

EXTREME ULTRAVIOLET MASK ABSORBER MATERIALS

TECHNICAL FIELD

[0001] The present disclosure relates generally to extreme ultraviolet lithography, and more particularly to extreme ultraviolet mask blanks with an absorber comprised of
5 two or more materials and methods of manufacture.

BACKGROUND

[0002] Extreme ultraviolet (EUV) lithography, also known as soft x-ray projection lithography, are used for the manufacture of 0.0135 micron and smaller minimum feature size semiconductor devices. However, extreme ultraviolet light, which is
10 generally in the 5 to 100 nanometer wavelength range, is strongly absorbed in virtually all materials. For that reason, extreme ultraviolet systems work by reflection rather than by transmission of light. Through the use of a series of mirrors, or lens elements, and a reflective element, or mask blank, coated with a non-reflective absorber mask pattern, the patterned actinic light is reflected onto a resist-coated semiconductor
15 substrate.

[0003] The lens elements and mask blanks of extreme ultraviolet lithography systems are coated with reflective multilayer coatings of materials such as molybdenum and silicon. Reflection values of approximately 65% per lens element, or mask blank, have been obtained by using substrates that are coated with multilayer coatings that
20 strongly reflect light within an extremely narrow ultraviolet bandpass, for example, 12.5 to 14.5 nanometer bandpass for 13.5 nanometer ultraviolet light.

[0004] FIG. 1 shows a conventional EUV reflective mask 10, which is formed from an EUV mask blank, which includes a reflective multilayer stack 12 on a substrate 14, which reflects EUV radiation at unmasked portions by Bragg interference. Masked
25 (non-reflective) areas 16 of the conventional EUV reflective mask 10 are formed by etching buffer layer 18 and absorbing layer 20. The absorbing layer typically has a thickness in a range of 51 nm to 77 nm. A capping layer 22 is formed over the reflective multilayer stack 12 and protects the reflective multilayer stack 12 during the etching process. As will be discussed further below, EUV mask blanks are made of
30 on a low thermal expansion material substrate coated with multilayers, capping layer

and an absorbing layer, which is then etched to provide the masked (non-reflective) areas 16 and reflective areas 24.

[0005] The International Technology Roadmap for Semiconductors (ITRS) specifies a node's overlay requirement as some percentage of a technology's minimum half-pitch feature size. Due to the impact on image placement and overlay errors inherent in all reflective lithography systems, EUV reflective masks will need to adhere to more precise flatness specifications for future production. Additionally, EUV blanks have a very low tolerance to defects on the working area of the blank. There is a need to provide EUV mask blanks having a thinner absorber layer to mitigate 3D effects and improve imaging performance.

SUMMARY

[0006] One or more embodiments of the disclosure are directed to an extreme ultraviolet (EUV) mask blank comprising a substrate; a multilayer stack of reflective layers on the substrate, the multilayer stack of reflective layers including a plurality of reflective layer pairs; and an absorber layer on the multilayer stack of reflective layers comprising an alloy selected from an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of Ru and one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O), an alloy of Ru and one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and one or more elements of Group 1 and one or more elements of Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te) and aluminum (Al).

[0007] Additional embodiments are directed to a method of manufacturing an extreme ultraviolet (EUV) mask blank comprising forming on a substrate a multilayer stack of reflective layers on the substrate, the multilayer stack including a plurality of reflective layer pairs; and forming an absorber layer on the multilayer stack of reflective layers, the absorber layer comprising an alloy selected from an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese

(Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of Ru and one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O), an alloy of Ru and one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and one or more elements of Group 1 and Ta and one or more elements of Group 2, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te) and aluminum (Al).

[0008] Further embodiments of the disclosure are directed to an extreme ultraviolet (EUV) mask blank comprising a substrate; a multilayer stack on the substrate, the multilayer stack including a plurality of reflective layer pairs including reflective layer pairs of molybdenum (Mo) and silicon (Si); and an absorber layer on the multilayer stack comprising an alloy selected from an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of Ru and one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O), an alloy of Ru and one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and one or more elements of Group 1 and one or more elements of Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te) and aluminum (Al).

[0009] Additional embodiments of the disclosure are direct to extreme ultraviolet (EUV) mask blanks, the EUV mask blanks comprising an absorber layer comprising a material selected from the group consisting of ruthenium (Ru) and one or more elements of Group 1, Ru and one or more elements of Group 1 and one or more elements of Group 2, Ru and one or more elements of Group 1 and tantalum (Ta), Ru and one or more elements of Group 1 and Ta and one or more elements of Group 2, tellurium (Te) and nickel (Ni), and tellurium (Te) and aluminum (Al).

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the

appended drawings illustrate only typical embodiments of this disclosure and are therefore not to be considered limiting of its scope, for the disclosure may admit to other equally effective embodiments.

5 [0011] FIG. 1 schematically illustrates a background art EUV reflective mask employing a conventional absorber;

[0012] FIG. 2 schematically illustrates an embodiment of an extreme ultraviolet lithography system;

[0013] FIG. 3 illustrates an embodiment of an extreme ultraviolet reflective element production system;

10 [0014] FIG. 4 illustrates an embodiment of an extreme ultraviolet reflective element such as an EUV mask blank;

[0015] FIG. 5 illustrates an embodiment of an extreme ultraviolet reflective element such as an EUV mask blank; and

15 [0016] FIG. 6 illustrates an embodiment of a multi-cathode physical deposition chamber.

DETAILED DESCRIPTION

[0017] Before describing several exemplary embodiments of the disclosure, it is to be understood that the disclosure is not limited to the details of construction or process steps set forth in the following description. The disclosure is capable of other
20 embodiments and of being practiced or being carried out in various ways.

[0018] The term "horizontal" as used herein is defined as a plane parallel to the plane or surface of a mask blank, regardless of its orientation. The term "vertical" refers to a direction perpendicular to the horizontal as just defined. Terms, such as "above", "below", "bottom", "top", "side" (as in "sidewall"), "higher", "lower", "upper", "over", and
25 "under", are defined with respect to the horizontal plane, as shown in the figures.

[0019] The term "on" indicates that there is direct contact between elements. The term "directly on" indicates that there is direct contact between elements with no intervening elements.

[0020] As used in this specification and the appended claims, the terms "precursor",
30 "reactant", "reactive gas" and the like are used interchangeably to refer to any gaseous species that react with the substrate surface.

[0021] Those skilled in the art will understand that the use of ordinals such as "first" and "second" to describe process regions do not imply a specific location within the processing chamber, or order of exposure within the processing chamber.

[0022] As used in this specification and the appended claims, the term "substrate" refers to a surface, or portion of a surface, upon which a process acts. It will also be understood by those skilled in the art that reference to a substrate can refer to only a portion of the substrate, unless the context clearly indicates otherwise. Additionally, reference to depositing on a substrate means both a bare substrate and a substrate with one or more films or features deposited or formed thereon.

[0023] According to one or more embodiments, the term "on" with respect to a film coating or a layer includes the layer being directly on a surface, for example, a substrate surface, as well as there being one or more underlayers between the layer and the surface, for example the substrate surface. Thus, in one or more embodiments, the phrase "on the substrate surface" is intended to include one or more underlayers. In other embodiments, the phrase "directly on" refers to a layer or a film that is in contact with a surface, for example, a substrate surface, with no intervening layers. Thus, the phrase "a layer directly on the substrate surface" refers to a layer in direct contact with the substrate surface with no layers in between.

[0024] As used in this specification and the appended claims, the term "one or more elements of Group 1" or "Group 1 element(s)" refers to one or more elements selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni).

[0025] As used in this specification and the appended claims, the term "one or more elements of Group 2" or "Group 2 element(s)" refers to one or more elements selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O).

[0026] Referring now to FIG. 2, an exemplary embodiment of an extreme ultraviolet lithography system 100 is shown. The extreme ultraviolet lithography system 100 includes an extreme ultraviolet light source 102 for producing extreme ultraviolet light 112, a set of reflective elements, and a target wafer 110. The reflective elements include a condenser 104, an EUV reflective mask 106, an optical reduction assembly 108, a mask blank, a mirror, or a combination thereof.

[0027] The extreme ultraviolet light source 102 generates the extreme ultraviolet light 112. The extreme ultraviolet light 112 is electromagnetic radiation having a wavelength in a range of 5 to 50 nanometers (nm). For example, the extreme ultraviolet light source 102 includes a laser, a laser produced plasma, a discharge
5 produced plasma, a free-electron laser, synchrotron radiation, or a combination thereof.

[0028] The extreme ultraviolet light source 102 generates the extreme ultraviolet light 112 having a variety of characteristics. The extreme ultraviolet light source 102 produces broadband extreme ultraviolet radiation over a range of wavelengths. For
10 example, the extreme ultraviolet light source 102 generates the extreme ultraviolet light 112 having wavelengths ranging from 5 to 50 nm.

[0029] In one or more embodiments, the extreme ultraviolet light source 102 produces the extreme ultraviolet light 112 having a narrow bandwidth. For example, the extreme ultraviolet light source 102 generates the extreme ultraviolet light 112 at 13.5 nm. The
15 center of the wavelength peak is 13.5 nm.

[0030] The condenser 104 is an optical unit for reflecting and focusing the extreme ultraviolet light 112. The condenser 104 reflects and concentrates the extreme ultraviolet light 112 from the extreme ultraviolet light source 102 to illuminate the EUV reflective mask 106.

20 [0031] Although the condenser 104 is shown as a single element, it is understood that the condenser 104 in some embodiments includes one or more reflective elements such as concave mirrors, convex mirrors, flat mirrors, or a combination thereof, for reflecting and concentrating the extreme ultraviolet light 112. For example, the condenser 104 in the embodiment shown is a single concave mirror or an optical
25 assembly having convex, concave, and flat optical elements.

[0032] The EUV reflective mask 106 is an extreme ultraviolet reflective element having a mask pattern 114. The EUV reflective mask 106 creates a lithographic pattern to form a circuitry layout to be formed on the target wafer 110. The EUV reflective mask 106 reflects the extreme ultraviolet light 112. The mask pattern 114
30 defines a portion of a circuitry layout.

[0033] The optical reduction assembly 108 is an optical unit for reducing the image of the mask pattern 114. The reflection of the extreme ultraviolet light 112 from the EUV

reflective mask 106 is reduced by the optical reduction assembly 108 and reflected on to the target wafer 110. The optical reduction assembly 108 of some embodiments includes mirrors and other optical elements to reduce the size of the image of the mask pattern 114. For example, the optical reduction assembly 108 in some
5 embodiments includes concave mirrors for reflecting and focusing the extreme ultraviolet light 112.

