01)

G02B 27/09 (2006.01)

G02B 5/02 (2006.01)

(21) International Application Number:

PCT/EP2020/076765

(22) International Filing Date:

24 September 2020 (24.09.2020)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

19202644.1

11 October 2019 (11.10.2019) EP

(71) Applicant: ASML NETHERLANDS B.V. [NL/NL]; P.O. Box 324, 5500 AH Veldhoven (NL).

(72) Inventors: KLUGKIST, Joost, André; P.O. Box 324, 5500 AH Veldhoven (NL). NIKIPELOV, Andrey; P.O. Box 324, 5500 AH Veldhoven (NL). ENGELLEN, Wouter Joep; P.O. Box 324, 5500 AH Veldhoven (NL). LIAN, Jin; P.O. Box 324, 5500 AH Veldhoven (NL). VERMEULEN, Paul, Alexander; P.O. Box 324, 5500 AH Veldhoven (NL). YEGEN, Halil, Gökay; P.O. Box 324, 5500 AH Veldhoven (NL).

(74) Agent: ASML NETHERLANDS B.V.; P.O. Box 324, 5500 AH Veldhoven (NL).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,

CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

- with international search report (Art. 21(3))
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

(54) Title: TRANSMISSIVE DIFFUSER

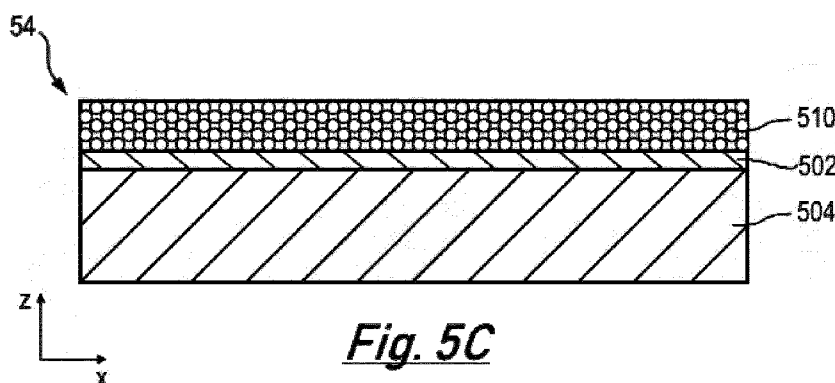


Fig. 5C

(57) Abstract: A diffuser is configured to receive and transmit radiation. The diffuser comprises a scattering layer (510) configured to scatter the received radiation, the scattering layer (510) comprising a first substance and having distributed therein a plurality of voids. The first substance may be a scattering substance, or alternatively, at least one of the voids may contain the scattering substance and the first substance has a lower refractive index than the scattering substance.



TRANSMISSIVE DIFFUSERCROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority of EP application 19202644.1 which was filed on 11 October 2019, and which is incorporated herein in its entirety by reference.

FIELD

[0002] The present invention relates to transmissive diffusers, i.e. diffusers configured to receive and transmit radiation, the transmitted radiation having an altered angular distribution. The diffusers may be suitable for use with EUV radiation and may form part of a measurement system within an EUV lithography 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 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. A lithographic apparatus, which uses extreme ultraviolet (EUV) radiation, having a wavelength within the range 4-20 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] It is known for lithographic apparatus to comprise measurement systems for determining one or more pupil function variations. Pupil function variations may comprise: relative phase variations within the pupil plane and/or relative intensity variations within the pupil plane. Such measurement systems typically comprise an object level patterning device (for example a diffraction grating or pinhole or the like); an illumination system; and an image level sensor apparatus. The illumination system is arranged to illuminate the patterning device with radiation. At least a portion of the radiation scattered by the patterning device is received by the projection system (whose properties are being measured) which is arranged to form an image of the patterning device on the image level sensor apparatus. It is desirable for such measurement systems that the entire entrance pupil of the projection system receives radiation from the patterning device. However, the illumination system is typically also used by a lithographic apparatus for forming a (diffraction limited) image of an object level reticle or mask on an image level substrate (e.g. a resist coated silicon wafer) wherein it may be desirable to only illuminate one or more discrete portions of the entrance pupil of the projection system.

[0006] It may be desirable to provide a mechanism whereby an angular distribution of an illumination beam that would otherwise illuminate one or more discrete portions of the entrance pupil of the projection system can be altered such that the entire entrance pupil of the projection system can receive radiation from the patterning device.

5

SUMMARY

[0007] There is described herein a diffuser configured to receive and transmit radiation. The diffuser comprises a scattering layer configured to scatter the received radiation. The scattering layer comprises a first substance and has a plurality of voids distributed therein. The first substance may be a scattering substance. Alternatively, at least one of the voids may contain a scattering substance and the first substance may be a substance with a lower refractive index than the scattering substance. The scattering material acts to provide an array of microlenses, causing scattering of the radiation received by the diffuser. Such a diffuser can be configured so as to be capable of changing an angular distribution of the received radiation in such a way that would that the entire entrance pupil of a projection system can receive radiation from a patterning device.

10

15

[0008] The voids may contain a vacuum (or an environment that is substantially or functionally a vacuum). Alternatively, the voids may contain a second substance and one of the first and second substances may be a scattering substance, with the other of the first and second substances having a lower refractive index than the scattering substance. Where the first substance is the scattering substance, the second substance may be an inert gas. The substance with the lower refractive index may have a refractive index close to 1 for the received radiation. Such substances may be considered to be optically neutral (or relatively optically neutral in comparison to the scattering material) to the received radiation. For example, if the received radiation is EUV radiation, the substance with the lower refractive index may have a refractive index close to 1 for EUV radiation. It will be appreciated, however, that the radiation may have any wavelength (i.e. may not be EUV radiation).

20

25

[0009] Where the first substance is the scattering substance, the scattering substance may comprise a foam having pores and the voids may be provided by the pores. One or more of the voids may contain a vacuum or an inert gas. One or more of the voids may contain one of silicon or silicon nitride. In this way the second substance will be optically neutral for EUV radiation. Further, the second substance will have a low attenuation for the received radiation. The substance within the voids will also have a contrasting index of refraction to the scattering substance. Further, in this way the scattering layer is particularly easy to manufacture as there is no need to perform an intermediate step in which a second substance is removed from the scattering substance.

30

[0010] Where the voids contain the scattering substance, the first substance may comprise a porous silicon-based structure, the voids being defined by pores of the first substance.

35

[0011] Where a porous substance is used in an example described herein, the pores of the porous substance may have an extent that is of the order of nanometres in at least one dimension.

[00012] The scattering substance may comprise a body of contacting particles. The voids may be provided between adjacent contacting particles. Such a diffuser may be fabricated with relative ease using various deposition methods, for example liquid phase deposition methods. By the term 'contacting particles' it will be understood that each particle in the body of particles is in physical contact with at least one other particle in the body of particles.

[00013] The particles may be fused. That is, each particle in the body of contacting particles may be fused together with at least one other particle in the body of contacting particles. For example, the particles may be fused using sintering.

[00014] The particles may comprise a binary mixture comprising a first material and a second material with a refractive index different to the first material. The refractive indices of the first and second materials may be contrasting. The first and second materials may have low attenuation for the received radiation. The first material may comprise silicon. The second material may comprise molybdenum or ruthenium. It will be appreciated that one or both of the first or second material may be a mixture of two or more materials. For example, the first material may be molybdenum silicide.

[00015] The particles may have an extent which is in the order of nanometers in at least one dimension. The particles may differ in size in at least one dimension. That is, the particles may be polydisperse. The particle size, particle size distribution and/or packing density of the particles may be selected based on one or more desired properties of the scattering layer, for example a high scattering angle and/or a suppression of zero-order scattering.

[00016] The scattering substance may comprise a substance having a ratio of a first parameter to a second parameter of or less than 1, wherein the first parameter is a maximum thickness of a layer of the substance that will allow 10 percent transmission of the received radiation and the second parameter is a minimum thickness of a layer of the substance that will result in a phase shift of π nm.

[00017] By way of example only, the scattering substance may be, for example, molybdenum, ruthenium, niobium, rhodium, yttrium, boron, molybdenum disilicide, zirconium, rhodium or technetium.

[00018] The voids may be distributed in a plurality of layers within the first substance, each layer lying generally in a plane perpendicular to the direction of propagation of the radiation during use.

[00019] The voids may be distributed in a single layer within the first substance, the layer lying generally in a plane perpendicular to the direction of propagation of the radiation during use.

[00020] The scattering substance may comprises a dealloyed material. The dealloyed material will provide a scattering material with a plurality of interfaces with the voids.

[00021] The voids may have an extent which is in the order of nanometers in at least one dimension. The voids may be polydisperse within the first material. The voids may be randomly or quasi-randomly arranged within the first material.

[00022] The scattering layer may have a thickness of between 50 nm to 1000 nm. The thickness of the material is measured in a direction of propagation of the received radiation during use of the diffuser.

[00023] The diffuser may be configured such that the angular scattering distribution in at least one scattering direction has a width of 5° or greater. The scattering direction may preferably have a width of 9° or greater.

[00024] The scattering substance may comprises one of the following: molybdenum, ruthenium, niobium, rhodium, yttrium or technetium.

[00025] The diffuser may comprise a plurality of scattering layers. Each of the scattering layers may be manufactured in accordance with any technique described herein or elsewhere.

[00026] A first scattering layer may be separated from a second scattering layer by an intermediate layer. The intermediate layer may comprise silicon, or some other material that is relatively optically neutral for the received radiation.

[00027] The intermediate layer may comprise a layer of separated particles having a lower refractive index than the scattering substance. Because the particles are separated, at least part of the intermediate layer may be occupied by, for example, an inert gas or a vacuum, thereby reducing attenuation of the received radiation.

[00028] The separated particles may be arranged randomly or quasi-randomly within the intermediate layer. The separated particles may comprise particles which differ in size in at least one dimension.

[00029] The first substance and voids therein may collaborate to produce, upon receipt of radiation at a surface of the scattering layer, a hologram. That is, the first substance and voids may comprise a holographic interference pattern. The holographic interference pattern may be selected so as to form a desired hologram given a desired wavelength of radiation. The radiation may be EUV radiation. The first substance may be a scattering substance. A diffuser operable to produce a hologram may beneficially provide controlled diffusion of radiation in combination with minimal absorption of radiation. Such a diffuser may have an increased lifetime compared to known diffusers, for example due to the reduced absorption of radiation.

[00030] The hologram may have an angular intensity profile which is at least as intense in a radially outer portion of the hologram compared to a central region of the hologram. The angular intensity profile may have a similar intensity in a central region compared to a radially outer portion of the hologram. The angular intensity profile may be a top hat profile. The angular intensity profile may have a lower intensity in a central region compared to a radially outer portion of the hologram.

[00031] The radially outer portion may be angularly spaced from the centre of the hologram by at least 9° . Such a diffuser may be of particular benefit in an apparatus with a high numerical aperture.

[00032] The first substance may comprise a plurality of structures of varying thicknesses. That is, the thickness profile of the plurality of structures varies. The thickness profile may be measured in a plane of the diffuser, for example the plane of the surface arranged to receive radiation. The thickness profile may vary on the order of nanometers. For example, the thickness profile of the structures may vary between a thickness of 0 nm and 200 nm.

[00033] The diffuser may be operable to form the hologram upon receipt of radiation with a wavelength λ . The wavelength may be an EUV wavelength. The holographic diffuser may have an effective refractive index n_{eff} . The thickness of each of the plurality of structures may be an integer multiple of $\frac{\lambda}{n_{eff}}$. Beneficially, such a diffuser may impart a phase shift of 0, pi or 2 pi to portions of radiation travelling therethrough.

[00034] The voids may contain a second substance. That is, a second substance may be provided so as to fill the voids.

[00035] The real part of the refractive index of the second substance may differ to the real part of the refractive index of the first substance. Beneficially, the first and second substance having different real parts of their refractive indices may scatter radiation. The imaginary part of the second substance may be similar to the imaginary part of the refractive index of the first substance. Beneficially, the first and second substance having similar imaginary parts of their refractive indices may reduce attenuation through the diffuser. The combined first and second substance act to reduce the relative difference in attenuation experienced by radiation travelling through structures and the voids.

[00036] The combined first substance and second substance may have a combined thickness profile that is substantially constant. That is, the surface of the diffuser arranged to receive radiation is substantially smooth. The surface may be smooth on a microscale. The surface may be smooth on a nanoscale.

[00037] The first substance may comprise one of the following: molybdenum, ruthenium, niobium, rhodium, yttrium or technetium. The second substance may comprise silicon.

[00038] There is also described herein a holographic diffuser comprising a scattering layer comprising a plurality of structures configured to produce, upon receipt of extreme ultraviolet radiation at a surface of the scattering layer, a hologram, wherein the hologram has an angular intensity profile which is at least as intense in a radially outer portion of the hologram compared to a central region of the hologram.

[00039] Any diffuser described herein may further comprise a protective layer configured to protect the scattering layer against EUV plasma etching. The diffuser may further comprise a cap layer which at least partially covers scattering layer to protect the scattering layer during use.

[00040] There is also described herein a measurement system for determining an aberration map or relative intensity map for a projection system comprising the diffuser of any example described herein.

[00041] The measurement system may comprise: a patterning device; an illumination system arranged to illuminate the patterning device with radiation; and a sensor apparatus. The illumination system and patterning device may be configured such that the projection system receives at least a portion of the radiation scattered by the patterning device and the sensor apparatus is configured such that the projection system projects the received radiation onto the sensor apparatus. The diffuser may

be operable to receive the radiation produced by the illumination system and to alter an angular distribution of the radiation before it illuminates the patterning device.

[00042] The diffuser may be moveable between at least: a first, operating position wherein the diffuser is at least partially disposed in a path of the radiation produced by the illumination system and is arranged to alter an angular distribution of the radiation before it illuminates the patterning device; and a second, stored position wherein the diffuser is disposed out of the path of the radiation produced by the illumination system.

[00043] When a measurement system as described herein is used with a holographic diffuser as described herein, holographic diffuser may be designed and/or arranged such that the hologram is formed at an input plane of the measurement system. The input plane may comprise the input plane of a sensor apparatus of the measurement system.

[00044] There is also described herein a lithographic apparatus comprising a measurement system as described in any example herein; and a projection system configured to receive at least a portion of the radiation scattered by the patterning device and configured to project the received radiation onto the sensor apparatus.

[00045] The diffuser may be mounted on a patterning device masking blade of the lithographic apparatus, an edge of the patterning device masking blades defining a field region of the lithographic apparatus.

[00046] There is also described herein a method of forming a diffuser to receive and transmit radiation. The method comprises forming an alloy layer, the layer comprising a first substance and a third substance, wherein the first substance is a scattering substance. The method further comprises dealloying the alloy layer so as to remove the third substance from the alloy layer and so as to form a scattering layer comprising the first substance and having distributed therein a plurality of voids.

[00047] The second substance may be zinc, and the dealloying may be dezincification.

[00048] There is also described herein a method of forming a diffuser for receiving and transmitting radiation, the method comprising forming a scattering layer by infiltrating a porous structure with a scattering material.

[00049] The porous structure may be porous silicon. The pores may have an extent of the order of nanometers in at least one dimension.

[00050] The scattering layer may be formed on a support layer.

[00051] There is also described a method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles on a surface of a support layer to form a mask; depositing a scattering material onto the support layer over the mask to form a scattering layer around the plurality of particles.

[00052] The second material may be a material that is relatively optical neutral for the intended radiation. For example, the second material may be relatively optical neutral to EUV radiation. For example, the second material may be silicon.

[00053] The method may further comprise shrinking one or more of the plurality of particles deposited on the support layer, so as to expose a greater area of the surface of the support layer prior to depositing the scattering material.

[00054] The particles may be deposited on the support layer through vertical colloidal deposition.

5 The particles may form a single layer deposited on the surface of the support layer and the scattering layer forms an undulating scattering surface on the support layer. The particles form a plurality of layers deposited on the surface of the support layer, each of the plurality of layers lying, in use, in a plane generally perpendicular to a direction of received radiation.

[00055] The method may further comprise removing the particles after depositing the scattering material.

10

[00056] There is also described a method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles on a surface of a support layer to form a mask; depositing a second material onto the surface of the support layer over the mask to form a layer of the second material around the plurality of particles; removing at least some of the plurality of particles to form pits within the layer of the second material; depositing a scattering material into at least some of the pits within the second material to form scattering features within the layer of the second material.

15

[00057] There is also described a method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles onto a surface of a support layer to form a mask; depositing a second material onto the surface of the support layer over the mask; selectively etching the surface of the support layer to form a plurality of structures on the surface of the support layer; depositing a scattering material onto the surface of the support layer, the scattering material forming over the plurality of structures to form a scattering layer; wherein the second material is a catalyst and the selective etching comprises etching areas of the support layer in contact with the second material or wherein the second material is a protective material and the selective etching comprises etching areas of the support layer not in contact with the second material.

20

25

[00058] There is also described herein a method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles onto a surface of a support layer such that the particles form a body of contacting particles. The particles may be deposited from a dispersion of particles in a liquid. The particles may be deposited with a particle density such that the majority of particles are in contact with one or more adjacent particles.

30

[00059] Depositing may comprise at least one of: vertical colloidal deposition, spin coating and inkjet printing. Such deposition methods provide an easy method of diffuser fabrication.

[00060] Depositing the plurality of particles may further comprise fusing the plurality of particles.

35

The plurality of particles may be fused through the provision of heat and/or pressure. The plurality of particles may be fused using sintering.

[00061] The particles may comprise a binary mixture comprising a first material and a second material with a refractive index different to the first material. The first material may comprise molybdenum, ruthenium, niobium, rhodium, yttrium or technetium. The second material may comprise silicon.

5 [00062] The method may further comprise forming a further scattering layer on the diffuser. The further scattering layer may be formed in accordance with the method of any of the examples described herein.

[00063] Forming a further scattering layer may comprise depositing an intermediate layer over the scattering layer and forming the further scattering layer atop the intermediate layer. The intermediate
10 layer may be, for example, silicon or silicon nitride.

[00064] In any of the example methods for forming a diffuser described herein, the support layer may be formed on a carrier layer which acts to support the support layer while the diffuser is being formed and wherein the method further comprises removing said carrier layer once the first and second layers have been formed. The carrier layer may be, for example, silicon. For example the carrier layer
15 may be a standard silicon wafer of the type generally used in semiconductor manufacture.

[00065] There is also described herein a method of forming a diffuser for receiving and transmitting radiation, the method comprising generating a plurality of structures on a surface of a support layer of the diffuser, wherein the structures are arranged to, upon receipt of radiation at the surface, produce a hologram. The radiation may be EUV radiation. A diffuser operable to produce a hologram may
20 beneficially provide controlled diffusion of radiation in combination with minimal absorption of radiation. Such a diffuser may have an increased lifetime compared to known diffusers, for example due to the reduced absorption of radiation.

[00066] The hologram may have an angular intensity profile which is at least as intense in a radially outer portion of the hologram compared to a central region of the hologram. The angular intensity
25 profile may have a similar intensity in a central region compared to a radially outer portion of the hologram. The angular intensity profile may be a top hat profile. The angular intensity profile may have a lower intensity in a central region compared to a radially outer portion of the hologram. The radially outer portion may be angularly spaced from the centre of the hologram by at least 9°. Such a diffuser may be of particular benefit in an apparatus with a high numerical aperture.

30 [00067] The plurality of structures may be generated using lithography. Each portion of the plurality of structures may be provided with a thickness an integer multiple of $\frac{\lambda}{n_{eff}}$ where λ is the wavelength of radiation which, when received by the diffuser, produces the hologram, and the holographic diffuser has an effective refractive index of n_{eff} .

[00068] The method may further comprise depositing a second substance into a plurality of voids
35 distributed within the plurality of structures. The second substance is provided with a thickness such that a combined thickness profile of the first and second substance is substantially constant. That is,

upon provision of the second substance, the surface of the diffuser operable to produce a hologram upon receipt of a radiation may be substantially smooth. The second substance may be a scattering substance. The real part of the refractive index of the second substance may be different to the real part of the refractive index of the first substance. Beneficially, the first and second substance having different real parts of their refractive indices may scatter radiation. The imaginary part of the second substance may be similar to the imaginary part of the refractive index of the first substance. Beneficially, the first and second substance having similar imaginary parts of their refractive indices may reduce attenuation through the diffuser. The combined first and second substance act to reduce the relative difference in attenuation experienced by radiation travelling through structures and the voids.

[00069] The method may further comprise generating a thickness profile corresponding to a desired arrangement of the plurality of surface features, the desired arrangement based on a desired angular profile of the hologram. The generation of the thickness profile may comprise numerical methods. Generating the thickness profile may comprise iteratively solving and/or performing calculations based on optical relationships. The optical relationships may represent one or more of: attenuation, refractive index, scattering angle, layer thickness, phase shift. The thickness profile generation may include limitations as to the maximum and/or minimum allowed thickness. The maximum and/or minimum allowed thicknesses may be based on fabrication parameters. The maximum and/or minimum allowed thicknesses may be based on desired optical properties, for example attenuation.

[00070] Generating the thickness profile may comprise using the Gerchberg-Saxton algorithm. Generating the thickness profile may comprise using a modified version of the Gerchberg-Saxton algorithm.

[00071] Any of the example methods of forming a diffuser described herein may further comprise etching the support layer from a surface of the support layer that is opposite to a surface of the support layer supporting the scattering layer.

[00072] Any of the example methods for forming a diffuser described herein may further comprising providing a cap layer which at least partially covers the support layer and/or the scattering layer.

[00073] The methods described herein may further comprise etching the support layer from a surface of the support layer that is opposite to a surface of the support layer supporting the layer of nanoparticles once the plurality of nanoparticles have been deposited so as to form the layer of nanoparticles supported by the support layer.

[00074] This back-etching of the support layer allows a thicker, more stable support layer to be used during the manufacture of the diffuser. Advantageously, this can prevent damage, or even rupture, of the support layer. This final etching step may be particularly beneficial for embodiments wherein nanoparticles are deposited using a colloid since it can prevent capillary forces from braking the support layer. Once the layer of nanoparticles has been formed, the thickness of this layer can be finalized using the etching process.

[00075] The methods described herein may further comprise providing a cover layer which at least partially covers the support layer and/or the capping layer.

[00076] The term patterning device as used herein, may also be referred to herein as a mask or reticle, terms which will be understood to be synonymous.

5

BRIEF DESCRIPTION OF THE DRAWINGS

[00077] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

10

[00078] - Figure 1 depicts a lithographic system comprising a lithographic apparatus and a radiation source;

[00079] - Figure 2 is a schematic illustration of a reflective marker;

[00080] - Figures 3A and 3B are schematic illustrations of a sensor apparatus;

[00081] - Figure 4A shows the intensity distribution for a dipole illumination mode of the lithographic apparatus shown in Figure 1;

15

[00082] - Figure 4B shows the intensity distribution for a quadrupole illumination mode of the lithographic apparatus shown in Figure 1;

[00083] - Figures 5A-5C schematically depict intermediate stages in an example process for manufacturing a transmissive diffuser;

20

[00084] - Figures 6A-6C schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

[00085] - Figures 7A-7E schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

[00086] - Figures 8A-7D schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

25

[00087] - Figures 9A-9E schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

[00088] - Figures 10A-10E schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

30

[00089] - Figures 11A-11C schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

[00090] - Figure 12 schematically illustrates an EUV diffuser;

[00091] - Figure 13 shows a plot of an extinction coefficient k for EUV radiation against the magnitude of $(1-n)$ for EUV radiation for some materials;

35

[00092] - Figures 14A-14C schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

[00093] - Figure 15A illustrates height map of an example diffuser made according to the process of Figures 14A-C;

[00094] - Figures 15B and C depict a scattering angle for a plane wave of radiation incident upon the diffuser of Figure 15A;

[00095] - Figures 16A and 16B schematically depict intermediate stages in another example process for manufacturing a transmissive diffuser;

5 [00096] - Figure 17 illustrates properties of an example diffuser made according to the process of Figures 16A and 16B;

[00097] - Figure 18 illustrates properties of an example diffuser made according to the process of Figures 16A and 16B;

10 [00098] - Figure 19 illustrates properties of an example diffuser made according to the process of Figures 16A and 16B; and

[00099] - Figure 20 illustrates properties of an example diffuser made according to the process of Figures 16A and 16B.

DETAILED DESCRIPTION

15 [000100] Figure 1 shows a lithographic system comprising a radiation source SO and a lithographic apparatus LA. 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.

20 [000101] 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.

25 [000102] 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 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).

30

35

[000103] 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.

[000104] 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.

[000105] 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.

[000106] The lithographic apparatus may, for example, be used in a scan mode, wherein 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 substrate W (i.e. a 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 demagnification and image reversal characteristics of the projection system PS. The patterned radiation beam that is incident upon the substrate W may comprise a band of radiation. The band of radiation may be referred to as an exposure slit. During a scanning exposure, the movement of the substrate table WT and the support structure MT may be such that the exposure slit travels over an exposure field of the substrate W.

