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(54) **OPTICAL DEVICE FILM WITH TUNABLE REFRACTIVE INDEX**

(71) Applicant: **Applied Materials, Inc.**, Santa Clara, CA (US)

(72) Inventors: **Kenichi OHNO**, Sunnyvale, CA (US); **Andrew CEBALLOS**, Palo Alto, CA (US); **Karl J. ARMSTRONG**, Santa Clara, CA (US); **Rami HOURANI**, Santa Clara, CA (US); **Takashi KURATOMI**, San Jose, CA (US); **Ludovic GODET**, Sunnyvale, CA (US)

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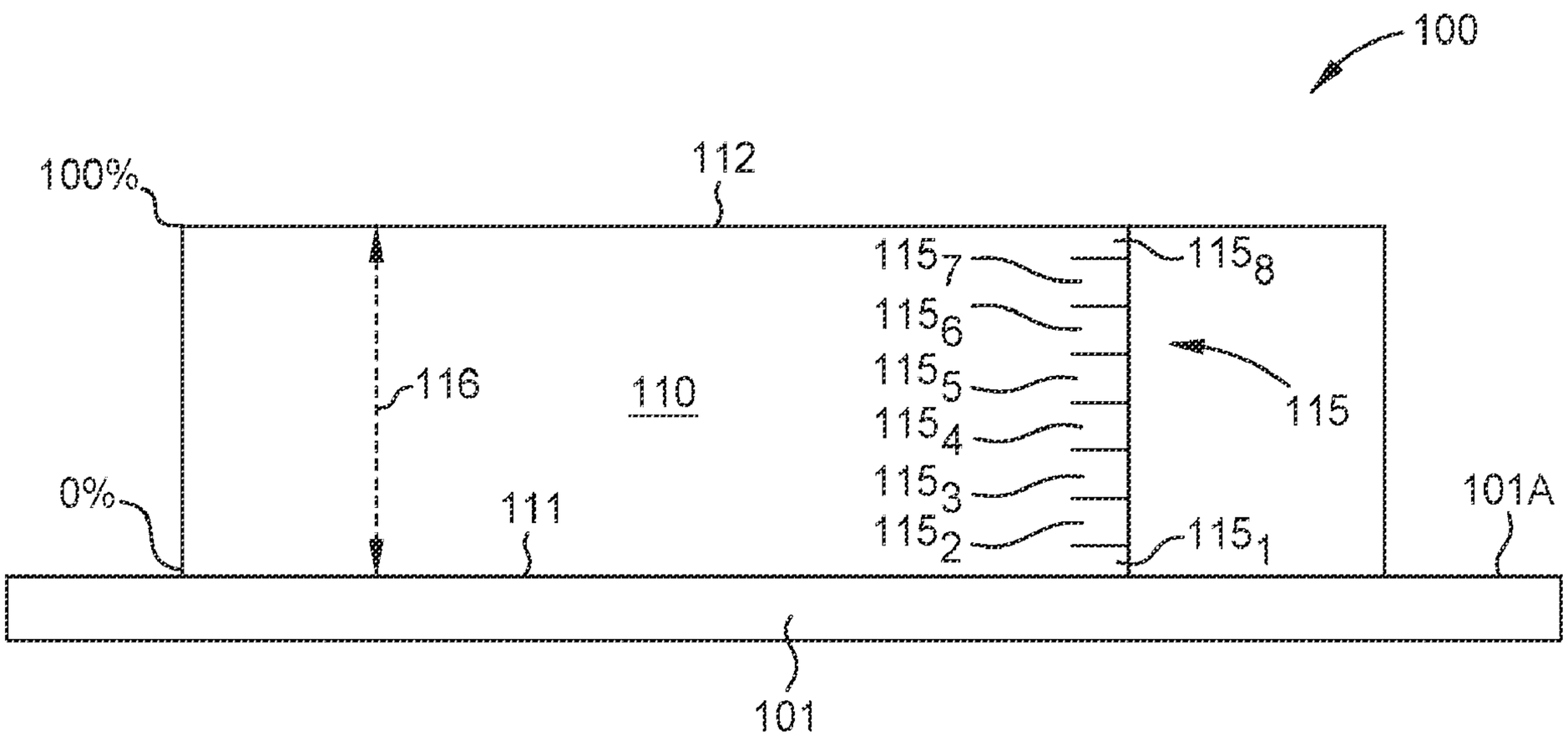
(57) **ABSTRACT**

An optical device is provided. The optical device includes an optical device substrate having a first surface; and a plurality of optical device structures disposed over the first surface of the optical device substrate, the plurality of optical device structures spaced apart from each other in a direction parallel to the first surface, and each optical device structure of the plurality of optical device structures including an optical device film. The optical device film of each optical device structure includes a first zone and a second zone, the first zone positioned between the optical device substrate and the second zone, wherein the first zone and the second zone each include one or more of oxygen and nitrogen, and the first zone and the second zone collectively include three or more metal, metalloid, or semiconductor elements.