[0034] The optical reduction assembly 108 reduces the size of the image of the mask pattern 114 on the target wafer 110. For example, the mask pattern 114 is imaged at a 4:1 ratio by the optical reduction assembly 108 on the target wafer 110 to form the
10 circuitry represented by the mask pattern 114 on the target wafer 110. The extreme ultraviolet light 112 scans the EUV reflective mask 106 synchronously with the target wafer 110 to form the mask pattern 114 on the target wafer 110.

[0035] Referring now to FIG. 3, an embodiment of an extreme ultraviolet reflective element production system 200 is shown. The extreme ultraviolet reflective element
15 includes an EUV mask blank 204, an extreme ultraviolet mirror 205, or other reflective element such as an EUV reflective mask 106.

[0036] The extreme ultraviolet reflective element production system 200 produces mask blanks, mirrors, or other elements that reflect the extreme ultraviolet light 112 of FIG. 2. The extreme ultraviolet reflective element production system 200 fabricates
20 the reflective elements by applying thin coatings to source substrates 203.

[0037] The EUV mask blank 204 is a multilayered structure for forming the EUV reflective mask 106 of FIG. 2. The EUV mask blank 204 is formed using semiconductor fabrication techniques. The EUV reflective mask 106 has the mask pattern 114 of FIG. 2 formed on the EUV mask blank 204 by etching and other
25 processes.

[0038] The extreme ultraviolet mirror 205 is a multilayered structure reflective in a range of extreme ultraviolet light. The extreme ultraviolet mirror 205 is formed using semiconductor fabrication techniques. The EUV mask blank 204 and the extreme ultraviolet mirror 205 are in some embodiments similar structures with respect to the
30 layers formed on each element, however, the extreme ultraviolet mirror 205 does not have the mask pattern 114.

[0039] The reflective elements are efficient reflectors of the extreme ultraviolet light 112. In an embodiment, the EUV mask blank 204 and the extreme ultraviolet mirror 205 has an extreme ultraviolet reflectivity of greater than 60%. The reflective elements are efficient if they reflect more than 60% of the extreme ultraviolet light 112.

5 [0040] The extreme ultraviolet reflective element production system 200 includes a wafer loading and carrier handling system 202 into which the source substrates 203 are loaded and from which the reflective elements are unloaded. An atmospheric handling system 206 provides access to a wafer handling vacuum chamber 208. The wafer loading and carrier handling system 202 includes substrate transport boxes,
10 loadlocks, and other components to transfer a substrate from atmosphere to vacuum inside the system. Because the EUV mask blank 204 is used to form devices at a very small scale, the source substrates 203 and the EUV mask blank 204 are processed in a vacuum system to prevent contamination and other defects.

[0041] The wafer handling vacuum chamber 208 contains two vacuum chambers, a
15 first vacuum chamber 210 and a second vacuum chamber 212. The first vacuum chamber 210 includes a first wafer handling system 214 and the second vacuum chamber 212 includes a second wafer handling system 216. Although the wafer handling vacuum chamber 208 is described with two vacuum chambers, it is understood that the system can have any number of vacuum chambers.

20 [0042] The wafer handling vacuum chamber 208 has a plurality of ports around its periphery for attachment of various other systems. The first vacuum chamber 210 has a degas system 218, a first physical vapor deposition system 220, a second physical vapor deposition system 222, and a pre-clean system 224. The degas system 218 is for thermally desorbing moisture from the substrates. The pre-clean system 224 is for
25 cleaning the surfaces of the wafers, mask blanks, mirrors, or other optical components.

[0043] The physical vapor deposition systems, such as the first physical vapor deposition system 220 and the second physical vapor deposition system 222, are used in some embodiments to form thin films of conductive materials on the source
30 substrates 203. For example, the physical vapor deposition systems of some embodiments include a vacuum deposition system such as magnetron sputtering systems, ion sputtering systems, pulsed laser deposition, cathode arc deposition, or a

combination thereof. The physical vapor deposition systems, such as the magnetron sputtering system, form thin layers on the source substrates 203 including the layers of silicon, metals, alloys, compounds, or a combination thereof.

[0044] The physical vapor deposition system forms reflective layers, capping layers, and absorber layers. For example, the physical vapor deposition systems are configured to form layers of silicon, molybdenum, titanium oxide, titanium dioxide, ruthenium oxide, niobium oxide, ruthenium tungsten, ruthenium molybdenum, ruthenium niobium, chromium, tantalum, nitrides, compounds, or a combination thereof. Although some compounds are described as an oxide, it is understood that the compounds include oxides, dioxides, atomic mixtures having oxygen atoms, or a combination thereof.

[0045] The second vacuum chamber 212 has a first multi-cathode source 226, a chemical vapor deposition system 228, a cure chamber 230, and an ultra-smooth deposition chamber 232 connected to it. For example, the chemical vapor deposition system 228 of some embodiments includes a flowable chemical vapor deposition system (FCVD), a plasma assisted chemical vapor deposition system (CVD), an aerosol assisted CVD, a hot filament CVD system, or a similar system. In another example, the chemical vapor deposition system 228, the cure chamber 230, and the ultra-smooth deposition chamber 232 are in a separate system from the extreme ultraviolet reflective element production system 200.

[0046] The chemical vapor deposition system 228 forms thin films of material on the source substrates 203. For example, the chemical vapor deposition system 228 is used to form layers of materials on the source substrates 203 including monocrystalline layers, polycrystalline layers, amorphous layers, epitaxial layers, or a combination thereof. The chemical vapor deposition system 228 forms layers of silicon, silicon oxides, silicon oxycarbide, carbon, tungsten, silicon carbide, silicon nitride, titanium nitride, metals, alloys, and other materials suitable for chemical vapor deposition. For example, the chemical vapor deposition system forms planarization layers.

[0047] The first wafer handling system 214 is capable of moving the source substrates 203 between the atmospheric handling system 206 and the various systems around the periphery of the first vacuum chamber 210 in a continuous vacuum. The second

wafer handling system 216 is capable of moving the source substrates 203 around the second vacuum chamber 212 while maintaining the source substrates 203 in a continuous vacuum. The extreme ultraviolet reflective element production system 200 transfers the source substrates 203 and the EUV mask blank 204 between the first
5 wafer handling system 214, the second wafer handling system 216 in a continuous vacuum.

[0048] Referring now to FIG. 4, an embodiment of an extreme ultraviolet reflective element 302 is shown. In one or more embodiments, the extreme ultraviolet reflective element 302 is the EUV mask blank 204 of FIG. 3 or the extreme ultraviolet mirror 205
10 of FIG. 3. The EUV mask blank 204 and the extreme ultraviolet mirror 205 are structures for reflecting the extreme ultraviolet light 112 of FIG. 2. The EUV mask blank 204 is used to form the EUV reflective mask 106 shown in FIG. 2.

[0049] The extreme ultraviolet reflective element 302 includes a substrate 304, a multilayer stack 306 of reflective layers, and a capping layer 308. In one or more
15 embodiments, the extreme ultraviolet mirror 205 is used to form reflecting structures for use in the condenser 104 of FIG. 2 or the optical reduction assembly 108 of FIG. 2.

[0050] The extreme ultraviolet reflective element 302, which in some embodiments an EUV mask blank 204, includes the substrate 304, the multilayer stack 306 of reflective layers, the capping layer 308, and an absorber layer 310. The extreme ultraviolet
20 reflective element 302 in some embodiments is an EUV mask blank 204, which is used to form the EUV reflective mask 106 of FIG. 2 by patterning the absorber layer 310 with the layout of the circuitry required.

[0051] In the following sections, the term for the EUV mask blank 204 is used interchangeably with the term of the extreme ultraviolet mirror 205 for simplicity. In
25 one or more embodiments, the EUV mask blank 204 includes the components of the extreme ultraviolet mirror 205 with the absorber layer 310 added in addition to form the mask pattern 114 of FIG. 2.

[0052] The EUV mask blank 204 is an optically flat structure used for forming the EUV reflective mask 106 having the mask pattern 114. In one or more embodiments, the
30 reflective surface of the EUV mask blank 204 forms a flat focal plane for reflecting the incident light, such as the extreme ultraviolet light 112 of FIG. 2.

[0053] The substrate 304 is an element for providing structural support to the extreme ultraviolet reflective element 302. In one or more embodiments, the substrate 304 is made from a material having a low coefficient of thermal expansion (CTE) to provide stability during temperature changes. In one or more embodiments, the substrate 304
5 has properties such as stability against mechanical cycling, thermal cycling, crystal formation, or a combination thereof. The substrate 304 according to one or more embodiments is formed from a material such as silicon, glass, oxides, ceramics, glass ceramics, or a combination thereof.

[0054] The multilayer stack 306 is a structure that is reflective to the extreme
10 ultraviolet light 112. The multilayer stack 306 includes alternating reflective layers of a first reflective layer 312 and a second reflective layer 314.

[0055] The first reflective layer 312 and the second reflective layer 314 form a reflective pair 316 of FIG. 4. In a non-limiting embodiment, the multilayer stack 306 includes a range of 20-60 of the reflective pairs 316 for a total of up to 120 reflective
15 layers.

[0056] The first reflective layer 312 and the second reflective layer 314 are formed from a variety of materials. In an embodiment, the first reflective layer 312 and the second reflective layer 314 are formed from silicon and molybdenum, respectively. Although the layers are shown as silicon and molybdenum, it is understood that the
20 alternating layers in some embodiments are formed from other materials or have other internal structures.

[0057] The first reflective layer 312 and the second reflective layer 314 can have a variety of structures. In an embodiment, both the first reflective layer 312 and the second reflective layer 314 are formed with a single layer, multiple layers, a divided
25 layer structure, non-uniform structures, or a combination thereof.

[0058] Because most materials absorb light at extreme ultraviolet wavelengths, the optical elements used are reflective instead of the transmissive as used in other lithography systems. The multilayer stack 306 forms a reflective structure by having alternating thin layers of materials with different optical properties to create a Bragg
30 reflector or mirror.

[0059] In an embodiment, each of the alternating layers has dissimilar optical constants for the extreme ultraviolet light 112. The alternating layers provide a

resonant reflectivity when the period of the thickness of the alternating layers is one half the wavelength of the extreme ultraviolet light 112. In an embodiment, for the extreme ultraviolet light 112 at a wavelength of 13 nm, the alternating layers are about 6.5 nm thick. It is understood that the sizes and dimensions provided are within
5 normal engineering tolerances for typical elements.

[0060] The multilayer stack 306 is formed in a variety of ways. In an embodiment, the first reflective layer 312 and the second reflective layer 314 are formed with magnetron sputtering, ion sputtering systems, pulsed laser deposition, cathode arc deposition, or a combination thereof.

10 **[0061]** In an illustrative embodiment, the multilayer stack 306 is formed using a physical vapor deposition technique, such as magnetron sputtering. In an embodiment, the first reflective layer 312 and the second reflective layer 314 of the multilayer stack 306 have the characteristics of being formed by the magnetron sputtering technique including precise thickness, low roughness, and clean interfaces
15 between the layers. In an embodiment, the first reflective layer 312 and the second reflective layer 314 of the multilayer stack 306 have the characteristics of being formed by the physical vapor deposition including precise thickness, low roughness, and clean interfaces between the layers.

