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(54) **AIRGAP STRUCTURES FOR IMPROVED EYEPIECE EFFICIENCY**

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

(72) Inventors: **Erica Chen**, Cupertino, CA (US); **Kang Luo**, Santa Clara, CA (US); **Hao Tang**, San Jose, CA (US); **Jinrui Guo**, San Jose, CA (US); **Ludovic Godet**, Sunnyvale, CA (US)

(73) Assignee: **Applied Materials, Inc.**, Santa Clara, CA (US)

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G02B 1/11	(2015.01)
G02B 5/18	(2006.01)

(52) **U.S. Cl.**

CPC ***G02B 1/002*** (2013.01); ***G02B 1/11*** (2013.01); ***G02B 5/1842*** (2013.01)

(58) **Field of Classification Search**

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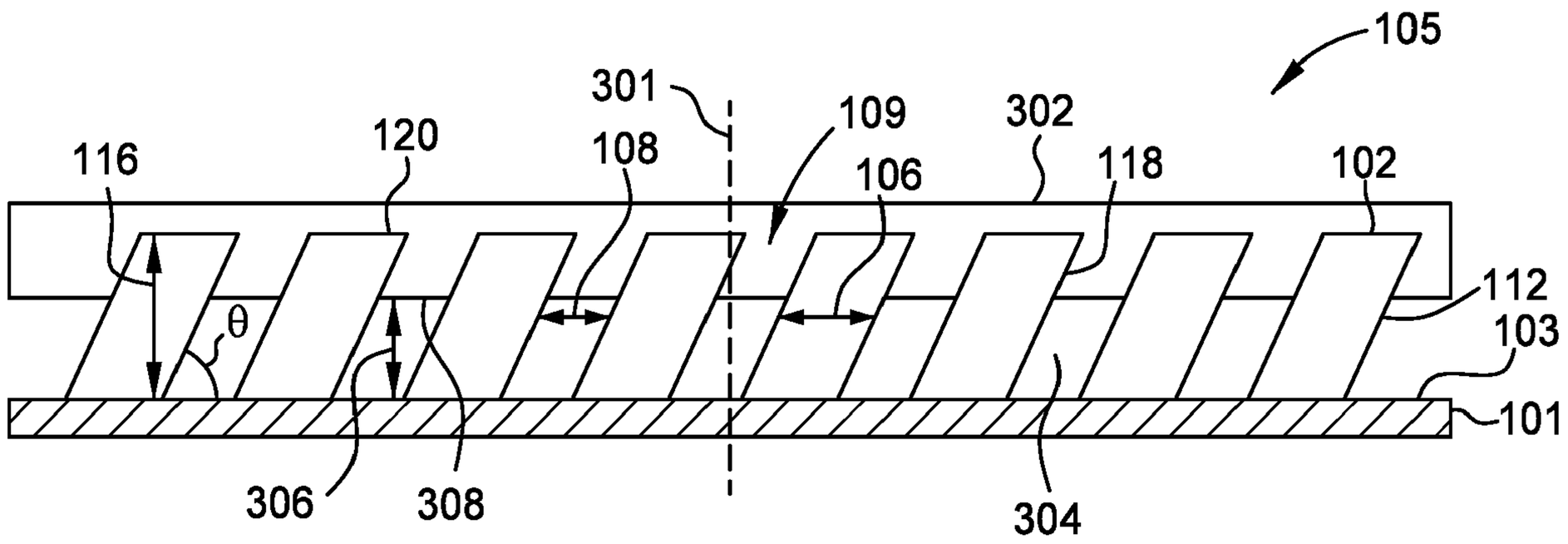
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Primary Examiner — Stephone B Allen
Assistant Examiner — Wai-Ga D Ho
(74) *Attorney, Agent, or Firm* — Patterson + Sheridan, LLP; B. Todd Patterson

(57) **ABSTRACT**

Embodiments of the present disclosure generally relate to encapsulated optical devices and methods of forming encapsulated optical devices. The optical devices include a plurality of optical device structures disposed on a substrate. An encapsulation coating is disposed over the plurality of optical device structures. The encapsulation coating includes a ratio of encapsulation material to solvent. A plurality of gaps are formed in the optical device. The plurality of gaps are formed when the solvent is evaporated from the encapsulation coating. The material composition of the encapsulation coating, the width and device angle of the plurality of optical device structures, as well as process parameters of the spin on coating process, the curing process, the baking process, the drying process, and the developing process will affect the formation of the plurality of gaps and the depth at which the plurality of gaps are formed.

20 Claims, 3 Drawing Sheets



(58) **Field of Classification Search**
CPC G02B 1/113; G02B 1/115; G02B 1/12; G02B 1/14; G02B 5/1819; G02B 5/1842; G02B 5/1847; G02B 5/1866; G02B 27/0081; G02B 2027/0174; G02B 6/4239; B29D 11/00; B01D 63/0225; B81B 7/0032
See application file for complete search history.

