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CONFIGURING OPTICAL LAYERS IN IMPRINT LITHOGRAPHY PROCESSES

Abstract

An imprint lithography method of configuring an optical layer includes selecting one or more parameters of a nanolayer to be applied to a substrate for changing an effective refractive index of the substrate and imprinting the nanolayer on the substrate to change the effective refractive index of the substrate such that a relative amount of light transmittable through the substrate is changed by a selected amount.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 18/734,904, filed on Jun. 5, 2024, which is a continuation of U.S. application Ser. No. 18/080,490, filed on Dec. 13, 2022, now U.S. Pat. No. 12,044,976, which is a continuation of U.S. application Ser. No. 17/685,781, filed on Mar. 3, 2022, now U.S. Pat. No. 11,550,226, which is a continuation of U.S. application Ser. No. 17/222,492, filed on Apr. 5, 2021, now U.S. Pat. No. 11,281,109, which is a divisional of U.S. application Ser. No. 16/859,584, filed on Apr. 27, 2020, now U.S. Pat. No. 10,969,692, which is a continuation of U.S. application Ser. No. 16/165,027, filed on Oct. 19, 2018, now U.S. Pat. No. 10,670,971, which claims the benefit of the filing date of U.S. Provisional Application No. 62/574,826, filed on Oct. 20, 2017, all of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

[0002] This invention relates to configuring optical layers in imprint lithography processes, and more particularly to forming anti-reflective features on a substrate to tune light transmission through the substrate.

BACKGROUND

[0003] Nanofabrication (e.g., nanoimprint lithography) is the fabrication of very small structures that have features on the order of 100 nanometers or smaller. One application in which nanofabrication has had a significant impact is in the processing of integrated circuits. The semiconductor processing industry continues to strive for larger production yields, while increasing a number of circuits formed on a substrate per unit area of the substrate. To this end, nanofabrication has become increasingly important to achieving desired results in the semiconductor processing industry. Nanofabrication provides greater process control while allowing continued reduction of minimum feature dimensions of structures formed on substrates. Other areas of development in which nanofabrication has been employed include biotechnology, optical technology, mechanical systems, and the like. In some examples, nanofabrication includes fabricating structures on substrates that are assembled to form an optical device.

SUMMARY

[0004] The invention involves a realization that imprinting certain types of nanoscale features on a substrate can significantly improve transmission of light (e.g., source light and world side light) through the substrate. For example, anti-reflective (AR) patterns can be formed from of nanoscale pillars, nanoscale holes, and nanoscale gratings that diminish light reflection losses at a substrate, thereby increasing light transmission through the substrate. Depending on a size, a shape, an aspect ratio, and a pitch of the nanoscale features, light transmission through a substrate can be tuned to a desired level using patterned polymer films of index varying from 1.49 to 1.74. In this regard, AR patterns formed on a substrate can also provide the substrate with a new effective refractive index.

Such features can be imprinted within ultra thin films of less than 150 nm thickness, thereby conserving material use and further enabling use of stacked waveguides using thin imprinted layers over glass substrates. Nanoscale features being imprinted have an overall pitch and dimensions of less than 300 nm, such that the nanoscale features do not cause unwanted diffraction or light scattering as light propagates through each layer in a multicolor waveguide stack. Such imprinted nanoscale features also enable higher transmission of world side light through each layer, thereby enhancing world side objects as viewed through a user's eye (e.g., pupil). Such nanoscale features can also act as dummy fill regions around edges of waveguide pattern geometry, enabling smooth transition of resist fluid prior to curing through a patterned region to another patterned region versus a patterned region to a blank un-patterned region. These nanoscale features are imprinted with a very thin residual layer thicknesses of less than 100 nm, which allows the pattern transfer into any underlying material layer or directly into the substrate to enhance the anti-reflective properties of that layer or just the bare substrate, itself.

[0005] One aspect of the invention features an imprint lithography method of configuring an optical layer. The imprint lithography method includes selecting one or more parameters of a nanolayer to be applied to a substrate for changing an effective refractive index of the substrate and imprinting the nanolayer on the substrate to change the effective refractive index of the substrate such that a relative amount of light transmittable through the substrate is changed by a selected amount

[0006] In some embodiments, the relative amount of light is a first relative amount of light, and imprinting the nanolayer on the substrate to change the effective refractive index of the substrate includes changing a second relative amount of light reflected from a surface of the substrate.

[0007] In certain embodiments, the imprint lithography method further includes selecting one or more of a shape, a dimension, and a material formulation of the nanolayer.

[0008] In some embodiments, the imprint lithography method further includes imprinting a flat nanoimprint on the substrate.

[0009] In certain embodiments, the imprint lithography method further includes imprinting a featured nanoimprint on the substrate.

[0010] In some embodiments, the imprint lithography method further includes imprinting one or more anti-reflective (AR) features on the substrate.

[0011] In certain embodiments, the one or more AR features have a height in a range of about 10 nm to about 300 nm.

[0012] In some embodiments, the one or more AR features have a width in a range of about 10 nm to about 150 nm.

[0013] In certain embodiments, the imprint lithography method further includes distributing the one or more AR features with a pitch in a range of about 20 nm to about 200 nm.

[0014] In some embodiments, the imprint lithography method further includes forming pillars on the substrate.

[0015] In certain embodiments, the imprint lithography method further includes forming holes on the substrate.

[0016] In some embodiments, the imprint lithography method further includes forming one or both of continuous gratings and discontinuous gratings on the substrate.

[0017] In certain embodiments, the imprint lithography method further includes forming afunctional pattern on a first side of the substrate and imprinting the nanolayer along one or both of the first side of the substrate and a second side of the substrate opposite the first side of the substrate.

[0018] In some embodiments, the imprint lithography method further includes forming an array of AR features of the nanolayer along a specific direction with respect to the functional pattern. In certain embodiments, the imprint lithography method further includes forming the AR features of the nanolayer on the substrate to change the effective refractive index of the substrate based on a direction of light propagation such that light transmitted through the substrate is changed by the selected amount.