[0062] The physical dimensions of the layers of the multilayer stack 306 formed using
20 the physical vapor deposition technique is precisely controlled to increase reflectivity. In an embodiment, the first reflective layer 312, such as a layer of silicon, has a thickness of 4.1 nm. The second reflective layer 314, such as a layer of molybdenum, has a thickness of 2.8 nm. The thickness of the layers dictates the peak reflectivity wavelength of the extreme ultraviolet reflective element. If the thickness of the layers
25 is incorrect, the reflectivity at the desired wavelength 13.5 nm is reduced.

[0063] In an embodiment, the multilayer stack 306 has a reflectivity of greater than 60%. In an embodiment, the multilayer stack 306 formed using physical vapor deposition has a reflectivity in a range of 66%-67%. In one or more embodiments, forming the capping layer 308 over the multilayer stack 306 formed with harder
30 materials improves reflectivity. In some embodiments, reflectivity greater than 70% is achieved using low roughness layers, clean interfaces between layers, improved layer materials, or a combination thereof.

[0064] In one or more embodiments, the capping layer 308 is a protective layer allowing the transmission of the extreme ultraviolet light 112. In an embodiment, the capping layer 308 is formed directly on the multilayer stack 306. In one or more embodiments, the capping layer 308 protects the multilayer stack 306 from
5 contaminants and mechanical damage. In one embodiment, the multilayer stack 306 is sensitive to contamination by oxygen, carbon, hydrocarbons, or a combination thereof. The capping layer 308 according to an embodiment interacts with the contaminants to neutralize them.

[0065] In one or more embodiments, the capping layer 308 is an optically uniform
10 structure that is transparent to the extreme ultraviolet light 112. The extreme ultraviolet light 112 passes through the capping layer 308 to reflect off of the multilayer stack 306. In one or more embodiments, the capping layer 308 has a total reflectivity loss of 1% to 2%. In one or more embodiments, each of the different materials has a different reflectivity loss depending on thickness, but all of them will be in a range of
15 1% to 2%.

[0066] In one or more embodiments, the capping layer 308 has a smooth surface. For example, the surface of the capping layer 308 in some embodiments has a roughness of less than 0.2 nm RMS (root mean square measure). In another example, the surface of the capping layer 308 has a roughness of 0.08 nm RMS for a
20 length in a range of 1/100 nm and 1/1 μm . The RMS roughness will vary depending on the range it is measured over. For the specific range of 100 nm to 1 micron that roughness is 0.08 nm or less. Over a larger range the roughness will be higher.

[0067] The capping layer 308 is formed in a variety of methods. In an embodiment, the capping layer 308 is formed on or directly on the multilayer stack 306 with
25 magnetron sputtering, ion sputtering systems, ion beam deposition, electron beam evaporation, radio frequency (RF) sputtering, atomic layer deposition (ALD), pulsed laser deposition, cathode arc deposition, or a combination thereof. In one or more embodiments, the capping layer 308 has the physical characteristics of being formed by the magnetron sputtering technique including precise thickness, low roughness,
30 and clean interfaces between the layers. In an embodiment, the capping layer 308 has the physical characteristics of being formed by the physical vapor deposition including precise thickness, low roughness, and clean interfaces between the layers.

[0068] In one or more embodiments, the capping layer 308 is formed from a variety of materials having a hardness sufficient to resist erosion during cleaning. In one embodiment, ruthenium is used as a capping layer material because it is a good etch stop and is relatively inert under the operating conditions. However, it is understood
5 that in some embodiments, other materials are used to form the capping layer 308. In specific embodiments, the capping layer 308 has a thickness in a range of 2.5 and 5.0 nm.

[0069] In one or more embodiments, the absorber layer 310 is a layer that absorbs the extreme ultraviolet light 112. In an embodiment, the absorber layer 310 is used to
10 form the pattern on the EUV reflective mask 106 by providing areas that do not reflect the extreme ultraviolet light 112. The absorber layer 310, according to one or more embodiments, comprises a material having a high absorption coefficient for a particular frequency of the extreme ultraviolet light 112, such as about 13.5 nm. In an embodiment, the absorber layer 310 is formed directly on the capping layer 308, and
15 the absorber layer 310 is etched using a photolithography process to form the pattern of the EUV reflective mask 106.

[0070] According to one or more embodiments, the extreme ultraviolet reflective element 302, such as the extreme ultraviolet mirror 205, is formed with the substrate 304, the multilayer stack 306, and the capping layer 308. The extreme ultraviolet
20 mirror 205 has an optically flat surface and efficiently and uniformly reflects the extreme ultraviolet light 112.

[0071] According to one or more embodiments, the extreme ultraviolet reflective element 302, such as the EUV mask blank 204, is formed with the substrate 304, the multilayer stack 306, the capping layer 308, and the absorber layer 310. The mask
25 blank 204 has an optically flat surface and efficiently and uniformly reflects the extreme ultraviolet light 112. In an embodiment, the mask pattern 114 is formed with the absorber layer 310 of the EUV mask blank 204.

[0072] According to one or more embodiments, forming the absorber layer 310 over the capping layer 308 increases reliability of the EUV reflective mask 106. The
30 capping layer 308 acts as an etch stop layer for the absorber layer 310. When the mask pattern 114 of FIG. 2 is etched into the absorber layer 310, the capping layer 308 beneath the absorber layer 310 stops the etching action to protect the multilayer

stack 306. In one or more embodiments, the absorber layer 310 is etch selective to the capping layer 308. In some embodiments, the capping layer 308 comprises ruthenium, and the absorber layer 310 is etch selective to ruthenium.

[0073] In one or more embodiments, the absorber layer 310 comprises an alloy of ruthenium (Ru) and at least one or more elements. In one or more embodiments, an alloy of Ru and the at least one or more elements have an "n" value of less than 0.92, which provides a range from about 180 degrees to about 220 degrees phase shift. The "n" value of less than about 0.92 improves the normalized image log slope (NILS) and mitigates 3D effects. As used in the specification and appended claims, "normalized image log slope (NILS)" refers to a metric describing the lithographic quality of an aerial image. As used in the specification and appended claims, "n" or "n value" refers to an index of refraction. The index of refraction is a measurement of the bending of a ray of light when passing from one medium into another. The low "n" value improves the NILS and mitigates 3D effects.

[0074] In an embodiment, the absorber layer 310 comprises an alloy of ruthenium (Ru) and one or more elements of Group 1. In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 50 nm, and 15 nm to about 40 nm.

[0075] In an embodiment, the absorber layer 310 comprises an alloy of ruthenium (Ru) and one or more elements of Group 1 and one or more elements of Group 2. In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 50 nm, and 15 nm to about 50 nm.

- [0076] In an embodiment, the absorber layer 310 comprises an alloy of ruthenium (Ru) and one or more elements of Group 1 and tantalum (Ta). In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 50 nm, and 15 nm to about 50 nm.
- 10 [0077] In an embodiment, the absorber layer 310 comprises an alloy of ruthenium (Ru) and one or more elements of Group 1 and one or more elements of Group 2 and tantalum (Ta). In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 50 nm, and 15 nm to about 50 nm.
- 15 [0078] In one or more embodiments, the absorber layer 310 comprises an alloy of tellurium (Te) and nickel (Ni). In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 40 nm, and 15 nm to about 50 nm.
- 20 [0079] In an embodiment, the absorber layer 310 comprises an alloy of tellurium (Te) and aluminum (Al). In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 40 nm, and 15 nm to about 50 nm.
- 25 [0080] In one or more embodiments, the absorber layer 310 comprises an alloy of tellurium (Te) and aluminum (Al). In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 40 nm, and 15 nm to about 50 nm.
- 30 [0081] In one or more embodiments, the absorber layer 310 comprises an alloy of tellurium (Te) and aluminum (Al). In some embodiments, the absorber layer 310 has a thickness of less than about 55 nm, including less than about 50 nm, less than about 45 nm, less than about 40 nm, less than about 35 nm, less than about 30 nm, less than about 25 nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 40 nm, and 15 nm to about 50 nm.

nm, less than about 20 nm, less than about 15 nm, less than about 10 nm, less than about 5 nm, less than about 1 nm, or less than about 0.5 nm. In other embodiments, the absorber layer 310 has a thickness in a range of about 0.5 nm to about 55 nm, including a range of about 1 nm to about 54 nm, 1 nm to about 50 nm, and 15 nm to about 50 nm.

[0080] In an embodiment, the absorber layer 310 is made from an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni). In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 is selected from the group consisting of an alloy of Ru and Nb having from about 31.8 wt.% to about 86.1 wt.% Ru and from about 13.9 wt.% to about 68.2 wt.% Nb, an alloy of Ru and Ir having from about 2.6 wt.% to about 90.9 wt.% Ru and from about 9.1 wt.% to about 97.4 wt.% Ir, an alloy of Ru and Re having from about 18.8 wt.% to about 75.5 wt.% Ru and from about 24.5 wt.% to about 81.2 wt.% Re, an alloy of Ru and Pt having from about 2.6 wt.% to about 90.8 wt.% Ru and from about 9.2 wt.% to about 97.4 wt.% Pt, an alloy of Ru and Zr having from about 47.5 wt.% to about 95.5 wt.% Ru and from about 4.5 wt.% to about 52.5 wt.% Zr, an alloy of Ru and Os having from about 2.7 wt.% to about 91.0 wt.% Ru and from about 9.0 wt.% to about 97.3 wt.% Os, an alloy of Ru and Mn having from about 44.0 wt.% to about 88.1 wt.% Ru and from about 11.9 wt.% to about 56.0 wt.% Mn, an alloy of Ru and Ag having from about 4.7 wt.% to about 94.7 wt.% Ru and from about 5.3 wt.% to about 95.3 wt.% Ag, an alloy of Ru and Tc having from about 5.1 wt.% to about 95.2 wt.% Ru and from about 4.8 wt.% to about 94.9 wt.% Tc, an alloy of Ru and Co having from about 8.2 wt.% to about 97.1 wt.% and from about 2.9 wt.% to about 91.8 wt.% Co and an alloy of Ru and Ni having from about 23.3 wt.% to about 97.1 wt.% Ru and from about 2.9 wt.% to about 76.7 wt.% Ni.