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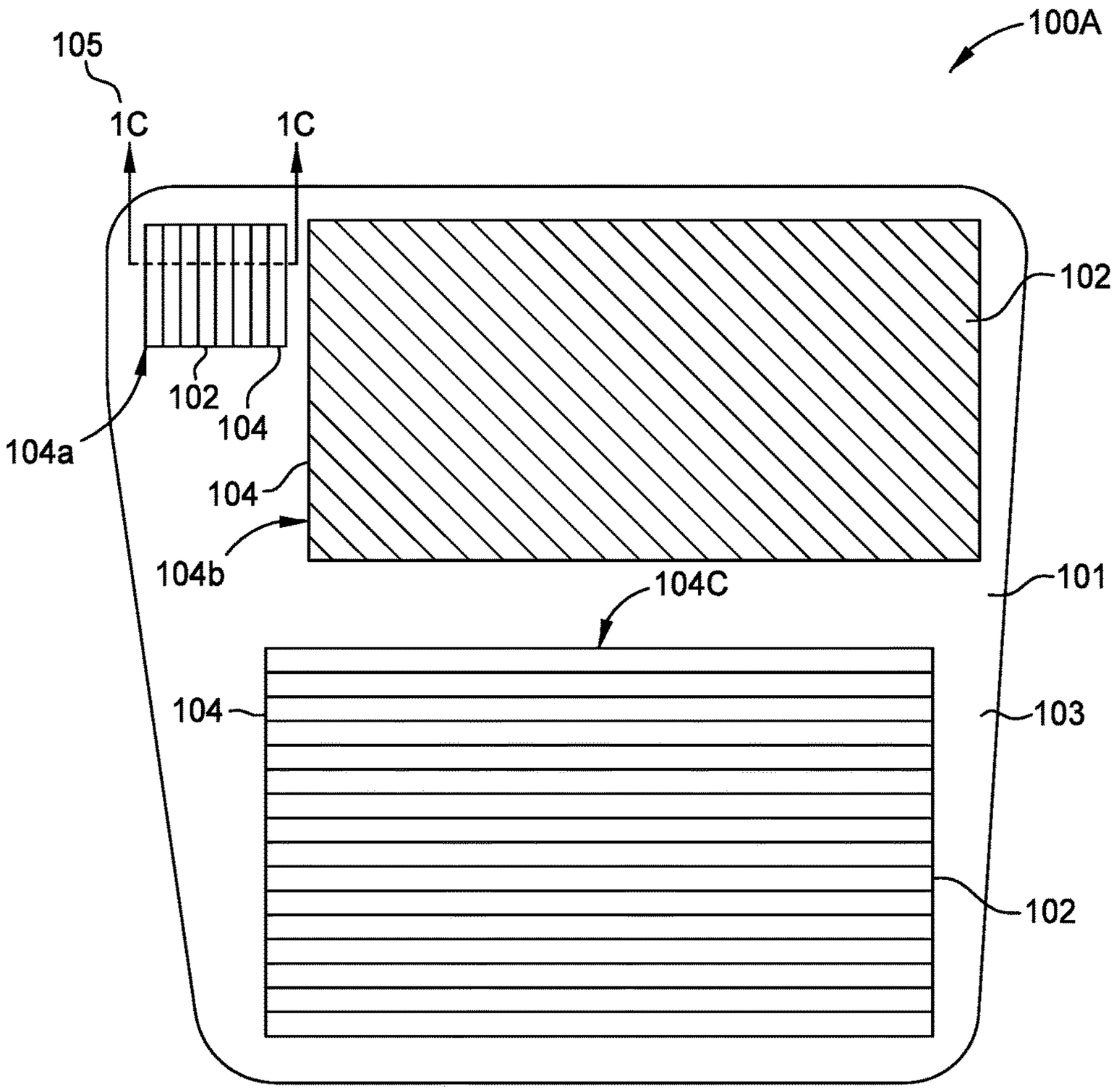


