US010707118B2

(12) **United States Patent**
Godet et al.

(10) **Patent No.: US 10,707,118 B2**
(45) **Date of Patent: Jul. 7, 2020**

(54) **MULTI STACK OPTICAL ELEMENTS USING TEMPORARY AND PERMANENT BONDING**

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(73) Assignee: **APPLIED MATERIALS, INC.**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/283,560**

(22) Filed: **Feb. 22, 2019**

(65) **Prior Publication Data**

US 2019/0318957 A1 Oct. 17, 2019

Related U.S. Application Data

(60) Provisional application No. 62/780,536, filed on Dec. 17, 2018, provisional application No. 62/658,553, filed on Apr. 16, 2018.

(51) **Int. Cl.**
H01L 21/768 (2006.01)
H01L 21/3213 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H01L 21/76816*** (2013.01); ***H01L 21/311*** (2013.01); ***H01L 21/32134*** (2013.01); ***H01L 25/043*** (2013.01); ***H01L 25/167*** (2013.01)

(58) **Field of Classification Search**
CPC H01L 21/76816; H01L 21/311; H01L 25/043; H01L 25/167
See application file for complete search history.

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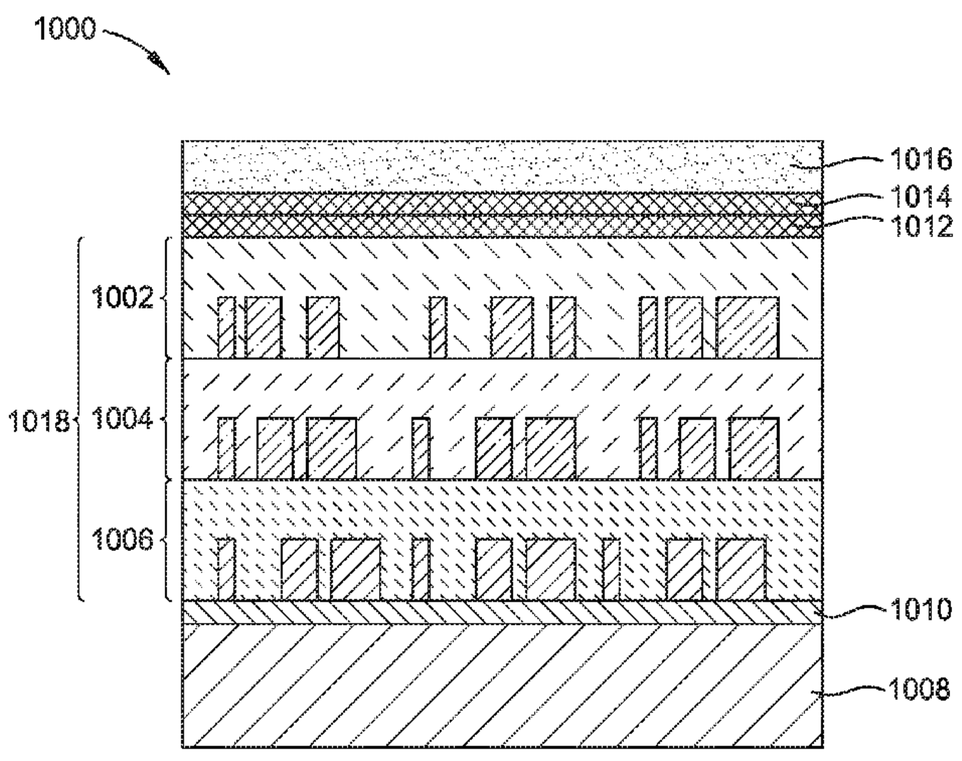
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Primary Examiner — Yosef Gebreyesus
(74) *Attorney, Agent, or Firm* — Patterson + Sheridan LLP

(57) **ABSTRACT**

Systems and methods herein are related to the formation of optical devices including stacked optical element layers using silicon wafers, glass, or devices as substrates. The optical elements discussed herein can be fabricated on temporary or permanent substrates. In some examples, the optical devices are fabricated to include transparent substrates or devices including charge-coupled devices (CCD), or complementary metal-oxide semiconductor (CMOS) image sensors, light-emitting diodes (LED), a micro-LED (uLED) display, organic light-emitting diode (OLED) or vertical-cavity surface-emitting laser (VCSELs). The optical
(Continued)



elements can have interlayers formed in between optical element layers, where the interlayers can range in thickness from 1 nm to 3 mm.

20 Claims, 19 Drawing Sheets

(51) **Int. Cl.**

H01L 21/311	(2006.01)
H01L 25/04	(2014.01)
H01L 25/16	(2006.01)

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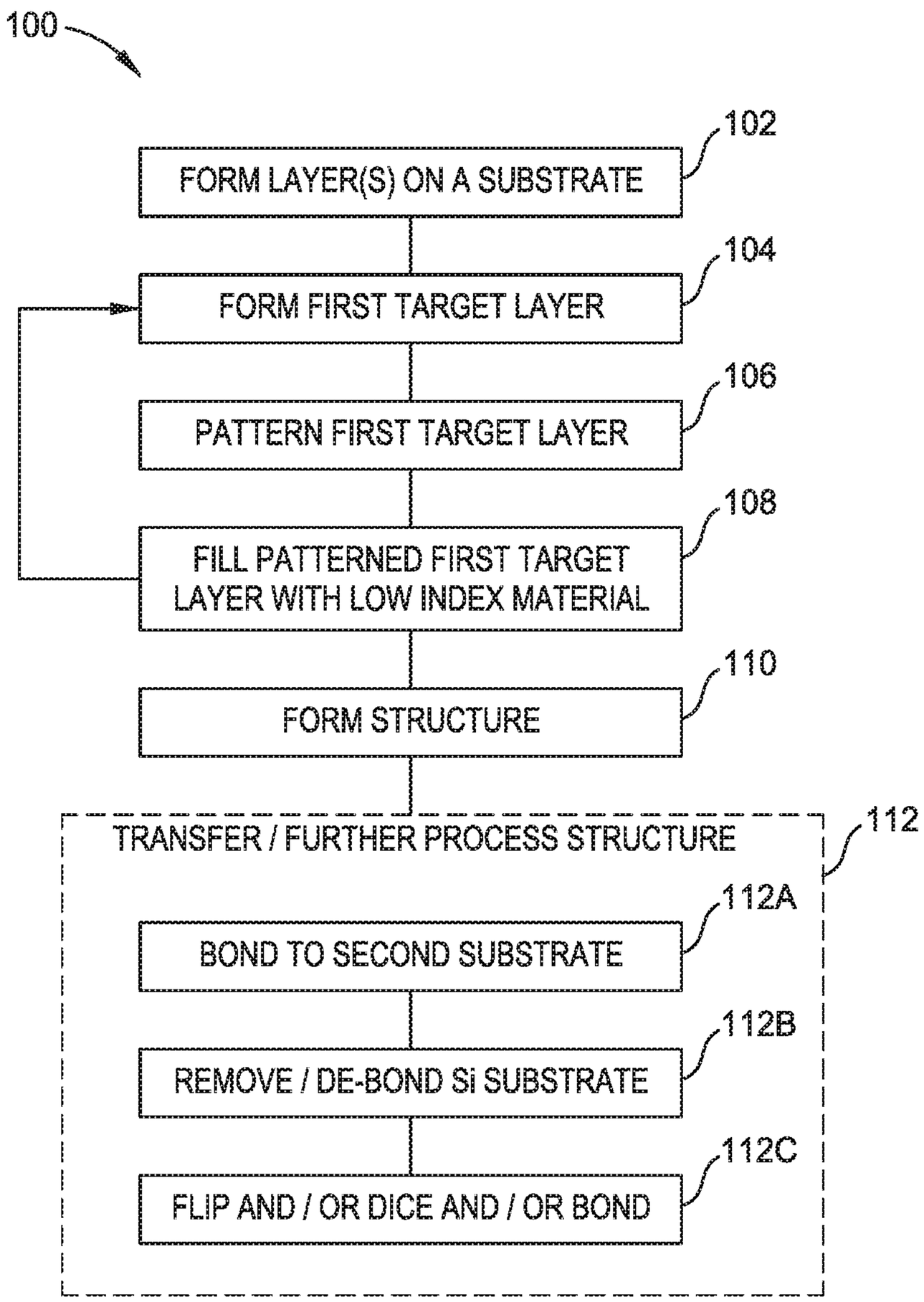

100
FORM LAYER(S) ON A SUBSTRATE
102
FORM FIRST TARGET LAYER
104
PATTERN FIRST TARGET LAYER
106
FILL PATTERNED FIRST TARGET LAYER WITH LOW INDEX MATERIAL
108
FORM STRUCTURE
110
TRANSFER / FURTHER PROCESS STRUCTURE
112
BOND TO SECOND SUBSTRATE
112A
REMOVE / DE-BOND Si SUBSTRATE
112B
FLIP AND / OR DICE AND / OR BOND
112C

FIG. 1

FIG. 2A

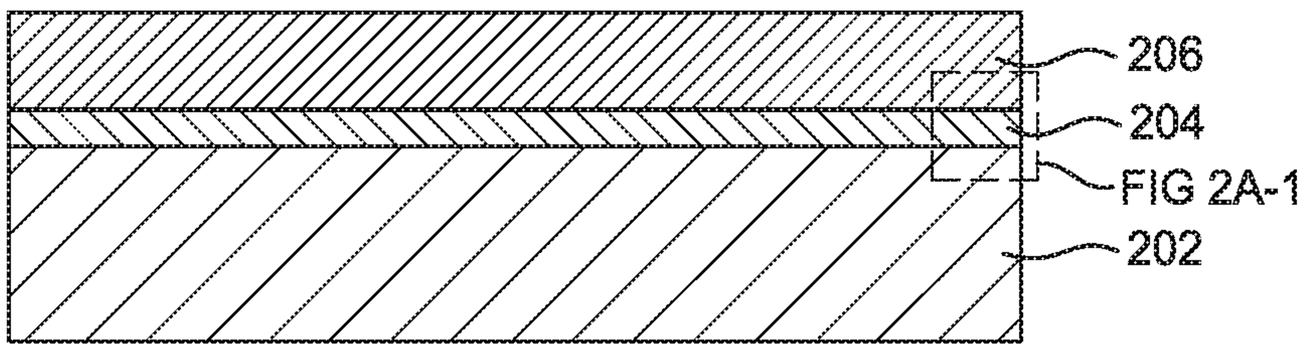


FIG. 2A-1

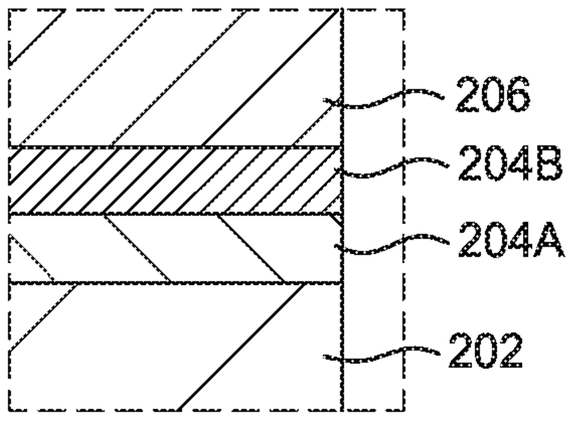


FIG. 2B

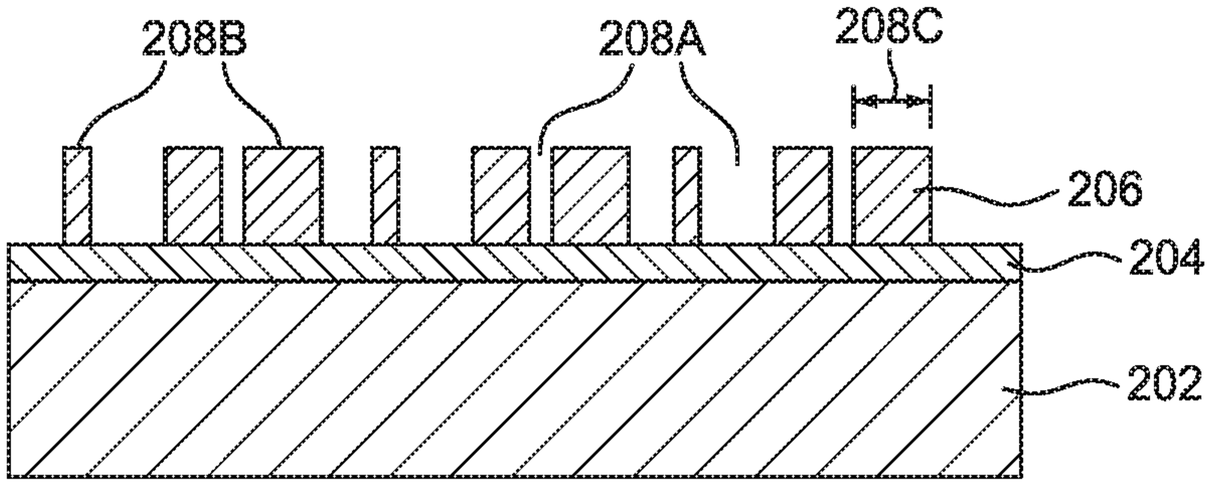
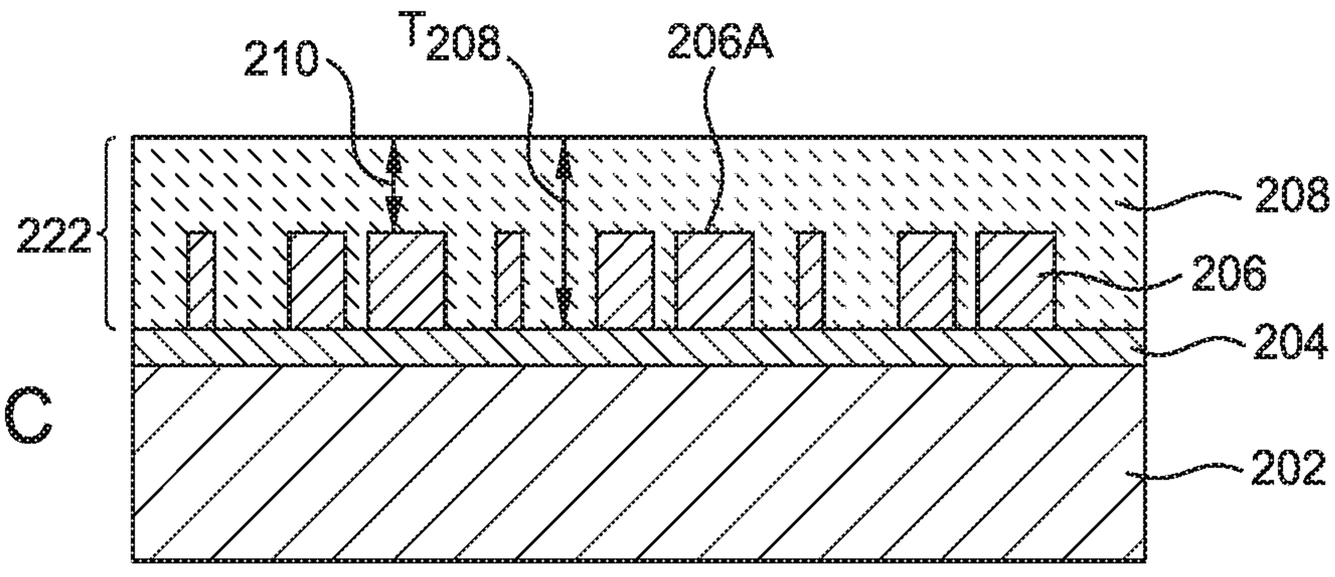


