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Dong et al.

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(54) **EYEPIECE ASSEMBLY ADHESION USING A ZERO RESIDUAL LAYER REGION**

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G03F 7/00 (2006.01)

(52) **U.S. Cl.**
CPC ***G03F 7/0005*** (2013.01); ***G03F 7/0002*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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Primary Examiner — Jethro M. Pence
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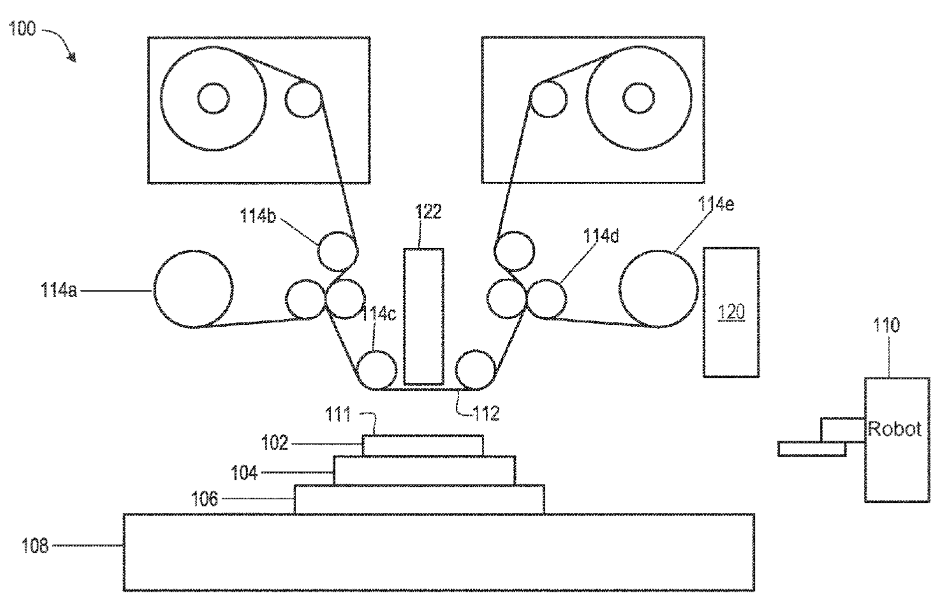
(57) **ABSTRACT**

Methods and systems for manufacturing an optical waveguide include depositing an adhesion promoting layer on a substrate. Multiple curable resist droplets are dispensed on the adhesion promoting layer. The adhesion promoting layer is disposed between and contacts the substrate and the curable resist droplets. The curable resist droplets define an optical eyepiece layer such that a zero residual layer thickness (RLT) region of the optical eyepiece layer is free of the curable resist droplets. The optical eyepiece layer is incised from the substrate to form the optical waveguide.

12 Claims, 11 Drawing Sheets



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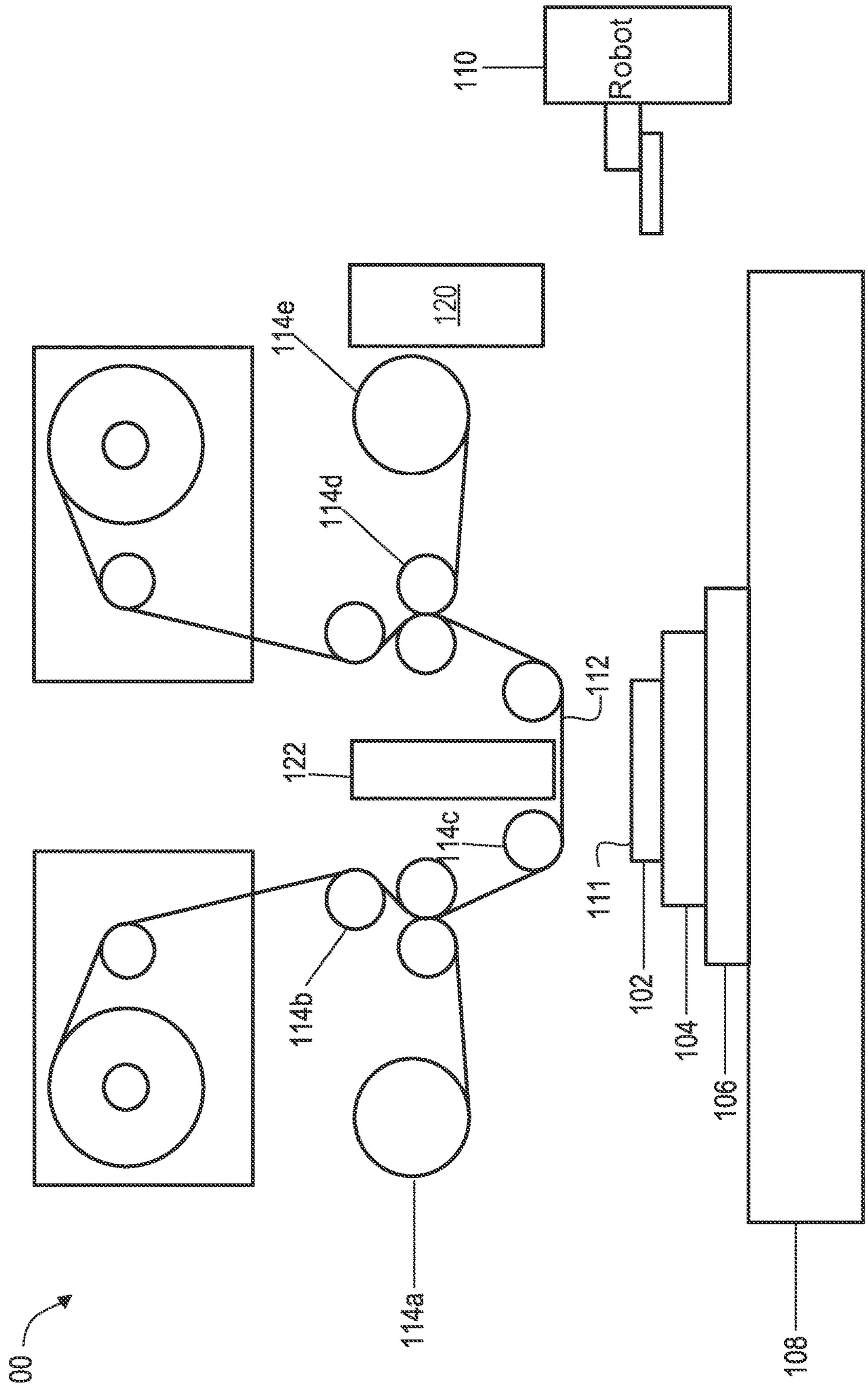
Robot
110
120
114e
114d
112
122
114c
111
102
104
106
114b
114a
108
100