FIG. 1A

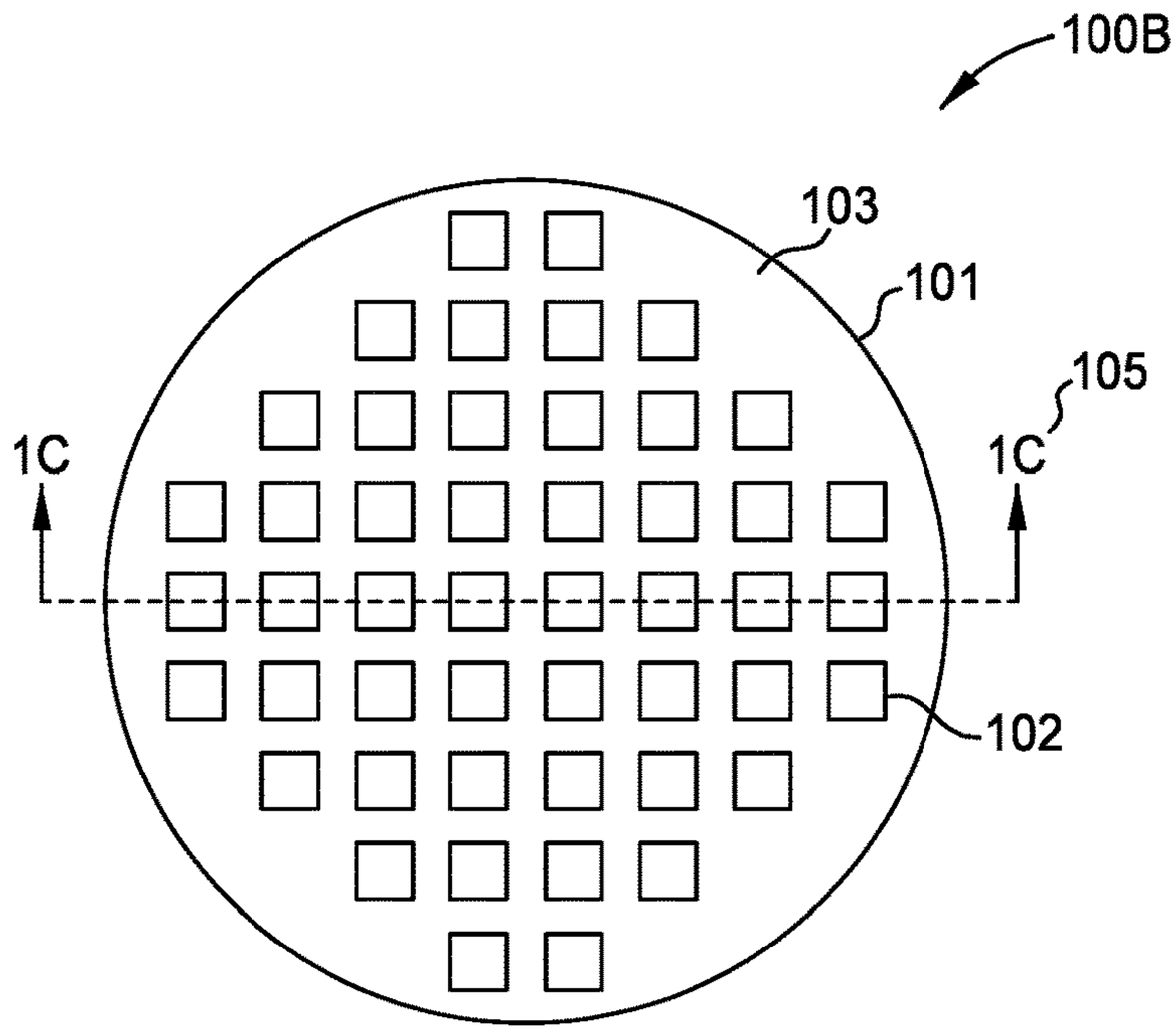


FIG. 1B

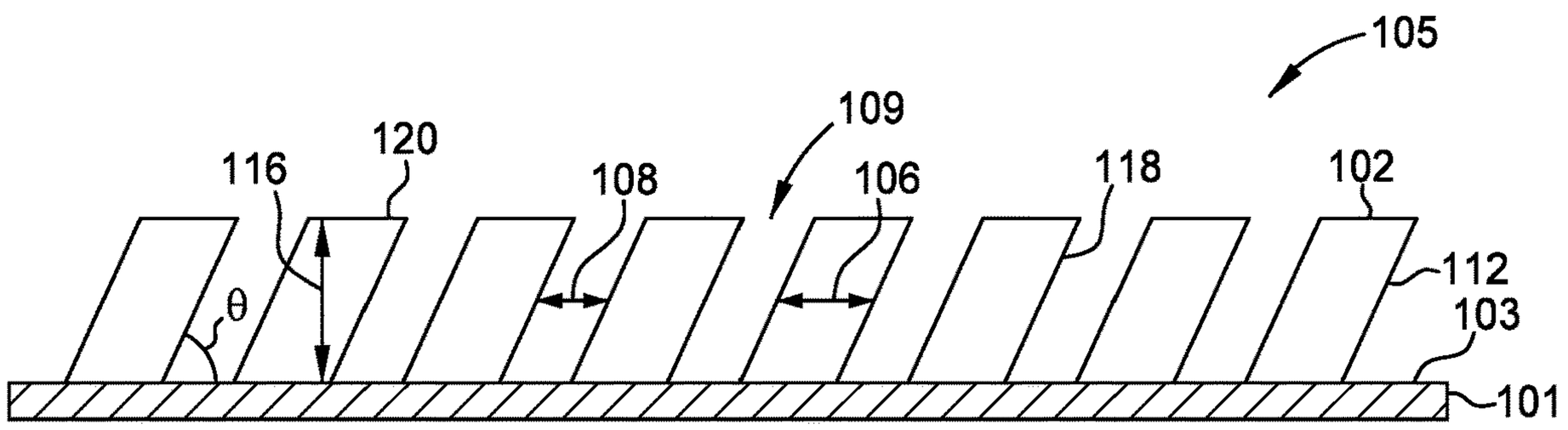


FIG. 1C

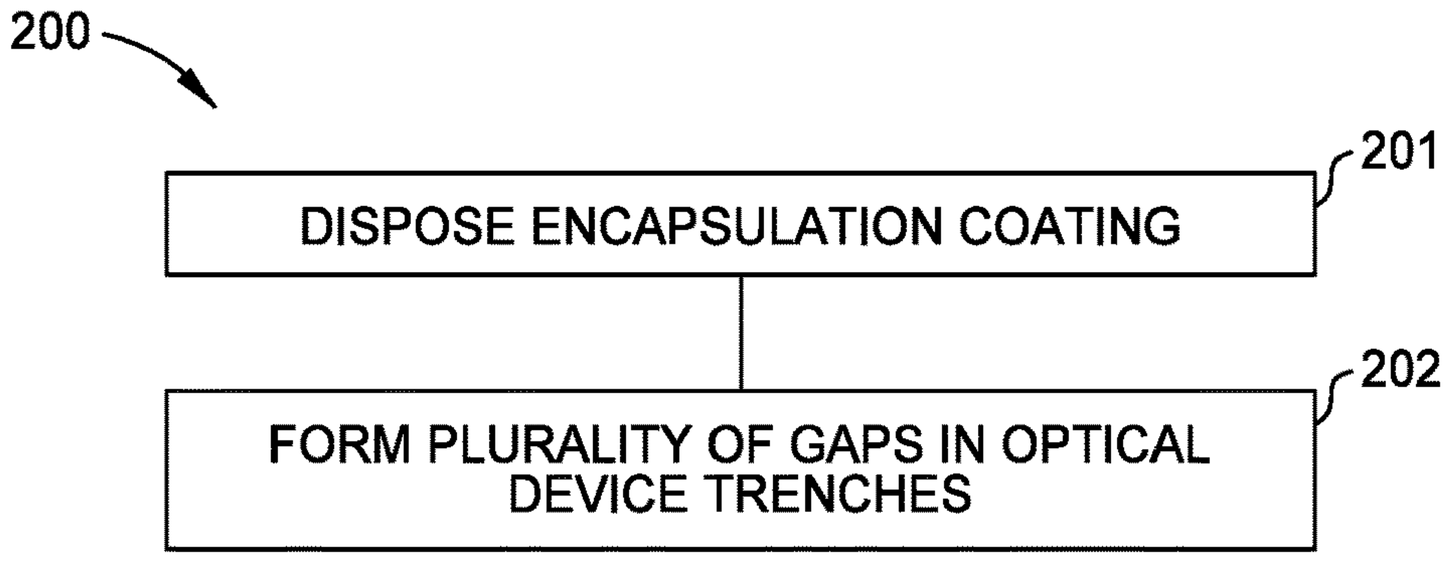


FIG. 2

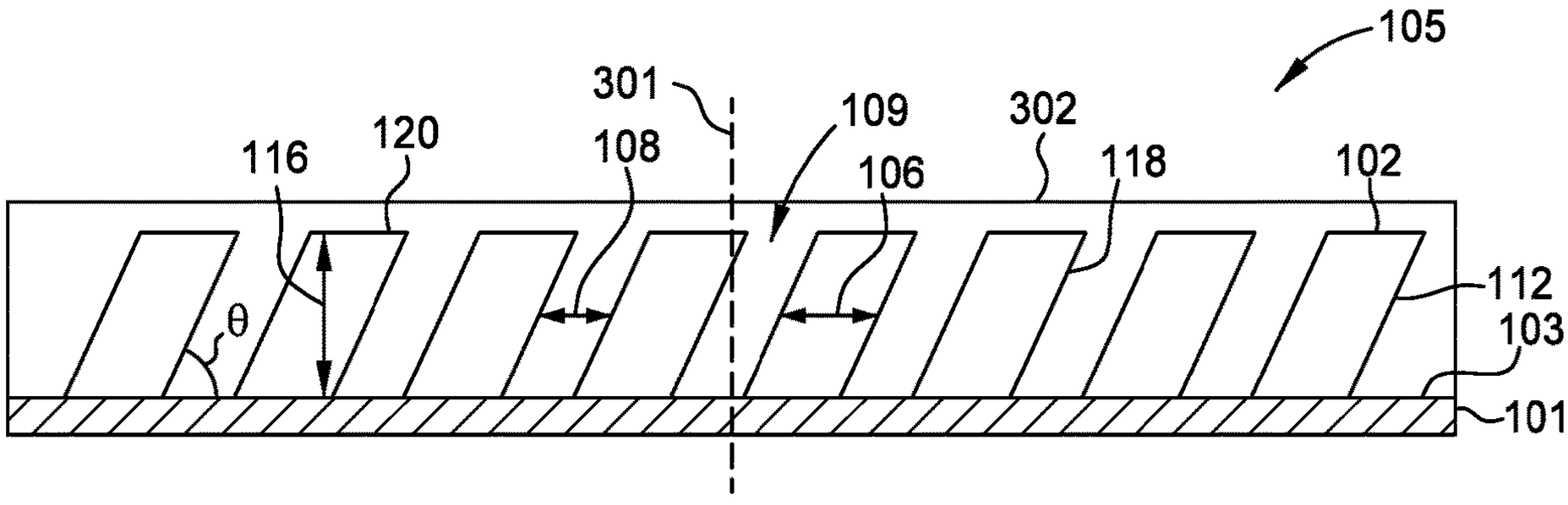

105
301
109
302
116
120
108
106
118
102
112
103
θ
101

FIG. 3A

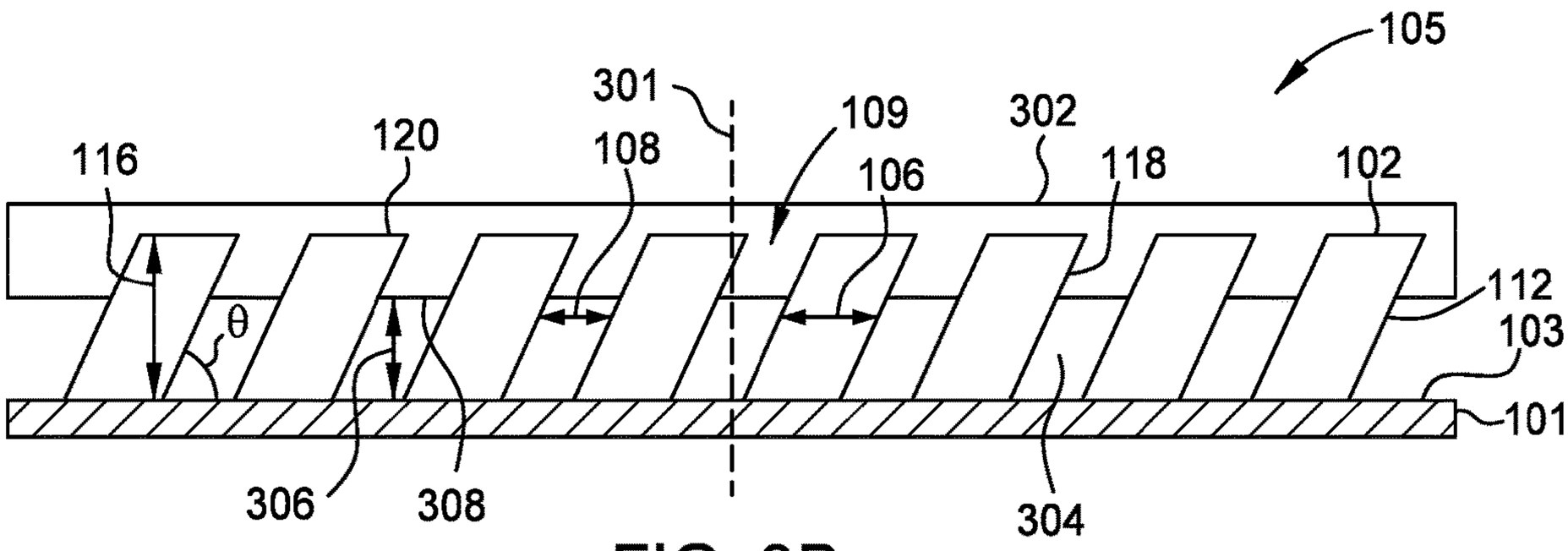

105
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FIG. 3B

AIRGAP STRUCTURES FOR IMPROVED EYEPIECE EFFICIENCY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of U.S. Provisional Patent Application No. 63/162,459, filed Mar. 17, 2021, which is herein incorporated by reference in its entirety.