FIG. 2C



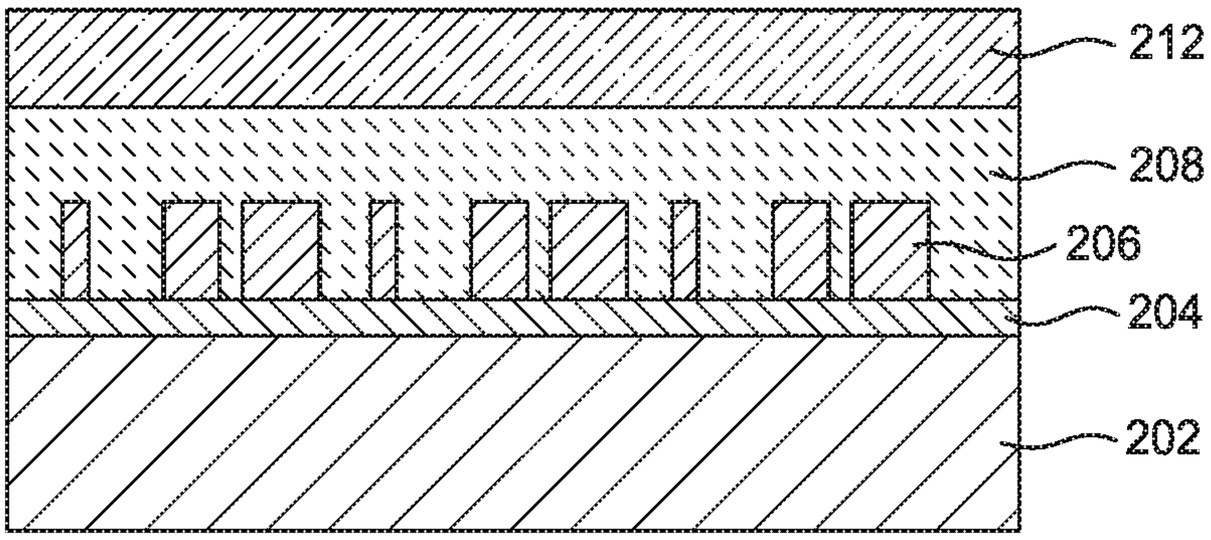


FIG. 2D

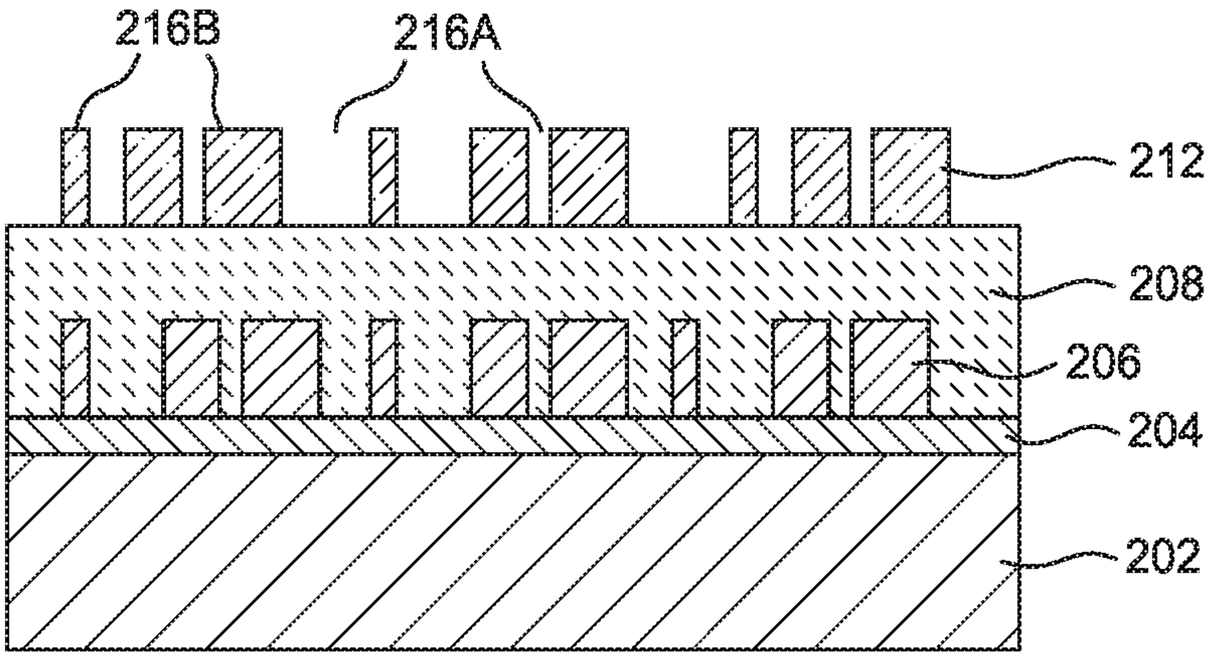


FIG. 2E

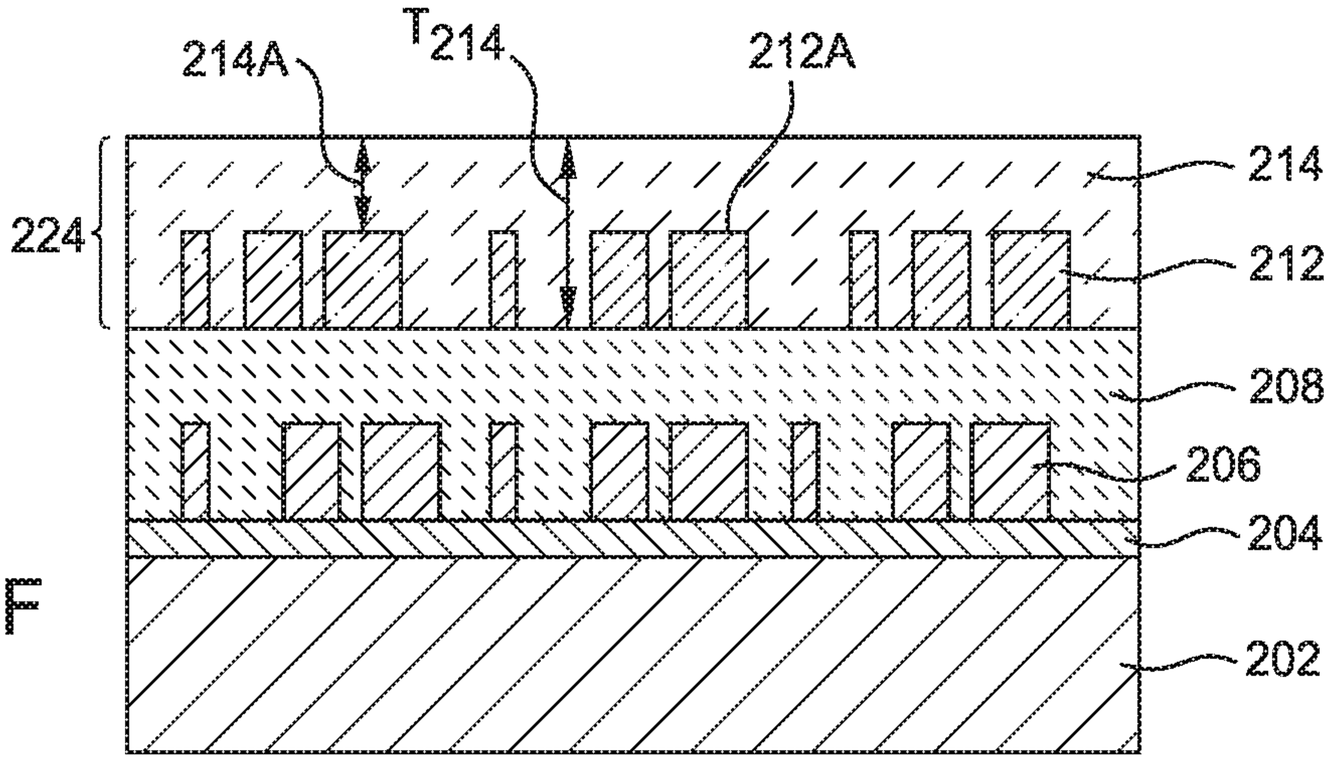


FIG. 2F

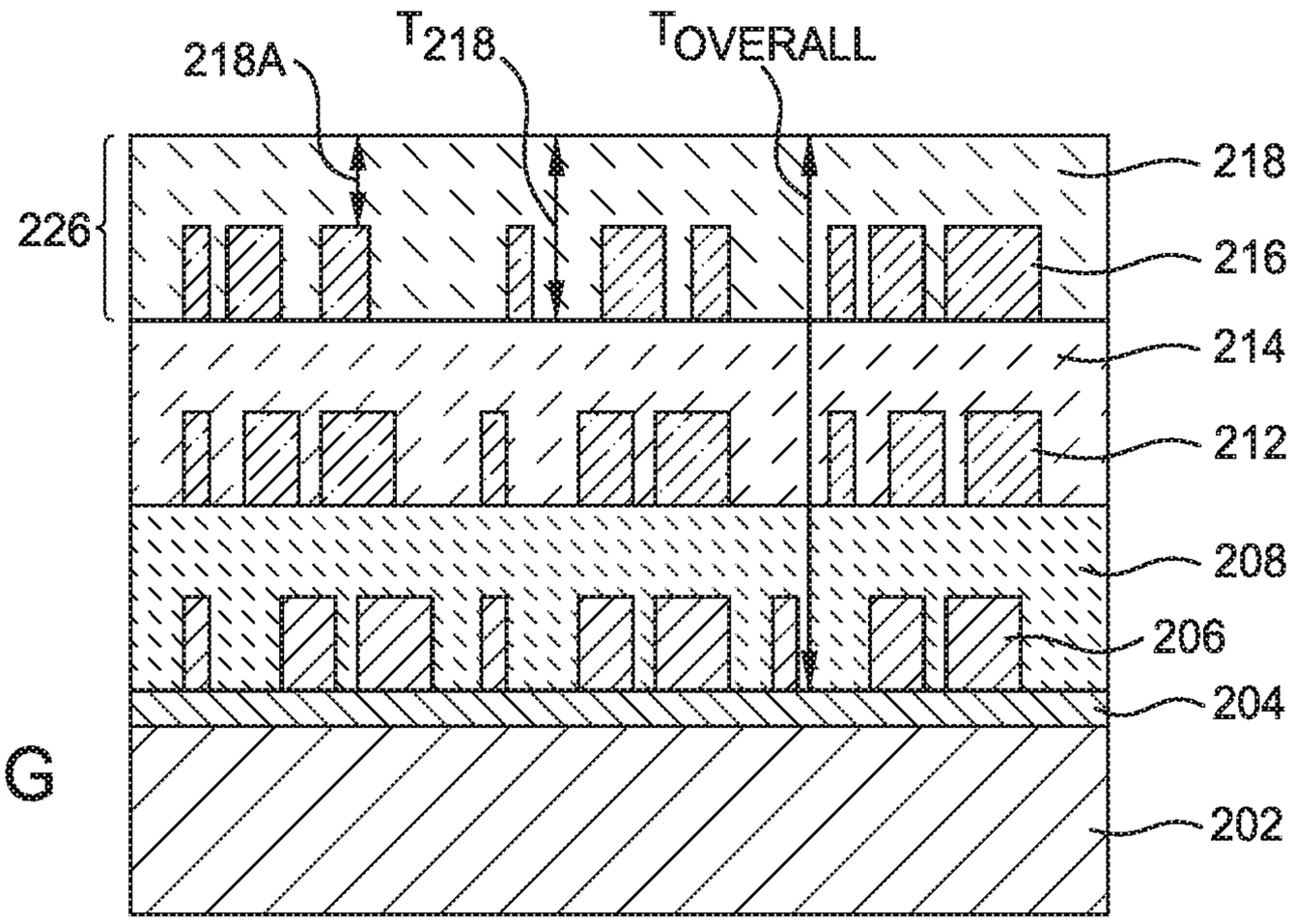


FIG. 2G

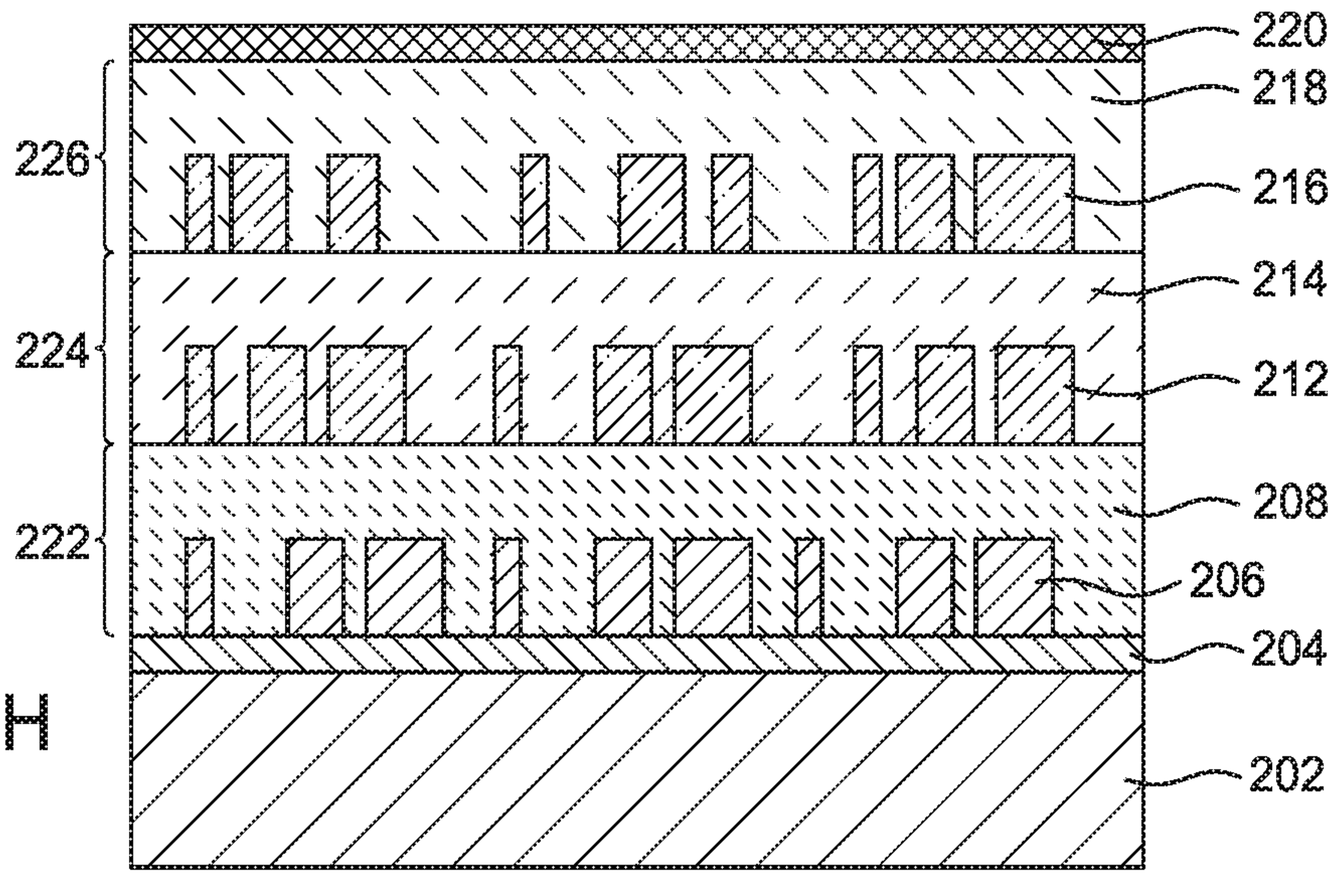


FIG. 2H

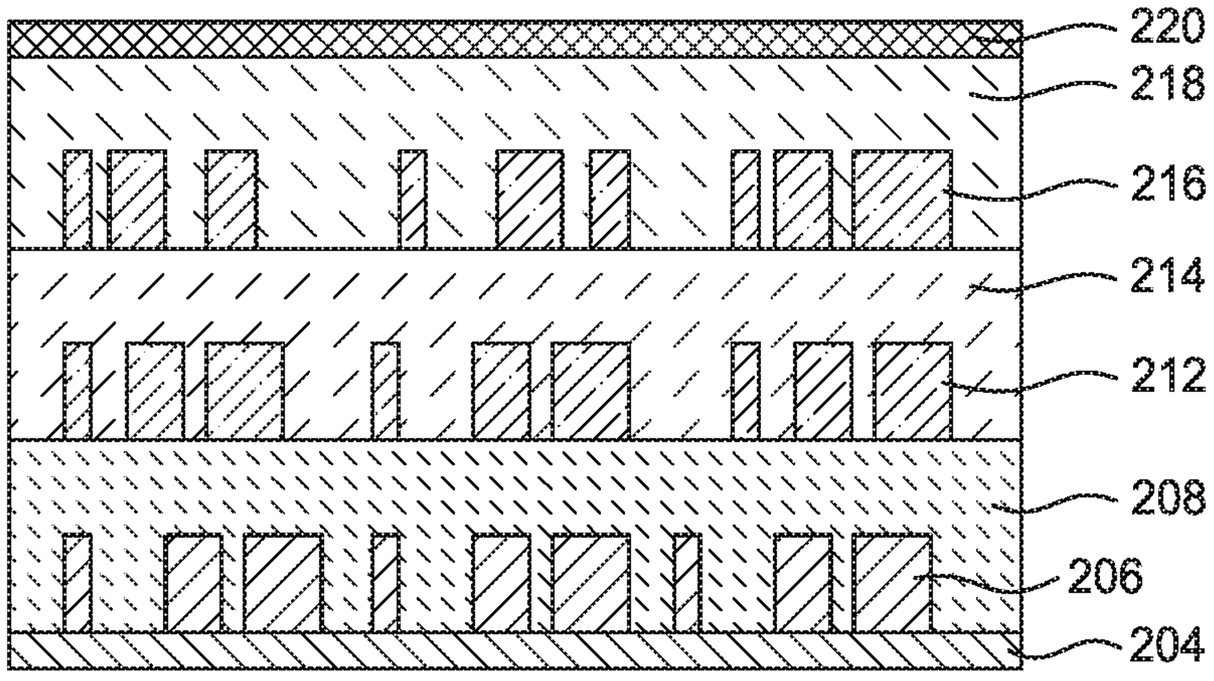


FIG. 2I

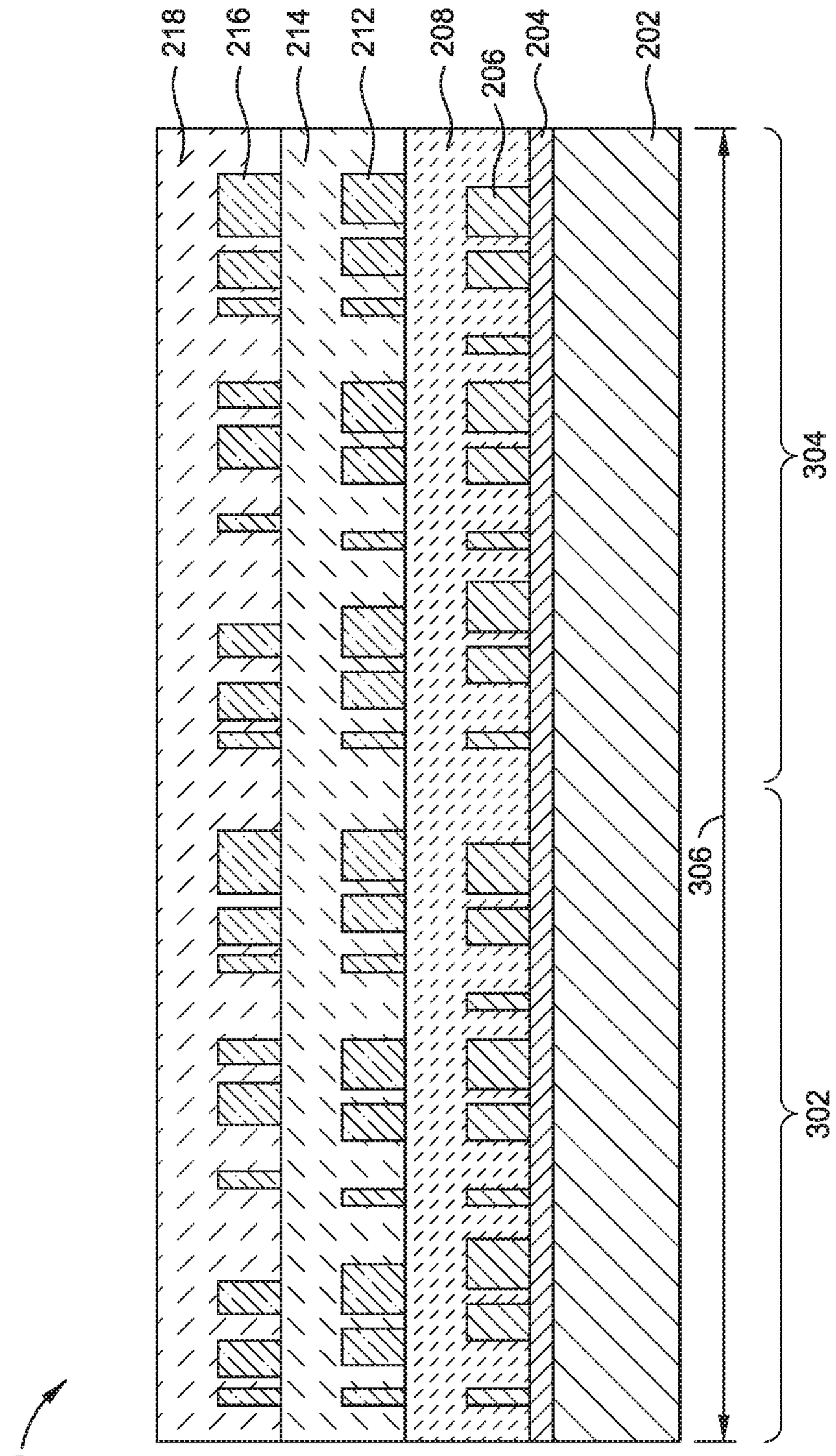


FIG. 3

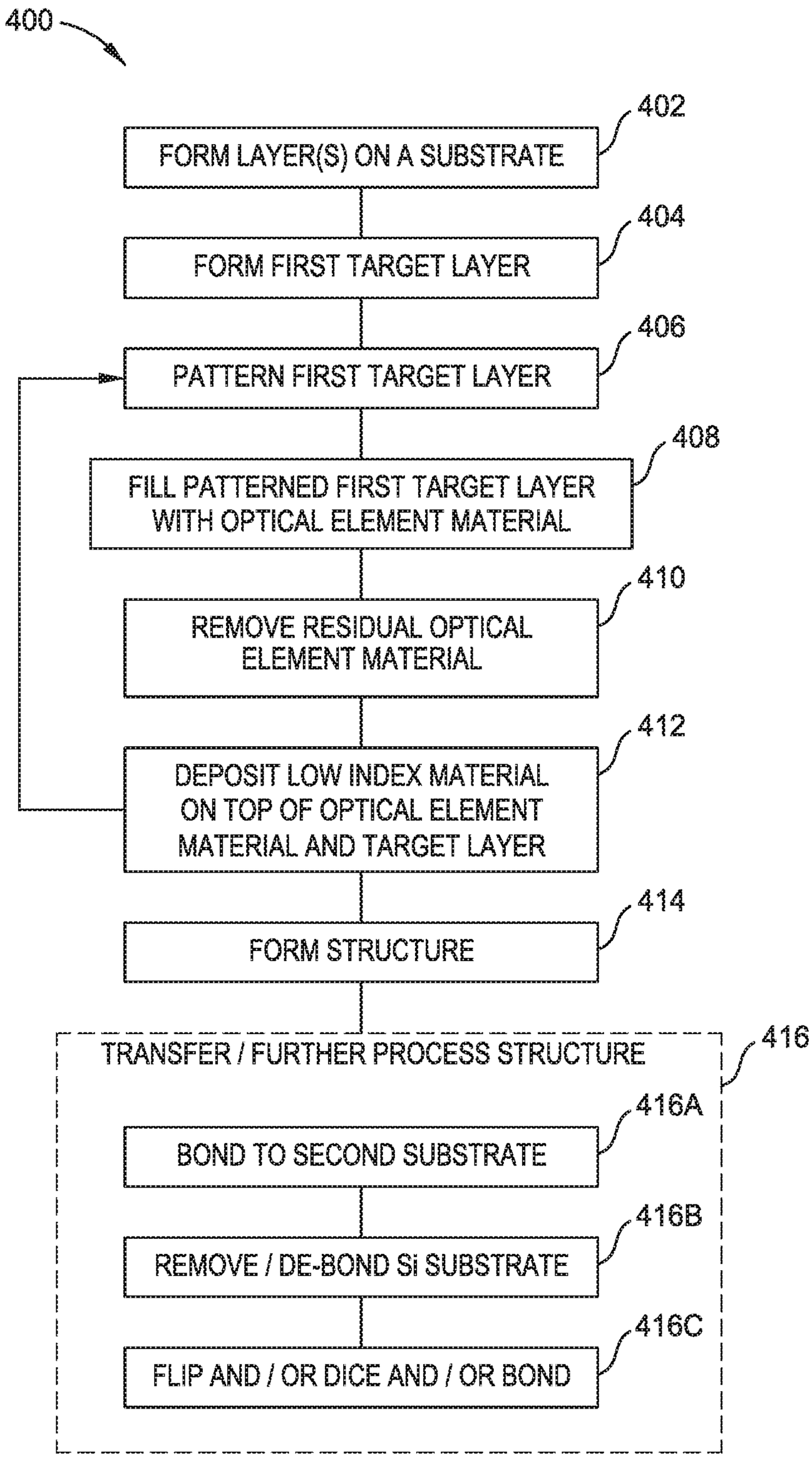

400
FORM LAYER(S) ON A SUBSTRATE
402
FORM FIRST TARGET LAYER
404
PATTERN FIRST TARGET LAYER
406
FILL PATTERNED FIRST TARGET LAYER WITH OPTICAL ELEMENT MATERIAL
408
REMOVE RESIDUAL OPTICAL ELEMENT MATERIAL
410
DEPOSIT LOW INDEX MATERIAL ON TOP OF OPTICAL ELEMENT MATERIAL AND TARGET LAYER
412
FORM STRUCTURE
414
TRANSFER / FURTHER PROCESS STRUCTURE
416
BOND TO SECOND SUBSTRATE
416A
REMOVE / DE-BOND Si SUBSTRATE
416B
FLIP AND / OR DICE AND / OR BOND
416C