[0019] In some embodiments, the imprint lithography method further includes applying a film coating to the substrate and imprinting the nanolayer atop the film coating.

[0020] In certain embodiments, the imprint lithography method further includes changing the relative amount of light transmittable through the substrate by about 0.5% to about 15%.

[0021] In some embodiments, the nanolayer is a first nanolayer, and the imprint lithography method further includes imprinting a second nanolayer atop the first nanolayer.

[0022] In certain embodiments, the imprint lithography method further includes changing the effective refractive index to a first value based on the first nanolayer and changing the effective refractive index to a second value based on the second nanolayer.

[0023] Another aspect of the invention features an optical layer that includes a substrate and a nanolayer imprinted on the substrate, the nanolayer determining an effective refractive index of the substrate such that the nanolayer effects a relative amount of light transmittable through the substrate.

[0024] Another aspect of the invention features an optical device that includes a first optical layer and a second optical layer. The first optical layer includes a first substrate and a nanolayer imprinted on the first substrate. The second optical layer includes a second substrate, and a functional pattern disposed along the second substrate. The nanolayer imprinted on the first substrate determines an effective refractive index of the first substrate such that the nanolayer increases a relative amount of light transmittable through the first substrate to the second optical layer.

[0025] In some embodiments, the functional pattern disposed along the second substrate is a first functional pattern, and the optical device further includes a third optical layer including a third substrate and a second functional pattern disposed along the third substrate.

[0026] In certain embodiments, the nanolayer imprinted on the first substrate is a first nanolayer, the effective refractive index of the first substrate is a first refractive index, the relative amount of light is a first relative amount of light, and the second optical layer includes a second nanolayer imprinted on the second substrate, the second nanolayer determining a second effective refractive index of the second substrate such that the second nanolayer increases a second relative amount of light transmittable through the second substrate to the third optical layer.

[0027] In some embodiments, the first and second nanolayers are configured such that a final amount of light transmitted through the first and second substrates to the third optical layer is about equal to an amount of light directed from a source to the first nanolayer, minus a first amount of light reflected from the first substrate and minus a second amount of light reflected from the second substrate.

[0028] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the invention will be apparent from the description, the drawings, and the claims.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIG. **1** is a diagram of an imprint lithography system.

[0030] FIG. **2** is diagram of patterned layer formed by the imprint lithography system of FIG. **1**.

[0031] FIG. **3** is a top view of an optical layer.

[0032] FIG. **4** is a side view of the optical layer of FIG. **3**.

[0033] FIG. **5** is a top view of an optical layer.

[0034] FIG. **6** is a top view of an optical layer.

[0035] FIG. **7** is a side view of an optical layer.
[0036] FIG. **8** is a side view of an optical layer.
[0037] FIG. **9** is a side view of an optical layer.
[0038] FIG. **10** provides SEM images (a)-(d) illustrating side views of various anti-reflective (AR) features.
[0039] FIG. **11** is a diagram illustrating effects of nanopatterns applied directly atop a substrate.
[0040] FIG. **12** is a diagram illustrating effects of stacking featured nanopatterns atop a substrate.
[0041] FIG. **13** is a graph of light transmission through a substrate with various treatments applied to the substrate.
[0042] FIG. **14** is a diagram illustrating a substrate with nanoimprint gratings applied in a same direction (a) and in a perpendicular direction (b) as compared to a direction of diffraction gratings of a functional pattern on the substrate.
[0043] FIG. **15** is a graph of light transmitted through a substrate with various treatments applied to the substrate.
[0044] FIG. **16** is a graph of light transmitted through a WGP substrate with various treatments applied to the WGP substrate.
[0045] FIG. **17** is a graph of indexes of refraction for various substrate treatments.
[0046] FIG. **18** is diagram illustrating light transmission through a multi-layer optical device.
[0047] FIG. **19** is a diagram illustrating a light source directed towards multiple layers of a waveguide eye-piece that include a non-imprinted AR film.
[0048] FIG. **20** is a diagram illustrating a light source directed towards multiple layers of a waveguide eye-piece that include an imprinted AR nanolayer.
[0049] FIG. **21** is a flow chart of an example process for configuring an optical layer in an imprint lithography process.
[0050] Like reference symbols in the various figures indicate like elements.
[0051] In some examples, illustrations shown in the drawings may not be drawn to scale.

DETAILED DESCRIPTION

[0052] An imprint lithography process for configuring an optical layer is described below. The imprint lithography process involves forming nanoscale surface relief pattern anti-reflective (AR) imprints on substrates. Such AR imprints serve to increase light transmission through the substrate to varying degrees, depending on various geometric properties of the AR imprints.
[0053] FIG. **1** illustrates an imprint lithography system **100** that is operable to form a relief pattern on a top surface **103** of a substrate **101** (e.g., a wafer). The imprint lithography system **100** includes a support assembly **102** that supports and transports the substrate **101**, an imprinting assembly **104** that forms the relief pattern on the top surface **103** of the substrate **101**, a fluid dispenser **106** that deposits a polymerizable substance upon the top surface **103** of the substrate **101**, and a robot **108** that places the substrate **101** on the support assembly **102**. The imprint lithography system **100** also includes one or more processors **128** that can operate on a computer readable program stored in memory and that are in communication with and programmed to control the support assembly **102**, the imprinting assembly **104**, the fluid dispenser **106**, and the robot **108**.
[0054] The substrate **101** is a substantially planar, thin slice that is typically made of one or more materials including silicon, silicon dioxide, titanium dioxide, zirconium dioxide, aluminum oxide, sapphire, germanium, gallium arsenide (GaAs), an alloy of silicon and germanium, indium phosphide (InP), or other example materials. The substrate **101** typically has a substantially circular or rectangular shape. The substrate **101** typically has a diameter in a range of about 50 mm to about 200 mm (e.g., about 65 mm, about 150 mm, or about 200 mm) or a length and a width in a range of about 50 mm to about 200 mm (e.g., about 65 mm, about 150 mm, or about 200 mm). The substrate **101** typically has and a thickness in a range of about 0.2 mm to about 1.0 mm. The thickness of the substrate **101** is substantially uniform (e.g., constant) across the substrate **101**. The relief pattern is formed as a set of structural features (e.g., protrusions and recesses) in the

polymerizable substance upon the top surface **103** of the substrate **101**, as will be discussed in more detail below.