FIG. 1

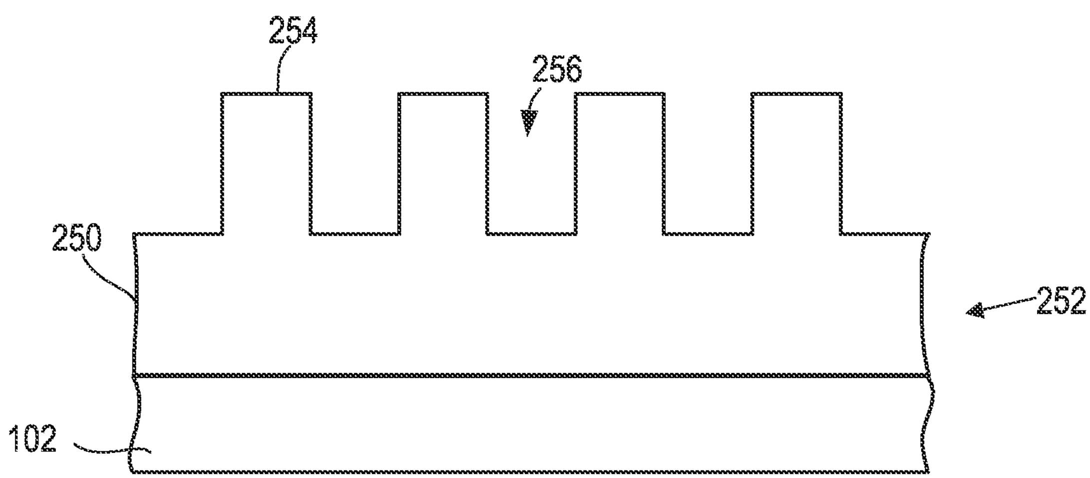

FIG. 2A

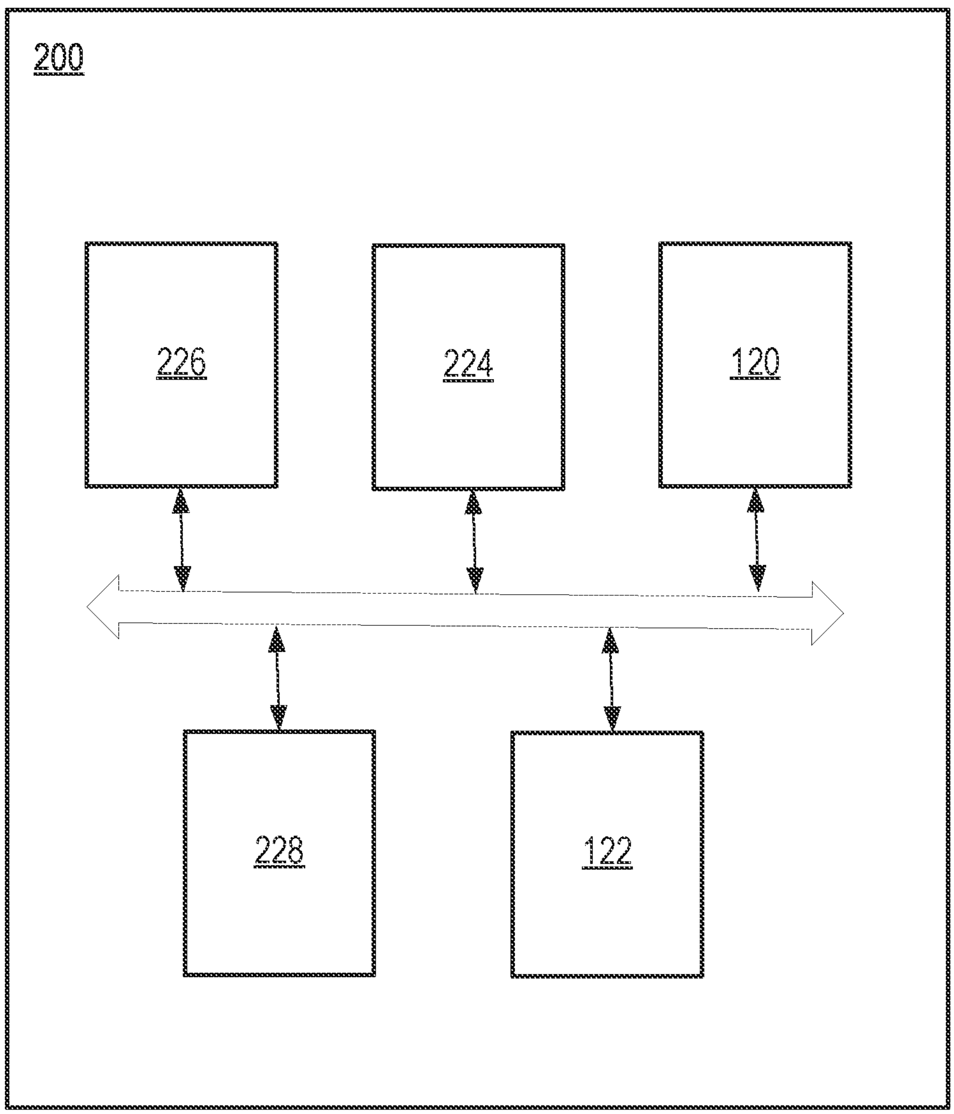

FIG. 2B

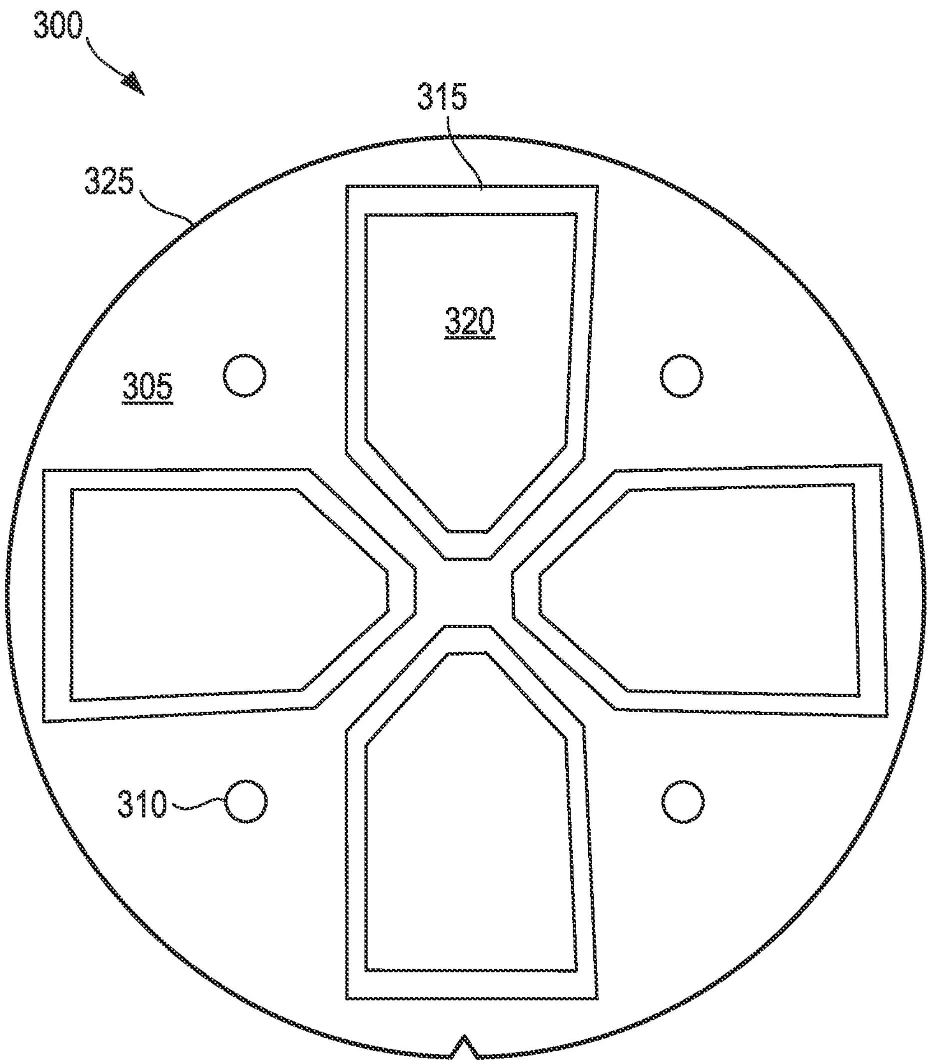

FIG. 3

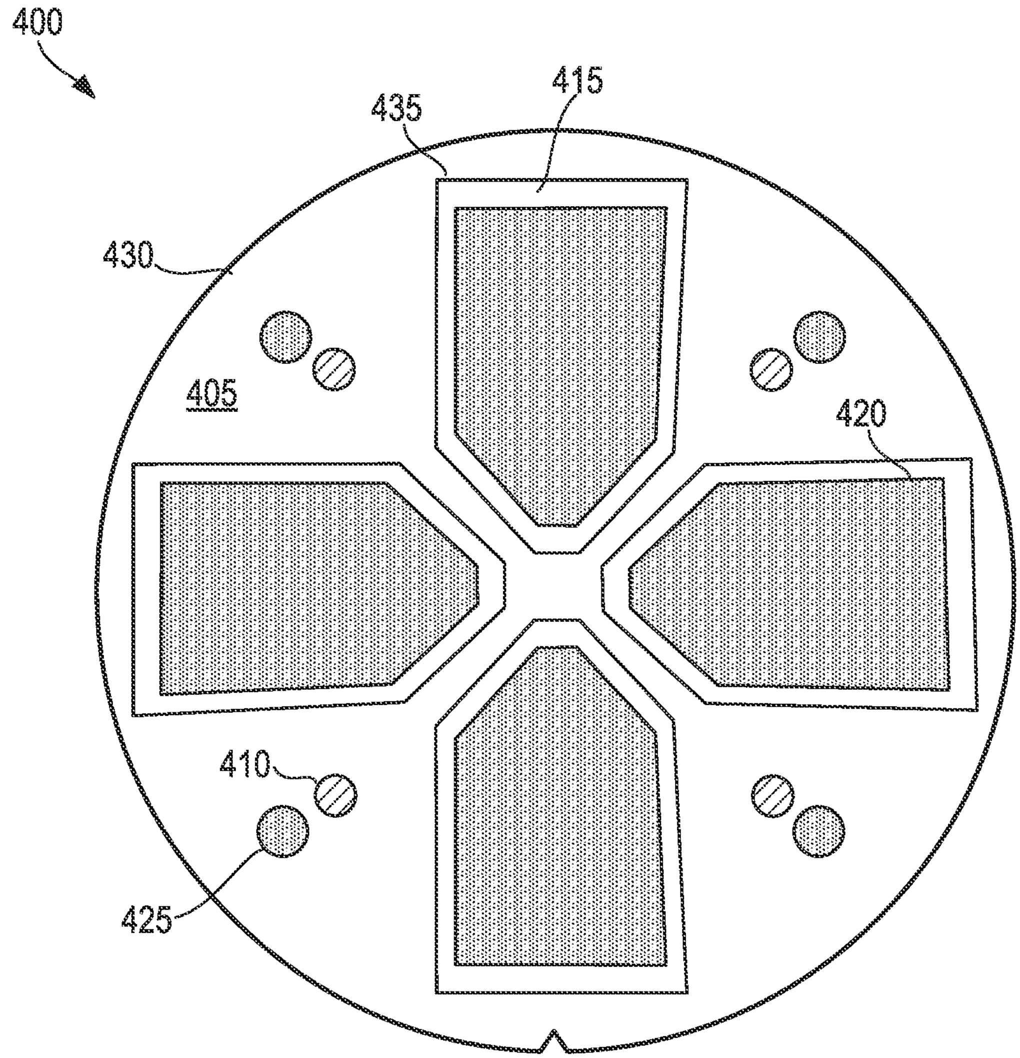

FIG. 4

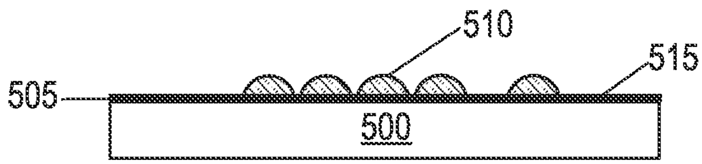

FIG. 5A

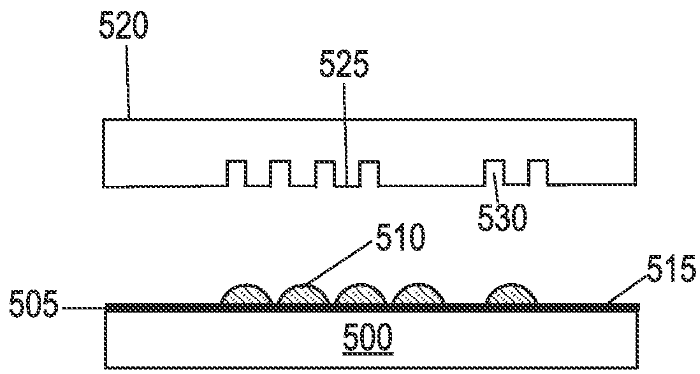

FIG. 5B

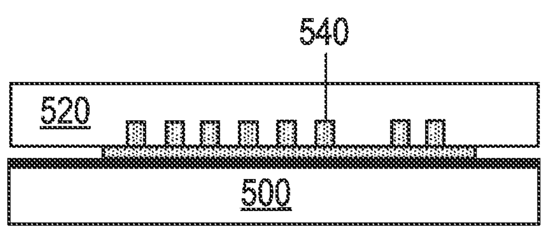

FIG. 5C

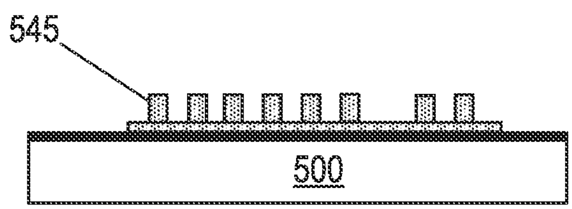

FIG. 5D

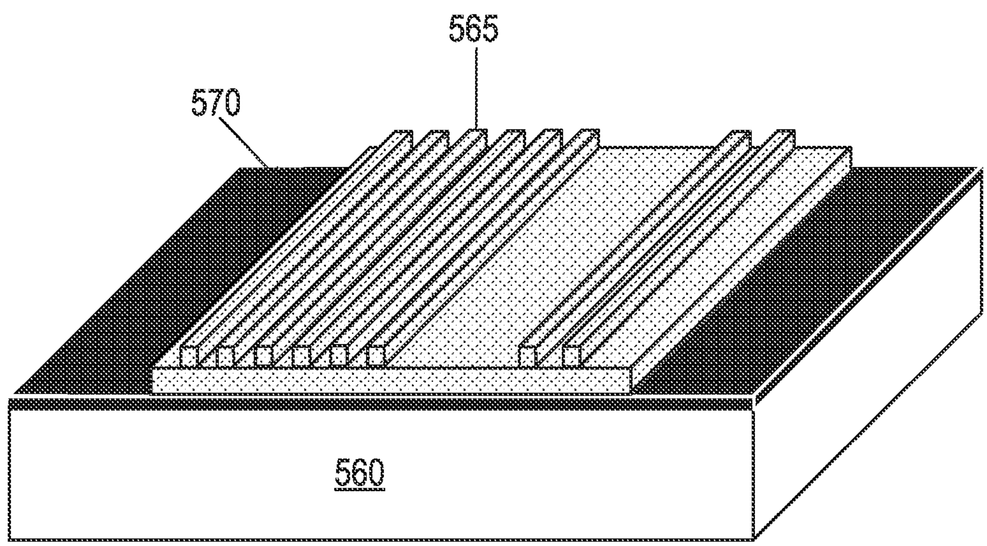

FIG. 5E

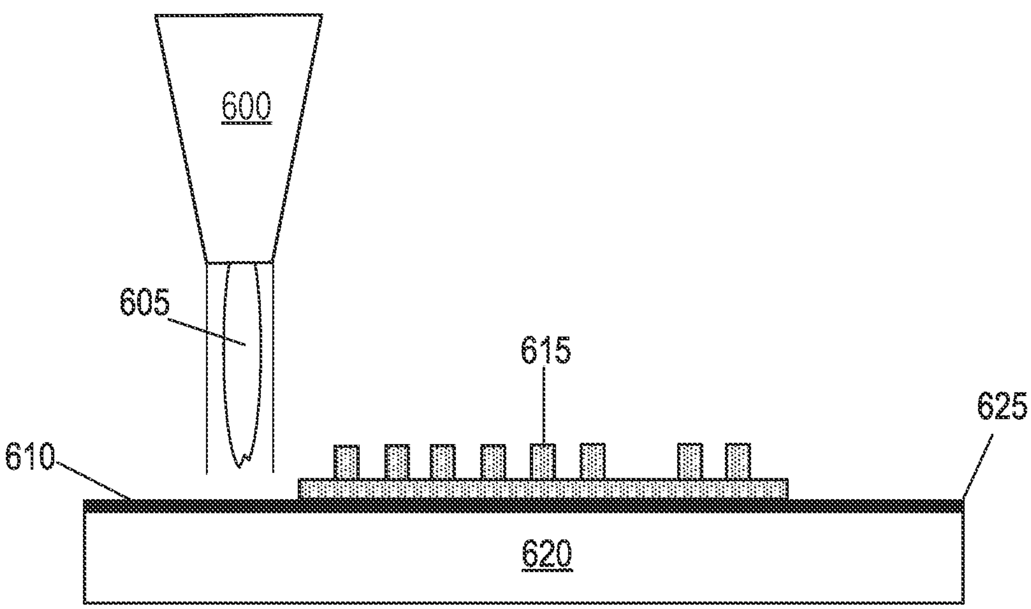

FIG. 6A

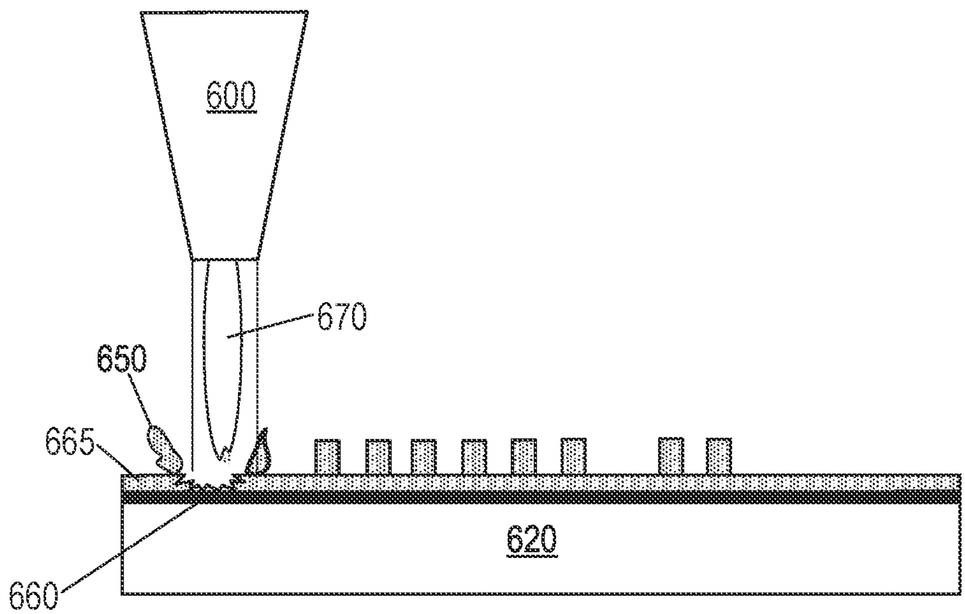

FIG. 6B

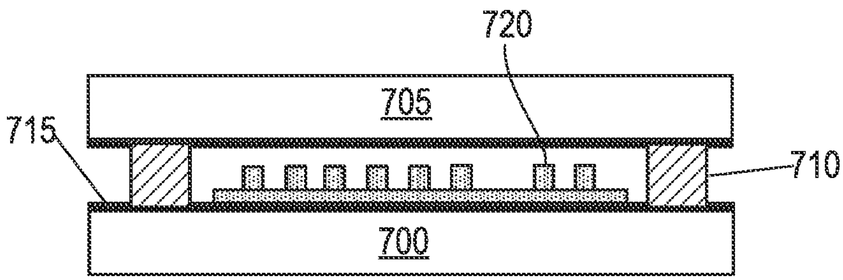

FIG. 7A

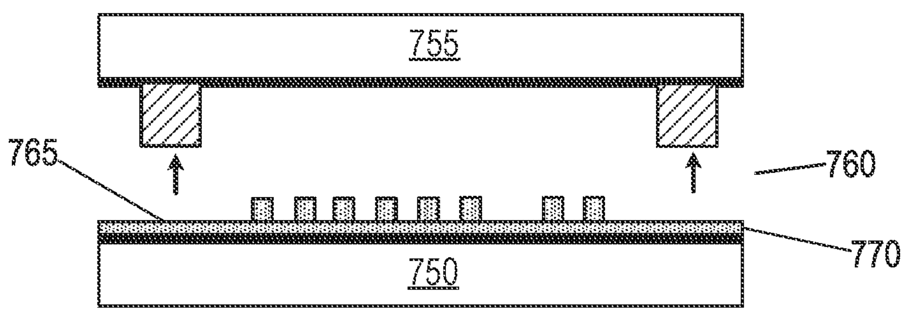

FIG. 7B

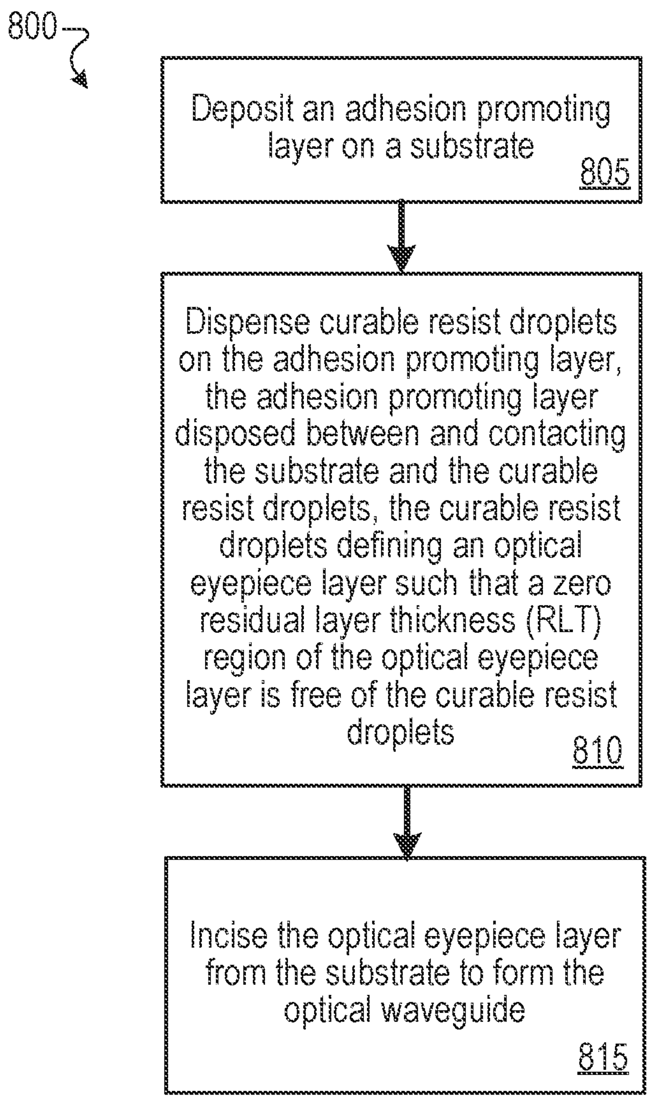
800
Deposit an adhesion promoting layer on a substrate
805
Dispense curable resist droplets on the adhesion promoting layer, the adhesion promoting layer disposed between and contacting the substrate and the curable resist droplets, the curable resist droplets defining an optical eyepiece layer such that a zero residual layer thickness (RLT) region of the optical eyepiece layer is free of the curable resist droplets
810
Incise the optical eyepiece layer from the substrate to form the optical waveguide
815

FIG. 8

EYEPIECE ASSEMBLY ADHESION USING A ZERO RESIDUAL LAYER REGION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims is a divisional of U.S. application Ser. No. 16/518,547, filed on Jul. 22, 2019, which claims the benefit of U.S. Provisional Application 62/702,508, filed on Jul. 24, 2018, which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

This disclosure relates to manufacturing an optical waveguide by selectively dispensing curable resist droplets on a substrate.

BACKGROUND

Imprint lithography is used to fabricate nanometer-scale patterns on wafers. However, a layer of imprint resist material used by traditional lithography methods may react with a layer of stacking glue material, thus reducing the shear strength of the fabricated product. Stacked optical structures manufactured using traditional lithography methods may therefore suffer delamination and yield loss. Moreover, the layer of imprint resist material may result in scattered light due to non-uniformity and a lower diffraction index. Uncontrolled light scatter in traditional lithography methods may bounce back, reducing image quality, sharpness, and uniformity.

SUMMARY

Innovative aspects of the subject matter described in this specification include a method of manufacturing an optical waveguide. The method includes depositing an adhesion promoting layer on a substrate. Multiple curable resist droplets are dispensed on the adhesion promoting layer. The adhesion promoting layer is disposed between and contacts the substrate and the curable resist droplets. The curable resist droplets define an optical eyepiece layer such that a zero residual layer thickness (RLT) region of the optical eyepiece layer is free of the curable resist droplets. The optical eyepiece layer is incised from the substrate to manufacture the optical waveguide.