[000107] As has been described above, a lithographic apparatus may be used to expose portions of a substrate W in order to form a pattern in the substrate W. In order to improve the accuracy with which a desired pattern is transferred to a substrate W one or more properties of the lithographic apparatus LA may be measured. Such properties may be measured on a regular basis, for example before and/or after exposure of each substrate W, or may be measured more infrequently, for example, as part of a calibration process. Examples of properties of the lithographic apparatus LA which may be measured include a relative alignment of components of the lithographic apparatus LA and/or an aberration of components of the lithographic apparatus. For example, measurements may be made in order to determine the relative alignment of the support structure MT for supporting a patterning device MA and the substrate table WT for supporting a substrate W. Determining the relative alignment of the support structure MT and the substrate table WT assists in projecting a patterned radiation beam onto a desired portion of a substrate W. This may be particularly important when projecting patterned radiation onto a substrate W which includes portions which have already been exposed to radiation, so as to improve alignment of the patterned radiation with the previously exposed regions. Additionally or alternatively, measurements may be made in order to determine deformations of the patterning device MA.

[000108] Additionally or alternatively, measurements may be made in order to determine optical aberrations of the projection system PS. An optical aberration is a departure of the performance of an optical system from paraxial optics and may result in blurring or distortion of the pattern which is

exposed at the substrate W. Aberrations of the projection system PS may be adjusted for and/or accounted for so as to increase the accuracy with which a desired pattern is formed on a substrate W.

[000109] Measurements, such as the alignment and aberration measurements described above may be performed by illuminating a reflective marker 17 (as schematically shown in Figure 1) with radiation.

5 In alternative arrangements, a transmissive marker may be used. A marker is a reflective feature which when placed in the field of view of an optical system appears in an image produced by the optical system. Reflective markers described herein are suitable for use as a point of reference and/or for use as a measure of properties of the image formed by the optical system. For example, radiation reflected from a reflective marker may be used to determine an alignment of one or more components and/or optical aberrations of one or more components.

10 [000110] In the embodiment which is shown in Figure 1, the reflective marker 17 forms part of a patterning device MA. One or more markers 17 may be provided on patterning devices MA used to perform lithographic exposures. A marker 17 may be positioned outside of a patterned region of the patterning device MA, which is illuminated with radiation during a lithographic exposure. In some 15 embodiments, one or more markers 17 may additionally or alternatively be provided on the support structure MT. For example, a dedicated piece of hardware, often referred to as a fiducial, may be provided on the support structure MT. A fiducial may include one or more markers. For the purposes of this description a fiducial is considered to be an example of a patterning device. In some embodiments, a patterning device MA specifically designed for measuring one or more properties of 20 the lithographic apparatus LA may be placed on the support structure MT in order to perform a measurement process. The patterning device MA may include one or more markers 17 for illumination as part of a measurement process.

[000111] In the embodiment which is shown in Figure 1, the lithographic apparatus LA is an EUV lithography apparatus and therefore uses a reflective patterning device MA. The marker 17 is thus a 25 reflective marker 17. The configuration of a marker 17 may depend on the nature of the measurement which is to be made using the marker 17. A marker may, for example, comprise one or more reflective pin hole features comprising a reflective region surrounded by an absorbing region, a reflective line feature, an arrangement of a plurality of reflective line features and/or a reflective grating structure such as a reflective diffraction grating.

30 [000112] In order to measure one or more properties of the lithographic apparatus LA, a sensor apparatus 19 (as shown schematically in Figure 1) is provided to measure radiation which is output from the projection system PS. The sensor apparatus 19 may, for example, be provided on the substrate table WT as shown in Figure 1. In order to perform a measurement process, the support structure MT may be positioned such that the marker 17 on the patterning device MA is illuminated with radiation. 35 The substrate table WT may be positioned such that radiation which is reflected from the marker is projected, by the projection system PS, onto the sensor apparatus 19. The sensor apparatus 19 is in communication with a controller CN which may determine one or more properties of the lithographic

apparatus LA from the measurements made by the sensor apparatus 19. In some embodiments a plurality of markers 17 and/or sensor apparatuses 19 may be provided and properties of the lithographic apparatus LA may be measured at a plurality of different field points (i.e. locations in a field or object plane of the projection system PS).

5 [000113] As was described above, in some embodiments radiation reflected from a marker may be used to determine a relative alignment of components of the lithographic apparatus LA. In such embodiments, a marker 17 may comprise a feature which when illuminated with radiation imparts the radiation with an alignment feature. The feature may, for example, comprise one or more reflective patterns in the form of a grating structure.

10 [000114] The position of the alignment feature in the radiation beam B may be measured by a sensor apparatus 19 positioned at a substrate W level (e.g. on the substrate table WT as shown in Figure 1). The sensor apparatus 19 may be operable to detect the position of an alignment feature in the radiation incident upon it. This may allow the alignment of the substrate table WT relative to the marker on the patterning device MA to be determined. With knowledge of the relative alignment of the patterning device MA and the substrate table WT, the patterning device MA and the substrate table WT may be moved relative to each other so as to form a pattern (using the patterned radiation beam B reflected from the patterning device MA) at a desired location on the substrate W. The position of the substrate W on the substrate table may be determined using a separate measurement process.

15 [000115] As was further described above, in some embodiments a patterning device MA may be provided with one or more markers 17 which may be used to measure aberrations of the projection system PS. Similarly to the alignment measurement described above, aberrations may be detected by measuring radiation reflected from a marker 17 with a sensor apparatus 19 located at or near to the substrate table WT. One or more markers 17 on a patterning device MA may be illuminated with EUV radiation, by the illumination system IL. Radiation reflected from the one or more markers is projected, by the projection system PS onto an image plane of the projection system PS. One or more sensor apparatuses 19 are positioned at or near to the image plane (e.g. on the substrate table WT as shown in Figure 1) and may measure the projected radiation in order to determine aberrations of the projection system PS. An embodiment of a marker 17 and a sensor apparatus 19 which may be used to determine aberrations of the projection system PS will now be described with reference to Figures 2 and 3.

20 [000116] Figure 2 is a schematic representation of a marker 17 which may form part of a patterning device MA according to an embodiment of the invention. Also shown in Figure 2 is a Cartesian coordinate system. The y-direction may represent a scanning direction of the lithographic apparatus. That is, during a scanning exposure, the movement of the substrate table WT and the support structure MT may be such that a patterning device MA is scanned relative to a substrate W in the y-direction. 25 The marker 17 lies generally in an x-y plane. That is the marker generally extends in a direction which is perpendicular to the z-direction. Although reference is made to the marker lying generally in a plane, it will be appreciated that the marker is not entirely constrained to a plane. That is, portions of the

marker may extend out of a plane in which the marker generally lies. As will be explained further below, a marker may comprise a diffraction grating. A diffraction grating may comprise a three-dimensional structure including portions which do not lie entirely in a plane but instead extend out of the plane.

5 [000117] The marker 17 which is shown in Figure 2 comprises a first portion 17a and a second portion 17b. Both the first and second portions comprise reflective diffraction gratings comprising a periodic grating structure. The grating structures extend in grating directions. The first portion 17a comprises a diffraction grating extending in a first grating direction which is denoted as the u-direction in Figure 2. The second portion 17b comprises a diffraction grating extending in a second grating
10 direction which is denoted as the v-direction in Figure 2. In the embodiment of Figure 2, the u and v-directions are both aligned at approximately 45° relative to both the x and y-directions and are substantially perpendicular to each other. The first and second portions 17a, 17b of the marker 17 may be illuminated with radiation at the same or different times.

[000118] Whilst the embodiment which is shown in Figure 2 includes a first portion 17a and a second
15 portion 17b comprising diffraction gratings orientated with perpendicular grating directions, in other embodiments a marker 17 may be provided in other forms. For example, a marker 17 may comprise reflective and absorbing regions arranged to form a checkerboard pattern. In some embodiments, a marker 17 may comprise an array of pinhole features. A reflective pinhole feature may comprise a region of reflective material surrounded by absorbing material.

20 [000119] When the first and/or second portions 17a, 17b of the marker are illuminated with radiation, a plurality of diffraction orders are reflected from the marker. At least a portion of the reflected diffraction orders enter the projection system PS. The projection system PS forms an image of the marker 17 on a sensor apparatus 19. Figures 3A and 3B are schematic illustrations of a sensor apparatus 19. Figure 3A is a side-on view of the sensor apparatus and Figure 3B is a top-down view of the sensor
25 apparatus. Cartesian co-ordinates are also shown in Figures 3A and 3B.

[000120] The Cartesian co-ordinate system which is used in Figures 2, 3A and 3B is intended as a co-ordinate system of radiation propagating through the lithographic apparatus. At each reflective optical element, the z-direction is defined as the direction which is perpendicular to the optical element. That is, in Figure 2, the z-direction is perpendicular to an x-y plane in which the patterning device MA and the marker 17 generally extend. In Figures 3A and 3B, the z-direction is perpendicular to an x-y
30 plane in which the diffraction grating 19 and the radiation sensor 23 generally extend. The y-direction denotes a scanning direction, in which the support structure MT and/or the substrate table WT are scanned relative to each other during a scanning exposure. The x-direction denotes a non-scanning direction which is perpendicular to the scanning direction. It will be appreciated (for example, from
35 Figure 1) that, in a lithographic apparatus, the z-direction at the patterning device MA is not aligned with the z-direction at the substrate W. As explained above, the z-direction is defined at each optical element in the lithographic apparatus, as being perpendicular to the optical element.

[000121] The sensor apparatus 19 comprises a transmissive diffraction grating 21 and a radiation sensor 23. At least some of the radiation 25 which is output from the projection system PS passes through the diffraction grating 21 and is incident on the radiation sensor 23. The diffraction grating 21 is shown in more detail in Figure 3B and comprises a checkerboard diffraction grating. Regions of the diffraction grating 21 shown in Figure 3B which are shaded black represent regions of the diffraction grating 21 which are configured to be substantially opaque to incident radiation. Regions of the diffraction grating 21 shown in Figure 3B which are not shaded represent regions which are configured to transmit radiation. For ease of illustration, the opaque and transmissive regions of the diffraction grating 21 are not shown to scale in Figure 3B. For example, in practice the scale of the diffraction grating features, relative to the size of the diffraction grating itself may be smaller than is indicated in Figure 3B.

[000122] The diffraction grating 21 which is shown in Figure 3B is depicted as having a checkerboard configuration comprising square shaped transmissive and opaque regions. However, in practice it may be difficult or impossible to manufacture a transmissive diffraction grating comprising perfectly square shaped transmissive and opaque regions. The transmissive and/or opaque regions may therefore have cross-sectional shapes other than perfect squares. For example, the transmissive and/or opaque regions may have cross-sectional shapes comprising squares (or more generally rectangles) having rounded corners. In some embodiments, the transmissive and/or opaque regions may have cross-sectional shapes which are substantially circular or elliptical. In some embodiments, the diffraction grating 21 may comprise an array of pinholes formed in an opaque material.

[000123] The radiation sensor 23 is configured to detect the spatial intensity profile of radiation which is incident on the radiation detector 23. The radiation detector 23 may, for example, comprise an array of individual detector elements. For example, the radiation detector 23 may comprise a CCD or CMOS array. During a process for determining aberrations, the support structure MT may be positioned such that the marker 17 is illuminated with radiation from the illumination system IL. The substrate table WT may be positioned such that radiation reflected from the marker is projected by the projection system PS onto the sensor apparatus 19.

[000124] As was described above, a plurality of diffraction orders are formed at the marker 17. Further diffraction of radiation occurs at the diffraction grating 21. The interaction between diffraction orders formed at the marker 17 and diffraction patterns formed at the diffraction grating 21 results in an interference pattern being formed on the radiation detector 23. The interference pattern is related to the derivative of the phase of wavefronts which have propagated through the projection system. The interference pattern may therefore be used to determine aberrations of the projection system PS.

[000125] As was described above, the first and second portions of the marker 17 comprise diffraction gratings which are aligned perpendicular to each other. Radiation which is reflected from the first portion 17a of the marker 17 may provide information related to gradients of the wavefronts along a first direction. Radiation which is reflected from the second portion 17b of the marker may provide

information related to gradients of the wavefront along a second direction, which is perpendicular to the first direction. In some embodiments, the first and second portions of the marker may be illuminated at different times. For example, the first portion 17a of the marker 17 may be illuminated at a first time in order to derive information about gradients of the wavefront along the first direction and the second portion 17b of the marker 17 may be illuminated at a second time in order to derive information about gradients of the wavefront along the second direction.

[000126] In some embodiments, the patterning device MA and/or the sensor apparatus 19 may be sequentially scanned and/or stepped in two perpendicular directions. For example, the patterning device MA and/or the sensor apparatus 19 may be stepped relative to each other in the u and v-directions. The patterning device MA and/or the sensor apparatus 19 may be stepped in the u-direction whilst the second portion 17b of the marker 17 is illuminated and the patterning device MA and/or the sensor apparatus 19 may be stepped in the v-direction whilst the first portion 17a of the marker 17 is illuminated. That is, the patterning device MA and/or the sensor apparatus 19 may be stepped in a direction which is perpendicular to the grating direction of a diffraction grating which is being illuminated.

[000127] The patterning device MA and/or the sensor apparatus 19 may be stepped by distances which correspond with a fraction of the grating period of the diffraction gratings. Measurements which are made at different stepping positions may be analysed in order to derive information about a wavefront in the stepping direction. For example, the phase of the first harmonic of the measured signal may contain information about the derivative of a wavefront in the stepping direction. Stepping the patterning device MA and/or the sensor apparatus 19 in both the u and v-directions (which are perpendicular to each other) therefore allows information about a wavefront to be derived in two perpendicular directions, thereby allowing the full wavefront to be reconstructed.

[000128] In addition to stepping of the patterning device MA and/or the sensor apparatus 19 in a direction which is perpendicular to the grating direction of a diffraction grating which is being illuminated (as was described above), the patterning device MA and/or the sensor apparatus 19 may also be scanned relative to each other. Scanning of the patterning device MA and/or the sensor apparatus 19 may be performed in a direction which is parallel to the grating direction of a diffraction grating which is being illuminated. For example, the patterning device MA and/or the sensor apparatus 19 may be scanned in the u-direction whilst the first portion 17a of the marker 17 is illuminated and the patterning device MA and/or the sensor apparatus 19 may be scanned in the v-direction whilst the second portions 17a of the marker 17 is illuminated. Scanning of the patterning device MA and/or the sensor apparatus 19 in a direction which is parallel to the grating direction of a diffraction grating which is being illuminated allows measurements to be averaged out across the diffraction grating, thereby accounting for any variations in the diffraction grating in the scanning direction. Scanning of the patterning device MA and/or the sensor apparatus 19 may be performed at a different time to the stepping of the patterning device MA and/or the sensor apparatus 19 which was described above.

[000129] As was described above the diffraction grating 21 which forms part of the sensor apparatus 19 is configured in the form of a checkerboard. This may allow the sensor apparatus 19 to be used during a determination of wavefront phase variations in both the u-direction and the v-direction. The arrangements of diffraction gratings which form the marker 17 and the sensor apparatus 19 are presented merely as an example embodiment. It will be appreciated that a variety of different arrangements may be used in order to determine wavefront variations.

[000130] In some embodiments the marker 19 and/or the sensor apparatus 19 may comprise components other than a diffraction grating. For example, in some embodiments the marker 17 and/or the sensor apparatus 19 may comprise a single slit or one or more pin-hole feature through which at least a portion of a radiation beam may propagate. In the case of the marker 17, a pin-hole feature may comprise a portion of reflective material surrounded by absorbing material such that radiation is only reflected from a small portion of the marker. A single slit feature may have the form of a single strip of reflective material surrounded by absorbing material. A pin-hole feature and/or a single slit feature at the sensor apparatus 19, may be a transmissive feature. In general a marker 17 may be any feature which imparts a radiation beam with a feature, which may be used as a point of reference or to determine a measure of the radiation beam.

[000131] Whilst, in the embodiment described above a single marker 17 and sensor apparatus 19 is provided, in other embodiments a plurality of markers 17 and sensor apparatuses 19 may be provided in order to measure wavefront phase variations at different field points. In general any number and configuration of markers and sensor apparatuses 19 may be used to provide information about wavefront phase variations.

[000132] A controller CN (as shown in Figure 1) receives measurements made at the sensor apparatus 19 and determines, from the measurements, aberrations of the projection system PS. The controller may be further configured to control one or more components of the lithographic apparatus LA. For example, the controller CN may control a positioning apparatus which is operable to move the substrate table WT and/or the support structure MT relative to each other. The controller CN may control an adjusting means PA for adjusting components of the projection system PS. For example, the adjusting means PA may adjust elements of the projection system PS so as to correct for aberrations which are determined by the controller CN.

[000133] The projection system PS comprises a plurality of reflective lens elements 13, 14 and an adjusting means PA for adjusting the lens elements 13, 14 so as to correct for aberrations. To achieve this, the adjusting means PA may be operable to manipulate reflective lens elements within the projection system PS in one or more different ways. The adjusting means PA may be operable to do any combination of the following: displace one or more lens elements; tilt one or more lens elements; and/or deform one or more lens elements.

[000134] The projection system PS has an optical transfer function which may be non-uniform, which can affect the pattern which is imaged on the substrate W. For unpolarized radiation such effects

can be fairly well described by two scalar maps, which describe the transmission (apodization) and relative phase (aberration) of radiation exiting the projection system PS as a function of position in a pupil plane thereof. These scalar maps, which may be referred to as the transmission map and the relative phase map, may be expressed as a linear combination of a complete set of basis functions. It will be appreciated that the terms “transmission map” and “relative intensity map” are synonymous and that the transmission map may alternatively be referred to as a relative intensity map. A particularly convenient set of basis functions for expressing these scalar maps is the Zernike polynomials, which form a set of orthogonal polynomials defined on a unit circle. A determination of each scalar map may involve determining the coefficients in such an expansion. Since the Zernike polynomials are orthogonal on the unit circle, the Zernike coefficients may be determined by calculating the inner product of a measured scalar map with each Zernike polynomial in turn and dividing this by the square of the norm of that Zernike polynomial.

[000135] The transmission map and the relative phase map are field and system dependent. That is, in general, each projection system PS will have a different Zernike expansion for each field point (i.e. for each spatial location in its image plane).

[000136] Determining aberrations of the projection system PS may comprise fitting the wavefront measurements which are made by the sensor apparatus 19 to Zernike polynomials in order to obtain Zernike coefficients. Different Zernike coefficients may provide information about different forms of aberration which are caused by the projection system PS. Zernike coefficients may be determined independently at different positions in the x and/or the y-directions (i.e. at different field points).

[000137] Different Zernike coefficients may provide information about different forms of aberration which are caused by the projection system PS. Typically Zernike polynomials are considered to comprise a plurality of orders, each order having an associated Zernike coefficient. The orders and coefficients may be labelled with an index, which is commonly referred to as a Noll index. The Zernike coefficient having a Noll index of 1 may be referred to as the first Zernike coefficient, the Zernike coefficient having a Noll index of 2 may be referred to as the second Zernike coefficient and so on.

[000138] The first Zernike coefficient relates to a mean value (which may be referred to as a piston) of a measured wavefront. The first Zernike coefficient may not be relevant to the performance of the projection system PS and as such may not be determined using the methods described herein. The second Zernike coefficient relates to the tilt of a measured wavefront in the x-direction. The tilt of a wavefront in the x-direction is equivalent to a placement in the x-direction. The third Zernike coefficient relates to the tilt of a measured wavefront in the y-direction. The tilt of a wavefront in the y-direction is equivalent to a placement in the y-direction. The fourth Zernike coefficient relates to a defocus of a measured wavefront. The fourth Zernike coefficient is equivalent to a placement in the z-direction. Higher order Zernike coefficients relate to other forms of aberration (e.g. astigmatism, coma, spherical aberrations and other effects).

[000139] Throughout this description the term “aberrations” is intended to include all forms of deviation of a wavefront from a perfect spherical wavefront. That is, the term “aberrations” may relate to the placement of an image (e.g. the second, third and fourth Zernike coefficients) and/or to higher order aberrations such as those which relate to Zernike coefficients having a Noll index of 5 or more.

5 [000140] As was described in detail above, one or more reflective markers 17 may be used to determine the alignment and or aberration of components of the lithographic apparatus LA. In some embodiments, separate markers 17 may be used for determining the alignment of components to markers used to determine aberrations. For example, a patterning device MA suitable for use in a lithographic exposure process may be provided with one or more markers outside of a patterned region
10 suitable for use in a lithographic exposure process. The one or more markers may be suitable for determining the alignment of the patterning device MA relative to the substrate table WT.

[000141] One or more markers 17 suitable for determining aberrations may be provided on a measurement patterning device which is separate from patterning devices MA (e.g. reticles) used to perform lithographic exposures. A measurement patterning device MA may, for example, be positioned
15 on the support structure MT for the purposes of performing aberration measurements. The measurement patterning device MA may include other features suitable for determining other properties of the projection system PS. For example, a measurement patterning device may additionally include a marker suitable for determining the alignment of the measurement patterning device relative to the substrate table WT.

20 [000142] In some embodiments, the same marker may be used to determine both alignment and aberrations. For example, both alignment and aberrations may be determined using one or more markers in the form of a reflective grating structure (e.g. a diffraction grating). In some embodiments, both alignment and aberrations may be determined simultaneously using the same set of measurements.

[000143] References herein to a patterning device MA should be interpreted to include any device
25 including one or more features configured to modify radiation. A patterning device MA may, for example, be provided with a pattern for use during a lithographic exposure (for example, the patterning device may be a reticle). Additionally or alternatively a patterning device may be provided with one or more markers for use in a measurement process. In general, patterning devices MA are removable components which are placed on the support structure MT in order to perform a specific process (e.g.
30 to perform a lithographic exposure and/or perform one or more measurement processes). However, in some embodiments a lithographic apparatus LA itself may be provided with one or more patterning features. For example, the support structure MT may be provided with one or more patterning features (e.g. markers) for use in a measurement process. For example, the support structure MT may be provided with one or more fiducials which include one or more markers. In such embodiments, the
35 support structure MT itself may be considered to be an example of a patterning device, since it is provided with one or more features configured to modify radiation. References herein to a patterning

device comprising a reflective marker should not be interpreted to be limited to removable patterning devices but should be interpreted to include any device having a reflective marker disposed thereon.

[000144] Referring to Figure 1, the patterning device MA may be considered to be disposed in an object plane of the projection system PS and the substrate W may be considered to be disposed in an image plane of the projection system PS. In the context of such a lithographic apparatus, the object plane of the projection system PL (where the patterning device MA is disposed), the image plane of the projection system PL (where the substrate W is disposed) and any planes conjugate thereto may be referred to as field planes of the lithographic apparatus. It will be appreciated that within an optical system (e.g. a lithographic apparatus) two planes are conjugate if each point within the first plane P is imaged onto a point in the second plane P'.

[000145] It will be appreciated that the lithographic apparatus LA comprises optics with optical power (i.e. focusing and/or diverging optics) in order to form an image in the image plane of an object in the object plane. Within such an optical system, between each pair of field planes it is possible to define a pupil plane which is a Fourier transform plane of a preceding field plane and a successive field plane. The distribution of the Electric field within each such pupil plane is related to a Fourier transform of an object disposed in a preceding field plane. It will be appreciated that the quality of such a pupil plane will depend on the optical design of the system and that such a pupil plane may even be curved. It is useful to consider two such pupil planes an illumination system pupil plane and a projection system pupil plane. The illumination system pupil plane and the projection system pupil plane (and any other pupil planes) are mutually conjugate planes. The intensity (or, equivalently, the electric field strength) distribution of radiation in the illumination system pupil plane PP_{IL} may be referred to as the illumination mode or pupil fill and characterizes the angular distribution of the light cone at the patterning device MA (i.e. in the object plane). Similarly, the intensity (or, equivalently, the electric field strength) distribution of radiation in the projection system pupil plane PP_{IL} characterizes the angular distribution of the light cone at the wafer level (i.e. in the image plane).

[000146] The illumination system IL may alter the intensity distribution of the beam in the illumination system pupil plane. This may be achieved by configuring the faceted field mirror device 10 and faceted pupil mirror device 11 appropriately.

[000147] During exposure of a substrate W the illumination system IL and the projection system PS are used to form a (diffraction limited) image of an object level patterning device MA on an image level substrate W (e.g. a resist coated silicon wafer). During such an exposure, it may be desirable for the illumination mode to use a localized illumination mode. For example, it may be desirable to use a multipole (e.g. dipole or quadrupole) illumination mode, wherein in the pupil plane of the illumination system PP_{IL} only a finite number (e.g. two or four) of discrete pole regions receive radiation. Two examples of such illumination modes are shown in Figures 4A and 4B. For example, the illumination mode may be a dipole distribution 30 as shown in Figure 4A or a quadrupole distribution 32 as shown in Figure 4B. Also shown in Figures 4A and 4B is a circle 34 which represents the limit of what can

physically be captured by the projection system PS and imaged onto the image plane (this represents the numerical aperture NA, or the sine of the maximum angle that can be captured by the projection system PS). In coordinates that are normalised by the numerical aperture NA of the projection system PS, circle 34 has a radius $\sigma=1$. The dipole distribution 30 comprises two diametrically opposed pole regions 36 where the intensity is non-zero. The quadrupole distribution 32 comprises a first dipole distribution similar to that shown in Figure 4A and a second dipole distribution rotated relative to the first by $\pi/2$ radians but otherwise identical to it. Therefore the quadrupole distribution 32 comprises four pole regions 34 where the intensity is non-zero.