[0055] The support assembly **102** includes a chuck **110** that supports and secures the substrate **101**, an air bearing **112** that supports the chuck **110**, and a base **114** that supports the air bearing **112**. The base **114** is located in a fixed position, while the air bearing **112** can move in up to three directions (e.g., x, y, and z directions) to transport the chuck **110** (e.g., in some instances, carrying the substrate **101**) to and from the robot **108**, the fluid dispenser **106**, and the imprinting assembly **104**. In some embodiments, the chuck **110** is a vacuum chuck, a pin-type chuck, a groove-type chuck, an electromagnetic chuck, or another type of chuck.

[0056] Still referring to FIG. **1**, the imprinting assembly **104** includes a flexible template **116** with a patterning surface defining an original pattern from which the relief pattern is formed complementarily on the top surface **103** of the substrate **101**. Accordingly, the patterning surface of the flexible template **116** includes structural features, such as protrusions and recesses. The imprinting assembly **104** also includes multiple rollers **118**, **120**, **122** of various diameters that rotate to allow one or more portions of the flexible template **116** to be moved in the x direction within a processing region **130** of the imprint lithography system **100** to cause a selected portion of the flexible template **116** to be aligned (e.g., superimposed) with the substrate **101** along the processing region **130**. One or more of the rollers **118**, **120**, **122** are individually or together moveable in the vertical direction (e.g., the z direction) to vary a vertical position of the flexible template **116** in the processing region **130** of the imprinting assembly **104**. Accordingly, the flexible template **116** can push down on the substrate **101** in the processing region **130** to form an imprint atop the substrate **101**. An arrangement and a number of the rollers **118**, **120**, **122** can vary, depending upon various design parameters of the imprint lithography system **100**. In some embodiments, the flexible template **116** is coupled to (e.g., supported or secured by) a vacuum chuck, a pin-type chuck, a groove-type chuck, an electromagnetic chuck, or another type of chuck.

[0057] In operation of the imprint lithography system **100**, the flexible template **116** and the substrate **101** are aligned in desired vertical and lateral positions by the rollers **118**, **120**, **122** and the air bearing **112**, respectively. Such positioning defines a volume **124** within the processing region **130** between the flexible template **116** and the substrate **101**. The volume **124** can be filled by the polymerizable substance once the polymerizable substance is deposited upon the top surface **103** of the substrate **101** by the fluid dispenser **106**, and the chuck **110** (e.g., carrying the substrate **101**) is subsequently moved to the processing region **130** by the air bearing **112**. Accordingly, both the flexible template **116** and the top surface **103** of the substrate **101** can be in contact with the polymerizable substance in the processing region **130** of the imprint lithography system **100**. Example polymerizable substances may be formulated from one or more substances, such as isobornyl acrylate, n-hexyl acrylate, ethylene glycol diacrylate, 2-hydroxy-2-methyl-1-phenyl-propan-1-one, (2-Methyl-2-Ethyl-1,3-dioxolane-4-yl)methyl acrylate, hexanediol diacrylate, 2-methyl-1-[4-(methylthio)phenyl]-2-(4-morpholinyl)-1-propanone, diphenyl(2,4,6-trimethylbenzoyl)-phosphine oxide, 2-hydroxy-2-methyl-1-phenyl-1-propanone, and various surfactants. Example techniques by which the polymerizable substance may be deposited atop the substrate **101** by the fluid dispenser **106** include drop dispense, spin-coating, dip coating, slot-die, knife-edge coating, micro-gravure, screen-printing, chemical vapor deposition (CVD), physical vapor deposition (PVD), thin film deposition, thick film deposition, and other techniques. In some examples, the polymerizable substance is deposited atop the substrate **101** in multiple droplets.

[0058] The printing system **104** includes an energy source **126** that directs energy (e.g., broadband ultraviolet radiation) towards the polymerizable substance atop the substrate **101** within the processing region **130**. Energy emitted from the energy source **126** causes the polymerizable substance to solidify and/or cross-link, thereby resulting in a patterned layer that conforms to a shape of the portion of the flexible template **116** in contact with the polymerizable substance in the processing region **130**.

[0059] FIG. **2** illustrates an example patterned layer **105** formed on the substrate **101** by the imprint lithography system **100**. The patterned layer **105** includes a residual layer **107** and multiple features including protrusions **109** extending from the residual layer **107** and recessions **111** formed by adjacent protrusions **109** and the residual layer **107**.

[0060] While the imprint lithography system **100** is described and illustrated as a roll-to-plate or plate-to-roll system, imprint lithography systems of different configurations can also be used to produce the example patterned layer **105** and the example patterns discussed below. Such imprint lithography systems may have a roll-to-roll or a plate-to-plate configuration.

[0061] In some embodiments, a substrate (e.g., the substrate **101** of the imprint lithography system **100**) is processed (e.g., imprinted on one or both sides, supplied with additional features, and/or cut out to shape) to form an optical layer of an optical device. For example, a nanolayer can be imprinted on the substrate to enhance optical performances of the substrate, such as to increase or reduce a transmissivity of the substrate to light of certain wavelengths and/or to enhance birefringence of the substrate. Example optical devices include optical films (e.g., Wire Grid Polarizer (WGP) films) of high transmission (e.g., greater than 42%) and high Extinction Ratio (ER) (e.g., greater than 1000)) used in display applications (e.g., liquid crystal display (LCD) applications), touchscreen display applications (e.g., touch sensors), and to improve intensity of light transmitted from either side of an optical film, such as in a wearable eyepiece, an optical sensor, or an optical film.

