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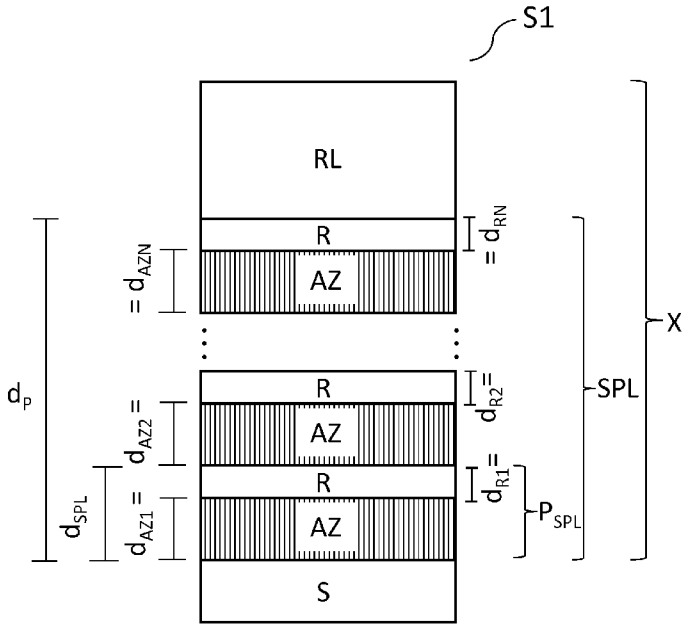
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(54) Title: MIRROR FOR THE EUV WAVELENGTH RANGE

FIG.1A



(57) Abstract: The invention relates to a mirror (S1, S2) for the EUV wavelength range and a projection lens (4) and illumination system (3) for microlithography comprising such a mirror (S1, S2). Furthermore, the invention relates to a projection exposure apparatus (1) for microlithography comprising such a projection lens (4) and/or such an illumination system (3). A mirror for the EUV wavelength range (S1, S2) according to the invention comprises a substrate and a layer arrangement, wherein the layer arrangement (X) comprises a reflective layer system (RL) having at least one layer subsystem (P') and a protective layer system (SPL) protecting the substrate, wherein the protective layer system (SPL) comprises a periodical sequence of at least two periods (P_{SPL}), consisting of in each case two individual layers (AZ, R), characterized in that the first individual layer (AZ) of the

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period (P_{SPL}) simultaneously protects the substrate by absorbing the EUV radiation and compensates for layer stresses in the layer arrangement (X), and the respective second individual layer (R) reduces the surface roughness of the protective layer system (SPL) by smoothing the surface roughness of the first individual layer (AZ).

MIRROR FOR THE EUV WAVELENGTH RANGE

DESCRIPTION

The invention relates to a mirror for the EUV wavelength range and a projection lens and an illumination system for microlithography comprising such a mirror. Furthermore, the invention relates to a projection exposure apparatus for microlithography comprising such a projection lens and/or such an illumination system.

Projection exposure apparatuses for microlithography for the EUV wavelength range rely on the fact that the mirrors used for the exposure or imaging of a mask into an image plane have a high reflectivity. This is because, firstly, the product of the reflectivity values of the individual mirrors determines the total transmission of the projection exposure apparatus and, secondly, the light power of EUV light sources is limited. Furthermore, such mirrors must also have the desired optical imaging quality and ensure the latter even over a number of years under continuous irradiation with EUV radiation of high intensity.

In order to obtain the high reflectivity of the mirrors, the mirrors for the EUV wavelength range usually comprise a layer arrangement which is applied on a substrate and which comprises a reflective layer system. In this case, the reflective layer system usually comprises at least one layer subsystem which consists of a periodic sequence of at least two periods of individual layers. In this case, the periods comprise two individual layers composed of different materials for a high refractive index layer and a low refractive index layer, which are adapted in terms of their thickness such that a high reflectivity is obtained. In this case, in the EUV wavelength range, the terms high refractive index and low refractive index are relative terms regarding the respective partner layer in a period of a layer subsystem. Layer subsystems function in the EUV wavelength range in general only if a layer acting with an optically high refractive index is combined with an optically lower refractive index layer relative thereto as main constituent of a period of the layer subsystem.

Furthermore, in order to obtain the high reflectivity of the mirrors, it is necessary to avoid the loss on account of stray light, which leads to stringent requirements made of the surface roughness of the mirrors for the EUV wavelength range, in particular for the surface roughness in the range with spatial wavelengths of 10 nm to 1.5 µm.

In order to achieve the desired optical imaging quality, the layer stress of the layer arrangement must additionally be very low in order that the substrate dose not warp impermissibly on account of the layer stresses in the layer arrangement. To that end, the layer stresses that arise for example in the reflective layer system have to be compensated for by the layer stresses of other parts of the layer arrangement. In this case, the layer stress is subdivided into tensile stress and compressive stress. Depending on whether the resultant forces that act perpendicularly to the surface of the substrate have a positive sign (tensile stress) or a negative sign (compressive stress).

In order to ensure the desired optical imaging quality over a number of years under continuous irradiation with EUV radiation of high intensity, it is furthermore necessary to prevent too much EUV radiation from being transmitted as far as the substrate, in order that the substrate is not exposed to high doses of EUV radiation over a long period of time. Substrates for EUV mirrors composed of materials such as e.g. Zerodur® from Schott AG or ULE® from Corning Inc. tend toward compaction of the order of magnitude of a few percent by volume under high doses of EUV radiation. With generally non-uniform irradiation of the mirrors, this compaction leads to a non-uniform change in their surface shape, as a result of which the optical imaging properties of the mirrors are changed undesirably during the operational period.

DE 10 2009 054 653 A1 discloses for example a mirror for the EUV wavelength range comprising a substrate and a layer arrangement. Said layer arrangement comprises a reflective layer system and a protective layer system, wherein the protective layer system reduces the transmission of EUV radiation through the layer arrangement overall in conjunction with low surface roughness values. By means of an intermediate layer arrangement fitted between the substrate and the layer arrangement, it is additionally possible to generate a tensile stress for compensating for layer stresses in the layer arrangement.

Different protective layer subsystems and thus also different materials for protecting the substrate from EUV radiation by absorption, for compensating for layer stress and for smoothing the surface roughnesses are usually used in this case.

It is an object of the invention to provide a mirror for the EUV wavelength range having a simplified protective layer system in comparison with the prior art, which mirror, in conjunction with low surface roughness values, reduces the transmission of EUV

radiation through the layer arrangement and generates a layer stress for compensating for layer stresses in the layer arrangement.

This is achieved by means of a mirror for the EUV wavelength range comprising a substrate and a layer arrangement, wherein the layer arrangement comprises

- a reflective layer system having at least one layer subsystem and
- a protective layer system protecting the substrate, wherein the protective layer system comprises a periodical sequence of at least two periods, consisting of in each case two individual layers,

  characterized in that the respective first individual layer of the period simultaneously protects the substrate by absorbing the EUV radiation and compensates for layer stresses in the layer arrangement,

  and the respective second individual layer reduces the surface roughness of the protective layer system by smoothing the surface roughness of the first individual layer.