FIG. 4

FIG. 5A

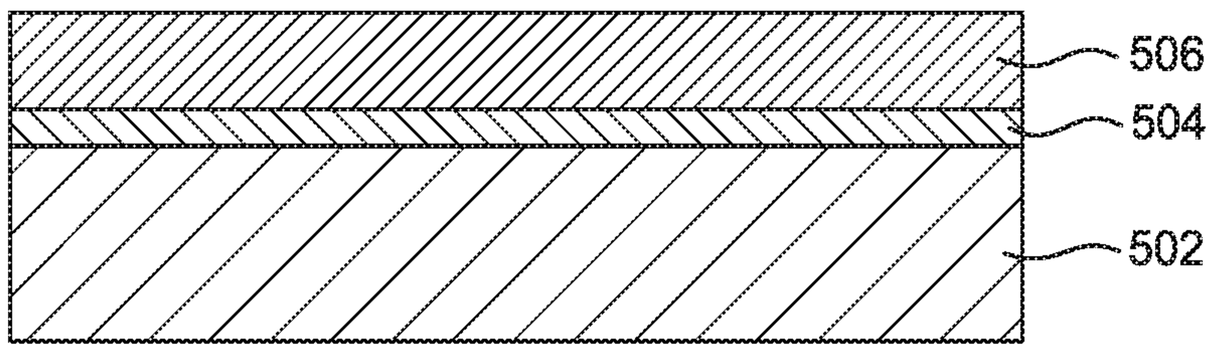


FIG. 5B

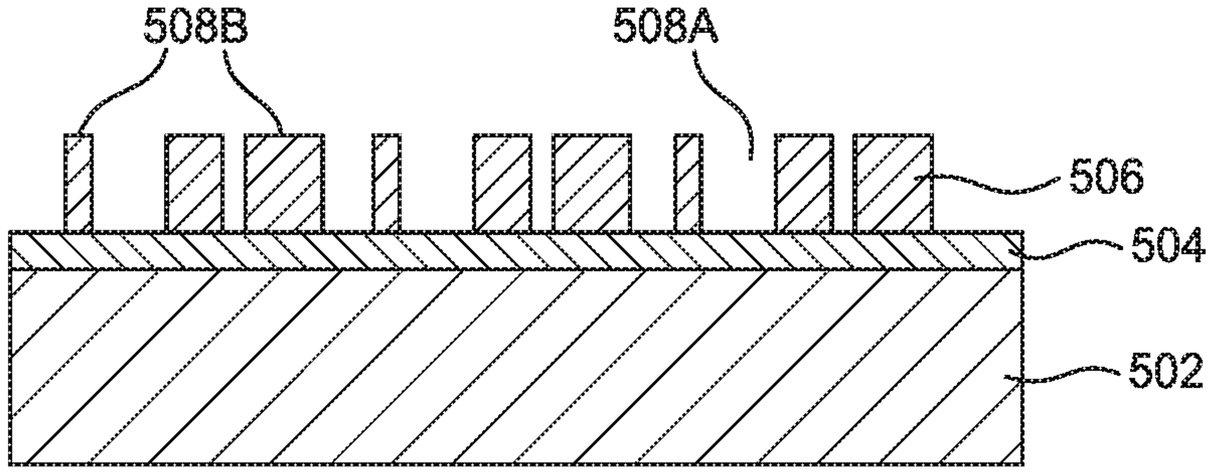


FIG. 5C

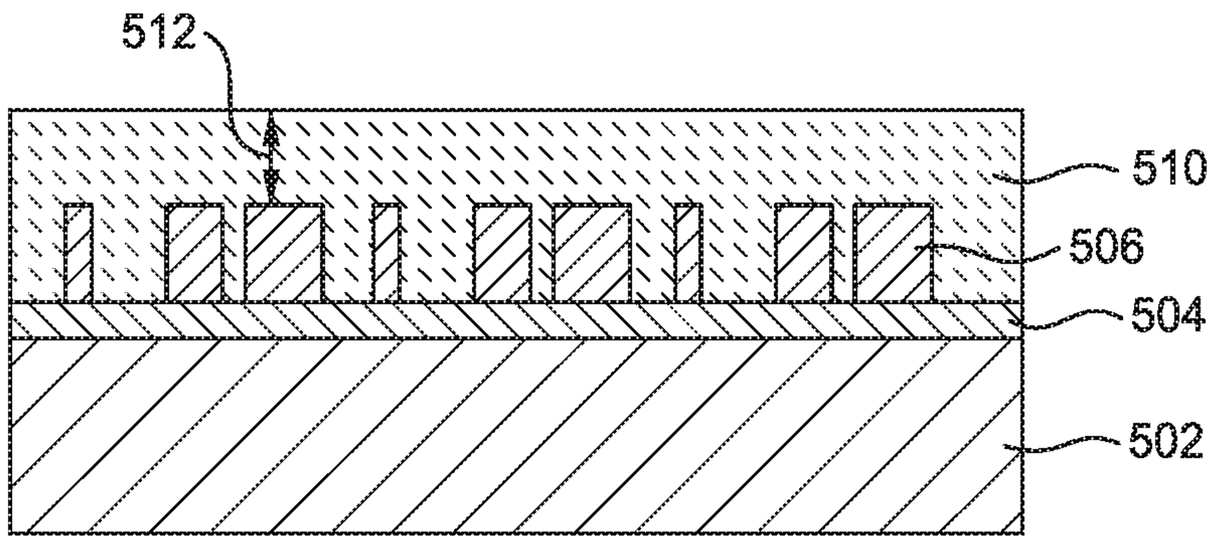
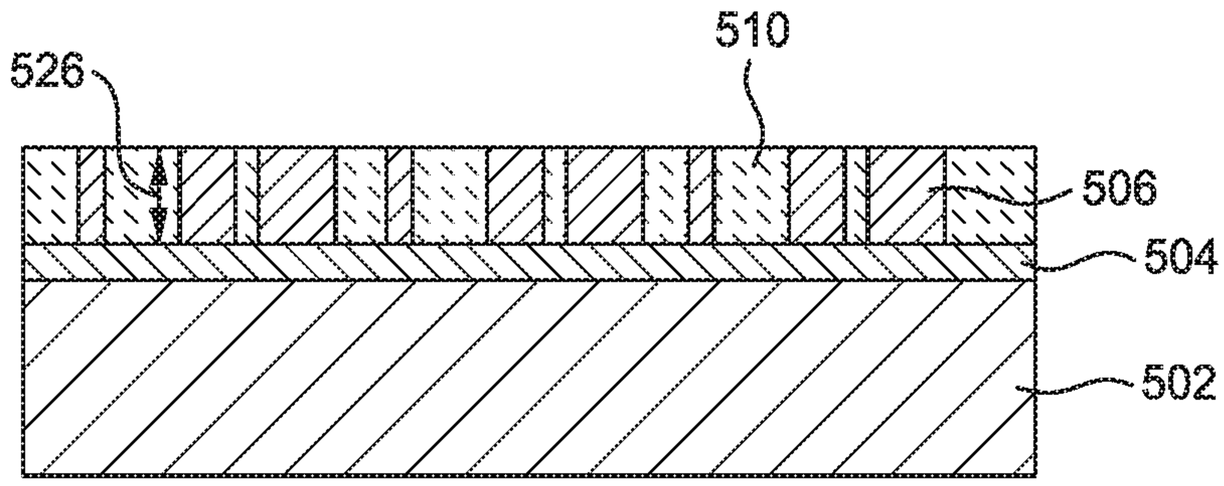


FIG. 5D



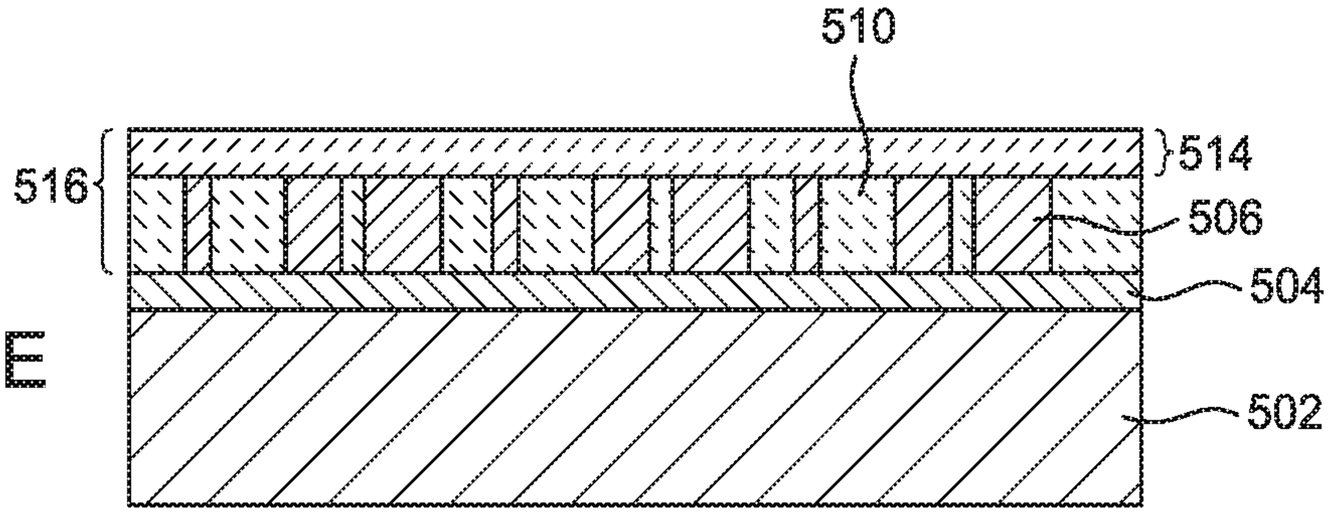


FIG. 5E

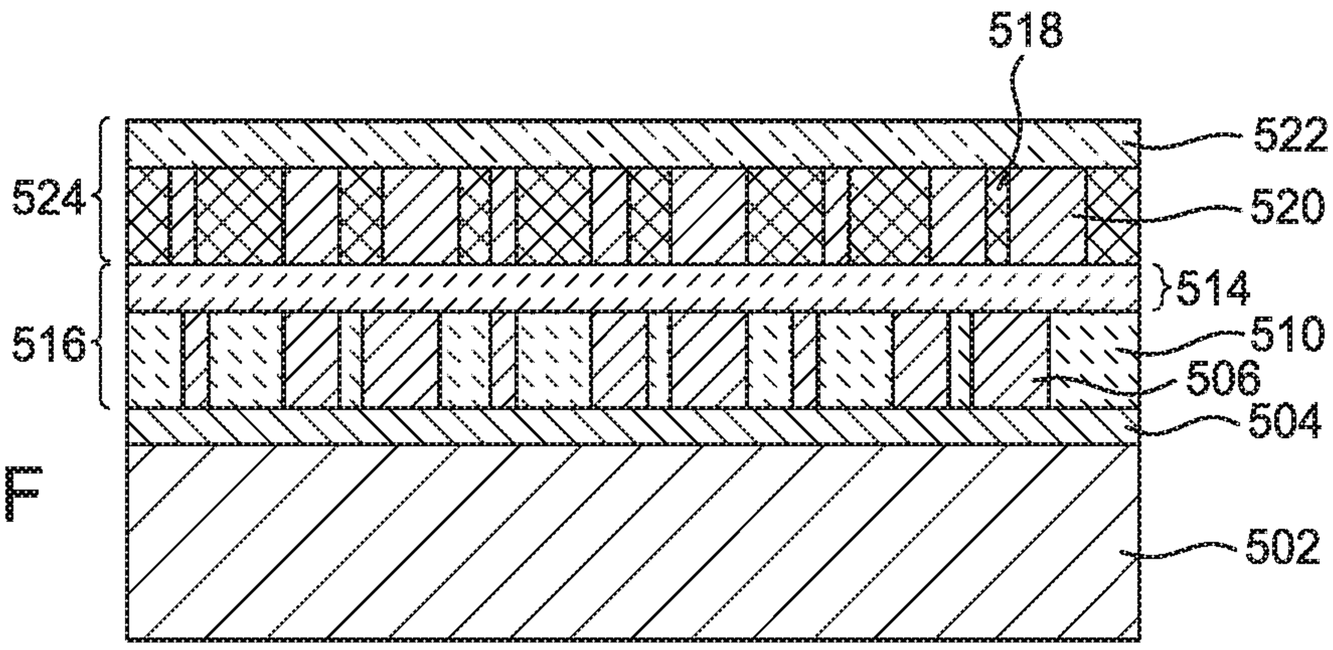


FIG. 5F

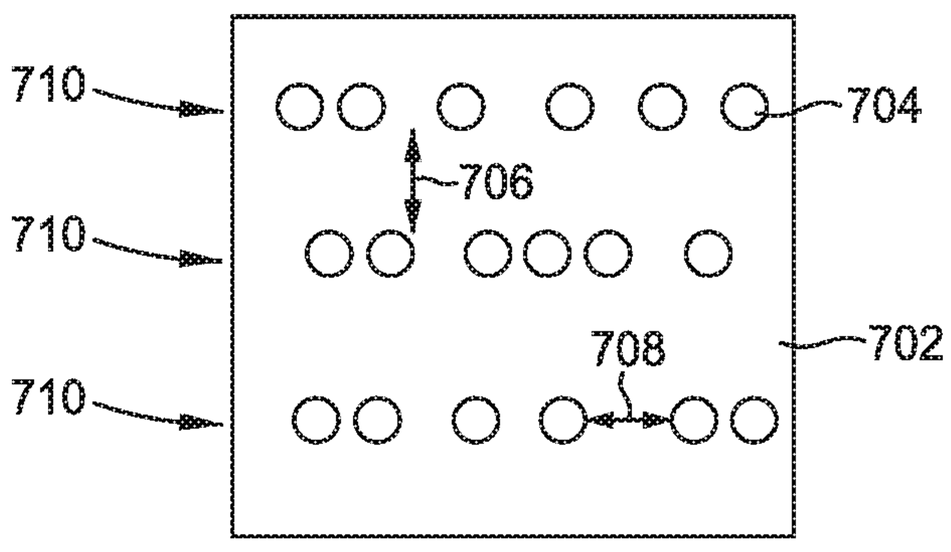


FIG. 6A

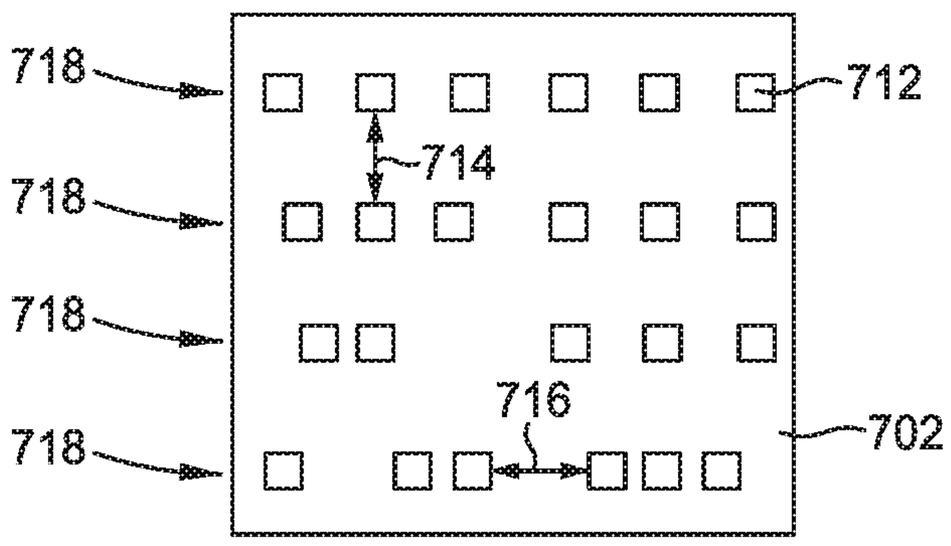


FIG. 6B

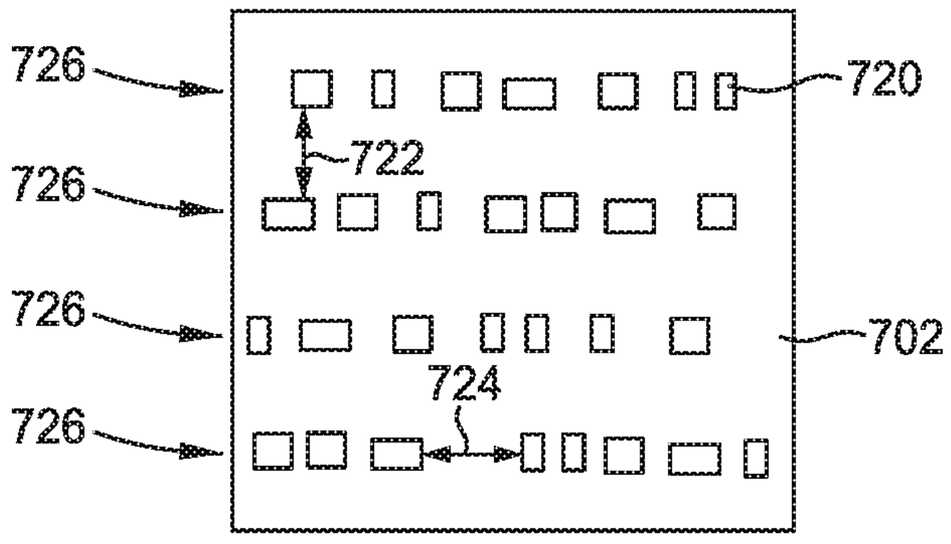


FIG. 6C

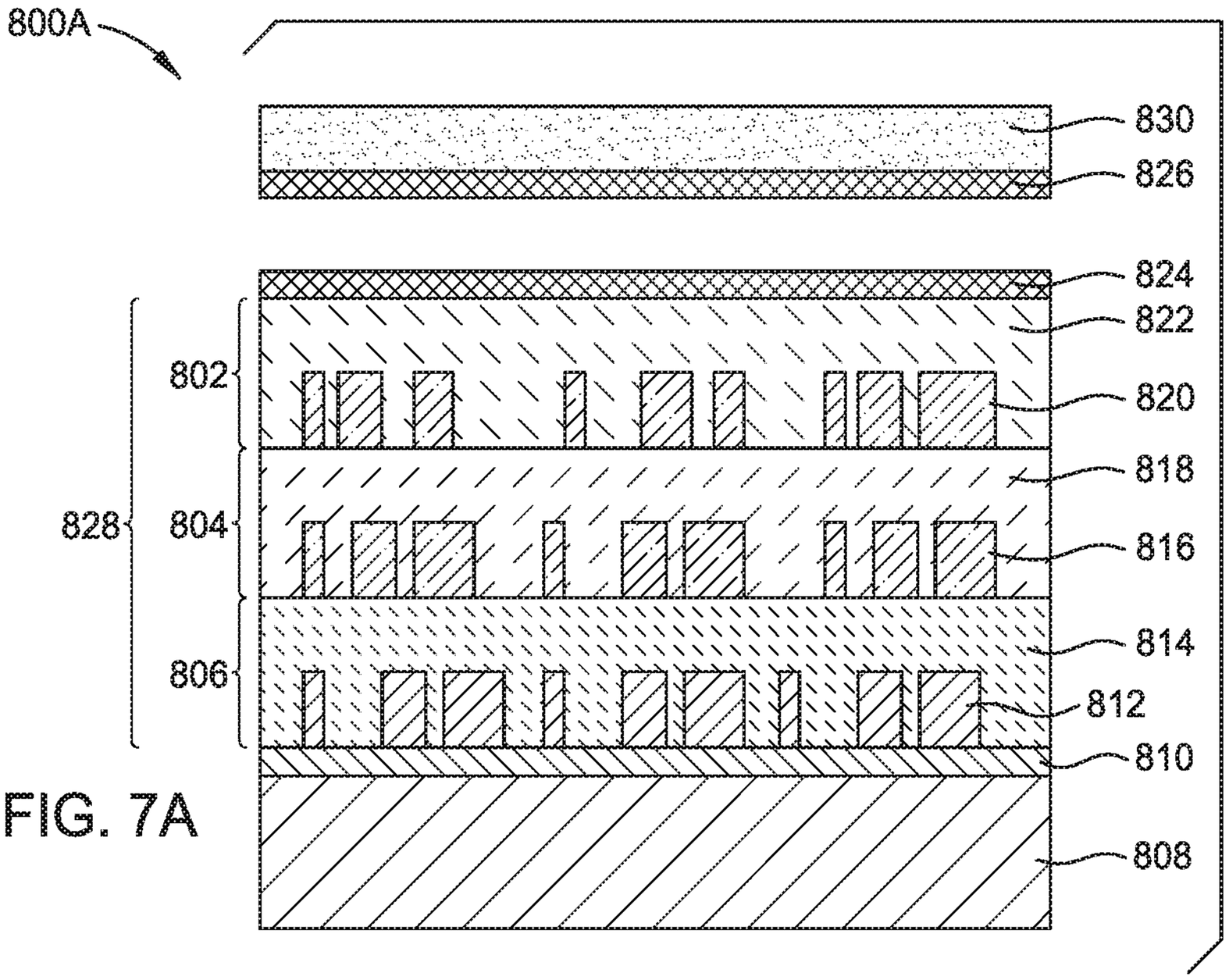

800A
830
826
824
822
802
820
818
828
804
816
814
806
812
810
808

FIG. 7A

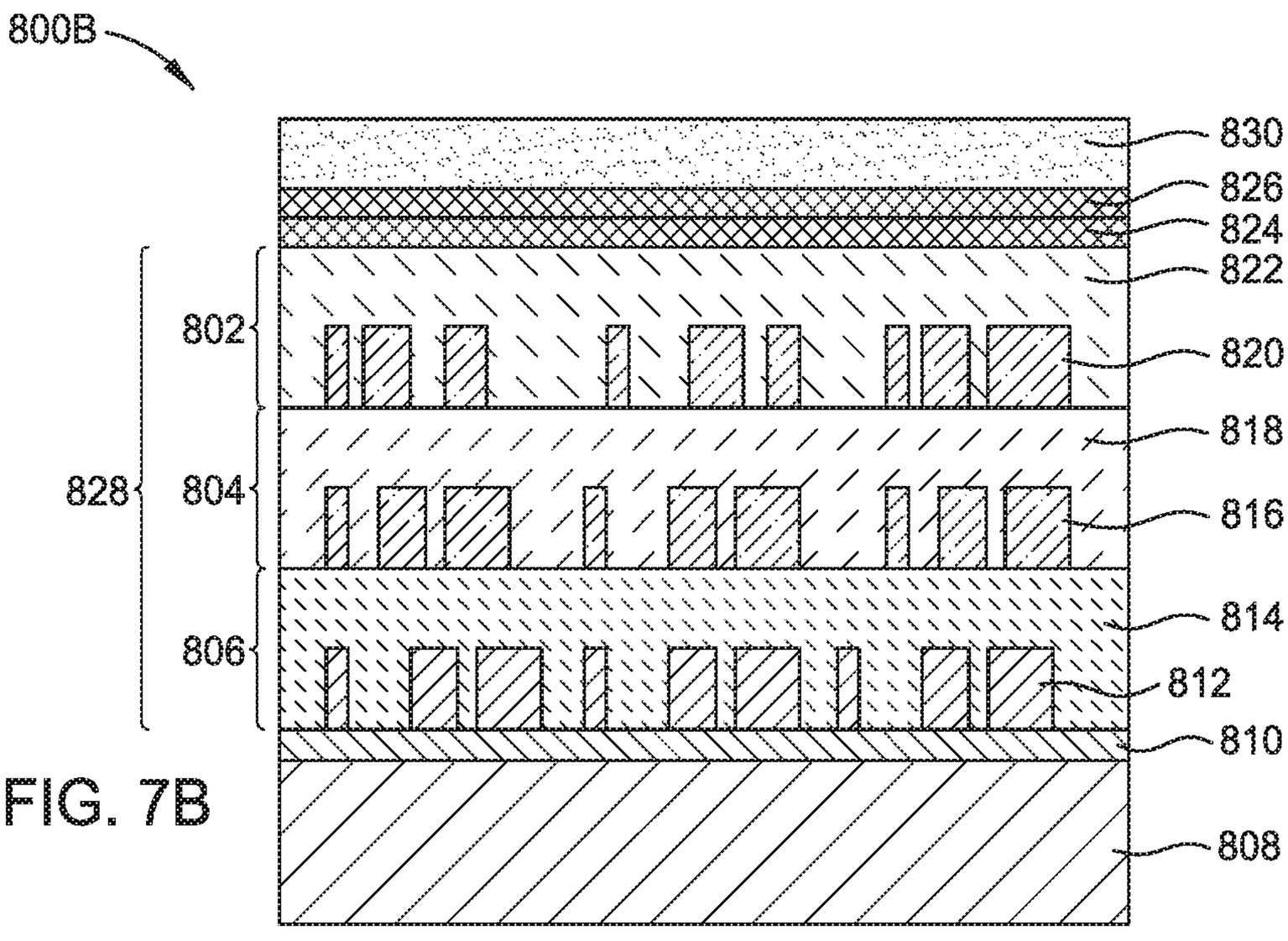

800B
830
826
824
822
802
820
828
804
818
816
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814
812
810
808