BACKGROUND

Field

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to encapsulated optical devices and methods of forming encapsulated optical devices.

Description of the Related Art

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

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

One such challenge is displaying a virtual image overlaid on an ambient environment. Optical devices including waveguide combiners, such as augmented reality waveguide combiners, and flat optical devices, such as metasurfaces, are used to assist in overlaying images. Generated light is propagated through an optical device until the light exits the optical device and is overlaid on the ambient environment. The optical device structures of the optical devices need encapsulation to serve as a protective layer, to function as a spacer layer between successive layers of a multilayer arrangement, and to maximize light transmission. Furthermore, a greater difference between the refractive index of the material of the structures and the refractive index of the air in the gaps between the structures is vital to achieve desired optical device performance and efficiency. Air, having a refractive index of about 1.0, between each of the structures is desired to achieve the greater difference of refractive indices. Currently, fabricating air gaps inside optical devices requires decomposition of materials coupled with additional encapsulation steps.

Accordingly, what is needed in the art are encapsulated optical devices and methods of forming encapsulated optical devices.

SUMMARY

In one embodiment, a device is provided. The device includes a plurality of optical device structures disposed in or on a first substrate. The device further includes an encapsulation coating disposed over the plurality of optical device structures. The encapsulation coating includes a ratio of an encapsulation material to a solvent of about 1:10 to about 1:1.

In another embodiment, an optical device is provided. The optical device is formed with a method. The method includes disposing an encapsulation coating over a substrate, over a plurality of optical device structures, and between adjacent optical device structures of the plurality of optical device structures. The encapsulation coating includes a ratio of an encapsulation material to a solvent of about 1:10 to about 1:1. The method further includes forming a plurality of gaps. The plurality of gaps defined by adjacent optical device structures of the plurality of optical device structures, the substrate, and the encapsulation coating. The forming the plurality of gaps includes evaporating the solvent from the encapsulation coating.

In yet another embodiment, a method is provided. The method includes disposing an encapsulation coating over a substrate, over a plurality of optical device structures, and between adjacent optical device structures of the plurality of optical device structures. The encapsulation coating includes a ratio of an encapsulation material to a solvent of about 1:10 to about 1:1. The method further includes forming a plurality of gaps. The plurality of gaps defined by adjacent optical device structures of the plurality of optical device structures, the substrate, and the encapsulation coating. The forming the plurality of gaps includes evaporating the solvent from the encapsulation coating.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

FIG. **1**A is a perspective frontal view of an optical device according to embodiments described herein.

FIG. **1**B is schematic top view of an optical device according to embodiments described herein.

FIG. **1**C is a schematic cross-sectional view of a plurality of optical device structures according to embodiments described herein.

FIG. **2** is a flow diagram of a method of forming an optical device according to embodiments described herein.

FIGS. **3**A and **3**B are schematic, cross-sectional views of a substrate during operations of a method of forming an optical device according to embodiments described herein.

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

DETAILED DESCRIPTION

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to encapsulated optical devices and methods of forming encapsulated optical devices. In one embodiment, a

device is provided. The device includes a plurality of optical device structures disposed in or on a substrate. The device further includes an encapsulation coating disposed over the plurality of optical device structures. The encapsulation coating includes a ratio of an encapsulation material to a solvent of about 1:10 to about 1:1. The device further includes a plurality of gaps. The plurality of gaps are defined by adjacent optical device structures of the plurality of optical device structures, the substrate, and the encapsulation coating.

FIG. **1**A is a perspective, frontal view of an optical device **100**A. FIG. **1**B is a schematic, top view of an optical device **100**B. It is to be understood that the optical devices **100**A and **100**B described below are exemplary optical devices. In one embodiment, which can be combined with other embodiments described herein, the optical device **100**A is a waveguide combiner, such as an augmented reality waveguide combiner. In another embodiment, which can be combined with other embodiments described herein, the optical device **100**B is a flat optical device, such as a metasurface. The optical devices **100**A and **100**B include a plurality of optical device structures **102** disposed on a surface **103** of a substrate **101**. The optical device structures **102** may be nanostructures having sub-micron dimensions, e.g., nano-sized dimensions. In one embodiment, which can be combined with other embodiments described herein, regions of the optical device structures **102** correspond to one or more gratings **104**, such as a first grating **104***a*, a second grating **104***b*, and a third grating **104***c*. In another embodiment, which can combined with other embodiments described herein, the optical device **100**A is a waveguide combiner that includes at least the first grating **104***a* corresponding to an input coupling grating and the third grating **104***c* corresponding to an output coupling grating. The waveguide combiner, according to the embodiment, which can be combined with other embodiments described herein, includes the second grating **104***b* corresponding to an intermediate grating. While FIG. **1**B depicts the optical device structures **102** as having square or rectangular shaped cross-sections, the cross-sections of the optical device structures **102** may have other shapes including, but not limited to, circular, triangular, elliptical, regular polygonal, irregular polygonal, and/or irregular shaped cross-sections. In some embodiments, which can be combined with other embodiments described herein, the cross-sections of the plurality of optical device structures **102** have different shaped cross-sections. In other embodiments, which can be combined with other embodiments described herein, the cross-sections of the optical device structures **102** have cross-sections with substantially the same shape.