[000148] When the lithographic apparatus is not exposing a substrate W, one of more reflective markers provided on a patterning device MA may be used in a measurement process, for example, to determine an alignment and/or aberrations associated with a lithographic apparatus LA. When using reflections from a marker to measure alignment and/or aberrations it may be desirable for the radiation reflected from the marker to fill a substantial portion of the pupil of the projection system PS. To achieve this, in principle, the illumination system IL may be reconfigured so as to fill the illumination system pupil plane (and therefore also fill the entrance pupil of the projection system). However, to do so (and to revert back to an exposure illumination mode before the next exposure) may take more time than is desired for such in-line measurements. Therefore, it is known to provide a diffuser during such measurements that is arranged to increase the angular spread of the radiation scattered from the object level patterning device so as to increase the proportion of the entrance pupil of the projection system PS which is filled with radiation.

[000149] Such a diffuser can be placed in a path of the radiation beam during these metrology measurements but not during exposure of a substrate W. This allows EUV lithography apparatus to be operable to perform semi-continuous in-line metrology, which in turn can be used to maintain an optimum dynamic setup of the projection system PS, the support structure MT and the substrate table WT. In addition, such measurement systems may be used to align patterning devices MA to substrates W before exposure of the substrate W.

[000150] Some existing measurement systems use, at object level, a combined diffuser and patterning device (for example a one-dimensional diffraction grating). One arrangement uses a three-dimensional structure mounted on the support structure MT, comprising a recessed diffuser and a grating membrane that are disposed in two different planes. The EUV radiation beam B radiation beam exits the illumination system IL, reflects from the recessed diffuser (which increases the angular spread of the radiation) and then, after reflection, passes through the grating membrane (which scatters the radiation, some of the scattered radiation being captured by the projection system). Such a three-dimensional arrangement cannot be formed on a reticle and therefore is formed on a fiducial.

[000151] Another arrangement, as described in WO2017/207512, uses a reflective object that is a combined diffuser and patterning device. This arrangement is of the form of a multilayer reflective stack, arranged to preferentially reflect EUV radiation, to which is applied a pattern (for example a

diffraction grating) of EUV absorbing material. The layers of the multilayer reflective stack are provided with a surface roughness such that the reflected radiation is diffuse. However, although such a patterning device can, in principle, be provided on a reticle, it is significantly more complex to manufacture a patterning device with such a built in surface roughness. Therefore, in practice, such a patterning device is more likely to be formed on a fiducial.

[000152] Embodiments of the present invention relate to novel diffusers and methods for their preparation that are particularly suitable for use with EUV measurement systems within EUV lithography apparatus of the type discussed above.

[000153] Stages in a method of preparing a diffuser according to a first example are shown schematically in Figures 5A-5C (collectively, Figure 5). A diffuser may be constructed from multiple layers, referred to herein as a stack. Intermediate stacks of layers in one example process for creating a diffuser are depicted in cross-section in Figures 5A-5C. With reference to Figure 5A, a first intermediate stack 50 comprises a layer of support material 502. The support material may, for example, comprise silicon nitride (SiN), silicon, molybdenum silicide (MoSi₂). The layer 502 of support material may have a thickness of the order of 10-60 nm. In some embodiments, the support material is a material having a refractive index close to 1 for EUV radiation and a relatively low absorption coefficient for EUV radiation. For such embodiments, the support material may be considered to be relatively optically neutral for EUV radiation. The layer 502 of support material is formed on a carrier layer 504, which may act to support the layer 502 of support material while the diffuser is being formed. The carrier layer 504 may be formed from, for example, silicon, silicon nitride (SiN), porous silicon (pSi) or molybdenum silicide (MoSi). The carrier layer 504 may, for example, have any thickness that is suitable to provide sufficient support during manufacture, and in some arrangements may have a thickness of the order of 100-500 µm. For example, the carrier layer may be a standard silicon wafer. Alternatively, the carrier layer 504 and the support layer 502 may be provided by a single layer of the same material.

[000154] A layer 506 of a scattering material is provided on the support layer 502. The scattering material may be, for example, a substance such as molybdenum, ruthenium or niobium, but may be other suitable scattering materials as discussed in further detail below. The layer of scattering material 506 may be, for example, of the order of between 50 and 400 nm thick (in the depicted z direction), in dependence upon the particular scattering material.

[000155] A further layer 508 of a further, different, metal is deposited atop the intermediate stack 50 to form a second intermediate stack 52. For example, the further metal may be zinc (Zn). The layers 506 and 508 are processed to form an alloy layer (not shown) comprising an alloy of the scattering metal and the further metal (for example a molybdenum-zinc alloy). The scattering material 506 provides a first component of the alloy, while the further metal 508 provides a second component of the alloy. For example, the layers 506, 508 may be annealed. The annealing may be performed at, for

example, 400 degrees. The annealing may be performed in a protective gas environment. For example, the annealing may be performed in the presence of a noble gas, such as argon.

[000156] The resulting alloy layer is subjected to a dealloying process to selectively corrode the second component of the alloy. For example, where the second component is zinc, the dealloying comprises a process of dezincification. The dealloying may be performed by any suitable method. For example the dealloying may comprise selective dissolution of the zinc by immersion in an acid, such as nitric acid.

[000157] Following the dealloying processing, an intermediate stack 54 is provided, comprising a porous scattering layer 510 on the support layer 502. The scattering layer 510 may be considered to be a scattering substance having a plurality of voids distributed therein. The method may further comprise etching the carrier layer 504 from a surface that is opposite to a surface of the support layer supporting the porous scattering layer 510. Where the carrier layer 502 and the support layer 504 are separate layers, the carrier layer 502 may provide an etch-stop during this back-etching process. This back-etching of the carrier layer 504 allows a thicker, more stable carrier 502 and support layer 504 to be used during manufacture. Advantageously, this can prevent damage, or even rupture, of the support layer 504.

[000158] Optionally, the porous scattering layer 510 may contain a further substance within the pores (or voids). For example, the pores of the porous scattering layer 510 may be filled with an inert gas. Alternatively, the pores of the porous scattering layer 510 may be filled with a vacuum. For example, where the scattering layer 510 is subsequently capped (discussed in more detail below), the capping could be performed in an atmosphere of an inert gas, or in a vacuum. Alternatively, the porous scattering layer 510 may be infiltrated (by any suitable processing such as ALD, CVD or sputtering, for example) with an optically contrasting material (for example a material that is relatively optically neutral for EUV radiation, for example a material having a refractive index of or substantially close to 1). Such infiltration of the porous scattering layer 510 may be beneficial to protect against degradation, structural integrity, allow thermal diffusion.

[000159] While in practice, a diffuser is likely to contain multiple layers (such as the scattering layer and the support layer), the term diffuser herein may also refer only to the scattering layer (i.e. the layer that is configured to diffuse the incident radiation).

[000160] A further example process for manufacturing a diffuser suitable for EUV radiation is depicted in Figures 6A-6C (collectively, Figure 6). Intermediate stacks of layers in the example process are depicted in cross-section in Figures 6A-6C. With reference to Figure 6A, a first intermediate stack 60 comprises a support layer 602 and a carrier layer 604. The support layer 602 and the carrier layer 604 may be as described above in connection with the support layer 502 and carrier layer 504 of Figures 5A-C.

[000161] The intermediate stack 60 further comprises a porous layer 606 formed from a material which has been processed to form a structure. The porous layer 606 may, for example, comprise silicon

or porous silicon. The processing to create the porous layer 606 may comprise, for example, selective etching (e.g. metal-assisted chemical etching, anodization, selective leaching).

[000162] A scattering material is deposited onto the porous layer 602 to form a second intermediate stack 62 so that the scattering material at least partially occupies the pores (or voids) within the porous layer 602 to thereby form a scattering layer 608. The scattering layer 604 may have a thickness of the order of between 50 and 1000 nm in dependence upon the scattering material used. The scattering layer 604 may be considered to provide a first substance having voids distributed therein, at least some of the voids being filled with a scattering substance.

[000163] As described with reference to the preceding example process, the method may further comprise etching the carrier layer 604 from a surface that is opposite to a supporting the scattering layer 604 to provide a further stack 64 (which may be the final stack or may be a further intermediate stack). It will be appreciated that in the further examples discussed below, while no carrier layer is depicted, a carrier layer may be provided and may be etched after the scattering layers have been provided on the support structure.

[000164] Further, in all examples described herein, additional layers may be provided other than those shown in Figures 5 and 6. For example, with reference to Figure 5 by way of example, a further layer may be provided between the support layer 502 and the scattering layer 510 or between the carrier layer 504 and the support layer 502. The additional layer may be beneficial to provide additional protection to the scattering layer during use, in particular from particles present within the interior of the lithographic apparatus. Similarly, an additional (or “capping”) layer may be provided atop the scattering layer 510, for the same purpose. Such additional layers may have a thickness of the order of 10 nm. Such an additional layer be formed from a metal oxide or metal nitrate. For example, additional layers may be provided from silicon nitride or molybdenum silicide.

[000165] Figures 7A-7E (collectively, Figure 7) depict a further example process for manufacturing a diffuser suitable for use with EUV radiation. In the example of Figure 7, an inhomogeneous layer of a scattering material is deposited on a random or quasi random arrangement of structures (such as pillars on or holes in a surface of a support layer). The structures may be provided in accordance with any suitable technique. For example, and as depicted in Figure 7, the structures may be provided through nanoparticle lithography. Alternatively, the structures may be created using normal (e.g. resist) lithography with a pseudo-random mask, de-alloying with selective leaching, metal assisted chemical etching using a random deposition of metal catalyst particles, etc.

[000166] In the example depicted in Figure 7, an intermediate stack 70 comprises a support layer 702. The support layer 702 may, for example, take the same or a similar form as the support layers 502, 602 described with reference to Figures 5 and 6 above. While not depicted in Figure 7, it will be appreciated that the intermediate stack 70 may comprise a carrier layer, which may take the same or a similar form as the carrier layers 504, 604 described above.

[000167] A layer 704 of nanoparticles is deposited on a support layer 702 in a random or quasi-random distribution. The particles in the layer 704 may be formed polystyrene particles. Alternatively, the particles in the layer 704 may be formed from another material suitable for nanosphere lithography, such as latex, or silica, cellulose, etc. In the example depicted in Figure 7A, the particles in the layer 704 are polydisperse, comprising a plurality of particles that have a range of different sizes. In particular, for example, it can be some of the particles 704 have a smaller diameter than others of the particles 704. By way of example, the particles may have diameters in the range of 20 nm to 300 nm. The particles have a random distribution of displacements of adjacent particles. The particles in the layer 704 may take the form of spheres. The particles may be applied to the support layer 702 in any appropriate way. For example, the particles may be applied using a process of vertical deposition from a colloid containing the particles. For example, a Langmuir-Blodgett deposition process may be used as generally described for example in Langmuir, 20042041524-1526, December 25, 2003, <https://doi.org/10.1021/la035686y>. The vertical deposition process is suitable for providing a mono-layer of polystyrene particles. It will be appreciated, however, that the deposition may be according to any method that is able to suitable for producing a mono-layer or a small number of layers. For example, the deposition may be by way of spin coating or ink jetting the particles in a solvent. The particles may be spherical or generally spherical (e.g the particles may be ellipsoids). The particles may, however, have other shapes.

[000168] As depicted in Figure 7B, the particles in the layer 704 may be shrunk to provide a second intermediate stack 72. The shrinking of the particles in the layer 704 is an optional step, and may be beneficial to further expose areas of the support layer 702, allowing for tuning the dimensions (sizes, pitch, density) of the structures created, as described in more detail below. For example, the particles may be processed using reactive ion etching (RIE) which causes each of the particles in the layer 704 to shrink.

[000169] Whether or not the particles in the layer 704 are shrunk, the particles in the layer 704 are operable to provide a mask on a surface of the support layer 702. It will be appreciated that where the arrangement of particles on the surface is random or quasi-random, the mask provided by those particles will also be random or quasi-random.

[000170] A catalyst is deposited onto the surface of the support layer 702 adjacent the particle layer 704, such that the portions of the surface that are not masked by the particles are coated with deposits 712 of catalyst. The catalyst may be a metal catalyst such as gold or platinum. The particles in the layer 704 are removed and the surface of the support layer 702 on which the catalyst is deposited is selectively etched so as to form a modified layer of support material 714 and a third intermediate stack 74. In effect, the support layer 702 is etched where it is in contact with the deposits of catalyst 712 so as to create a plurality of structures (or features) on the surface of the support material in contact with the catalyst. This type of metal-assisted catalytic etching is also a known and robust process. The structures in this example comprise a plurality of cavities or pits, with corresponding peaks, or pillars.

[000171] In the alternative, a process may be used whereby a mask is deposited onto the support layer 704 between the particles and the surface of the support layer etched in those areas not protected by the mask. Where the process depicted in Figure 7 creates cavities in the areas beneath the catalyst, this alternative process may be thought of as creating pillars in the areas beneath the protective mask.
5 Any appropriate mask material and etching processes may be used as will be well known to those skilled in the art.

[000172] Following creation of the modified support structure 714, the catalyst or mask may be removed to provide a fourth intermediate stack 76, although it is to be understood that this is an optional step.

10 [000173] A scattering material 716 may then be deposited onto the modified support structure 714, forming within and around the structures provided on a surface of the modified support structure 714 to provide a further stack 78 (which may be a final stack or may be a further intermediate stack). Due to the structures present on the modified support structure 714, the scattering material 716 acts as an array of microlenses, causing scattering of the EUV radiation that is incident on a diffuser created
15 therefrom. The lens formation is (partially) a result of shadowing caused by the presence of the structures. Shadowing may therefore be increased by directing the particle flow of scattering material 716 at an angle that is not 90 degrees to the surface of the substrate.

[000174] While not depicted, as in the previous examples and where a carrier layer is provided, the carrier layer may be back-etched. Additionally or alternatively, a part of the support structure 714,
20 in particular from a surface opposite the surface on which the scattering material 716 is deposited, may be etched to provide a diffuser.

[000175] Figures 8A-8D (collectively, Figure 8) depict a further example process for manufacturing a diffuser suitable for use with EUV radiation. Figure 8A depicts a first intermediate stack 80 comprising a support layer 802 on which is deposited a polydisperse mono-layer of
25 nanoparticles 804. The nanoparticles in the layer 804 may be the same as, and may be deposited by any process, as discussed above in relation to the nanoparticles in the layer 704. For example, the nanoparticles 704 may be formed from polystyrene and may be deposited on the support layer 802 in a random or pseudo-random distribution using a vertical deposition process.

[000176] A second intermediate stack 82 is created by depositing a layer of a scattering material
30 806 on the support layer 802 between the nanoparticles 804. The layer of scattering material 806 may be deposited by, for example, means of electrodeposition. In this way, the nanoparticles 804 form a mask on the support layer 802 such that the scattering material 806 forms in the gaps around the particles 804 to provide a non-homogeneous layer of scattering material. The nanoparticles 804 may optionally be shrunk prior to depositing of the scattering layer to alter the pitch between the nanoparticles and to
35 expose more of the support layer 802.

[000177] The nanoparticles 804 are optionally removed to provide a third stack 84. The third stack 84 may be used to provide a diffuser (for example, after any required back-etching of a carrier

layer (not shown)). It will be appreciated that the scattering material 806 forms an undulating, or wave-like, structure on the support layer 802. The undulating structure is defined by peaks and troughs, with the pitch between adjacent peaks defined by the size of the nanoparticle or nanoparticles 804 that separated those peaks during manufacture of the diffuser. The depth of the troughs (i.e. in the direction of propagation of the radiation beam) is similarly defined by the shape and depth of the nanoparticles 804 and the depth to which the layer of the scattering material 806 was deposited around the nanoparticles 804 (which may vary in dependence upon the desired scattering/attenuation properties and the particular scattering material used).

[000178] The undulations will match the distribution of the nanoparticles 804, such that the undulations may be randomly or quasi-randomly distributed across the scattering layer, and have a plurality of different extents in each dimension. For example, some of the peaks may have a different extent in any of the x, y or z directions than others of the peaks, and a pitch between any pair of adjacent peaks (in either the x or y directions) may be different to a pitch between any other pair of adjacent peaks. Additionally, it will be appreciated due to the differing sizes of the nanoparticles 804, the undulations will have different rates of curvature (e.g. the undulations will have different gradients).

[000179] Further, an optional second layer of scattering material may be provided as depicted in Figure 8D. In this example, an intermediate layer 808 is deposited atop the scattering layer 806 to create a further intermediate stack 86. The intermediate layer 808 may be formed from a material that is relatively optically neutral for EUV radiation (for example having a refractive index close to 1 for EUV radiation and a relatively low absorption coefficient for EUV radiation). For example, the intermediate layer 808 may be formed from silicon. The intermediate layer 808 may have a thickness in the range of 30-400 nm, and preferably in the range of 30-150 nm. The process depicted in Figures 8A-8C may then be repeated to form a second scattering layer 810 on the intermediate layer 808. It will be appreciated that the second scattering layer will provide additional scattering of the incident EUV radiation when used as a diffuser, and will help to prevent or reduce zero-order scattering.

[000180] Figures 9A-9E (collectively, Figure 9) depict a further example process for manufacturing a diffuser suitable for use with EUV radiation. As shown in Figure 9A, a first intermediate stack 90 takes the same form as the intermediate stack 80 of Figure 8A, having a layer of nanoparticles 904 deposited atop a support layer 902. Similarly, to the process depicted in Figure 8, a first scattering layer 906 is deposited on the support layer 902 between the nanoparticles 904. In contrast to the method depicted in Figure 8, a second intermediate stack 92 (Figure 9B) is created by depositing an intermediate (or sacrificial) layer 908 between the first scattering layer 906 and a further scattering layer 910. The intermediate layer 908 may be formed from a material suitable for selective etching, or any other process of removal that leaves the remaining components of the stack intact.

[000181] A third intermediate stack 94 (Figure 9C) is created by removing the nanoparticles 904, leaving cavities within layers 906, 908, 910. The nanoparticles 904 may be removed by any appropriate technique within the field sometimes referred to as “nanoparticle lithography”, and indeed any other

appropriate technique as will be apparent to the skilled person. By way of example only, the nanoparticles 904 may be removed through heating. A fourth intermediate stack 96 (Figure 9D) is created by filling the cavities with a material that is relatively optically neutral for EUV radiation. For example, the cavities may be filled with silicon (for example through a process of silicon infiltration using liquid silicon, through deposition of the silicon, some of which will fill some of the cavities, or through any other appropriate method). The material within the cavities thereby form intermediate supporting structures 912 supporting the scattering layer 910 above the scattering layer 906.

[000182] A fifth stack 98 (Figure 9E) is created by removing the intermediate layer 908. For example, the intermediate layer 908 may be removed by etching. The stack 98 thereby comprises two scattering layers 906, 910 separated and supported by relatively sparse intermediate supporting structures 912 (i.e. separated particles). As in the preceding examples, the process of Figure 9 may be repeated to create further multilayers on top of the scattering layer 910.

[000183] In an alternative arrangement, the nanoparticles 904 may be made from, for example, silicon. In this case, the nanoparticles need not be removed prior to removing the sacrificial layer. In a further alternative arrangement, both the nanoparticles and the sacrificial layer may be formed from silicon. In this case, the stack 92 depicted in Figure 9B may be considered to be the final stack and may be used to provide a diffuser (after any other processing required such as back etching or depositing of a capping layer). That is, in some arrangements, the combination of layers 910, 908, 906 and the nanoparticles 904 may together provide the scattering layer of a diffuser.

[000184] Figures 10A-10E schematically depict a further example process for creating a diffuser suitable for EUV radiation. In Figure 10A, an intermediate stack 100 is shown. The intermediate stack 100 comprises a support layer 1002 onto which is deposited a layer of nanoparticles 1004. The intermediate stack 100 may be, and may be produced in accordance with, the intermediate stacks 70, 80, 90.

[000185] A second intermediate stack 102 is created by depositing a relatively optically neutral material, for example, silicon, onto a surface between the nanoparticles 1004 between and around the nanoparticles 1004. A top portion of the at least some of the nanoparticles remains above a top-level of the optically neutral material. The optically neutral material thereby forms a filler layer 1006. Optionally, the nanoparticles 1004 may be processed to shrink the nanoparticles 1004 prior to depositing of the filler layer 1006 to further expose portions of the support layer 1002.

[000186] A third intermediate stack 104 is created by removing the nanoparticles to leave pits, or cavities, within the filler layer 1006. The nanoparticles 1004 may be removed in accordance with any appropriate technique as described above and as will depend upon their composition.

[000187] A fourth stack 106 is created by filling the cavities within the filler layer 1006 with a scattering material to form a plurality of scattering particles 1008 within the filler layer. The fourth stack 106 may be used to provide a diffuser (e.g. after any required back etching of carrier layers and/or of the support layer 1002). Alternatively, the fourth stack 106 may be an intermediate stack, and a

further intermediate stack 108 may be created by depositing a further layer 1010 of a relatively optically neutral material (which may be the same as the material used for the filler layer 1006, e.g. silicon, or may be different). The further layer 1010 provides support to create a further scattering layer (for example using the process set out in Figures 10A to 10D, or another process taught herein or elsewhere).

5 [000188] Figures 11A-11C (collectively Figure 11) depict a further example process for creating a diffuser suitable for EUV radiation. In Figure 11A, an intermediate stack 110 comprises a support layer 1102 onto which is provided a random or quasi-random multi-layer deposit of polydisperse nanoparticles 1104., such as polystyrene particles. The multi-layer deposit of nanoparticles 1104 may be provided on the support layer 1102 in any appropriate way as previously described herein, such as
10 by vertical colloidal deposition. Within a volume occupied by the nanoparticles 1104, the nanoparticles may have a packing density of the order of 60-70%. That is, for a volume occupied by the nanoparticles 60-70% of that volume may be occupied by the nanoparticles, with the remaining 30-40% being void.

[000189] A second intermediate stack 112 is created by infiltrating the voids between the nanoparticles 1104 with a scattering material 1106. The scattering material 1106 may be provided
15 according to any suitable method. Example methods of providing the scattering material 1106 include atomic laser deposition (ALD) and electrodeposition (e.g. as described in *Fabrication and optical characterization of polystyrene opal templates for the synthesis of scalable, nanoporous (photo)electrocatalytic materials by electrodeposition*, J. Mater. Chem. A, 2017, 5, 11601–11614).

[000190] Optionally, a third stack 114 is created by removing the nanoparticles 1104 to leave
20 voids 1108 within the scattering material 1106. For example, the nanoparticles may be removed through heating the second stack 112 at a high enough temperature to cause the nanoparticles to evaporate. (e.g. 500 degrees). In the example processes set out in Figures 7 to 11, nanoparticles are used to in the creation of scattering structures/layers. At intermediate stages in the manufacturing process, the nanoparticles may be removed. For example, where the nanoparticles are polystyrene particles, the
25 nanoparticles may be removed by heating and evaporation. As indicated above, other types of nanoparticles may be used in place of polystyrene, such as silica, cellulose, etc., which may also be removed through evaporation. As an alternative, titanium oxide (TiO₂) nanoparticles may also be used, and may be removed through, for example, selective etching.

[000191] In some example processes, the nanoparticles may not be removed.

30 [000192] The nanoparticles may be made from materials other than polystyrene. In another example, the nanoparticles may be made from a material that is relatively optically neutral for EUV radiation, such as silicon. Where the nanoparticles are made from, e.g., silicon (or another optically neutral material or material that provides a contrasting index of refraction in comparison to the scattering material 1106), it may be beneficial to retain the nanoparticles for the final diffuser. This
35 provides a further benefit of requiring fewer processing steps.

[000193] More generally in the examples above, multilayer stacks of materials are created to provide a diffuser suitable for EUV. As will be understood by the skilled person, methods of creating a

particular layer of a material (e.g. a scattering layer, an intermediate layer, a particle layer and such as aerosol deposition, vertical deposition, electrodeposition, etc.) described in the context of one example, may be used in any other example. Further, the embodiments described above provide methods for creating scattering surfaces or structures in a multilayer stack. It is to be understood that any one or more of the processes set out above may be combined to form multilayer stacks having multiple scattering layers or structures. For example, a scattering layer as described with reference to Figure 8C may be provided atop the porous scattering structure 510 described with reference to Figure 5. Any other combinations of scattering layers are possible and should be understood to be within the scope of the present disclosure.

[000194] Further, while different layers are generally described as having different thicknesses, it will be appreciated that those thicknesses may change in dependence upon the material used within that layer and the desired optical interaction of that layer (if any) with the incident EUV radiation. Generally, however, in each example, the diffuser layers (or scattering layers, i.e. those layers that are configured to scatter the incident EUV radiation) may have a total combined thickness of the order of between 100 nm and 1000 nm along a direction of propagation of the received radiation.

[000195] It will be appreciated that the diffuser made according to the processes described herein will be a transmissive diffuser for use with EUV radiation. In general, in order to maximise the intensity of the EUV radiation which is output by the diffuser it is desirable to minimize the attenuation caused by the layers of scattering material. This can be done by minimizing the extinction coefficient of the scattering material and/or minimizing the thickness of the scattering material. Furthermore, it will be understood that, for a given scattering material, in order to increase the amount of angular dispersion it is desirable to increase the thickness of the layer(s) whereas in order to reduce the attenuation caused by the scattering material it is desirable to decrease the thickness of the layer(s). Having a scattering material with for which the magnitude of $(1-n)$ is large allows the thickness to be reduced (while still providing reasonable angular dispersion). Having a scattering material with a small extinction coefficient k for EUV radiation allows the thickness to be increased (while still providing reasonable transmission).

[000196] Suitable materials for the layers of scattering material include: molybdenum, ruthenium, yttrium, rhodium, technetium or niobium. Figure 13 shows a plot of extinction coefficient k for EUV radiation against the magnitude of $(1-n)$ for EUV radiation for some of these three materials and for carbon and silicon.