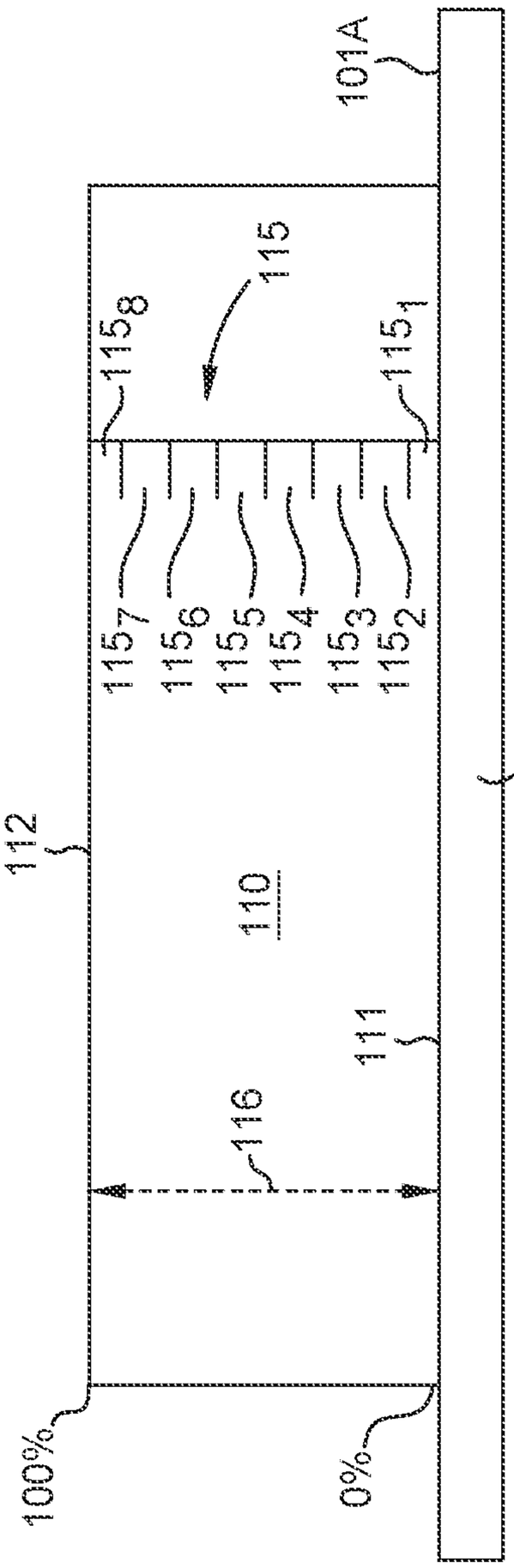

100
101A
115
1158
1151
1157
1156
1155
1154
1153
1152
112
110
111
116
101
100%
0%

FIG. 1

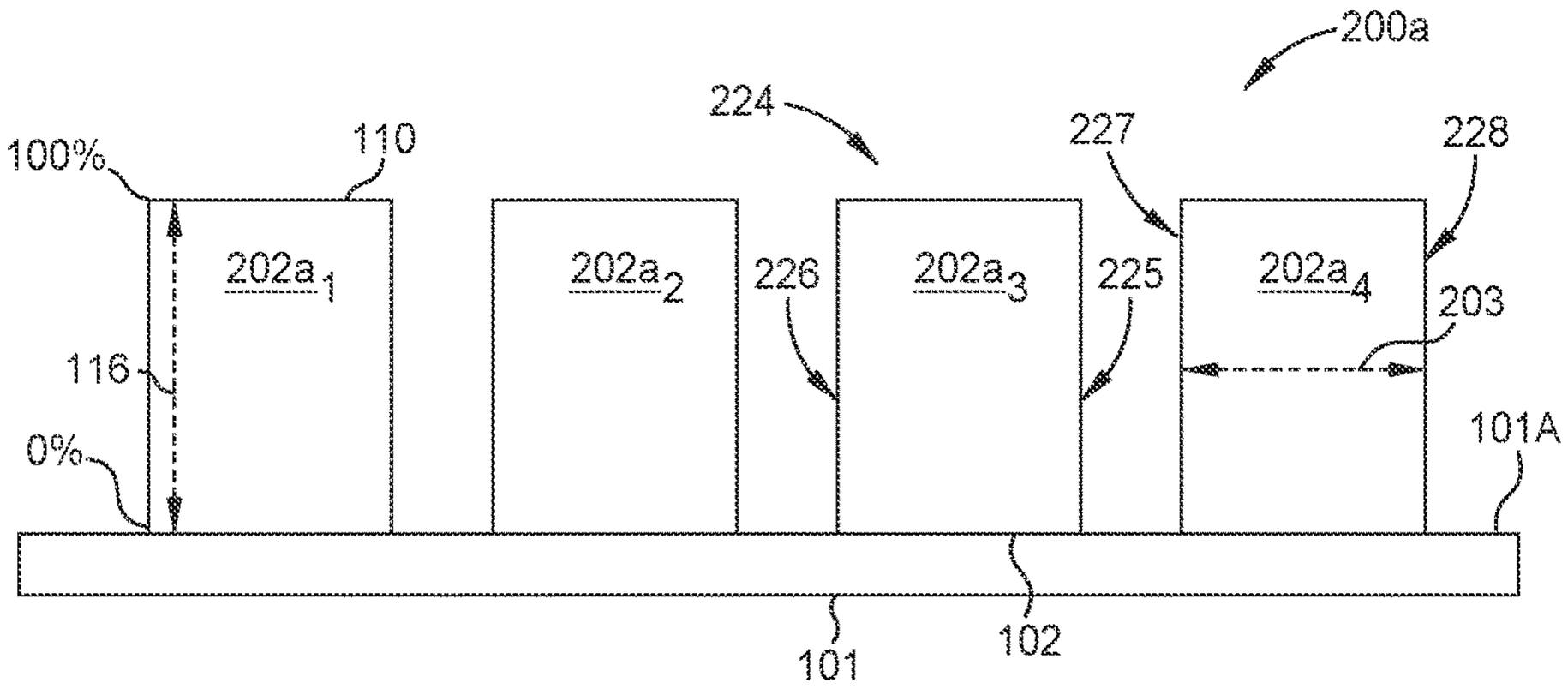
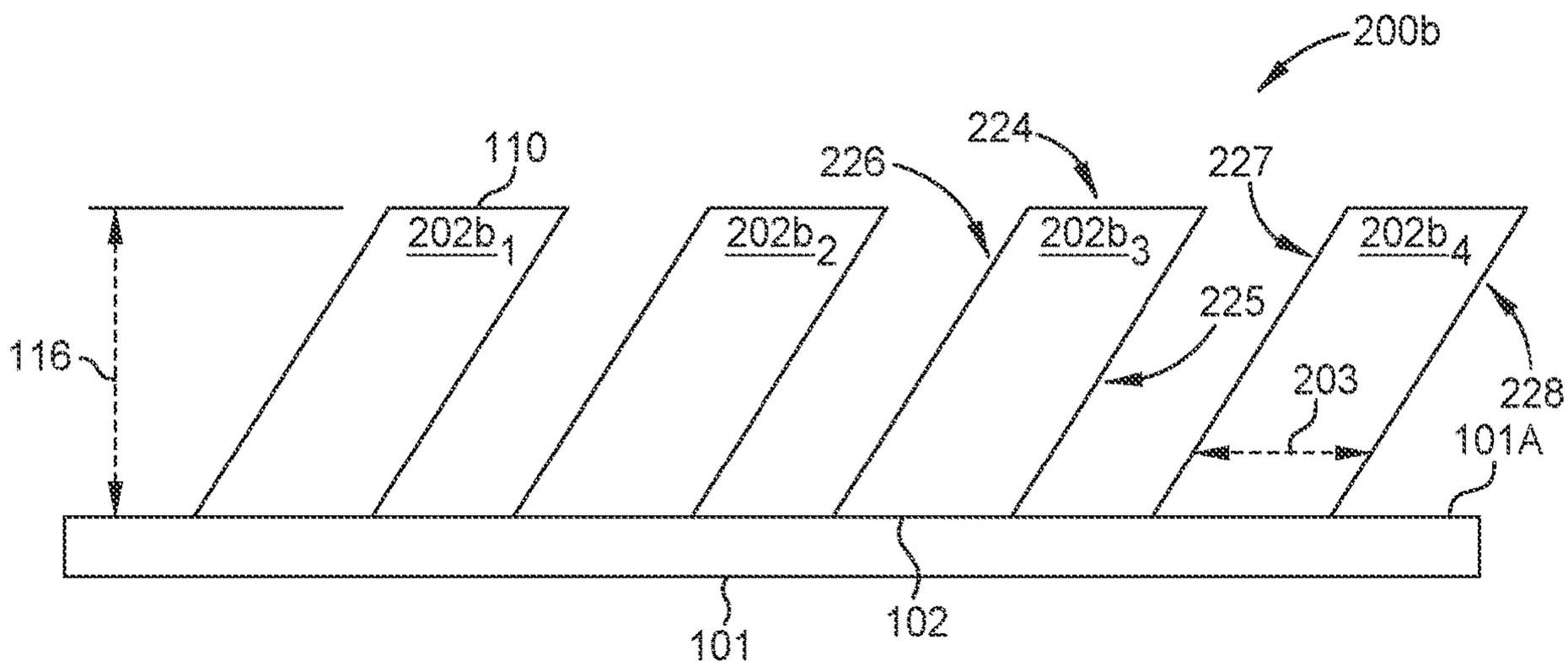

200a
224
227
228
100%
110
202a1
202a2
226
202a3
225
202a4
203
116
101A
0%
101
102

FIG. 2A


200b
224
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202b1
202b2
202b3
202b4
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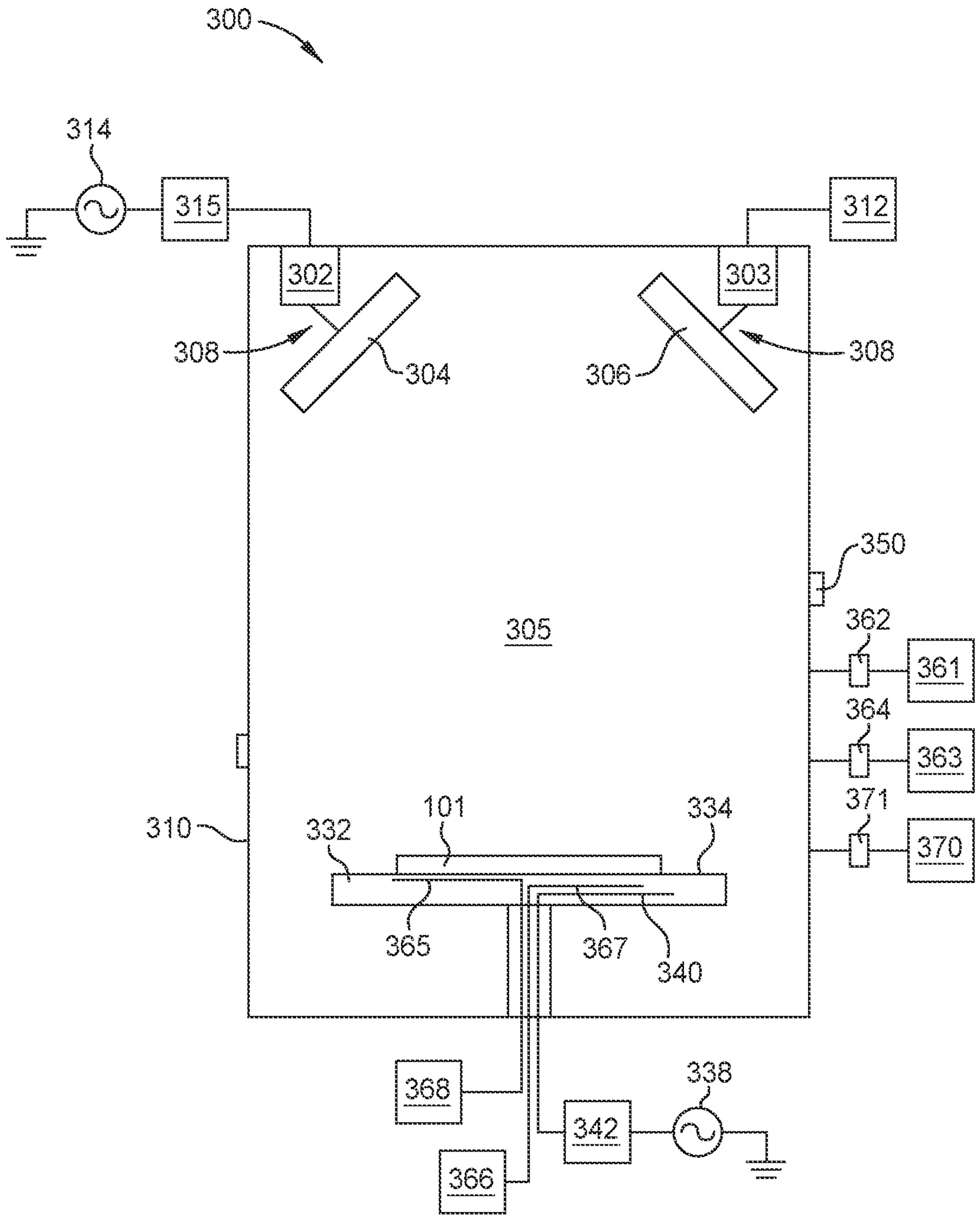
228
101A
101
102

FIG. 2B


300
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350
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101
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365
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368
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342
366