Innovative aspects of the subject matter described in this specification further include a system for manufacturing an optical waveguide. The system includes a vapor deposition machine configured to deposit an adhesion promoting layer on a substrate. The system further includes a fluid dispenser configured to dispense multiple curable resist droplets on the adhesion promoting layer. The adhesion promoting layer is disposed between and contacts the substrate and the curable resist droplets. The curable resist droplets define an optical eyepiece layer such that a zero RLT region of the optical eyepiece layer is free of the curable resist droplets. The system further includes a controller configured to incise, by a laser beam, the optical eyepiece layer from the substrate to manufacture the optical waveguide.

Innovative aspects of the subject matter described in this specification further include an optical structure for manufacturing an optical waveguide. The optical structure includes a substrate and an adhesion promoting layer deposited on the substrate. Multiple curable resist droplets are disposed on the adhesion promoting layer. The adhesion promoting layer is disposed between and contacts the substrate and the curable resist droplets. The curable resist droplets define an optical eyepiece layer such that a zero RLT region of the optical eyepiece layer is free of the curable resist droplets.

Among other advantages and benefits of the embodiments disclosed herein, the scattering of light at the edges of each optical eyepiece layer is reduced compared to traditional lithography methods. Because there is no imprint resist material on the edges of each eyepiece layer, a laser beam can make direct contact with the substrate for incision. The sharpness of the optics is thereby improved compared to traditional lithography methods. The presence of particle defects is reduced on the zero RLT region of the optical eyepiece layer compared to traditional lithography methods. The absence of imprint resist reduces the formation of amplified imprint defects and increases the product quality and optical performance compared to traditional lithography methods. Moreover, a mechanically stable and hermetically sealed encapsulation is achieved from the improved adhesion at the adhesion promoting layer disposed on the substrate. A bond at the exposed portion of the adhesion promoting layer provides improved protection of the sensitive internal optical structures from environmental influences and results in longer-term stability and reliability of the optical elements and compatibility with the surrounding periphery. The embodiments disclosed herein therefore provide an imprint lithography process having lower cost, higher throughput, and higher resolution. A three-dimensional patterning process can be used and imprint molds can be fabricated with multiple layers of topography stacked vertically. The resulting imprints replicate multiple layers in a single imprint step, which allows optics manufacturers to reduce particle defects and fabrication costs, and improve optical performance compared to traditional lithography methods.

The details of one or more embodiments of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other potential features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure (FIG. **1** illustrates an example side view of a lithography system.