FIG. 7B

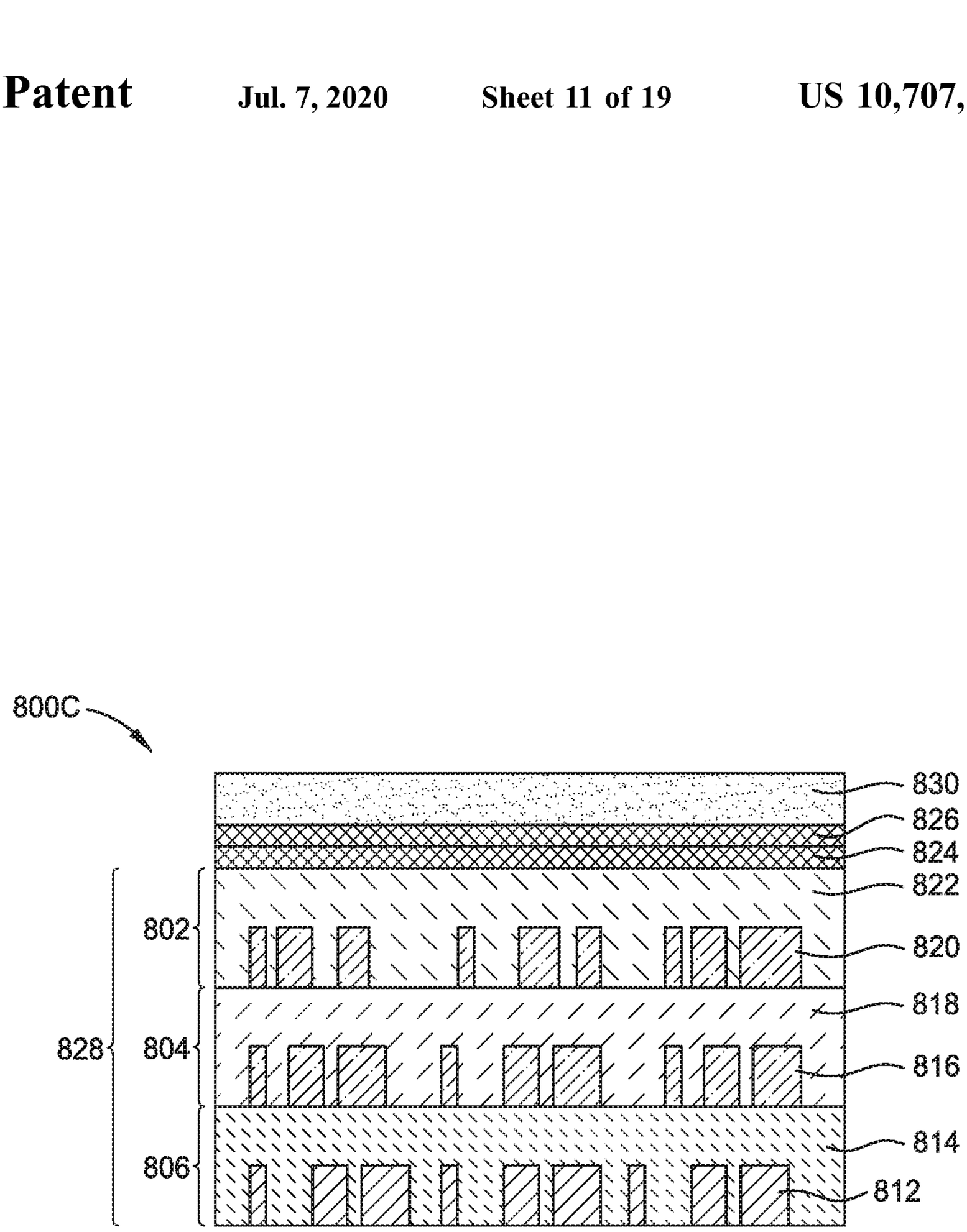


FIG. 7C

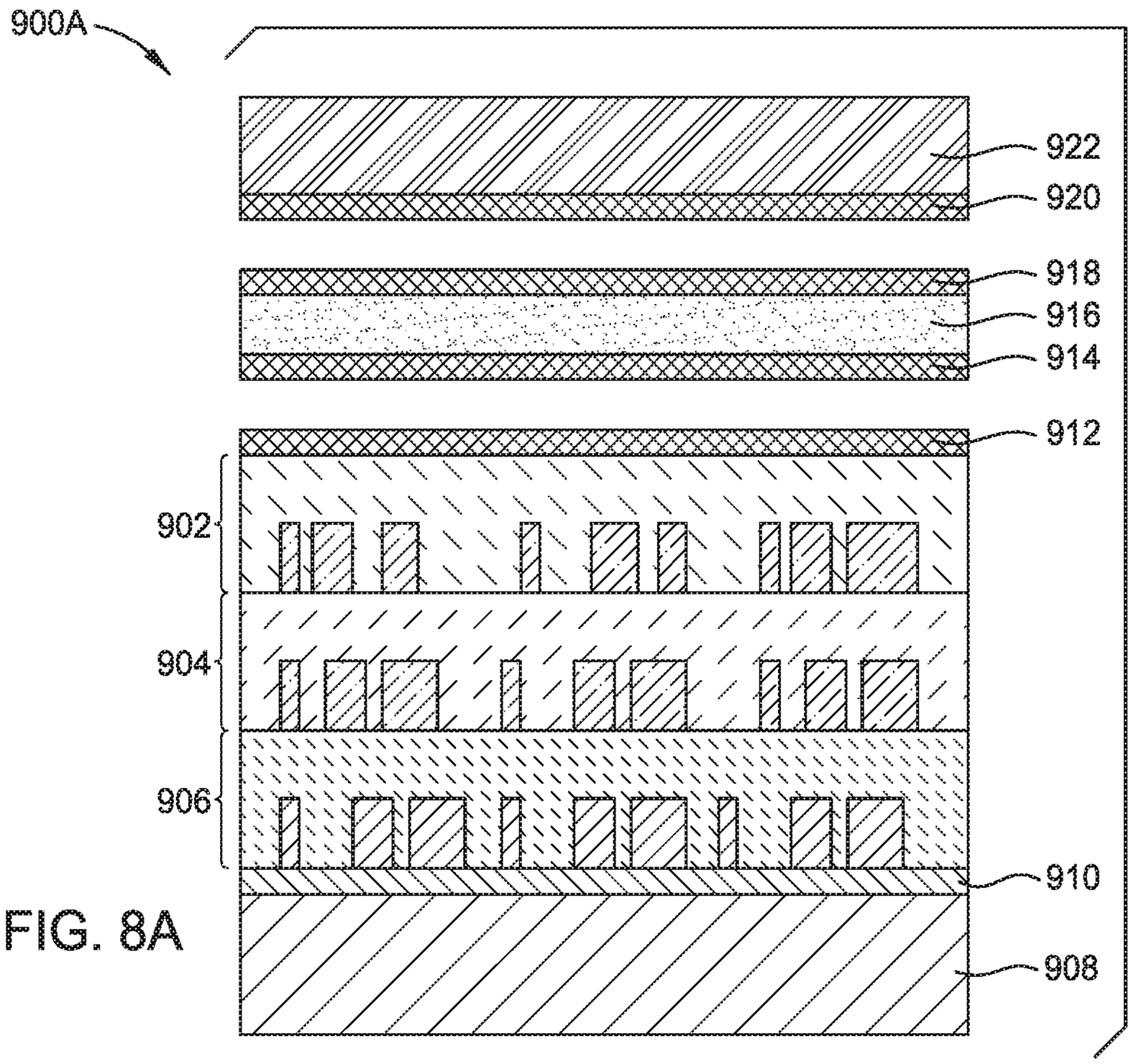

900A
922
920
918
916
914
912
902
904
906
910
908

FIG. 8A

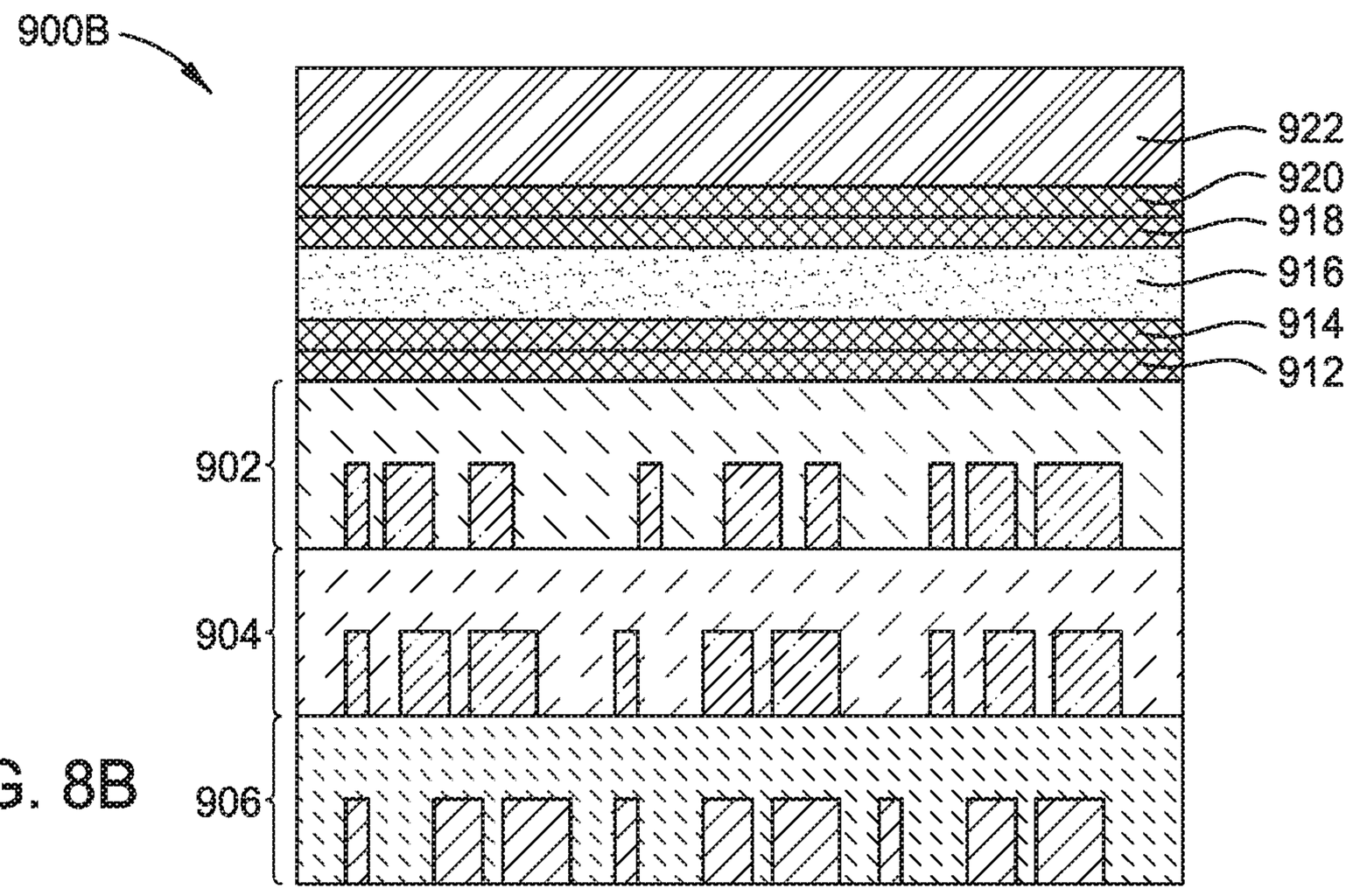

900B
922
920
918
916
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902
904
906

FIG. 8B

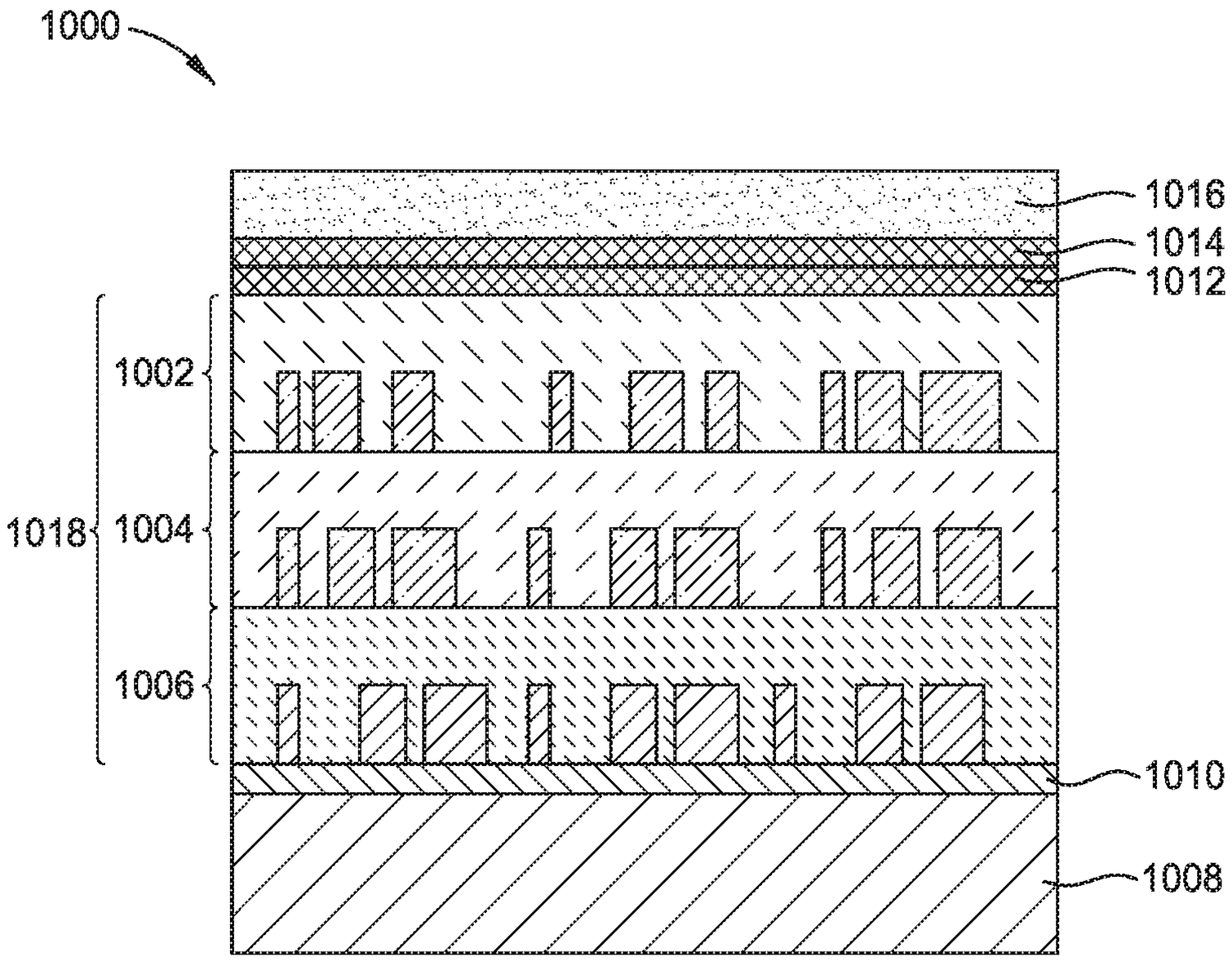


FIG. 9

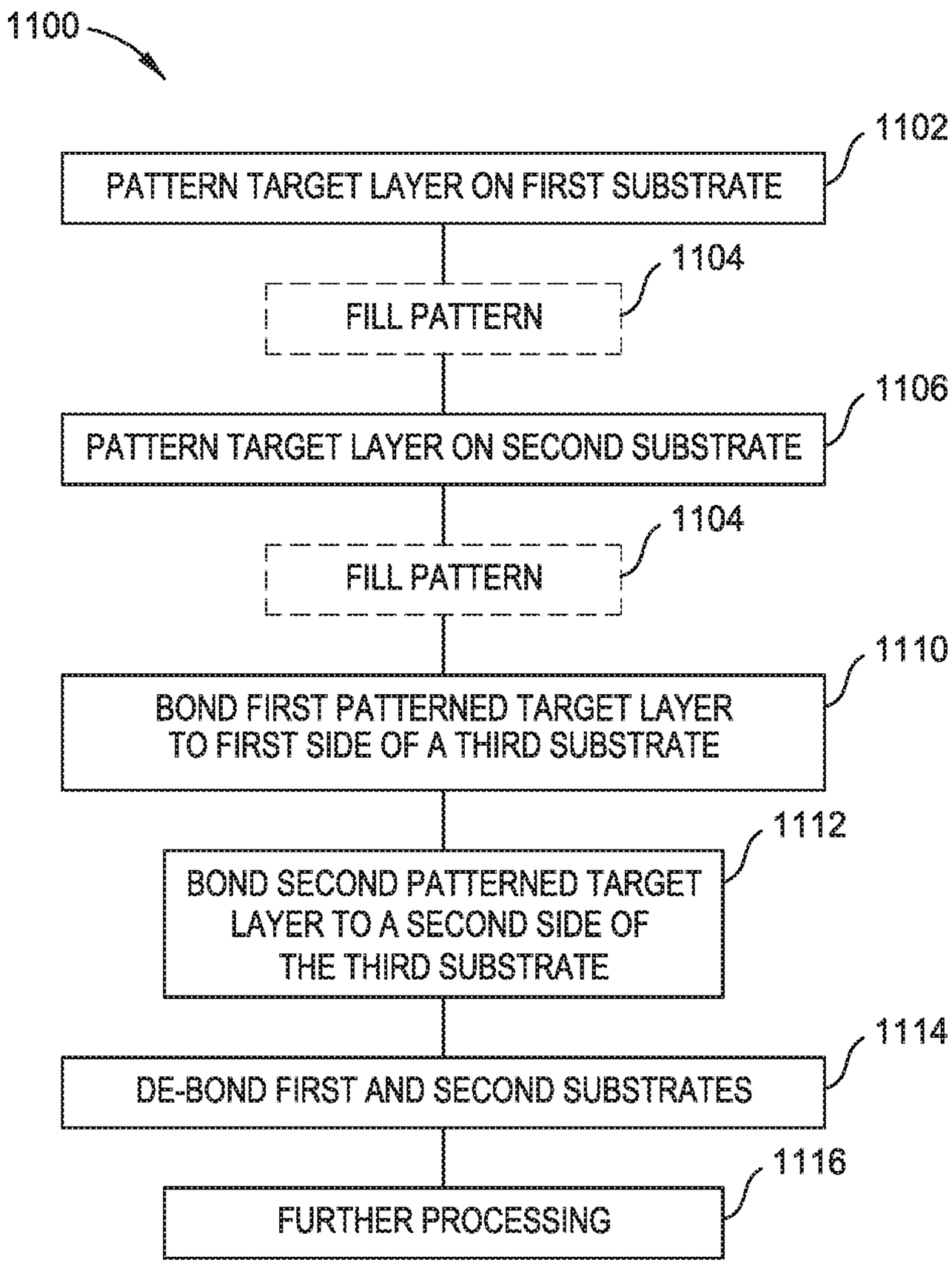

1100
PATTERN TARGET LAYER ON FIRST SUBSTRATE
1102
FILL PATTERN
1104
PATTERN TARGET LAYER ON SECOND SUBSTRATE
1106
FILL PATTERN
1104
BOND FIRST PATTERNED TARGET LAYER TO FIRST SIDE OF A THIRD SUBSTRATE
1110
BOND SECOND PATTERNED TARGET LAYER TO A SECOND SIDE OF THE THIRD SUBSTRATE
1112
DE-BOND FIRST AND SECOND SUBSTRATES
1114
FURTHER PROCESSING
1116