[0081] In other embodiments, the absorber layer 310 is made from an alloy of Ru and the one or more elements of Group 1 and Ta. In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 and Ta is selected from the group consisting of an alloy of Ru, Nb and Ta having from about 18.1 wt.% to about 84.8 wt.% Ru, from about 6.6 wt.% to about 73.3 wt.% Nb and from about 8.6 wt.% to

about 75.3 wt.% Ta, an alloy of Ru, Ir and Ta having from about 2.7 wt.% to about 88.6 wt.% Ru, from about 6.6 wt.% to about 92.5 wt.% Ir and from about 4.8 wt.% to about 90.7 wt.% Ta, an alloy of Ru, Re and Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.4 wt.% to about 92.4 wt.% Re and from about 4.9 wt.% to about 90.9 wt.% Ta, an alloy of Ru, Pt and Ta having from about 2.6 wt.% to about 88.7 wt.% Ru, from about 6.6 wt.% to about 92.7 wt.% Pt and from about 4.7 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Zr and Ta having from about 28.8 wt.% to about 88.2 wt.% Ru, from about 3.2 wt.% to about 62.6 wt.% Zr and from about 8.6 wt.% to about 68.0 wt.% Ta, an alloy of Ru, Os and Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.5 wt.% to about 92.5 wt.% Os and from about 4.8 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Mn and Ta having from about 19.5 wt.% to about 87.0 wt.% Ru, from about 4.0 wt.% to about 71.5 wt.% Mn and from about 9.0 wt.% to about 76.5 wt.% Ta, an alloy of Ru, Ag and Ta having from about 3.5 wt.% to about 88.1 wt.% Ru, from about 3.8 wt.% to about 88.4 wt.% Ag and from about 8.1 wt.% to about 92.7 wt.% Ta, an alloy of Ru, Tc and Ta having from about 3.6 wt.% to about 88.0 wt.% Ru, from about 3.4 wt.% to about 87.8 wt.% Tc and from about 8.6 wt.% to about 93.0 wt.% Ta, an alloy of Ru, Co and Ta having from about 19.3 wt.% to about 86.8 wt.% Ru, from about 4.3 wt.% to about 71.8 wt.% Co and from about 8.9 wt.% to about 76.4 wt.% Ta and an alloy of Ru, Ni and Ta having from about 37.4 wt.% to about 89.2 wt.% Ru, from about 2.1 wt.% to about 53.9 wt.% Ni and from about 8.7 wt.% to about 60.5 wt.% Ta.

[0082] In one or more embodiments, the absorber layer 310 is made from an alloy of ruthenium (Ru) and one or more elements of Group 1 and one or more elements of Group 2.

[0083] In one or more embodiments, the absorber layer 310 is made from an alloy of ruthenium (Ru) and one or more elements of Group 1 and one or more elements of Group 2 and tantalum (Ta).

[0084] In another embodiment, the absorber layer 310 is made from an alloy of Te and Ni, wherein the alloy of Te and Ni includes from about 10.0 wt.% to about 97.7 wt.% Te and from about 2.3 wt.% to about 90.0 wt.% Ni.

[0085] In another embodiment, the absorber layer 310 is made from an alloy of Te and Al, wherein the alloy of Te and Al includes from about 19.9 wt.% to about 98.9 wt.% Te and about 1.1 wt.% to about 80.1 wt.% Al.

[0086] In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 comprises a dopant. In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 and Ta comprises a dopant. The dopant may include one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O). In an embodiment, the dopant is present in the alloy in an amount in the range of about 0.1 wt.% to about 5.0 wt.%, based on the weight of the alloy. In other embodiments, the dopant is present in the alloy in an amount of about 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.%, 0.5 wt.%, 0.6 wt.%, 0.7 wt.%, 0.8 wt.%, 0.9 wt. %, 1.0 wt.%, 1.1 wt.%, 1.2 wt.%, 1.3 wt.%, 1.4 wt.%, 1.5 wt.%, 1.6 wt.%, 1.7 wt.%, 1.8 wt.%, 1.9 wt. %, 2.0 wt.% 2.1 wt.%, 2.2 wt.%, 2.3 wt.%, 2.4 wt.%, 2.5 wt.%, 2.6 wt.%, 2.7 wt.%, 2.8 wt.%, 2.9 wt. %, 3.0 wt.%, 3.1 wt.%, 3.2 wt.%, 3.3 wt.%, 3.4 wt.%, 3.5 wt.%, 3.6 wt.%, 3.7 wt.%, 3.8 wt.%, 3.9 wt. %, 4.0 wt.%, 4.1 wt.%, 4.2 wt.%, 4.3 wt.%, 4.4 wt.%, 4.5 wt.%, 4.6 wt.%, 4.7 wt.%, 4.8 wt.%, 4.9 wt. %, or 5.0 wt.%.

[0087] In one or more embodiments, the alloy selected from an alloy of Te and Ni comprises a dopant. In one or more embodiments, the alloy selected from an alloy of Te and Al comprises a dopant. The dopant may be selected from one or more of nitrogen or oxygen. In an embodiment, the dopant comprises oxygen. In an alternative embodiment, the dopant comprises nitrogen. In an embodiment, the dopant is present in the alloy in an amount in the range of about 0.1 wt.% to about 5.0 wt.%, based on the weight of the alloy. In other embodiments, the dopant is present in the alloy in an amount of about 0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.4 wt.%, 0.5 wt.%, 0.6 wt.%, 0.7 wt.%, 0.8 wt.%, 0.9 wt. %, 1.0 wt.%, 1.1 wt.%, 1.2 wt.%, 1.3 wt.%, 1.4 wt.%, 1.5 wt.%, 1.6 wt.%, 1.7 wt.%, 1.8 wt.%, 1.9 wt. %, 2.0 wt.% 2.1 wt.%, 2.2 wt.%, 2.3 wt.%, 2.4 wt.%, 2.5 wt.%, 2.6 wt.%, 2.7 wt.%, 2.8 wt.%, 2.9 wt. %, 3.0 wt.%, 3.1 wt.%, 3.2 wt.%, 3.3 wt.%, 3.4 wt.%, 3.5 wt.%, 3.6 wt.%, 3.7 wt.%, 3.8 wt.%, 3.9 wt. %, 4.0 wt.%, 4.1 wt.%, 4.2 wt.%, 4.3 wt.%, 4.4 wt.%, 4.5 wt.%, 4.6 wt.%, 4.7 wt.%, 4.8 wt.%, 4.9 wt. %, or 5.0 wt.%.

[0088] In one or more embodiments, the alloy of the absorber layer is a co-sputtered alloy absorber material formed in a physical deposition chamber, which provides much thinner absorber layer thickness (less than 30nm) while achieving less than 2% reflectivity and suitable etch properties. In one or more embodiments, the alloy of the absorber layer is co-sputtered by gases selected from one or more of argon (Ar), oxygen (O₂), or nitrogen (N₂). In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen gases (Ar + O₂). In some embodiments, co-sputtering by a mixture of argon and oxygen forms an oxide of Ru and/or an oxide of the one or more elements of Group 1. In other embodiments, co-sputtering by a mixture of argon and oxygen does not form an oxide of Ru or the one or more elements of Group 1. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and nitrogen gases (Ar + N₂). In some embodiments, co-sputtering by a mixture of argon and nitrogen forms a nitride of Ru and/or a nitride of the one or more elements of Group 1. In other embodiments, co-sputtering by a mixture of argon and nitrogen does not form a nitride of Ru or the one or more elements of Group 1. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen and nitrogen gases (Ar + O₂ + N₂). In some embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen forms an oxide and/or nitride of Ru and/or an oxide and/or nitride of the one or more elements of Group 1. In other embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen does not form an oxide or a nitride of Ru or the one or more elements of Group 1. In an embodiment, the etch properties and/or other properties of the absorber layer are tailored to specification by controlling the alloy percentage(s), as discussed above.

[0089] In some embodiments, co-sputtering by a mixture of argon and oxygen forms an oxide of ruthenium (Ru) and/or an oxide of the one or more elements of Group 1 and/or an oxide of the one or more elements of Group 2. In other embodiments, co-sputtering by a mixture of argon and oxygen does not form an oxide of Ru or the one or more elements of Group 1 or the one or more elements of Group 2. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and nitrogen gases (Ar + N₂). In some embodiments, co-sputtering by a mixture of argon and nitrogen forms a nitride of Ru and/or a nitride of the one or more elements of

Group 1 and/or a nitride of the one or more elements of Group 2. In other embodiments, co-sputtering by a mixture of argon and nitrogen does not form a nitride of Ru or the one or more elements of Group 1 or the one or more elements of Group 2. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen and nitrogen gases ($\text{Ar} + \text{O}_2 + \text{N}_2$). In some embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen forms an oxide and/or nitride of Ru and/or an oxide and/or nitride of the one or more elements of Group 1 and/or an oxide and/or nitride of the one or more elements of Group 2. In other embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen does not form an oxide or a nitride of Ru or the one or more elements of Group 1 or the one or more elements of Group 2.

[0090] In some embodiments, co-sputtering by a mixture of argon and oxygen forms and oxide of Ru and/or an oxide of the one or more elements of Group 1 and/or an oxide of tantalum (Ta). In other embodiments, co-sputtering by a mixture of argon and oxygen does not form an oxide of Ru or the one or more elements of Group 1 and/or Ta. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and nitrogen gases ($\text{Ar} + \text{N}_2$). In some embodiments, co-sputtering by a mixture of argon and nitrogen forms a nitride of Ru and/or a nitride of the one or more elements of Group 1 and/or a nitride of Ta. In other embodiments, co-sputtering by a mixture of argon and nitrogen does not form a nitride of Ru or the one or more elements of Group 1 or Ta. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen and nitrogen gases ($\text{Ar} + \text{O}_2 + \text{N}_2$). In some embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen forms an oxide and/or nitride of Ru and/or an oxide and/or nitride of the one or more elements of Group 1 and/or an oxide and/or nitride of Ta. In other embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen does not form an oxide or a nitride of Ru or the one or more elements of Group 1 or Ta.

[0091] In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen gases ($\text{Ar} + \text{O}_2$). In some embodiments, co-sputtering by a mixture of argon and oxygen forms and oxide of Ru and/or an oxide of the one or more elements of Group 1 and/or an oxide of the one or more elements of Group 2 and/or an oxide of Ta. In other embodiments, co-sputtering by a mixture of argon and

oxygen does not form an oxide of Ru or the one or more elements of Group 1 or the one or more elements of Group 2 or Ta. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and nitrogen gases (Ar + N₂). In some embodiments, co-sputtering by a mixture of argon and nitrogen forms a nitride of Ru and/or a nitride of the one or more elements of Group 1 and/or a nitride of the one or more elements of Group 2 and/or a nitride of Ta. In other embodiments, co-sputtering by a mixture of argon and nitrogen does not form a nitride of Ru or the one or more elements of Group 1 or the one or more elements of Group 2 or Ta. In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen and nitrogen gases (Ar + O₂ + N₂). In some embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen forms an oxide and/or nitride of Ru and/or an oxide and/or nitride of the one or more elements of Group 1 and/or an oxide and/or nitride of the one or more elements of Group 2 and/or an oxide and/or nitride of Ta. In other embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen does not form an oxide or a nitride of Ru or the one or more elements of Group 1 or the one or more elements of Group 2 or Ta.