FIG. **2**A illustrates an example side view of a substrate having a patterned layer positioned thereon.

FIG. **2**B illustrates an example lithography system for manufacturing an optical waveguide.

FIG. **3** illustrates a planar view of an optical structure having an optical eyepiece layer.

FIG. **4** illustrates a planar view of an optical structure having a diffraction grating.

FIGS. **5**A-E illustrate steps in a sequence of manufacturing an optical waveguide.

FIGS. **6**A-B illustrate directing of a laser beam onto an edge of an optical eyepiece.

FIGS. **7**A-B illustrate bonding of an optical eyepiece layer to a second optical eyepiece layer.

FIG. **8** illustrates a process of manufacturing an optical waveguide.

DETAILED DESCRIPTION

Imprint lithography is used to fabricate nanometer-scale patterns on wafers. Imprint lithography can create optical patterns by mechanical deformation of imprint resist. However, using traditional lithography methods, when a layer of imprint resist material is deposited on top of a non-grating pattern area of an optical eyepiece, the imprint resist may react with stacking glue material, thus reducing the adhesion and shear strength of the fabricated product. When stacked optical structures are manufactured and handled downstream using traditional lithography methods to build a final product, delamination and yield loss may therefore occur. Moreover, a layer of dummy imprint resist material on top of the non-grating pattern area may result in scattered light due to non-uniformity and a lower diffraction index. Uncontrolled light scatter in traditional lithography methods may bounce back from the optical structure, reducing image quality, sharpness, and uniformity.

This document describes methods and systems for manufacturing an optical waveguide by selectively dispensing curable resist droplets on a substrate. The manufacturing of the optical waveguide includes depositing an adhesion promoting layer on the substrate. The curable resist droplets are selectively dispensed on the adhesion promoting layer in accordance with a resist drop pattern to form a diffraction grating of the optical waveguide. The adhesion promoting layer is disposed between and contacts the substrate and the dispensed curable resist droplets. The curable resist droplets are dispensed on a region of the substrate corresponding to an optical eyepiece layer of the optical waveguide. A zero residual layer thickness (RLT) region of the optical eyepiece layer that corresponds to an edge of the optical eyepiece layer is free of the curable resist droplets. The absence of the curable resist droplets from the edge of the optical eyepiece layer provides reduced particle defects, improved sharpness of images using the optical waveguide, and improved optical performance compared to traditional lithography methods. Moreover, the improved adhesion at the adhesion promoting layer provides improved protection of the sensitive internal optical structures from environmental influences compared to traditional lithography methods.

