US 20260050127A1

(19) **United States**

(12) **Patent Application Publication**

WANG et al.

(10) **Pub. No.: US 2026/0050127 A1**

(43) **Pub. Date: Feb. 19, 2026**

(54) **METHOD FOR FORMING STAIRCASE GRATINGS WITH REDUCED TOP AND BOTTOM CRITICAL DIMENSIONS**

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

(72) Inventors: **Zefang WANG**, Santa Clara, CA (US); **Lei JIANG**, San Ramon, CA (US); **Wenhui WANG**, San Jose, CA (US); **Yongan XU**, Santa Clara, CA (US); **Ranida WONGPIYA**, Santa Clara, CA (US); **Elise LAFFOSSE**, Santa Clara, CA (US); **Ludovic GODET**, Sunnyvale, CA (US)

(21) Appl. No.: **19/301,241**

(22) Filed: **Aug. 15, 2025**

Related U.S. Application Data

(60) Provisional application No. 63/684,028, filed on Aug. 16, 2024.

Publication Classification

(51) **Int. Cl.**

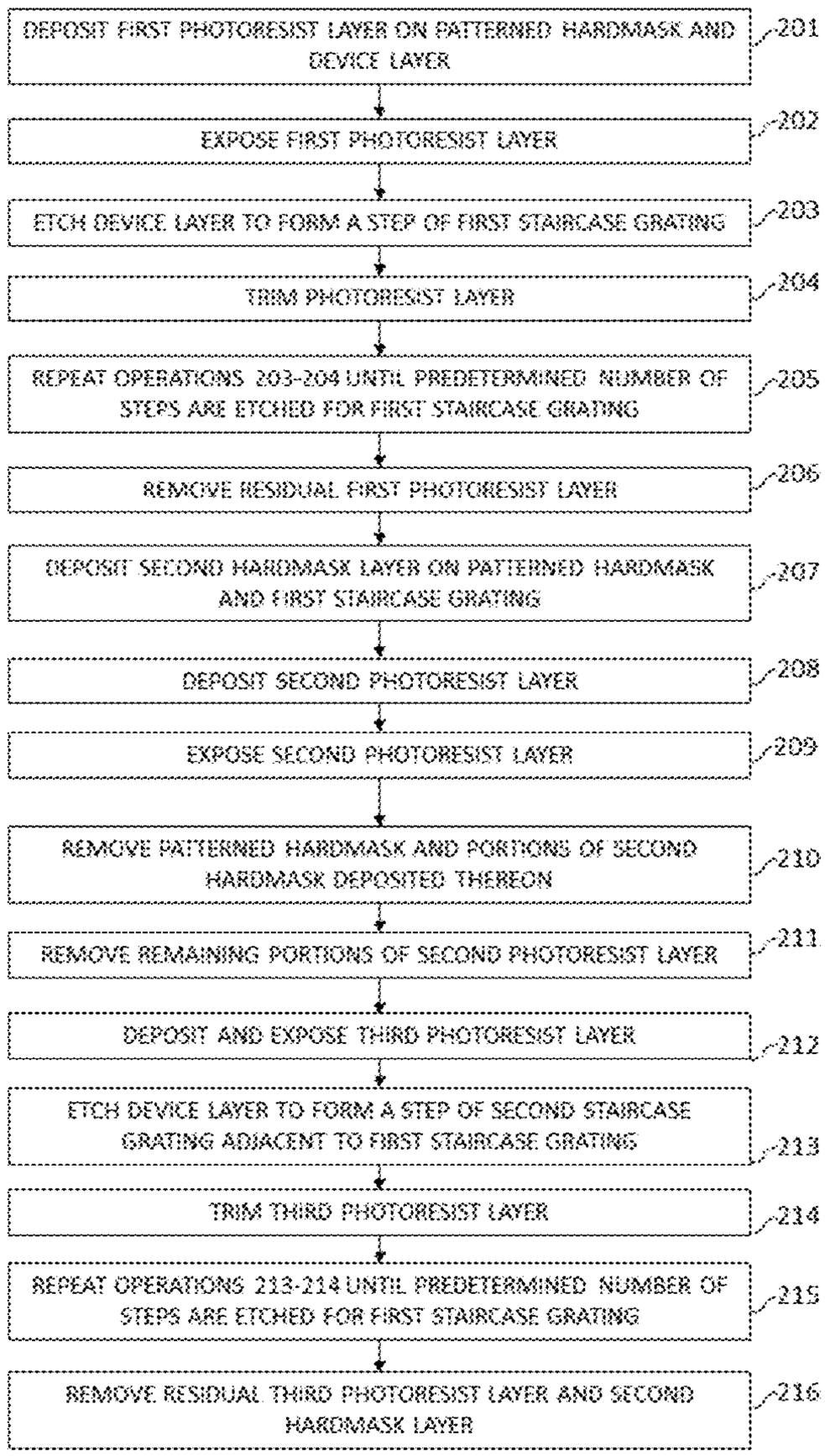
G02B 6/34	(2006.01)
G02B 27/01	(2006.01)
G03F 7/00	(2006.01)
G03F 7/26	(2006.01)