FIG. 3A

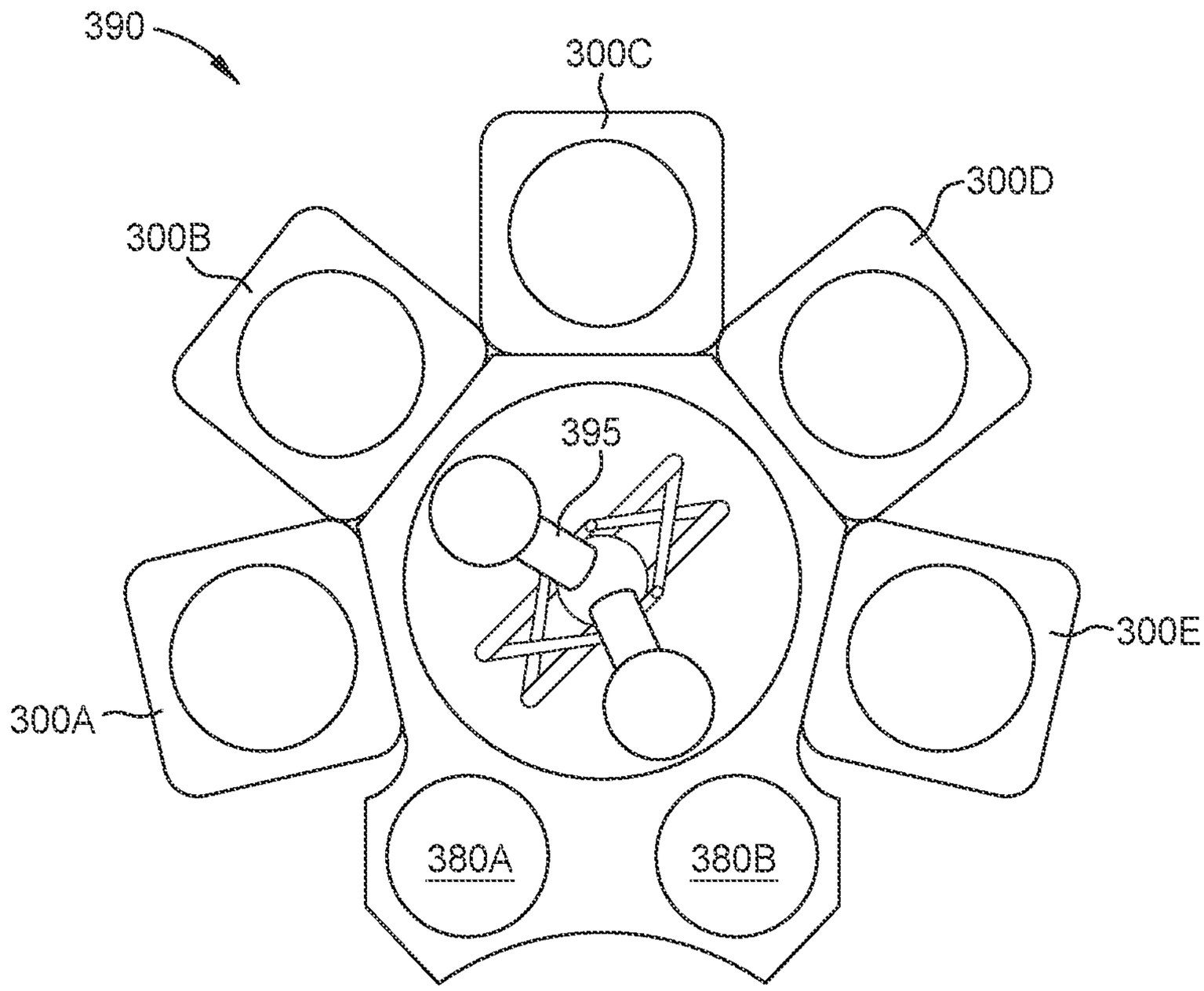

FIG. 3B

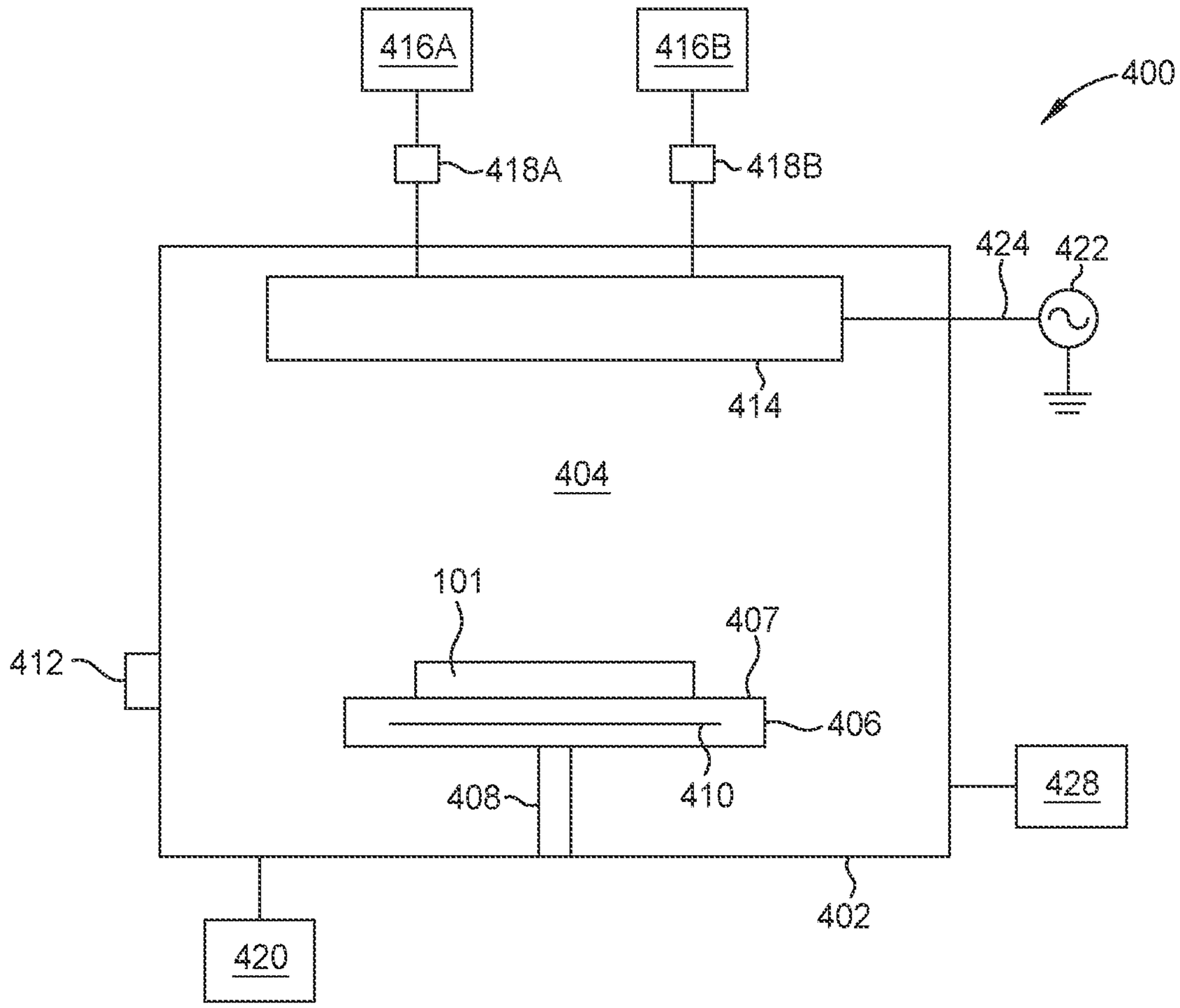
416A
416B
400
418A
418B
424
422
414
404
101
407
412
406
410
408
428
402
420

FIG. 4

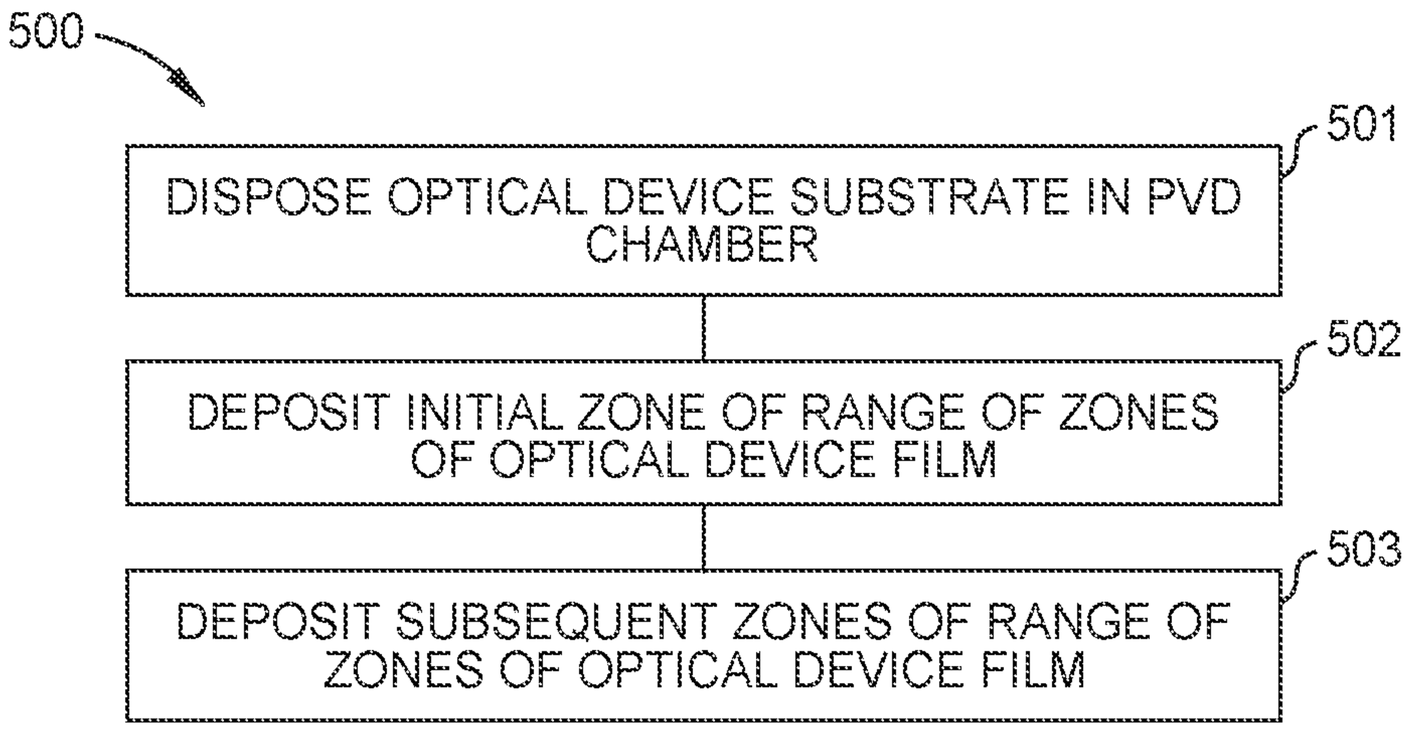
500
DISPOSE OPTICAL DEVICE SUBSTRATE IN PVD CHAMBER
501
DEPOSIT INITIAL ZONE OF RANGE OF ZONES OF OPTICAL DEVICE FILM
502
DEPOSIT SUBSEQUENT ZONES OF RANGE OF ZONES OF OPTICAL DEVICE FILM
503