Example Lithography System

FIG. **1** illustrates an example side view of a lithography system **100**. The lithography system **100** forms a relief pattern on a substrate **102**. For example, the substrate **102** can include glass or silicon. The substrate **102** can be coupled to a substrate chuck **104**. In some embodiments, the substrate chuck **104** includes a vacuum chuck, a pin-type chuck, a groove-type chuck, or an electromagnetic chuck. In some embodiments, the substrate **102** and the substrate chuck **104** are positioned on an air bearing **106**. The air bearing **106** provides motion about the x-, y-, and/or z-axes. In some embodiments, the substrate **102** and the substrate chuck **104** are positioned on a base. The air bearing **106**, the substrate **102**, and the substrate chuck **104** can also be positioned on a stage **108**. In some embodiments, a robot **110** positions the substrate **102** on the substrate chuck **104**.

The lithography system **100** further includes a flexible, coated resist template **112** that can be coupled to one or more rollers **114***a*, **114***b*, **114***c*, **114***d*, or **114***e*. The rollers provide movement of a least a portion of the flexible, coated resist template **112**. Such movement can selectively superimpose different portions of the flexible, coated resist template **112** onto the substrate **102**. In some embodiments, the flexible, coated resist template **112** includes a patterning surface that includes multiple patterning features, e.g., spaced-apart recesses and protrusions. The patterning surface can define any arbitrary pattern to be imprinted on the substrate **102**. In some embodiments, the flexible, coated resist template **112** is coupled to a template chuck, e.g., a vacuum chuck, a pin-type chuck, a groove-type chuck, or an electromagnetic chuck.

The lithography system **100** further includes a fluid dispenser **120**. The fluid dispenser **120** can be used to deposit a polymerizable material on the substrate **102**. The polymerizable material can be positioned upon the substrate **102** using drop dispense, spin-coating, dip coating, chemical vapor deposition, physical vapor deposition, thin film deposition, or thick film deposition. In some embodiments, the polymerizable material is positioned upon the substrate **102** in the form of multiple curable resist droplets. The lithography system **100** can further include an energy source **122** to direct energy (e.g., broadband ultraviolet radiation) towards the substrate **102**. In some embodiments, the rollers and the air bearing **106** are configured to position a desired portion of the flexible, coated resist template **112** and the substrate **102** to receive the energy. The lithography system **100** can be regulated by a controller in communication with the air bearing **106**, the rollers, the fluid dispenser **120**, and/or the energy source **122**. An example controller is illustrated and described in more detail below with reference to FIG. **2**B.

Example Substrate Having a Patterned Layer

FIG. **2**A illustrates an example side view of a substrate **102** having a patterned layer **250** positioned thereon. In some embodiments, the rollers or the air bearing **106** shown in FIG. **1** above are used to vary a distance between the flexible, coated resist template **112** and the substrate **102** to define a desired volume therebetween that is filled by polymerizable material. The flexible, coated resist template **112** thus directly contacts the polymerizable material. After the desired volume is filled by the polymerizable material, the energy source **122** produces energy, e.g., broadband ultraviolet radiation, causing the polymerizable material to solidify and/or cross-link conforming to a shape of a surface of the substrate **102** and a portion of the patterning surface of the flexible, coated resist template **122**. The cured polymerizable material thus defines a patterned layer **250** on the substrate **102**. In some embodiments, the patterned layer **250** includes a residual layer **252** and multiple patterning features shown as protrusions **254** and recessions **256** in FIG. **2**A.

Example Lithography System for Manufacturing an Optical Waveguide

FIG. **2**B illustrates an example lithography system **200** for manufacturing an optical waveguide. The lithography system **200** includes a vapor deposition machine **226**, a controller **224**, a fluid dispenser **120**, a laser **228**, and an energy source **122**. The lithography system **200** can be used to manufacture a multi-layered waveguide structure stacked to intercept light passing sequentially through each waveguide. Each waveguide can be associated with a differing color and a differing depth of plane.

The vapor deposition machine **226** is configured to deposit an adhesion promoting layer on a substrate (e.g., the substrate **102**). The vapor deposition machine **226** can be used to produce a thin film or coating of the adhesion promoting layer on the substrate **102**. For example, the adhesion promoting layer can be transformed from a condensed phase to a vapor phase and then back to a thin film condensed phase onto the substrate **102** using sputtering or evaporation. The adhesion promoting layer is intended to improve the adhesion of curable resist droplets to the substrate **102**. The vapor deposition machine **226** can apply the adhesion promoting layer by spinning a diluted solution on to the substrate **102** and allowing the solution to spin dry.

The fluid dispenser **120** dispenses a thin layer of imprint resist (e.g., thermoplastic polymer) in the form of curable droplets onto the adhesion promoting layer. The adhesion promoting layer is thus disposed between and directly contacts the substrate **102** and the dispensed curable resist droplets. The curable resist droplets define an optical eyepiece layer of the waveguide. The curable resist droplets are selectively dispensed such that an edge of the optical eyepiece layer is free of the curable resist droplets. The edge of the optical eyepiece layer corresponds to a zero RLT region of the optical eyepiece layer, where the thickness of the residual imprint resist is zero.

In some embodiments, the fluid dispenser **120** dispenses the curable resist droplets on the adhesion promoting layer by injecting the curable resist droplets at predefined coordinates and a predefined frequency. The injection of the curable resist droplets thus causes adjacent pairs of droplets to have a predefined separation (XY pitch) on the adhesion promoting layer. For example, the fluid dispenser **120** can be programmed with a resist drop pattern to indicate points or regions where the imprint resist is to be or is not to be dispensed. The resist drop pattern can further define multiple void fiducials to monitor the placement of the imprint resist. A high-resolution resist drop pattern can be programmed that includes predefined coordinates for individual resist droplets and a predefined XY pitch between adjacent pairs of droplets. The curable resist droplets are therefore dispensed on the adhesion promoting layer at predefined coordinates and a predefined frequency, such that at least two adjacent droplets of the curable resist droplets have a predefined separation on the adhesion promoting layer.

In some embodiments, the fluid dispenser **120** includes inkjet heads that propel the curable resist droplets onto the substrate. One or more inkjet heads of the fluid dispenser **120** are translated relative to the substrate. For example, the fluid dispenser **120** can operate at a high frequency while dispensing the curable resist droplets while the substrate **102** is positioned and moved under the inkjet heads. Ultra-high resolution and precision (X, Y, volume) are achieved by the inkjet dispense frequency, head voltage, and stage movement control. The curable resist droplets can be injected on the adhesion promoting layer by moving the inkjet heads of the fluid dispenser **120** across the substrate **102**, moving the substrate **102** across the inkjet heads of the fluid dispenser **120**, or moving the inkjet heads of the fluid dispenser **120** and the substrate **102** across each other.

The lithography system **200** can be regulated by a controller **224** in communication with the vapor deposition machine **126**, the fluid dispenser **120**, the laser **228**, and/or the energy source **122**. In some embodiments, the controller **224** operates on a computer-readable program stored in a computer memory. The controller **224** can be implemented in software, hardware, or a combination thereof. For example, the controller **224** can be part of a personal computer (PC), a tablet PC, an internet of things (IoT) appliance, or any other machine capable of executing instructions that specify actions to be taken by that machine.

In some embodiments, the controller **224** instantiates void fiducials in the optical structure being manufactured to monitor the dispensing of the curable resist droplets within the optical eyepiece layer. The controller **224** instantiates void fiducials on the substrate **102** to determine whether the curable resist droplets are being dispensed in accordance with the resist drop pattern. The controller **224** also instantiates fiducial markers in the optical eyepiece layer by superimposing a coated resist template (e.g., the flexible, coated resist template **112** of FIG. **1**) onto the curable resist droplets. Void fiducials and fiducial markers are markers that can be placed in a field of view of an optical structure for use as a point of reference or a measure. The void fiducials can be placed into or on the imaging subject or on a mark or set of marks in the optical structure.

The controller **224** superimposes the flexible, coated resist template **112** onto the curable resist droplets to contact and pattern the curable resist droplets. The flexible, coated resist template **112** includes a patterning surface comprising one or more recesses and protrusions. An example recess **256** and protrusion **254** is illustrated and described in more detail above with reference to FIG. **2**A. The flexible, coated resist template **112** can further include a deep grating structure or dam configured to prevent the curable resist droplets from flowing into the zero RLT region of the optical eyepiece layer. The deep grating structure or dam has ridges or rulings having a raised height that physically prevent the curable resist droplets from flowing into the zero RLT region of the optical eyepiece layer.

The controller **224** is configured to direct energy (e.g., broadband ultraviolet radiation) from an energy source **122** to cure the curable resist droplets. After the imprint resist is cured, the controller **224** removes the flexible, coated resist template **112** to expose the patterned resist, which then conforms to a portion of the patterning surface of the flexible, coated resist template **112**. The cured, patterned imprint resist forms a diffraction grating of the waveguide for diffraction of light to generate an image using the eyepiece. The diffraction gratings diffract light traveling through the optical waveguide. In some embodiments, the diffraction grating formed on the optical structure is etched to manufacture the optical eyepiece layer. In other embodiments, the need to dry etch the substrate **102** (e.g., dry etching high-index glass or sapphire) is abrogated. In some embodiments, the substrate **102** can be partially etched (e.g., using a plasma process under atmospheric or low pressure conditions) to remove a residual imprint layer and/or transfer the grating pattern into the substrate **102** while maintaining a portion of the residual imprint layer on a surface of the substrate **102**. While the imprint resist can be removed by laser ablation in one embodiment, in other embodiments the imprint resist is simply not placed on the substrate **102** (e.g., by masking), etched off (e.g., by plasma), or a combination thereof.