It has been recognized according to the invention that the construction of the protective layer system protecting the substrate can be simplified and the thickness of the protective layer system can thus be reduced if the individual layers each inherently combine more than one functionality. In this regard, the first individual layer is designed in such a way that it firstly protects the substrate by absorbing the EUV radiation, since otherwise, as mentioned in the introduction, compaction of the substrate and thus an undesired change in the optical imaging properties during the operational period can occur under high doses of EUV radiation. Secondly, the first individual layer simultaneously compensates for layer stresses in the layer arrangement, since otherwise the substrate warps impermissibly on account of the layer stresses. In this case, the reflective layer system and the roughness-reducing layers usually have a compressive stress, which must be compensated for by a tensile stress generated in the protective layer system. The first individual layer thus has two functionalities.

Moreover, the second individual layer is designed in such a way that it reduces the surface roughness of the protective layer system. This is achieved, firstly, by virtue of the fact that the absorbing and layer-stress-compensating effect is not produced by a thick layer, but rather as a multiplicity of thinner first individual layers that are interrupted by the second individual layers.

Thus, in terms of their total thickness the first individual layers indeed have the respectively desired effect with regard to absorption and, respectively, layer stress, but the crystal growth in the first individual layers is interrupted. Therefore, the surface roughness at the surfaces of the first individual layers is reduced relative to a single thick layer. Secondly, the second individual layers are designed such that the surface roughness is additionally reduced. In this case, the resulting surface roughness of the second individual layer is dependent both on the material and on the type of deposition method of the individual layer.

As a result, it is possible to produce very smooth surfaces without high stray light losses.

The stringent requirements made of the surface roughness of the protective system are necessary in order that the losses on account of stray light are avoided in order to obtain a high reflectivity of the mirror. Said requirements apply in particular to the transitions of the individual layers of the reflective layer system, since the EUV radiation is reflected here. In order, however, that the reflective layer system can satisfy the requirements made of the surface roughness, the underlying protective layer system must already have a sufficiently low surface roughness.

In one advantageous embodiment, the ratio of the thickness of the first individual layer to the thickness of the second individual layer is constant for all periods. By virtue of the facilitated measurability of the parameters, for example of the thicknesses of the individual layers, of such a protective layer system and the process control facilitated thereby, the production of such protective layer systems is simplified. This is because only regular, repeating structures enable the determination of the period thickness by means of X-ray optical methods.

In one particularly advantageous embodiment, the ratio of the thickness of the first individual layer to the thickness of the second individual layer decreases with greater distance from the substrate. As a result, the layer-stress-generating first individual layers, relative to the smoothing second individual layers, have higher thicknesses in the lower plies than in the upper plies. Thus, the generation of layer stresses is dominant in the lower region, while the effect of the roughness-reducing individual layers predominates in the upper part. The roughening of the lower layer section is thus compensated for again in the upper section. As a result, with a lower total thickness of the protective layer system, it is possible overall to achieve the same layer-stress-generating and roughness-reducing effect as in the case of a layer stack in which the

ratio of the thickness of the first individual layer to the thickness of the second individual layer is constant for all periods.

In one advantageous embodiment, the material of the first individual layer (AZ) has an absorption index k at 13.5 nm of more than 0.03. In this case, the absorption index (k-value) is the imaginary part of the imaginary refractive index $\tilde{n} = n - i \cdot k$.

In one advantageous embodiment, the transmission of EUV radiation through the layer arrangement as far as the substrate is less than 0.1%. It has been recognized according to the invention that protecting the substrate against excessively high doses of EUV radiation necessitates designing the layer arrangement on the substrate of the mirror such that only a fraction of the EUV radiation reaches the substrate. In a manner adapted to the reflective layer system, which can comprise many periods of individual layers and thus also absorbs a proportion of the EUV radiation, in this case the protective layer system protecting the substrate is designed such that at all events the transmission of EUV radiation through the layer arrangement to the substrate is less than 0.1%.

In one advantageous embodiment, the mirror for the EUV wavelength range is characterized in that the protective layer under EUV radiation experiences an irreversible change in volume of less than 1%.

In this case, irreversible change in volume under EUV radiation is understood to mean, rather than the reversible change in volume on account of thermal expansion, the long-term irreversible change in volume – brought about by high doses of EUV radiation – on account of structural changes in the material under consideration. In this case, it has been recognized according to the invention that it must also be taken into consideration that the protective layer system must remain stable even under EUV radiation at high doses that are accumulated over the lifetime of a lithography apparatus. Otherwise the problem of the irreversible change in volume is merely shifted from the substrate to the protective layer system.

Furthermore, the object of the present invention is achieved by means of a mirror for the EUV wavelength range that is characterized in that the protective layer system is provided to prevent an irreversible change in the surface of the substrate under EUV radiation of more than 0.1 nm as measured in the normal direction at a location within the irradiated region of the substrate relative to the surface of the substrate at a location

outside the irradiated region as measured in the same direction and simultaneously to exert a layer stress for compensating for layer stresses in the layer arrangement.

In this case, it has been recognized according to the invention that, besides protection of the substrate, care must also be taken to ensure that the protective layer system is simultaneously adapted for compensating for the layer stresses in the layer arrangement, since otherwise the substrate warps impermissibly on account of the layer stresses. Consequently, in the design of a protective layer system, the layer stress resulting therefrom must be taken into account. Furthermore, by means of the material selection in the case of the protective layer system, care must be taken to ensure that these do not change in the case of EUV radiation of high doses, since this inevitably entails a change in the layer stress and thus in the surface shape.

In one advantageous embodiment, the periods of the protective layer system have a thickness of 5 nm – 100 nm in order both to compensate for the occurring roughness of the tensile-stress-generating sublayer and to be able to produce tensile stresses overall.

In one advantageous embodiment, the protective layer system has a thickness of 50 nm – 1000 nm in order thus to be able to produce the substrate protection, the necessary layer stress and also the measurability.

In one advantageous embodiment, the protective layer for compensating for layer stresses in the layer arrangement exerts a tensile stress of +10 MPa to +2000 MPa, which is suitable for being able to compensate for the layer stress of conventional EUV reflective layer systems in the range of from -1000 MPa to a few -10 MPa.

In one advantageous embodiment, the material of the first individual layer (AZ) consists of copper, chromium or a nickel-chromium alloy, wherein the ratio of chromium:nickel in this case lies between 30:70 and 70:30. In this case, it has been recognized according to the invention that copper, chromium or a nickel-chromium alloy are materials which can simultaneously absorb enough EUV radiation to protect the substrate against high doses of EUV radiation and have a layer-stress-generating effect.

In one advantageous embodiment, the second individual layer consists of a material which is selected or made up from the group of the materials: B_4C, C, Si nitride, Si carbide, Si boride, Mo nitride, Mo carbide, Mo boride, Ru nitride, Ru carbide and Ru boride.

In one advantageous embodiment, the mirror for the EUV wavelength range is characterized in that the protective layer system has a surface roughness of less than 0.6 nm rms, in particular less than 0.1 nm rms, in the spatial wavelength range of 10 nm to 1.5 µm. Such layers, as mentioned in the introduction, lead to low stray light losses.

In one advantageous embodiment, the mirror for the EUV wavelength range is characterized in that the individual layers of the protective layer system are applied using vacuum coating methods. Only with these methods is it possible to produce sufficiently precise and reproducible layers for EUV lithography.