[0062] FIGS. **3** and **4** illustrate a top view and a side view, respectively, of an optical layer **200** that includes a substrate **202** with an upper side **204** and a lower side **206**. The optical layer **200** also includes a functional pattern **208** imprinted on the upper side **204** of the substrate **202**, an AR pattern **210** imprinted on the upper side **204** of the substrate **202**, a film coating **212** disposed on the lower side **206** of the substrate **202**, and an AR pattern **214** imprinted on the film coating **212**. The substrate **202** may be laser cut from a larger substrate (e.g., the substrate **101**) and is provided as a layer of transparent or semi-transparent plastic (e.g., a flexible material) or glass (e.g., a rigid material) that is made of one or more organic or inorganic materials, in accordance with the various material formulations described above with respect to the substrate **101**. The substrate **202** may have a length of about 10 mm to about 150 mm (e.g., about 50 mm), a width of about 10 mm to about 150 mm (e.g., about 50 mm), and a thickness of about 0.1 mm to about 10.0 mm (e.g., about 0.3 mm). The substrate **202** has a relatively high refractive index in a range of about 1.6 to about 1.9 (e.g., about 1.8). Assuming that the substrate **202** is surrounded by air (i.e., n=1), the substrate **202** has a transmissivity (e.g., a portion of light impinging on the substrate **202** that passes through the substrate **202**) in a range of about 80.00% to about 95.00% (e.g., about 91.84%) and accordingly has a reflectivity (e.g., the portion of light impinging on the substrate **202** that is reflected backwards from the substrate **202**) of about 5.00% to about 20.00% (e.g., about 8.16%).

[0063] The functional pattern **208** is imprinted (e.g., via the imprint lithography system **100**) along an interior region **216** of the substrate **202**. The functional pattern **208** is a waveguide pattern formed of multiple diffraction gratings that provide a basic working functionality of the optical layer **200**. The diffraction gratings have dimensions in a range of about 10 nm to about 600 nm. The diffraction gratings are configured to project light of wavelengths within a particular range and to focus a virtual image at a particular depth plane. The focused light, together with focused light projected through proximal optical layers, forms a multi-color virtual image over one or more depth planes. The transmitted light may be red light with wavelengths in a range of about 560 nm to about 640 nm (e.g., about 625 nm), green light with wavelengths in a range of about 490 nm to about 570 nm (e.g., about 530 nm), or blue light with wavelengths in a range of about 390 nm to about 470 nm (e.g., about 455 nm). The diffraction gratings can include multiple combinations and arrangements of protrusions and recessions (e.g., such as the protrusions **109** and the recessions **111**) that together provide desired optical effects. The diffraction gratings include in-coupling gratings and may form an orthogonal pupil expander region and an exit pupil expander region. The functional pattern **208** has a total length of about 10 mm to about 150 mm and a total width of about 10 mm to about 150 mm.

[0064] The film coating **212** is also disposed along the interior region **216** of the substrate **202**. The film coating **212** can provide the substrate **202** with various properties or capabilities, such as abrasion resistance, improved surface hydrophobicity, color filtration, and brightness enhancement. Example film coatings **212** include Zirconium Dioxide based hard coats for chemical barrier coating and adding hydrophobicity and a Titanium Dioxide and Silicon Dioxide hard coating for abrasion resistance and use as inorganic based anti-reflective films. The film coating **212** may be applied to the substrate **202** via techniques such as lamination, slot-die coating, physical vapor deposition, evaporation, sputtering, and chemical vapor deposition.

[0065] The AR pattern **210** is imprinted (e.g., via the imprint lithography system **100**) along the interior region **216** of the substrate **202** and surrounding the functional pattern **208**. The AR pattern **210** has a length of about 0.5 mm to about 150 mm and a width of about 0.5 mm to about 150 mm. The AR pattern **214** is imprinted (e.g., via the imprint lithography system **100**) across the film coating **212**. The AR pattern **214** has a length of about 0.5 mm to about 150 mm and a width of about 0.5 mm to about 150 mm. The AR patterns **210**, **214** include AR features of a nano-scale that may be distributed in various quantities, arrangements, shapes, sizes, and orientations anywhere within the AR patterns **210**, **214**. AR features within the AR pattern **210** may be either abutted seamlessly to the nearest diffraction grating of the functional pattern **208** or positioned at least about 5 μm from a nearest diffraction grating of the functional pattern **208**. The AR features are sized, arranged, and shaped to increase light transmission (e.g., to reduce surface reflection) at the side of the substrate **202** on which the AR patterns **210**, **214** are imprinted.

[0066] While FIGS. **3** and **4** illustrate a certain embodiment of an optical layer **200**, optical layers can include other arrangements of functional patterns, AR patterns, and film coatings. For example, FIG. **5** illustrates a top view of an optical layer **500** that includes the substrate **202** and the functional pattern **208** of the optical layer **200**, as well as an AR pattern **510**. The functional pattern **208** is imprinted atop the upper side **204** of the substrate **202**, as in the optical layer **200**. The AR pattern **510** is also imprinted atop the upper side **204** of the substrate **202** and is substantially similar in construction and function to the AR pattern **210**, except that the AR pattern **510** extends across the interior region **216** to a peripheral edge **218** of the substrate **202**.

[0067] In another example embodiment, FIG. **6** illustrates a top view of an optical layer **600** that includes the substrate **202** and the functional pattern **208** of the optical layer **200**, as well as an AR pattern **610**. The functional pattern **208** is imprinted atop the upper side **204** of the substrate **202**, as in the optical layer **200**. The AR pattern **610** is also imprinted atop the upper side **204** of the substrate **202** and is substantially similar in construction and function to the AR pattern **210**, except that the AR pattern **610** is provided as two separate regions **640**, **642** that surround separate portions of the functional pattern **208**.