FIG. 5

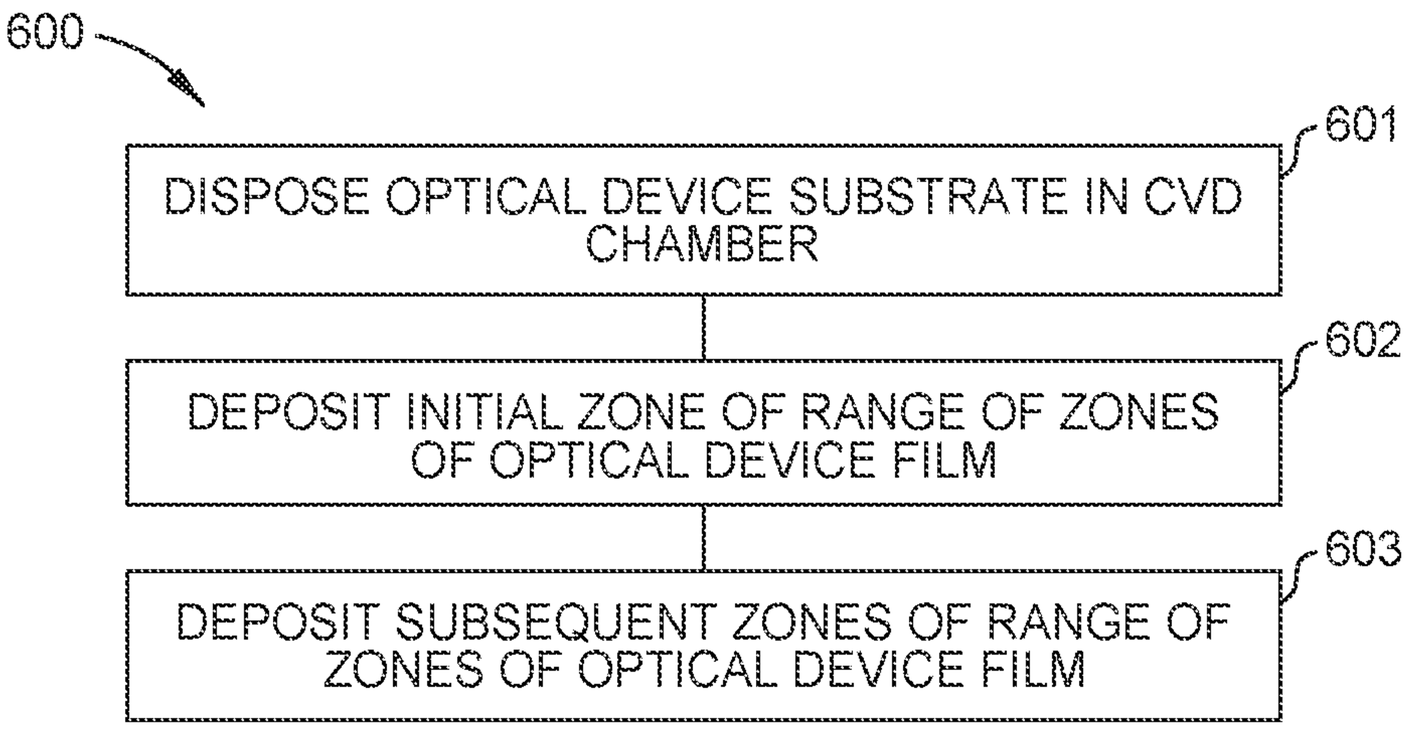
600
DISPOSE OPTICAL DEVICE SUBSTRATE IN CVD CHAMBER
601
DEPOSIT INITIAL ZONE OF RANGE OF ZONES OF OPTICAL DEVICE FILM
602
DEPOSIT SUBSEQUENT ZONES OF RANGE OF ZONES OF OPTICAL DEVICE FILM
603

FIG. 6

OPTICAL DEVICE FILM WITH TUNABLE REFRACTIVE INDEX

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 63/150,416, filed on Feb. 17, 2021, and U.S. Provisional Patent Application No. 63/301,759, filed on Jan. 21, 2022. The contents of both of these provisional patent applications are herein incorporated by reference.

BACKGROUND

Field

[0002] Embodiments of the present disclosure relate to optical device films and methods of forming optical device films.

Description of the Related Art

[0003] Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

[0004] Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated to appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

[0005] One such challenge is displaying a virtual image overlaid on an ambient environment. Optical devices including waveguide combiners, such as augmented reality waveguide combiners, and flat optical devices, such as metasurfaces, are used to assist in overlaying images. Generated light is propagated through an optical device until the light exits the optical device and is overlaid on the ambient environment. As light transmits through these devices, optical loss remains a problem.

[0006] Accordingly, what is needed in the art are optical device films, methods and equipment for forming optical device films, and optical devices formed from the optical device films that reduce the problems associated with optical loss.

SUMMARY

[0007] In one embodiment, an optical device is provided. The optical device includes an optical device substrate having a first surface; and a plurality of optical device structures disposed over the first surface of the optical device substrate, the plurality of optical device structures spaced apart from each other in a direction parallel to the first surface, and each optical device structure of the plurality of optical device structures including an optical device film. The optical device film of each optical device structure includes a first zone and a second zone, the first zone positioned between the optical device substrate and the second zone, wherein the first zone and the second zone each include one or more of oxygen and nitrogen, and the first zone and the second zone collectively include three or more metal, metalloid, or semiconductor elements.

[0008] In another embodiment, a method of forming an optical device film on an optical device substrate is provided. The method includes disposing an optical device substrate on a substrate support in a process chamber. The method further includes depositing an optical device film over the optical device substrate, wherein the optical device film comprises a first zone and a second zone, the first zone positioned between the optical device substrate and the second zone, wherein the first zone and the second zone each include one or more of oxygen and nitrogen, and the first zone and the second zone collectively include three or more metal, metalloid, or semiconductor elements.

[0009] In another embodiment, a method of forming an optical device film on an optical device substrate is provided. The method includes disposing an optical device substrate on a substrate support in a first process chamber. The method further includes depositing a first zone of the optical device film over the optical device substrate, wherein the first zone of the optical device film comprises: one or more of oxygen and nitrogen, and two or more metal, metalloid, or semiconductor elements; disposing an optical device substrate on a substrate support in a second process chamber. The method further includes depositing a second zone of the optical device film over the first zone of the optical device film, wherein the second zone of the optical device film comprises: one or more of oxygen and nitrogen, and two or more metal, metalloid, or semiconductor elements, wherein the two or more metal, metalloid, or semiconductor elements included in the second zone are different than the two or more metal, metalloid, or semiconductor elements included in the second zone.

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 exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

[0011] FIG. **1** is a schematic, cross-sectional view of an optical device film according to embodiments described herein.

[0012] FIG. **2**A and FIG. **2**B are schematic, cross-sectional views of optical devices formed from the optical device film of FIG. **1** according to embodiments described herein.

[0013] FIG. **3**A is a schematic, cross-sectional view of a physical vapor deposition (PVD) chamber according to embodiments described herein.

[0014] FIG. **3**B is a schematic top view of a cluster tool, according to one embodiment.

[0015] FIG. **4** is a schematic, cross-sectional view of a chemical vapor deposition (CVD) chamber according to embodiments described herein.

[0016] FIGS. **5** and **6** are flow diagrams of methods for forming an optical device film according to embodiments described herein.

[0017] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0018] Embodiments of the present disclosure relate to optical devices including optical device films and methods of forming the optical device films of the optical devices. Specifically, embodiments described herein provide for optical devices including optical device films that are formed of three or more materials, such as three or more elements from the Periodic Table of Elements. The three or more elements in the optical device film can include (1) at least two elements classified as a metal, a metalloid, or semiconductor element, and (2) at least one of oxygen and nitrogen. In some embodiments, another non-metallic element is used instead of oxygen or nitrogen, such as carbon.

[0019] A non-limiting list of different metal, metalloid, and semiconductor elements are provided below. Although many of the embodiments of optical device films described herein are described as including only three elements (e.g, Si, Ti, and O), the optical device films can include three or more (e.g., 5-10) different metal, metalloid, or semiconductor elements as well as both oxygen and nitrogen (e.g., an oxynitride material) at the same locations in an optical device film or at different locations in an optical device film. Including more elements (e.g., more than three) in an optical device film can assist in forming a film that has a varying refractive index across the thickness of the film in which the refractive index can (1) span a larger range than if only three elements were included in the optical device film, or (2) span a range of refractive indexes that results in less optical loss when compared to spanning the same range with only three elements.

[0020] In some embodiments, the optical device films include layers with different materials, such as different element that are not included in other layers. In other embodiments, the optical device film includes changing relative concentrations of the same materials, such as a film in which a relative concentration of titanium and silicon change throughout a thickness of an optical device film formed of titanium, silicon, and oxygen. Used herein, unless otherwise noted, relative concentration refers to a relative concentration of an element (e.g., Ti) at a particular location in the optical device film compared to one or more other elements at that particular location in the optical device film, where the relative concentration is determined without reference to a concentration of oxygen or nitrogen. For example, for a layer including titanium, silicon, and oxygen, a relative concentration of 25% silicon at a particular location means that the particular location has a relative concentration that is 25% silicon out of a total amount of silicon and titanium regardless of the concentration of oxygen. Thus, for a layer including three elements (e.g., Si, Ti, and O) where one of the elements is oxygen or nitrogen, then the relative concentrations of the two elements that are not oxygen or nitrogen can be expressed as X and 1−X. For example, a relative concentration of 25% silicon (i.e., X) at a particular location in a layer that includes silicon, titanium, and oxygen means that the relative concentration of titanium is 75% (i.e., 1−X) at that location.

[0021] FIG. **1** is a schematic, cross-sectional view of an optical device **100**, according to one embodiment. The optical device **100** includes an optical device film **110** disposed on an optical device substrate **101**.