Furthermore, the object of the present invention is achieved by means of a mirror for the EUV wavelength range, wherein the reflective layer system comprises at least one layer subsystem which consists of a periodic sequence of at least two periods of individual layers, wherein the periods comprise two individual layers composed of different materials for a high refractive index layer and a low refractive index layer.

In this case, as mentioned in the introduction, in the EUV wavelength range, the terms high refractive index and low refractive index are relative terms with regard to the respective partner layer in a period of a layer subsystem. Layer subsystems function in the EUV wavelength range in general only if a layer acting with an optically high refractive index is combined with an optically lower refractive index layer relative thereto as main constituent of a period of the layer subsystem.

In one advantageous embodiment, the mirror for the EUV wavelength range is furthermore characterized in that the reflective layer system comprises a capping layer system, which terminates the layer arrangement of the mirror. As a result, the mirror is protected against environmental influences.

Furthermore, the object of the present invention is achieved by means of a projection lens for microlithography which comprises a mirror according to the invention.

Furthermore, the object of the present invention is achieved by means of an illumination system for microlithography which comprises a mirror according to the invention.

Furthermore, the object of the present invention is achieved by means of a projection exposure apparatus for microlithography which comprises a projection lens according to the invention and/or an illumination system according to the invention.

Further features and advantages of the invention emerge from the following description of exemplary embodiments of the invention on the basis of the figures, which show details essential to the invention, and from the claims. The individual features may be realized in each case individually by themselves or as a plurality in any desired combination in a variant of the invention.

BRIEF DESCRIPTION OF THE FIGURES

Exemplary embodiments of the invention are explained in more detail below with reference to the figures. In the figures:

Figures 1A-1B show a schematic illustration of a first mirror according to the invention;

Figures 2A – 2B show a schematic illustration of a second mirror according to the invention;

Figure 3 shows a schematic illustration of a projection lens according to the invention for a projection exposure apparatus for microlithography.

EXEMPLARY EMBODIMENTS

Figures 1A and 1B show a schematic illustration of a mirror (S1) according to the invention for the EUV wavelength range comprising a substrate (S) and a layer arrangement (X). In this case, the layer arrangement (X) comprises a reflective layer system (RL) and a protective layer system (SPL) protecting the substrate. In this case, the protective layer system (SPL) is illustrated in detail in Figure 1A, whereas Figure 1B shows the reflective layer system (RL) in detail. A protective layer system (SPL) serves, inter alia, to protect the substrate against excessively high doses of EUV radiation since mirror substrates (S) produced from Zerodur® or ULE®, for example, at high doses of EUV radiation, exhibit an irreversible compaction of the order of magnitude of a few percent by volume. The protective layer system (SPL) comprises a periodic sequence of at least two periods (P_{SPL}) which consist of in each case two individual layers (AZ, R),

see Figure 1A. In this case, the first individual layer (AZ) is designed in such a way that it firstly protects the substrate (S) by absorbing the EUV radiation. By way of example, the first individual layer has an absorption index at 13.5 nm of more than 0.03. Secondly, the first individual layer (AZ) simultaneously compensates for layer stresses in the layer arrangement (X), since otherwise the substrate (S) warps impermissibly on account of the layer stresses. By way of example, the protective layer system (SPL) for compensation of layer stresses in the layer arrangement (X) exerts a tensile stress of +10 MPa to +2000 MPa. The first individual layer (AZ) thus has two functionalities. The first individual layer (AZ) is produced for example from copper, chromium or a chromium-nickel alloy having a ratio of chromium:nickel of between 30:70 and 70:30.

In addition, the second individual layer (R) is designed in such a way that it reduces the surface roughness of the protective layer system (SPL) by smoothing the surface roughness of the first individual layer (AZ). All absorbing individual layers (AZ) of the protective layer system which are manifested in the protective layer system (SPL) and generate layer stress, in their cumulated total thickness, here have the respectively desired effect with regard to absorption and/or layer stress. However, since they are interrupted by the second individual layers (R), the crystal growth of the first individual layer (AZ) is interrupted. The second individual layer consists for example of a material which is selected or made up from the group of the materials: B_4C, C, Si nitride, Si carbide, Si boride, Mo nitride, Mo carbide, Mo boride, Ru nitride, Ru carbide and Ru boride. As a result, it is possible to produce very smooth surfaces without high stray light losses; by way of example, the protective layer system has a surface roughness of less than 0.6 nm rms in the spatial wavelength range of 10 nm to 1.5 µm. In particular, the surface roughness can also be less than 0.1 nm rms.

According to the invention, by virtue of the fact that the individual layer (AZ) inherently combines more than one functionality, the construction of the protective layer system protecting the substrate is simplified and the thickness of the protective layer system d_P is thus reduced. By way of example, the protective layer system (SPL) has a thickness (d_P) of 50 nm – 1000 nm. Alternatively, different protective layer subsystems would have to be provided for the effect of protection against EUV radiation and generation of layer stress.

In this case, in Figure 1A, by way of example, the thickness of the first individual layer (AZ) and of the second individual layer (R) is constant ($d_{AZ1} = d_{AZ2} = \ldots = d_{AZN} = d_{AZ}$ and $d_{R1} = d_{R2} = \ldots = d_{RN} = d_R$). The ratio of the thickness d_{AZN} of the first individual layer (AZ) to the thickness dR of the second individual layer (R) is thus also constant for all periods (PSPL).

The reflective layer system (RL) is elucidated in greater detail in Figure 1B. The reflective layer system can comprise a plurality of layer subsystems (P', P", P"') each consisting of a periodic sequence of at least two periods (P_1, P_2, P_3) of individual layers. The periods (P_1, P_2, P_3) comprise two individual layers composed of different materials for a high refractive index individual layer (H', H",H"') and a low refractive index individual layer (L', L", L"') and have within each layer subsystem (P', P", P"') for example a constant thickness (d_1, d_2, d_3), which deviates from a thickness of the periods of an adjacent layer subsystem. In this case, the layer subsystem P"' the furthest away from the substrate can have a number N_3 of periods P_3 which is greater than the number N_2 of periods P_2 for the layer subsystem (P") the second furthest away from the substrate. In addition, the layer subsystem (P") the second furthest away from the substrate (S) can have a sequence of the periods (P_2) such that the first high refractive index individual layer (H"') of the layer subsystem (P"') the furthest away from the substrate directly follows the last high refractive index individual layer (H") of the layer subsystem P" the second furthest away from the substrate.

Consequently, in Figure 1B, the order of the high (H") and low refractive index (L") individual layers within the periods (P_2) in the layer subsystem (P") the second furthest away from the substrate is reversed relative to the order of the high (H', H"') and low refractive index (L', L") individual layers within the other periods (P_1, P_3) of the other layer subsystems (P', P"'), such that the first low refractive index layer (L") of the layer subsystem P" the second furthest away from the substrate also optically effectively follows the last low refractive index layer (L') of the layer subsystem (P') situated the closest to the substrate.