[0068] In another example embodiment, FIG. **7** illustrates a side view of an optical layer **700** that includes the substrate **202**, the functional pattern **208** of the optical layer **200**, and the AR pattern **214** of the optical layer **200** without including the AR pattern **210** and the film coating **212**. In the example optical layer **700**, the AR pattern **214** is imprinted directly on the lower side **206** of the substrate **202**.

[0069] In another example embodiment, FIG. **8** illustrates a side view of an optical layer **800** that includes the substrate **202**, the functional pattern **208** of the optical layer **200**, the AR pattern **210** of the optical layer **200**, and the film coating **212** of the optical layer **200** without including the AR pattern **214**.

[0070] In another example embodiment, FIG. **9** illustrates a side view of an optical layer **900** that includes the substrate **202**, the functional pattern **208** of the optical layer **200**, the AR pattern **210** of the optical layer **200**, and the AR pattern **214** of the optical layer **200** without including the film coating **212**. In the example optical layer **900**, the AR pattern **214** is imprinted directly on the lower side **206** of the substrate **202**. In other embodiments, optical layers may include functional patterns and AR patterns with different shapes and/or arrangements not shown in the example optical layers **200**, **500**, **600**, **700**, **800**, **900**.

[0071] FIG. **10** provides scanning electron micrograph (SEM) images (a)-(d) of example AR features that may form the AR patterns **210**, **214**. For example, SEM image (a) illustrates AR features formed as free standing, isolated protrusions such as pillars **300**. The pillars **300** can be cylindrical, polygonal prism, conical, tetrahedral or frustoconical in shape. The pillars **300** have a height of about 10 nm to about 300 nm, a width of about 10 nm to about 150 nm, and a pitch (e.g., a distance between corresponding points on adjacent, like elements) of less than about 200 nm. SEM image (b) illustrates AR features formed as holes **302**. The holes **302** can be cylindrical, polygonal prism, conical, tetrahedral or frustoconical in shape. The holes **302** have a depth of about 10 nm to about 300 nm, a width of about 10 nm to about 150 nm and a pitch of less than about 200 nm. The pillars **300** and holes **302** may be distributed in a hexagonally closed packed array or a square packed array. SEM image (c) illustrates AR features formed as gratings **304** (e.g., elongate horizontal bars having a length greater than a maximum width and a maximum height). The gratings **204** can be rectangular, frustoconical, ellipsoidal, or triangular in cross-sectional shape in a plane orthogonal to the direction of the gratings **304**. The gratings **304** have a height of about 10 nm to about 300 nm, a width of about 10 nm to about 150 nm, and a pitch of less than about 200 nm. SEM image (d) illustrates AR features formed as discontinuous or short gratings or rods **306**. These features can be rectangular, frustoconical, ellipsoidal, or triangular in cross-sectional shape in a plane orthogonal to the direction of the longer dimension axis. The features **306** have a height of about 10 nm to about 300 nm, a width of about 10 nm to about 150 nm, a length greater than about 5 μm, and a pitch of less than about 200 nm. In general, AR features of the AR patterns **210**, **214** may have heights in a range of about 30 nm to about 300 nm, may have widths in a range of about 20 nm to about 100 nm, and may be distributed with pitches in a range of about 50 nm to about 200 nm.

[0072] FIG. **11** illustrates effects of AR nanolayers applied (e.g.,) directly atop a substrate (e.g., the substrate **202** or another substrate used to form optical layers in imprint lithography processes) according to a process such as nano-imprint lithography, photolithography, dry or wet etch, coat, lift-off, or lamination. Light passing from a first medium of a first refractive index no to a second medium of a second refractive index n.sub.s at a 0 degree incidence will be reflected at an interface of the first and the second mediums according to a reflectivity R given by Eqn. 1 and transmitted through the second medium according to a transmissivity T given by Eqn. 2 (ignoring loss due to absorption, scatter, etc.). An optimal index of refraction n.sub.1 of an intermediate layer between the first and second mediums can be approximated from the refractive indexes of the first and second mediums according to Eqn. 3 to produce low reflection loss at the interface. For example, Eqn. 1 is a general equation for reflection loss at a single interface (e.g., a flat interface) of a given index. Nanofeatures etched into such a substrate will change the index of the surface and thus change the reflection loss. Therefore, in a general estimation, a single layer over a flat surface for reducing reflection loss has a general index that is given by Eqn. 3.

[00001] $R_{s-0} = \text{.Math.} \frac{n_s - n_0}{n_s + n_0} \text{.Math.}^2$ (1) $T = 1 - R$ (2) n_1 (3) $\sqrt{n_0 \text{ .Math. } n_s}$

For example, as shown in illustration (a), about 8.16% (R.sub.s-0=0.0816) of light passing through air (n.sub.0=1.0) and directly incident on the substrate (n.sub.s=1.8) is reflected from the substrate, while about 91.84% (T=0.9184) of the incident light is transmitted to the substrate. For light passing through air and incident on the substrate, the optimal index of refraction n.sub.1 for an intermediate layer at that interface is around 1.34.