[0022] The optical device substrate **101** includes a first surface **101**A (top surface). The optical device film **110** is formed over the first surface **101**A of the optical device substrate **101**. The optical device substrate **101** is any suitable optical device substrate on which an optical device may be formed. In one embodiment, the optical device substrate **101** is a silicon (Si) containing optical device substrate. In one embodiment, the optical device substrate **101** is a glass substrate, such as a silicon oxide-based glass, a metal oxide-based glass, or a high refractive index glass substrate (e.g, a glass substrate with a refractive index greater than 2.0). In some embodiments, the optical device substrate **101** includes, but is not limited to, silicon (Si), silicon nitride (SiN), silicon dioxide (SiO_2), fused silica, quartz, silicon carbide (SiC), germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium oxide (GaO), lanthanum oxide (LaO), magnesium oxide (MgO), diamond, lithium niobate ($LiNbO_3$), gallium nitride (GaN), sapphire, tantalum oxide (Ta_2O_5), titanium dioxide (TiO_2), or combinations thereof. In some embodiments, the optical device substrate **101** may include a perovskite material that is optically transparent. In another embodiment, the optical device substrate **101** is a layered optical device substrate, for example a thin glass bonded to a silicon carrier. The layered optical device substrate may be a substrate with optical device stacks disposed on the substrate (e.g., patterned optical device films for gratings, waveguides, optoelectronics, monolithically-integrated CMOS-photonic device, heterogeneously-integrated CMOS-photonic devices). In yet another embodiment, the optical device substrate **101** is a laminated substrate comprising multiple layers of bonded glass. More generally, the optical device substrate **101** can be formed from any suitable material, provided that the substrate can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the plurality of optical device films.

[0023] The optical device film **110** is an oxide and/or nitride optical device film that further includes two or more, such as three or more, metal, metalloid, or semiconductor elements. Generally any element classified as a metal, metalloid, or semiconductor element that can be used to form an optical device film can be used to obtain the benefits of this disclosure. That said, some specific non-limiting examples of metal, metalloid, or semiconductor elements that can benefit from this disclosure include titanium (Ti), silicon (Si), niobium (Nb), tantalum (Ta), aluminum (Al), indium (In), chromium (Cr), ruthenium (Ru), hafnium (Hf), magnesium (Mg), zirconium (Zr), vanadium (V), molybdenum (Mo), tungsten (W), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), tin (Sn), bismuth (Bi), antimony (Sb), gadolinium (Gd), praseodymium (Pr), scandium (Sc), and yttrium (Y).

[0024] The optical device film **110** has a first surface **111** and a second surface **112**. The first surface **111** can be formed over (e.g., directly on) the optical device substrate **101**. The first surface **111** may also be referred to as a bottom

surface. The second surface **112** is an opposing surface to the first surface **111**. The second surface **112** may also be referred to as a top surface. The second surface **112** is spaced apart from the first surface **111** by a thickness **116**.

[0025] The thickness **116** of the optical device film **110** is divided into a range of zones **115**. Each individual zone **115**n is identified by a subscript, where the subscript is an integer identifying the location of the zone **115** relative to the first surface **111** (bottom surface) that is formed over the optical device substrate **101**. For example, the optical device film **110** includes eight zones $\mathbf{115}_{1\text{-}8}$ with the first zone being $\mathbf{115}_1$ and the eight zone being $\mathbf{115}_8$. The first zone $\mathbf{115}_1$ is disposed between the second zone $\mathbf{115}_2$ and the optical device substrate **101**.

[0026] In some embodiments, the first zone $\mathbf{115}_1$ can be formed to have a refractive index that is equal to or substantially close to (e.g., within 0.02) the refractive index of the optical device substrate **101**. For example, in one embodiment, a layer of TiSiO can be formed to have a refractive index of 2.0 to be matched with a glass optical device substrate having a refractive index of 2.0. Having the refractive index of the first zone $\mathbf{115}_1$ formed on top of the substrate **101** be the same or substantially the same as the refractive index of the substrate **101** can help reduce light scattering and optical loss that can occur as a result of light passing through the two materials (i.e., the substrate **101** and the first zone $\mathbf{115}_1$).

[0027] Although eight zones **115** are shown, embodiments can include more or less zones **115**. Each zone **115** includes (1) at least one of oxygen and nitrogen, and (2) at least one metal, metalloid, or semiconductor element. That said individual zones **115** can include oxygen and nitrogen and/or two or more metal, metalloid, or semiconductor elements, such as four metal, metalloid, or semiconductor elements at a same location across the thickness **116** of the optical device film **110**.

[0028] In different optical device films **110**, the zones **115** can represent different things. For example, in some embodiments, the different zones **115** can represent different layers that include different materials (e.g., different elements). In other embodiments, the zones **115** represent different relative concentrations of the same materials, such as different relative concentrations of silicon and titanium in a layer that includes silicon, titanium, and oxygen. Generally, each pair of zones **115** that share a border generally have a different refractive index although this is not required. In some embodiments, zones **115** that are spaced apart from each other can have a same refractive index.

[0029] In one embodiment, which can be combined with other embodiments described herein, the thickness **116** can have a constant or substantially constant oxygen or nitrogen concentration throughout the range of zones **115** of the optical device film **110**. In one embodiment, the difference in oxygen or nitrogen concentration between each zone **115** of range of zones **105** is an atomic percentage of 10% (e.g., plus or minus 5%). In one embodiment, the oxygen concentration of an optical device film **110** of a first material of TiO_2 and a second material of SiO_2 is about 66.67 atomic percent at plus or minus 10%.

[0030] In FIG. **1**, each zone **115** is shown having a same thickness, but this is not required as one or more of the zones **115** may have a different thickness than the other zones **115**. In some embodiments, each individual zone $\mathbf{115}_n$ has a zone thickness of about 0.001% to about 99.999% of the total thickness **116**, such as from about 1% to about 50% of the total thickness **116**. In one embodiment, one or more of the zones **115**n in the optical device film **110** can be formed of a different material, such as including a different element that is not included in one or more of the other zones $\mathbf{115}_n$. For example, in one embodiment, the first zone $\mathbf{115}_1$ can be formed titanium, silicon, and oxygen while the eighth zone $\mathbf{115}_8$ can be formed of titanium, niobium, and nitrogen. In another embodiment, each zone **115** can include a substantially different relative concentration of two or more elements (e.g., titanium and silicon). For example, in one embodiment, the first zone $\mathbf{115}_1$ can be formed of titanium, silicon, and oxygen while the second zone $\mathbf{115}_2$ can also be formed of titanium, silicon, and oxygen with (1) the relative concentration of titanium being higher in the first zone $\mathbf{115}_1$ than the second zone $\mathbf{115}_2$ and (2) the relative concentration of silicon being higher in the second zone $\mathbf{115}_2$ than the first zone $\mathbf{115}_1$. In another embodiment, the relative concentrations of two or more of the elements gradually change across individual zones $\mathbf{115}_n$, so that there is not a significant step change in the relative concentrations of the elements at the border between two individual zones $\mathbf{115}_n$.

[0031] Forming the zones **115** to have different relative concentrations of different elements (e.g., Ti and Si) across the thickness **116** of the optical device film **110** allows for the modification of the optical properties (e.g., refractive index), of the optical device film **110**.

[0032] In some embodiments, the relative concentration of a first element (e.g., Ti) can have a first concentration profile through the range of zones **115** of the thickness **116**, and a second element (e.g., Si) can have a second concentration profile through the range of zones **115** of the thickness **116**. In one of these embodiments, the first element can have a maximum relative concentration at the first zone $\mathbf{115}_1$ and a minimum relative concentration at the top eight zone $\mathbf{115}_8$. Although not required, in some embodiments, the minimum relative concentration can be 0% and the maximum relative concentration can be 100%. Conversely, the second element can have a minimum relative concentration at the first zone $\mathbf{115}_1$ and a maximum relative concentration at the top eight zone $\mathbf{115}_8$. In some embodiments that include oxygen, the oxygen concentration can be about **66.67** atomic percent plus or minus 10% (e.g., of a first material of TiO_2 and a second material of SiO_2). Across the zones **115**, the concentrations of the silicon and titanium can vary from a minimum concentration of about 0 atomic percent and a maximum concentration of about 33.3 atomic percent.

[0033] In another embodiment, the first element (e.g., Ti) has a minimum relative concentration at the first zone $\mathbf{115}_1$ and a maximum concentration at the eighth zone $\mathbf{115}_8$. Conversely, the second element (e.g., Si) has a maximum concentration at the first zone $\mathbf{115}_1$ and a minimum concentration at the eighth zone $\mathbf{115}_8$. In this embodiment, the relative concentrations of the first element and/or the second element can increase or decrease for each successive individual zone $\mathbf{115}_n$ of the zones **115** as the relative concentration of the elements goes from minimum to maximum (i.e., first element) or maximum to minimum (i.e., second element). This increase or decrease in the relative concentrations can include gradual changes within the individual zones $\mathbf{115}_n$ or only include step-changes in relative concentrations between the different zones **115**. For embodiments including gradual changes in the relative concentrations, the gradual changes can span the entire thickness **116** of the

optical device film **110**, so that there is a continuous gradual change in the refractive index across the thickness **116** of the optical device film **110**.

[0034] In some embodiments, the relative concentrations of the first element (e.g., Ti) and the second element (e.g., Si) can follow sinusoidal profiles across the range of zones **115**. In one of these embodiments, the first element can have a relative concentration that (1) has a maximum at the first zone $\mathbf{115}_1$, (2) decreases to a minimum concentration at a midpoint of the range of zones **115**, and (3) increases back to the maximum concentration at the final zone $\mathbf{115}_8$. Conversely, the second element can have a relative concentration that (1) has a minimum concentration at the first zone $\mathbf{115}_1$, (2) increases to a maximum concentration at a midpoint of the range of zones **115** and (3) decreases back to the minimum concentration at the final zone $\mathbf{115}_8$. These sinusoidal profiles can follow a gradual change in the relative concentrations within the individual zones $\mathbf{115}_n$ or the sinusoidal profiles can include a step change between each pair of neighboring zones **115** with the relative concentrations staying constant within the individual zones $\mathbf{115}_n$.