FIG. **1**C is a schematic cross-sectional view of a plurality of optical device structures **102**. FIG. **1**C is a portion **105** of the optical device **100**A or the optical device **100**B. The portion **105** of the optical devices **100**A and **100**B include the plurality of optical device structures **102** disposed on a surface **103** of a substrate **101**. The portion **105** may correspond to one or more gratings **104**. Each optical device structure of the plurality of optical device structures **102** has an optical device structure width **106**. In one embodiment, which may be combined with other embodiments described herein, the optical device structure width **106** is less than 1 micrometer (μm) and corresponds to the width or the diameter of each optical device structure **102**, depending on the cross-section of the optical device structure **102**. In one embodiment, which can be combined with other embodiments described herein, at least one optical device structure width **106** may be different from another optical device structure width **106**. In another embodiment, which can be combined with other embodiments described herein, each optical device structure width **106** of the plurality of optical device structures **102** is substantially equal to each other.

Each optical device structure **102** of the plurality of optical device structures **102** has a height **116**. The height **116** is the distance from the surface **103** of the substrate to a top surface **120** of each optical device structure **102**. In one embodiment, which can be combined with other embodiments described herein, at least one height **116** of the plurality of optical device structures **102** is different that the height **116** of the other optical device structures **102**. In another embodiment, which can be combined with other embodiments described herein, each height **116** of the plurality of optical device structures **102** is substantially equal to the adjacent optical device structures **102**.

The optical device structures **102** are formed from a device material **112**. In some embodiments, which can be combined with other embodiments described herein, the device material **112** includes, but is not limited to, one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), aluminum-doped zinc oxide (AZO), indium tin oxide (ITO), tin dioxide (SnO_2), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), zirconium dioxide (ZrO_2), niobium oxide (Nb_2O_5), cadmium stannate (Cd_2SnO_4), silicon carbon-nitride (SiCN) containing materials, or combinations thereof.

The substrate **101** may also be selected to transmit a suitable amount of light of a desired wavelength or wavelength range, such as one or more wavelengths from about 100 to about 3000 nanometers. Without limitation, in some embodiments, the substrate **101** is configured such that the substrate **101** transmits greater than or equal to about 50% to about 100%, of an infrared to ultraviolet region of the light spectrum. The substrate **101** may be formed from any suitable material, provided that the substrate **101** can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the optical devices **100**A and **1006** described herein. In some embodiments, which can be combined with other embodiments described herein, the material of substrate **101** has a refractive index that is relatively low, as compared to the refractive index of the device material **112**. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, or combinations thereof. In some embodiments, which may be combined with other embodiments described herein, the substrate **101** includes a transparent material. In one embodiment, which may be combined with other embodiments described herein, the substrate **101** is transparent with absorption coefficient smaller than 0.001. Suitable examples may include, but are not limited to, an oxide, sulfide, phosphide, telluride or combinations thereof. In one example, the substrate **101** includes silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), InP, GaAs, GaN, fused silica, quartz, sapphire, and high-index transparent materials such as glass, or combinations thereof.

The optical device structures **102** include a critical dimension **108**, i.e., a linewidth, defined as the distance between adjacent optical device structures **102**. As shown in FIG. **1**C, the critical dimension **108** of each of the adjacent optical device structure **102** is substantially equal to each other. In some embodiments, which can be combined with other embodiments described herein, at least one critical dimen-

sion **108** of adjacent optical device structures **102** is different from the critical dimension **108** of other adjacent optical device structures **102** of the portion **105**. An optical device trench **109** is defined by each pair of adjacent optical device structures **102** of the plurality of optical device structures **102** and the surface **103** of the substrate **101**. The width of each optical device trench **109** corresponds to the critical dimension **108**. The height of each optical device trench **109** corresponds to the height **116** of the adjacent optical device structures **102**.

The optical device structures **102** are formed at a device angle ϑ relative to the substrate **101**. The device angle ϑ is the angle between the surface **103** of the substrate **101** and a sidewall **118** of the optical device structure **102**. In one embodiment, which can be combined with other embodiments described herein, each respective device angle ϑ for each optical device structure **102** is substantially equal throughout the portion **105**. In another embodiment, which can be combined with other embodiments described herein, at least one respective device angle ϑ of the plurality of optical device structures **102** is different than another device angle ϑ of the plurality of optical device structures **102**.

FIG. **2** is a flow diagram of a method **200** for forming an optical device **100**A or **100**B as shown in FIGS. **3**A and **3**B. FIGS. **3**A and **3**B are schematic, cross-sectional views of a substrate during operations of the method **200** of forming an optical device **100**A or **100**B. FIGS. **3**A and **3**B are a portion **105** of the optical device **100**A or the optical device **100**B. The portion **105** of the optical devices **100**A and **100**B include the plurality of optical device structures **102** disposed on a surface **103** of a substrate **101**. In one embodiment, which can be combined with other embodiments described herein, the portion **105** may correspond to a portion or a whole surface of the substrate **101** of a flat optical device. In another embodiment, which can be combined with other embodiments described herein, the portion **105** may correspond to a portion or a whole surface of the substrate **101** of a waveguide combiner.

At operation **201**, as shown in FIG. **3**A, an encapsulation coating **302** is disposed over the plurality of optical device structures **102**. The encapsulation coating **302** is deposited by a spin coating process. The encapsulation coating **302** is a single layer of encapsulation disposed over the plurality of optical device structures **102**. The encapsulation coating **302** is operable to fill optical device trenches **109**.

The encapsulation coating **302** includes a material composition of an encapsulation material and a solvent. In one embodiment, which can be combined with other embodiments described herein, the encapsulation material may include, but is not limited to, at least one of a material such as spin on glass (SOG), flowable SOG, organic, inorganic, and hybrid (organic and inorganic) materials that may contain at least one of silicon oxycarbide (SiOC), titanium dioxide (TiO2), silicon dioxide (SiO2), vanadium (IV) oxide (VOx), aluminum oxide (Al2O3), indium tin oxide (ITO), zinc oxide (ZnO), tantalum pentoxide (Ta2O5), silicon nitride (Si3N4), titanium nitride (TiN), and zirconium dioxide (ZrO2) containing materials, organic materials such as acrylates, or combinations thereof. In another embodiment, which can be combined with other embodiments described herein, the encapsulation material is an anti-reflective coating material. Examples of the solvent precursor include, but are not limited to, methanol, ethanol, and isopropanol.