Furthermore, by way of example, the individual layers of the reflective layer system of the mirror according to the invention in Figures 1A, B can be separated by at least one barrier layer (B), wherein the barrier layer (B) consists of a material which is selected or made up from the group of the materials: B_4C, C, Si nitride, Si carbide, Si boride, Mo nitride, Mo carbide, Mo boride, Ru nitride, Ru carbide and Ru boride. Such a barrier layer (B) suppresses the interdiffusion between the two individual layers of a period,

thereby increasing the optical contrast upon the transition of the two individual layers. With the use of the materials molybdenum and silicon for the two individual layers of a period, one barrier layer (B) above the Si layer as viewed from the substrate suffices to provide for a sufficient contrast. The second barrier layer (B) above the Mo layer can be dispensed with in this case. In this respect, at least one barrier layer (B) should be provided for separating the two individual layers of a period, wherein the at least one barrier layer (B) can be constructed from various of the above-indicated materials or the compounds thereof or in this case can also exhibit a layered construction of different materials or compounds.

The layer arrangement (X) of the mirror (S1) according to the invention is terminated in Figures 1A, B by a capping layer system (C) comprising at least one layer composed of a chemically inert material such as, for example, Rh, Pt, Ru, Pd, Au, SiO_2 as terminating layer (M). Said terminating layer (M) thus prevents the chemical alteration of the mirror surface on account of environmental influences. The capping layer system (C) in Figures 1A, B consists of a high refractive index individual layer (H), a low refractive index individual layer (L) and a barrier layer (B) in addition to the terminating layer (M).

It should be taken into consideration here that the reflectivity properties, the transmission properties and the stress properties of all the individual layers must be taken into account simultaneously in any overall optimization of a layer arrangement (X).

Table 1 indicates the refractive indices used for the materials of the layer arrangement (X) $\tilde{n} = n - i \cdot k$ for a wavelength of 13.5 nm.

Table 1

Material	Chemical symbol	Layer design symbol	n	k
Substrate			0.974	0.013
Silicon	Si	H, H‘, H“, H“‘	0.999	0.002
Boron carbide	B_4C	B, R	0.964	0.005

Carbon	C	B, R	0.961	0.007
Molybdenum	Mo	L, L‘, L“, L“‘	0.921	0.006
Ruthenium	Ru	M, L, L‘, L“, L“‘	0.889	0.017
Chromium-Nickel	CrNi	AZ	0.93..0.94	0.05..0.07
Chromium	Cr	AZ	0.932	0.040
Vacuum			1	0

Furthermore, the following brief notation corresponding to the layer sequence in Figures 1A,B is stipulated for the layer designs associated with Figures 1A,B:

Substrate/ (AZ R)· N_{SPL} /(P_1)· N_1/(P_2)· N_2/(P_3)· N_3/Capping layer system C where

P_1 = H'BL'B; P_2 = H"BL"B; P_3 = H"'BL"'B; C = HBLM.

Here the letters AZ symbolically denote the thickness of the first individual layers of the protective layer system, R denotes the thickness of the second individual layer of the protective layer system, H denotes the thickness of high refractive index layers, L denotes the thickness of low refractive index layers, the letter B denotes the thickness of the barrier layer and the letter M denotes the thickness of the chemically inert terminating layer. In this case, the unit [nm] applies to the thicknesses of the individual layers that are indicated between parentheses.

The exemplary embodiments associated with Figures 1A, B can thus be specified as follows in the brief notation:

Exemplary embodiment 1: the transmission of EUV radiation through the layer arrangement to the substrate is less than 0.1% and the protective layer experiences under EUV irradiation an irreversible change in volume of less than 1% and a surface roughness of less than 0.5 nm rms.

Substrate / (8 nm Cr 2 nm B_4C) · 25 / RL

Exemplary embodiment 2: the periods of the protective layer system have a thickness of 10 nm – 100 nm and the protective layer system has a thickness of 50 nm – 1000 nm.

Substrate / (30 nm Cu 1 nm C) · 5 / RL

Exemplary embodiment 3: the layer arrangement exerts a tensile stress of +10 MPa to +2000 MPa whilst preventing an irreversible change in the surface of the substrate under EUV radiation of more than 0.1 nm in the normal direction.

Substrate / (40 nm CrNi 2 nm B_4C) · 4 / RL

In this case, the reflective layer system RL can be constructed for example as follows:

RL= (0.4 B_4C 2.921 Si 0.4 B_4C 4.931 Mo) · 8 /

(0.4 B_4C 4, 145 Mo 0.4 B_4C 2.911 Si) · 5 /

(3.509 Si 0.4 B4C 3.216 Mo 0.4 B_4C) · 16 / 2.975 Si 0.4 B_4C 2 Mo 1.5 Ru

Since the barrier layer B_4C in this example is always 0.4 nm thick, it can also be omitted in order to illustrate the basic construction of the layer arrangement, such that the layer design of the reflective layer system can be indicated in shortened form as follows:

(2.921 Si 4.931 Mo) · 8 / (4.145 Mo 2.911 Si) · 5 /

(3.509 Si 3.216 Mo) · 16 / 2.975 Si 2 Mo 1.5 Ru

It is evident from this first exemplary embodiment in accordance with Figures 1A, B that the order of the high refractive index layer Si and the low refractive index layer Mo in the second layer subsystem comprising five periods was reversed relative to the other layer subsystems, such that the first high refractive index layer of the layer subsystem the furthest away from the substrate with a thickness of 3.509 nm directly follows the last high refractive index layer of the layer subsystem the second furthest away from the substrate with a thickness of 2.911 nm.

Figure 2A und Figure 2B illustrate a further embodiment of the invention. In this case, in contrast to the first exemplary embodiment described in Figures 1A, B, the ratio of the thickness d_{AZ} of the first individual layer (AZ) to the thickness d_R of the second individual layer (R) decreases with greater distance from the substrate (S), see Figure 2A. In this case, the layer-stress-generating first individual layers (AZ), relative to the smoothing second individual layers (R), have higher thicknesses in the lower plies (nearer to the substrate) compared with in the upper plies (more distant from the substrate). Thus, the generation of the compensating layer stresses predominates in the lower region, while the effect of the roughness-reducing individual layers is predominant in the upper part. The roughening of the lower layer section is thus compensated for again in the upper

section. As a result, with the same or even a smaller total thickness of the protective layer system (SPL) overall it is possible to achieve the same layer-stress-compensating and roughness-reducing effect as in the case of a layer stack in which the ratio of the thickness of the first individual layer (AZ) to the thickness of the second individual layer (R) is constant for all periods.

In this case, the reflective layer system (RL) comprises a plurality of layer subsystems (P', P", P"') each consisting of a periodic sequence of at least two periods (P_1, P_2, P_3) of individual layers, see Figure 2B. The periods (P_1, P_2, P_3) comprise two individual layers composed of different materials for a high refractive index layer (H', H", H"') and a low refractive index layer (L', L", L"') and have within each layer subsystem (P', P", P"') a constant thickness (d_1, d_2, d_3) that deviates from a thickness of the periods of an adjacent layer subsystem. In this case, the layer subsystem (P"') the furthest away from the substrate has a number N_3 of periods P_3 which is greater than the number N_2 of periods P_2 for the layer subsystem (P") the second furthest away from the substrate. In this case, unlike in the exemplary embodiment with regard to Figures 1A, B, the layer subsystem (P") the second furthest away from the substrate has a sequence of periods P_2 which corresponds to the sequence of periods P_1 and P_3 of the other layer subsystems P' and P"', such that the first high refractive index layer (H"') of the layer subsystem (P"') the furthest away from the substrate optically effectively follows the last low refractive index layer (L") of the layer subsystem (P") the second furthest away from the substrate.