FIG. 10

FIG. 11A

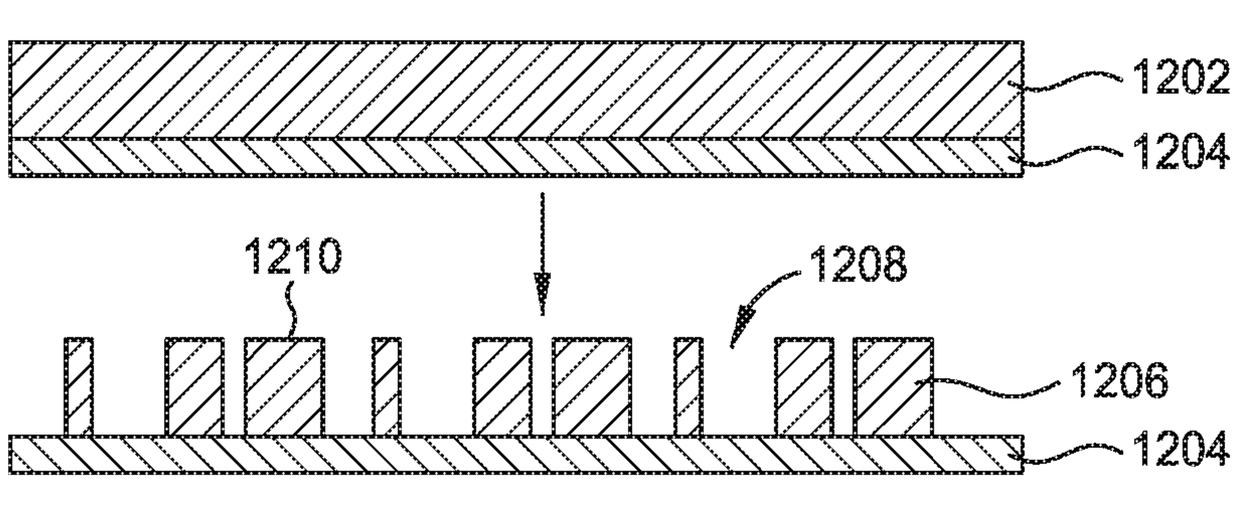


FIG. 11B

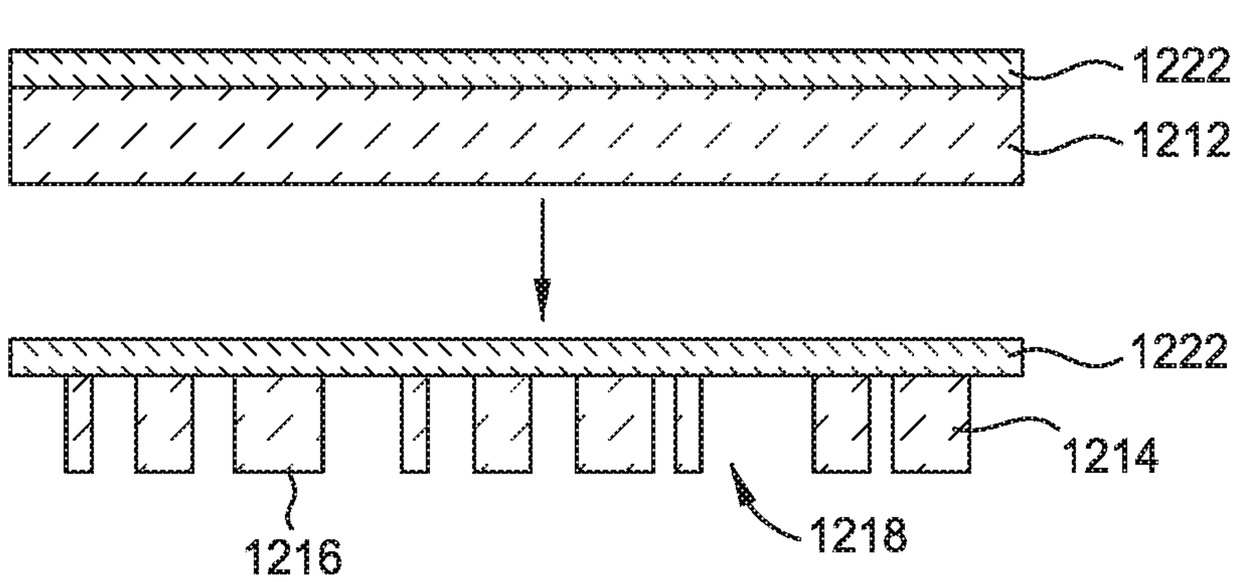


FIG. 11C

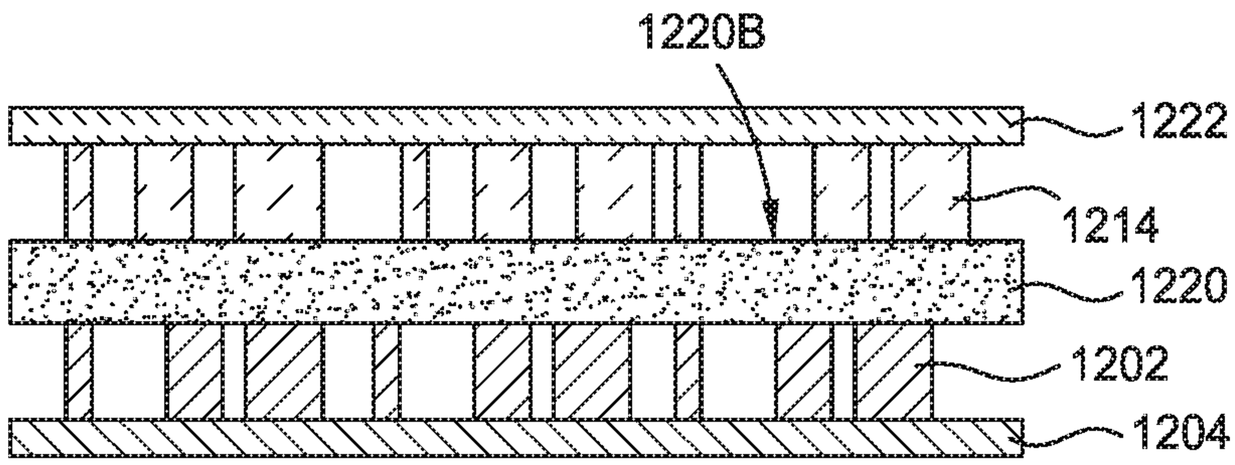
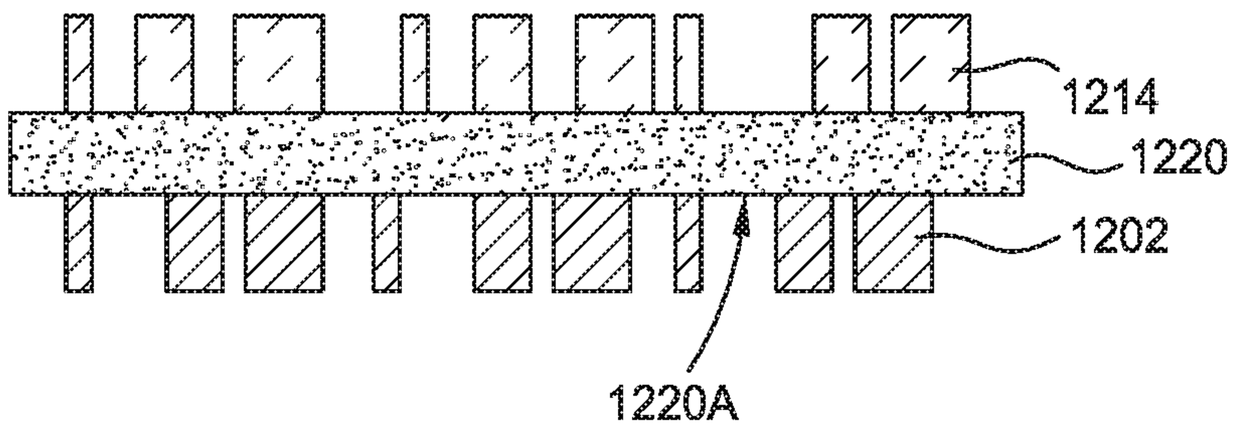


FIG. 11D



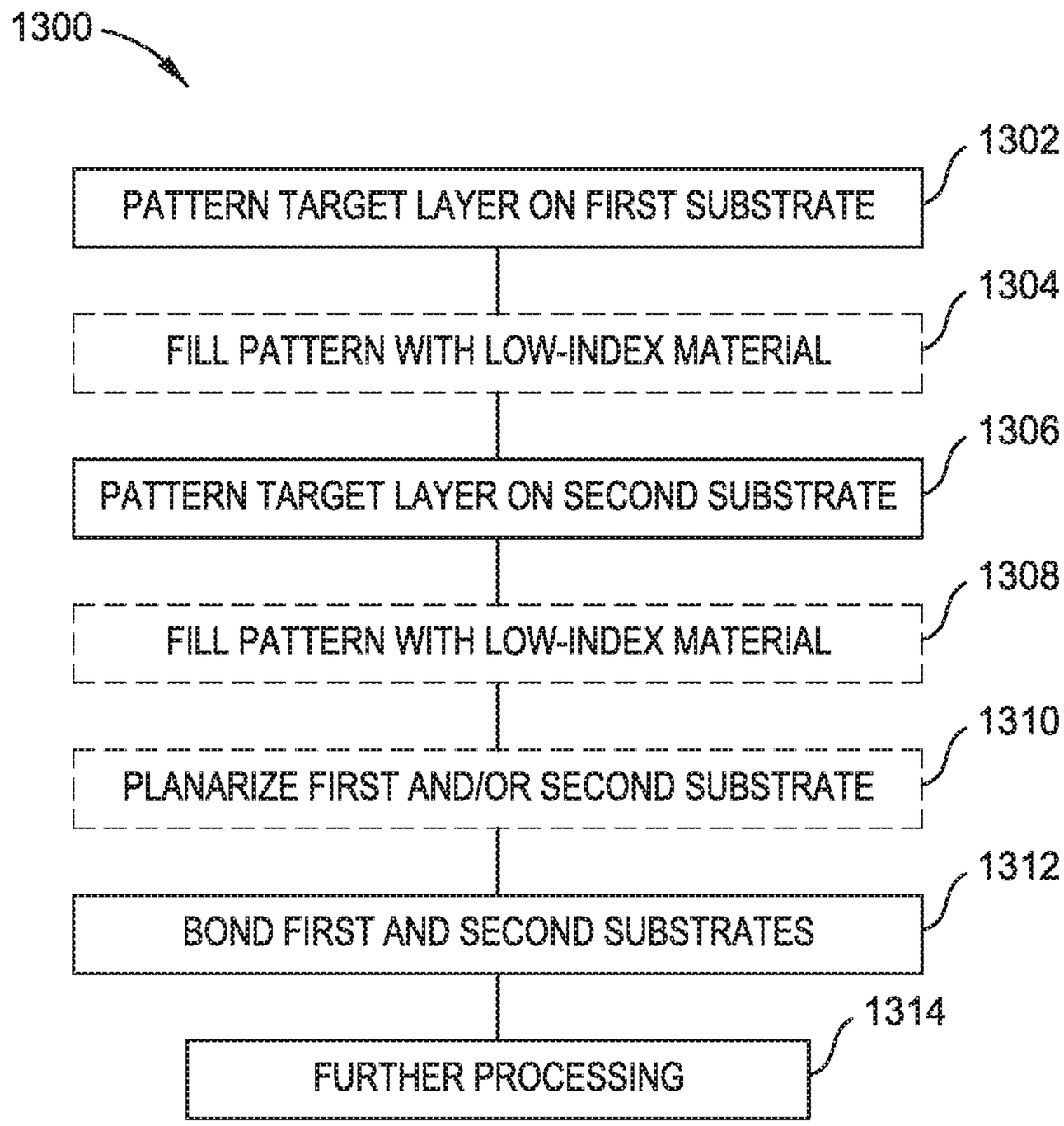

1300
PATTERN TARGET LAYER ON FIRST SUBSTRATE
1302
FILL PATTERN WITH LOW-INDEX MATERIAL
1304
PATTERN TARGET LAYER ON SECOND SUBSTRATE
1306
FILL PATTERN WITH LOW-INDEX MATERIAL
1308
PLANARIZE FIRST AND/OR SECOND SUBSTRATE
1310
BOND FIRST AND SECOND SUBSTRATES
1312
FURTHER PROCESSING
1314

FIG. 12

FIG. 13A

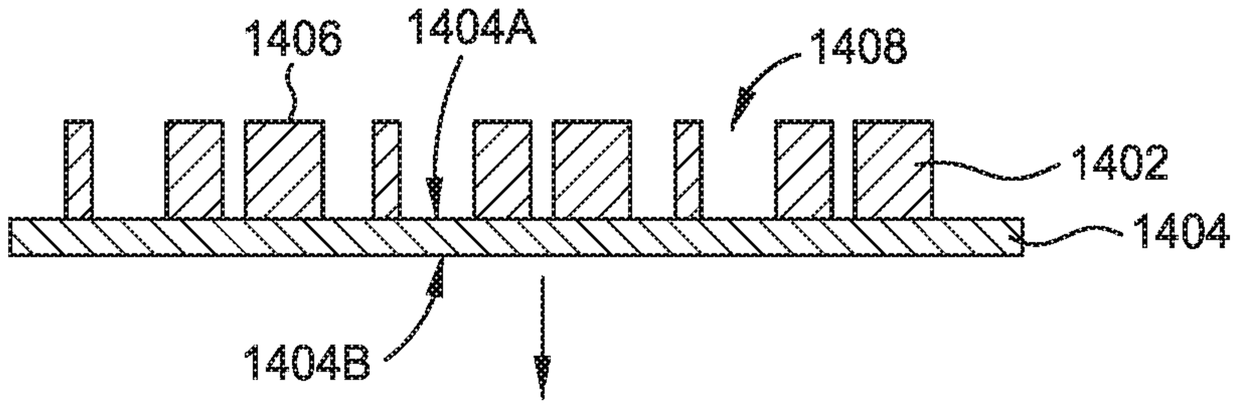


FIG. 13B

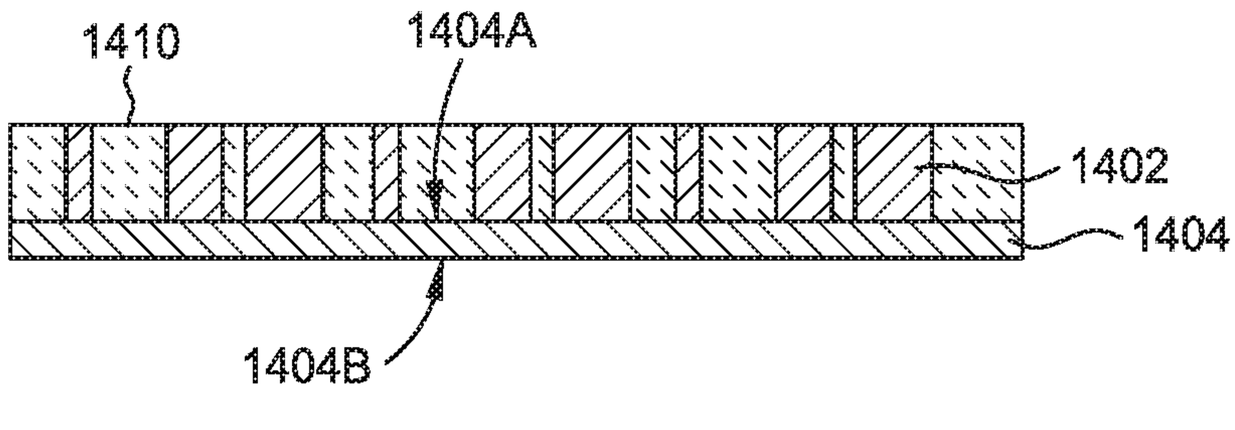


FIG. 13C

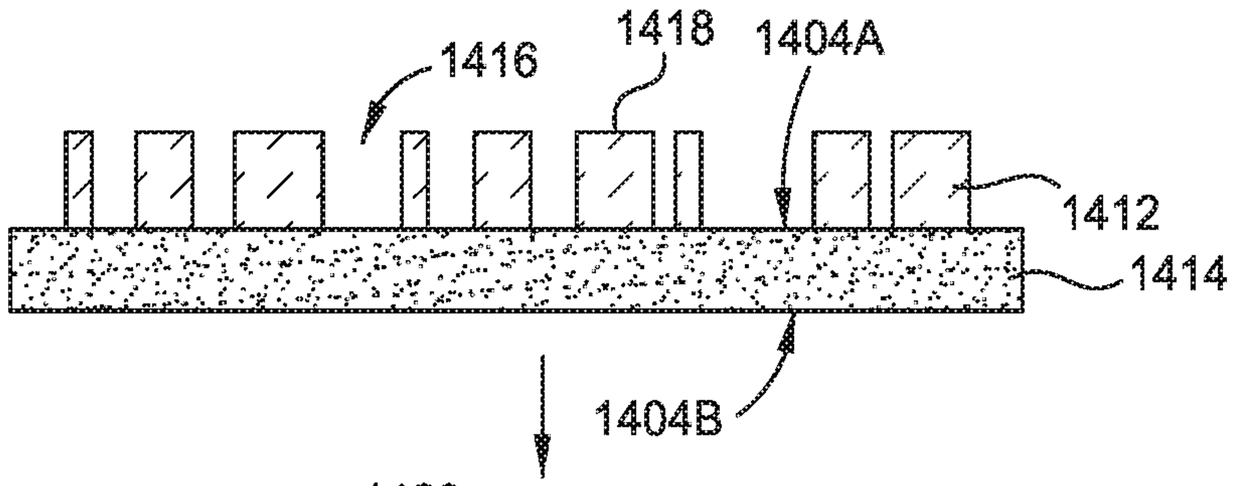


FIG. 13D

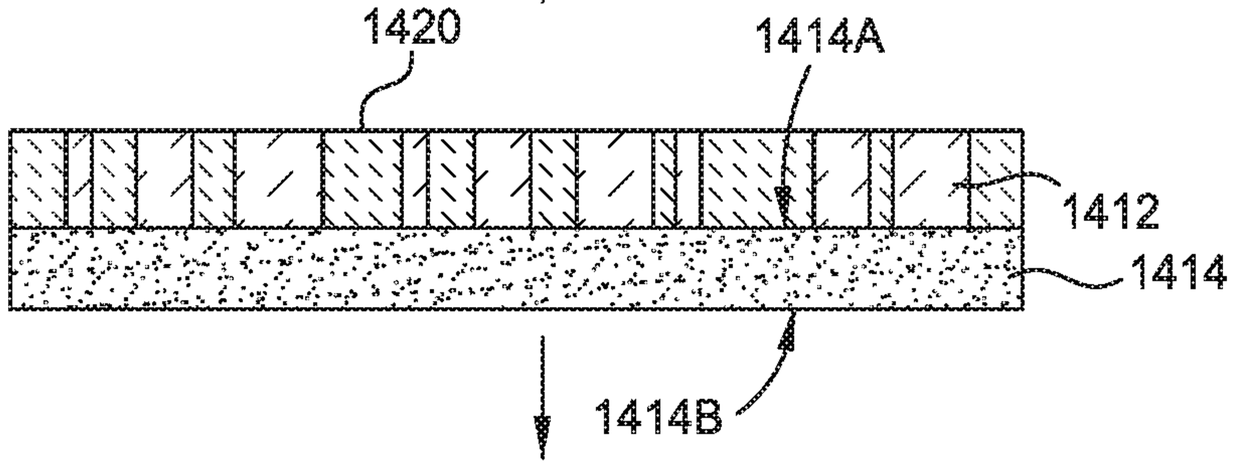
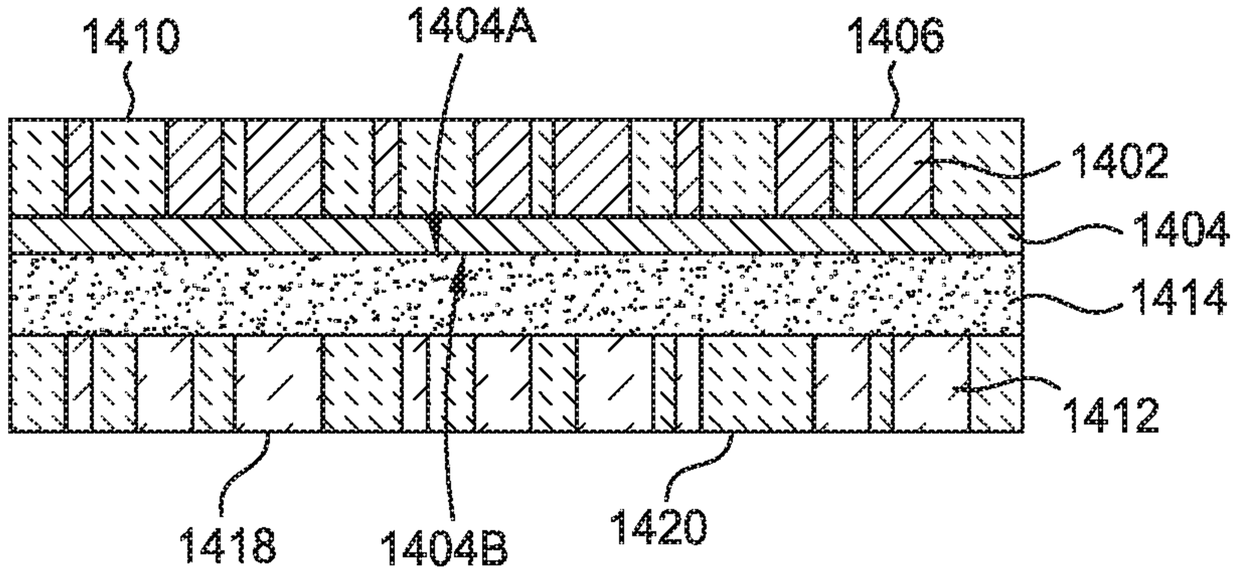


FIG. 13E



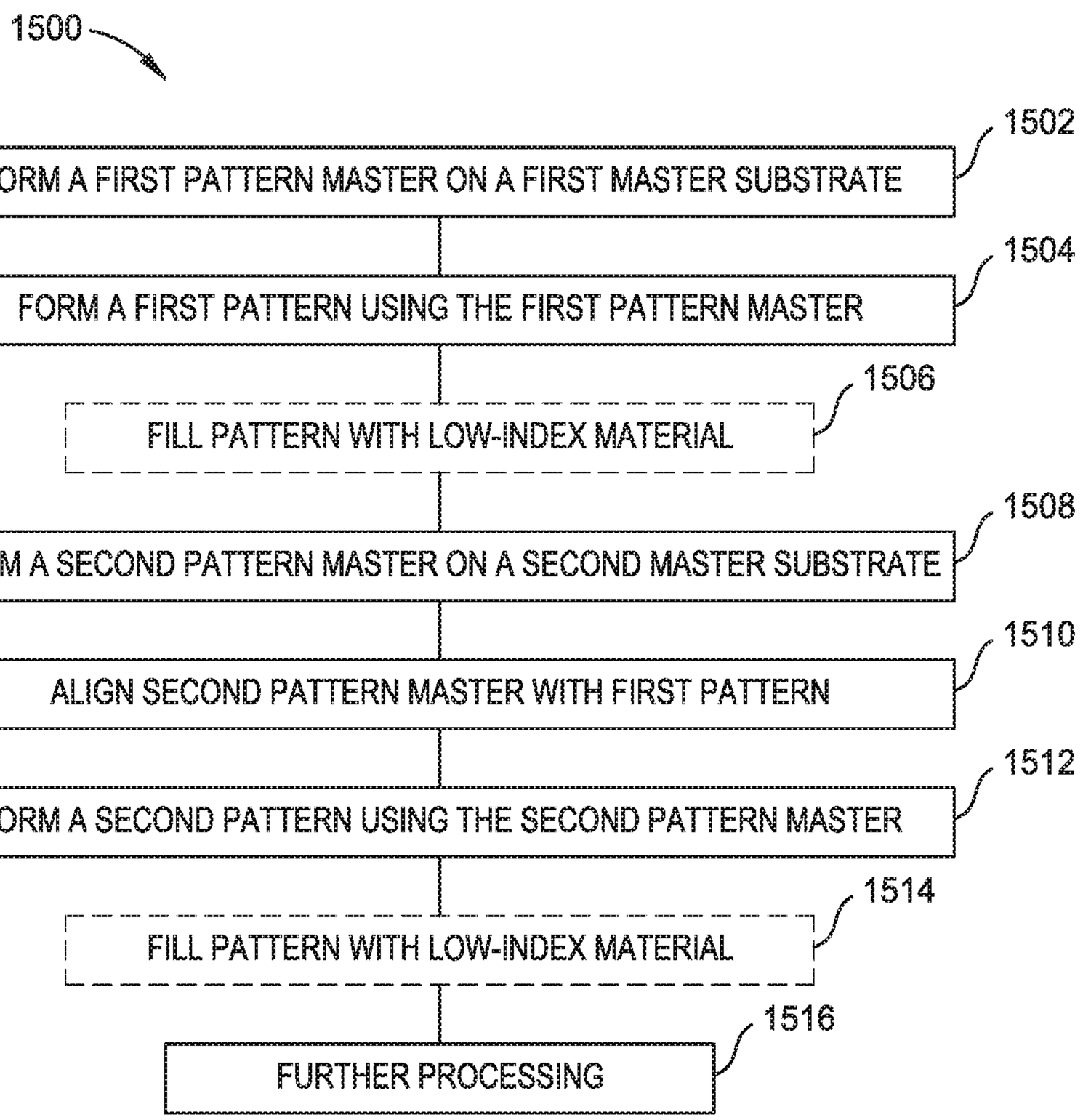

1500
FORM A FIRST PATTERN MASTER ON A FIRST MASTER SUBSTRATE
1502
FORM A FIRST PATTERN USING THE FIRST PATTERN MASTER
1504
FILL PATTERN WITH LOW-INDEX MATERIAL
1506
FORM A SECOND PATTERN MASTER ON A SECOND MASTER SUBSTRATE
1508
ALIGN SECOND PATTERN MASTER WITH FIRST PATTERN
1510
FORM A SECOND PATTERN USING THE SECOND PATTERN MASTER
1512
FILL PATTERN WITH LOW-INDEX MATERIAL
1514
FURTHER PROCESSING
1516