The encapsulation coating **302** provides mechanical protection for the plurality of optical device structures **102**. Additionally, in embodiments where the encapsulation material is an anti-reflective coating, the anti-reflective coating maximizes light transmission through the optical device **100**A or the optical device **100**B by reducing reflection of the incident light. In one embodiment, which can be combined with other embodiments described herein, prior to operation **201**, a hydrophobic material or hydrophilic material is disposed over the plurality of optical device structures **102** to make the encapsulation coating **302** more or less resistant to filling the optical device trenches **109**. An optical device trench **109** is defined by each pair of adjacent optical device structures **102** of the plurality of optical device structures **102** and the surface **103** of the substrate **101**.

At operation **202**, as shown in FIG. **3**B, a plurality of gaps **304** are formed in the optical device trenches **109**. The encapsulation coating **302**, the plurality of optical device structures **102**, and the surface **103** of the substrate **101** define the plurality of gaps **304**. Forming the plurality of gaps **304** allows for an increase in throughput as sacrificial material is not needed to be deposited into the optical device trenches **109** in addition to depositing the encapsulation coating **302**. It is desirable to have a large contrast between refractive indices of the device material **112** of the plurality of optical device structures **102** and the material of the surrounding structures including the substrate **101**, the encapsulation coating **302**, and the plurality of gaps **304**. Further, air of the plurality of gaps **304** has a refractive index of about 1.0. Thus, it is desirable to form the plurality of gaps **304** including air with a refractive index of about 1.0, such that there is a greater difference of refractive indices present between the device material **112** and the air of the plurality of gaps **304**. The difference of refractive indices reduces the thickness of the optical device **100**A or the optical device **100**B. The reduction of thicknesses provides ease of use, a shorter optical path, less optical distortion, and better image quality of the optical devices. The refractive index of the device material **112** is about 2.0 to about 2.6. The material composition of the encapsulation coating **302** includes a refractive index of about 1.4 to about 2.0. In one embodiment, the difference between the refractive index of the device material **112** and the material composition of the encapsulation coating **302** is about 0.6 to about 1.0. In one embodiment, the difference between the refractive index of the device material **112** and the refractive index of the air in the plurality of gaps **304** is about 1.0 to about 1.6.

A depth **306** is the distance between a lower surface **308** of the encapsulation coating **302** and the surface **103** of the substrate **101**. The depth **306** corresponds to the plurality of gaps **304**. The depth **306** may be formed by evaporating the solvent of the encapsulation coating **302**. Each depth **306** of the plurality of gaps **304** is between about 10% and about 100% of a height **116** of the plurality of optical device structures **102**. The depth **306** is between about 0.02 μm and about 1 μm. When the depth **306** is 100% of the height **116**, the depth **306** is equal to the height **116** of the optical device structure **102**. The depth **306** is operable to be increased or decreased based on different process parameters. The optical device structure width **106** of the plurality of optical device structures **102** and a device angle ϑ of the plurality of optical device structures **102** may be adjusted to increase or decrease the efficiency of the encapsulation coating **302** filling the optical device trenches **109**. The optical device structure width **106** is between about 0.1 μm and about 0.5 μm. The device angle ϑ is between about 25 degrees and about 90 degrees.

In one embodiment, which can be combined with other embodiments described herein, during operation **201**, the substrate **101** is rotated (i.e., spun) about a central axis **301** of the substrate **101**. The rotation rate may be varied during

the deposition process. The rotation of the substrate **101** during the deposition of the encapsulation coating **302** may determine the rate at which the encapsulation coating **302** enters the optical device trenches **109**. Therefore, the encapsulation coating **302** might not reach the surface **103** of the substrate **101**. The rotation rate of the substrate **101** may be increased or decreased to increase or decrease the depth **306**. The rotation rate is between about 500 rpm and about 4000 rpm.

The amount of solvent that evaporates is dependent on the concentration of the encapsulation coating **302**. The encapsulation coating **302** includes a ratio of the concentration of encapsulation material to the concentration of the solvent. The ratio is between about 1:10 to about 1:1. Increasing the concentration of the solvent to the concentration of the encapsulation material will increase the depth **306** as more solvent is evaporated from the encapsulation coating **302**. For example, a second substrate with a second encapsulation coating disposed thereover may be processed. Increasing a concentration of solvent in the second encapsulation coating increases a second depth of a second plurality of gaps relative to the plurality of gaps of the first substrate. Decreasing a concentration of solvent in the second encapsulation coating decreases a second depth of a second plurality of gaps relative to the plurality of gaps of the first substrate.

Additionally, a difference in viscosity between the encapsulation material and the solvent may alter the depth **306**. As the difference in viscosity increases, the solvent will move closer to the surface **103** of the substrate **101** in the optical device trenches **109**. Therefore, as the plurality of gaps **304** are dependent upon evaporation of the solvent, the difference in viscosity between the encapsulation material and the solvent will alter the depth **306**. The viscosity of the encapsulation material is between about 10 centipoise (cP) to about 10,000 cP. The viscosity of the solvent is less than about 10 cP.