[0073] As shown in illustration (b), applying a flat nanoimprint **316** with a thickness of less than 100 nm with a bulk index of refraction of 1.52 (n=1.52) to the substrate causes a first amount of incident light (i.e., 4.26%) to be reflected at an interface between air and the flat nanoimprint **316** and causes a second amount of incident light (i.e., 0.71%) to be reflected at an interface between the flat nanoimprint **316** and the substrate. The reflected amounts of light can be summed to give a total amount of light reflection loss of 4.97%. Thus, light passing through material **316** first requires the index at that air-material interface to be about 1.23, and applying the flat nanoimprint **316** to the substrate has reduced the reflectivity and increased the transmissivity of the substrate **202** by 3.19%. As shown in illustration (c), applying a featured nanoimprint **318** (e.g., n=1.25) to the substrate causes a first amount of incident light (i.e., 1.23%) to be reflected at an interface between air and the featured nanoimprint **318** and causes a second amount of incident light (i.e., 0.65%) to be reflected at an interface between the featured nanoimprint **318** and the substrate. The reflected amounts of light can be summed to give a total amount of light reflection loss of 1.89%. Thus, applying the featured nanoimprint layer **318** to the substrate has reduced the reflectivity and increased the transmissivity of the substrate by about 3%. In a general, AR features such as those of the featured nanoimprint **318** have an interface with air that has a refractive index in a range of about 1.24 to about 1.34.

[0074] Table 1 describes measured refractive indexes of film-air interfaces of various film stack architectures that include nano-feature AR patterns along with improved through transmission of light at a wavelength of 590 nm. For example, a blank film of 100 nm thickness with a material refractive index of 1.52 over a transparent glass substrate of refractive index 1.78 gives a 4.25% improved transmission through that interface, when compared to the bare glass surface to air interface. When a blank film of higher refractive index 1.65 is used with similar 100 nm thickness instead of a refractive index of 1.52, the reflection loss is higher, and the net improvement is lower at 1.96% when compared to the bare 1.78 index glass. However, when the films are stacked in with the lowest index on top facing air and highest index 1.65 at the glass **1.78** interface, the reflection loss is lower, and improvement in transmission is 5.09% versus bare glass-air interface. This can be much improved if nanofeatures are fabricated with such material indices to bring the effective refractive index down to a more optimal level.

[0075] Patterning a single material (of index 1.52) with nanofeatures such as pillars of width of 50 nm, height of 100 nm and pitch of 100 nm in a square array with a very thin (<50 nm) residual layer thickness (interconnecting material film for nanofeatures of same material), the effective refractive index at the nanofeature material-air interface now becomes 1.28, which further improves transmission by 7.71% when compared to bare glass-air interface. Similarly, if the material index was 1.65, then this effective refractive index at the nanofeature material-air interface now becomes 1.32, thus improving transmission by 7.02% over bare glass-air interface. This type of embodiment is captured in FIG. **12**, where the low index material (e.g., **1.52**) AR nano-feature **318***a* is imprinted over a higher index material (e.g., **1.65**) AR nano-feature **318***b* that is flush with the surface of the high index glass **1.78**.

TABLE-US-00001 TABLE 1 Measured refractive indexes of film-air interfaces of various film stack architectures. Measured Refractive % Transmission Index of surface Through Improvement open to Air Transmission over Bare Description of Nanofilm Structure Layers over Substrate (n = 1) at 590 nm Substrate Bare High Index Substrate (n = 1.78) 300 um thick w/Back NA 91.91% — side Inorganic AR Coating Blank Imprint Film (n = 1.52) 100 nm thick on High Index 1.52 95.82% 4.25% Substrate (n = 1.78) 300 um thick w/Back side Inorganic AR Coating Blank Imprint Film (n = 1.65) 100 nm thick on High Index 1.65 93.71% 1.96% Substrate (n = 1.78) 300 um thick w/Back side Inorganic AR Coating Blank Imprint Film (n = 1.52) 100 nm thick over Blank Imprint 1.52 96.59% 5.09% Film (n = 1.65) 100 nm thick on High Index Substrate (n = 1.78) (Imprint over 1.65) 300 um thick w/Back side Inorganic AR Coating Imprint Geometry with 100 nm Pitch 50 nm Diameter Pillar 1.28 99.00% 7.71% with n = 1.52 material on High Index Substrate (n = 1.78) (using 1.52 material) 300 um thick w/Back side Inorganic AR Coating Imprint Geometry with 100 nm Pitch 50 nm Diameter Pillar 1.32 98.36% 7.02% with n = 1.65 material on High Index Substrate (n = 1.78) (using 1.65 material) 300 um thick w/Back side Inorganic AR Coating Imprint

Geometry with 100 nm Pitch 50 nm Diameter Pillar 1.28 99.49% 8.25% with n = 1.52 material over Imprint Geometry with 100 nm (using pillar geometry Pitch 50 nm Diameter Pillar with n = 1.65 material on High material 1.52 over Index Substrate (n = 1.78) 300 um thick w/Back side pillar of geometry Inorganic AR Coating material 1.65)

[0076] By further combining these two nano-feature imprinted films with the same nano-pattern where the lower index material (**1.52**) film with nano-features is exposed to air and the residual layer of the nano-patterned higher index material (**1.65**) film touches the glass surface (**1.78**) such that the residual layer thickness of the lower index (**1.52**) film covers the nano-features of the higher index material (**1.65**), the effective refractive index at the material-air interface remains 1.28, but the stack overall is more transmissive to light at a 590 nm wavelength due to a gradual change of index as light propagates through to the glass interface. For example, an improved transmittance over the visible wavelength spectrum is shown in FIG. **13***a*. FIGS. **13***b*-**13***e* also shows examples of a near optimally patterned nano-feature film surface with film thicknesses less than 130 nm and with pillar (refer to FIGS. **13***b*, **13***c*, and **13***e*) and hole tone (refer to FIG. **13***d*) geometry, as compared to a standard anti-reflective multi-layer film (refer to FIG. **13***f*), which can be several hundred nanometers of high and low index film coatings.

[0077] FIG. **14** illustrates a diagram (a) showing a substrate **400** with nanoimprint gratings **402** (blue) applied in a same direction as diffraction gratings **404** (gray) of a functional pattern (wire grid polarizer) on the substrate. The nanoimprint gratings **402** and the diffraction gratings **404** are located on opposite sides of the substrate **400**. FIG. **14** also illustrates a diagram (b) showing a substrate **400** with the nanoimprint gratings **402** (blue) applied across (e.g., at an angle of 90 degrees to) the diffraction gratings **404** (gray) of the functional pattern. The nanoimprint gratings **402** and the diffraction gratings **404** are located on opposite sides of the substrate **400**.