Furthermore, by way of example, the individual layers of the reflective layer system of the mirror according to the invention in Figures 2A, B can be separated by at least one barrier layer (B), analogously to the exemplary embodiment in Figures 1A, B. Likewise analogously to the first exemplary embodiment, the layer arrangement (X) of the mirror (S2) according to the invention can be terminated by a capping layer system (C).

Furthermore, for the layer designs associated with Figures 2A,B, the following short notation is stipulated in accordance with the layer sequence in Figures 2A,B:

Substrate/ (AZ R … AZ R) /(P_1)· N_1/(P_2)· N_2/(P_3)· N_3/Capping layer system C where

P_1 = BH'BL'; P_2 = BL"BH"; P_3 = H"'BL"'B; C = HBLM.

In this case, analogously to the description of the first exemplary embodiment, the letters symbolically denote the thickness of the respective individual layers in the unit

[nm]. The exemplary embodiments associated with Figures 2A, B can thus be specified as follows in the short notation:

Exemplary embodiment 4: the transmission of EUV radiation through the layer arrangement to the substrate is less than 0.1% and the protective layer experiences under EUV irradiation an irreversible change in volume of less than 1% and a surface roughness of less than 0.5 nm rms.

Substrate / (10 nm Cr 2 nm B4C) · 10 / (8 nm Cr 2 nm B4C) · 6 / (5 nm Cr 2 nm B4C) · 6 / RL

Exemplary embodiment 5: the periods of the protective layer system have a thickness of 10 nm – 100 nm and the protective layer system has a thickness of 50 nm – 1000 nm.

Substrate / (50 nm Cu 1 nm B4C) ·2 / (30 nm Cu 1 nm B4C) ·X / (5 nm Cu 2 nm B4C) ·6 / RL

Exemplary embodiment 6: the layer arrangement exerts a tensile stress of +10 MPa to +2000 MPa whilst preventing an irreversible change in the surface of the substrate under EUV radiation of more than 0.1 nm in the normal direction.

Substrate / (50 nm CrNi 2 nm B4C) ·2 / (25 nm CrNi 1 nm B4C) ·1 / (5 nm CrNi 2 nm B4C) ·4 / RL

In this case, the reflective layer system RL of the second exemplary embodiment can be specified as:

RL= (4.737 Si 0.4 B_4C 2.342 Mo 0.4 B_4C) · 28
/ (3.443 Si 0.4 B_4C 2.153 Mo 0.4 B_4C) · 5
/ (3.523 Si 0.4 B_4C 3.193 Mo 0.4 B_4C) · 15
/ 2.918 Si 0.4 B_4C 2 Mo 1.5 Ru

Since the barrier layer B_4C in this example is once again always 0.4 nm thick, it can also be omitted in order to elucidate said layer arrangement, such that the layer design with regard to Figures 2A, B can be specified in an abbreviated manner as follows:
RL= (4.737 Si 2.342 Mo) · 28 / (3.443 Si 2.153 Mo) · 5 /

(3.523 Si 3.193 Mo) · 15 / 2.918 Si 2 Mo 1.5 Ru

It goes without saying that the layer designs specified above should be understood to be merely by way of example, and that the protective layer system (SPL) of the second

exemplary embodiment can in particular also be combined with a different reflective layer system (RL), for example from the first exemplary embodiment.

Figure 3 schematically shows a projection exposure apparatus (1) consisting of a beam-shaping system (2), an illumination system (3) and a projection lens (4), which are arranged successively in a beam path (6) proceeding from an EUV light source 5 of the beam shaping system (2). By way of example, a plasma source or a synchrotron source can serve as EUV light source (5). The emerging radiation in the wavelength range of between approximately 5 nm and approximately 20 nm is firstly focused in a collimator (7). With the aid of a downstream monochromator (8), the desired operating wavelength is filtered out by variation of the angle of incidence, as is indicated by a double-headed arrow. In the stated wavelength range, the collimator (7) and the monochromator (8) are usually designed as mirrors, wherein at least the monochromator (8), on its optical surface, has no multilayer system, in order to reflect a wavelength range having the greatest possible bandwidth.

The radiation treated with regard to wavelength and spatial distribution in the beam shaping system (2) is introduced into the illumination system (3), which has for example a first and a second mirror (9, 10). The two mirrors (9, 10) guide the radiation onto a photomask (11) as a further reflective optical element, which has a structure that is imaged by means of the projection system (4) onto a wafer (12) on a reduced scale. For this purpose, by way of example, a third and a fourth mirror (13, 14) are provided in the projection system (4). The mirrors (9, 10, 13, 14) used in the projection exposure apparatus can be formed here for example in each case by a mirror (S1, S2) according to the invention from the first or second exemplary embodiment, see Figures 1A, B and Figures 2A, B.

PATENT CLAIMS

1. Mirror (S1, S2) for the EUV wavelength range comprising
a substrate (S) and
a layer arrangement (X), wherein the layer arrangement comprises
a reflective layer system (RL) having at least one layer subsystem (P') and
a protective layer system (SPL) protecting the substrate,
wherein the protective layer system (SPL) comprises a periodical sequence of at least two periods (P_{SPL}), consisting of in each case two individual layers (AZ, R),
characterized in that the first individual layer (AZ) of the period (P_{SPL}) simultaneously protects the substrate by absorbing the EUV radiation and compensates for layer stresses in the layer arrangement (X),
and the respective second individual layer (R) reduces the surface roughness of the protective layer system (SPL) by smoothing the surface roughness of the first individual layer (AZ) and
that the material of the first individual layer (AZ) consists of copper, chromium or a nickel-chromium alloy, wherein the ratio of chromium:nickel is between 30:70 and 70:30.

2. Mirror (S1, S2) for the EUV wavelength range according to Claim 1, characterized in that the transmission of EUV radiation through the layer arrangement as far as the substrate is less than 0.1%.

3. Mirror (S1, S2) for the EUV wavelength range according to either of the preceding claims, characterized in that the protective layer (SPL) under EUV radiation experiences an irreversible change in volume of less than 1%.

4. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the protective layer system (SPL) prevents an irreversible change in the surface of the substrate (S) under EUV radiation of more than 0.1 nm as measured in the normal direction at a location within the irradiated region of the substrate (S) relative to the surface of the substrate (S) at a location outside the irradiated region as measured in the same direction and simultaneously

exerts a layer stress for compensating for layer stresses in the layer arrangement (X).

5. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the ratio of the thickness (d_{AZ}) of the first individual layer (AZ) to the thickness (d_R) of the second individual layer (R) is constant for all periods (P_{SPL}) .

6. Mirror (S1, S2) for the EUV wavelength range according to Claims 1-4, characterized in that the ratio of the thickness (d_{AZ}) of the first individual layer (AZ) to the thickness (d_R) of the second individual layer (R) decreases with greater distance from the substrate (S).

7. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the material of the first individual layer (AZ) has an absorption index at 13.5 nm of more than 0.03.

8. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the periods (P_{SPL}) of the protective layer system (SPL) have a thickness (d_{SPL}) of 10 nm – 100 nm.

9. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the protective layer system (SPL) has a thickness (d_P) of 50 nm – 1000 nm.

10. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the protective layer system (SPL) for compensating for layer stresses in the layer arrangement (X) exerts a tensile stress of +10 MPa to +2000 MPa.

11. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the second individual layer (R) consists of a material which is selected or made up from the group of the materials: B_4C, C, Si nitride, Si carbide, Si boride, Mo nitride, Mo carbide, Mo boride, Ru nitride, Ru carbide and Ru boride.

12. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the protective layer system (SPL) has a surface roughness of less than 0.6 nm rms, in particular less than 0.1 nm rms, in the spatial wavelength range of 10 nm to 1.5 µm.

13. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the individual layers (AZ, R) of the protective layer system (SPL) are applied using low pressure plasmas.

14. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the reflective layer system (RL) comprises at least one layer subsystem (P',P",P"') which consists of a periodic sequence of at least two periods (P1, P2, P3) of individual layers, wherein the periods (P1, P2, P3) comprise two individual layers composed of different materials for a high refractive index layer (H"') and a low refractive index layer (L"').

15. Mirror (S1, S2) for the EUV wavelength range according to any of the preceding claims, characterized in that the reflective layer system (RL) furthermore comprises a capping layer system (C), which terminates the layer arrangement (X) of the mirror.

16. Projection lens for microlithography comprising a mirror (S1, S2) according to any of Claims 1 to 15.

17. Illumination system for microlithography comprising a mirror (S1, S2) according to any of Claims 1 to 15.

18. Projection exposure apparatus for microlithography comprising a projection lens according to Claim 16 and/or an illumination system according to Claim 17.