[0035] The following provides some additional non-limiting examples of some different embodiments of optical device films **110**. In one embodiment, the optical device film **110** is formed of a single ternary material (e.g., $TixSi_{1-x}O$), where the relative concentration of titanium and silicon change for each zone **115** in a bordering pair of zones **115** in the optical device film **110**. In the formula $Ti_xSi_{1-x}O$, x can range from zero to one, x is the relative concentration of titanium and 1−x is the relative concentration of silicon such that x and 1−x always add up to one. In some of these embodiments, the relative concentrations are constant throughout the thickness of the individual zones **115**, but vary between the zones **115**, so that the refractive index varies between the zones **115**. In some embodiments, two zones that are spaced apart from each other can have the same relative concentrations and the same refractive index, such as the second zone $\mathbf{115}_2$ and the sixth zone $\mathbf{115}_6$.

[0036] In other of these embodiments, the relative concentrations vary gradually across the zones **1115**, so that the refractive index varies gradually across the zones **115**. Gradual adjustments of the refractive index across the different zones **115** can help to reduce light scattering and optical loss. In some of these embodiments, the relative concentrations of titanium and oxygen can be the same or substantially the same at the border between the zones **115**. For example, the top of the first zone **1151** can have the same or substantially the same relative concentrations of titanium and silicon as the bottom the second zone **115**, so that there is little to no change in the refractive index at the border between the bordering zones **115**.

[0037] Some embodiments of the optical device film can include three or more different metal, metalloid, or semiconductor elements in a single zone **115** or collectively across multiple zones **115**. For example, in one embodiment, the three or more metals, metalloids, and semiconductor elements collectively include silicon and titanium in the first zone $\mathbf{115}_1$ and niobium in another zone, such as the second zone $\mathbf{115}_2$.

[0038] In another embodiment, the first zone $\mathbf{115}_1$ includes two or more metal, metalloid, or semiconductor elements (e.g., Ti and Si), and another zone **115** (e.g., the eighth zone $\mathbf{115}_8$ includes two or more metal, metalloid, or semiconductor elements (e.g., Nb and Ta) that are different than the two or more metal, metalloid, or semiconductor elements in first zone $\mathbf{115}_1$. In a variation of this embodiment, another zone **115** that is between the two other zones **115**, such as the fifth zone $\mathbf{115}_5$, can include a fifth metal, metalloid, or semiconductor element that is not included in the other zones **115**, such as chromium.

[0039] In another embodiment, the first zone $\mathbf{115}_1$ includes two or more metal, metalloid, or semiconductor elements (e.g., Ti and Si), and another zone **115** (e.g., the eighth zone $\mathbf{115}_8$ includes two or more metal, metalloid, or semiconductor elements (e.g., Ti and Nb), so that one metal, metalloid, or semiconductor element included in the first zone $\mathbf{115}_1$ is a same element as one metal, metalloid, or semiconductor element included in the eighth zone $\mathbf{115}_8$, and one metal, metalloid, or semiconductor element included in the first zone $\mathbf{115}_1$ is different than one metal, metalloid, or semiconductor element included in the eighth zone $\mathbf{115}_8$. In a variation of this embodiment, another zone **115** that is between the two other zones **115**, such as the fifth zone $\mathbf{115}_5$, can include a fourth metal, metalloid, or semiconductor element that is not included in the other zones **115**, such as chromium.

[0040] In another embodiment, the first zone $\mathbf{115}_1$ includes titanium, silicon, and oxygen, the third zone $\mathbf{115}_3$ includes titanium, niobium, and oxygen, and the second zone $\mathbf{115}_2$ includes only silicon and oxygen (i.e., a binary material layer). Other embodiments can include (1) at least two zones **115** formed of ternary materials (e.g., TiSiO) that include two metal, metalloid, or semiconductor elements along with oxygen or nitrogen, and (2) at least two at least two zones **115** formed of binary materials (e.g., TiO or SiO) that include only one metal, metalloid, or semiconductor element along with oxygen or nitrogen. Another embodiment can include (1) one zone **115** formed of a binary material that includes only one metal, metalloid, or semiconductor element along with oxygen or nitrogen, and (2) at least two zones **115** formed of ternary materials that include two metal, metalloid, or semiconductor elements along with oxygen or nitrogen. Another embodiment can include at least three different zones **115** that each include formed of ternary materials that include two or more metal, metalloid, or semiconductor elements along with oxygen or nitrogen, where the two or more metal, metalloid, or semiconductor elements are different for each of the three zones (e.g., three zones **115** that include six different metal elements with each zone **115** including two of the six metal elements).

[0041] In one embodiment, the zones **115** can be an alternating stack of binary materials (e.g., TiO and SiO). In one of these embodiments, each individual zone $\mathbf{115}_n$ has a thickness (i.e., a thickness in the same direction as thickness **116**) of less than 1 nm. In some of these embodiments, the process conditions (e.g., RF power, DC bias, DC power to one or more of the cathodes, temperature, pressure and gas flows), can be varied to make small adjustments to the refractive index of the different zones being deposited.

[0042] In some embodiments, one or more of the zones **115** can be formed of an oxynitride material that includes one or more metal, metalloid, or semiconductor elements, such as SiON.

[0043] FIG. **2**A and FIG. **2**B are schematic, cross-sectional views of two different optical devices **200***a*,**200***b* that can be formed from the optical device film **110** in the optical device **100** shown in FIG. **1**. The optical devices **200***a*, **200***b* include respective optical device structures **202***a*, **202***b* disposed

over the first surface **101**A of the optical device substrate **101**. The plurality of optical device structures **202***a*, **202***b* spaced apart from each other in a direction parallel to the first surface **101**A of the optical device substrate **101**.

[0044] The optical device structures **202***a*, **202***b* include sub-micron critical dimensions, e.g., nanosized dimensions, corresponding to the widths **203** of the optical device structures **202***a*, **202***b*. The optical devices **200***a*, **200***b* shown in FIGS. **2**A, **2**B can form part of a waveguide combiner, a flat optical device (e.g., a metasurface), or another optical device.

[0045] In the optical device **200***a* shown in FIG. **2**A, the optical device structures **202***a* may be binary structures with a top surface **224** of the optical device structures **202***a* parallel to a top surface **102** of the optical device substrate **101**. Furthermore, in some embodiments the sidewalls of the different optical device structures **220***a* can be parallel to each other. For example, FIG. **2**A shows a first sidewall **225** and a second sidewall **226** of a third optical device structure **220***a***3** parallel to a third sidewall **227** and a fourth sidewall **228** of a fourth optical device structure **202***a***4**. Additionally, the sidewalls **225**, **226**, **227**, and **228** can be oriented normal to the top surface **102** of the optical device substrate **101**.

[0046] In the optical device **200***b* shown in FIG. **2**B, the optical device structures **202***b* may be angled structures. The angled structures **202***b* can include sidewalls that are slanted relative to the top surface **102** of the optical device substrate **101**. For example, FIG. **2**B shows sidewalls **225**, **226** of a third optical device structure **202***b***3** and sidewalls **227**, **228** of a fourth optical device structure **202***b***4** slanted relative to the top surface **102** of the optical device substrate **101**.

[0047] FIG. **3**A is a schematic, cross-sectional view of a physical vapor deposition (PVD) chamber **300**. The PVD chamber **300** may be used to perform the PVD methods described below, such as the methods described in reference to FIGS. **5** and **6**. It is to be understood that the PVD chamber **300** described below is an exemplary PVD chamber and other PVD chambers may be used with or modified to accomplish aspects of the present disclosure.

[0048] The PVD chamber **300** includes a chamber body **310** that encloses a process volume **305**. The PVD chamber **300** further includes a substrate support **332** disposed in the process volume **305**. The substrate support **332** includes a support surface **334** that can be used to support a substrate during a process, such as the optical device substrate **101** from FIG. **1**.

[0049] The PVD chamber **300** further includes a plurality of cathodes including a first cathode **302** and a second cathode **303**. The PVD chamber **300** additionally includes a plurality of targets including a first target **304** and a second target **306**. Each cathode **302**, **303** can be attached (e.g., mounted) to the chamber body **310**. The first target **304** and the second target **306** can each be attached to the corresponding first cathode **302** and second cathode **303** through a chamber body adapter **308**. The chamber body adapter **308** can be used to mechanically and electrically connect the targets **304**, **306** to the corresponding cathodes **302**, **303**. The first target **304** includes a first material, such as a first element (e.g., silicon). The second target **306** includes a second material, such as a second element (e.g., titanium). Each cathode **302**, **303** can be coupled to a DC power source **312** or to an RF power source **314** and matching network **315**, so that DC power or RF power can be coupled to the targets **304**, **306** during processing.

[0050] Although only two cathode and targets are shown, in some embodiments, the PVD chamber can include three or more (e.g., 5-10) targets and corresponding cathodes, with each target formed of a different material, such as a different element. These additional targets can allow a larger variety of layers to be deposited on a single optical device film as well as on different optical device films. Often, two or more of the targets can be co-sputtered during a deposition, so that multiple elements are deposited at the same location within the optical device film **110**. For example, a silicon target and a titanium target can be co-sputtered while oxygen is provided to the process volume **305** to deposit an optical device film **110** of a ternary material that includes titanium, silicon, and oxygen.

[0051] The PVD chamber **300** further includes an opening **350** (e.g., a slit valve) through which an end effector (not shown) can extend to place an optical device substrate **101** onto lift pins (not shown) for lowering the optical device substrate **101** onto the support surface **334** of the substrate support **332**.

[0052] The PVD chamber **300** includes a sputter gas source **361** operable to supply a sputter gas, such as argon (Ar) to the process volume **305**. A gas flow controller **362** is disposed between the sputter gas source **361** and the process volume **305** to control a flow of the sputter gas from the sputter gas source **361** to the process volume **305**. The PVD chamber **300** further includes a reactive gas source **363** operable to supply a reactive gas, such as an oxygen-containing gas or nitrogen-containing gas to the process volume **305**. A gas flow controller **364** is disposed between the reactive gas source **363** and the process volume **305** to control a flow of the reactive gas from the reactive gas source **363** to the process volume **305**. The PVD chamber **300** may further include a precursor gas source **370** operable to supply a precursor gas to the process volume **305**. A gas flow controller **371** is disposed between the precursor gas source **370** and the process volume **305** to control a flow of the precursor gas from the precursor gas source **370** to the process volume **305**.