[000197] As already stated, it is desirable to maximise the magnitude of $(1-n)$ of the scattering material for EUV radiation. In some embodiments, the magnitude of $(1-n)$ of the scattering material for EUV radiation may be greater than a threshold value of 0.06 (i.e. to the right of line 60 in Figure 13). In some embodiments, the magnitude of $(1-n)$ of the scattering material for EUV radiation may be greater than a threshold value of 0.08 (i.e. to the right of line 62 in Figure 13). In some embodiments, the magnitude of $(1-n)$ of the scattering material for EUV radiation may be greater than a threshold

value of 0.1 (i.e. to the right of line 64 in Figure 13). In some embodiments, the magnitude of $(1-n)$ of the scattering material for EUV radiation may be greater than a threshold value of 0.12 (i.e. to the right of line 66 in Figure 13).

[000198] As already stated, it is desirable to minimise extinction coefficient k of the scattering material for EUV radiation. In some embodiments, the scattering material may have an extinction coefficient k for EUV radiation of less than a threshold value of 0.04 nm^{-1} (i.e. below the line 70 in Figure 13). In some embodiments, the scattering material may have an extinction coefficient k for EUV radiation of less than a threshold value of 0.03 nm^{-1} (i.e. below the line 72 in Figure 13). In some embodiments, the scattering material may have an extinction coefficient k for EUV radiation of less than a threshold value of 0.02 nm^{-1} (i.e. below the line 74 in Figure 13). In some embodiments, the scattering material may have an extinction coefficient k for EUV radiation of less than a threshold value of 0.01 nm^{-1} (i.e. below the line 76 in Figure 13).

[000199] It will be understood that, for a given scattering material, in order to increase the amount of angular dispersion it is desirable to increase the thickness of the layer(s) whereas in order to reduce the attenuation caused by the scattering material it is desirable to decrease the thickness of the layer(s). Having a scattering material for which the magnitude of $(1-n)$ is large allows the thickness to be reduced (while still providing reasonable angular dispersion). Having a scattering material with a small extinction coefficient k for EUV radiation allows the thickness to be increased (while still providing reasonable transmission). It will therefore be appreciated that, in practice, a suitable material may be selected balancing these two requirements.

[000200] In some embodiments, the magnitude of $(1-n)$ is greater than a threshold value of 0.06 and the magnitude of the extinction coefficient k for EUV radiation is less than a threshold value of 0.01 nm^{-1} ; or the magnitude of $(1-n)$ is greater than a threshold value of 0.08 and the magnitude of the extinction coefficient k for EUV radiation is less than a threshold value of 0.02 nm^{-1} ; or the magnitude of $(1-n)$ is greater than a threshold value of 0.1 and the magnitude of the extinction coefficient k for EUV radiation is less than a threshold value of 0.03 nm^{-1} ; or the magnitude of $(1-n)$ is greater than a threshold value of 0.12 and the magnitude of the extinction coefficient k for EUV radiation is less than a threshold value of 0.04 nm^{-1} . That is, the material may be found in the cross hatched region of Figure 13.

[000201] In some embodiments, the magnitude of $(1-n)$ and the extinction coefficient k for EUV radiation satisfy the following relationship:

$$\frac{|1-n|}{(k+0.025)} > 2 \quad (1)$$

[000202] where $|1-n|$ is the magnitude of $(1-n)$. This is equivalent to being below the line 80 in Figure 13.

[000203] The embodiments described herein provide one or more layers of a scattering material (referred to herein as scattering layers, scattering structures, etc.) that cause scattering and have a

nanostructure formed thereon or therein. The layer (or layers) of scattering material can act as a random array of microlenses, causing scattering of EUV radiation that is incident on a diffuser that includes the scattering layer. This is particularly advantageous for use with EUV radiation (which may, for example, have a wavelength of 13.5 nm) because such a nanostructure comprises features with a dimension that is comparable to, or smaller than, the wavelength of the radiation that it is desired to diffuse. Under these conditions, the scattering is in the Mie-scattering regime, and significant angular dispersion can be achieved. For example, in some embodiments, the nanostructures formed in the layers of scattering material comprise features with a dimension in the range 2-220 nm.

[000204] A diffuser 120 is shown schematically in Figure 12. The diffuser 120 comprises the remnants of a carrier layer 1202 that has been back-etched to allow radiation to pass through the diffuser 120. In other embodiments, the entirety of the carrier layer may have been back-etched. The diffuser 120 further comprises a support layer 1204 and a capping layer 1206. Between the support layer 1204 and capping layer 1206 is a scattering layer 1208. In the depicted example, the scattering layer 1208 takes the form of the scattering layer 1106 of Figure 11C, although it will be appreciated that the scattering layer 1208 may take any form as described herein. In use, radiation 1210 is incident on the diffuser 120 propagating generally in the depicted z direction. This incident radiation 1210 may correspond to the radiation beam B output by the illumination system IL. It will be appreciated that the incident radiation may comprise radiation having a range of different angles of incidence and the arrow 1210 shown in Figure 12 may represent the direction of a chief ray. The scattering layer 1208 causes this incident radiation to be spread over a greater range of angles. This is indicated schematically by arrows 1212.

[000205] In use, diffuser 120 may be used to increase the range of angles with which radiation reflected from an object level marker enters the projection system PS. In particular, it may be desirable for each part of the diffuser 120 to cause a divergence of the radiation 1210 which is of the order of angular range of radiation accepted by a patterning device MA in the lithographic apparatus LA. For example, in one embodiment, the numerical aperture of the patterning device MA (and the projection system PS) in the lithographic apparatus may be of the order of 0.08, which corresponds to an angular range of approximately 7°. Therefore, it may be desirable for microlens provided by the scattering layer 1208 to cause a divergence of the radiation 1210 which is of the order of 7°. This may ensure that each field point on the patterning device MA receives radiation from substantially the whole range of angles within a cone with a full angular extent of the order of 7°. Equivalently, this may ensure that the patterning device is illuminated with a substantially full pupil fill. For some applications, such as in the case of dipole illumination (as depicted in Fig. 4A), it may be preferable to provide a diffuser to cause divergence of the radiation 1210 which is of the order of ($\sqrt{2} * 7$) degrees to provide a substantially full pupil fill. In another embodiment, the numerical aperture of the patterning device MA (and the projection system PS) in the lithographic apparatus may be higher than 0.08, for example a numerical aperture of 0.16 rad corresponding to an angular range of approximately 9°.

[000206] In some embodiments, the diffuser 120 may have a thickness (in the z-direction in Figure 12) arranged to cause a phase shift of $(2m+1)\pi$ radians for EUV radiation 1210 propagating across the thickness of the diffuser 120. Advantageously, this suppresses zero-order (or specular) scattering.

[000207] Table 1 below, lists a number of example materials that may be used as a scattering material. In Table 1, **n** is the refractive index for radiation with a wavelength of 13.5 nm (e.g. EUV radiation), **k** is the extinction co-efficient of the material for radiation with a wavelength of 13.5 nm, **Lt** indicates the maximum thickness (in a direction of propagation of the radiation) of a layer of that material that will attenuate incident radiation by no more than 90%, and **Lr** is the minimum thickness of a layer of that material that would be required for a phase shift of π radians. The column **Lr/Lt** is a ratio that indicates a balance between diffusing potential against attenuation of each material.

	n	k	Lt	Lr	Lr/Lt
	@13.5 nm	@13.5 nm	10% transmission nm	π phase shift nm	
Ce	1.0065	0.0062	398	6707	16.9
Si	0.9970	0.0018	1374	6750	4.9
La	0.9974	0.0050	494	2596	5.3
Y	0.9738	0.0023	1075	257	0.2
SiO2	0.978	0.011	224	306	1.4
SiN4	0.973	0.009	274	250	0.9
B	0.9719	0.0036	687	240	0.3
MoSi2	0.97	0.004	610	240	0.4
Y2O3	0.9620	0.01	247	177	0.7
C	0.9616	0.0069	358	175	0.5
Zr	0.9589	0.0038	650	164	0.3
Ti	0.9519	0.0142	174	140	0.8
ZrO2	0.9464	0.015	164	125	0.8
MoO2	0.9343	0.017	145	102	0.7
Nb	0.9337	0.0052	475	101	0.2
Mo	0.9233	0.0065	380	88	0.2
Ru	0.8864	0.0171	144	59	0.4

Table 1

[000208] It can be seen from Table 1 that there are a number of materials that would, for a particular thickness of material, provide sufficient transmission and sufficient scattering. In particular, those materials having a ratio **Lr/Lt** of less than 1 may be considered to provide suitable candidates. Lower

Lr/Lt ratios may indicate preferable materials, although it will be appreciated that other considerations may apply, such as ease of working, sourcing, longevity, etc.

[000209] As described above, some examples include diffusers that comprise a plurality of scattering layers, each layer arranged to change an angular distribution of EUV radiation passing through it differently. Advantageously, by providing a plurality of layers, each layer being arranged to change an angular distribution of EUV radiation passing through it differently, the diffuser provides an arrangement whereby an EUV radiation beam can be more efficiently diffused over a desired range of angles. In addition, the plurality of layers which change the angular distribution of the EUV radiation passing through it differently provides more control over the angular distribution of the radiation exiting the diffuser.

[000210] A further example process for manufacturing a diffuser suitable for EUV radiation is depicted in Figures 14A-C. Intermediate stacks of layers in the example process are depicted in cross-section in Figure 14A-C. The first intermediate stack 140 comprises a support layer 1402. The support layer 1402 may, for example, take the same or a similar form as the support layers 502, 602 described with reference to Figures 5 and 6 above. While not depicted in Figure 14, it will be appreciated that the intermediate stack 70 may comprise a carrier layer, which may take the same or a similar form as the carrier layers 504, 604 described above.

[000211] A random or quasi-random multi-layer deposit of particles 1406 is provided to the support layer 1402 in any appropriate way as previously described herein, such as by vertical colloidal deposition. The particles are polydisperse. Each particle of the multi-layer deposit of particles 1406 is in contact with one or more adjacent particles such that voids 1408 are formed between adjacent particles. The multi-layer deposit of particles 1406 may be considered to form a body of particles 1406. The particles in the body of particles 1406 can be referred to as contacting particles, as each particle is in contact with one or more adjacent particles.

[000212] The body of particles 1406 includes a first population of particles 1406A of a first material and a second population of particles 1406B of a second material, and may be referred to as a binary mixture of particles. The two materials are scattering materials, examples of which are discussed in more detail with reference to Figure 13 and Table 1. In particular, the first and second material are selected to have different refractive indices. The composition of the binary mixture (i.e. the composition of the first population of particles 1406A and the population of the second population of particles 1406B) is selected based on the desired properties of the diffuser. Example binary mixtures include silicon and molybdenum, ruthenium and silicon, molybdenum silicide and silicon.

[000213] In addition to the composition of the particles 1406A, 1406B, other characteristics of the body of particles 1406 may be selected based on the desired optical properties of the diffuser. For example, the angular distribution of scattering of radiation through the diffuser depends on particle size, particle size distribution, and packing density. By altering the composition, particle size, particle size distribution, and/or packing density, properties such as scattering angle, suppression of zero-order

scattering, emissivity, and attenuation. Within a volume occupied by the body of particles 1406, the particles 1406A, 1406B may have a packing density of the order of 60-70%. That is, for a volume occupied by the particles 60-70% of that volume may be occupied by the particles 1406A, 1406B, with the remaining 30-40% being empty (i.e. comprising voids 1408).

5 [000214] In a second intermediate stack 142, the body of particles 1406 are fixed in position, for example by fusing the particles, to form a fused body of particles 1014. Procedures for fixing the particles 1406 may include the provision of heat and/or pressure. Specifically, sintering may be used to fix the particles, for example laser flash sintering, spark plasma sintering or electrical discharge sintering. Other methods of fixing are available. Fixing particles in position may be performed as part
10 of the deposition process or as a separate process.

[000215] In a third intermediate stack 144, a protective layer is be provided atop the fused body of particles 1410. The protective layer may provide protection to the scattering layer (i.e. the fused body of particles 1410) in use e.g. in the environment in a lithographic apparatus. Additionally or alternatively, the protective layer may provide increased emissivity to the diffuser.

15 [000216] Figures 15A-C illustrate an example diffuser made according to the process described with reference to Figures 14A-C, and the performance of said diffuser. In particular, the particles comprise molybdenum silicide and silicon (MoSi and Si) and are polydisperse with radii between 75 to 85 nm. The particles are deposited with a (quasi-)random distribution. Approximately six layers of particles are deposited on the support layer.

20 [000217] Figure 15A depicts a height map 1500 of the resulting body of particles. The height map 1500 omits the support layer, but in use the body of particles would be supported by a support layer.

[000218] Figure 15B and 15C depict the scattering angle for a plane wave of EUV radiation incident upon the example diffuser. In particular Figures 15B and 15C collaborate to illustrate the beam
25 profile of scattered EUV radiation, with Figure 15B depicting the intensity of scattered EUV radiation across a range of angles in a plane orthogonal to the direction of travel of the radiation, and Figure 15C depicts a cross-sectional representation of said beam profile. The EUV radiation experiences scattering at a wide range of angles up to 40°. The EUV radiation experiences scattering with relatively constant intensity within an angular distribution of approximately 10°. As such, such an example diffuser may
30 provide an effective diffuser for a high numerical aperture patterning device.

[000219] A further example process for manufacturing a diffuser suitable for EUV radiation is depicted in Figures 16A and 16B. In particular, the diffuser in Figures 16A and 16B is a holographic diffuser suitable for EUV radiation. Intermediate stacks 160, 162 in the example process are depicted in cross-section.

35 [000220] The first intermediate stack 160 comprises a support layer 1602. The support layer 1602 may, for example, take the same or a similar form as the support layers 502, 602 described with reference to Figures 5 and 6 above. While not depicted in Figures 16A and 16B, it will be appreciated

that the intermediate stack 70 may comprise a carrier layer, which may take the same or a similar form as the carrier layers 504, 604 described above.

[000221] Structures 1604 are provided atop the support layer 1602. The structures 1604 may be provided in accordance with any suitable technique. For example, and as depicted in Figure 16, the structures 1604 may be provided through photolithography using an electron-beamed mask. Alternatively, the structures may be created using electron beam lithography or nanoimprint lithography etc.

[000222] Voids 1605 are formed between the structures 1604. That is, within the volume of space occupied by the structures 1604, there are volumes which contain no structure which hence comprise voids 1605.

[000223] The structures 1604 (and hence voids 1605) are arranged in a holographic interference pattern such that, when illuminated by radiation, the radiation is diffracted so as to form a hologram. An arrangement of structures is selected such that a desired hologram is produced. The hologram may be produced at an input plane of a measurement system, for example a measurement system as described above.

[000224] In an example arrangement, the holographic interference pattern is selected which forms a hologram with an angular profile (i.e. an angular intensity profile) that is substantially constant across a selected angular distribution, for example 10° . An angular profile that is substantially constant across may be referred to as a top hat profile. In another example arrangement, the holographic interference pattern is selected so as to form a hologram with an angular profile which is more intense in a radially outer portion of the hologram compared to a radially inner portion of the hologram. That is, the holographic diffuser diffuses EUV radiation such that light is scattered with a higher intensity for larger scattering angles.

[000225] The structures 1604 are arranged upon the plane of the support layer 1602 (e.g. in an x-y plane) in a particular arrangement. Each portion of each structure 1604 has a height by which it extends from the support layer 1602. The height may be referred to as a thickness of the portion of the structure 1604. The arrangement of structures 1604 on the support layer 1602 comprises a combination of the positions and thicknesses of each structure 1604 on the support layer 1602, and can be referred to as a thickness profile $L(x, y)$ of the holographic interference pattern. A method of determining the thickness profile $L(x, y)$ is described in more detail further below.

[000226] The second intermediate stack 162 depicts a step of providing a padding layer 1606 atop the support layer 1602 and/or structures 1604. The padding layer 1606 may be provided in accordance with any suitable technique, for example atomic layer deposition (ALD) or electrodeposition.

[000227] The padding layer 1606 is provided so as to fill the volume which previously comprised voids 1605 (e.g. as shown in Figure 16A). The padding layer 1606 is provided with a thickness such that the combined thickness of the structure 1604 and the padding layer 1606 in the z-direction (i.e. extending from the support structure 1604) is substantially constant. The padding layer 1606 may be

considered to level the structures, providing a smooth surface (e.g. substantially smooth on a microscale or nanoscale).

[000228] The padding layer 1606 comprises a material with a different refractive index than the material of the structures 1604. In particular, the padding layer 1606 comprises a material with a different real part of the refractive index ($n_{padding}$) compared to the real part of the refractive index ($n_{structure}$) of the structures 1604.

[000229] A differential refractive index $\delta n_{padding}, \delta n_{structure}$ may be used to quantify the amount by which the real part of the refractive index $n_{padding}, n_{structure}$ of the padding layer 1606 and structures 1604 deviates from 1. When a padding layer 1606 and structures 1604 are combined in a thin layer as depicted in Figure 16B, the thin layer has an effective real part of the refractive index n_{eff} approximated using equation (2). For simplicity, the effective real part of the refractive index may be referred to simply as the effective refractive index.

$$n_{eff} = \delta n_{padding} - \delta n_{structure} \quad (2)$$

[000230] The real part of the refractive index $n_{padding}, n_{structure}$ affects the refraction of radiation, and hence controls the scattering properties of the diffuser. The padding layer 1606 is chosen such that it has a real part of the refractive index $n_{padding}$ that is higher than the real part of the refractive index $n_{structure}$ of the structures 1604.

[000231] The padding layer 1606 further comprises a material with a similar imaginary part of the refractive index ($k_{padding}$) compared to the similar imaginary part of the refractive index ($k_{structure}$) of the structures 1604. When a padding layer 1606 and structures 1604 are combined in a thin layer as depicted in Figure 16B, the thin layer has an effective imaginary part of the refractive index n_{eff} approximated using equation (3).

$$k_{eff} = \delta k_{structure} - \delta k_{padding} \quad (3)$$

[000232] The effective imaginary part of the refractive index k_{eff} affects the attenuation of the diffuser. As such, by providing a padding layer 1606 and structures 1604 with a similar imaginary part of the refractive index, they each have comparable attenuation.

[000233] The effective layer thickness L of the thin layer may be approximated using equation (4).

$$L = \frac{\lambda}{n_{eff}} \quad (4)$$

[000234] Radiation travelling through the diffuser experiences phase shift and attenuation based on the thickness of each of the padding layer 1606 and structure 1604 at the position of the diffuser through which the radiation travels. A phase shift of zero (0) is experienced when radiation passes through an area of the diffuser in which the thickness of the padding layer 1606 is zero (0) and the thickness of the structure 1604 is L . A phase shift of pi (π) is experienced when radiation passes through an area of the diffuser in which the padding layer 1606 and structure 1604 each have a thickness of $\frac{L}{2}$. A phase shift of two pi (2π) is experienced when radiation passes through an area of the diffuser in which the thickness

of the padding layer 1606 is L and the thickness of the structure 1604 is zero (0). By limiting the thickness of the padding layer 1606 and structures 1604 to multiples of $\frac{L}{2}$, the phase shift may be controlled to multiples of π phase shift, thereby providing controlled phase modulation. The use of such controlled thicknesses in a holographic diffuser may be referred to as binary phase modulation or ternary phase modulation.

[000235] It is noted that a holographic diffuser as described herein employs controlled phase modulation due to the controlled selection of thicknesses and arrangements within the scattering layer. This is in contrast to other diffusers described herein, for example the diffuser as described with reference to Figures 14A-C, which uses random phase modulation due to the (quasi-)random arrangement of nanoparticles in the scattering layer.

[000236] The thickness of portions of the padding layer 1606 and structures 1604 may be further limited to a minimum thickness, e.g. 50nm or 0nm, for example based on manufacturing limitations. The thickness of portions of the padding layer 1606 and structures 1604 may be further limited to a maximum thickness, e.g. 200nm, for example to limit attenuation.

[000237] An example method of determining an arrangement and thickness of the structures 1604 is as follows. Considering a thin diffusing layer which extends in a plane denoted the (x, y) plane, the scattering of light through the diffusing layer may be approximated according to equation (5).

$$M(x, y) = e^{\frac{2\pi}{\lambda}(i\Delta n - k)L(x, y)} \quad (5)$$

[000238] $M(x, y)$ quantifies the scattering angle experienced by a ray of radiation with wavelength λ , travelling through a particular position (in x and y) of the diffusing layer. The calculated scattering of light $M(x, y)$ may be referred to as an angular profile $M(x, y)$. The diffusing layer has a thickness profile $L(x, y)$ which represents the effective thickness of the diffusing layer at each position in x and y . Δn denotes the deviation of the real part of the refractive index from 1 of the diffusing layer, and k is the imaginary part of the refractive index.

[000239] Given the approximation in equation (4), the spatial distribution of diffused light $S(fx, fy)$ (i.e. a spatial intensity profile) associated with the diffusing layer may be approximated by taking a Fourier transform $\mathfrak{F}$ according to equation (5).

$$S(fx, fy) = \mathfrak{F}(M(x, y)) \quad (5)$$

[000240] A desired angular profile $M_D(x, y)$ can be selected. The desired angular profile $M_D(x, y)$ may comprise, for example and as described above, a top hat profile. Given the desired angular profile $M_D(x, y)$, approximations such as those in equations (4) and (5) may be used to determine a thickness profile $L(x, y)$ which will generate a hologram with the desired angular profile $M_D(x, y)$ given radiation of a specific wavelength λ . It should be understood that, additionally or alternatively, a similar approach may be used to determine a refractive index profile (for example the deviation Δn of the real part of the refractive index from 1 and/or the imaginary part of the refractive index) which will generate a hologram with the desired angular profile $M_D(x, y)$, given radiation of a specific wavelength λ .

Furthermore, rather than selecting a desired angular profile $M_D(x, y)$, a desired spatial intensity profile at a distance from the holographic diffuser may be selected for the determination of a corresponding thickness profile. However, in the example described herein, determination of the thickness profile $L(x, y)$ is described for simplicity.

[000241] In a specific example, the determination of the thickness profile $L(x, y)$ is performed numerically using the Gerchberg-Saxton algorithm. The algorithm receives the desired angular profile $M_D(x, y)$, a wavelength λ a refractive index and/or deviation Δn of a selected material (e.g. one of the scattering substances described above with reference to Table 1). The algorithm then iteratively performs calculations such as modified versions of equations (2) and (3) in order to determine a thickness profile $L(x, y)$. The determination may be an estimate. The number of iterations may be predetermined. Alternatively, the number of iterations may be selected based on a quality metric associated with the estimated thickness profile $L(x, y)$. The algorithm may use height limits, for example to limit the thickness profile such that no area of the diffusing layer exceeds a maximum thickness and/or is thinner than a minimum thickness. Such maximum and minimum thicknesses may be selected based on manufacturing methods, for example resolution limits of a manufacturing method. It should be understood that other approaches may be used to determine the thickness profile $L(x, y)$ and/or refractive index profile, for example an analytical approach may be used or different numerical methods may be used.

[000242] Returning to Figure 16A and 16B, by arranging the structures 1604 corresponding to the determined thickness profile $L(x, y)$, a holographic diffuser may be fabricated which scatters radiation with the desired angular profile $M_D(x, y)$.

[000243] Figures 17, 18 and 19 illustrate example holographic diffusers and their performance, each comprising molybdenum, ruthenium and molybdenum silicide, respectively. The example holographic diffusers of Figures 17, 18 and 19 do not comprise a padding layer but instead comprise voids between the structures thereon.

[000244] Each holographic diffuser comprises structures 1604 arranged according to a determined thickness profile $L(x, y)$. The thickness profile $L(x, y)$ for each holographic diffuser is determined using the above described method, for a desired angular profile $M_D(x, y)$, comprising a top hat profile with an angular distribution of 9° . The thickness profile $L(x, y)$ for each holographic diffuser is determined using refractive index data for the material of which each respective holographic diffuser comprises (i.e. molybdenum, ruthenium and molybdenum silicide).

[000245] Figure 17 illustrates a thickness profile $L(x, y)$ 172 determined for a holographic diffuser comprising molybdenum structures. The thickness profile $L(x, y)$ comprises a quasi-random arrangement of structures with heights measuring $0, \frac{L}{2}$ or L , with L calculated for molybdenum.

[000246] Also shown in Figure 17 is a phase shift profile 170 and transmission profile 174 for a holographic diffuser comprising molybdenum structures. The phase shift profile 170 illustrates how the

phase shift experienced by EUV radiation transmitted through the holographic diffuser is, at different positions across the diffuser, $-\pi$, 0 or π (i.e. equivalent to 0, π and 2π), in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The transmission profile 174 illustrates how the transmission of EUV radiation through the holographic diffuser ranges from 0.6 to 1, in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The mean transmission of the holographic diffuser is approximately 78%.

[000247] Also shown in Figure 17 is the angular profile 176 of EUV radiation diffused by the holographic diffuser comprising molybdenum structures. The angular profile 176 is generally constant within an angular distribution of 9° . That is, the angular profile 176 generally corresponds to the desired angular profile $M_D(x, y)$. The angular profile 176 does not correspond exactly to the desired angular profile $M_D(x, y)$, as there is some non-uniformity within the angular distribution of 9° . In particular, there is a bright spot 177 at 0° , indicating some zero-order scattering. Furthermore, some EUV radiation is scattered by more than 9° which is apparent due to the appearance of a 'halo' 178 of scattered light at angles greater than 9° .