[0092] In some embodiments, co-sputtering by a mixture of argon and oxygen forms and oxide of tellurium (Te) and/or an oxide of nickel (Ni). In other embodiments, co-sputtering by a mixture of argon and oxygen does not form an oxide of tellurium (Te) or nickel (Ni). In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and nitrogen gases (Ar + N₂). In some embodiments, co-sputtering by a mixture of argon and nitrogen forms a nitride of tellurium (Te) and/or a nitride of nickel (Ni). In other embodiments, co-sputtering by a mixture of argon and nitrogen does not form a nitride of tellurium (Te) or nickel (Ni). In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen and nitrogen gases (Ar + O₂ + N₂). In some embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen forms an oxide and/or nitride of tellurium (Te) and/or an oxide and/or nitride of nickel (Ni). In other embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen does not form an oxide or a nitride of tellurium (Te) or nickel (Ni). In an embodiment, the etch properties and/or other properties of the absorber layer are tailored to specification by controlling the alloy percentage(s), as discussed above.

[0093] In some embodiments, co-sputtering by a mixture of argon and oxygen forms and oxide of tellurium (Te) and/or an oxide of aluminum (Al). In other embodiments, co-sputtering by a mixture of argon and oxygen does not form an oxide of tellurium (Te) or aluminum (Al). In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and nitrogen gases (Ar + N₂). In some embodiments, co-sputtering by a mixture of argon and nitrogen forms a nitride of tellurium (Te) and/or a nitride of aluminum (Al). In other embodiments, co-sputtering by a mixture of argon and nitrogen does not form a nitride of tellurium (Te) or aluminum (Al). In an embodiment, the alloy of the absorber layer is co-sputtered by a mixture of argon and oxygen and nitrogen gases (Ar + O₂ + N₂). In some embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen forms an oxide and/or nitride of tellurium (Te) and/or an oxide and/or nitride of aluminum (Al). In other embodiments, co-sputtering by a mixture of argon and oxygen and nitrogen does not form an oxide or a nitride of tellurium (Te) or aluminum (Al). In some embodiments, the alloy percentage(s) are precisely controlled by operating parameters such voltage, pressure, flow, etc., of the physical vapor deposition chamber.

[0094] In one or more embodiments, as used herein "co-sputtering" means that two targets comprising two different materials or three or more targets comprising three or more different materials as described herein are sputtered at the same time using one or more gases selected from argon (Ar), oxygen (O₂), or nitrogen (N₂) to deposit/form an absorber layer comprising an alloy of the materials from the two targets or the three or more targets. As used herein, co-sputtering means that the two targets or the three or more targets are sputtered at the same time using one or more gases selected from argon (Ar), oxygen (O₂), or nitrogen (N₂) to deposit/form an absorber layer comprising an alloy of materials from the following groups: an alloy of Ru and one or more elements of Group 1; an alloy of Ru and one or more elements of Group 1 and one or more elements of Group 2; an alloy of Ru and one or more elements of Group 1 and Ta; an alloy of Ru and one or more elements of Group 1 and Ta and one or more elements of Group 2; an alloy of Te and Ni; and an alloy of Te and Al.

[0095] In other embodiments, the alloy of two different materials or three or more different materials is deposited layer by layer as a laminate of two different materials or a laminate of three or more materials described herein using gases selected from

one or more of argon (Ar), oxygen (O₂), or nitrogen (N₂). As used herein, the alloy of two different materials or three or more different materials comprises an alloy of materials from the following groups: an alloy of Ru and one or more elements of Group 1; an alloy of Ru and one or more elements of Group 1 and one or more elements of Group 2; an alloy of Ru and one or more elements of Group 1 and Ta; an alloy of Ru and one or more elements of Group 1 and Ta and one or more elements of Group 2; an alloy of Te and Ni; and an alloy of Te and Al. Such alloys of two different materials or three or more different materials deposited layer by layer as a laminate of two different materials or a laminate of three or more materials described are made according to one or more embodiments in a physical deposition chamber having a first cathode comprising a first absorber material, a second cathode comprising a second absorber material, and in some embodiments, a third cathode comprising a third absorber material, a fourth cathode comprising a fourth absorber material, and a fifth cathode comprising a fifth absorber material, wherein the first absorber material, second absorber material, third absorber material, fourth absorber material and fifth absorber materials are different from each other. Alternating layers can be formed by alternately sputtering the first cathode and the second cathode, and in some embodiments the third cathode, the fourth cathode and the fifth cathode at different times to form alternating layers of different absorber materials.

[0096] In other embodiments, a non-alloy of two different materials or three or more different materials is deposited layer by layer as a laminate of two different materials or a laminate of three or more materials described herein using gases selected from one or more of argon (Ar), oxygen (O₂), or nitrogen (N₂). As used herein, the non-alloy of two different materials or three or more different materials comprises a non-alloy of materials from the following groups: Ru and one or more elements of Group 1; Ru and one or more elements of Group 1 and one or more elements of Group 2; Ru and one or more elements of Group 1 and Ta; Ru and one or more elements of Group 1 and Ta and one or more elements of Group 2; Te and Ni; and Te and Al. Such non-alloys of two different materials or three or more different materials deposited layer by layer as a laminate of two different materials or a laminate of three or more materials described are made according to one or more embodiments in a physical deposition chamber having a first cathode comprising a first absorber material, a second cathode

comprising a second absorber material, and in some embodiments, a third cathode comprising a third absorber material, a fourth cathode comprising a fourth absorber material, and a fifth cathode comprising a fifth absorber material, wherein the first absorber material, second absorber material, third absorber material, fourth absorber material and fifth absorber materials are different from each other. Alternating layers can be formed by alternately sputtering the first cathode and the second cathode, and in some embodiments the third cathode, the fourth cathode and the fifth cathode at different times to form alternating layers of different absorber materials.

[0097] In one or more embodiments, bulk targets of the alloy compositions described herein may be made, which is sputtered by normal sputtering using gases selected from one or more of argon (Ar), oxygen (O₂), or nitrogen (N₂). In one or more embodiments, the alloy is deposited using a bulk target having the same composition of the alloy and is sputtered using a gas selected from one or more of argon (Ar), oxygen (O₂), or nitrogen (N₂) to form the absorber layer. In an embodiment, the alloy of the absorber layer is deposited using a bulk target having the same composition of the alloy and is sputtered using a mixture of argon and oxygen gases (Ar + O₂).

[0098] Referring now to FIG. 5, an extreme ultraviolet mask blank 400 is shown as comprising a substrate 414, a multilayer stack of reflective layers 412 on the substrate 414, the multilayer stack of reflective layers 412 including a plurality of reflective layer pairs. In one or more embodiments, the plurality of reflective layer pairs are made from a material selected from a molybdenum (Mo) containing material and silicon (Si) containing material. In some embodiments, the plurality of reflective layer pairs comprises alternating layers of molybdenum and silicon. The extreme ultraviolet mask blank 400 further includes a capping layer 422 on the multilayer stack of reflective layers 412, and there is a multilayer stack 420 of absorber layers on the capping layer 422. In one or more embodiment, the plurality of reflective layers 412 are selected from a molybdenum (Mo) containing material and a silicon (Si) containing material and the capping layer 422 comprises ruthenium.

[0099] The multilayer stack 420 of absorber layers including a plurality of absorber layer pairs 420a, 420b, 420c, 420d, 420e, 420f, each pair (420a/420b, 420c/420d, 420e/420f) comprising an alloy selected from the group consisting of an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group

consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of Ru and the one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B),
5 nitrogen (N) and oxygen (O), an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni), and an alloy of tellurium (Te) and aluminum (Al). In some embodiments, the alloy of Ru and the one or more elements of Group 1 is selected from the group consisting of
10 an alloy of Ru and Nb having from about 31.8 wt.% to about 86.1 wt.% Ru and from about 13.9 wt.% to about 68.2 wt.% Nb, an alloy of Ru and Ir having from about 2.6 wt.% to about 90.9 wt.% Ru and from about 9.1 wt.% to about 97.4 wt.% Ir, an alloy of Ru and Re having from about 18.8 wt.% to about 75.5 wt.% Ru and from about 24.5 wt.% to about 81.2 wt.% Re, an alloy of Ru and Pt having from about 2.6 wt.% to
15 about 90.8 wt.% Ru and from about 9.2 wt.% to about 97.4 wt.% Pt, an alloy of Ru and Zr having from about 47.5 wt.% to about 95.5 wt.% Ru and from about 4.5 wt.% to about 52.5 wt.% Zr, an alloy of Ru and Os having from about 2.7 wt.% to about 91.0 wt.% Ru and from about 9.0 wt.% to about 97.3 wt.% Os, an alloy of Ru and Mn having from about 44.0 wt.% to about 88.1 wt.% Ru and from about 11.9 wt.% to
20 about 56.0 wt.% Mn, an alloy of Ru and Ag having from about 4.7 wt.% to about 94.7 wt.% Ru and from about 5.3 wt.% to about 95.3 wt.% Ag, an alloy of Ru and Tc having from about 5.1 wt.% to about 95.2 wt.% Ru and from about 4.8 wt.% to about 94.9 wt.% Tc, an alloy of Ru and Co having from about 8.2 wt.% to about 97.1 wt.% and from about 2.9 wt.% to about 91.8 wt.% Co and an alloy of Ru and Ni having from
25 about 23.3 wt.% to about 97.1 wt.% Ru and from about 2.9 wt.% to about 76.7 wt.% Ni. In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 is amorphous.

[00100] In one example, absorber layer 420a is made from a ruthenium (Ru) material and the material that forms absorber layer 420b is made from a material of the one or
30 more elements of Group 1. Likewise, absorber layer 420c is made from a ruthenium material and the material that forms absorber layer 420d is made from a material of the one or more elements of Group 1, and absorber layer 420e is made from a

ruthenium (Ru) material and the material that forms absorber layer 420f is that of the one or more elements of Group 1.