[0053] The substrate support **332** includes a bias electrode **340**. An RF bias power source **338** coupled to the bias electrode **340** disposed in the substrate support **332** via a matching network **342**. The substrate support **332** can include a mechanism (not shown) that retains the optical device substrate **101** on the support surface **334** of the substrate support **332**, such as an electrostatic chuck, a vacuum chuck, a substrate retaining clamp, or the like. The substrate support **332** can further include a cooling conduit **365** disposed in the substrate support **332**. The cooling conduit **365** can be used to controllably cool the substrate support **332** and the optical device substrate **101** positioned thereon to a predetermined temperature. The cooling conduit **365** is coupled to a cooling fluid source **368** to provide cooling fluid (not shown). The substrate support **332** can further include a heater **367** embedded therein. The heater **367** (e.g., a resistive element), disposed in the substrate support **332** can be coupled to a heater power source **366**. The heater **367** can be used to controllably heat the substrate support **332** and the optical device substrate **101** positioned thereon to a predetermined temperature.

[0054] While FIG. **3**A depicts a first cathode **302** coupled to a first target **304** and a second cathode **303** coupled to a second target **306**, the PVD chamber **300** may include additional cathodes and targets. In embodiments including

additional targets, each target can be formed of a different material (e.g., a different element) enabling a variety of materials to be formed in the different zones **115** (see FIG. **1**) of the optical device film **110**.

[0055] FIG. **3**B is a schematic top view of a cluster tool **390**, according to one embodiment of the disclosure. The cluster tool **390** includes five physical vapor deposition (PVD) chambers **300**A-E. Each PVD chamber **300**A-E can be the same as the PVD chamber **300** described above in reference FIG. **3**A. The cluster tool **390** further includes two transfer chambers **380**A, **380**B for transferring optical device substrates **101** into and out of the cluster tool **390**. The cluster tool **390** further includes a transfer robot **395** for moving the optical device substrates **101** between the different PVD chambers **300**A-E and into and out of the transfer chambers **380**A, **380**B.

[0056] In some embodiments, one or more of the PVD chambers **300**A-E in the cluster tool **390** include one or more different target materials, so that different materials can be deposited in the different PVD chambers **300**. For example, in one embodiment, the first PVD chamber **300**A can include a silicon material for the first target **304** and a titanium material for the second target **306** while the fifth PVD chamber **300**E can include a tantalum material for the first target **304** and a niobium material for the second target **306**. Thus, using this example, the first PVD chamber **300**A can be used to deposit a first zone **1151** including titanium and silicon along with oxygen and/or nitrogen, while the fifth PVD chamber **300**E can be used to deposit another zone (e.g., the eighth zone **1158**) including tantalum and niobium along with oxygen and/or nitrogen.

[0057] FIG. **4** is a schematic, cross-sectional view of a chemical vapor deposition (CVD) chamber **400** that may be used to perform the method **700** described below in reference to FIG. **7**. It is to be understood that the CVD chamber **400** described herein is an exemplary CVD chamber and other CVD chambers may be used with or modified to accomplish aspects of the present disclosure.

[0058] The CVD chamber **400** includes a chamber body **402** that encloses a processing volume **404**. The CVD chamber **400** further includes a substrate support **406** disposed in the process volume **404**. The substrate support **406** includes a support surface **407** that can be used to support a substrate during a process, such as the optical device substrate **101** from FIG. **1**.

[0059] The substrate support **406** further includes a heating/cooling conduit **410** and a mechanism (not shown) that can retain the optical device substrate **101** on the support surface **407** of the substrate support **406**, such as an electrostatic chuck, a vacuum chuck, a substrate retaining clamp, or the like. The substrate support **406** is coupled to and movably disposed in the processing volume **404** by a stem **408** connected to a lift system (not shown) that moves the substrate support **406** between an elevated processing position and a lowered position that facilitates transfer of the optical device substrate **101** to and from the CVD chamber **400** through an opening **412**.

[0060] The CVD chamber **400** further includes a showerhead **414**, a first gas source **416**A, a second gas source **4166**, a first flow controller **418**A, and a second flow controller **418**B. The first flow controller **418**A is disposed between the first gas source **416**A and the chamber body **402** to control a first flow rate of a first process gas from the first gas source **416**A to the showerhead **414**. The second flow controller **418**B is disposed between the second gas source **416**B and the chamber body **402** to control a second flow rate of a second process gas from the second gas source **416**B to the showerhead **414**. The showerhead **414** is connected to an RF power source **422** by an RF feed **424** for generating a plasma in the processing volume **404** from the first process gas and/or the second process gas. The RF power source **422** provides RF energy to the showerhead **414** to facilitate generation of a plasma between the showerhead **414** and the substrate support **406**. A vacuum pump **420** is coupled to the chamber body **402** for controlling the pressure within the processing volume **404**. A controller **428** is coupled to the CVD chamber **400** and configured to control aspects of the CVD chamber **400** during processing.

[0061] While FIG. **4** depicts a first gas source **416**A and a second gas source **416**B, the CVD chamber **400** may include one or more additional gas sources, for example to provide other process gases the processing volume **404** during a deposition. For example, **3**-**5** gas sources may be included in the CVD chamber **400**. In embodiments with three or more gas sources, each gas source can be used to deposit a different material (e.g., element, such as silicon, oxygen, etc.).

[0062] FIG. **5** is a flow diagram of a method **500** of forming the optical device film **110** shown in FIG. **1**, according to one embodiment. The optical device film **110** may be modified in subsequent processes to form the devices **200***a* (FIG. **2**A), **200***b* (FIG. **2**B). The method **500** can be performed using the PVD chamber **300** of FIG. **3**A. However, it is to be noted that a PVD chamber other than the PVD chamber **300** of FIG. **3**A may be used to perform the method **500**.

[0063] The method **500** begins at operation **501**. The method **500** is described as being performed using the PVD chamber **300** from FIG. **3**A, but the method **500** can also be performed using the PVD chambers **300**A-**300**E in the cluster tool **390** shown in FIG. **3**B as well as with other PVD chambers (not shown). At operation **501**, the optical device substrate **101** is disposed on the substrate support **332** in the PVD chamber **300**.

[0064] At operation **502**, the first zone $\mathbf{115}_1$ of the range of zones **115** of the optical device film **110** is deposited. The first target **304** having a first element (e.g., silicon) is set to a first power level, and the second target **306** having a second element (e.g., titanium) is set to a second power level. A sputter gas (e.g., argon) can be provided to the process volume **305** from sputter gas source **361** to sputter the targets **304**, **306**. Having the refractive index of the first zone $\mathbf{115}_1$ be equal to or substantially close to the refractive index of the optical device substrate **101** can help limit optical loss that can occur as light passes across the boundary between the optical device substrate **101** and the first zone $\mathbf{115}_1$.

[0065] In one embodiment, the first material of the first target **304** and/or the second material of the second target **306** can include an oxygen-containing material or a nitrogen-containing material. In another embodiment, an oxygen-containing gas or a nitrogen-containing gas is supplied to the process volume **305**, for example from reactive gas source **363**. In the embodiment, the first element from the first target **304** and the second element from the second target **306** react with the oxygen-containing gas or nitrogen-containing gas to form the first zone $\mathbf{115}_1$ of the optical device film **110**.

[0066] In one embodiment, a relative concentration of the first element (e.g., Si) from the first target **304** has a maximum concentration in the first zone $\mathbf{115}_1$ of the range of zones **115** by applying a high power level to the first target **304**. In the embodiment, a relative concentration of the second element (e.g., Ti) from the second target has a minimum concentration at the first zone $\mathbf{115}_1$ not applying power to the second target **306** or by applying power at a low power level to the second target **306**. In another embodiment, the power levels applied to the targets **304**, **306** can be adjusted so that the relative concentration of the first element is at a minimum in the first zone $\mathbf{115}_1$, and the relative concentration of the second element is at a maximum in the first zone $\mathbf{115}_1$.

[0067] In yet another embodiment, the relative concentration of the first element and the second element deposited in the first zone $\mathbf{115}_1$ may be controlled by at least one of setting the power level provided to the first target **304** and setting the power level provided to the second target **306** at different power levels between the power levels described above, so that one or both of the relative concentrations of the first element and the second element are not at a minimum or maximum relative concentration in the first zone $\mathbf{115}_1$.

[0068] At operation **503**, subsequent zones **115** of the optical device film **110** are deposited until the final zone $\mathbf{115}_8$ of the range of zones **115** is deposited. In embodiments in which the cluster tool **390** of FIG. **3**B is used to form the optical device film **110**, one or more of the subsequent zones **115** deposited during operation **503** can be performed in a different PVD chamber **300**A-**300**E than the PVD chamber **300**A-E used to deposit the first zone $\mathbf{115}_1$. When the cluster tool **390** includes one or more different target materials in the different PVD chambers **300**A-**300**E, then different zones **115** including one or more different metal, metalloid, or semiconductor elements can be deposited in the different PVD chambers **300**A-**300**E.

[0069] The deposition of the subsequent zones includes at least one of varying the power level provided to the first target **304** or varying the power level provided to the second target **306** as the different zones are deposited to form the optical device film **110**. Varying these power levels can cause different relative concentrations of the elements from the targets **304**, **306** to be deposited in the different zones **115** or across different locations in the same zone **115**. To deposit a binary material, such as silicon oxide, the power level provided to the target including the other metal, metalloid, or semiconductor (e.g., a target including titanium) can be set to zero while power is provided to the target including the metal, metalloid, or semiconductor that is to be included in the binary material.

[0070] The optical device film **110** also includes a concentration of oxygen and/or nitrogen. In some embodiments, the optical device film **110** includes an oxygen concentration and/or nitrogen concentration that varies across the thickness **116** of the optical device film **110**. In another embodiment, which can be combined with other embodiments described herein, the optical device film **110** can have a constant or substantially constant oxygen or nitrogen concentration throughout the range of zones **115** of the optical device film **110**.