[000248] Figure 18 illustrates a thickness profile $L(x, y)$ 182 determined for a holographic diffuser comprising ruthenium structures. The thickness profile $L(x, y)$ comprises a quasi-random arrangement of structures with heights measuring $0, \frac{L}{2}$ or L , with L calculated for ruthenium.

[000249] Also shown in Figure 18 is a phase shift profile 180 and transmission profile 184 for a holographic diffuser comprising ruthenium structures. The phase shift profile 180 illustrates how the phase shift experienced by EUV radiation transmitted through the holographic diffuser is, at different positions across the diffuser, $-\pi$, 0 or π (i.e. equivalent to 0, π and 2π), in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The transmission profile 184 illustrates how the transmission of EUV radiation through the holographic diffuser ranges from 0.4 to 1, in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The mean transmission of the holographic diffuser is approximately 66%.

[000250] Also shown in Figure 18 is the angular profile 186 of EUV radiation diffused by the holographic diffuser comprising ruthenium structures. The angular profile 186 is generally constant within an angular distribution of 9° . That is, the angular profile 186 generally corresponds to the desired angular profile $M_D(x, y)$. The angular profile 186 does not correspond exactly to the desired angular profile $M_D(x, y)$, as there is some non-uniformity within the angular distribution of 9° . In particular, there is a bright spot 187 at 0° , indicating some zero-order scattering. Furthermore, some EUV radiation is scattered by more than 9° which is apparent due to the appearance of a 'halo' 188 of scattered light at angles greater than 9° .

[000251] Figure 19 illustrates a thickness profile $L(x, y)$ 192 determined for a holographic diffuser comprising molybdenum silicide structures. The thickness profile $L(x, y)$ comprises a quasi-random arrangement of structures with heights measuring $0, \frac{L}{2}$ or L , with L calculated for molybdenum silicide.

[000252] Also shown in Figure 19 is a phase shift profile 190 and transmission profile 194 for a holographic diffuser comprising molybdenum silicide structures. The phase shift profile 190 illustrates how the phase shift experienced by EUV radiation transmitted through the holographic diffuser is, at different positions across the diffuser, $-\pi$, 0 or π (i.e. equivalent to 0, π and 2π), in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The transmission profile 194 illustrates how the transmission of EUV radiation through the holographic diffuser ranges from 0.45 to 1, in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The mean transmission of the holographic diffuser is approximately 68%.

[000253] Also shown in Figure 19 is the angular profile 196 of EUV radiation diffused by the holographic diffuser comprising molybdenum silicide structures. The angular profile 196 is generally constant within an angular distribution of 9° . That is, the angular profile 196 generally corresponds to the desired angular profile $M_D(x, y)$. The angular profile 196 does not correspond exactly to the desired angular profile $M_D(x, y)$, as there is some non-uniformity within the angular distribution of 9° . In particular, there is a bright spot 197 at 0° , indicating some zero-order scattering. Furthermore, some EUV radiation is scattered by more than 9° which is apparent due to the appearance of a 'halo' 198 of scattered light at angles greater than 9° .

[000254] Figure 20 illustrates a thickness profile $L(x, y)$ 2002 of the ruthenium structures as determined for a holographic diffuser comprising ruthenium structures and a silicon oxide padding layer. The thickness profile $L(x, y)$ 2002 is shown prior to deposition of the padding layer. The thickness profile $L(x, y)$ 2002 comprises a quasi-random arrangement of structures with heights measuring 0, $\frac{L}{2}$ or L , with L calculated for ruthenium. Following provision of the padding layer, the resulting thickness profile is substantially equal to L without any substantial thickness variation.

[000255] Also shown in Figure 20 is a phase shift profile 2000 and transmission profile 2004 for a holographic diffuser comprising ruthenium structures and a silicon oxide padding layer. The phase shift profile 2000 illustrates how the phase shift experienced by EUV radiation transmitted through the holographic diffuser is, at different positions across the diffuser, $-\pi$, 0 or π (i.e. equivalent to 0, π and 2π), in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The transmission profile 2004 illustrates how the transmission of EUV radiation through the holographic diffuser ranges from 0.3 to 0.5, in a quasi-random pattern that generally corresponds to the quasi-random arrangement of structures. The mean transmission of the holographic diffuser is approximately 39%.

[000256] Also shown in Figure 20 is the angular profile 2006 of EUV radiation diffused by the holographic diffuser comprising molybdenum silicide structures. The angular profile 2006 is generally constant within an angular distribution of 9° . That is, the angular profile 2006 generally corresponds to the desired angular profile $M_D(x, y)$. The angular profile 2006 does not correspond exactly to the desired angular profile $M_D(x, y)$, as there is some non-uniformity within the angular distribution of 9° .

However, the non-uniformity is lower compared to the non-uniformity of the previous example holographic diffusers without a padding layer. In particular, there is no bright spot at 0° , indicating reduced zero-order scattering

[000257] A holographic diffuser comprising a padding layer may be beneficially used in applications where a highly uniform scattering profile is desired. A holographic diffuser without a padding layer be beneficially used in applications where a high EUV transmission is desired.

[000258] According to some embodiments of the present invention, there is provided a measurement system for determining an aberration map or relative intensity map for a projection system PS comprising one of the above described diffusers. According to some embodiments of the present invention, there is provided a lithographic apparatus comprising such a measurement system.

[000259] In use, the diffuser is disposed such that it can be moved into and out of the optical path of radiation between the illumination system IL and the projection system PS. Such an optical apparatus provides control over the angular distribution of radiation in field planes of the lithographic apparatus LA that are downstream of the apparatus. Such field planes include the plane of the support structure MT (i.e. the plane of a patterning device MA) and the plane of the substrate table WT (i.e. the plane of a substrate W). In order to ensure that the diffuser can be moved into and out of the optical path of radiation between the illumination system IL and the projection system PS, the diffuser may be mounted on a patterning device masking blade of the lithographic apparatus LA, as now discussed.

[000260] The lithographic apparatus LA is provided with four reticle masking blades (which may also be referred to as patterning device masking blades), which define the extent of the field on the patterning device MA which is illuminated. The illumination system IL is operable to illuminate a generally rectangular region of an object disposed on the support structure MT (for example a patterning device MA). This generally rectangular region may be referred to as the slit of the illumination system IL and is defined by four reticle masking blades. The extent of the generally rectangular region in a first direction, which may be referred to as the x direction, is defined by a pair of x masking blades. The extent of the generally rectangular region in a second direction, which may be referred to as the y direction, is defined by a pair of y masking blades.

[000261] Each of the masking blades is disposed close to, but slightly out of the plane of the support structure MT. The x masking blades are disposed in a first plane and the y masking blades are disposed in a second plane.

[000262] Each of the masking blades defines one edge of a rectangular field region in the plane of the object which receives radiation. Each blade may be independently movable between a retracted position wherein it is not disposed in the path of the radiation beam and an inserted position wherein it at least partially blocks the radiation beam projected onto the object. By moving the masking blades into the path of the radiation beam, the radiation beam B can be truncated (in the x and/or y direction) thus limiting the extent of the field region which receives radiation beam B.

[000263] The x direction may correspond to a non-scanning direction of the lithographic apparatus LA and the y direction may correspond to a scanning direction of the lithographic apparatus LA. That is, the object (and a substrate W in the image plane) may be movable in the y-direction through the field region so as to expose a greater target region of the object (and the substrate W) in a single dynamic scanning exposure. During such a dynamic scanning exposure the y masking blades are moved to control the field region so as to ensure that no parts of the substrate W outside of a target region are exposed. At the start of the scanning exposure one of the y masking blades is disposed in the path of the radiation beam B, acting as a shutter, such that no part of the substrate W receives radiation. At the end of the scanning exposure the other y masking blade is disposed in the path of the radiation beam B, acting as a shutter, such that no part of the substrate W receives radiation.

[000264] The diffuser may be mounted on a patterning device masking blade of the lithographic apparatus LA. In particular, the diffuser may be positioned such that it is not generally disposed in the path of the radiation beam when the masking blades are disposed in a position within their nominal movement ranges during a scanning exposure.

[000265] The diffuser may have any of the following properties. The diffuser may result in an angular scattering distribution in at least one scattering direction having a width of 5° to 10° or greater. The diffuser may result in a uniform or Gaussian angular power distribution (as a function of scattering angle). The diffuser may have an absorption for EUV radiation of less than 90%, for example less than 50% (for a single pass). The diffuser may have a lifetime more than 7 years in a lithographic apparatus (for example with an illumination duty cycle of the order of ~ 0.1 -1%). The diffuser may be operable to survive an un-attenuated EUV power density of the order of 1 to 10 W/cm². The diffuser may have dimensions of the order of ~ 1 to 3 mm² x 1 to 3 mm².

[000266] Where reference is made to vertical colloidal deposition as a deposition method, the following procedures may be additionally or alternatively used: inkjet printing and spin coating.

[000267] According to another embodiment, a transmissive diffuser comprises a support structure comprising an porous structure with holes. The support structure may be a network of nanotubes, e.g. carbon nanotubes, multi-walled carbon nanotubes, bundles of single-wall carbon nanotubes, Boron-Nitride or MoS₂ nanotubes as core fibres. The nanotubes may be randomly aligned, providing the structural support for an optically active diffuser material deposited onto the tubes.

[000268] A scattering layer at least partially covers the support structure, configured to scatter the received radiation. The scattering layer comprises at least one of Mo, Y, Zr, Nb, Ru. The scattering layer provides the optical active material to diffuse the light into a desired light profile. Ideally the scattering layer has a relatively low absorption of EUV light and a high contrast in refractive index compared to that of vacuum. The scattering layer has a thickness of at least 10nm, optionally at least 20nm, optionally at least 40nm, optionally at least 100nm. The thickness determines the absorption.

[000269] Optionally, the scattering layer supports a top layer comprising at least one MoO₃, Y₂O₃, ZrO₂, Al₂O₃, HfO₂, ZrO₂, Ru, W, a metal, with a thickness of at least 0.3nm, optionally at least 1nm.

This top layer may provide plasma and high-temperature resistance and mitigation. The diffuser may be a holographic diffuser.

[000270] The support structure described in this embodiment may also be used in other embodiments.

5 [000271] 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.

10 [000272] 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
15 lithographic tool may use vacuum conditions or ambient (non-vacuum) conditions.

[000273] 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 clauses
20 set out below.

[000274] Clause 1. A diffuser configured to receive and transmit radiation, wherein the diffuser comprises: a scattering layer configured to scatter the received radiation, the scattering layer comprising a first substance and having distributed therein a plurality of voids, wherein either: the first substance is a scattering substance, or at least one of the voids contains a scattering substance and the first
25 substance has a lower refractive index than the scattering substance.

[000275] Clause 2. The diffuser of clause 1, wherein the first substance is the scattering substance.

[000276] Clause 3. The diffuser of clause 2, wherein scattering substance comprises a foam having pores and the voids are provided by the pores and the voids contain a vacuum or an inert gas.

[000277] Clause 4. The diffuser of clause 2, wherein the voids contain one of silicon or silicon
30 nitride.

[000278] Clause 5. The diffuser of clause 1, wherein voids contain the scattering substance.

[000279] Clause 6. The diffuser of clause 5, wherein the first substance comprises a porous silicon-based structure, the voids being defined by pores of the first substance.

[000280] Clause 7. The diffuser of any of clauses 1 to 4, wherein the scattering substance
35 comprises a body of contacting particles and the voids are provided between adjacent particles.

[000281] Clause 8. The diffuser of clause 7, wherein each particle within the body of contacting particles is fused with at least one other particle in the body of contacting particles.

[000282] Clause 9. The diffuser of clause 7 or 8, wherein the particles comprise a binary mixture comprising a first material and a second material with a refractive index different to the first material.

[000283] Clause 10. The diffuser of clause 9, wherein the first material comprises silicon.

[000284] Clause 11. The diffuser of clause 9 or 10, wherein the second material comprises molybdenum or ruthenium.

[000285] Clause 12. The diffuser of any of clauses 7 to 11, wherein the particles have an extent which is in the order of nanometers in at least one dimension.

[000286] Clause 13. The diffuser of any of clauses 7 to 12, wherein the particles differ in size in at least one dimension.

[000287] Clause 14. The diffuser of any preceding clause, wherein the scattering substance comprises a substance having a ratio of a first parameter to a second parameter of or less than 1, wherein the first parameter is a maximum thickness of a layer of the substance that will allow 10 percent transmission of the received radiation and the second parameter is a minimum thickness of a layer of the substance that will result in a phase shift of π .

[000288] Clause 15. The diffuser of any preceding clause, wherein voids are distributed in a plurality of layers within the first substance, each layer lying generally in a plane perpendicular to the direction of propagation of the radiation during use.

[000289] Clause 16. The diffuser of any preceding clause, wherein the voids are distributed in a single layer within the first substance, the layer lying generally in a plane perpendicular to the direction of propagation of the radiation during use.

[000290] Clause 17. The diffuser of any preceding clause, wherein the scattering substance comprises a dealloyed material.

[000291] Clause 18. The diffuser of any preceding clause, wherein the voids have an extent which is in the order of nanometers in at least one dimension.

[000292] Clause 19. The diffuser of any preceding clause, wherein the voids are polydisperse within the first material.

[000293] Clause 20. The diffuser of any preceding clause, wherein the voids are randomly or quasi-randomly arranged within the first material.

[000294] Clause 21. The diffuser of any preceding clause, wherein the scattering layer has a thickness of between 50 nm to 1000 nm.

[000295] Clause 22. The diffuser of any preceding clause configured such that the angular scattering distribution in at least one scattering direction has a width of 5° or greater.

[000296] Clause 23. The diffuser of any preceding clause, wherein the scattering substance comprises one of the following: molybdenum, ruthenium, niobium, rhodium, yttrium or technetium.

[000297] Clause 24. A diffuser according to any preceding clause, comprising a plurality of scattering layers.

[000298] Clause 25. The diffuser according to clause 24, wherein a first scattering layer is separated from a second scattering layer by an intermediate layer.

[000299] Clause 26. The diffuser according to clause 25, wherein the intermediate layer comprises silicon.

5 [000300] Clause 27. The diffuser according to clause 25 or 26, wherein the intermediate layer comprises a layer of separated particles having a lower refractive index than the scattering substance.

[000301] Clause 28. The diffuser of clause 27, wherein the separated particles are arranged randomly or quasi-randomly within the intermediate layer.

10 [000302] Clause 29. The diffuser of clause 27 or 28, wherein the separated particles comprises particles which differ in size in at least one dimension.

[000303] Clause 30. The diffuser of clause 1, wherein the first substance and the voids cooperate to produce, upon receipt of radiation at a surface of the scattering layer, a hologram.

15 [000304] Clause 31. The diffuser of clause 30, wherein the hologram has an angular intensity profile which is at least as intense in a radially outer portion of the hologram as it is in a central region of the hologram.

[000305] Clause 32. The diffuser of clause 31, wherein the radially outer portion is angularly spaced from the centre of the hologram by at least 9°.

[000306] Clause 33. The diffuser of any of clauses 30 to 32, wherein the first substance comprises a plurality of structures of varying thicknesses perpendicular to the surface of the scattering layer.

20 [000307] Clause 34. The diffuser of clause 33, wherein: the diffuser is operable to form the hologram upon receipt of radiation with a wavelength λ ; the holographic diffuser has an effective refractive index n_{eff} ; and the thickness of each of the plurality of structures is an integer multiple of $\frac{\lambda}{n_{eff}}$.

25 [000308] Clause 35. The diffuser of any of clause 30 to 34, wherein the voids contain a second substance.

[000309] Clause 36. The diffuser of clause 35, wherein the real part of the refractive index of the second substance is different to the real part of the refractive index of the first substance, and the imaginary part of the second substance is similar to the imaginary part of the refractive index of the first substance.

30 [000310] Clause 37. The diffuser of clause 35 or 36, wherein the combined first substance and second substance have a combined thickness profile that is substantially constant.

[000311] Clause 38. The diffuser of any of clauses 30 to 37, wherein the first substance comprises one of the following: molybdenum, ruthenium, niobium, rhodium, yttrium or technetium.

35 [000312] Clause 39. The diffuser of any of clauses 35 to 38, wherein the second substance comprises silicon.

[000313] Clause 40. A holographic diffuser comprising a scattering layer comprising a plurality of structures configured to produce, upon receipt of extreme ultraviolet radiation at a surface of the scattering layer, a hologram, wherein the hologram has an angular intensity profile which is at least as intense in a radially outer portion of the hologram compared to a central region of the hologram.

5 [000314] Clause 41. The diffuser of any preceding clauses, further comprising a protective layer configured to protect the scattering layer against EUV plasma etching.

[000315] Clause 42. The diffuser of any preceding clause, wherein the diffuser further comprises a cap layer which at least partially covers scattering layer to protect the scattering layer during use.

10 [000316] Clause 43. A measurement system for determining an aberration map or relative intensity map for a projection system comprising the diffuser of any preceding clause.

[000317] Clause 44. The measurement system of clause 43, the measurement system comprising: a patterning device; an illumination system arranged to illuminate the patterning device with radiation; and a sensor apparatus; wherein the illumination system and patterning device are configured such that the projection system receives at least a portion of the radiation scattered by the patterning device and the sensor apparatus is configured such that the projection system projects the received radiation onto the sensor apparatus; and wherein the diffuser is operable to receive the radiation produced by the illumination system and to alter an angular distribution of the radiation before it illuminates the patterning device.

15 [000318] Clause 45. The measurement system of clause 44, wherein the diffuser is moveable between at least: a first, operating position wherein the diffuser is at least partially disposed in a path of the radiation produced by the illumination system and is arranged to alter an angular distribution of the radiation before it illuminates the patterning device; and a second, stored position wherein the diffuser is disposed out of the path of the radiation produced by the illumination system.

20 [000319] Clause 46. The measurement system of any of clauses 43 to 45 when comprising the diffuser of any of clauses 30 to 40, wherein the hologram is formed at an input plane of the measurement system.

25 [000320] Clause 47. A lithographic apparatus comprising: the measurement system of any one of clauses 43 to 46; and a projection system configured to receive at least a portion of the radiation scattered by the patterning device and configured to project the received radiation onto the sensor apparatus.

30 [000321] Clause 48. The lithographic apparatus of clause 47, wherein the diffuser is mounted on a patterning device masking blade of the lithographic apparatus, an edge of the patterning device masking blades defining a field region of the lithographic apparatus.

35 [000322] Clause 49. A method of forming a diffuser to receive and transmit radiation according to clauses 1-3 or 14-20, the method comprising: forming an alloy layer, the layer comprising a first substance and a third substance, wherein the first substance is a scattering substance; dealloying the

alloy layer so as to remove the third substance from the alloy layer and so as to form a scattering layer comprising the first substance and having distributed therein a plurality of voids.

[000323] Clause 50. A method of forming a diffuser for receiving and transmitting radiation, the method comprising: forming a scattering layer by infiltrating a porous structure with a scattering material.

[000324] Clause 51. The method of clause 50, wherein the scattering layer is formed on a support layer.

[000325] Clause 52. A method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles on a surface of a support layer to form a mask; depositing a scattering material onto the support layer over the mask to form a scattering layer around the plurality of particles.

[000326] Clause 53. The method of clause 52, further comprising shrinking one or more of the plurality of particles deposited on the support layer, so as to expose a greater area of the surface of the support layer prior to depositing the scattering material.

[000327] Clause 54. The method of clause 52 or 53, wherein the particles are deposited on the support layer through vertical colloidal deposition.

[000328] Clause 55. The method of clause 52, 53 or 54, wherein the particles form a single layer deposited on the surface of the support layer and the scattering layer forms an undulating scattering surface on the support layer.

[000329] Clause 56. The method of clause 52, 53 or 54, wherein the particles form a plurality of layers deposited on the surface of the support layer, each of the plurality of layers lying, in use, in a plane generally perpendicular to a direction of received radiation.

[000330] Clause 57. The method of any one of clauses 52 to 56, further comprising removing the particles after depositing the scattering material.

[000331] Clause 58. A method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles on a surface of a support layer to form a mask; depositing a second material onto the surface of the support layer over the mask to form a layer of the second material around the plurality of particles; removing at least some of the plurality of particles to form pits within the layer of the second material; depositing a scattering material into at least some of the pits within the second material to form scattering features within the layer of the second material.

[000332] Clause 59. A method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles onto a surface of a support layer to form a mask; depositing a second material onto the surface of the support layer over the mask; selectively etching the surface of the support layer to form a plurality of structures on the surface of the support layer; depositing a scattering material onto the surface of the support layer, the scattering material forming over the plurality of structures to form a scattering layer; wherein the second material is a catalyst and the selective etching comprises etching areas of the support layer in contact with the second material or

wherein the second material is a protective material and the selective etching comprises etching areas of the support layer not in contact with the second material.

[000333] Clause 60. A method of forming a diffuser for receiving and transmitting radiation, the method comprising: depositing a plurality of particles onto a surface of a support layer such that the particles form a body of contacting particles.

[000334] Clause 61. The method of clause 50, wherein depositing comprises at least one of: vertical colloidal deposition, spin coating and inkjet printing.

[000335] Clause 62. The method of clause 60 or 61, wherein depositing comprises fusing the plurality of particles.

[000336] Clause 63. The method of clause 62, wherein the plurality of particles are fused through the provision of heat and/or pressure.

[000337] Clause 64. The method of clause 62 or 63 wherein the plurality of particles are fused using sintering.

[000338] Clause 65. The method of any of clauses 60 to 64, wherein the particles comprise a binary mixture comprising a first material and a second material with a refractive index different to the first material.

[000339] Clause 66. The method of any of clauses 52 to 65, further comprising forming a further scattering layer.

[000340] Clause 67. The method of clause 66, wherein the further scattering layer is formed in accordance with the method of any one of clauses 33 to 40.

[000341] Clause 68. The method of clause 66 or 67, wherein forming a further scattering layer comprises depositing an intermediate layer over the scattering layer and forming the further scattering layer atop the intermediate layer.

[000342] Clause 69. The method of any one of clauses 52 to 68, wherein the support layer is formed on a carrier layer which acts to support the support layer while the diffuser is being formed and wherein the method further comprises removing said carrier layer once the first and second layers have been formed.

[000343] Clause 70. A method of forming a diffuser for receiving and transmitting radiation, the method comprising generating a plurality of structures on a surface of a support layer of the diffuser, wherein the structures are arranged to, upon receipt of radiation at the surface, produce a hologram.

[000344] Clause 71. The method of clause 70, wherein the hologram has an angular intensity profile which is at least as intense in a radially outer portion of the hologram compared to a central region of the hologram.

[000345] Clause 72. The method of any of clauses 69 to 71, wherein the plurality of structures are generated using lithography.

[000346] Clause 73. The method of any of clauses 69 to 72, further comprising depositing a second substance into a plurality of voids distributed within the plurality of structures.

[000347] Clause 74. The method of any of clauses 70 to 73, further comprising generating a thickness profile corresponding to a desired arrangement of the plurality of surface features, the desired arrangement based on a desired angular profile of the hologram.

[000348] Clause 75. The method of clause 74, wherein generating the surface profile comprises using the Gerchberg-Saxton algorithm.

[000349] Clause 76. The method of any one of clauses 52 to 75, further comprising etching the support layer from a surface of the support layer that is opposite to a surface of the support layer supporting the scattering layer.

[000350] Clause 77. The method of any one of clauses 52 to 76, further comprising providing a cap layer which at least partially covers the support layer and/or the scattering layer.

[000351] Clause 78. A diffuser configured to receive and transmit radiation, wherein the diffuser comprises: a support structure comprising an porous structure with holes; a scattering layer at least partially covers the support structure, configured to scatter the received radiation.

[000352] Clause 79. The diffuser of clause 78, wherein the support structure comprises nanotubes.

[000353] Clause 80. The diffuser of any one of clauses 78 to 79, wherein the scattering layer comprises at least one of: molybdenum, ruthenium, niobium, rhodium, yttrium, zirconium or technetium.

[000354] Clause 81. The diffuser of any one of clauses 78 to 80, wherein the scattering layer has a thickness of at least 10nm, optionally at least 20nm, optionally at least 40nm, optionally at least 100nm.

[000355] Clause 82. The diffuser of any one of clauses 78 to 81, wherein the scattering layer supports a top layer comprising at least one: MoO₃, Y₂O₃, ZrO₂, Al₂O₃, HfO₂, ZrO₂, Ru, W, a metal, with a thickness of at least 0.3nm, optionally at least 1nm.

[000356] Clause 83. The diffuser of any one of clauses 78 to 82, wherein diffuser has a porosity fraction of at least 10%, optionally at least 20%, optionally at least 30%, optionally at least 40%, optionally at least 50%.

[000357] Clause 84. The diffuser of any previous clause, wherein the diffuser is a transmissive diffuser.