[00101] In one or more embodiments, the multilayer stack 420 of absorber layers including a plurality of absorber layer pairs 420a, 420b, 420c, 420d, 420e, 420f, each pair (420a/420b, 420c/420d, 420e/420f) comprising an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta). In some embodiments, the alloy of Ru and the one or more elements of Group 1 and Ta is selected from the group consisting of an alloy of Ru, Nb and Ta having from about 18.1 wt.% to about 84.8 wt.% Ru, from about 6.6 wt.% to about 73.3 wt.% Nb and from about 8.6 wt.% to about 75.3 wt.% Ta, an alloy of Ru, Ir and Ta having from about 2.7 wt.% to about 88.6 wt.% Ru, from about 6.6 wt.% to about 92.5 wt.% Ir and from about 4.8 wt.% to about 90.7 wt.% Ta, an alloy of Ru, Re and Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.4 wt.% to about 92.4 wt.% Re and from about 4.9 wt.% to about 90.9 wt.% Ta, an alloy of Ru, Pt and Ta having from about 2.6 wt.% to about 88.7 wt.% Ru, from about 6.6 wt.% to about 92.7 wt.% Pt and from about 4.7 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Zr and Ta having from about 28.8 wt.% to about 88.2 wt.% Ru, from about 3.2 wt.% to about 62.6 wt.% Zr and from about 8.6 wt.% to about 68.0 wt.% Ta, an alloy of Ru, Os and Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.5 wt.% to about 92.5 wt.% Os and from about 4.8 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Mn and Ta having from about 19.5 wt.% to about 87.0 wt.% Ru, from about 4.0 wt.% to about 71.5 wt.% Mn and from about 9.0 wt.% to about 76.5 wt.% Ta, an alloy of Ru, Ag and Ta having from about 3.5 wt.% to about 88.1 wt.% Ru, from about 3.8 wt.% to about 88.4 wt.% Ag and from about 8.1 wt.% to about 92.7 wt.% Ta, an alloy of Ru, Tc and Ta having from about 3.6 wt.% to about 88.0 wt.% Ru, from about 3.4 wt.% to about 87.8 wt.% Tc and from about 8.6 wt.% to about 93.0 wt.% Ta, an alloy of Ru, Co and Ta having from about 19.3 wt.% to about 86.8 wt.% Ru, from about 4.3 wt.% to about 71.8 wt.% Co and from about 8.9 wt.% to about 76.4 wt.% Ta and an alloy of Ru, Ni and Ta having from about 37.4 wt.% to about 89.2 wt.% Ru, from about 2.1 wt.% to about 53.9 wt.% Ni and from about 8.7 wt.% to about 60.5 wt.% Ta. In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 and Ta is amorphous.

[00102] In one example, absorber layer 420a is made from a ruthenium (Ru) material and the material that forms absorber layer 420b is made from a material of the one or more elements of Group 1. Likewise, absorber layer 420c is made from a tantalum (Ta) material and the material that forms absorber layer 420d is made from a ruthenium (Ru) material, and absorber layer 420e is made from a material of the one or more elements of Group 1 and the material that forms absorber layer 420f is that of tantalum (Ta).

[00103] In one or more embodiments, the multilayer stack 420 of absorber layers including a plurality of absorber layer pairs 420a, 420b, 420c, 420d, 420e, 420f, each pair (420a/420b, 420c/420d, 420e/420f) comprising an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2. In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 is amorphous.

[00104] In one example, absorber layer 420a is made from a ruthenium (Ru) material and the material that forms absorber layer 420b is made from a material of the one or more elements of Group 1. Likewise, absorber layer 420c is made from a material of the one or more elements of Group 2 and the material that forms absorber layer 420d is made from a ruthenium (Ru) material, and absorber layer 420e is made from a material of the one or more elements of Group 1 and the material that forms absorber layer 420f is that of the one or more elements of Group 2.

[00105] In one or more embodiments, the multilayer stack 420 of absorber layers including a plurality of absorber layer pairs 420a, 420b, 420c, 420d, 420e, 420f, each pair (420a/420b, 420c/420d, 420e/420f) comprising an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and tantalum (Ta). In one or more embodiments, the alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and tantalum (Ta) is amorphous.

[00106] In one example, absorber layer 420a is made from a ruthenium (Ru) material and the material that forms absorber layer 420b is made from a material of the one or more elements of Group 1. Likewise, absorber layer 420c is made from a material of the one or more elements of Group 2 and the material that forms absorber layer 420d is made from a tantalum (Ta) material, and absorber layer 420e is made from a

ruthenium (Ru) material and the material that forms absorber layer 420f is that of the one or more elements of Group 1.

[00107] In one embodiment, the extreme ultraviolet mask blank 400 includes the plurality of reflective layers 412 selected from molybdenum (Mo) containing material and silicon (Si) containing material, for example, molybdenum (Mo) and silicon (Si). The absorber materials that are used to form the absorber layers 420a, 420b, 420c, 420d, 420e and 420f are an alloy selected from the group consisting of an alloy of ruthenium (Ru) and one or more elements of Group 1, an alloy of Ru and the one or more elements of Group 1 and one or more elements of Group 2, an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te) and aluminum (Al).

[00108] In one or more embodiments, the absorber layer pairs 420a/420b, 420c/420d, 420e/420f comprise a first layer (420a, 420c, 420e) including an absorber material comprising an alloy of ruthenium (Ru) and one or more elements of Group 1 and a second absorber layer (420b, 420d, 420f) including an absorber material including an alloy of ruthenium (Ru) and one or more elements of Group 1. In specific embodiments, the absorber layer pairs comprise a first layer (420a, 420c, 420e) including an alloy of Ru and the one or more elements of Group 1, wherein the alloy of Ru and the one or more elements of Group 1 is selected from the group consisting of an alloy of Ru and Nb having from about 31.8 wt.% to about 86.1 wt.% Ru and from about 13.9 wt.% to about 68.2 wt.% Nb, an alloy of Ru and Ir having from about 2.6 wt.% to about 90.9 wt.% Ru and from about 9.1 wt.% to about 97.4 wt.% Ir, an alloy of Ru and Re having from about 18.8 wt.% to about 75.5 wt.% Ru and from about 24.5 wt.% to about 81.2 wt.% Re, an alloy of Ru and Pt having from about 2.6 wt.% to about 90.8 wt.% Ru and from about 9.2 wt.% to about 97.4 wt.% Pt, an alloy of Ru and Zr having from about 47.5 wt.% to about 95.5 wt.% Ru and from about 4.5 wt.% to about 52.5 wt.% Zr, an alloy of Ru and Os having from about 2.7 wt.% to about 91.0 wt.% Ru and from about 9.0 wt.% to about 97.3 wt.% Os, an alloy of Ru and Mn having from about 44.0 wt.% to about 88.1 wt.% Ru and from about 11.9 wt.% to about 56.0 wt.% Mn, an alloy of Ru and Ag having from about 4.7 wt.% to about 94.7 wt.% Ru and from about 5.3 wt.% to about 95.3 wt.% Ag, an alloy of Ru and Tc having

- from about 5.1 wt.% to about 95.2 wt.% Ru and from about 4.8 wt.% to about 94.9 wt.% Tc, an alloy of Ru and Co having from about 8.2 wt.% to about 97.1 wt.% and from about 2.9 wt.% to about 91.8 wt.% Co and an alloy of Ru and Ni having from about 23.3 wt.% to about 97.1 wt.% Ru and from about 2.9 wt.% to about 76.7 wt.%
- 5 Ni, and a second absorber layer (420b, 420d, 420f) including an absorber material including an alloy of Ru and the one or more elements of Group 1, wherein the alloy of Ru and the one or more elements of Group 1 is selected from the group consisting of an alloy of Ru and Nb having from about 31.8 wt.% to about 86.1 wt.% Ru and from about 13.9 wt.% to about 68.2 wt.% Nb, an alloy of Ru and Ir having from about 2.6
- 10 wt.% to about 90.9 wt.% Ru and from about 9.1 wt.% to about 97.4 wt.% Ir, an alloy of Ru and Re having from about 18.8 wt.% to about 75.5 wt.% Ru and from about 24.5 wt.% to about 81.2 wt.% Re, an alloy of Ru and Pt having from about 2.6 wt.% to about 90.8 wt.% Ru and from about 9.2 wt.% to about 97.4 wt.% Pt, an alloy of Ru and Zr having from about 47.5 wt.% to about 95.5 wt.% Ru and from about 4.5 wt.% to
- 15 about 52.5 wt.% Zr, an alloy of Ru and Os having from about 2.7 wt.% to about 91.0 wt.% Ru and from about 9.0 wt.% to about 97.3 wt.% Os, an alloy of Ru and Mn having from about 44.0 wt.% to about 88.1 wt.% Ru and from about 11.9 wt.% to about 56.0 wt.% Mn, an alloy of Ru and Ag having from about 4.7 wt.% to about 94.7 wt.% Ru and from about 5.3 wt.% to about 95.3 wt.% Ag, an alloy of Ru and Tc having
- 20 from about 5.1 wt.% to about 95.2 wt.% Ru and from about 4.8 wt.% to about 94.9 wt.% Tc, an alloy of Ru and Co having from about 8.2 wt.% to about 97.1 wt.% and from about 2.9 wt.% to about 91.8 wt.% Co and an alloy of Ru and Ni having from about 23.3 wt.% to about 97.1 wt.% Ru and from about 2.9 wt.% to about 76.7 wt.% Ni.
- 25 **[00109]** According to one or more embodiments, the absorber layer pairs comprise a first layer (420a, 420c, 420e) and a second absorber layer (420b, 420d, 420f) each of the first absorber layers (420a, 420c, 420e) and second absorber layer (420b, 420d, 420f) have a thickness in a range of 0.1 nm and 10 nm, for example in a range of 1 nm and 5 nm, or in a range of 1 nm and 3 nm. In one or more specific embodiments,
- 30 the thickness of the first layer 420a is 0.5 nm, 0.6 nm, 0.7 nm, 0.8 nm, 0.9 nm, 1 nm, 1.1 nm, 1.2 nm, 1.3 nm, 1.4 nm, 1.5 nm, 1.6 nm, 1.7 nm, 1.8 nm, 1.9 nm, 2 nm, 2.1 nm, 2.2 nm, 2.3 nm, 2.4 nm, 2.5 nm, 2.6 nm, 2.7 nm, 2.8 nm, 2.9 nm, 3 nm, 3.1 nm,

3.2 nm, 3.3 nm, 3.4 nm, 3.5 nm, 3.6 nm, 3.7 nm, 3.8 nm, 3.9 nm, 4 nm, 4.1 nm, 4.2 nm, 4.3 nm, 4.4 nm, 4.5 nm, 4.6 nm, 4.7 nm, 4.8 nm, 4.9 nm, and 5 nm. In one or more embodiments, the thickness of the first absorber layer and second absorber layer of each pair is the same or different. For example, the first absorber layer and second absorber layer have a thickness such that there is a ratio of the first absorber layer thickness to second absorber layer thickness of 1:1, 1.5:1, 2:1, 2.5:1, 3:1, 3.5:1, 4:1, 4.5:1, 5:1, 6:1, 7:1, 8:1, 9:1, 10:1, 11:1, 12:1, 13:1, 14:1, 15:1, 16:1, 17:1, 18:1, 19:1, or 20:1, which results in the first absorber layer having a thickness that is equal to or greater than the second absorber layer thickness in each pair. Alternatively, the first absorber layer and second absorber layer have a thickness such that there is a ratio of the second absorber layer thickness to first absorber layer thickness of 1.5:1, 2:1, 2.5:1, 3:1, 3.5:1, 4:1, 4.5:1, 5:1, 6:1, 7:1, 8:1, 9:1, 10:1, 11:1, 12:1, 13:1, 14:1, 15:1, 16:1, 17:1, 18:1, 19:1, or 20:1 which results in the second absorber layer having a thickness that is equal to or greater than the first absorber layer thickness in each pair.