The controller **224** is further configured to direct a laser beam from the laser **228** onto a portion of the adhesion promoting layer to incise the substrate **102**. An example laser beam **605** is illustrated and described below with reference to FIG. **6**A. The optical eyepiece layer can be incised from the substrate **102** by pulsing the laser beam onto the adhesion promoting layer to generate nanoperforations in the substrate **102**. The laser beam is applied to the generated nanoperforations to expand the nanoperforations and separate the optical eyepiece layer from the substrate **102**. The optical eyepiece layer can be bonded to a second optical eyepiece layer imprinted on a second substrate to manufacture the optical waveguide.

The laser **228** provides the laser beam to incise the substrate **102**. In some embodiments, the laser **228** includes a gain medium, an energizing mechanism, and an optical feedback mechanism to generate the laser beam. The gain medium is a material with properties that allow the laser **228** to amplify light by way of stimulated emission. The laser **228** can use feedback from an optical cavity, and can affect properties of the emitted light, such as the polarization, wavelength, and shape of the laser beam.

The energy source **122** provides radiation to strengthen (e.g., polymerize, cure, or cross-link) the curable resist droplets, leaving behind an imprint resist coating on the substrate **102**. In some embodiments, the energy source **122** decreases a wavelength of the radiation to achieve a higher resolution. For example, the energy source **122** can provide the energy at wavelengths in the ultraviolet spectrum or shorter (<400 nm) or the deep ultraviolet spectrum.

Optical Structure Having Optical Eyepiece Layer

FIG. **3** illustrates a planar view of an optical structure **300** having an optical eyepiece layer **320**. The optical structure **300** includes a substrate **325**, a resist dispense region **305**, a void fiducial **310**, and the optical eyepiece layer **320**. The optical eyepiece layer **320** has an edge **315** corresponding to a zero RLT region.

The optical structure **300** is manufactured by depositing an adhesion promoting layer on the substrate **325**. The substrate **325** is made of a high refractive index material, such as glass or silicon. Curable resist droplets are dispensed on the adhesion promoting layer in accordance with a programmed resist drop pattern to form the optical eyepiece layer **320**. A first region of the resist drop pattern defines the optical eyepiece layer **320** and a second region of the resist drop pattern defines the edge **315**. The edge **315** of the optical eyepiece layer **320** is free of the curable resist droplets. In some embodiments, the dispensing of the curable resist droplets includes injecting the curable resist droplets onto the substrate **325** at predefined coordinates and a predefined frequency. The injection of the curable resist droplets thus causes pairs of adjacent droplets to have a predefined separation. The fluid dispenser **120** performs steps to translate the inkjet heads of the fluid dispenser **120** relative to the substrate **325**. For example, the curable resist droplets can be injected on the adhesion promoting layer by moving the inkjet heads of the fluid dispenser **120**, moving the substrate **325** across the inkjet heads of the fluid dispenser **120**, or moving the inkjet heads of the fluid dispenser **120** and the substrate **325** across each other.

In some embodiments, the void fiducial **310** is instantiated in the optical structure **300** to monitor the dispensing of the curable resist droplets within the optical eyepiece layer **320**. Because the second region of the resist drop pattern defining the edge **315** of the optical eyepiece layer **320** is free of the curable resist droplets, the optical performance of the optical waveguide is increased by reducing the scattering of light at the edge **315** and reducing a number of particle defects on the zero RLT region of the optical eyepiece layer **320** compared to traditional lithography methods. The zero RLT region of the optical eyepiece layer **320** corresponds to the edge **315**. The thickness of the imprint residual layer can be determined by various process parameters including the initial thickness of the applied imprint resist material, the viscosity of the imprint resist, the imprint pressure, and the structure of the imprint coated resist template and pattern area. A uniform and reduced-thickness residual imprint layer achieved using the embodiments disclosed herein reduces the number of imprint defects and improves optical performance of the optical waveguide compared to traditional lithography methods.

Optical Structure Having Diffraction Grating

FIG. **4** illustrates a planar view of an optical structure **400** having a diffraction grating **420**. The optical structure **400** includes a substrate **430**, a resist dispense region **405**, a void fiducial **410**, an optical eyepiece layer **435**, the diffraction grating **420**, and a fiducial marker **425**. The optical eyepiece layer **435** has an edge **415** corresponding to a zero RLT region of the optical eyepiece layer **435**.

The optical structure **400** is an intermediate device in a process of manufacturing an optical waveguide on the substrate **430**. The process includes depositing an adhesion promoting layer on the substrate **430**. Curable resist droplets are dispensed on the resist dispense region **405** to form a diffraction grating (e.g., the diffraction grating **420**). The adhesion promoting layer is disposed between and directly contacts the substrate **430** and the dispensed curable resist droplets. For example, the resist drop pattern may include the diffraction grating **420** and a residual layer having a thickness less than 50 nanometers. The diffraction grating **420** can include a critical dimension of approximately 100 nanometers.

In some embodiments, the dispensing of the curable resist droplets includes injecting the curable resist droplets onto the adhesion promoting layer at predefined coordinates and a predefined frequency to cause a pair of adjacent droplets to have a predefined separation on the adhesion promoting layer. A zero RLT region of the optical eyepiece layer **435** that corresponds to the edge **415** of the optical eyepiece layer **435** is free of the curable resist droplets. The resist dispense region **405** is therefore wholly or partially excluded from the no-imprint pattern area (e.g., the edge **415**) by defining the resist drop pattern area on the substrate **430**. The non-grating pattern area (e.g., the edge **415**) is thus omitted from the resist drop pattern, such that no or minimal imprint resist is dispensed at this location (the edge **415**) during imprint. An alignment budget (e.g., ~250 μm) is designed to be sufficient to ensure that there is enough resist volume at the imprint diffraction grating area (e.g., the diffraction grating **420**).

The diffraction grating **420** is an optical component having a periodic structure that splits and diffracts light into several beams travelling in different directions. The directions of these beams depend on the spacing of the diffraction grating **420** and the wavelength of the light, such that the diffraction grating **420** acts as a dispersive element. The diffraction grating **420** thus diffracts light traveling through the optical waveguide. The diffraction grating **420** can have ridges or rulings on the surface. In some embodiments, an interference pattern between two or more coherent light waves is set up and recorded in the imprint resist to form the diffraction grating **420**. The interference pattern can include a periodic series of fringes representing intensity minima and maxima. In some embodiments, the diffraction grating **420** is etched to manufacture the optical eyepiece layer **435**.

In some embodiments, the forming of the diffraction grating **420** includes superimposing a flexible, coated resist template onto the curable resist droplets to contact and pattern the curable resist droplets. Such a flexible, coated resist template **112** is illustrated and described in more detail above with reference to FIG. **1**. The flexible, coated resist template **112** (also known as a submaster) makes direct contact with the imprint resist on top of the high-index substrate **430**. In some embodiments, a deep grating structure or a dam is added to the flexible, coated resist template **112** to prevent the curable resist droplets from flowing into the zero RLT region of the optical eyepiece layer **435**. The deep grating structure or dam has a larger pitch, such that there is reduced light interference on the red-green-blue (RGB) wavelength compared to traditional lithography methods. The flexible, coated resist template **112** is removed to expose the diffraction grating **420**. The diffraction grating

420 conforms to a portion of the patterning surface of the flexible, coated resist template 112.

In some embodiments, the void fiducial 410 is instantiated on the substrate 430 in accordance with the resist drop pattern to monitor the dispensing of the curable resist droplets within the optical eyepiece layer 435. The void fiducial 410 is designed to monitor whether the process conforms to the resist drop pattern for field alignment to improve accuracy of the alignment process and avoid non-fill defects within the functioning area of the optical structure 400.

The fiducial marker 425 is instantiated to align the dispensed curable resist droplets with the void fiducial 410 defined by the resist drop pattern. The fiducial marker 425 can be instantiated in the field of view of the optical structure 400 for use as a point of reference. In some embodiments, the fiducial marker 425 can be instantiated on an opposite side of the optical eyepiece layer 435 rather than on the optically active side of the diffraction grating 420. The fiducial marker 425 can thus partially overlap the optically active diffraction grating 420, such that the fiducial marker 425 is visible to a camera viewing the optical structure 400 through the diffraction grating 420.

The fiducial marker 425 is instantiated by superimposing the flexible, coated resist template 112 onto the curable resist droplets. An offset is measured between the void fiducial 410 and the fiducial marker 425. The measured offset is corrected to align the zero RLT region of the optical eyepiece layer 435 with a deep grating structure or dam located on the flexible, coated resist template 112. The deep grating structure or dam corresponds to the edge 415 of the optical eyepiece layer 435. By measuring and correcting the offset between the void fiducial 410 and the fiducial marker 425 during the imprint process (i.e., the direct-contact submaster with the imprint resist on top of the substrate 430), the no-resist droplet zone on the substrate 430 is aligned with the dam structure on the edge 415 of the eyepiece layer from the submaster.