FIG. 14

FIG. 15A

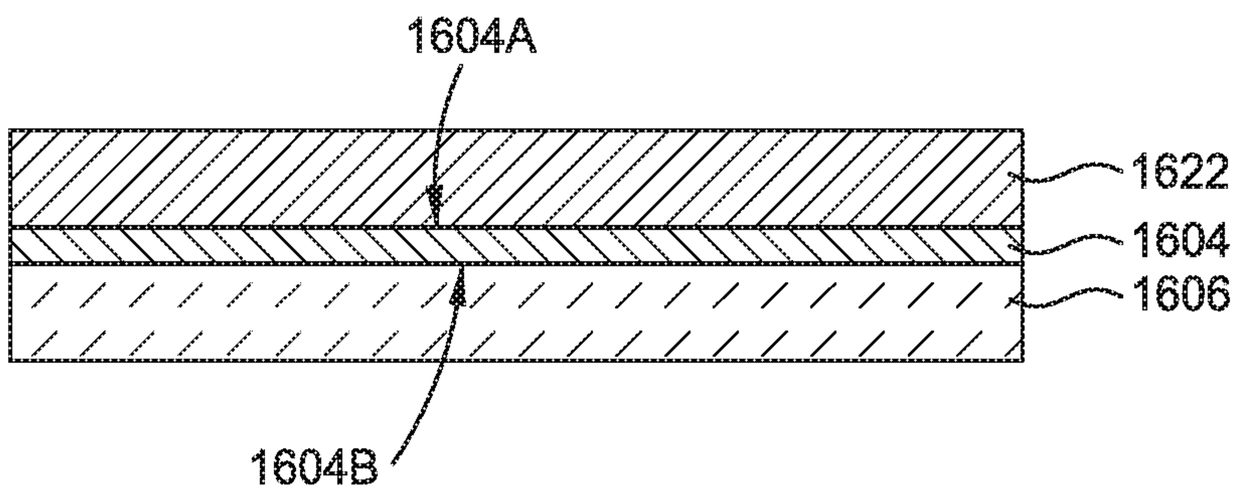


FIG. 15B

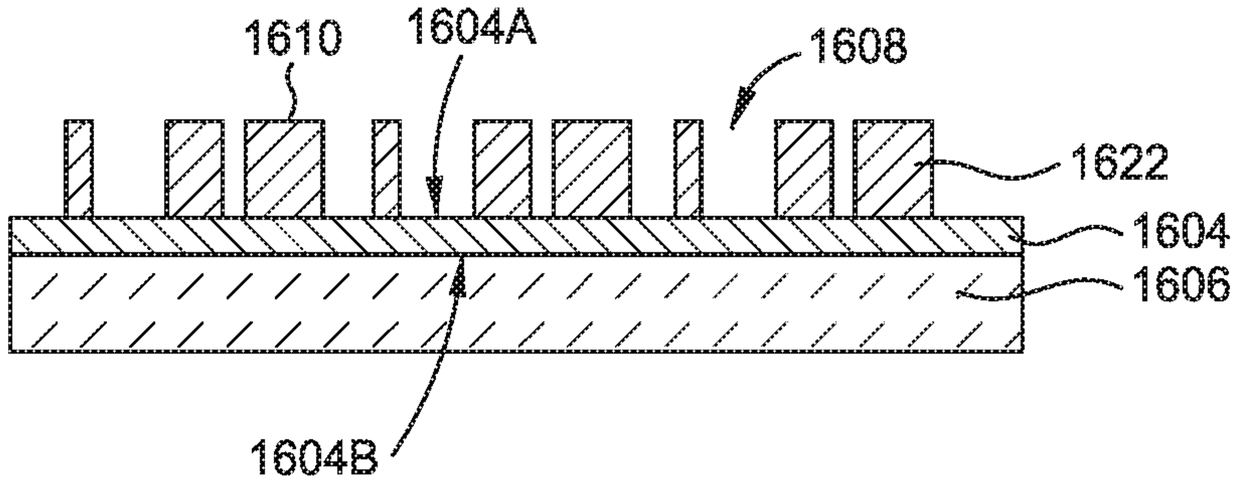


FIG. 15C

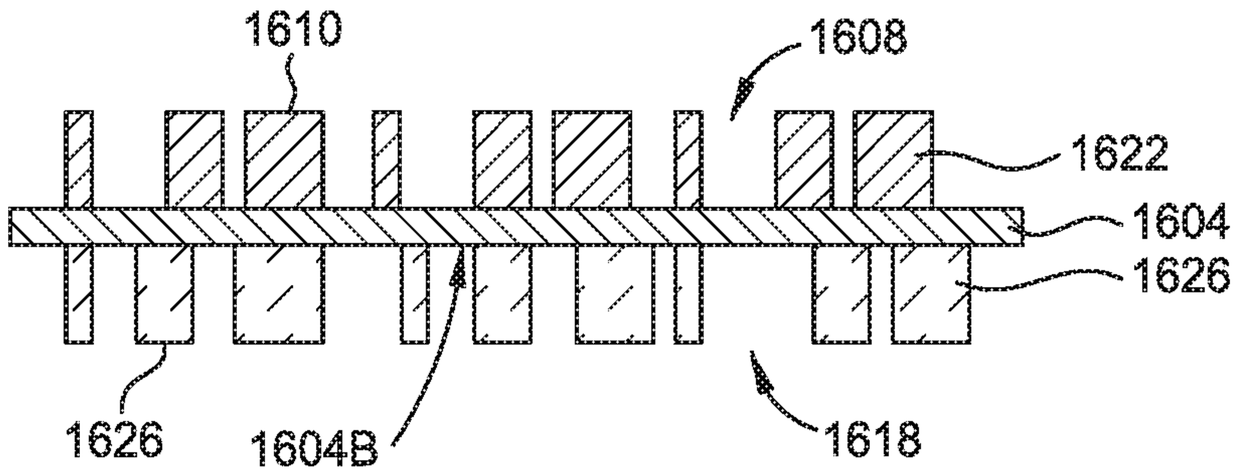
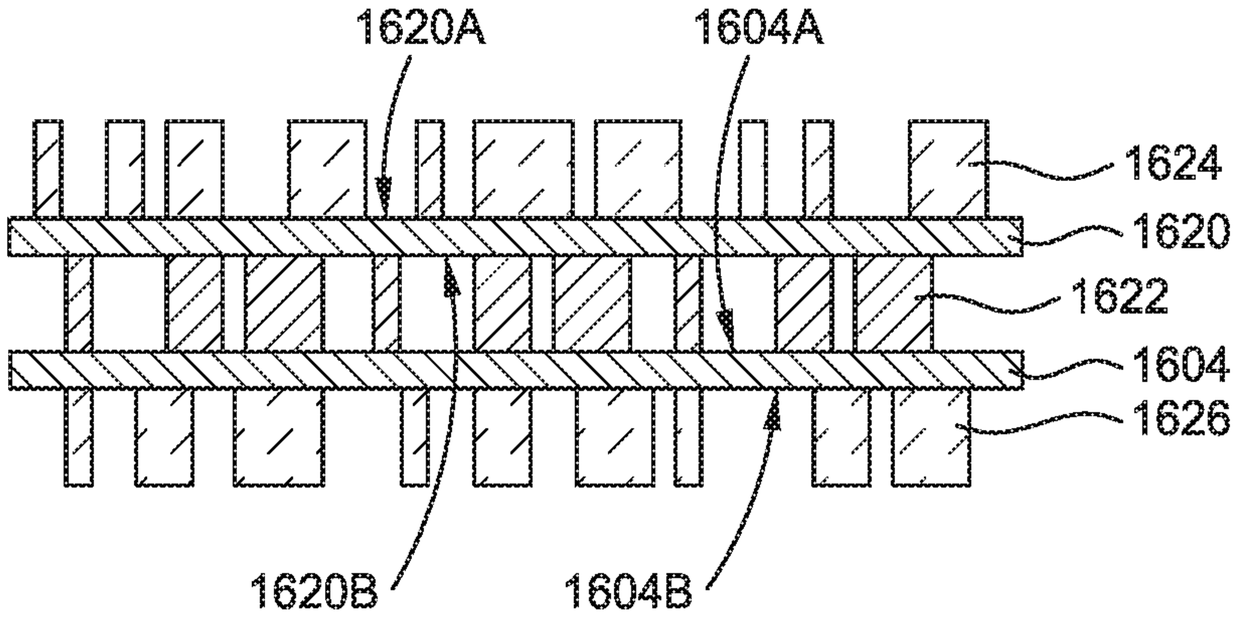


FIG. 15D



MULTI STACK OPTICAL ELEMENTS USING TEMPORARY AND PERMANENT BONDING

PRIORITY CLAIM

The instant application claims priority to U.S. Provisional Patent Application 62/658,553, "MULTISTACK OPTICAL ELEMENTS USING TEMPORARY AND PERMANENT BONDING," filed Apr. 16, 2018, and incorporated by reference in its entirety herein, and further claims priority to U.S. Provisional Patent Application 62/780,536 "MULTI-STACK OPTICAL ELEMENTS USING TEMPORARY AND PERMANENT BONDING," filed Dec. 17, 2018, and incorporated by reference in its entirety herein.

BACKGROUND

Field

The embodiments of the disclosure generally relate to optical devices and systems and methods of fabricating optical element devices.

Description of the Related Art

Novel optical devices, including metasurfaces can be patterned on one or both sides of transparent substrates and enable many optical device possibilities. However, a minimum thickness of a glass substrate is required for traditional processing techniques including optical lithography, and, for most optical devices of interest these thickness limitations are not commercially viable. The substrate minimum thickness limits processing options for later thinning the substrate when fabricating optical devices with elements present on both the front and the back surfaces of a substrate.

There are many concerns to address in the fabrication of novel optical devices on glass substrates, including metallic contamination from the substrate to the lithography tool chuck, handling breakage, glass transparency, metrology performance in the lithography tool, as well as other factors. For various optical applications, multiple layers of optical elements are used in an optical device to correct aberrations. Using multiple optical element layers may include patterning on the backside of a glass substrate to make a doublet. Bonding this doublet to another glass substrate to make a triplet and so on may be performed. These are challenging processes to do cost effectively and without damage to the nano-scale features.

Further challenges in optical device fabrication include the fabrication of buffer layers of thicknesses up to several millimeters in between optical elements. Conventional methods of optical element and structure fabrication can face fabrication issues including pattern alignment that can make fabrication of these double-sided optical elements challenging.

Thus, there remains a need for systems and methods of improved optics and methods of manufacturing improved optics.

SUMMARY

Embodiments of the present disclosure are generally directed towards optical devices that include optical element layers, and methods of forming the optical devices. In one example, a method of forming an optical device includes: (a) forming a pattern in a target layer on a first substrate, wherein the pattern includes a plurality of islands separated by a plurality of trenches; and (b) forming a low-refractive index material on top of the patterned target layer and in the plurality of trenches formed in the patterned target layer to form a first optical device. The method can further include (c) forming a stack of optical element layers on the first optical device by repeating (a) and (b) for a plurality of iterations.

In another example, a method of fabricating optical elements, includes forming a first pattern in a first target layer formed on a first substrate and forming a second pattern in a second target layer formed on a second substrate. The first pattern is then bonded to a first side of a third substrate formed from a transparent material and being from about 10 μm thick to 3 mm thick. The method further includes bonding the second pattern to a second side of the third substrate; de-bonding the first substrate from the first pattern; and de-bonding the second substrate from the second pattern.

In another example, a method of forming an optical element, includes: forming a first pattern by imprinting a first target layer in a first location using a first pattern master, the first target layer being formed on a first side of a transparent substrate, wherein the transparent substrate is from about 10 μm thick to about 3 mm thick. The method further includes forming a second pattern by imprinting a second pattern in a second location on a second target layer formed on a second side of the transparent substrate using a second pattern master. Forming the second pattern in the second location includes determining the second location relative to the first pattern and aligning the second pattern master in the second location.

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 implementations, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical implementations of this disclosure and are therefore not to be considered limiting of its scope, for the disclosure may admit to other equally effective implementations.

FIG. **1** is a flow chart of a method of fabricating optical devices according to embodiments of the present disclosure.

FIGS. **2**A-**2**I is a series of partial schematic illustrations of cross-sections of optical element structures formed during optical device fabrication according to embodiments of the present disclosure.

FIG. **3** is a partial schematic illustration of a cross-section of an optical element structure according to embodiments of the present disclosure.

FIG. **4** is a flow chart of a method of fabricating optical elements according to embodiments of the present disclosure.

FIGS. **5**A-**5**F is a series of partial schematic illustrations of cross-sections of optical element structures and optical element manufacture according to embodiments of the present disclosure.

FIGS. **6**A-**6**C are schematic illustrations of a top view of optical element structures according to embodiments of the present disclosure.

FIGS. **7**A-**7**C are schematic illustrations of a bonding method during optical device fabrication according to embodiments of the present disclosure.

FIGS. **8**A-**8**B are a schematic illustration of an optical element structure according to embodiments of the present disclosure.

FIG. **9** is a schematic illustration an optical element structure formed on a device according to embodiments of the present disclosure.

FIG. **10** is a flow chart of a method of fabricating optical elements according to embodiments of the present disclosure.

FIGS. **11**A-**11**D are cross-sectional views of optical element structures discussed in conjunction with operations of a method of fabricating optical elements according to embodiments of the present disclosure.

FIG. **12** is a flow chart of a method of fabricating optical elements according to embodiments of the present disclosure.

FIGS. **13**A-**13**E are cross-sectional views of optical element structures discussed in conjunction with operations of a method of fabricating optical elements according to embodiments of the present disclosure.

FIG. **14** is a flow chart of a method of fabricating optical elements according to embodiments of the present disclosure.

FIGS. **15**A-**15**D are cross-sectional views of optical element structures discussed in conjunction with operations of a method of fabricating optical elements according to embodiments of the present disclosure.

Identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements disclosed in one implementation may be beneficially utilized in other implementations without specific recitation.

DETAILED DESCRIPTION

The systems and methods discussed herein may include the mass production of optical devices, including double-sided and stacked optical element layers. As discussed herein, an "optical device" is a device configured to have a predetermined effect on light introduced therein. Optical devices can include one or more optical element layers. An "optical element layer" includes one or more optical elements that may or may not have encapsulation (fill) material formed thereon. The optical element layers discussed herein include positive features that can be referred to herein as islands. Each island of an optical element layer is separated from an adjacent island by a negative feature, referred to herein as a trench. In some examples, trenches can be filled with fill materials. Depending upon the example, islands and trenches can be formed from either high or low refractive index materials. The islands and trenches can have various top-view and cross-sectional dimensions, including polygonal, rounded, tapered, and combination geometries. The islands, and thus the trenches, can be arranged, in a top-down view, in ordered arrays, random arrays, patterned arrays, or combinations thereof. An optical element comprises a single island or trench feature which individually contributes to the optical response of light introduced to the optical device.

The optical devices contemplated herein can include lenses, dot projectors or holographic projectors, color filters, and collimators, as well as elements and components thereof. In some examples, the optical devices discussed herein can be implemented in augmented reality devices. In order to make broadband elements and other optical devices for short wavelength light, the nano-sized optical elements in an optical element layer can have, for example, a maximum dimension of less than about 100 nm. Alternative patterning methods may be used to pattern these structures. In some examples, nano Imprint (NIL) or EUV lithography may be employed. In one embodiment, nano-imprint lithography may be employed to imprint a hardmask, and then to directly etch features based upon the hardmask imprint without performing a hardmask etch. Further, nano-imprint lithography may be employed to form the optical element layers directly on the substrate. The systems and methods discussed herein enable the consistent formation of both high aspect ratio features with aspect ratios of 20:1 or greater, and low aspect ratio features with aspect ratios, for example, from 1:1 to 1:3.

In one example, the optical devices are fabricated without using glass substrates. In another example, the optical devices are fabricated to include glass substrates. In one embodiment, target layers formed on top of a silicon (Si) substrate are patterned and subsequently transferred to a device or transparent substrate. As discussed herein, a transparent substrate is a substrate that is optically transparent in a predetermined wavelength range within which the optical device is intended to operate. The target layer can be a low index material or a high index material, depending upon the embodiment. Target layers can be single layers or can include one or more stacked layers of the same composition or of varying compositions. The methods herein can further include stacking the patterned target layers directly onto completed devices while still on the original substrate, before dicing, if dicing is performed. For example, optical element layers can be stacked directly onto a substrate of completed charge-coupled devices (CCD), or complementary metal-oxide semiconductor (CMOS) image sensors, light-emitting diodes (LED), a micro-LED (uLED) display, organic light-emitting diode (OLED) or vertical-cavity surface-emitting laser (VCSELs) or another substrate. The methods discussed herein are a form of Integrated Processing.

In one example, the optical devices discussed herein are formed to include a fill layer. The fill layer is formed in between optical elements of an optical element layer. The fill layer can include an interlayer, which is a portion of the fill layer formed in between and on top of the optical element layers to form a space in between optical element layers of stacked optical element layers. The fill layer can be engineered for specific functions associated with various wavelengths. Thus, the optical element layers discussed herein can be configured as independent optical element layers or interactive optical element layers. Nano-imprint lithography may also be employed to imprint a pattern of features directly on to a substrate, after which a fill material is subsequently deposited, which may involve inkjet, slot-die, spin-coating, or otherwise forming the inter-element (optical element) material, resulting in a low cost process. In alternate embodiments, CVD, PVD, or ALD may be employed to form the optical element layers and/or the fill layers discussed herein. The shapes of the optical elements in the optical elements layers of the optical devices discussed herein range from geometries as simple as circles, triangles, or polygons, to complex shapes that can be combinations of various geometries.

In another example, the optical devices may be fabricated by imprinting a negative tone of a target layer of the functional devices. The negative tone is a pattern that includes islands and trenches formed in the target layer, which can be a low-index material. The trench fill material can then be formed by atomic layer deposition (ALD) or chemical vapor deposition (CVD). If a low-index material is

used for the target layer, a trench fill material such as amorphous silicon (a-Si), SiN, TiO_2, GaP, or other material can be deposited in and/or on the trenches to form the optical elements of the optical element layer. In one example, a-Si or SiN may be used for optical wavelength bands near an IR range, and TiO_2 may be used for optical wavelength bands near visible light ranges. The trench fill material can be formed by spinning-on, CVD, or ALD. Subsequently, another layer of low-index material, such as silicon dioxide, doped silicon dioxide, fluorinated polymers, or other suitable porous materials, can be formed on the fill layer. This layer of low-index material can act as an interlayer to separate optical element layers (high-index material layers) instead of additional transparent substrates.

In some examples, the low-index materials discussed herein are self-planarizing materials and chosen in part for that characteristic since, in some embodiments, planar surfaces are used for optical element manufacture. In other examples, chemical-mechanical planarization (CMP) is used to achieve a predetermined flatness of one or more layers including the low-index layers. The flatness may be within a tolerance from between 1 nm to 5 nm. In some examples, the flatness tolerance is 2 nm. In other examples, the flatness tolerance can be less than 1 nm or greater than 5 nm, depending upon the optical device being fabricated.

In other examples, double-sided optical devices are formed on a transparent substrate that separates the optical elements in adjacent optical element layers. The transparent substrate can have a thickness from 10 μm to 3 mm or greater. In this example, two target layers are each formed on different temporary substrates. Each target layer is patterned, where the patterning can occur sequentially or simultaneously, or in an overlapping fashion. Depending upon the embodiment, each target layer can be a low-index or a high-index material. Each patterned target layer can be optionally filled. Each patterned target layer is bonded to a third substrate. The third substrate can be a transparent substrate and acts as an interlayer that separates the two patterned target layers. The patterned target layers can be subsequently de-bonded from each respective temporary substrate. In one example, pattern masters can be formed to fabricate the patterns in one or both target layers. Imprint masters can be used to directly imprint target layers and/or hardmasks for patterning. In one example, a first pattern master is used to form a first pattern in a first target layer and a second pattern master is used to form a second pattern in a second target layer.

In another example, a target layer on a substrate is patterned on a single side using nanoimprint lithography (NIL). The pattern formed in the target layer can be filled with a fill material, bonded to a second substrate, and then separated from the original substrate. In another example, a first target layer on a first substrate and a second target layer on a second substrate are patterned. The first substrate and the second substrate are bonded together to form a layer from 10 μm to 3 mm or greater in thickness. The first substrate and the second substrate can be of similar thicknesses or of differing thicknesses. Depending upon the embodiment, the target layers can be patterned by extreme ultraviolet lithography (EUV), nano-imprint lithography (NIL), and/or etching.

FIG. **1** is a flow chart of a method **100** of fabricating optical devices according to embodiments of the present disclosure. In one embodiment, the method **100** is a batch process involving a plurality of substrates that are fabricated simultaneously. At operation **102**, a first layer that may be a protective layer and/or a de-bonding layer is formed on a first substrate, such as a Si substrate or another substrate such a polymer or another material that may be transparent within a predetermined wavelength range. In one example of the method **100**, glass is not used as the substrate. In one example, the substrate is a finished device such as CCD, CMOS, VCSEL, LED, or other structure that acts as a substrate upon which the optical devices discussed herein may be directly fabricated. That is, there can be an in-situ fabrication of the optical devices discussed herein, described in further detail in the method **100** and **400** in FIGS. **1** and **4**. The first layer formed at operation **102** may be a protective layer formed from SiN, SiO_2, or may be a de-bonding layer formed from high temperature glue. In one example, the high temperature adhesive used can withstand temperatures of up to temperatures on the order of 280° C. In some examples, the first layer formed at operation **102** is a combination of a protective layer formed on the substrate and a de-bonding layer formed on the protective layer.

At operation **104**, a first target layer is formed on the de-bonding layer. Target layers, as discussed herein, can be low or high-index materials that are patterned through various operations. The first target layer can be formed from a-Si, SiN, TiO_2, GaP, or other material(s) suitable for the formation of a plurality of optical elements. At operation **106**, the layer formed at operation **104** is patterned (etched) via a wet or a dry-etch operation to form a plurality of trenches to expose the de-bonding layer formed at operation **102**. Subsequent to patterning the first target layer at operation **106**, a plurality of low-refractive-index material or materials are formed on the patterned first target layer at operation **108** via CVD, ALD, PVD, or a spin-on process. Further in an embodiment at operation **108**, CMP is used to achieve a predetermined flatness that may be from 1 nm to 5 nm across the layer surface.