In one embodiment, which can be combined with other embodiments described herein, a curing process is performed after the operation **202**. The cure process includes exposing the encapsulation coating **302** to electromagnetic radiation, such as infrared (IR) radiation or ultraviolet (UV) radiation. The curing process is performed with a dosage of about 0.05 J/cm^2 to about 10 J/cm^2. The curing process increases the density of the encapsulation coating **302**. In another embodiment which can be combined with other embodiments described herein, a baking process is performed after the operation **202**. The baking process occurs at a temperature between about 50° C. and about 200° C. In yet another embodiment, which can be combined with other embodiments described herein, a drying process is performed after the operation **202**. The drying process includes, but is not limited to, one or more of supercritical CO_2 drying, freeze drying, and pressure drying, such as ambient pressure drying. The drying process may further evaporate the solvent from the encapsulation coating **302**. In yet another embodiment, which can be combined with other embodiments described herein, a developing process is performed after the operation **202**.

In summation, encapsulated optical devices and methods of forming encapsulated optical devices are described herein. The optical devices include a plurality of optical device structures disposed on a substrate. An encapsulation coating is disposed over the plurality of optical device structures. The encapsulation coating includes a ratio of encapsulation material to solvent. A plurality of gaps are formed in the optical device. The plurality of gaps are defined by the encapsulation coating, the plurality of optical device structures, and the substrate. The plurality of gaps are formed when the solvent is evaporated from the encapsulation coating. The encapsulation coating provides mechanical protection for the plurality of optical device structures as well as maximizing light transmission by reducing reflection of the incident light. The air in the plurality of gaps provide a greater difference in refractive indices within the optical device, improving the performance of the optical device. The material composition of the encapsulation coating, viscosity of the encapsulation coating, the width and device angle of the plurality of optical device structures, as well as process parameters of the spin on coating process, the curing process, the baking process, the drying process, and the developing process will affect the formation of the plurality of gaps and the depth at which the plurality of gaps are formed.

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

What is claimed is:

1. An optical device formed by a method, comprising:

disposing an encapsulation coating over a first substrate, over a plurality of optical device structures, and between adjacent optical device structures of the plurality of optical device structures, wherein the encapsulation coating fills an entire area between each of the adjacent optical device structures, the encapsulation coating including a material composition with a ratio of an encapsulation material to a solvent of about 1:10 to about 1:1; and

forming a plurality of gaps, the plurality of gaps defined by the adjacent optical device structures of the plurality of optical device structures, the first substrate, and the encapsulation coating, the forming of the plurality of gaps including evaporating the solvent from the encapsulation coating such that between each of the adjacent optical device structures, the plurality of gaps have a depth from a lower surface of the encapsulation coating to the first substrate.

2. The optical device of claim **1**, wherein a difference of a refractive index of a device material of the plurality of optical device structures and a refractive index of the material composition of the encapsulation coating is about 0.6 to about 1.0 and a difference of the refractive index of the device material of the plurality of optical device structures and a refractive index of air disposed in the plurality of gaps is about 1.0 to about 1.6.

3. The optical device of claim **1**, wherein the encapsulation coating is an anti-reflective coating layer.

4. A method, comprising:

disposing a first encapsulation coating over a first substrate, over a plurality of optical device structures, and between adjacent optical device structures of the plurality of optical device structures, wherein the first encapsulation coating fills an entire area between each of the optical device structures, the first encapsulation coating including a material composition with a ratio of an encapsulation material to a solvent of about 1:10 to about 1:1; and

forming a plurality of gaps, the plurality of gaps defined by the adjacent optical device structures of the plurality of optical device structures, the first substrate, and the first encapsulation coating, the forming of the plurality of gaps including evaporating the solvent from the first

encapsulation coating such that between each of the adjacent optical device structures the plurality of gaps have a depth from a lower surface of the first encapsulation coating to the first substrate.

5. The method of claim **4**, wherein the depth is between 10% and 100% of a height of each optical device structure.

6. The method of claim **5**, further comprising depositing a second encapsulation coating over a second substrate, wherein increasing a concentration of solvent in the second encapsulation coating increases a second depth of a second plurality of gaps relative to the plurality of gaps of the first substrate.

7. The method of claim **5**, further comprising depositing a second encapsulation coating over a second substrate, wherein decreasing a concentration of solvent in the second encapsulation coating decreases a second depth of a second plurality of gaps relative to the plurality of gaps of the first substrate.

8. The method of claim **4**, further comprising exposing the first encapsulation coating to ultraviolet (UV) radiation in a curing process, the curing process performed with a dosage of about 0.05 J/cm^2 to about 10 J/cm^2.

9. The method of claim **4**, further comprising baking the first encapsulation coating at a temperature between about 50° C. and about 200° C.

10. The method of claim **4**, further comprising rotating the first substrate at a rotation rate of between about 500 rpm and about 4000 rpm.

11. The method of claim **4**, wherein the first encapsulation coating is an anti-reflective coating layer.

12. The method of claim **4**, wherein air disposed in the plurality of gaps has a refractive index of about 1.0, a device material of the plurality of optical device structures has a refractive index between about 2.0 to about 2.6, and the material composition has a refractive index of about 1.4 to about 2.0.

13. The method of claim **4**, wherein cross-sections of the plurality of optical device structures include circular, triangular, and elliptical shaped cross-sections.

14. The method of claim **1**, further comprising rotating the first substrate at a rotation rate to increase or decrease the depth of the plurality of gaps.

15. The method of claim **14**, wherein the rotation rate is between about 500 rpm and about 4000 rpm.

16. The method of claim **1**, wherein the encapsulation coating and the solvent have different viscosities.

17. The method of claim **16**, wherein a viscosity of the encapsulation coating is between about 10 centipoise (cP) and about 10,000 cP, and a viscosity of the solvent is less than about 10 cP.

18. The method of claim **4**, further comprising rotating the first substrate at a rotation rate to increase or decrease the depth of the plurality of gaps.

19. The method of claim **4**, wherein the first encapsulation coating and the solvent have different viscosities.

20. The method of claim **19**, wherein a viscosity of the first encapsulation coating is between about 10 centipoise (cP) and about 10,000 cP, and a viscosity of the solvent is less than about 10 cP.

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