In an artificial reality application (e.g., augmented reality or mixed reality), the fiducial marker 425 improves integration between a real world view and synthetic images that augment the real world view. Fiducial markers of known patterns and sizes can serve as real world anchors of location, orientation and scale. They can establish the identity of the scene or objects within the scene. The fiducial marker 425 can also serve to moor the coordinates of the augmented content to the three dimensional location, orientation and scale, to create a stable and accurate fusion of real and synthetic imagery. In some embodiments, the diffraction grating 420 includes an orthogonal pupil expander, an exit pupil expander, or a multidirectional pupil expander.

The controller 224 directs a laser beam from the laser 228 onto a portion of the adhesion promoting layer to incise the optical eyepiece layer 435 from the substrate 430. The laser beam is laterally spaced from the diffraction grating 420, such that the diffraction grating 420 is not disturbed. Excess or unwanted imprint resist is removed by laser ablation in some embodiments. In other embodiments, the imprint resist is simply not dispensed on unwanted regions (e.g., by masking). In other embodiments, unwanted imprint resist is etched off (e.g., by plasma).

Because the region defining the edge 415 of the optical eyepiece layer 435 is free of the curable resist droplets, the optical performance of the optical waveguide is increased compared to traditional lithography methods. The scattering of light at the edge 415 of the optical eyepiece layer 435 is reduced compared to traditional lithography methods. Further, a number of particle defects on the zero RLT region (e.g., the edge 415) of the optical eyepiece layer 435 is reduced compared to traditional lithography methods.

Manufacturing of Optical Waveguide

FIGS. 5A-E illustrate steps in a sequence of manufacturing an optical waveguide. Specifically, FIG. 5A illustrates a cross-sectional view of a substrate 500 and an adhesion promoting layer 505 deposited by a vapor deposition machine on the substrate 500. A fluid dispenser is configured to dispense the curable resist droplets 510 on the adhesion promoting layer 505 to form a diffraction grating. The adhesion promoting layer 505 is disposed between and directly contacts the substrate 500 and the dispensed curable resist droplets 510. A programmed resist drop pattern used for fabricating the optical waveguide corresponds to an optical eyepiece layer. The region 515 corresponding to an edge of the optical eyepiece layer is free of the curable resist droplets 510. The curable resist droplets 510 are therefore strategically injected on only a region of the optical eyepiece layer that is to be patterned into a diffraction grating.

The fluid dispenser is configured to dispense the curable resist droplets 510 on the adhesion promoting layer 505 at predefined coordinates and a predefined frequency to cause adjacent pairs of droplets to have a predefined separation on the adhesion promoting layer 505. The curable resist droplets 510 can be injected onto the adhesion promoting layer 505 by moving inkjet heads of the fluid dispenser, moving the substrate 500 across the inkjet heads, or moving the inkjet heads of the fluid dispenser and the substrate 500 across each other.

FIG. 5B illustrates a step in the sequence of manufacturing the optical waveguide. The components illustrated in FIG. 5B include the substrate 500, the adhesion promoting layer 505, the curable resist droplets 510, and a flexible, coated resist template 520. A controller (e.g., the controller 224 illustrated and described in more detail above with reference to FIG. 2B) is configured to superimpose the flexible, coated resist template 520 onto the curable resist droplets 510 to contact and pattern the curable resist droplets 510.

The flexible, coated resist template 520 includes a patterning surface comprising multiple recesses (e.g., recess 530) and protrusions (e.g., protrusion 525). In some embodiments, the protrusions 525 are associated with the resist drop pattern to minimize the striation of a virtual image caused by light exiting the optical eyepiece layer. In other embodiments, the pattern of the protrusions 525 is randomized. In other embodiments, the pattern of the protrusions 525 is geometric, e.g., circular or hexagonal. In some embodiments, the pattern of the protrusions 525 is associated with a density, and the pattern density of the protrusions 525 minimizes the striation of a virtual image. The pattern density of the protrusions 525 can include a quantity of the protrusions 525 included by the waveguide, or any sub-portion of the waveguide. That is, differing regions of the waveguide can include differing densities of protrusions 525 to minimize the striation of the virtual image. The flexible, coated resist template 520 can further include a deep grating structure or dam configured to prevent the curable resist droplets from flowing into the zero RLT region of the optical eyepiece layer. The zero RLT region corresponds to the region 515 corresponding to an edge of the optical eyepiece layer.

FIG. 5C illustrates a step in the sequence of manufacturing the optical waveguide. The components illustrated in FIG. 5C include the substrate 500, the patterned imprint resist 540, and the flexible, coated resist template 520. The controller **224** directs energy (e.g., broadband ultraviolet radiation) from an energy source (e.g., the energy source **122** of FIG. **2**B above) to cure the patterned imprint resist **540**.

FIG. **5**D illustrates a step in the sequence of manufacturing the optical waveguide. The components illustrated in FIG. **5**D include the substrate **500** and the patterned and cured imprint resist **545**. The flexible, coated resist template **520** shown above in FIG. **5**C has been removed to expose a diffraction grating.

FIG. **5**E illustrates a step in the sequence of manufacturing the optical waveguide. The components illustrated in FIG. **5**E include a substrate **560**, the exposed adhesion promoting layer **570**, and the patterned and cured imprint resist **565**. The diffraction grating illustrated in FIG. **5**E conforms to a portion of the patterning surface of the flexible, coated resist template **520** shown in FIG. **5**C. The optical eyepiece layer illustrated in FIG. **5**E can be bonded to a second optical eyepiece layer imprinted on a second substrate to manufacture the optical waveguide. The optical eyepiece layer is bonded to the second optical eyepiece layer at the exposed adhesion promoting layer **570** disposed on the substrate **560**. As illustrated in FIG. **5**E, the exposed portion **570** of the adhesion promoting layer is free of the cured, patterned imprint resist **565**.

Directing Laser Beam onto Edge of Optical Eyepiece Layer

FIG. **6**A illustrates the directing of a laser beam **605** onto an edge of an optical eyepiece layer. A controller (e.g., the controller **224** of FIG. **2**A above) can be configured to direct the laser beam **605** from the laser **600** onto the exposed portion **610** of the adhesion promoting layer **625** to incise the optical eyepiece layer from the substrate **620**. The optical eyepiece layer includes the cured, patterned imprint resist **615**. The controller **224** maintains the laser beam **605** spaced laterally from the diffraction grating formed on the substrate **620**. The laser beam **605** incises the optical eyepiece layer formed by the cured, patterned imprint resist **615** from the substrate **620**. The controller **224** maintains a lateral spacing between the laser beam **605** and the cured, patterned imprint resist **615**, such that the cured, patterned imprint resist **615** is not disturbed.

In some embodiments, the optical eyepiece layer is incised from the substrate **620** by pulsing the laser beam **605** onto the exposed portion **610** of the adhesion promoting layer **625** to generate nanoperforations in the substrate **620**. In some embodiments, a high-frequency, low-power pulsed laser beam is used at a wavelength that transmits through the substrate **620**. The pulsed laser beam can be focused to a point beneath a surface of the substrate **620**. When the laser beam **605** hits a peak power density at the focal point, the substrate **620** absorbs the laser energy, and a pinpoint hole is created. The laser beam **605** can also cause compressive and tensile stress near the hole. As the laser beam **605** travels the length of the substrate **620**, it perforates the substrate **620**.

In some embodiments, a high-power laser beam **605** is applied to the generated nanoperforations to expand the nanoperforations and separate the optical eyepiece layer from the substrate **620**. The sensitivity of the brittle substrate **620** to thermal fracture is used to perform the separation. A steady laser beam **605** is focused on the substrate **620** causing localized heating and thermal expansion. The expansion results in a crack that can be guided by moving the laser beam **605**. The separation of the individual optical eyepiece layer occurs when the substrate **620** is expanded. The stress area introduced by laser processing provides the separation. A compressive stress around each nanoperforation can be bounded on top and bottom by spots of tensile stress, and the stress creates fissures along the path of the laser beam **605**.

FIG. **6**B illustrates an alternate scenario in which the imprint resist material **665** has been dispensed on an edge **660** of an optical eyepiece layer on the substrate **620**. In this alternate scenario, the embodiments disclosed for manufacturing an optical waveguide by selective dispensing of curable resist droplets are not used. When a laser beam **670** from the laser **600** is directed onto the edge **660** of the optical eyepiece layer, particle defects **650** from the residual imprint resist **665** can form on the substrate **620**. The particle defects **650** on the substrate **620** can occur when the laser beam **670** pulverizes the imprint resist material **665** in the cutting path (known as dicing street or kerf). In doing so, problems such as the debris **650** on the substrate **620**, damage to the device, and loss of precious semiconductor material can occur. As a result, the optical structure can be damaged and/or become contaminated with the small (sub-micron) particle contaminants **650** (e.g., a small particle positioned on the substrate **620** can become lodged in the features of, or otherwise become adhered to, the optical structure.

Imprint defect-related high yield loss can be critical when such small particles **650** fall on sub-matter or product wafers at a non-pattern area. The size of such defects can be larger than the particle size due to imprint tenting effect. Such amplified imprint defects can serve as unexpected light scattering sources and may have to be quarantined. The dummy imprint resist **665** on top of the non-grating area **660**, especially at the edge of eyepiece layers, can serve as a source of scattered light due to the non-uniformity and lower index. Uncontrolled scatter light can bounce back from the device functioning area and reduce the image quality.