CLAIMS

1. A diffuser configured to receive and transmit radiation, wherein the diffuser comprises:
a scattering layer configured to scatter the received radiation,
5 the scattering layer comprising a first substance and having distributed therein a plurality of
voids,
wherein either: the first substance is a scattering substance, or
at least one of the voids contains a scattering substance and the first substance has a
lower refractive index than the scattering substance.
10
2. The diffuser of claim 1, wherein the first substance is the scattering substance, wherein
scattering substance comprises a foam having pores and the voids are provided by the pores and the
voids contain a vacuum or an inert gas.
- 15 3. The diffuser of claim 2, wherein the voids contain one of silicon or silicon nitride.
4. The diffuser of claim 1, wherein voids contain the scattering substance, wherein the first
substance comprises a porous silicon-based structure, the voids being defined by pores of the first
substance.
20
5. The diffuser of any of claims 1 to 3, wherein the scattering substance comprises a body of
contacting particles and the voids are provided between adjacent particles.
6. The diffuser of claim 5, wherein the particles comprise a binary mixture comprising a first
25 material and a second material with a refractive index different to the first material.
7. The diffuser of claim 6, wherein the first material comprises silicon and
the second material comprises molybdenum or ruthenium.
- 30 8. The diffuser of any of claims 1 to 7, further comprising a support structure, wherein the
scattering layer at least partially covers the support structure, wherein the support structure comprises
nanotubes.
- 35 9. The diffuser of claim 1, wherein the first substance and the voids cooperate to produce, upon
receipt of radiation at a surface of the scattering layer, a hologram.

10. The diffuser of claim 9, wherein the voids contain a second substance, wherein the real part of the refractive index of the second substance is different to the real part of the refractive index of the first substance, and the imaginary part of the second substance is similar to the imaginary part of the refractive index of the first substance.

5

11. The diffuser of any of previous claims, wherein the first substance comprises at least one of the following: molybdenum, ruthenium, niobium, rhodium, yttrium, zirconium or technetium.

12. The diffuser of any of claims 10-11, wherein the second substance comprises silicon.

10

13. A holographic diffuser comprising a scattering layer comprising a plurality of structures configured to produce, upon receipt of extreme ultraviolet radiation at a surface of the scattering layer, a hologram, wherein the hologram has an angular intensity profile which is at least as intense in a radially outer portion of the hologram compared to a central region of the hologram.

15

14. A lithographic apparatus comprising:

a measurement system for determining an aberration map or relative intensity map for a projection system comprising the diffuser of any preceding claim;

and a projection system configured to receive at least a portion of the radiation scattered by the patterning device and configured to project the received radiation onto a sensor apparatus.

20

15. A method of forming a diffuser for receiving and transmitting radiation, the method comprising generating a plurality of structures on a surface of a support layer of the diffuser, wherein the structures are arranged to, upon receipt of radiation at the surface, produce a hologram.

25

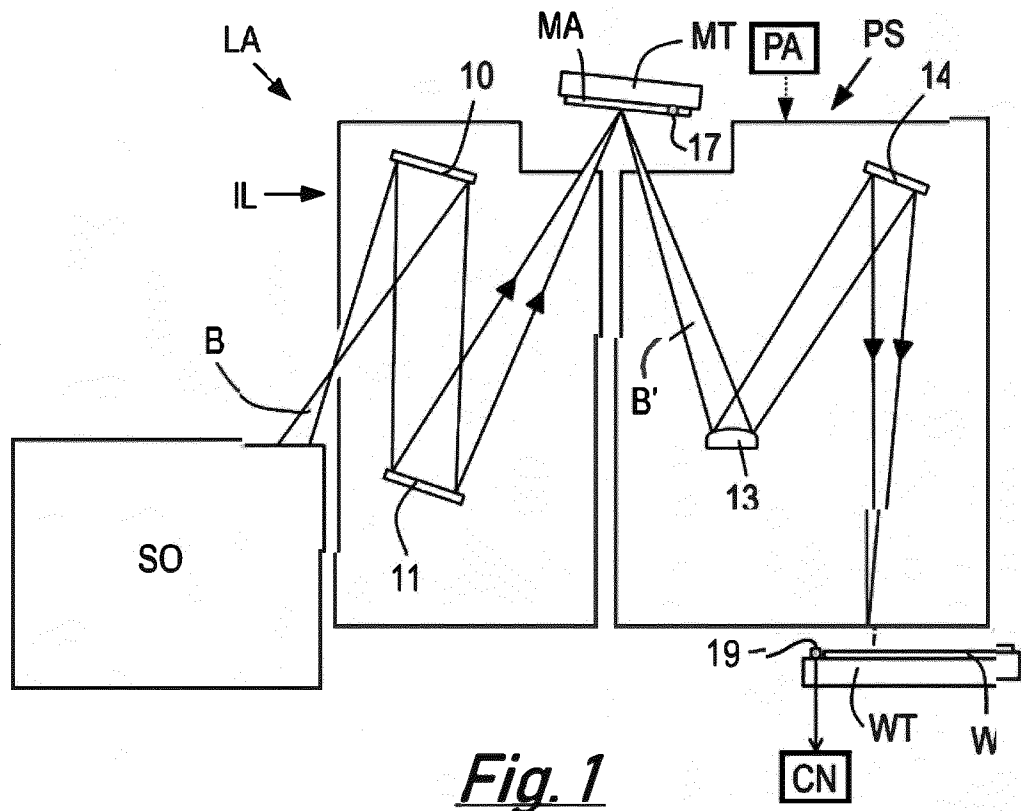


Fig. 1

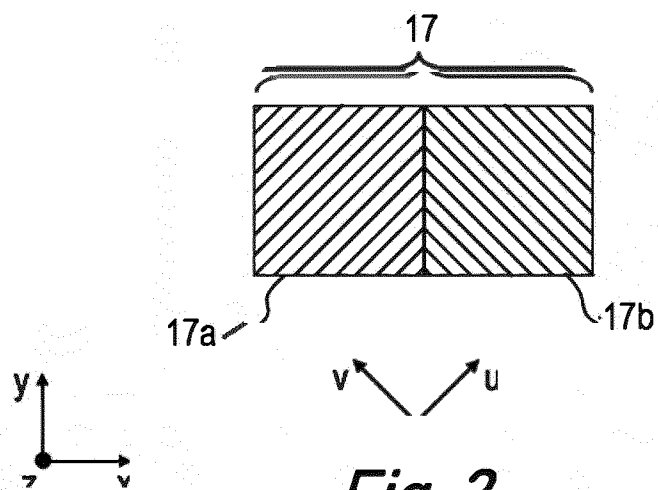
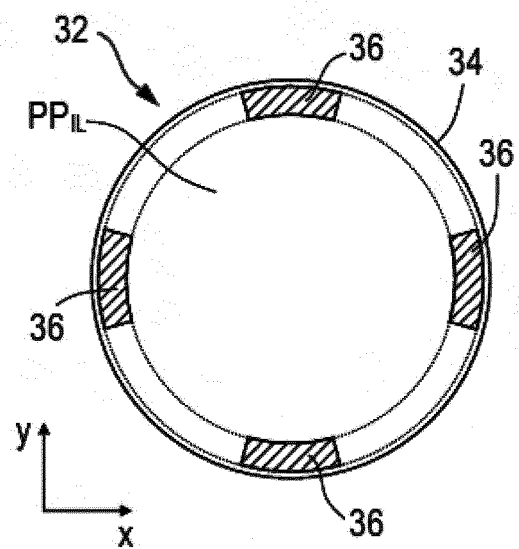
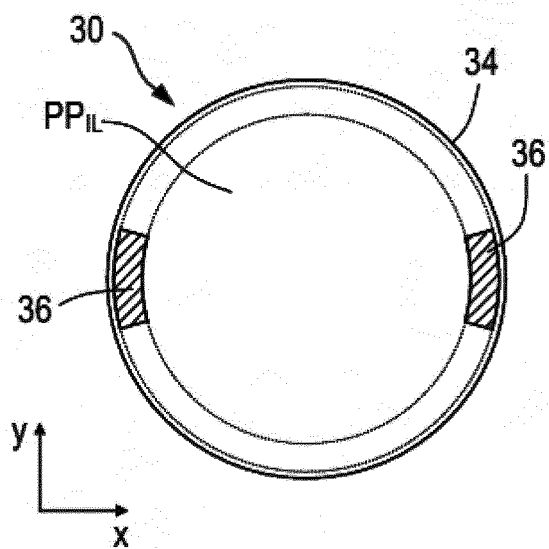
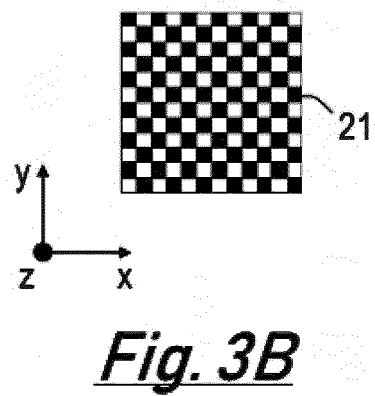
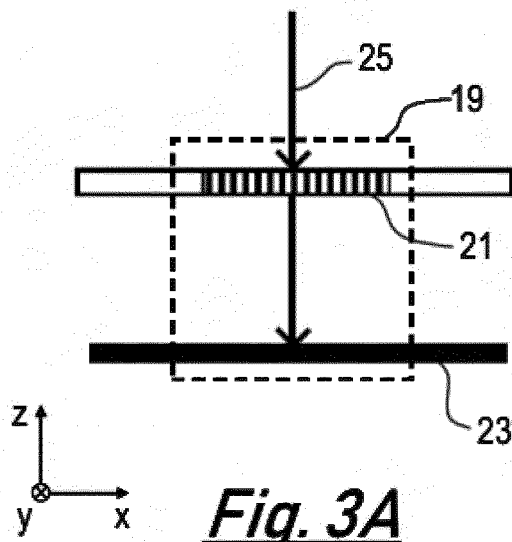
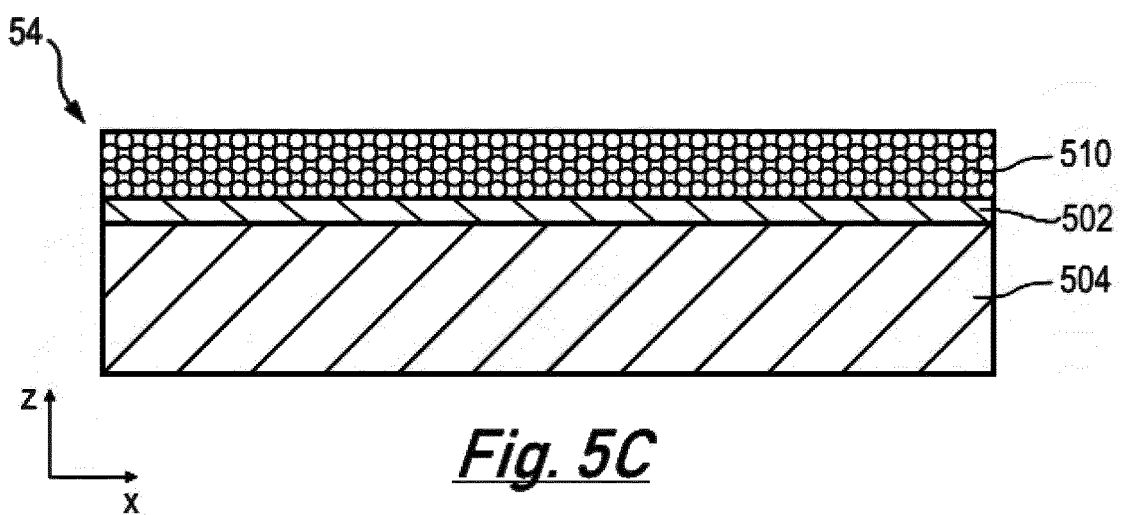
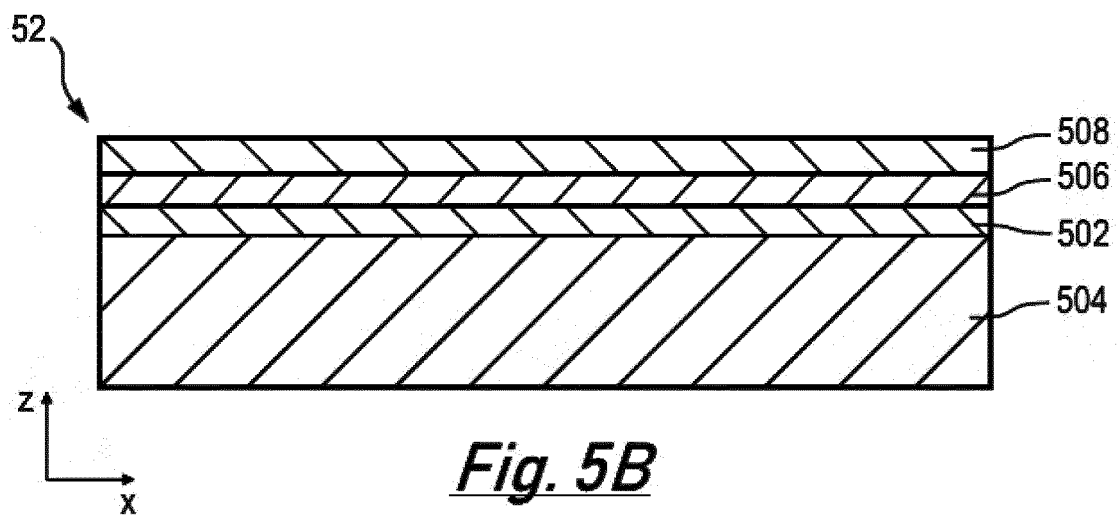
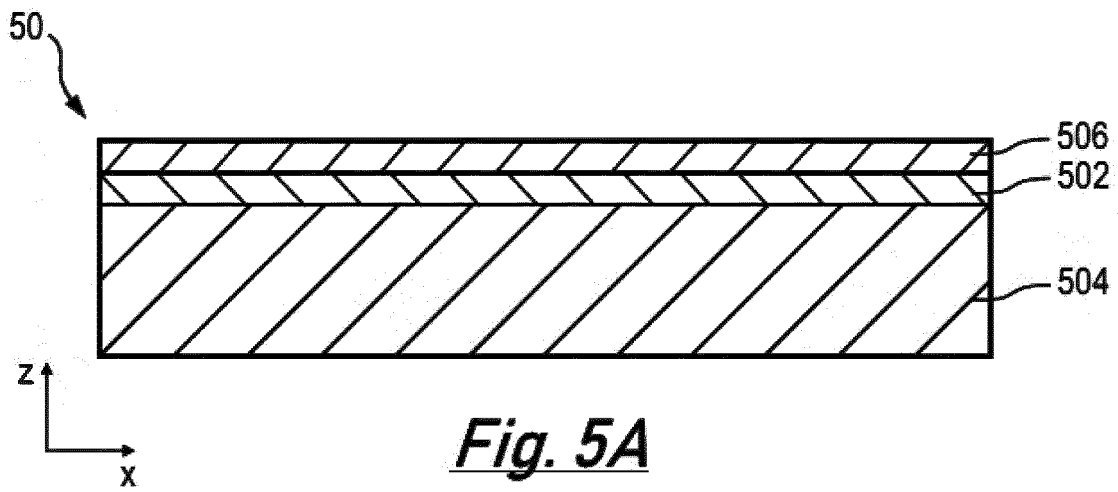
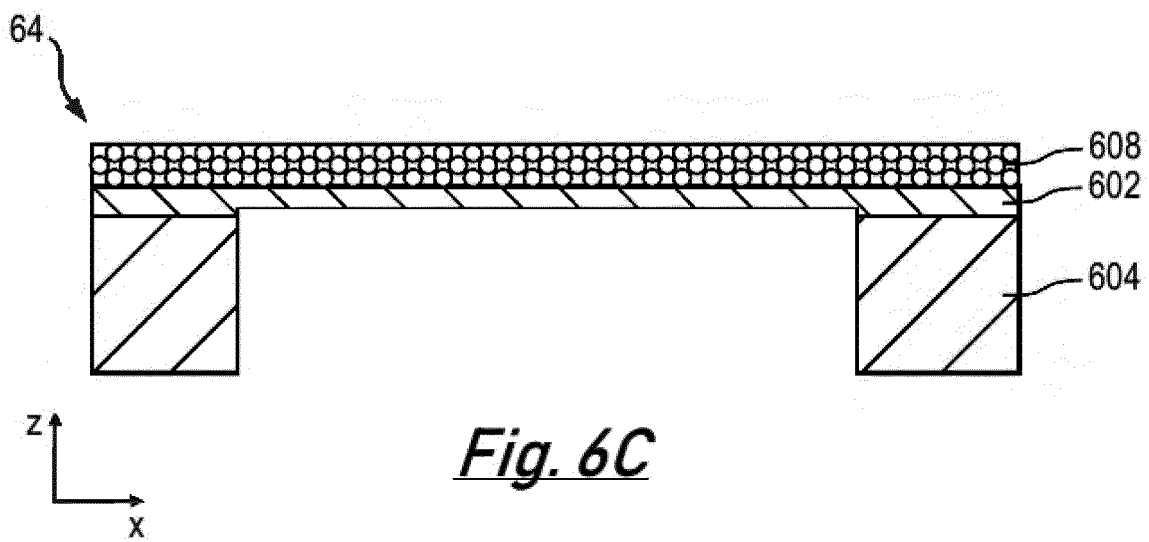
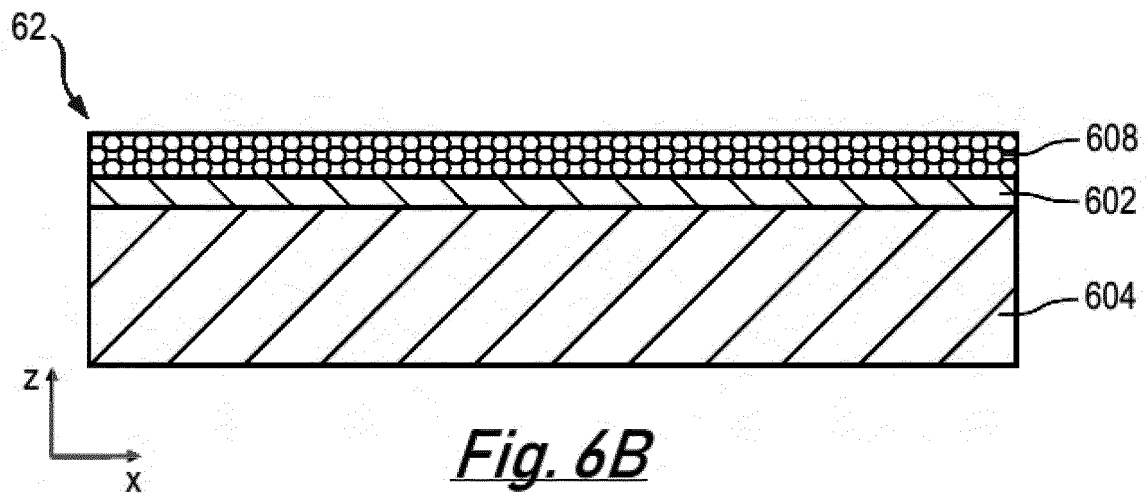
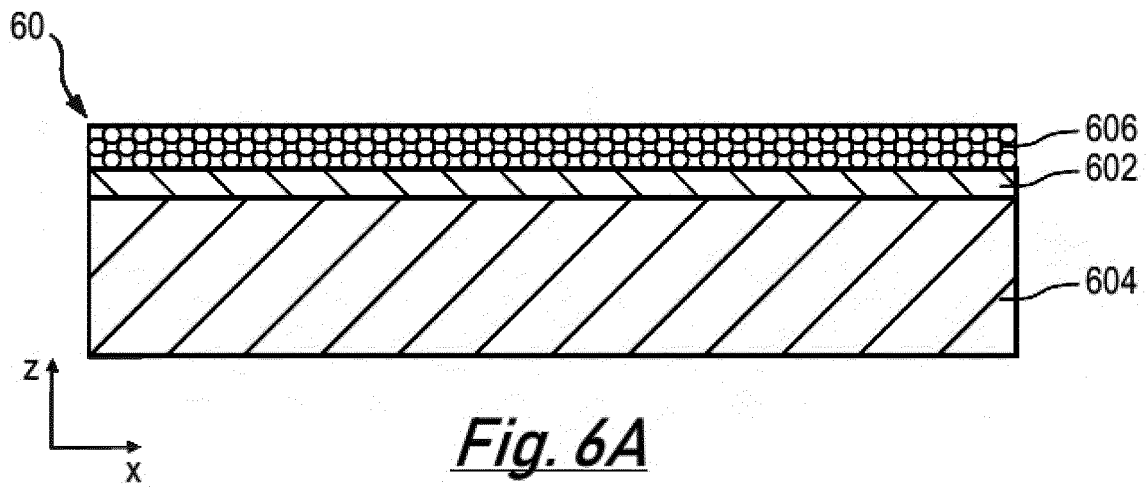
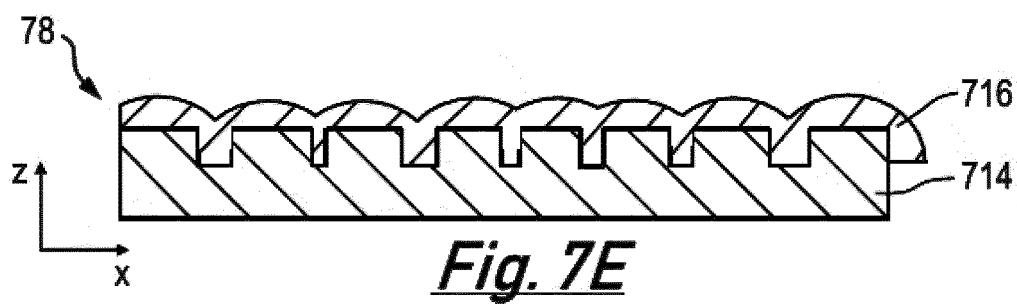
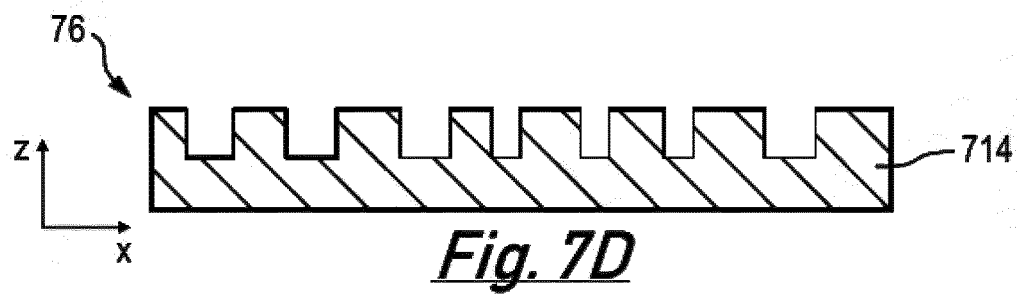
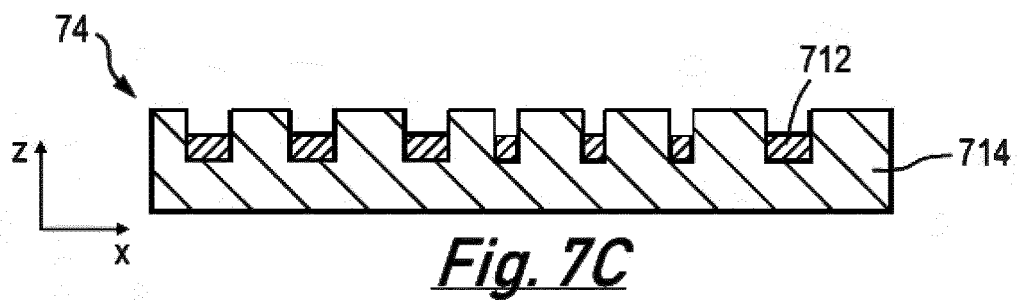
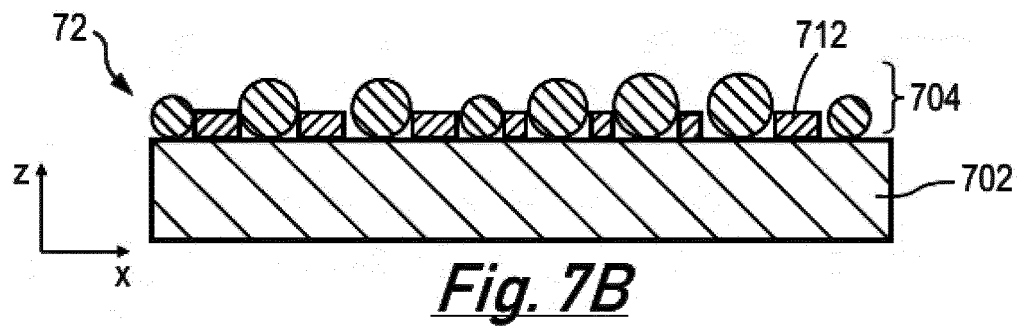
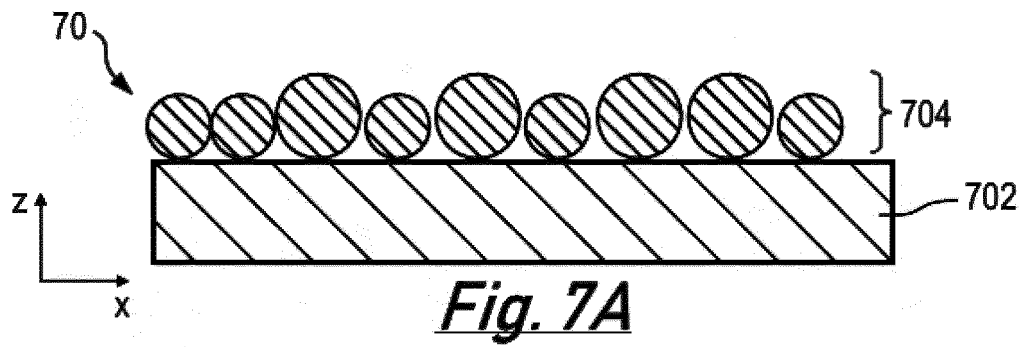