[0071] In some embodiments, a precursor gas can also be supplied to the process volume **305** from the precursor gas source **370** during one or more of operations **502**, **503** of the method **500**. In some embodiments, a precursor gas (e.g., a silicon-containing gas) is provided to the process volume instead of sputtering one of the two targets **304**, **306**. In another embodiment, a precursor gas is provided to the process volume **305** while both targets **304**, **306** are sputtered. In some of these embodiments, the precursor gas can include a different metal, metalloid, or semiconductor element than the two targets **304**, **306** being sputtered, so that three metal, metalloid, or semiconductor elements can be deposited in the optical device film **110** in addition to oxygen or nitrogen. The flow rate of precursor gas from the precursor gas source **370** can be adjusted during operation to control the relative concentration of the element from the precursor gas that is deposited in the different zones **115** of the optical device film **110**.

[0072] FIG. **6** is a flow diagram of a method **600** of forming the optical device film **110** shown in FIG. **1**, according to one embodiment. The optical device film **110** may be modified in subsequent processes to form the devices **200***a* (FIG. **2**A), **200***b* (FIG. **2**B). The method **600** can be performed using the CVD chamber **400** of FIG. **4**. However, it is to be noted that a CVD chamber other than the CVD chamber **400** of FIG. **4** may be used to perform the method **600**.

[0073] The method **600** begins at operation **601**. At operation **601**, the optical device substrate **101** is disposed on the substrate support **406** in the CVD chamber **400**.

[0074] At operation **602**, the first zone $\mathbf{115}_1$ of the range of zones **115** of the optical device film **110** is deposited. During operation **602**, a first gas can be provided to the process volume **404** from the first gas source **416**A, and a second gas can be provided to the process volume **404** from the second gas source **416**B. The first gas can have a first gas flow rate that is controlled by the first flow controller **418**A. The second gas can have a second gas flow rate that is controlled by the second flow controller **418**B. The first gas source **416**A can provide a first gas containing a metal, metalloid, or semiconductor element that is to be deposited in the optical device film **110**. The second gas source **416**B can provide a second gas containing a metal, metalloid, or semiconductor element that is to be deposited in the optical device film **110**. In some embodiments, another gas source and flow controller (not shown) can be used to provide an oxygen-containing gas or a nitrogen-containing gas to the process volume **404**.

[0075] During operation **602**, the relative concentrations of a first element (e.g., silicon) and a second element (e.g., titanium) deposited into the first zone $\mathbf{115}_1$ can be controlled by controlling the flow rate of gases containing these elements from the respective gas sources **416**A, **416**B.

[0076] At operation **603**, subsequent zones of the optical device film **110** are deposited until the final zone $\mathbf{115}_8$ of the range of zones **115** is deposited. The deposition of the subsequent zones **115** can include at least one of increasing or decreasing a first flow rate of the first gas from the first gas source **416**A and increasing or decreasing a second flow rate of the second gas from the second gas source **4166** to form the optical device film **110**. In one embodiment, which can be combined with other embodiments described herein, the thickness **116** has a constant or substantially constant oxygen or nitrogen concentration throughout the range of zones **115** of the optical device film **110**.

[0077] In some embodiments, RF power is provided to the showerhead **414** to perform a plasma enhanced chemical vapor deposition during operations **602**, **603**.

[0078] In summation, optical devices that include optical device films and methods of forming optical device films for optical devices are provided. The disclosed optical device films can include two or more, such as three or more metal, metalloid, or semiconductor elements at a same or across different locations within the optical device film, which enables the refractive index to be more tightly controlled compared to when a lower number of elements are included in an optical device film. Using a higher number of elements in the films can allow for more gradual changes in the refractive index of the optical device film across the thickness of the optical device film as well as provide for more options for limiting optical loss that can occur in an optical device film. For example, two different materials, such as two different ternary materials (i.e., ternary materials that include at least one different element) can have a same or substantially similar refractive index, but the one material may cause lower optical loss for a given application when compared to the other ternary material having the same or substantially refractive index.

[0079] While the foregoing is directed to examples of the present disclosure, other and further examples of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. An optical device comprising:

an optical device substrate having a first surface; and

a plurality of optical device structures disposed over the first surface of the optical device substrate, the plurality of optical device structures spaced apart from each other in a direction parallel to the first surface, and each optical device structure of the plurality of optical device structures including an optical device film, wherein the optical device film of each optical device structure comprises:

a first zone and a second zone, the first zone positioned between the optical device substrate and the second zone, wherein

the first zone and the second zone each include one or more of oxygen and nitrogen, and

the first zone and the second zone collectively include three or more metal, metalloid, or semiconductor elements.

2. The optical device film of claim **1**, wherein

the first zone includes two metal, metalloid, or semiconductor elements, and

the second zone includes one metal, metalloid, or semiconductor element that is different than the two metal, metalloid, or semiconductor elements in first zone.

3. The optical device film of claim **1**, wherein

the first zone includes two or more metal, metalloid, or semiconductor elements, and

the second zone includes two or more metal, metalloid, or semiconductor elements that are different than the two or more metal, metalloid, or semiconductor elements in first zone.

4. The optical device film of claim **3**, further comprising a third zone positioned between the first zone and the second zone, wherein the third zone includes a metal, metalloid, or semiconductor element that is different than the two or more metal, metalloid, or semiconductor elements in first zone and the second zone.

5. The optical device film of claim **1**, wherein

the first zone includes two or more metal, metalloid, or semiconductor elements,

the second zone includes two or more metal, metalloid, or semiconductor elements,

one metal, metalloid, or semiconductor element included in the first zone is a same element as one metal, metalloid, or semiconductor element included in the second zone, and

one metal, metalloid, or semiconductor element included in the first zone is different than one metal, metalloid, or semiconductor element included in the second zone.

6. The optical device of claim **5**, further comprising a third zone positioned between the first zone and the second zone, wherein the third zone includes a metal, metalloid, or semiconductor element that is different than the two or more metal, metalloid, or semiconductor elements in first zone and the second zone.

7. The optical device of claim **5**, further comprising a third zone positioned between the first zone and the second zone, wherein

the first zone comprises titanium, silicon, and oxygen,

the second zone comprises titanium, niobium, and oxygen, and

the third zone comprises silicon and oxygen.

8. The optical device film of claim **1**, wherein

the first zone includes two or more metal, metalloid, or semiconductor elements,

the second zone includes the same two or more metal, metalloid, or semiconductor elements.

9. The optical device of claim **8**, further comprising a third zone positioned between the first zone and the second zone, wherein the third zone includes a metal, metalloid, or semiconductor element that is different than the two or more metal, metalloid, or semiconductor elements in first zone and the second zone.

10. The optical device of claim **1**, wherein at least one of the first zone and the second zone include oxygen and nitrogen.

11. The optical device of claim **1**, wherein the three or more metal, metalloid, and semiconductor elements include three or more of Ti, Si, Nb, Ta, Al, In, Cr, Ru, Hf, Mg, Zr, V, Mo, W, Mn, Fe, Co, Ni, Cu, Zn, Ga, Sn, Bi, Sb, Gd, Pr, Sc, and Y.

12. A method of forming an optical device film on an optical device substrate, the method comprising:

disposing an optical device substrate on a substrate support in a process chamber; and

depositing an optical device film over the optical device substrate, wherein the optical device film comprises:

a first zone and a second zone, the first zone positioned between the optical device substrate and the second zone, wherein

the first zone and the second zone each include one or more of oxygen and nitrogen, and

the first zone and the second zone collectively include three or more metal, metalloid, or semiconductor elements.

13. The method of claim **12**, wherein

the first zone includes two metal, metalloid, or semiconductor elements, and

the second zone includes one metal, metalloid, or semiconductor element that is different than the two metal, metalloid, or semiconductor elements in first zone.

14. The method of claim **12**, wherein

the first zone includes two or more metal, metalloid, or semiconductor elements, and

the second zone includes two or more metal, metalloid, or semiconductor elements that are different than the two or more metal, metalloid, or semiconductor elements in first zone.

15. The method of claim **14**, wherein the optical device film further comprises a third zone positioned between the first zone and the second zone, wherein the third zone includes a metal, metalloid, or semiconductor element that is different than the two or more metal, metalloid, or semiconductor elements in first zone and the second zone.

16. The method of claim **12**, wherein

the first zone includes two or more metal, metalloid, or semiconductor elements,

the second zone includes two or more metal, metalloid, or semiconductor elements,

one metal, metalloid, or semiconductor element included in the first zone is a same element as one metal, metalloid, or semiconductor element included in the second zone, and

one metal, metalloid, or semiconductor element included in the first zone is different than one metal, metalloid, or semiconductor element included in the second zone.

17. The method of claim **16**, wherein the optical device film further comprises a third zone positioned between the first zone and the second zone, wherein the third zone includes a metal, metalloid, or semiconductor element that is different than the two or more metal, metalloid, or semiconductor elements in first zone and the second zone.

18. The method of claim **12**, wherein at least one of the first zone and the second zone includes oxygen and nitrogen.

19. The method of claim **12**, wherein the three or more metal, metalloid, and semiconductor elements include three or more of Ti, Si, Nb, Ta, Al, In, Cr, Ru, Hf, Mg, Zr, V, Mo, W, Mn, Fe, Co, Ni, Cu, Zn, Ga, Sn, Bi, Sb, Gd, Pr, Sc, and Y.

20. A method of forming an optical device film on an optical device substrate, the method comprising:

disposing an optical device substrate on a substrate support in a first process chamber;

depositing a first zone of the optical device film over the optical device substrate, wherein the first zone of the optical device film comprises:

one or more of oxygen and nitrogen, and

two or more metal, metalloid, or semiconductor elements;

disposing an optical device substrate on a substrate support in a second process chamber; and

depositing a second zone of the optical device film over the first zone of the optical device film, wherein the second zone of the optical device film comprises:

one or more of oxygen and nitrogen, and

two or more metal, metalloid, or semiconductor elements, wherein the two or more metal, metalloid, or semiconductor elements included in the second zone are different than the two or more metal, metalloid, or semiconductor elements included in the second zone.

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