Among other advantages and benefits, the embodiments disclosed herein (e.g., in FIG. **6**A) reduce the scattering of light at the edge of the optical eyepiece layer compared to traditional lithography methods. Because there is no imprint resist material on the edge of the optical eyepiece layer, the laser beam **605** can make direct contact with the substrate **620**. The sharpness of the optics is thereby improved compared to traditional lithography methods. Further, particle defects (e.g., **650**) are reduced on the zero RLT region of the optical eyepiece layer compared to traditional lithography methods. By removing the dummy imprint resist from the non-imprint area, the formation of amplified imprint defects is reduced and product quality and optical performance is improved compared to traditional lithography methods.

Bonding Optical Eyepiece Layers

FIG. **7**A illustrates the bonding of a first optical eyepiece layer imprinted on a first substrate **700** to a second optical eyepiece layer imprinted on a second substrate **705** to manufacture an optical waveguide. Bonding is used to manufacture the optical waveguide by joining separate components of a compound optical structure.

The manufactured waveguide shown in FIG. **7**A intercepts light passing therethrough, e.g., from a source of light and provides total internal refraction of the light. In some embodiments, the waveguide facilitates the generation of a virtual content display. The waveguide is a multi-layered structure that includes a patterned layer, an adhesive layer, one or more substrates **700**, **705**, and an anti-reflective layer. The multi-layered optical structure formed can include waveguide supports (e.g., the bond **710**). The waveguide support **710** connects and positions the multiple layers within the waveguide optical structure. To that end, the adhesive layer provides adhesion between the respective waveguide and the waveguide bond or support **710**. The waveguide bond or support **710** can be made of such materials as acrylated resin or epoxy resin.

The first optical eyepiece layer imprinted on the substrate **700** includes a cured, patterned imprint resist layer **720**. The cured, patterned imprint resist layer **720** does not cover an exposed portion **715** of an adhesion promoting layer disposed on the first substrate **700**. In some embodiments, lamination glue is dispensed on the exposed portion **715**, which corresponds to a zero RLT region of the first optical eyepiece layer. The zero RLT region of the first optical eyepiece layer is defined by the resist drop pattern preprogrammed in an inkjet program for the fluid dispenser **120** in accordance with the position of the stacking or lamination glue pattern. Therefore, the exposed portion **715** of the adhesion promoting layer is free of the imprint resist. The first optical eyepiece layer is bonded using the bond **710** (e.g., including stacking or lamination glue) to the second optical eyepiece layer imprinted on the second substrate **705** at the exposed portion **715** of the adhesion promoting layer disposed on the first substrate **700**.

FIG. **7**B illustrates an alternate scenario in which the embodiments for manufacturing an optical waveguide using selective deposition of curable resist droplets are not used. As shown in FIG. **7**B, the imprint resist layer **770** covers the region **765** on the substrate **750**. Therefore, the resulting bond **760** with the substrate **755** is weaker, leading to manufacturing and performance defects. For example, the imprint resist **770** on top of the non-grating pattern area **765**, especially at the edge of an eyepiece layer, can react with the stacking glue material to reduce the adhesion and shear strength. When such stacked eyepieces shown in FIG. **7**B are handled downstream to build a final product, delamination can occur and cause yield loss. The embodiments disclosed in FIG. **7**A overcome such problems.

Among other advantages and benefits, the embodiments disclosed in FIG. **7**A provide a mechanically stable and hermetically sealed encapsulation from the improved adhesion at the exposed portion **715** of the adhesion promoting layer disposed on the substrate **700** compared to traditional lithography methods. Other advantages resulting from the disclosed embodiments are that the bond **710** at the exposed portion of the adhesion promoting layer protects the sensitive internal optical structures from environmental influences and provides longer-term stability and reliability of the optical elements, compatibility with the surrounding periphery, and integrity of energy and information flow compared to traditional lithography methods.

Process of Manufacturing an Optical Waveguide

FIG. **8** illustrates a process **800** of manufacturing an optical waveguide by selective deposition of curable resist droplets. In some embodiments, the process **800** is performed by the lithography system **200** illustrated and described in more detail above with reference to FIG. **2**B. The process **800** is illustrated as a collection of referenced acts arranged in a logical flow graph. The order in which the acts are described is not intended to be construed as a limitation, and any number of the described acts can be combined in other orders and/or in parallel to implement the process.

The lithography system **200** deposits **805** an adhesion promoting layer **505** on a substrate **500**. The adhesion promoting layer **505** is intended to improve the adhesion of curable resist droplets **510** to the substrate **500**. The adhesion promoting layer **505** can be applied by spinning a diluted solution on to the substrate **500** and allowing the layer **505** to spin dry.

The lithography system **200** dispenses **810** multiple curable resist droplets **510** on the adhesion promoting layer **505** to form a diffraction grating of the optical waveguide. The adhesion promoting layer **505** is disposed between and directly contacts the substrate **500** and the dispensed curable resist droplets **510**. The curable resist droplets **510** define an optical eyepiece layer having an edge region **515**. The edge region **515** corresponds to a zero RLT region of the optical eyepiece layer and is free of the curable resist droplets **510**.

The lithography system **200** incises **815** the optical eyepiece layer from the substrate **500** to manufacture the optical waveguide. For example, the laser beam **605** from the laser **600** can be directed onto a portion of the adhesion promoting layer **505** to incise the optical eyepiece layer from the substrate **500**, while maintaining the laser beam **605** spaced laterally from the cured, patterned imprint resist **545**. By removing the imprint resist layer **545** from the non-pattern area **515**, uncontrolled light scattering effects are reduced, improving optical performance such as sharpness compared to traditional lithography methods. Further, the disclosed embodiments can expose a ValMat™ monolayer coating as the adhesion promoter to the lamination glue, improving mechanical properties such as layer adhesion, shear strength, or bonding for stacked eyepieces and reducing the imprint defect formation compared to traditional lithography methods.

Further benefits and advantages of the embodiments disclosed herein are that they provide a simplified imprint lithography process having lower cost, higher throughput, and higher resolution compared to traditional lithography methods. A three-dimensional patterning process can be used and imprint molds can be fabricated having multiple layers of topography stacked vertically. The resulting imprints can replicate multiple layers with a single imprint step, which allows optics manufacturers to reduce particle defects and fabrication costs, and improve optical performance compared to traditional lithography methods.

The invention claimed is:

1. A system for manufacturing an optical waveguide, the system comprising:

- a vapor deposition machine configured to deposit an adhesion promoting layer on a substrate;
- a fluid dispenser configured to dispense a plurality of curable resist droplets on the adhesion promoting layer, the adhesion promoting layer disposed between and contacting the substrate and the plurality of curable resist droplets, the plurality of curable resist droplets defining an optical eyepiece layer such that a zero residual layer thickness (RLT) region of the optical eyepiece layer is free of the plurality of curable resist droplets; and
- a controller operatively coupled to the vapor deposition machine and the fluid dispenser, the controller configured to perform incising, by at least one laser beam, of the optical eyepiece layer from the substrate to form the optical waveguide, wherein the incising comprises forming nanoperforations in the substrate.

2. The system of claim **1**, wherein the fluid dispenser is configured to dispense the plurality of curable resist droplets on the adhesion promoting layer at predefined coordinates and a predefined frequency, such that at least two adjacent droplets of the plurality of curable resist droplets have a predefined separation on the adhesion promoting layer.

3. The system of claim **1**, wherein the fluid dispenser is configured to dispense the plurality of curable resist droplets by performing steps to translate one or more inkjet heads of the fluid dispenser relative to the substrate.

4. The system of claim 1, wherein the controller is further configured to:

superimpose a coated resist template onto the plurality of curable resist droplets to contact and pattern the plurality of curable resist droplets, the coated resist template comprising a deep grating structure or dam configured to prevent the plurality of curable resist droplets from flowing into the zero RLT region of the optical eyepiece layer;

cure, by radiation, the plurality of curable resist droplets; and

remove the coated resist template to expose a diffraction grating formed by the plurality of curable resist droplets.

5. The system of claim 1, wherein the controller is further configured to:

instantiate a void fiducial on the substrate to monitor the dispensing of the plurality of curable resist droplets, wherein the void fiducial is defined by a resist drop pattern; and

instantiate a fiducial marker by superimposing a coated resist template onto the plurality of curable resist droplets to contact and pattern the plurality of curable resist droplets.

6. The system of claim 5, wherein the controller is further configured to:

measure an offset between the void fiducial and the fiducial marker; and

align the zero RLT region of the optical eyepiece layer, by the measured offset, with a deep grating structure or dam located on the coated resist template, wherein the deep grating structure or dam corresponds to an edge of the optical eyepiece layer.

7. The system of claim 1, wherein the controller is configured to incise the optical eyepiece layer from the substrate by:

pulsing the at least one laser beam onto the adhesion promoting layer to generate the nanoperforations in the substrate; and

expanding the nanoperforations to separate the optical eyepiece layer from the substrate.

8. The system of claim 1, wherein the controller is further configured to incise the optical eyepiece layer from the substrate by expanding the nanoperforations to separate the optical eyepiece layer from the substrate.

9. The system of claim 1, wherein the at least one laser beam is applied to the generated nanoperforations to expand the nanoperforations to separate the optical eyepiece layer from the substrate.

10. The system of claim 1, wherein the nanoperforations are generated by pulsing the at least one laser beam onto a portion of the zero RLT region of the optical eyepiece layer.

11. The system of claim 1, wherein the nanoperforations are generated by pulsing the at least one laser beam at a wavelength that transmits through the substrate.

12. The system of claim 1, wherein the nanoperforations are generated by focusing the at least one laser beam to a point beneath a surface of the substrate.

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