FIG.1A

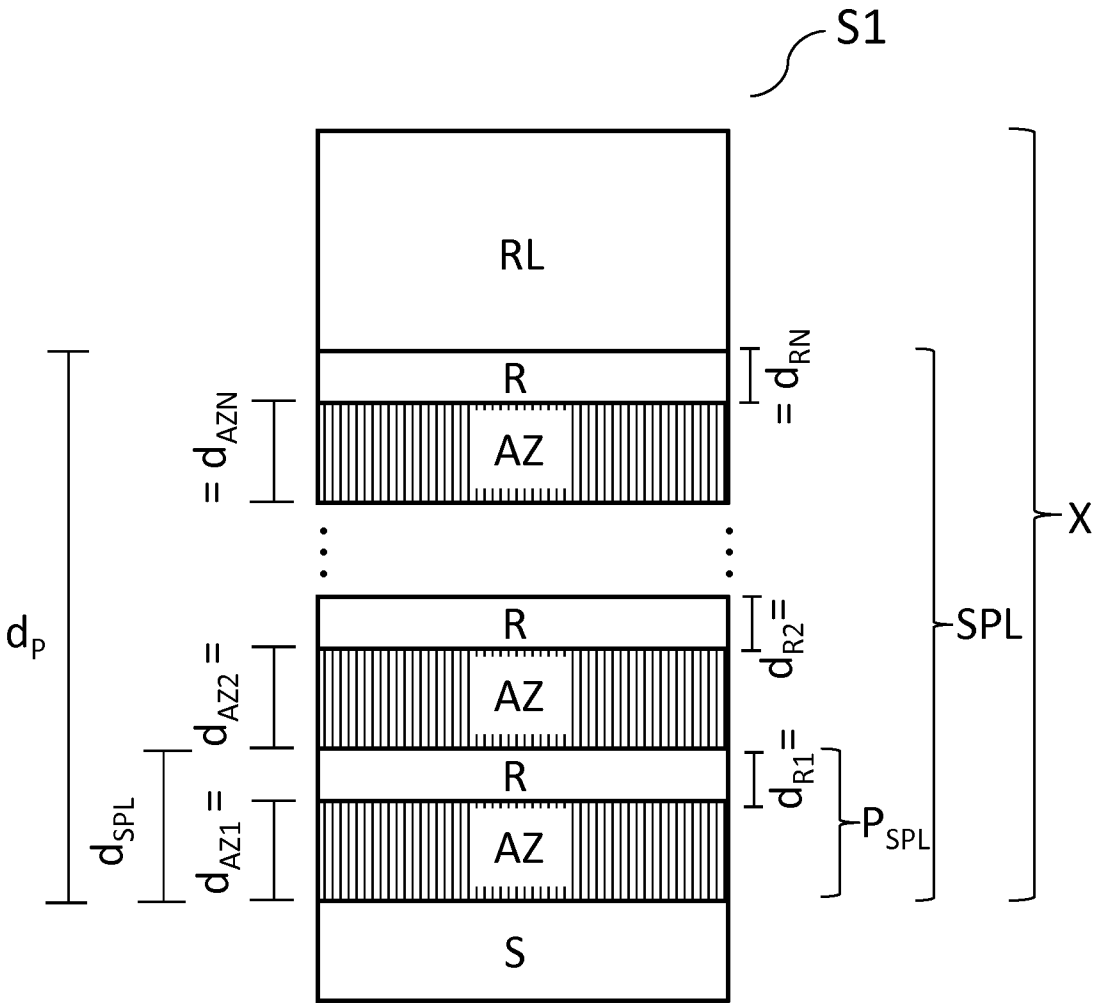


FIG.1B

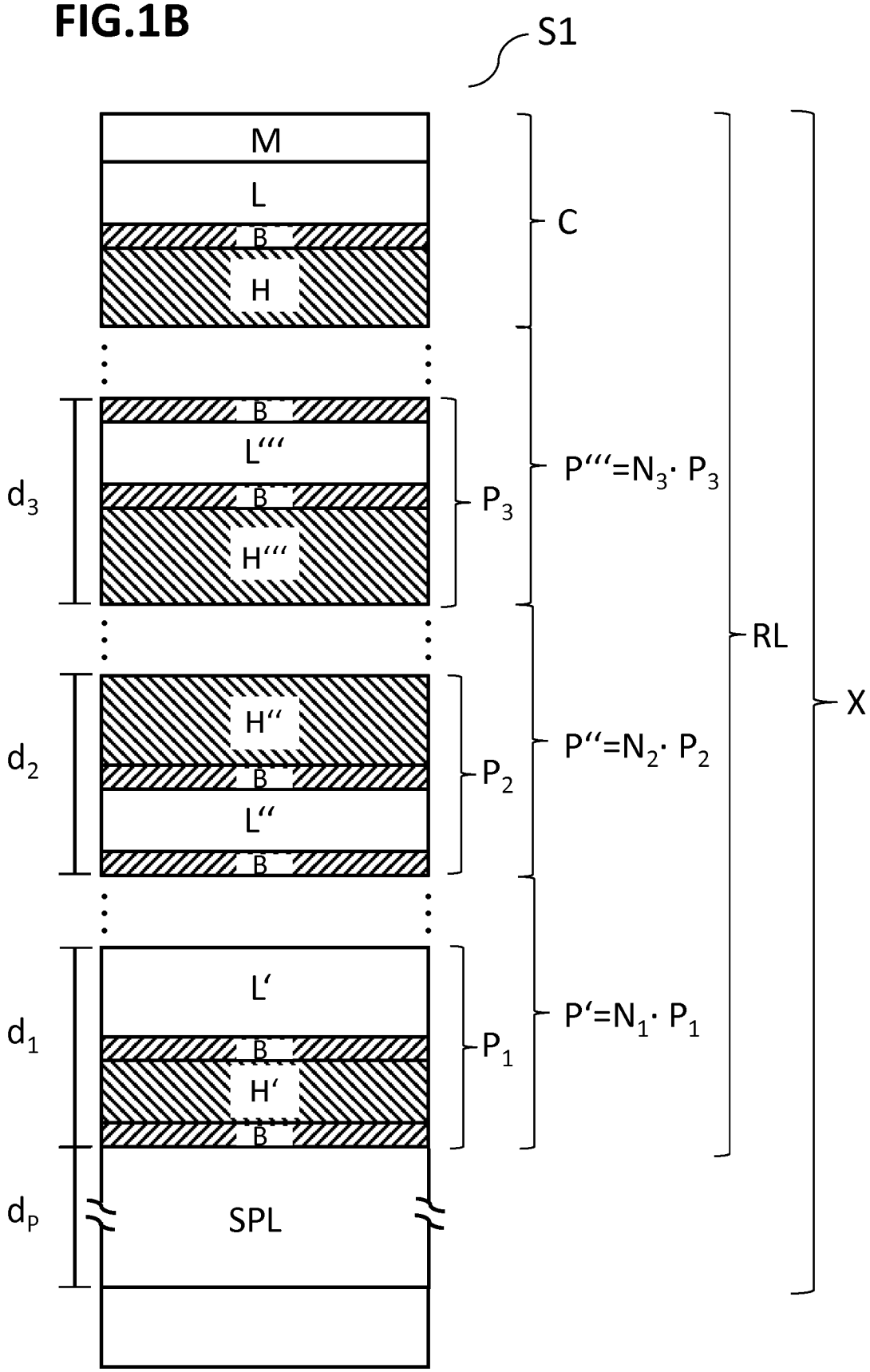

S1
M
L
B
H
C
B
L‘‘‘
B
H‘‘‘
d3
P3
P‘‘‘=N3· P3
RL
X
H‘‘
B
L‘‘
B
d2
P2
P‘‘=N2· P2
L‘
B
H‘
B
d1
P1
P‘=N1· P1
dP
SPL

FIG.2A

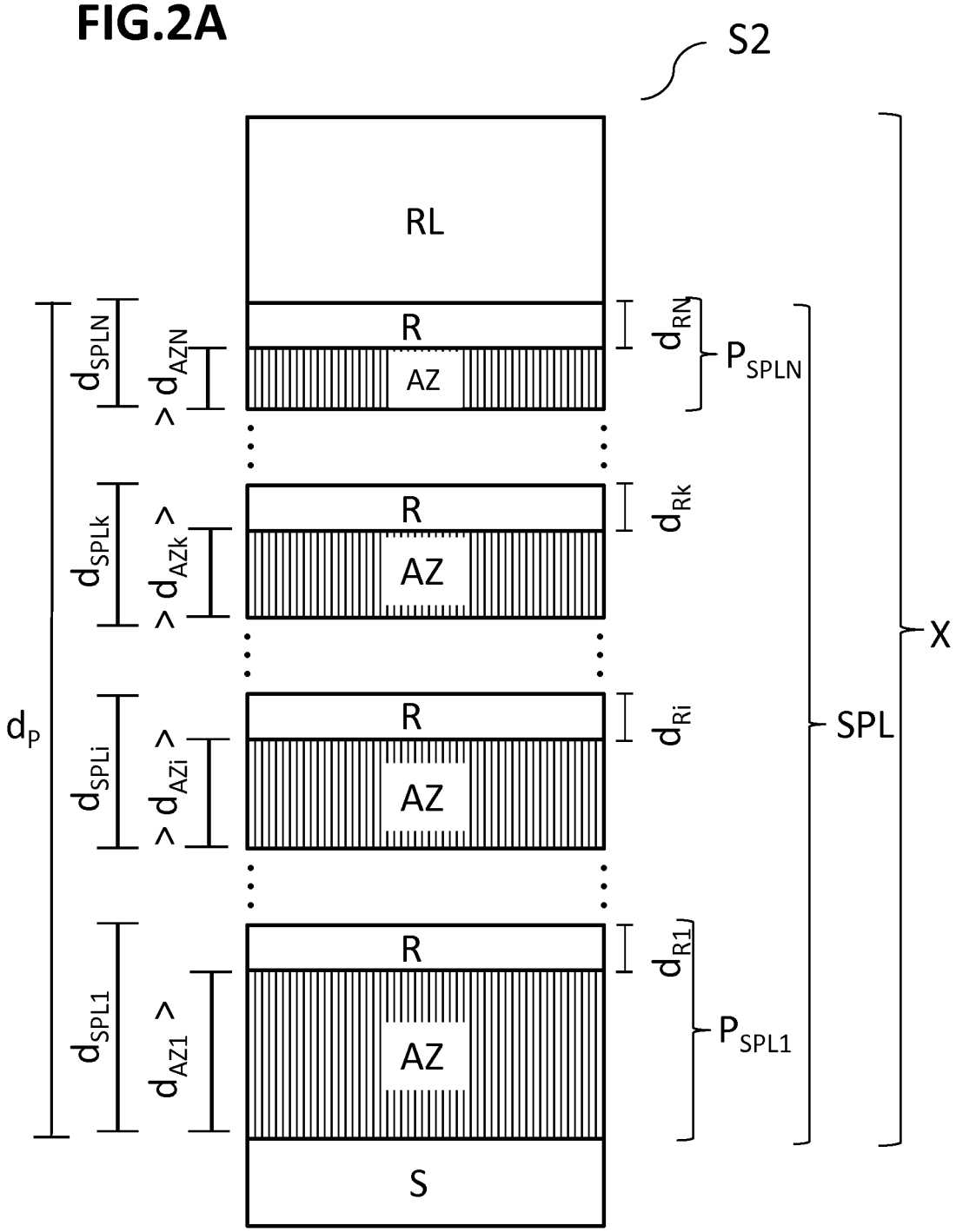

S2
RL
R
AZ
S
d_{SPLN}
> d_{AZN}
d_{RN}
P_{SPLN}
d_{SPLk}
> d_{AZk} >
d_{Rk}
d_{SPLi}
> d_{AZi} >
d_{Ri}
d_{SPL1}
d_{AZ1} >
d_{R1}
P_{SPL1}
d_P
SPL
X