[0078] FIG. **15** illustrates a graph plotting light transmitted through a substrate with and without AR nanofeature type film. The grating type AR nanofeature imprint is applied to the back side of a WGP substrate where the grating of the AR imprint is orthogonal to the grating direction of the wire grid polarizer. As shown in the graph, applying the nanoimprint gratings in a direction across the direction of diffraction gratings increases the light transmission up to a wavelength of about 650 nm and decreases the light transmission at wavelengths greater than about 650 nm. The result illustrates a weak birefringence property when using grating type AR nanofeatures and applying such features in an orthogonal direction to the polarized light exhibiting the WGP pattern as the light encounters the AR gratings. Such features can reduce polarized light transmitted at higher wavelengths in such applications. This effect does not occur when using hole or pillar type AR nanofeatures. FIG. **16** shows effects with and without applying the grating type AR nanofeature along the WGP functional grating direction. It is shown that the light transmission increases overall over the visible spectrum by the grating type AR nanofeature imprint along the WGP.

[0079] The weak birefringence property exhibited by grating type AR nanofeature film is also illustrated by the graph in FIG. **17**. The graph shows that effective surface refractive index of the grating type AR nano-feature changes from 1.25 (across grating) to about 1.32 (along grating) based on grating orientation to incoming linearly polarized light (provided by an ellipsometer) during refractive index measurement, which otherwise measures the refractive index of the material if a blank were to be imprinted as **1.52**.

[0080] FIG. **18** shows a multi-layer wearable eyepiece **1300** having first optical layer **1302**, second optical layer **1302′**, and third optical layer **1302″**. First optical layer **1302**, second optical layer **1302′**, and third optical layer **1302″** include first substrate **1304**, second substrate **1304′**, and third substrate **1304″**, respectively. First nanolayer **1306**, second nanolayer **1306′**, and third nanolayer **1306″** are imprinted on first substrate **1302**, second substrate **1302′**, and third substrate **1302″**, respectively. First substrate **1302**, second substrate **1302′**, and third substrate **1302″** include first functional pattern **1308**, second functional pattern **1308′**, and third functional pattern **1308″**, respectively. In an embodiment of the optical layer AR pattern as applied to a multi-layer wearable eyepiece **1300**, the AR pattern allows for more light to pass through from a projection system to the input coupling diffraction grating **1312** as light passes through multiple layers of the eyepiece. The AR pattern around the exit pupil diffraction grating **1314** allows for more world-side light to enter into the user's eye and reduces unwanted reflection or glare due to high reflectivity of the otherwise bare high index glass surface in air.

[0081] FIGS. **19** and **20** respectively show example stacks **1100**, **1200** of waveguide eye-pieces using a light source with a red color of wavelength 625 nm (a), a green color of wavelength 530 nm (b) and a blue color of wavelength 455 nm (c) on one side of the stacks **1100**, **1200**. The stacks **1100**, **1200** includes six layers **1101*a*-1101*f***, **1201*a*-1201*f*** (e.g., of color red, blue, or green) located at different depths to which the light has to travel. Each of the layers **1101*a*-1101*f*** of the stack **1100** include a substrate **1102**, a blank imprint layer **1104** around a region of input coupling grating (ICG) (e.g., refer to the example optical layer **600** of FIG. **6**), and a non-imprinted AR nanolayer **1106**. Each of the layers **1201*a*-1201*f*** of the stack **1200** include a substrate **1202**, a blank imprint layer **1204** around a region of ICG, and an imprinted AR nanolayer **1206**. As shown, only about 81.7% of light intensity reaches the last red layer **1101*f*** of the stack **1100** (i.e., with the flat AR nanolayer **1106**), whereas about 95.6% of light intensity reaches the last red layer **1201*f*** of the stack **1200** (i.e., with the imprinted AR nanolayer **1206**), such that the imprinted AR nanolayer **1206** provides a 13.9% absolute improvement in light intensity.

[0082] FIG. **21** displays a flow chart of an example process **1000** for configuring an optical layer (e.g., the optical layer **200**, **500**, **600**, **700**, **800**, **900**) in an imprint lithography process. One or more parameters of a nanolayer (e.g., the nanoimprint **210**, **214**, **316**, **318**, **510**, **610**) to be applied to a substrate (e.g., the substrate **202**, **400**) for changing an effective refractive index of a substrate (e.g., a material-air interface on the substrate) are selected (**1002**). In some examples, the one or more parameters include one or more of a shape, a dimension, and a material formulation of the nanolayer. The nanolayer is imprinted on the substrate (e.g., the upper side **204** or the lower side **206** of the substrate **202**) to change the effective refractive index of the substrate such that a relative amount of light transmittable through the substrate is changed by a selected amount (**1004**). For example, a bare substrate without any applied coating or nanoimprint may have an effective refractive index that is equal to an actual, bulk refractive index of the substrate. In some examples, applying the nanolayer changes the effective refractive index from the actual, bulk refractive index to new effective refractive index. In some embodiments, imprinting the nanolayer on the substrate to change the effective refractive index of the substrate includes changing a second relative amount of light reflected from a surface of the substrate.

[0083] In some embodiments, the nanolayer is a flat nanoimprint (e.g., the nanoimprint **316**). In some embodiments, the nanolayer is a featured nanoimprint (e.g., the nanoimprint **318**). In some embodiments, the nanopattern includes AR features (e.g., pillars, holes, and/or gratings). In some examples, the AR features have a height in a range of about 10 nm to about 300 nm. In some examples, the AR features have a width in a range of about 10 nm to about 150 nm. In some examples, the AR features are distributed with a pitch in a range of about 20 nm to about 200 nm. In some embodiments, imprinting the nanolayer includes forming pillars (e.g., the pillars **300**, **306**, **308**) on the substrate. In some embodiments, imprinting the nanolayer includes forming holes **302** on the substrate. In some embodiments, imprinting the nanolayer includes forming one or both of continuous gratings and discontinuous gratings (e.g., the gratings **314**, **402**) on the substrate.