The plurality of low-index materials that may be employed at operation **108** can be formed from silicon dioxide, doped silicon dioxide, fluorinated polymers, nanoparticle films, or porous materials. Low-index materials are discussed herein in contrast to "high" index materials such as amorphous and crystalline silicon, silicon nitride, titanium dioxide, gallium phosphide, tantalum pentoxide, gallium nitride, sulfur-inated materials, polymers, and other materials with appropriate optical properties. It is contemplated that materials and combinations of materials can be used to form the fill layers and/or the optical element layers discussed herein, and that these materials can be selected based on the targeted optical properties of the optical device(s) fabricated in the method **100**.

The low-index material(s) formed at operation **108** are formed on top of the target layer and in the trenches formed in between islands of the target layer as shown below in FIGS. **2**A-**2**I. A top surface of the low-index material may be parallel to the substrate. This layer may be of varying thicknesses up to about 10 microns or greater. Operations **104-108** may be employed to form a single optical element layer. In other examples, operations **104-108** can repeated for a plurality of iterations (cycles) that may employ the same or differing materials, heights, and patterns. Depending on the example, stacked optical element layers can be formed from the same or different materials. This cycle (of operations **104-108**) can be repeated from 2-100 times to form a plurality of stacked optical element layers.

In one embodiment, the low-index materials can be used for fill layers and act to encapsulate the optical elements of an optical element layer. The fill layer can be formed to include an interlayer that extends above the top surface of the optical elements of a first optical element layer to

separate the optical elements of the first optical element layer from the optical elements of a second optical element layer. Thus, the optical elements of different optical element layers are not in contact. The lower the refractive index of the material used for filling/encapsulation, the lower the aspect ratio of the constituent nanostructures (features patterned) for each optical element. In an embodiment, lower aspect ratios produce thinner optical element layers, as well as faster and cleaner etching. Thus, the systems and methods herein result in more efficient fabrication processes in terms of time, cost, and complexities. In another example, where a fill material has a high refractive index, the height of the optical elements, and thus of the optical element layer, increases.

Subsequent to forming a predetermined number of optical element layers via operations **104-108**, an optical element structure having one or more optical element layers is formed at operation **110**. As discussed herein, optical element structures are structures formed during various operations of optical device fabrication. The optical element structure can be a final optical device, or can be further processed via thermal, mechanical, or thermo-mechanical operations. In one example, subsequent to forming the optical element structure at operation **110**, one or more processes may occur at operation **112**. These operations at **112** may vary based upon whether a de-bonding and/or protective layer is used in the fabrication, as well as an end use of the optical device.

In one example, at operation **112**A, a second substrate may be bonded to a low-index layer, opposite to the first substrate. Subsequently at operation **112**B, the first substrate is removed. The removal at operation **112**B may be performed by etching, grinding, polishing, thermal, or other operations or combinations of operations designed to heat an adhesive de-bonding layer past a predetermined temperature. At operation **112**C, the optical element structure may be further processed including dicing and/or bonding to a secondary structure, which may include a transparent substrate or a device such as a CCD, CMOS, VCSEL, LED, or other structures. In various embodiments, the process or processes at operation **112** can include stacking two or more optical element layers directly on completed devices while the optical element layer remains coupled to the substrate from operation **102**.

In another example, operations **104-110** may be executed on a target layer or layers formed on a finished device, such as a CCD, CMOS, VCSEL, LED, or other device that acts as a substrate. In this example, the optical element layer or layers are formed in-situ on the device substrate. In this example, at an operation **112**, further operations such as dicing may occur. In an example where there is no de-bonding layer used, there is no removal of a first substrate via de-bonding. In various embodiments, the optical element layers may be permanently bonded to a permanent transparent substrate. The permanent transparent substrate may be formed from a glass, a polymer, or other materials as appropriate for various applications. This assembly can then be diced into smaller optical devices. Each optical device can be attached to a final device, or can be bonded as a wafer or sheet to an array of devices on a wafer or sheet. For example, the optical element layers may be stacked on to a substrate of a completed CCD device, CMOS image sensors, or VCSELs in what can be referred to as "Integrated Processing." In one example, the first substrate is removed via a thermal operation that melts or degrades the de-bonding layer until both the de-bonding layer and the first substrate are removed from the optical element structure. For example, if a de-bonding material that is heat resistant up to 280° C. is employed, the substrate may be removed by heating the optical element structure above about 280° C. to remove the substrate.

FIGS. **2**A-**2**I is a series of partial schematic illustrations of cross-sections of optical element structures formed during optical device fabrication according to embodiments of the present disclosure. FIG. **2**A shows a first substrate **202**. In one example, the first substrate **202** can be referred to as a temporary substrate and can be formed from Si. In alternate embodiments, the first substrate **202** may be a finished device such as a CCD, CMOS, VCSEL, LED, or other device structure as appropriate. The first substrate **202** can be bonded via a de-bonding layer **204** to a first target layer **206**. In an example where the first substrate **202** is a finished device, the de-bonding layer **204** may not be employed since the finished device is the permanent substrate. In one embodiment, glass is not used as the first substrate **202**. In an embodiment, the de-bonding layer **204** may be a single layer of high temperature adhesive or a protective dielectric layer.

In other embodiments, as shown in the inset (FIG. **2**A-**1**) in FIG. **2**A, the substrate includes a de-bonding interlayer **204**A on the first substrate **202** and a barrier interlayer **204**B on top of the de-bonding layer opposite the substrate. The de-bonding interlayer **204**A, or **204** when used as a single layer, can include glue or other adhesive configured to withstand temperatures up to about 280° C. and is from 1 nm to 100 nm thick. In another example, not shown here, the de-bonding layer **204** can include solely a dielectric layer of SiO_2 or SiN from 1 nm to 100 nm thick and is formed by PVD, CVD, or other deposition operations. In other examples, the de-bonding layer **204** can be greater than 100 nm thick. In an embodiment, FIG. **2**A may correspond to operation **102** in FIG. **1**. The first target layer **206** can include a variety of materials as discussed herein such as a-Si, SiN, TiO_2, or GaP.

FIG. **2**B shows the device of FIG. **2**A and further includes a patterned (etched) first target layer **206**. The first target layer **206** is patterned to have a plurality of negative features, referred to as a plurality of trenches **208**A, and a plurality of positive features, referred to as a plurality of islands **208**B. In an embodiment, FIG. **2**B illustrates an optical element structure resulting from operation **106** in FIG. **1**. Each island of the plurality of islands **208**B can have a width **208**C, as measured parallel to the first substrate **202**. In one example, the width **208**C of each island of the plurality of islands **208**B can vary within an optical element layer. While the optical elements are illustrated herein as having approximately square or rectangular-shaped cross-sections, it is contemplated that the optical elements can, in other examples, include tapered sidewalls and thus form a trapezoidal cross-section (not pictured).

FIG. **2**C illustrates an optical element structure that includes a first low-index layer **208**. The first low-index layer **208** is formed over a top surface **206**A of the islands **208**B and in between the islands **208**B, e.g., in the trenches **208**A. In an embodiment, the first low-index layer **208** extends a distance **210** above a top surface **206**A of the first target layer **206**. The distance **210** is part of the thickness (T_{208}) of the first low-index layer **208**. Accordingly, the first low-index layer **208** can include an interlayer because the distance **210** acts to separate the first target layer **206**, e.g., an optical element layer, from subsequently stacked optical element layers. The structure of FIG. **2**C may be similar to that formed in operation **108** in FIG. **1** and can be referred to as a first optical element layer **222**. As discussed above,

the distance **210** can include an interlayer since this distance separates a first optical element layer **222** from subsequently formed optical element layers. The fill material **210** can be tuned (e.g., via material type and/or thickness) among and between optical element layers to various distances to produce desired effects for single or multiple (doublet, triplet, or more) optical device embodiments. The first optical element layer **222** can be referred to as a singlet.

FIGS. **2**D-**2**G illustrate examples of iterations of a cycle of operations **104-108** in FIG. **1**. In an embodiment, FIG. **2**D shows a second target layer **212** formed on the fill material **210**. FIG. **2**E shows a plurality of trenches **216**A and a plurality of islands **216**B formed in the second target layer **212** in response to patterning. In FIG. **2**F, a second low-refractive index material forms a second low-index layer **214**, formed in a similar fashion to the first low-index layer **208**. The structure formed by the second low-index layer **214** and the second target layer **212** can be referred to as a second optical element layer **224**. The second low-index layer **214** may be formed to extend a distance of **214**A beyond a top **212**A of the second target layer **212**. In an embodiment, two different materials may be employed for each of the first target layer **206** and the second target layer **212**.

In some examples, which can be combined with other examples and embodiments herein, different materials may be employed for each of the first low-index layer **208** and the second low-index layer **214**. In an embodiment, the first optical element layer **222** may be configured for a first wavelength or first range of wavelengths, and the second optical element layer **224** may be a configured for a second wavelength or second range of wavelengths. The first target layer **206** and the second target layer **212** can include the same or different patterns. The first target layer **206** and the second target layer **212** can each have the same or differing pattern properties including height (thickness), spacing, and material type, depending upon the embodiment. The combination of the first optical element layer **222** and the second optical element layer **224** may be called a doublet.

In an embodiment, two different materials may be employed for each of the first target layer **206** and the second target layer **212**. In another example that can be combined with other examples, two different materials may be employed for each of the first low-index layer **208** and the second low-index layer **214**. In another embodiment, the same materials may be employed for each of the first target layer **206** and the second target layer **212**. In another example, which can be combined with other examples and embodiments, the same materials may be employed for each of the first low-index layer **208** and the second low-index layer **214**. Each of the first low-index layer **208** and the second low-index layer **214** has a thickness T_{208}, T_{214}, respectively. The thickness of each of the first low-index layer **208** and the second low-index layer **214** includes a distance that the respective low-index layer extends beyond the top surface of the optical elements. For example, the first low-index layer **208** and the second low-index layer **214** extend, respectively, from each top surface **206**A and **212**A for distances **210** and **214**A, which may be the same or different distances. Thus, each of the first optical element layer **222** and the second optical element layer **224** can be a different height. In another example, each of the first optical element layer **222** and the second optical element layer **224** can be the same height depending upon the embodiment. The extension of each fill layer beyond the optical elements may be employed as an interlayer in place of glass substrates or in place of additional layers of other materials.

FIG. **2**G shows a third optical element layer **226** formed from a third target layer **216** and a third low-index layer **218**. The third low-index layer **218** can be formed from the same as or different materials than the target layers and low-index layers used in other optical element layers such as the first optical element layer **222** and second optical element layer **224**. The third low-index layer **218** has a thickness T_{218} which includes a distance **218**A that the third low-index layer **218** extends beyond the third target layer **216**. The distance **218**A may be the same as or different than the distances **210** and **214**A, and the optical element layers **222**, **224**, and **226** may be configured using various thicknesses and thickness ratios. For example, ratios such as the thickness of the optical element layer: the thickness of the low-index layer; or dimensions among and between optical elements layers; or dimensions among and between fill layers, etc.) to produce desired effects. In an embodiment, each of the distances **210**, **214**A, and **218**A may be from about 1 micron to about 50 microns and, in some embodiments, may be from 50 nm to 2 microns, for example, if the optical element layers **222**, **224**, and/or **226** are configured to be optically interacting. The combination of the first optical element layer **222**, the second optical element layers **224**, and the third optical element layer **226** may be called a triplet. In one example, at least one of the distances **210**, **214**A, and **218**A is less than 1 micron, and in other examples, at least one of the distances may be from about 50 nm to about 300 nm.

While three optical element layers **222**, **224**, and **226** are shown in FIGS. **2**G-**2**I, it is contemplated that, in various embodiments a single optical element layer such as that shown in FIG. **2**C, or a double optical element layer as shown in FIG. **2**F may also be employed. In other examples, four or more optical element layers can be stacked to form an optical device. In an embodiment, T_{208}, T_{214}, and T_{218} may each be from about 100 nm to about 2 microns. In an embodiment, an overall thickness $T_{overall}$, shown in FIG. **2**G, of an optical device, which can include a one or more stacked optical element layers may be from about 1 micron thick to about 2000 microns thick or thicker. In an embodiment, a color filter or an interference filter or other optically filtering layer may be formed on the optical element layer stack, for example, on top of the one or more optical element layers such as the first optical element layer **222**, the second optical element layer **224**, or the third optical element layer **226**, depending upon how many optical element layers are employed in the example embodiment.

FIG. **2**G further illustrates an example spacing **228** between optical elements formed in the first target layer **206**. In an embodiment, a spacing **228** between optical elements may vary among and between optical elements formed in the first target layer **206** and among and between the target layers **206**, **212**, and **216**. In one example, a spacing **228** between elements is more than one wavelength in the encapsulating material (e.g., the first low-index layer **208**), where a wavelength may be equal to a spacing **228** of about 1 micron. In one example, an IR optical device may be fabricated using a single optical element layer, a doublet, or a triplet, or a larger stack. In another example, an RGB optical device may be fabricated using a singlet or doublet optical device. In another example, a white light or other broadband optical device may be fabricated from a doublet, a triplet, or an optical device including more than three optical element layers. In some examples, a white light optical device can be fabricated using a single optical element layer.

FIGS. **2**H and **2**I illustrate a transfer process for a plurality of optical element layers fabricated according to embodiments of the present disclosure. In FIG. **2**H, a second substrate **220** is bonded to the third optical element layer **226** which can be referred to as the "top" or as the "outermost" optical element layer in this example. The second substrate **220** may be fabricated from glass, plastic, or other materials and may be optically transparent. In FIG. **2**I, the first substrate **202** is removed and the optical element structure may be subsequently rotated. In one example, the structure can be rotated 180 degrees. In another example, the structure can be divided into a plurality of separate elements. Other subsequent operations may be performed before, after, or without dicing or removal of the first substrate **202**, as discussed in detail herein.

FIG. **3** is a partial schematic illustration of a cross-section **300** of an optical element structure according to embodiments of the present disclosure. FIG. **3** shows a first portion **302** that may be similar to that which is illustrated in FIGS. **2**A-**2**G, and a second portion **304** which is identical to the first portion **302**. FIG. **3** is shown to illustrate an extended pattern that may be repeated across an optical element structure and diced (divided) subsequently. In an embodiment, a width **306** of the first substrate **202** may be such that a plurality of individual optical devices may be formed via dicing such that each diced portion has a maximum diameter from 1 mm to 4 cm. In other examples, each diced portion can have a maximum diameter greater than 4 cm. The diced optical devices may be formed to be of the same size or of varying sizes, depending upon the embodiment. While the optical elements of the optical element layers **206**, **212**, **216** are shown as polygon-shaped, it is contemplated in other examples that the optical elements can have cross-sectional geometries that include rounded, triangular, or polygonal shapes, or combinations thereof. Further, it is contemplated that the cross-sectional geometries may be tapered, angled, bowed, or otherwise configured in various geometries.

FIG. **4** is a flow chart of a method **400** of fabricating optical elements according to embodiments of the present disclosure. In the method **400**, at operation **402**, a layer that may be a de-bonding layer and/or a protective layer may be formed on a substrate as discussed above. A target layer may be formed on the de-bonding layer at operation **404**, the target layer may be patterned at operation **406** to form a plurality of trenches to expose the de-bonding layer. The patterning at operation **406** may be done via dry or wet etching or via a nano-imprint operation. At operation **408**, a material such as a a-Si, SiN, TiO_2, GaP or others may be deposited in the plurality of trenches and across a top surface of the patterned target layer. At operation **410**, a plurality of residual material, for example, that which was formed across the top surface of the optical element layer, is removed to expose the optical element layer while the trenches remain filled with the material. At operation **412**, subsequent to the removal of the plurality of residual material at operation **410**, a plurality of low-refractive index material is formed on the resultant planar surface. In some examples, at operation **412**, CMP is used to achieve a predetermined flatness of the low-index material.

Operations **406-412** may be employed to form a single optical element layer. In other examples, operations **406-412** can be repeated for a plurality of iterations (cycles) to form a stack of optical element layers. Each optical element layer of the stack can have the same or differing optical element layer materials, heights, and patterns. If fill materials are included in one or more optical element layers of the stack, the fill materials used for each fill layer can be the same or different low-index materials. This cycle of operations **406-412** may be repeated from 2-100 times to form a plurality of optical elements. Subsequent to forming a predetermined number of optical element layers via operations **406-412**, an optical element structure is formed at operation **414** that can include one or more optical element layers. At operation **416**, the optical element structure **414** can be further processed. In one example, at operation **416**A, a second substrate may be bonded to a low-index layer opposite to the first substrate, and, subsequently at operation **416**B, the first substrate is removed. The second substrate can be a transparent substrate or a device such as a CCD, CMOS, VCSEL, an LED, OLED, or uLED. At operation **416**C, the structure may be further processed including dicing and/or bonding to a secondary structure.

In various embodiments at operation **416**, which may represent one or more operations, the optical element structures may be permanently bonded to another transparent substrate. Subsequent to bonding, the structures can be diced into smaller elements and attached individually to final devices, or the substrate can be bonded as a wafer or sheet to an array of devices on a wafer or sheet. For example, the optical element layers may be stacked on to a substrate of a completed CCD device, CMOS image sensors, or VCSELs or other devices. In another example, operations **406-412** may be executed on a finished device, such as a CCD, CMOS, VCSEL, LED, or other device, such that the optical element layer(s) are formed in-situ on the device. In this example, at operation **416**, further operations such as dicing may occur but there is no de-bonding layer used.

FIGS. **5**A-**5**F is a series of schematic illustrations of an alternate method of fabricating optical devices according to embodiments of the present disclosure. FIG. **5**A shows a substrate **502** that may be a Si wafer upon which a de-bonding layer **504** is formed. The de-bonding layer **504** may be similar to the de-bonding layer **204** in FIG. **2**A and can include a barrier layer (not shown). The barrier layer can be part of the de-bonding layer **504**, and can be formed in between an adhesive portion of the de-bonding layer **504** and a target layer **506**. In one example, the target layer **506** can be formed from a low-index material. In another example, the substrate **502** is a CCD, CMOS, VCSEL, LED, or other device as appropriate for various applications, and the optical elements are formed in-situ on the substrate **502**. The device of FIG. **5**A may be formed via operations **402** and **404** discussed in FIG. **4**.

FIG. **5**B illustrates a target layer **506** formed on the de-bonding layer **504**. The target layer **506** is etched to form a plurality of trenches **508**A and islands **508**B, as discussed at operation **406** above. In FIG. **5**C, a first optical element layer **510** may be formed over the target layer **506** and in between the islands **508**B and in the trenches **508**A, similarly to what is discussed at operation **408**. A portion of the first optical element layer **510**, indicated by a distance **512**, is removed as shown in FIG. **5**D and discussed at operation **410**. FIG. **5**D shows an optical element height **526**, which may range in some embodiments from about 400 nm to about 1500 nm. In alternate embodiments, the optical element height **526** may be from 100 nm to 400 nm, and in other embodiments the optical element height **526** may be from 50 nm to 100 nm. As discussed herein, the height of optical elements across an optical element layer is the same, creating a flat top surface of the optical element layer.

FIG. **5**E illustrates a second fill layer **514** formed over the first optical element layer **510** after the removal of a portion of the optical element layer **510**, as discussed at operation **410**. This operation is discussed at **412** in FIG. **4**, and the

second fill layer **514** may or may not include the same composition as the target layer **506**. The second fill layer **514** can include an interlayer, and may be tuned, for example, in thickness and composition among and between optical element layers structures in order to produce desired effects. The structure in FIG. **5**E can be referred to as a first optical element layer **516**. FIG. **5**F illustrates the structure of FIG. **5**E with an additional, second optical element layer **524** formed on the first optical element layer **516**. The second optical element layer **524** can be formed in a similar fashion to the first optical element layer **516**. The second optical element layer **524** includes second optical elements **520** and a third fill layer **518**. The third fill layer **518** can be formed from a low-index material. Another fill layer **522** is formed on top of the second optical elements **520** and the third fill layer **518**. The top surface of the second optical elements **520** is co-planar with the third fill layer **518**. In one example, a-Si or SiN may be used for optical wavelength bands near an IR range, and TiO_2 may be used for optical wavelength bands near visible light ranges.

FIGS. **6**A-**6**C are schematic illustrations of a top view of optical element structures according to embodiments of the present disclosure. FIGS. **6**A-**6**C are schematic illustrations of top-down views of optical elements which illustrate only a view of the uppermost optical element. Thus, optical element layers located in lower layers of the optical element layer stacks can include different configurations or the same configuration as that discussed for the top layers shown in FIGS. **6**A-**6**C. FIG. **6**A shows a first plurality of optical elements **704** formed on a substrate **702**. The first plurality of optical elements **704** are shown to have a top view cross-section of a circle or an elliptical shape. The first plurality of optical elements **704** has a vertical spacing **706** and a horizontal spacing **708**. One or both of the vertical spacing **706** and the horizontal spacing **708** can vary among and between the first plurality of optical elements **704**, depending upon the embodiment. While three rows **710** of optical elements, including first plurality of optical elements **704**, are shown in FIG. **6**A, various embodiments can contain more or fewer rows with varied spacing. The rows **710** can be spaced at equidistant intervals, or can be spaced at random intervals.

FIG. **6**B shows a second plurality of optical elements **712** formed on a substrate **702**. The second plurality of optical elements **712** is shown as having a top view cross-section of a square or other polygonal shape. The second plurality of optical elements **712** has a vertical spacing **714** and a horizontal spacing **716** among and between each pair of adjacent optical elements **712** of the plurality of optical elements **712**. Each of the vertical spacing **714** and the horizontal spacing **716** can vary depending upon the embodiment. While four rows **718** of optical elements are shown in FIG. **6**B, various embodiments can contain more or fewer rows. While the second plurality of optical elements **712** are illustrated in FIG. **6**B as being aligned along a shared axis for each of the four rows **718**, in alternate embodiments, the alignment occurs along a perpendicular axis in the direction of the vertical spacing **714**. In another example, the second plurality of optical elements **712** can be aligned along both a horizontal and vertical location (axis) to form an ordered array (not shown). In an ordered array example of optical elements, each optical element of the second plurality of optical elements **712** is spaced equidistant in both the horizontal spacing **716** and vertical spacing **714** directions. In various examples, the second plurality of optical elements **712** may have various polygonal or non-polygonal cross-sections and can include sharp edges or rounded edges, or combinations thereof.