[00110] According to one or more embodiments, the different absorber materials and thickness of the absorber layers are selected so that extreme ultraviolet light is absorbed due to absorbance and due to a phase change caused by destructive interfere with light from the multilayer stack of reflective layers. While the embodiment shown in FIG. 5 shows three absorber layer pairs, 420a/420b, 420c/420d and 420e/420f, the claims should not be limited to a particular number of absorber layer pairs. According to one or more embodiments, the EUV mask blank 400 includes in a range of 5 and 60 absorber layer pairs or in a range of 10 and 40 absorber layer pairs.

[00111] According to one or more embodiments, the absorber layers have a thickness which provides less than 2% reflectivity and other etch properties. A supply gas is used to further modify the material properties of the absorber layers, for example, nitrogen (N₂) gas is used to form nitrides of the materials provided above. The multilayer stack of absorber layers according to one or more embodiments is a repetitive pattern of individual thickness of different materials so that the EUV light not only gets absorbed due to absorbance but by the phase change caused by multilayer absorber stack, which will destructively interfere with light from multilayer stack of reflective materials beneath to provide better contrast.

[00112] Another aspect of the disclosure pertains to a method of manufacturing an extreme ultraviolet (EUV) mask blank comprising forming on a substrate a multilayer stack of reflective layers on the substrate, the multilayer stack including a plurality of reflective layer pairs, and forming an absorber layer on the multilayer stack, the absorber layer comprising an alloy selected from the group consisting of an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of Ru and the one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O), an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te) and aluminum (Al).

[00113] The EUV mask blank has any of the characteristics of the embodiments described above with respect to FIG. 4 and FIG. 5, and the method is performed in the system described with respect to FIG. 3.

[00114] Thus, in an embodiment, the plurality of reflective layers are selected from molybdenum (Mo) containing material and silicon (Si) containing material and the absorber layer is an alloy of ruthenium (Ru) and one or more elements of Group 1. In another embodiment, the plurality of reflective layers are selected from molybdenum (Mo) containing material and silicon (Si) containing material and the absorber layer is an alloy of ruthenium (Ru) and the one or more elements of Group 1 and one or more elements of Group 2. In a further embodiment, the plurality of reflective layers are selected from molybdenum (Mo) containing material and silicon (Si) containing material and the absorber layer is an alloy of ruthenium (Ru) and the one or more elements of Group 1 and tantalum (Ta). In a further embodiment, the plurality of reflective layers are selected from molybdenum (Mo) containing material and silicon (Si) containing material and the absorber layer is an alloy of ruthenium (Ru) and the one or more elements of Group 1 and the one or more elements of Group 2 and tantalum (Ta). In another embodiment, the plurality of reflective layers are selected from molybdenum (Mo) containing material and silicon (Si) containing material and the

absorber layer is an alloy of tellurium (Te) and nickel (Ni). In a further embodiment, the plurality of reflective layers are selected from molybdenum (Mo) containing material and silicon (Si) containing material and the absorber layer is an alloy of tellurium (Te) and aluminum (Al).

5 [00115] In another specific method embodiment, the different absorber layers are formed in a physical deposition chamber having a first cathode comprising a first absorber material and a second cathode comprising a second absorber material. Referring now to FIG. 6 an upper portion of a multi-cathode source chamber 500 is shown in accordance with an embodiment. The multi-cathode chamber 500 includes
10 a base structure 501 with a cylindrical body portion 502 capped by a top adapter 504. The top adapter 504 has provisions for a number of cathode sources, such as cathode sources 506, 508, 510, 512, and 514, positioned around the top adapter 504. The cathode sources 506, 508, 510, 512, and 514 according to one or more embodiments comprise different absorber materials as described herein to form laminates of
15 absorber materials.

[00116] In one or more embodiments, the method forms an absorber layer that has a thickness in a range of 5 nm and 60 nm. In one or more embodiments, the absorber layer has a thickness in a range of 51 nm and 57 nm. In one or more embodiments, the materials used to form the absorber layer are selected to effect etch properties of
20 the absorber layer. In one or more embodiments, the alloy of the absorber layer is formed by co-sputtering an alloy absorber material formed in a physical deposition chamber, which provides much thinner absorber layer thickness (less than 30nm) and achieving less than 2% reflectivity and desired etch properties. In an embodiment, the etch properties and other desired properties of the absorber layer are tailored to
25 specification by controlling the alloy percentage of each absorber material. In an embodiment, the alloy percentage is precisely controlled by operating parameters such voltage, pressure, flow etc., of the physical vapor deposition chamber. In an embodiment, a process gas is used to further modify the material properties, for example, N₂ gas is used to form nitrides of ruthenium (Ru) and one or more elements
30 of Group 1. In another embodiment, a process gas is used to further modify the material properties, for example, N₂ gas is used to form nitrides of ruthenium (Ru) and one or more elements of Group 1 and one or more elements of Group 2. In some

embodiments, a process gas is used to further modify the material properties, for example, N₂ gas is used to form nitrides of ruthenium (Ru) and one or more elements of Group 1 and tantalum (Ta). In a further embodiment, a process gas is used to further modify the material properties, for example, N₂ gas is used to form nitrides of ruthenium (Ru) and one or more elements of Group 1 and one or more elements of Group 2 and tantalum. In an embodiment, a process gas is used to further modify the material properties, for example, N₂ gas is used to form nitrides of tellurium (Te) and nickel (Ni). In a further embodiment, a process gas is used to further modify the material properties, for example, N₂ gas is used to form nitrides of and tellurium (Te) and aluminum (Al). The alloy absorber material comprises an alloy selected from the group consisting of an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of Ru and the one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O), an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te) and aluminum (Al).

[00117] In some embodiments, the multi-cathode source chamber 500 is part of the system shown in FIG. 3. In an embodiment, an extreme ultraviolet (EUV) mask blank production system comprises a substrate handling vacuum chamber for creating a vacuum, a substrate handling platform, in the vacuum, for transporting a substrate loaded in the substrate handling vacuum chamber, and multiple sub-chambers, accessed by the substrate handling platform, for forming an EUV mask blank, including a multilayer stack of reflective layers on the substrate, the multilayer stack including a plurality of reflective layer pairs, a capping layer on the multilayer stack of reflective layers, and an absorber layer on the capping layer, the absorber layer made from an alloy selected from the group consisting of an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of Ru and the

one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O), an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and
5 Ta, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te) and aluminum (Al). The system is used to make the EUV mask blanks shown with respect to FIG. 4 or FIG. 5 and have any of the properties described with respect to the EUV mask blanks described with respect to FIG. 4 or FIG. 5 above.

[00118] Processes may generally be stored in the memory as a software routine that,
10 when executed by the processor, causes the process chamber to perform processes of the present disclosure. The software routine may also be stored and/or executed by a second processor (not shown) that is remotely located from the hardware being controlled by the processor. Some or all of the method of the present disclosure may also be performed in hardware. As such, the process may be implemented in
15 software and executed using a computer system, in hardware as, e.g., an application specific integrated circuit or other type of hardware implementation, or as a combination of software and hardware. The software routine, when executed by the processor, transforms the general purpose computer into a specific purpose computer (controller) that controls the chamber operation such that the processes are
20 performed.

[00119] Reference throughout this specification to "one embodiment," "certain embodiments," "one or more embodiments" or "an embodiment" means that a particular feature, structure, material, or characteristic described in connection with the embodiment is included in at least one embodiment of the disclosure. Thus, the
25 appearances of the phrases such as "in one or more embodiments," "in certain embodiments," "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily referring to the same embodiment of the disclosure. Furthermore, the particular features, structures, materials, or characteristics may be combined in any suitable manner in one or more embodiments.

30 **[00120]** Although the disclosure herein has been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present disclosure. It will be

apparent to those skilled in the art that various modifications and variations can be made to the method and apparatus of the present disclosure without departing from the spirit and scope of the disclosure. Thus, it is intended that the present disclosure include modifications and variations that are within the scope of the appended claims
5 and their equivalents.

What is claimed is:

1. An extreme ultraviolet (EUV) mask blank comprising:
a substrate;
a multilayer stack of reflective layers on the substrate, the multilayer stack of
5 reflective layers including a plurality of reflective layers including reflective layer pairs;
and
an absorber layer on the multilayer stack of reflective layers, the absorber layer
comprising an alloy selected from the group consisting of an alloy of ruthenium (Ru)
and one or more elements of Group 1 selected from the group consisting of niobium
10 (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os),
manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel (Ni), an alloy of
Ru and the one or more elements of Group 1 and one or more elements of Group 2
selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen
(O), an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta), an
15 alloy of Ru and the one or more elements of Group 1 and the one or more elements of
Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni) and an alloy of tellurium (Te)
and aluminum (Al).
2. The extreme ultraviolet (EUV) mask blank of claim 1, wherein the alloy of Ru
20 and the one or more elements of Group 1 is selected from the group consisting of an
alloy of Ru and Nb having from about 31.8 wt.% to about 86.1 wt.% Ru and from
about 13.9 wt.% to about 68.2 wt.% Nb, an alloy of Ru and Ir having from about 2.6
wt.% to about 90.9 wt.% Ru and from about 9.1 wt.% to about 97.4 wt.% Ir, an alloy of
Ru and Re having from about 18.8 wt.% to about 75.5 wt.% Ru and from about 24.5
25 wt.% to about 81.2 wt.% Re, an alloy of Ru and Pt having from about 2.6 wt.% to
about 90.8 wt.% Ru and from about 9.2 wt.% to about 97.4 wt.% Pt, an alloy of Ru
and Zr having from about 47.5 wt.% to about 95.5 wt.% Ru and from about 4.5 wt.% to
about 52.5 wt.% Zr, an alloy of Ru and Os having from about 2.7 wt.% to about 91.0
wt.% Ru and from about 9.0 wt.% to about 97.3 wt.% Os, an alloy of Ru and Mn
30 having from about 44.0 wt.% to about 88.1 wt.% Ru and from about 11.9 wt.% to
about 56.0 wt.% Mn, an alloy of Ru and Ag having from about 4.7 wt.% to about 94.7
wt.% Ru and from about 5.3 wt.% to about 95.3 wt.% Ag, an alloy of Ru and Tc having

from about 5.1 wt.% to about 95.2 wt.% Ru and from about 4.8 wt.% to about 94.9 wt.% Tc, an alloy of Ru and Co having from about 8.2 wt.% to about 97.1 wt.% and from about 2.9 wt.% to about 91.8 wt.% Co and an alloy of Ru and Ni having from about 23.3 wt.% to about 97.1 wt.% Ru and from about 2.9 wt.% to about 76.7 wt.% Ni.