[0084] In some embodiments, the process further includes forming a functional pattern on a first side of the substrate and imprinting the nanolayer along one or both of the first side of the substrate and a second side of the substrate opposite the first side of the substrate. In some examples, imprinting the nanolayer includes forming AR features of the nanolayer along a specific direction with respect to the functional pattern the functional pattern. In some examples, imprinting the nanolayer includes forming AR features along a direction perpendicular to diffraction gratings of the functional pattern. In some embodiments, the process further includes applying a film coating

(e.g., the film coating **212**) to the substrate and imprinting the nanolayer atop the film coating.
[0085] In some embodiments, the process further includes changing the relative amount of light transmitted through the substrate by about 0.5% to about 15%. In some embodiments, the nanopattern is a first nanolayer, and process further includes imprinting a second nanolayer atop the first nanolayer. In some embodiments, the process further includes changing the effective refractive index to a first value based on the first nanolayer and changing the effective refractive index to a second value based on the second nanolayer.
[0086] Advantageously, the process **1000** can be used to produce AR patterns that may reduce the surface reflection of a substrate by about 1% to about 10%. Such AR patterns may increase the transmissivity of the substrate to greater than about 98% for a plastic substrate and up to about 99% for a glass substrate. The AR patterns may also provide the substrate with a new effective refractive index in a range of about 1.2 to about 1.4, such that transmission of light through the substrate is increased. Furthermore, the AR patterns discussed herein may introduce birefringence to diminish or enhance refraction of certain light wavelengths transmitted through the substrate. In some implementations, weak birefringence can be advantageous if there is a need to modulate the phase of light propagating within and through the substrate. In addition, at the specified dimensions of the AR nanopattern **214** and the functional diffraction patterns **208**, the AR nanopattern **214** does not diffract light as does the functional diffraction patterns **208**. As a result, the AR nanopattern **214** does not interfere with the diffractive optics of the optical device. Furthermore, the AR nanopattern **214** provides an anti-stick surface that can maintain a certain predefined gap in case two substrate layers in close proximity to each other should be pushed against each other.
[0087] While the substrates discussed herein have been assumed to have a refractive index of about 1.78 to about 1.8, other substrates that may be used in optical devices discussed herein may have a refractive index in a range of about 1.45 to about 2.4.
[0088] While a number of embodiments have been described for illustration purposes, the foregoing description is not intended to limit the scope of the invention, which is defined by the scope of the appended claims. There are and will be other examples, modifications, and combinations within the scope of the following claims.

Claims

1. (canceled)
2. An optical device, comprising: a transparent or semi-transparent substrate extending in a plane; a first layer disposed on a first surface of the substrate, the first layer comprising a first grating; a second layer disposed on a surface of the substrate, wherein the second layer comprises a nanopattern comprising a plurality of features having a dimension of 150 nm or smaller in at least one direction in the plane of the substrate, the nanopattern being configured to reduce a reflectivity of light incident on the surface, wherein the optical device is an eyepiece for a wearable display.
3. The optical device of claim 2, wherein the second layer is disposed on the surface of the substrate and the second layer at least partially surrounds the first grating of the first layer.
4. The optical device of claim 3, wherein the second layer is disposed without overlapping the first grating.
5. The optical device of claim 2, wherein there is an absence of a nanopattern on a second surface of the substrate opposite the first surface.
6. The optical device of claim 2, wherein the second layer is disposed on a second surface of the substrate opposite the first surface.
7. The optical device of claim 6, comprising a film disposed between the substrate and the second layer.
8. The optical device of claim 2, wherein the first grating comprises a plurality of grating portions, and the nanopattern comprises a plurality of nanopattern portions.

9. The optical device of claim 8, comprising a third layer disposed on a second side of the substrate opposite the first surface.
10. The optical device of claim 9, wherein the third layer abuts an edge of the second side of the substrate.
11. The optical device of claim 8, wherein a grating direction of each of the grating portions and a pattern direction of each of the nanopattern portions are aligned along a common direction.
12. The optical device of claim 8, wherein a grating direction of each of the grating portions is aligned along a first direction, and a pattern direction of each of the nanopattern portions is aligned along a second direction different from the first direction.
13. An optical device, comprising: a transparent or semi-transparent substrate extending in a plane; a first layer disposed on a surface of the substrate, the first layer comprising a first grating; a second layer disposed on the surface of the substrate, wherein the second layer comprises a nanopattern being configured to have an interface with air that has an effective refractive index in a range from 1.24 to 1.34; and wherein the optical device is an eyepiece for a wearable display.
14. The optical device of claim 13, wherein the second layer at least partially surrounds the first grating of the first layer.
15. The optical device of claim 13, comprising a third layer comprising a second grating and a fourth layer comprising a third grating, wherein the second layer at least partially surrounds each of the first grating of the first layer, the second grating of the third layer, and the third grating of the fourth layer.
16. The optical device of claim 15, comprising a fifth layer comprising a second nanopattern disposed on the surface of the substrate.
17. The optical device of claim 16, wherein the second nanopattern of the fifth layer at least partially surrounds the second grating of the third layer.
18. The optical device of claim 16, wherein the second nanopattern of the fifth layer abuts the nanopattern of the second layer.
19. The optical device of claim 16, wherein the second layer comprises a first material having a first refractive index, the fifth layer comprises a second material having a second refractive index, and the substrate comprises a third material having a third refractive index.
20. The optical device of claim 19, wherein the first refractive index is greater than the second refractive index, and the third refractive index is greater than the first refractive index.