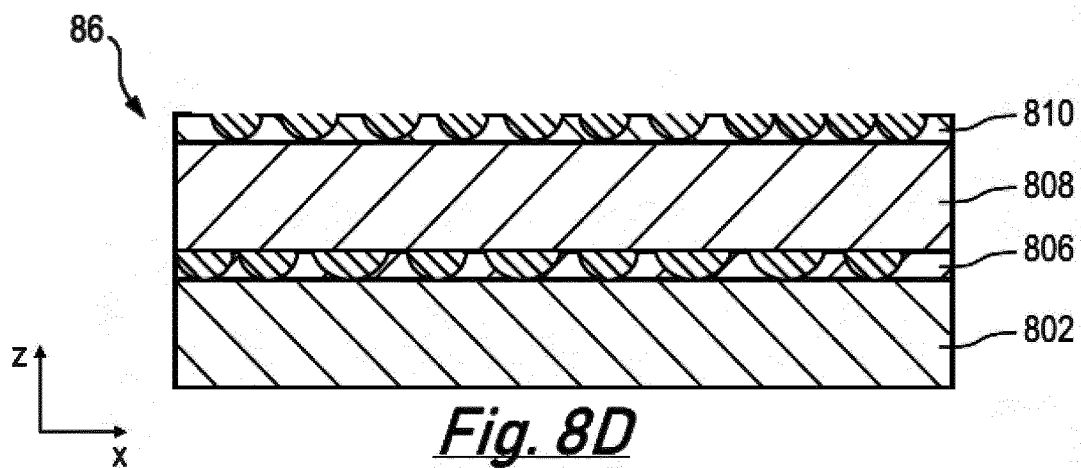
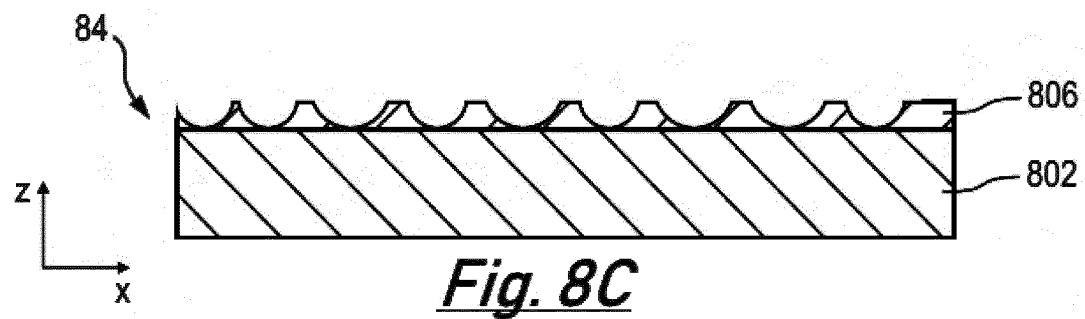
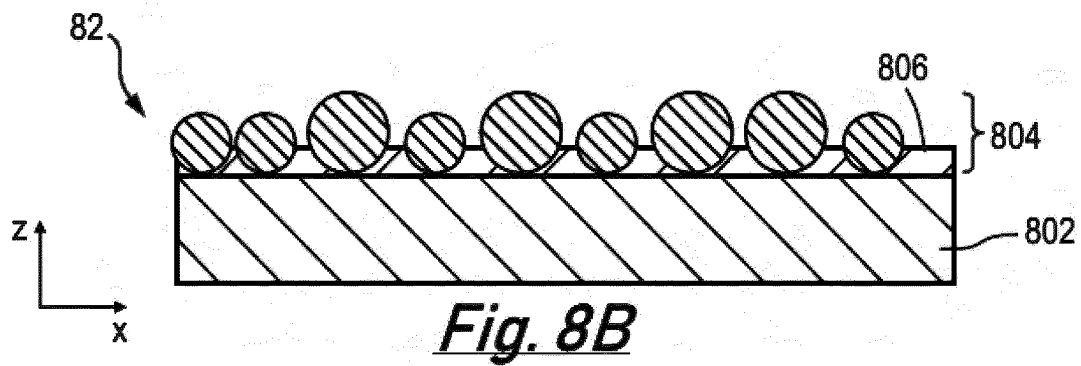
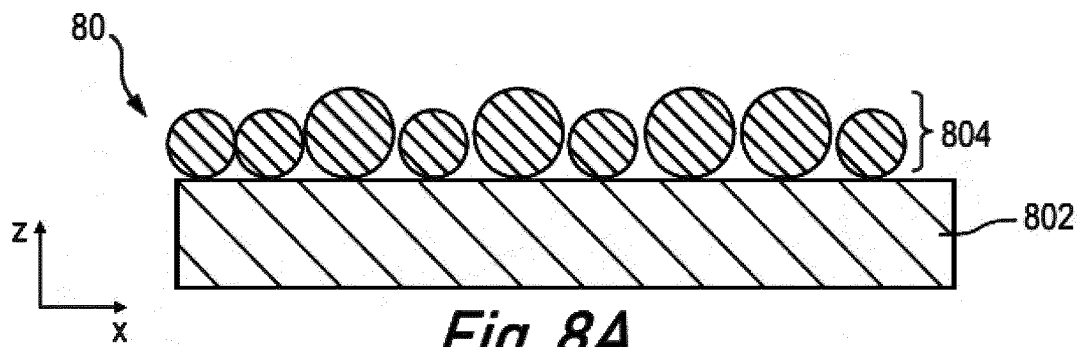
Fig. 2

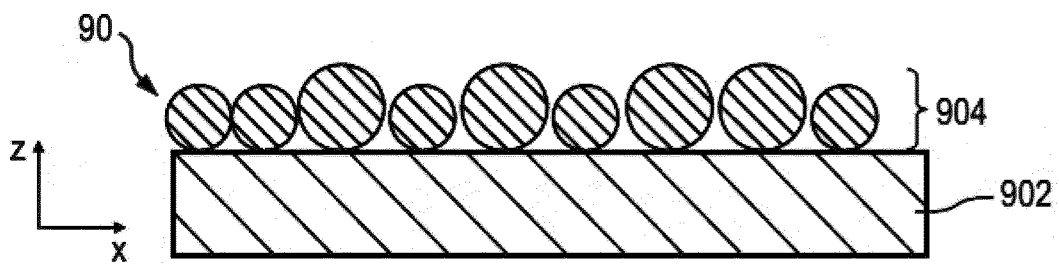
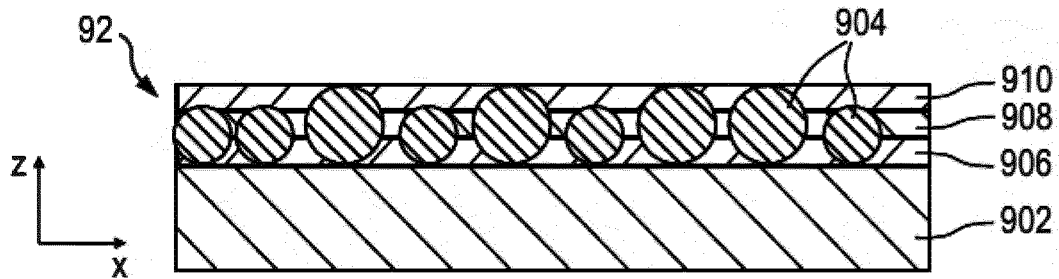
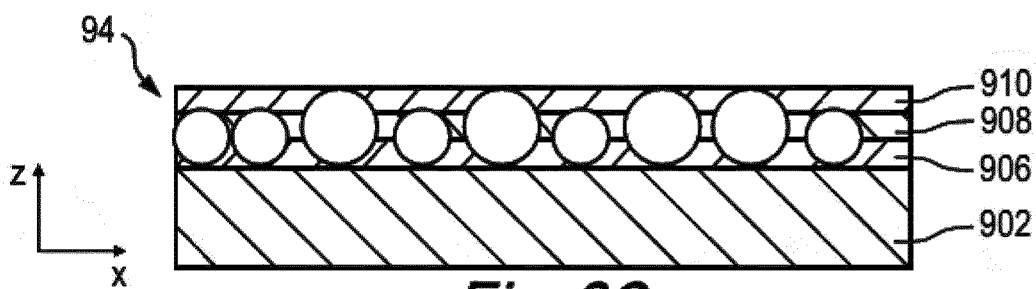
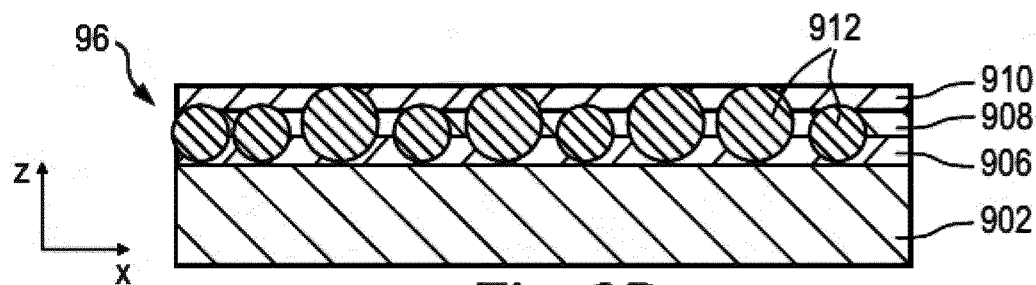
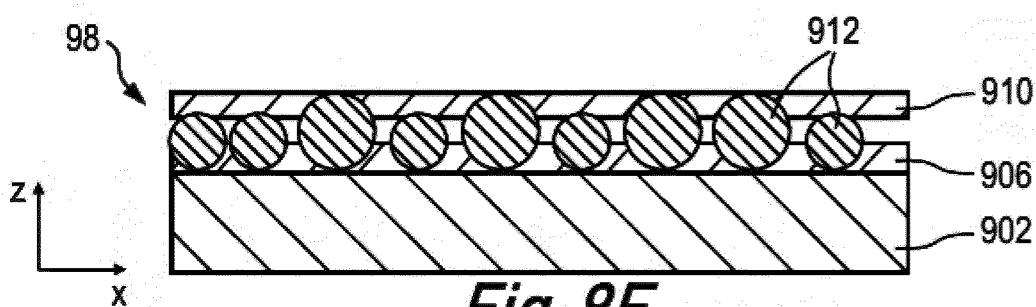


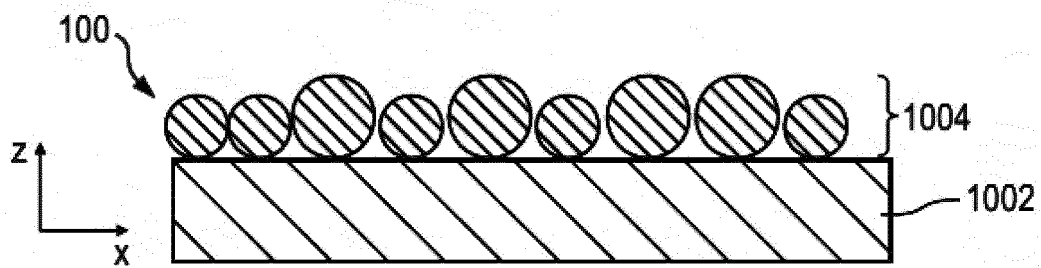
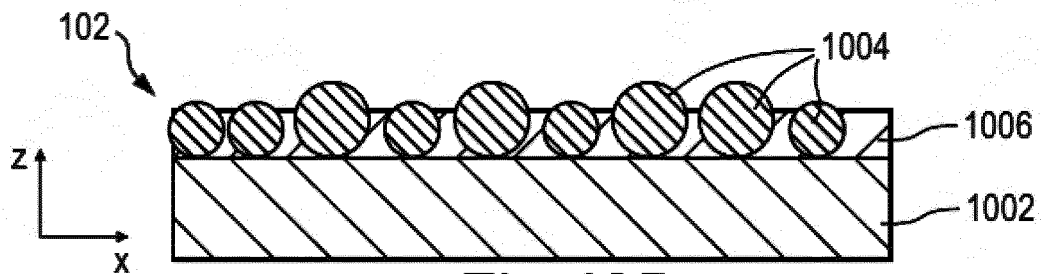
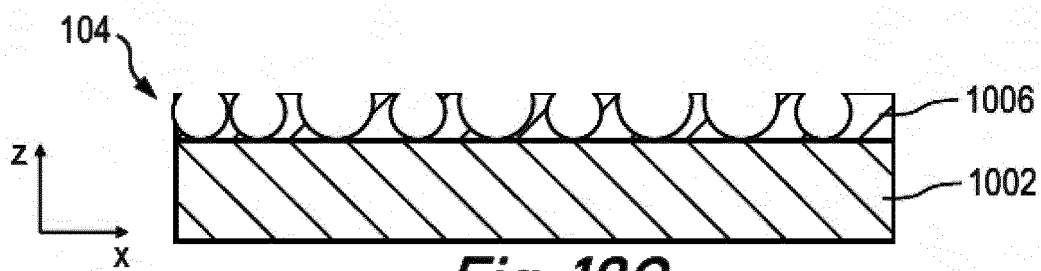
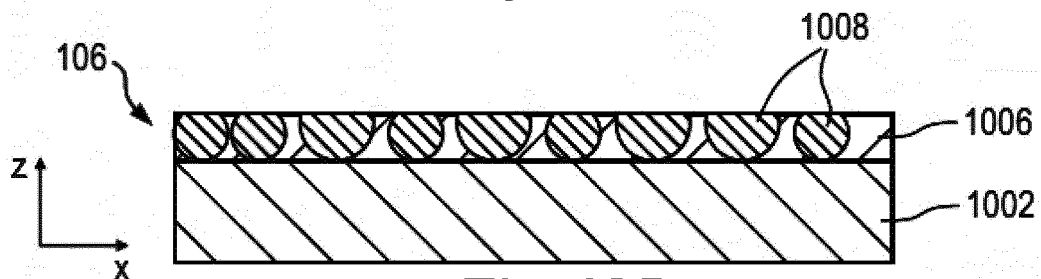
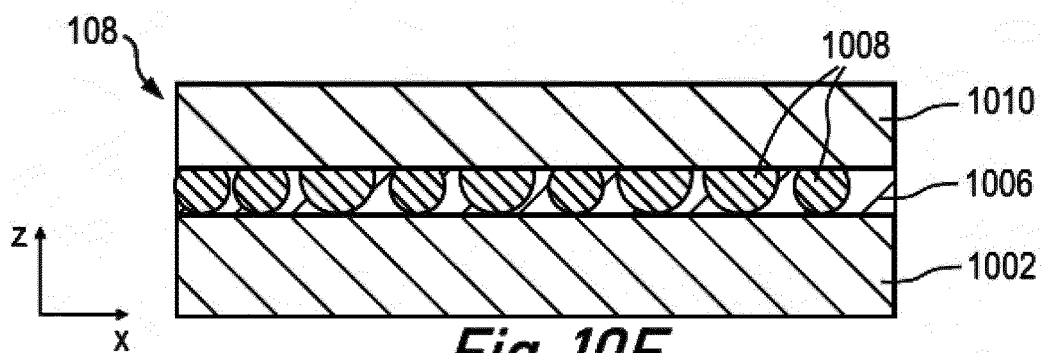


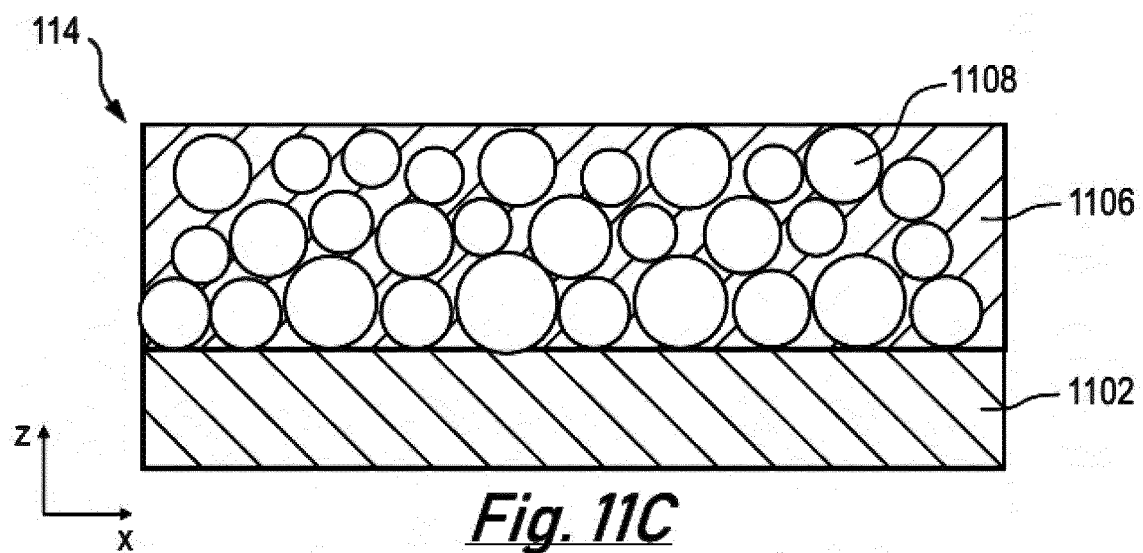
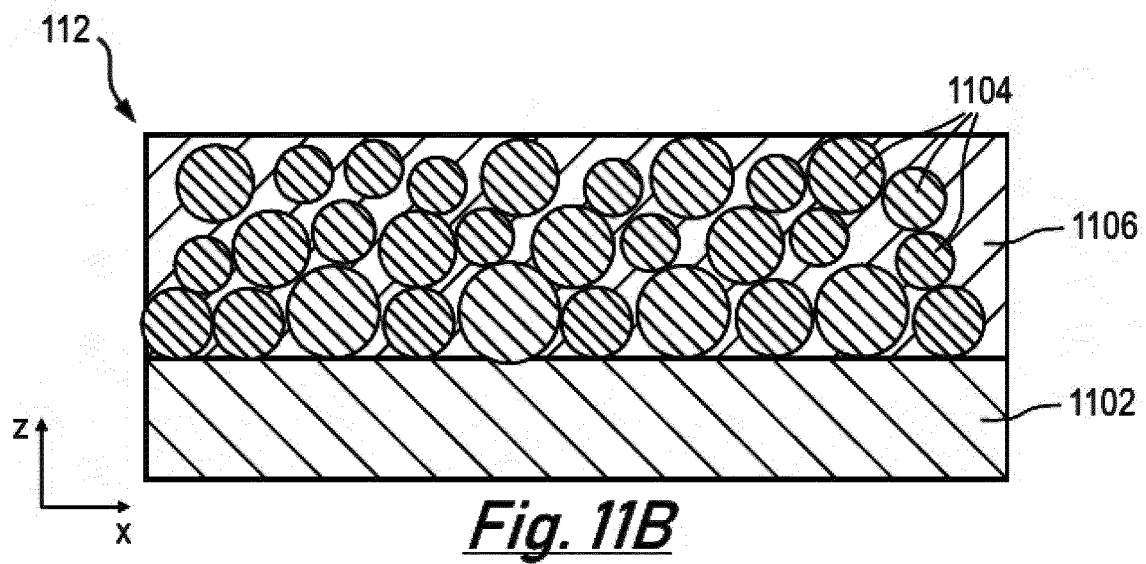
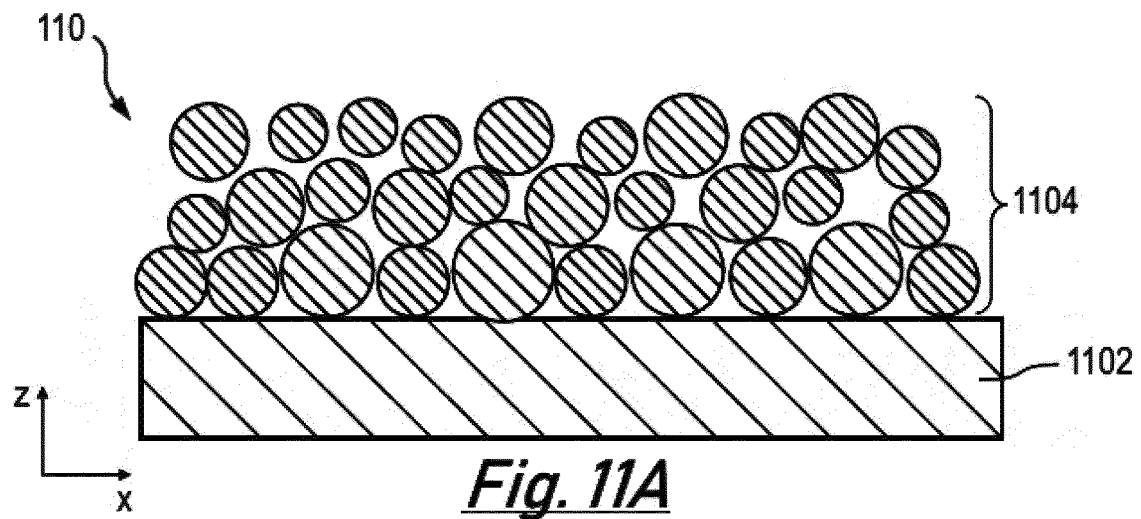