FIG.2B

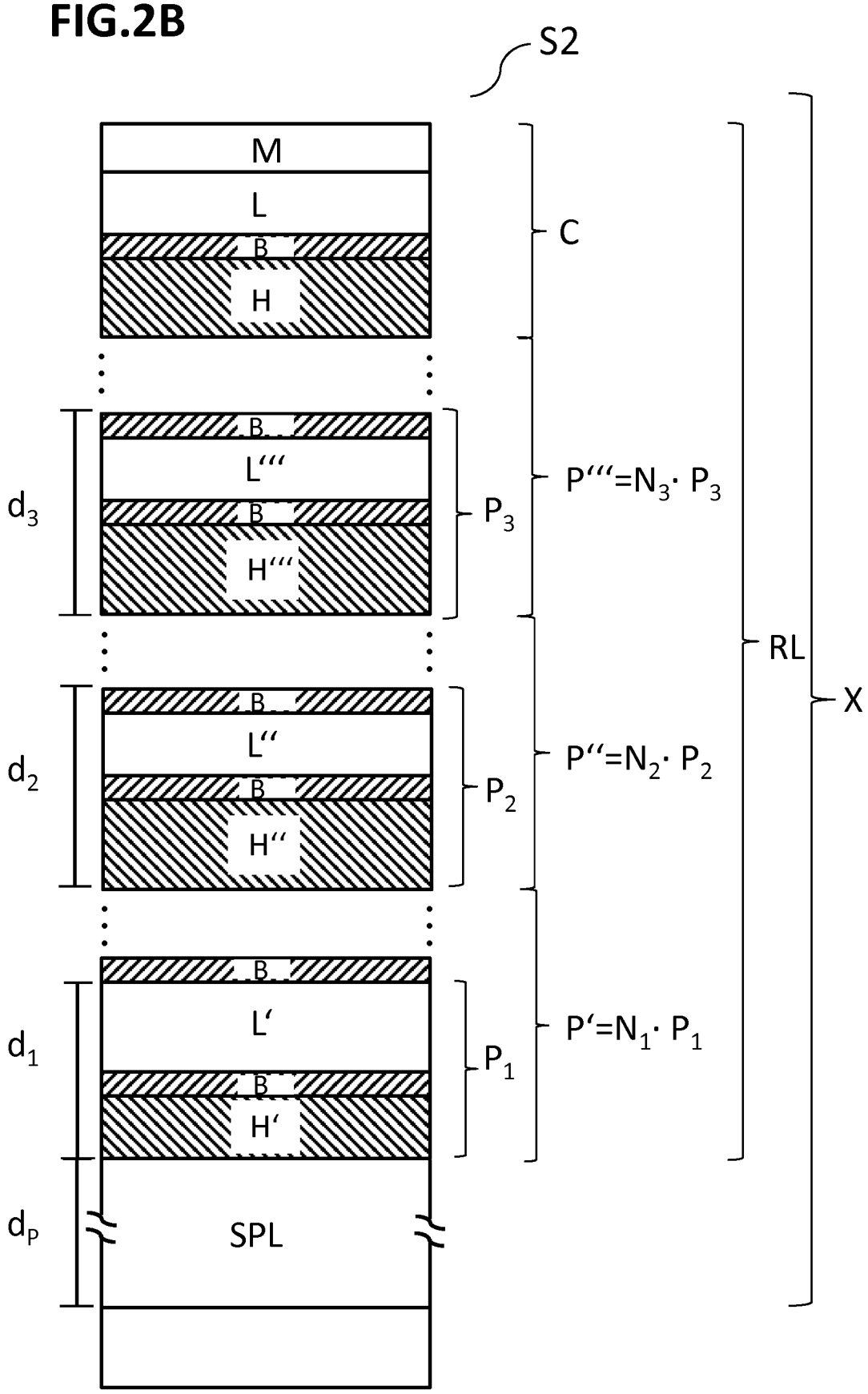
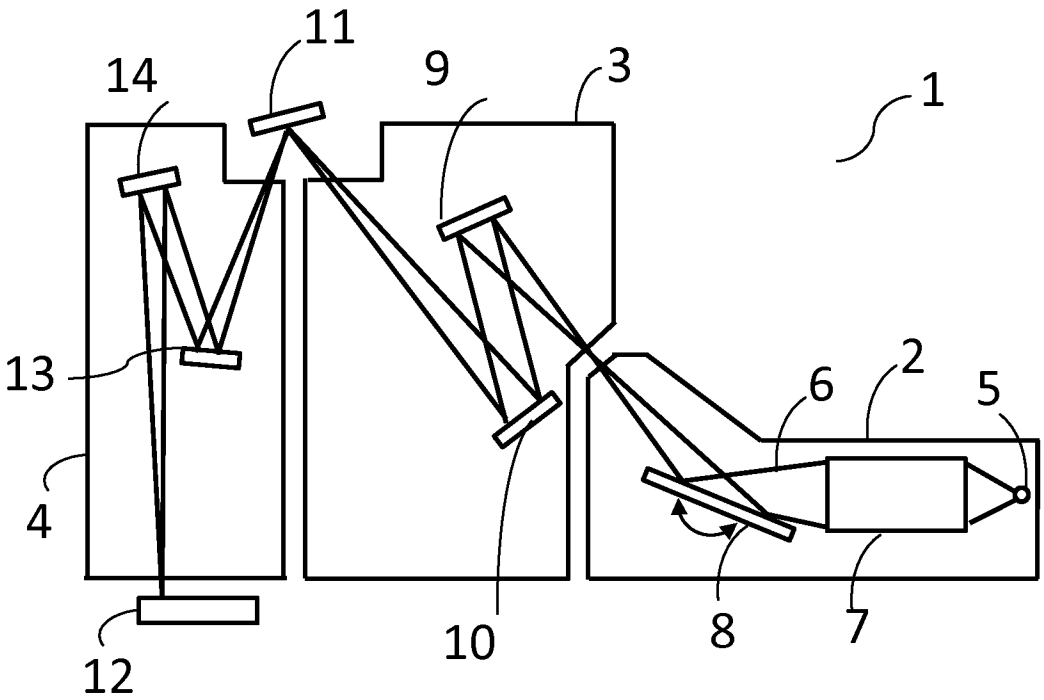

S2
M
L
B
H
C
B
L‴
B
H‴
d3
P3
P‴=N3· P3
RL
X
B
L‘‘
B
H‘‘
d2
P2
P‘‘=N2· P2
B
L‘
B
H‘
d1
P1
P‘=N1· P1
dP
SPL

FIG.3



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/061697

A. CLASSIFICATION OF SUBJECT MATTER
INV. G03F7/20 G21K1/06 G02B5/08
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G03F G21K 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, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	paragraphs [0002], [0015], [0083] - [0097], [0113]; claims 2, 3, 13, 21; figure 3a	6

X	US 2013/286471 A1 (FREIMANN ROLF [DE] ET AL) 31 October 2013 (2013-10-31) paragraphs [0110] - [0120], [0136]; figure 3a	1

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"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

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Date of the actual completion of the international search	Date of mailing of the international search report
4 August 2017	14/08/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Eisner, Klaus

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/061697

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	KATSUHIKO MURAKAMI ET AL: "Stress control of Mo/Si-based multilayer coatings deposited by ion-beam sputtering", SPIE - INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING. PROCEEDINGS, vol. 4506, 20 December 2001 (2001-12-20), pages 56-64, XP055349326, US ISSN: 0277-786X, DOI: 10.1117/12.450945 ISBN: 978-1-5106-0753-8 the whole document	1-18
A	US 2007/287076 A1 (MASAKI FUMITARO [JP] ET AL) 13 December 2007 (2007-12-13) paragraphs [0039], [0053]; figures 2, 6	1-18

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2017/061697

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