FIG. **6**C shows a third plurality of optical elements **720** formed on a substrate **702**, where the third plurality of optical elements **720** has a top view cross-section of an irregular shape that varies among and between individual optical elements of the third plurality of optical elements **720**. The third plurality of optical elements **720** has vertical spacing **722** and horizontal spacing **724** among and between elements that varies depending upon the embodiment. In one example, the vertical spacing **722** is uneven among and between the third plurality of optical elements **720**. In another example, the horizontal spacing **724** is uneven among and between the third plurality of optical elements **720**. In yet another example, both the vertical spacing **722** and the horizontal spacing **724** of the third plurality of optical elements **720** is uneven. While four rows **726** of optical elements are shown in FIG. **6**C, various embodiments can contain more or fewer rows. While the third plurality of optical elements **720** are illustrated in FIG. **6**C as being aligned along rows **726**, in alternate embodiments, the alignment occurs along a perpendicular axis in the direction of the vertical spacing **722**. In another example, the third plurality of optical elements **720** can be aligned in both a horizontal and vertical location to form an ordered array (not shown) where each optical element **720** is spaced equidistant in both the horizontal **724** and vertical **722** directions. The geometries employed for the pluralities of optical elements including **708**, **712**, **720**, and others as discussed herein can be irregular shapes as well as triangles, or other geometries as appropriate for various embodiments. In some examples, diameters of the optical elements vary among and between rows **726**. In other examples, the diameters of each optical element **720** in a single row may vary within that row. The top-views shown in FIGS. **6**A-**6**C are illustrative, and it is contemplated that other spacing of optical elements is possible. For example, the spacing of optical elements discussed herein can be varied spacing that is used to created ordered arrays having equidistant spacing among and between optical elements, random arrays, having random spacing, or patterned arrays where regular or irregular spacing patterns can be repeated.

FIGS. **7**A-**7**C are schematic illustrations of a bonding method for an optical element according to embodiments of the present disclosure. FIG. **7**A shows a first optical element structure **800**A that includes an optical element layer stack **828** of a first optical element layer **802**, a second optical element layer **804**, and a third optical element layer **806**. Each of the optical element layers **802**, **804**, and **806** includes a plurality of optical elements **812**, **816**, and **820**, respectively. Each optical element layer **802**, **804**, **806** further includes a layer of low-index material **814**, **818**, and **822** formed on top of and in the trenches in between each plurality of optical elements **812**, **816**, and **820**. The third optical element layer **806** is formed on a substrate **808**. In one example, the third optical element layer **806** has a layer **810** formed between the substrate **808** and the third optical element layer **806**. As discussed herein, the layer **810** may be a protective layer, a de-bonding layer, or combinations thereof, and may be formed to have a thickness of 100 nm or greater. The optical element layer stack **828** has a top bonding layer **824** formed on the first optical element layer **802**. The top bonding layer **824** has a thickness of 20 nm to 100 nm. A second substrate **830** has a second bonding layer **826** which is formed on the second substrate **830**. As discussed above, the second substrate **830** may be a trans-

parent substrate fabricated from glass, polymer, or other materials as appropriate for various applications.

FIG. **7**B shows a second optical element structure **800**B where the second substrate **830** is bonded to the optical element layer stack **828**. The second substrate **830** is bonded to the optical element layer stack **828** via the top bonding layer **824** and a second bonding layer **826** which is formed on the second substrate **830**. FIG. **7**C shows a third optical element structure **800**C which is the structure of the second optical element structure **800**B where the substrate **808** has been removed. While three optical element layers, **802**, **804**, and **806**, are shown in FIGS. **7**A-**7**C, a lesser or greater number of optical element layers can be used, depending upon the embodiment. The second substrate **830** may be from 100 microns to 500 microns or greater. In one example, the second substrate **830** can be thinned from an original thickness, for example, from 500 microns to 100 microns, using CMP or other methods after the second substrate **830** is bonded to the third optical element structure **800**C.

FIGS. **8**A-**8**B show an optical element structure according to embodiments of the present disclosure. FIG. **8**A shows a first optical element structure **900**A prior to assembly/stacking. The first optical element structure **900**A includes a first optical element layer **906** formed on a substrate **908**. The first optical element layer **906** is bonded via a layer **910** which may be formed from SiO_2 or other material. In other examples, the layer **910** can be a de-bonding layer of high-temperature resistant adhesive. A second optical element layer **904** is bonded to the first optical element layer **906**, and a third optical element layer **902** is bonded to the second optical element layer **904**. A second substrate **916** may have a first bonding layer **914** and a second bonding layer **918** formed on either side. Additionally, a device **922** has a device bonding layer **920** formed thereon. The device **922** can include SiO_2 from a thickness of 20 nm to 10 μm.

FIG. **8**B shows a second optical element structure **900**B. The second optical element structure **900**B includes the first optical element structure **900**A from FIG. **8**A. The second optical element structure **900**B shows the second substrate **916** bonded to the third optical element layer **902** via a top bonding layer **912** formed on the third optical element layer **902**. In the second optical element structure **900**B, the layer **910** and substrate **908** have been removed, for example, by etching, grinding, polishing, or other methods. Additionally, the device **922** such as a CMOS, CCD, VCSEL, or other device **922** is bonded to the second substrate **916** via the second bonding layer **918** and a device bonding layer **920**, each of which can include SiO_2 from a thickness of 1 nm to 100 nm. The second substrate **916** may be from 100 microns to 500 microns, and may be thinned from an original thickness, for example, from 500 microns to 100 microns, using CMP or other methods after the second substrate **916** is bonded to the second optical element structure **900**B.

FIG. **9** is an illustration of an optical element layer stack **1018**. The optical element layer stack **1018** is bonded to a device **1016**. In an example, an assembly **1000** of an optical element layer stack **1018** is bonded to a device **1016**, which may be a CMOS, CCD, VCSEL, or other device. The optical element layer stack **1018** is formed on a substrate **1008** that has a layer **1010** formed in between the optical element layer stack **1018** and the substrate **1008**. The layer **1010** can include a de-bonding layer or a protective layer, or combinations thereof. The optical element layer stack **1018** is made up of three optical element layers, a first optical element layer **1002**, a second optical element layer **1004**, and a third optical element layer **1006**. In other examples, it is contemplated that the optical element device can include more or fewer optical element layers than shown. The device **1016** is bonded to the optical element layer stack **1018** via a first bonding layer **1012** formed on the first optical element layer **1002** and a second bonding layer **1014** formed on the device **1016**. As discussed herein, the optical element layer stack **1018** may be formed and then bonded to the device **1016**. In another example, the optical element layer stack **1018** can be pre-formed and bonded to the device **1016**. In another example, the optical element layer stack **1018** can be formed in-situ on the device **1016**. In some examples, not shown here, a protective layer of fill material can be formed over an outermost optical element layer, such as the first optical element layer **1002** in FIG. **9**.

FIG. **10** is a flow chart of a method **1100** of fabricating optical elements according to embodiments of the present disclosure. FIGS. **11**A-**11**D are cross-sectional views of optical element structures discussed in conjunction with operations of the method **1100**. At operation **1102**, shown at FIG. **11**A, a first target layer **1202** on a first substrate **1204** is patterned to form a first pattern **1206**. The first pattern **1206** includes a plurality of islands **1210**. Each pair of adjacent islands of the plurality of islands **1210** is separated by a negative space that can be referred to as a trench **1208**. The first pattern **1206** can be formed by optical lithography and etching, or by nanoimprint lithography (NIL) and etching, or by direct imprinting of the first target layer **1202**. At operation **1104**, the first pattern **1206**, in particular the trenches **1208** of the first pattern **1206**, can be optionally filled with a low-index material (not shown).

At operation **1106**, shown at FIG. **11**B, a second target layer **1212** formed on a second substrate **1222** is patterned to form a second pattern **1214**. The second pattern **1214** includes a plurality of islands **1216**, each pair of adjacent islands of the plurality of islands **1216** is separated by a trench **1218**. The second pattern **1214** can be formed by optical lithography and etching, or by nanoimprint lithography (NIL) and etching, or by direct imprinting of the second target layer **1212**. At operation **1108**, the second pattern **1214**, in particular the trenches **1218** of the second pattern **1214**, can be optionally filled with a low-index material (not shown here). In some examples, neither the first pattern **1206** nor the second pattern **1214** is filled with low-index material. In some examples, the first pattern **1206** is filled with low-index material at operation **1104**. In other examples, the second pattern **1214** is filled with low-index material at operation **1108**. In further examples, the first pattern **1206** and the second pattern **1214** are each filled with low-index material at operations **1104** and **1108**, respectively.

FIG. **11**C is a view of an optical element structure subsequent to operations **1110** and **1112**. At operation **1110**, the first pattern **1206** is bonded to a first side **1220**A of a third substrate **1220**. The third substrate **1220** can be formed from a transparent material including glass, polymer, diamond, or other materials. Depending upon the embodiment, the third substrate **1220** can be from about 10 μm thick to 3 mm thick. At operation **1112**, the second pattern **1214** is bonded to a second side **1220**B of the third substrate **1220**, opposite the first pattern **1206**.

At operation **1114**, the first substrate **1204** and the second substrate **1222** are removed. Thus, the first substrate **1204** and the second substrate **1222** can each be referred to as temporary substrates or carrier substrates. FIG. **11**D shows an optical element structure after operation **1114**. In some examples, not shown here, there can be a layer of a bonding material, referred to as a de-bonding layer, similar to the de-bonding layer **204** discussed above. The de-bonding

layer can be formed in between the first target layer **1202** and the first substrate **1204**, and/or between the second target layer **1212** and the second substrate **1222**. The de-bonding layer can be an adhesive material or a thermally-activated material (e.g., that dissociates upon the application of heat). The de-bonding layers can be used at operation **1114** to promote the separation of the first pattern **1206** and the second pattern **1214** from the first substrate **1204** and second substrate **1222**, respectively, via thermal, chemical, and/or mechanical means. At operation **1116**, the optical element structure in FIG. **11**D can be further processed, for example, by annealing and/or by adding (stacking) additional optical elements and transparent substrates. In one example at operation **1116**, at least operations **1102**, **1106**, **1110**, **1112**, and **1114** can be repeated in an iterative fashion to form additional optical element layers.

FIG. **12** is a flow chart of a method **1300** of fabricating optical elements according to embodiments of the present disclosure. FIGS. **13**A-**13**E are cross-sectional views of optical element structures and are discussed in conjunction with operations of the method **1300**. At operation **1302**, a first pattern **1402** is formed in a first target layer on a first surface **1404**A of a first substrate **1404**, as shown in FIG. **13**A. The first pattern **1402** includes a plurality of trenches **1408** between the islands **1406**. The first pattern **1402** can be formed at operation **1302** using optical lithography and etching, NIL and etching, or direct imprinting.

At operation **1304**, the plurality of trenches **1408** of the first pattern **1402** is optionally filled with a low-index material **1410**, as shown in FIG. **13**B. The low-index material **1410** can be a self-planarizing material such that, subsequent to operation **1304**, the top of the low-index material **1410** is co-planar with the top of the plurality of islands **1406**. At operation **1306**, a second pattern **1412** is formed from a second target layer formed on a first surface **1414**A of a second substrate **1414**. The second pattern **1412** is shown in FIG. **13**C. The second pattern **1412** includes a plurality of trenches **1416**. Each trench of the plurality of trenches **1416** is formed between each pair of adjacent islands **1418**. The plurality of trenches **1416** and the plurality of islands **1418** can be of varying widths, heights, and cross-sectional shapes. While the plurality of islands **1418** are shown in the cross-sectional view as substantially polygon-shaped, it is contemplated that the geometries can take other shapes such as rounded, triangular, or combinations thereof, and may be tapered, angled, or bowed. The second pattern **1412** can be formed at operation **1306** using optical lithography and etching, NIL and etching, or direct imprinting.

At operation **1308**, the second pattern **1412** is optionally filled with a low-index material **1420**, as shown in FIG. **13**D. At operation **1310**, one or more of the first substrate **1404** and the second substrate **1414** is planarized. In one example of operation **1310**, a second side **1404**B of the first substrate **1404** and a second side **1414**B of the second substrate **1414** are each planarized in one or more sub-operations. Subsequently, at operation **1312**, the second side **1404**B of the first substrate **1404** is bonded to the second side **1414**B of the second substrate **1414**, as shown in FIG. **13**E. Thus, the optional planarization at operation **1310** can promote the bonding of the first substrate **1404** to the second substrate **1414** at operation **1312**. At operation **1314**, further processing of the optical element structure can occur. The further processing at operation **1314** can include annealing, the addition of other optical element structures via stacking, dicing, or other operations.

FIG. **14** is a flow chart of a method **1500** of fabricating optical elements according to embodiments of the present disclosure. FIGS. **15**A-**15**D are cross-sectional views of optical element structures that are discussed in conjunction with the method **1500**. FIG. **15**A is a cross-sectional view of a first transparent substrate **1604**. The first transparent substrate **1604** can be formed from glass, polymer, diamond, or other optically transparent materials or combinations of optically transparent materials. A first target layer **1602** is formed on a first side **1604**A of the first transparent substrate **1604**. A second target layer **1606** is formed on a second side **1604**B of the first transparent substrate **1604**.

At operation **1502**, a first master pattern is formed. The first master pattern can be used to imprint patterns in target layers on a substrate. The first master pattern can be formed at operation **1502** using a rigid material such as silicon or silicon-containing materials, or from less rigid materials including low or high index materials. The material used to form the first master pattern can be selected based on factors including the composition and material properties of the target layers to be imprinted at operation **1504**. The first master pattern can be formed at operation **1502** by optical lithography and etching, NIL and etching, or by direct imprinting of a first master target layer. The first master pattern formed at operation **1502** is used to make a first pattern **1622** at operation **1504**. The first pattern **1622** is shown in FIG. **15**B. The first pattern **1622** includes a plurality of islands **1610**, with islands **1610** separated by a trenches **1608**. The plurality of islands **1610** extend from the first side **1604**A of the first transparent substrate **1604**. At operation **1506**, a fill layer (not shown here) can be optionally formed in the trenches **1608**. The fill layer can be formed from a low-index material.

At operation **1508**, a second master pattern can be formed from a rigid material such as silicon or silicon-containing materials, or from less rigid materials including low or high index materials. The second master pattern can be used to imprint target layers on a substrate, and can include a different pattern than the first master pattern. The second master pattern can be formed from various materials depending upon the composition of the target layers that are to be imprinted at operation **1510**. The second master pattern can be formed at operation **1508** by optical lithography and etching, NIL and etching, or direct imprinting of a second master target layer. At operation **1510**, the second pattern master is aligned with the second target layer **1606** using the first pattern formed at operation **1506** as a reference point for alignment. At operation **1512**, a second pattern **1626** is formed in the second target layer **1606**. The second pattern **1626**, shown in FIG. **15**C, includes a plurality of islands **1616** extending from the second side **1604**B of the first transparent substrate **1604**. Islands **1616** are separated by the trenches **1618**. At operation **1514**, a fill layer can be optionally formed in the trenches **1618**. The fill layer can be formed from a low-index material.

At operation **1516**, the optical element structure can undergo further processing. The further processing at operation **1516** can include annealing, the addition of other optical element structures via stacking, dicing, or other operations. In one example of operation **1516**, at least operations **1504**, **1508**, **1510**, and **1512** can be repeated to form a stack of optical elements, as shown in FIG. **15**D. FIG. **15**D includes the first transparent substrate **1604**, the first pattern **1622**, and the second pattern **1626** formed at operations **1504** and **1508**. FIG. **15**D further includes a second transparent substrate **1620**. A first side **1620**A of the second transparent substrate **1620** includes a third pattern **1624**. A second side

1620B of the second transparent substrate **1620** is bonded to a first side **1602**A of the first pattern **1622**. In some examples, the third pattern **1624** can be optionally filled, not shown in FIG. **15**D. The third pattern **1624** can be formed from the first master, the second master, or from a third master that is different from the first master and the second master.

Accordingly, the examples discussed herein can, in various combinations, be used to fabricate stacked optical elements. Two or more optical elements can be fabricated via optical lithography or NIL and etching, and/or by direct imprinting using pattern masters. The optical elements can be fabricated on temporary substrates that are bonded to target layers and later removed after the patterned target layer is bonded to a permanent or carrier (second temporary) substrate. Optical element layers can be separated from each other using a fill layer that includes an interlayer. The fill layer can extend beyond the top surface of the underlying optical element layer for a distance from about 1 nm to about 3 mm that forms the interlayer portion of the fill layer. In other examples, the optical elements can be fabricated on a permanent substrate that is a transparent substrate of varying thicknesses up to about 3 mm.

Although various embodiments which incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings.

What is claimed:

1. A method of forming an optical device, comprising:

(a) forming a pattern in a target layer on a first substrate, wherein the pattern comprises a plurality of islands separated by a plurality of trenches;

(b) forming a fill layer on top of the patterned target layer and in the plurality of trenches formed in the patterned target layer to form a first optical element layer; and

(c) forming an optical element layer stack on the first optical element layer by repeating (a) and (b) for a plurality of iterations.

2. The method of claim **1**, further comprising (d), subsequent to (c), bonding a second substrate to the optical element layer stack opposite the first substrate.

3. The method of claim **2**, further comprising (e), removing, subsequent to (d), the first substrate.

4. The method of claim **1**, wherein the fill layer includes an interlayer, wherein the interlayer extends from a top surface of the target layer for a thickness of about 50 nm to about 50 microns.

5. The method of claim **1**, wherein the first substrate comprises a CCD, a CMOS sensor, a VCSEL, or an LED.

6. The method of claim **1**, further comprising:

(f) subsequent to (a), forming an optical element layer on top of the target layer and in the plurality of trenches of the patterned target layer;

(g) removing a portion of the optical element layer, wherein removing the portion creates a co-planar surface of the optical element layer and a top surface of the target layer;

(h) subsequent to (g), forming a second fill layer on top of the optical element layer and the target layer to form a first optical element layer, wherein a the second fill layer includes an interlayer extending beyond a top surface of the optical element layer for a distance from 0.5 microns to 50 microns; and

(i) repeating (a)-(h) to form a plurality of optical element layers on the first optical element layer.

7. The method of claim **6**, wherein the optical element layer comprises a-Si, SiN, TiO_2, or GaP.

8. A method of fabricating optical devices, comprising:

forming a first pattern in a first target layer, the first target layer being formed on a first substrate;

forming a second pattern in a second target layer formed on a second substrate;

bonding the first pattern to a first side of a third substrate, the third substrate being formed from a transparent material and being from about 10 μm thick to 3 mm thick;

bonding the second pattern to a second side of the third substrate;

de-bonding the first substrate from the first pattern; and

de-bonding the second substrate from the second pattern.

9. The method of claim **8**, wherein the first pattern is formed using nanoimprint lithography (NIL) and etching.

10. The method of claim **8**, wherein the first pattern is formed using optical lithography and etching.

11. The method of claim **8**, wherein forming the first pattern comprises directly imprinting the first target layer using a first pattern master.

12. The method of claim **8**, further comprising filling at least one of the first pattern or the second pattern with a low-index material.

13. The method of claim **8**, further comprising:

forming a third pattern in a third target material on a fourth substrate.

14. The method of claim **13**, further comprising:

bonding a first side of a fifth substrate to the second pattern, the fifth substrate being from about 10 μm thick to about 3 mm thick and formed from a transparent material; and

bonding the third pattern to a second side of the fifth substrate.

15. The method of claim **8**, wherein each of forming the first pattern and forming the second pattern comprises optical lithography or nanoimprint lithography.

16. A method of forming an optical device, comprising:

forming a first pattern by imprinting a first target layer in a first location using a first pattern master, the first target layer being formed on a first side of a transparent substrate, wherein the transparent substrate is from about 10 μm thick to about 3 mm thick; and

forming a second pattern by imprinting a second pattern in a second location on a second target layer formed on a second side of the transparent substrate using a second pattern master, wherein forming the second pattern in the second location comprises determining the second location relative to the first pattern and aligning the second pattern master in the second location.

17. The method of claim **16**, wherein the first pattern master is formed from silicon.

18. The method of claim **16**, further comprising, subsequent to forming the first pattern, filling the first pattern with a low-index material.

19. The method of claim **16**, wherein the first master pattern includes a first pattern and the second pattern master includes a second pattern, the first pattern being different from the second pattern.

20. The method of claim **16**, wherein the transparent substrate is formed from glass, polymer, or diamond.

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UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 10,707,118 B2
APPLICATION NO. : 16/283560
DATED : July 7, 2020
INVENTOR(S) : Ludovic Godet et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page

In item (57), in Column 2, in "Abstract", Line 10, delete "(uLED)" and insert -- (μLED) --, therefor.

On page 2, in Column 1, Line 4 (below Abstract), delete "20 Claims, 19 Drawing Sheets" and insert -- 19 Claims, 19 Drawing Sheets --, therefor.

In the Drawings

On sheet 6 of 19, in Figure 4, reference numeral 412, Line 1, delete "LOW INDEX" and insert -- LOW-INDEX --, therefor.

In the Specification

In Column 4, Lines 22-23, delete "low index" and insert -- low-index --, therefor.

In Column 4, Line 33, delete "(uLED)" and insert -- (μLED) --, therefor.

In Column 12, Line 13, delete "uLED." and insert -- μLED. --, therefor.

In the Claims

In Column 19, Line 36, in Claim 1, after "layer;" delete "and".

In Column 19, Line 39, in Claim 1, delete "iterations." and insert -- iterations; and (d), subsequent to (c), bonding a second substrate to the optical element layer stack opposite the first substrate. --, therefor.

In Column 19, Lines 40-42, in Claim 2, below "iterations." delete "2. The method of claim 1, further

Signed and Sealed this
First Day of September, 2020

Andrei Iancu
Director of the United States Patent and Trademark Office

comprising (d), subsequent to (c), bonding a second substrate to the optical element layer stack opposite the first substrate.", renumber Claims 3-20 as Claims 2-19.

In Column 19, Line 43, in Claim 3, delete "claim 2," and insert -- claim 1, --, therefor.

In Column 19, Line 47, in Claim 4, before "50 nm" delete "about".

In Column 19, Line 48, in Claim 4, before "50 microns." delete "about".

In Column 19, Line 50, in Claim 5, delete "CCD, a CMOS sensor, a VCSEL, or an LED." and insert -- charge-coupled devices (CCD), a complementary metal-oxide semiconductor (CMOS) image sensor, a vertical-cavity surface-emitting laser (VCSEL), or a light-emitting diode (LED). --, therefor.

In Column 19, Line 61, in Claim 6, delete "a the" and insert -- the --, therefor.

In Column 20, Line 11, in Claim 8, before "10 μm" delete "about".

In Column 20, Line 33, in Claim 14, before "10 μm" delete "about".

In Column 20, Line 34, in Claim 14, before "3 mm" delete "about".

In Column 20, Line 46, in Claim 16, before "10 μm" delete "about".

In Column 20, Line 46, in Claim 16, before "3 mm" delete "about".

In Column 20, Line 61, in Claim 19, delete "a" and insert -- the --, therefor.

In Column 20, Line 62, in Claim 19, delete "a" and insert -- the --, therefor.