*Fig. 9A**Fig. 9B**Fig. 9C**Fig. 9D**Fig. 9E*

***Fig. 10A******Fig. 10B******Fig. 10C******Fig. 10D******Fig. 10E***



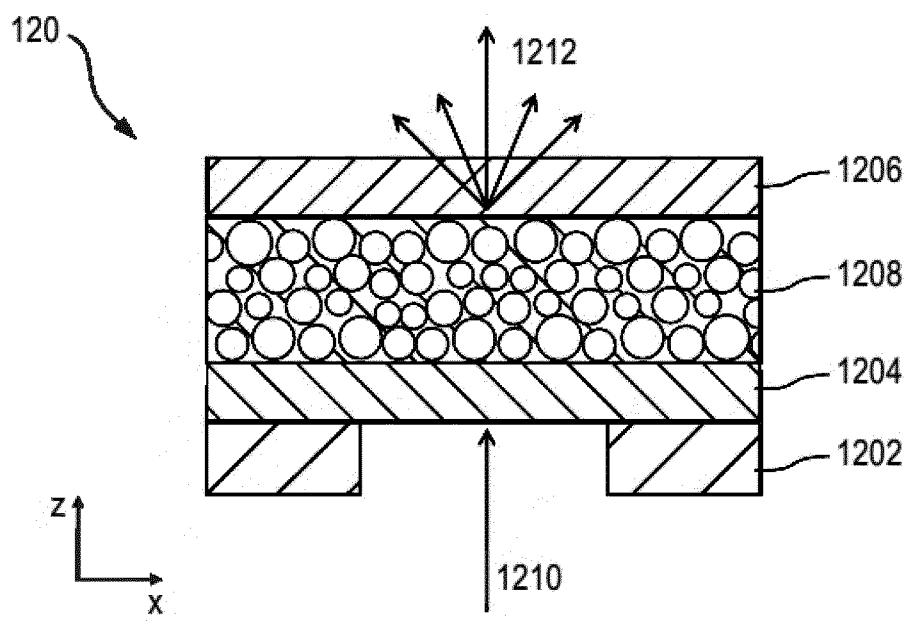


Fig. 12

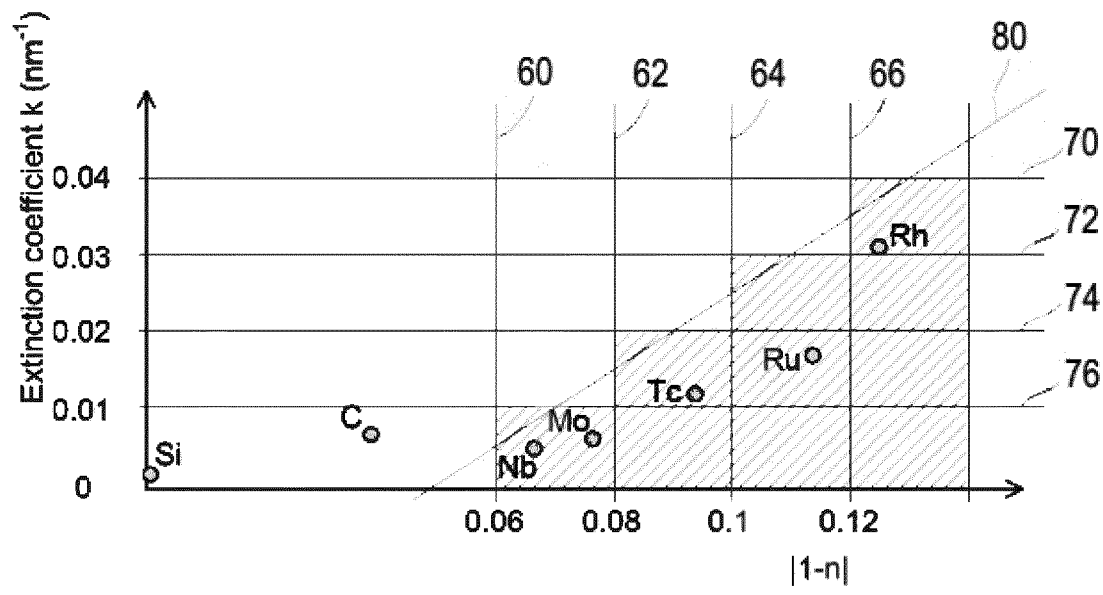


Fig. 13

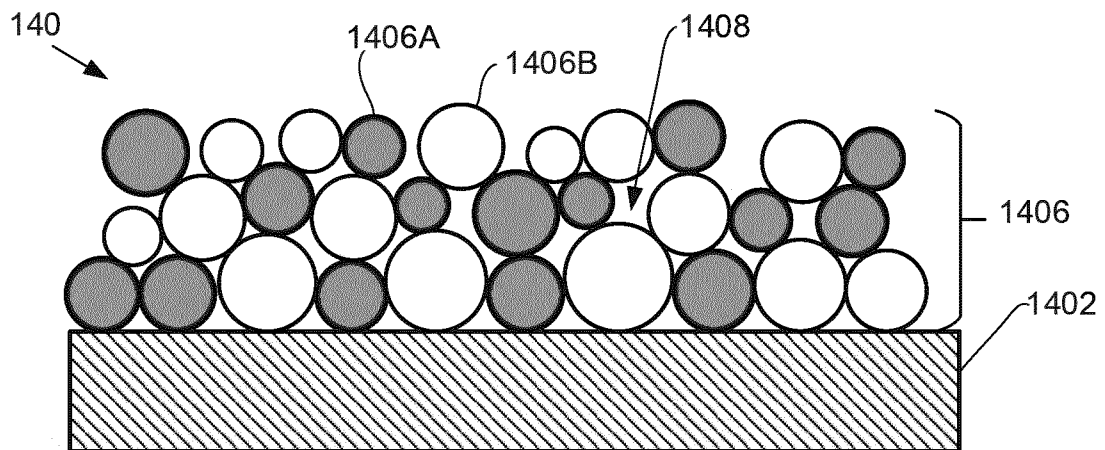


Fig. 14A

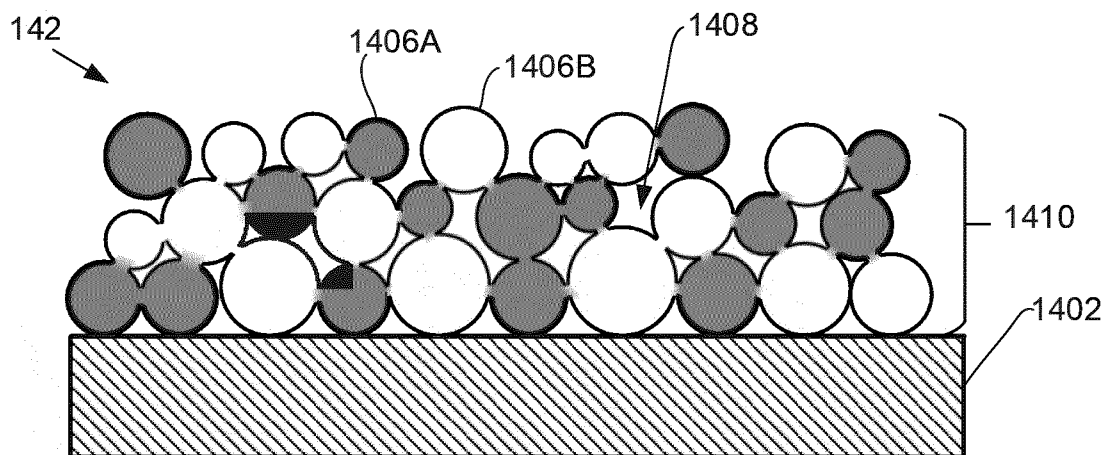


Fig. 14B

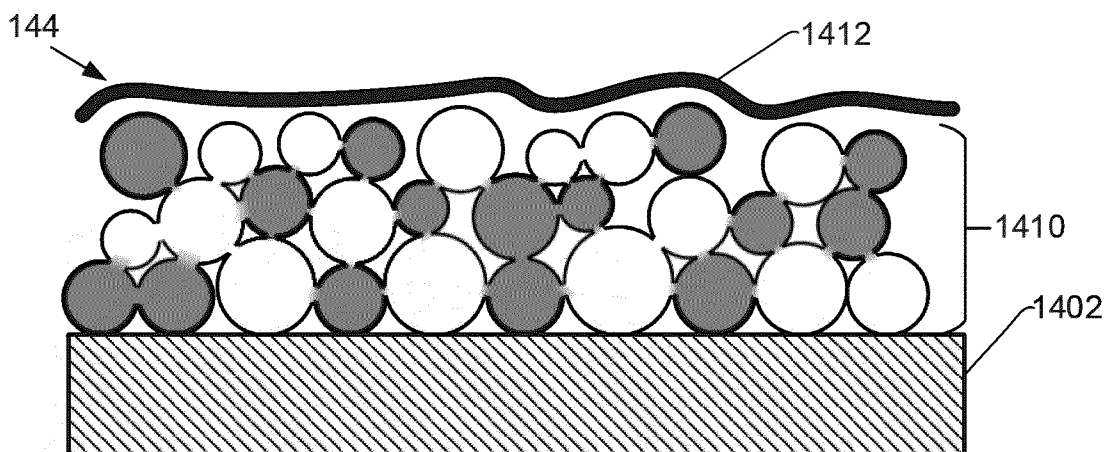


Fig. 14C

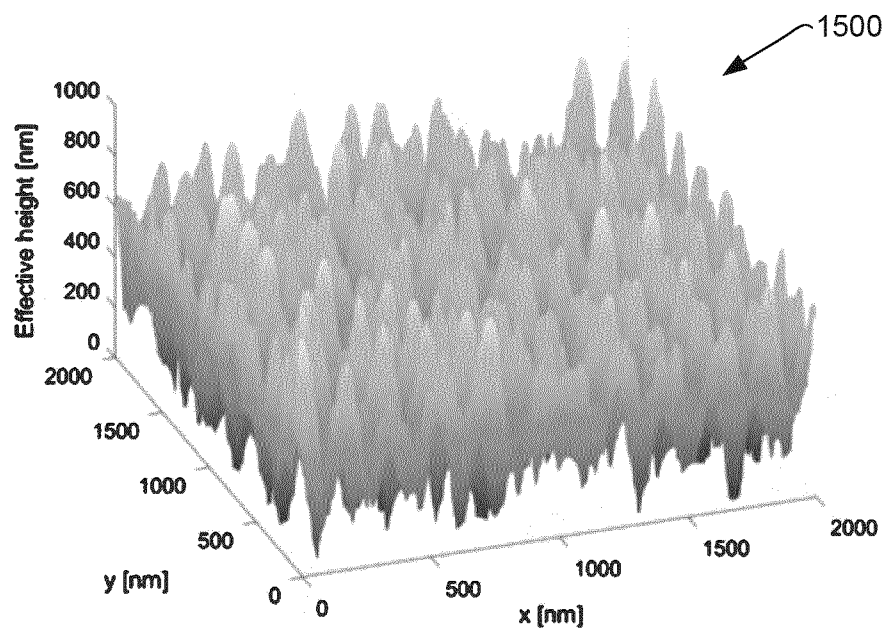


Fig. 15A

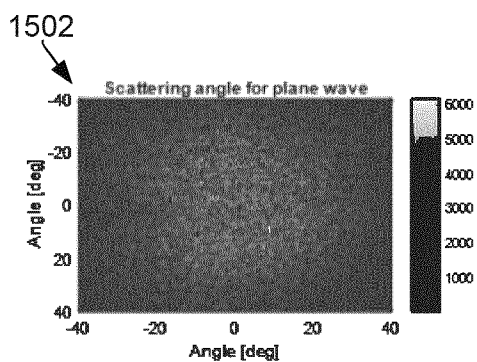


Fig. 15B

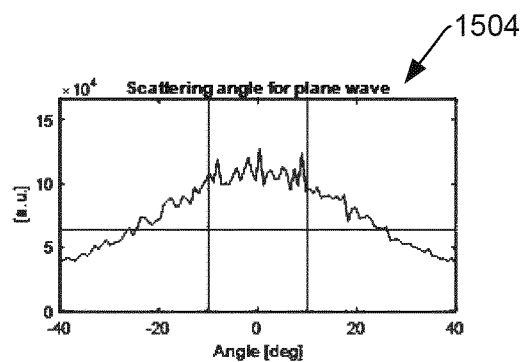


Fig. 15C

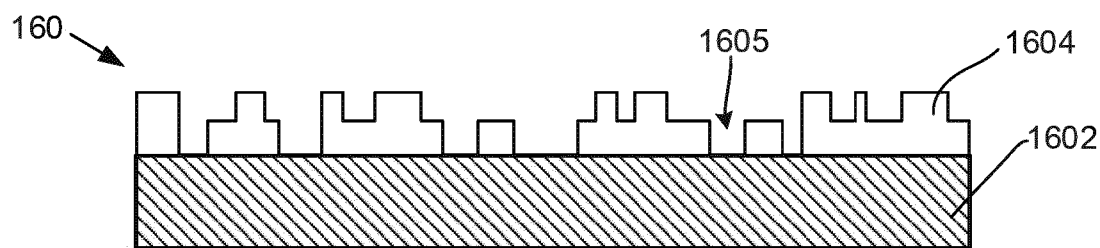


Fig. 16A

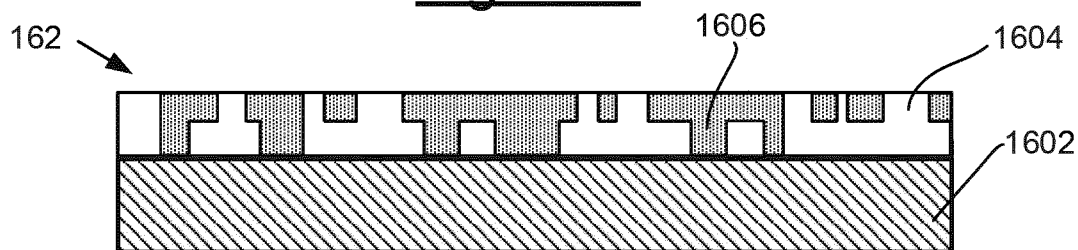


Fig. 16B

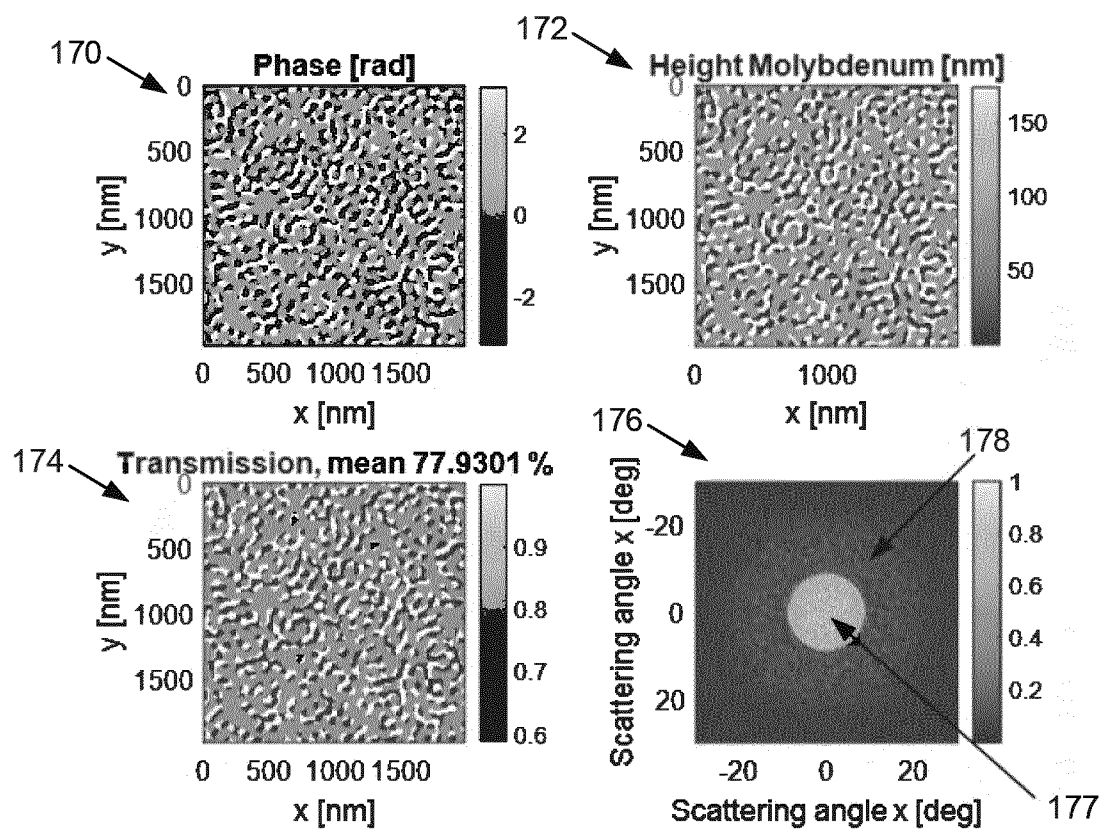


Fig. 17

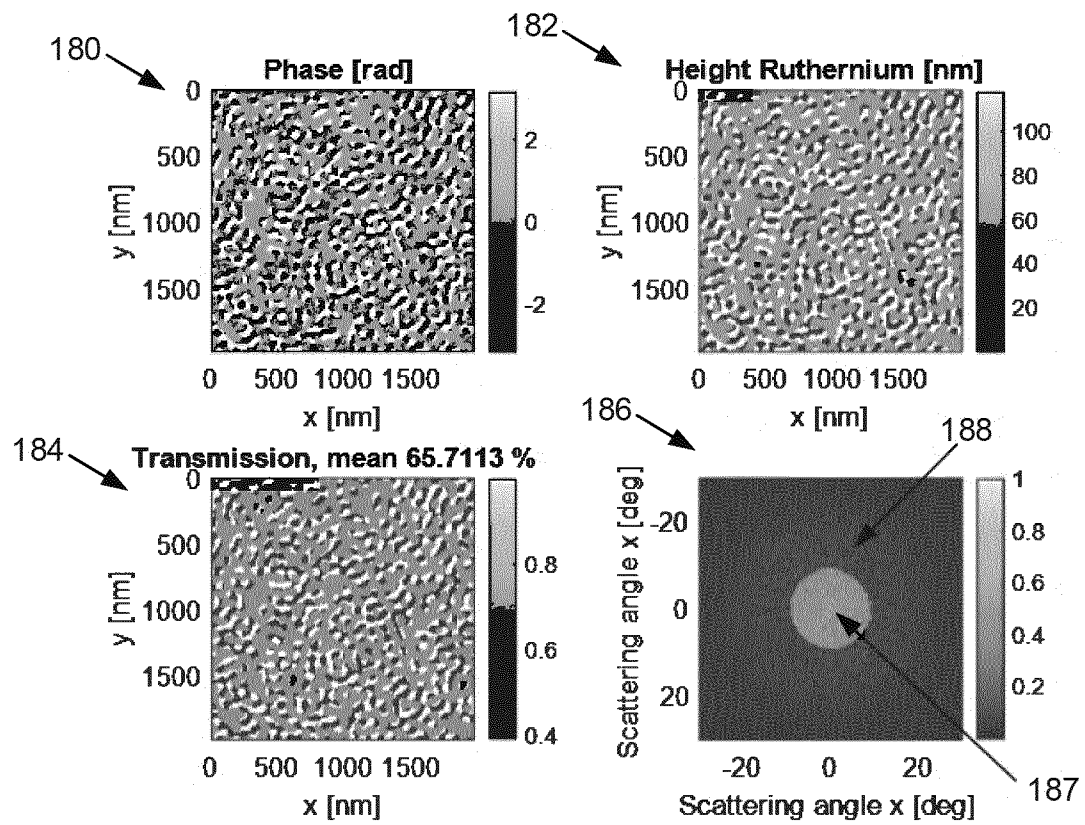


Fig. 18

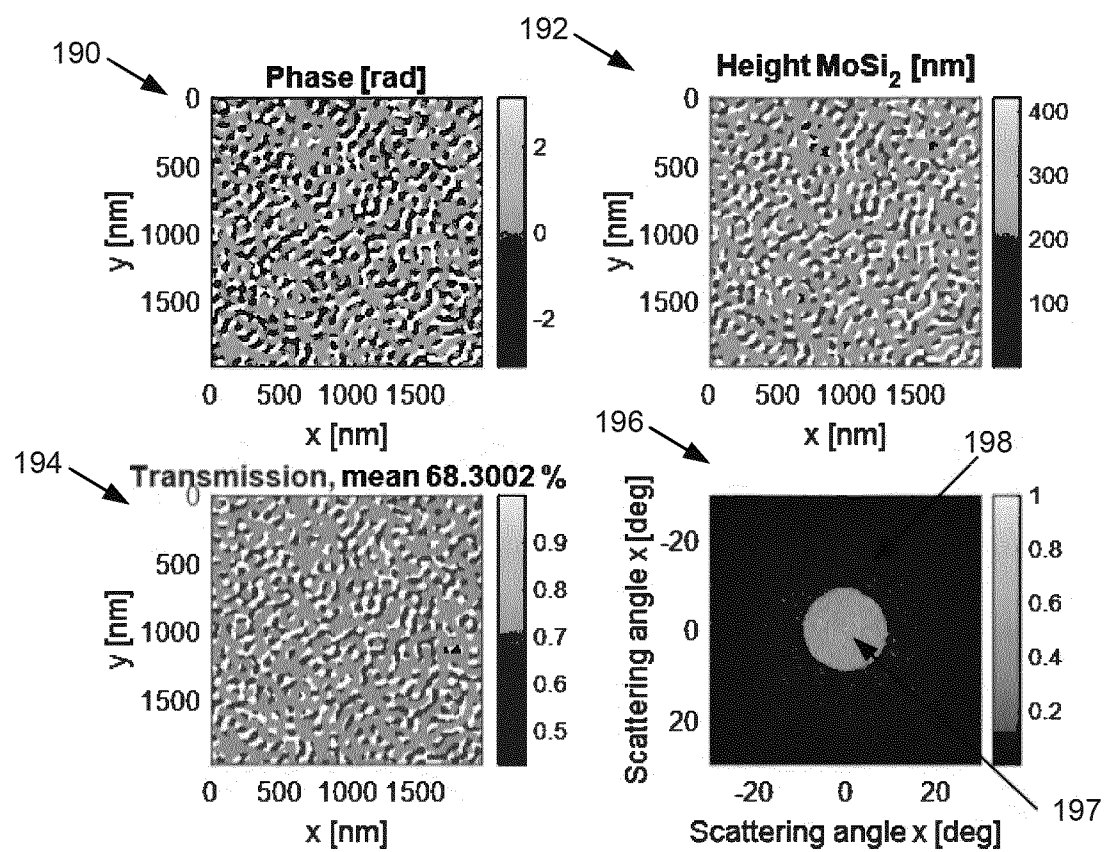


Fig. 19

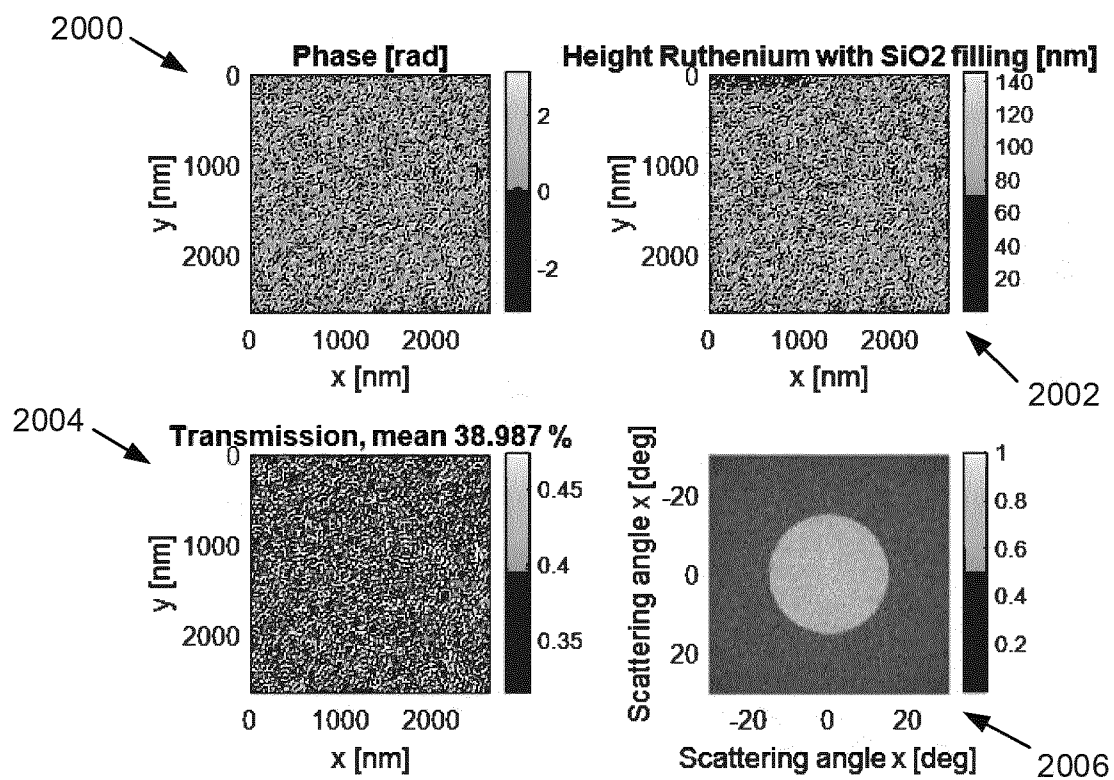


Fig. 20

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/076765

A. CLASSIFICATION OF SUBJECT MATTER INV. G02B5/18 G02B5/02 G02B27/09 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) G02B		
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	WO 2007/111353 A1 (OJI PAPER CO [JP]; KOJIMA JUNYA [JP] ET AL.) 4 October 2007 (2007-10-04) paragraph [0152]	1-3
Y	----- US 2004/066556 A1 (DONTULA NARASIMHARAO [US] ET AL) 8 April 2004 (2004-04-08) paragraph [0073]	8,11,12, 14
X	----- EP 2 784 374 A1 (AUTOMOTIVE LIGHTING ITALIA SPA [IT]) 1 October 2014 (2014-10-01) the whole document	1,2
X	----- US 2003/118750 A1 (BOURDELAIS ROBERT P [US] ET AL) 26 June 2003 (2003-06-26) the whole document ----- -/-	1,2
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "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 16 December 2020		Date of mailing of the international search report 04/03/2021
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Albayrak, Charlotte

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2020/076765

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2016/086204 A1 (JAISWAL SUPRIYA [US]) 2 June 2016 (2016-06-02) the whole document -----	1,5-7
Y	EP 3 476 589 A1 (NITTO DENKO CORP [JP]) 1 May 2019 (2019-05-01) paragraph [0170] -----	8
X	US 2009/268273 A1 (POWERS RICHARD M [US] ET AL) 29 October 2009 (2009-10-29) paragraph [0063] -----	1,9,10
Y	VAN DE KERKHOF MARK ET AL: "Diffuser concepts for in-situ wavefront measurements of EUV projection optics", PROCEEDINGS OF SPIE; [PROCEEDINGS OF SPIE ISSN 0277-786X VOLUME 10524], SPIE, US, vol. 10583, 19 March 2018 (2018-03-19), pages 105830S-105830S, XP060103211, DOI: 10.1117/12.2297433 ISBN: 978-1-5106-1533-5 the whole document -----	11,12,14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2020/076765

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

2, 3, 5-7(completely); 1, 8-12, 14(partially)

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 2, 3, 5-7(completely); 1, 8-12, 14(partially)

Diffuser comprising scattering substance having voids

2. claims: 4(completely); 1, 8-12, 14(partially)

Diffuser with scattering substance in voids

3. claims: 13(completely); 14(partially)

Diffuser to produce extreme UV flat top beam

4. claim: 15

Diffuser to produce hologram

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2020/076765

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2007111353 A1	04-10-2007	JP 2007264343 A TW 200745619 A WO 2007111353 A1	11-10-2007 16-12-2007 04-10-2007
US 2004066556 A1	08-04-2004	JP 2004133460 A US 2004066556 A1	30-04-2004 08-04-2004
EP 2784374 A1	01-10-2014	EP 2784374 A1 US 2014286031 A1	01-10-2014 25-09-2014
US 2003118750 A1	26-06-2003	JP 2003195016 A US 2003118750 A1 US 2005053729 A1 US 2007026167 A1	09-07-2003 26-06-2003 10-03-2005 01-02-2007
WO 2016086204 A1	02-06-2016	CN 107209293 A EP 3224657 A1 JP 6772169 B2 JP 2017538974 A KR 20170141646 A SG 11201704226P A TW 201626098 A WO 2016086204 A1	26-09-2017 04-10-2017 21-10-2020 28-12-2017 26-12-2017 29-06-2017 16-07-2016 02-06-2016
EP 3476589 A1	01-05-2019	CN 109476119 A EP 3476589 A1 JP 6809824 B2 JP 2018001633 A KR 20190025678 A US 2019232583 A1 WO 2018008534 A1	15-03-2019 01-05-2019 06-01-2021 11-01-2018 11-03-2019 01-08-2019 11-01-2018
US 2009268273 A1	29-10-2009	AU 2009240500 A1 CA 2754619 A1 CA 2825332 A1 CN 102066992 A CN 103513305 A EP 2269100 A2 HK 1154944 A1 JP 5671449 B2 JP 2011519065 A KR 20100135301 A US 2009268273 A1 US 2014368909 A1 WO 2009132215 A2	29-10-2009 29-10-2009 29-10-2009 18-05-2011 15-01-2014 05-01-2011 04-05-2012 18-02-2015 30-06-2011 24-12-2010 29-10-2009 18-12-2014 29-10-2009