3. The extreme ultraviolet (EUV) mask blank of claim 1, wherein the alloy of Ru and the one or more elements of Group 1 and Ta is selected from the group consisting of an alloy of Ru, Nb and Ta having from about 18.1 wt.% to about 84.8 wt.% Ru, from about 6.6 wt.% to about 73.3 wt.% Nb and from about 8.6 wt.% to about 75.3 wt.% Ta, an alloy of Ru, Ir and Ta having from about 2.7 wt.% to about 88.6 wt.% Ru, from about 6.6 wt.% to about 92.5 wt.% Ir and from about 4.8 wt.% to about 90.7 wt.% Ta, an alloy of Ru, Re and Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.4 wt.% to about 92.4 wt.% Re and from about 4.9 wt.% to about 90.9 wt.% Ta, an alloy of Ru, Pt and Ta having from about 2.6 wt.% to about 88.7 wt.% Ru, from about 6.6 wt.% to about 92.7 wt.% Pt and from about 4.7 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Zr and Ta having from about 28.8 wt.% to about 88.2 wt.% Ru, from about 3.2 wt.% to about 62.6 wt.% Zr and from about 8.6 wt.% to about 68.0 wt.% Ta, an alloy of Ru, Os and Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.5 wt.% to about 92.5 wt.% Os and from about 4.8 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Mn and Ta having from about 19.5 wt.% to about 87.0 wt.% Ru, from about 4.0 wt.% to about 71.5 wt.% Mn and from about 9.0 wt.% to about 76.5 wt.% Ta, an alloy of Ru, Ag and Ta having from about 3.5 wt.% to about 88.1 wt.% Ru, from about 3.8 wt.% to about 88.4 wt.% Ag and from about 8.1 wt.% to about 92.7 wt.% Ta, an alloy of Ru, Tc and Ta having from about 3.6 wt.% to about 88.0 wt.% Ru, from about 3.4 wt.% to about 87.8 wt.% Tc and from about 8.6 wt.% to about 93.0 wt.% Ta, an alloy of Ru, Co and Ta having from about 19.3 wt.% to about 86.8 wt.% Ru, from about 4.3 wt.% to about 71.8 wt.% Co and from about 8.9 wt.% to about 76.4 wt.% Ta and an alloy of Ru, Ni and Ta having from about 37.4 wt.% to about 89.2 wt.% Ru, from about 2.1 wt.% to about 53.9 wt.% Ni and from about 8.7 wt.% to about 60.5 wt.% Ta.

4. The extreme ultraviolet (EUV) mask blank of claim 2, wherein the alloy further comprises about 0.1 wt.% to about 5.0 wt.% of a dopant selected from the group consisting of the one or more elements of Group 2.
- 5 5. The extreme ultraviolet (EUV) mask blank of claim 3, wherein the alloy further comprises about 0.1 wt.% to about 5.0 wt.% of a dopant selected from the group consisting of the one or more elements of Group 2.
6. The extreme (EUV) mask blank of claim 1, wherein the alloy of Te and Ni
10 includes from about 10.0 wt.% to about 97.7 wt.% Te and from about 2.3 wt.% to about 90.0 wt.% Ni.
7. The extreme (EUV) mask blank of claim 1, wherein the alloy of Te and Al
15 includes from about 19.9 wt.% to about 98.9 wt.% Te and about 1.1 wt.% to about 80.1 wt.% Al.
8. The extreme ultraviolet (EUV) mask blank of claim 6, wherein the absorber layer further comprises from about 0.1 wt.% to about 5.0 wt.% of a dopant selected from one or more of nitrogen or oxygen.
20
9. The extreme ultraviolet (EUV) mask blank of claim 7, wherein the absorber layer further comprises from about 0.1 wt.% to about 5.0 wt.% of a dopant selected from one or more of nitrogen or oxygen.
- 25 10. The extreme ultraviolet (EUV) mask blank of claim 1, wherein the absorber layer has a thickness of less than 45 nm.
11. The extreme ultraviolet (EUV) mask blank of claim 1, wherein the absorber layer has a reflectivity of less than about 2%.
- 30 12. The extreme ultraviolet (EUV) mask blank of claim 1, wherein the absorber layer is etch selective relative to the capping layer.

13. A method of manufacturing an extreme ultraviolet (EUV) mask blank comprising:

forming a multilayer stack of reflective layers on a substrate, the multilayer stack of reflective layers including a plurality of reflective layer pairs; and

5 forming an absorber layer on the multilayer stack of reflective layers, the absorber layer comprising an alloy selected from the group consisting of an alloy of ruthenium (Ru) and one or more elements of Group 1 selected from the group consisting of niobium (Nb), iridium (Ir), rhenium (Re), platinum (Pt), zirconium (Zr), osmium (Os), manganese (Mn), silver (Ag), technetium (Tc), cobalt (Co) and nickel
10 (Ni), an alloy of Ru and the one or more elements of Group 1 and one or more elements of Group 2 selected from the group consisting of silicon (Si), boron, (B), nitrogen (N) and oxygen (O), an alloy of Ru and the one or more elements of Group 1 and tantalum (Ta), an alloy of Ru and the one or more elements of Group 1 and the one or more elements of Group 2 and Ta, an alloy of tellurium (Te) and nickel (Ni) and
15 an alloy of tellurium (Te) and aluminum (Al).

14. The method of claim 13, wherein the alloy of Ru and the one or more elements of Group 1 is selected from the group consisting of an alloy of Ru and Nb having from about 31.8 wt.% to about 86.1 wt.% Ru and from about 13.9 wt.% to about 68.2 wt.%
20 Nb, an alloy of Ru and Ir having from about 2.6 wt.% to about 90.9 wt.% Ru and from about 9.1 wt.% to about 97.4 wt.% Ir, an alloy of Ru and Re having from about 18.8 wt.% to about 75.5 wt.% Ru and from about 24.5 wt.% to about 81.2 wt.% Re, an alloy of Ru and Pt having from about 2.6 wt.% to about 90.8 wt.% Ru and from about 9.2 wt.% to about 97.4 wt.% Pt, an alloy of Ru and Zr having from about 47.5 wt.% to
25 about 95.5 wt.% Ru and from about 4.5 wt.% to about 52.5 wt.% Zr, an alloy of Ru and Os having from about 2.7 wt.% to about 91.0 wt.% Ru and from about 9.0 wt.% to about 97.3 wt.% Os, an alloy of Ru and Mn having from about 44.0 wt.% to about 88.1 wt.% Ru and from about 11.9 wt.% to about 56.0 wt.% Mn, an alloy of Ru and Ag having from about 4.7 wt.% to about 94.7 wt.% Ru and from about 5.3 wt.% to about
30 95.3 wt.% Ag, an alloy of Ru and Tc having from about 5.1 wt.% to about 95.2 wt.% Ru and from about 4.8 wt.% to about 94.9 wt.% Tc, an alloy of Ru and Co having from about 8.2 wt.% to about 97.1 wt.% and from about 2.9 wt.% to about 91.8 wt.% Co

and an alloy of Ru and Ni having from about 23.3 wt.% to about 97.1 wt.% Ru and from about 2.9 wt.% to about 76.7 wt.% Ni.

15. The method of claim 13, wherein the alloy of Ru and the one or more elements
5 of Group 1 and Ta is selected from the group consisting of an alloy of Ru, Nb and Ta having from about 18.1 wt.% to about 84.8 wt.% Ru, from about 6.6 wt.% to about 73.3 wt.% Nb and from about 8.6 wt.% to about 75.3 wt.% Ta, an alloy of Ru, Ir and Ta having from about 2.7 wt.% to about 88.6 wt.% Ru, from about 6.6 wt.% to about 92.5 wt.% Ir and from about 4.8 wt.% to about 90.7 wt.% Ta, an alloy of Ru, Re and
10 Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.4 wt.% to about 92.4 wt.% Re and from about 4.9 wt.% to about 90.9 wt.% Ta, an alloy of Ru, Pt and Ta having from about 2.6 wt.% to about 88.7 wt.% Ru, from about 6.6 wt.% to about 92.7 wt.% Pt and from about 4.7 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Zr and Ta having from about 28.8 wt.% to about 88.2 wt.% Ru, from about 3.2 wt.% to about
15 62.6 wt.% Zr and from about 8.6 wt.% to about 68.0 wt.% Ta, an alloy of Ru, Os and Ta having from about 2.7 wt.% to about 88.7 wt.% Ru, from about 6.5 wt.% to about 92.5 wt.% Os and from about 4.8 wt.% to about 90.8 wt.% Ta, an alloy of Ru, Mn and Ta having from about 19.5 wt.% to about 87.0 wt.% Ru, from about 4.0 wt.% to about 71.5 wt.% Mn and from about 9.0 wt.% to about 76.5 wt.% Ta, an alloy of Ru, Ag and
20 Ta having from about 3.5 wt.% to about 88.1 wt.% Ru, from about 3.8 wt.% to about 88.4 wt.% Ag and from about 8.1 wt.% to about 92.7 wt.% Ta, an alloy of Ru, Tc and Ta having from about 3.6 wt.% to about 88.0 wt.% Ru, from about 3.4 wt.% to about 87.8 wt.% Tc and from about 8.6 wt.% to about 93.0 wt.% Ta, an alloy of Ru, Co and Ta having from about 19.3 wt.% to about 86.8 wt.% Ru, from about 4.3 wt.% to about
25 71.8 wt.% Co and from about 8.9 wt.% to about 76.4 wt.% Ta and an alloy of Ru, Ni and Ta having from about 37.4 wt.% to about 89.2 wt.% Ru, from about 2.1 wt.% to about 53.9 wt.% Ni and from about 8.7 wt.% to about 60.5 wt.% Ta.

16. The method of claim 13, wherein the alloy of Te and Ni includes from about
30 10.0 wt.% to about 97.7 wt.% Te and from about 2.3 wt.% to about 90.0 wt.% Ni.

17. The method of claim 13, wherein the alloy of Te and Al includes from about 19.9 wt.% to about 98.9 wt.% Te and from about 1.1 wt.% to about 80.1 wt.% Al.
18. The method of claim 13, wherein the alloy is co-sputtered by a gas selected
5 from one or more of argon (Ar), oxygen (O₂), or nitrogen (N₂) to form the absorber layer.
19. The method of claim 13, wherein the alloy is deposited layer by layer as a laminate, using a gas selected from one or more of argon (Ar), oxygen (O₂), or
10 nitrogen (N₂) to form the absorber layer.
20. The method of claim 13, wherein the alloy is deposited using a bulk target having a composition that is same as the alloy and is sputtered using a gas selected from one or more of argon (Ar), oxygen (O₂), or nitrogen (N₂) to form the absorber
15 layer.