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

CPC ***G02B 6/34*** (2013.01); ***G02B 27/0172*** (2013.01); ***G03F 7/0007*** (2013.01); ***G03F 7/26*** (2013.01)

(57) **ABSTRACT**

A method for forming waveguide structures is provided. More specifically, embodiments described herein provide techniques for forming staircase gratings with reduced top and bottom critical dimensions.



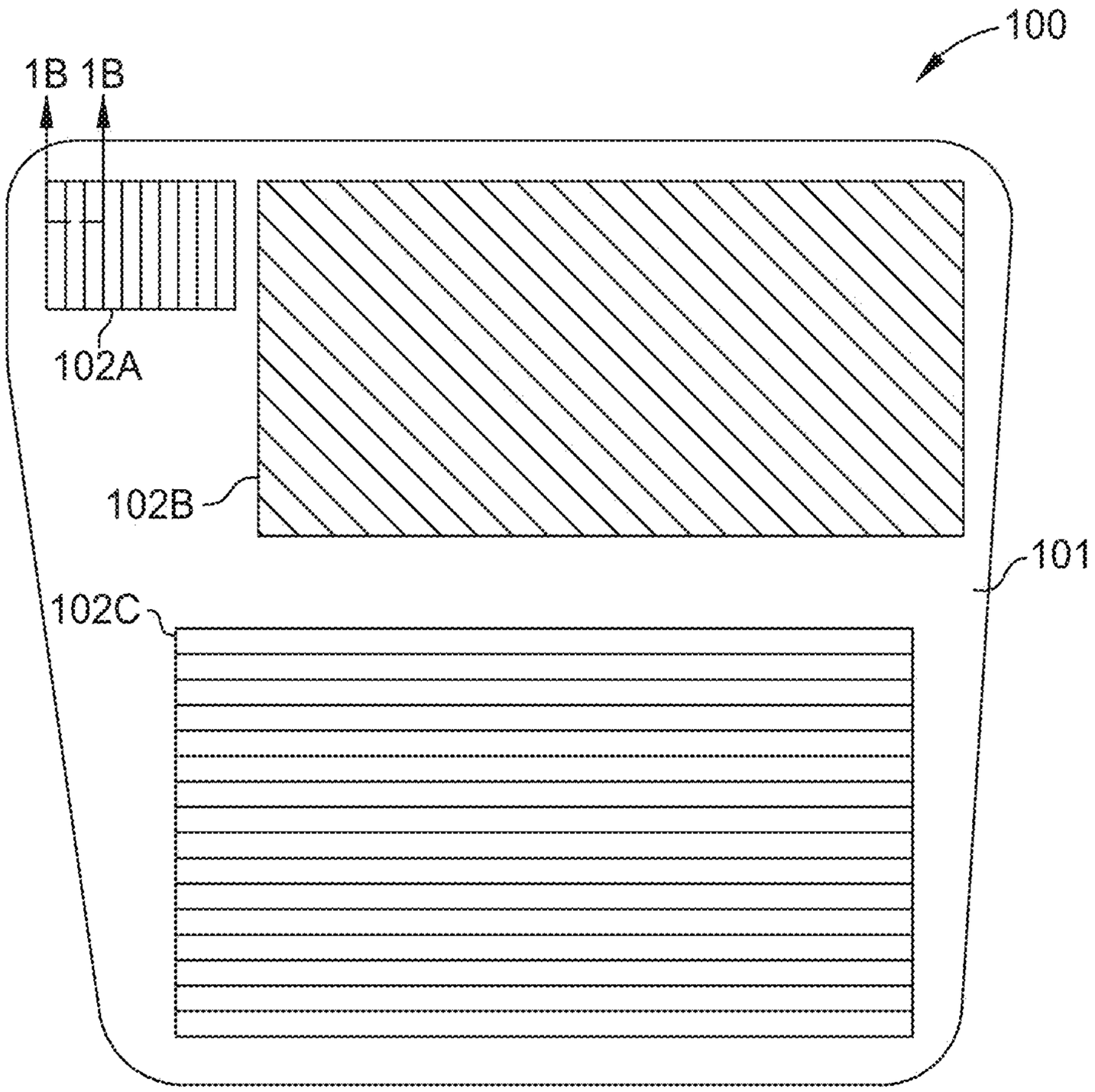


FIG. 1A

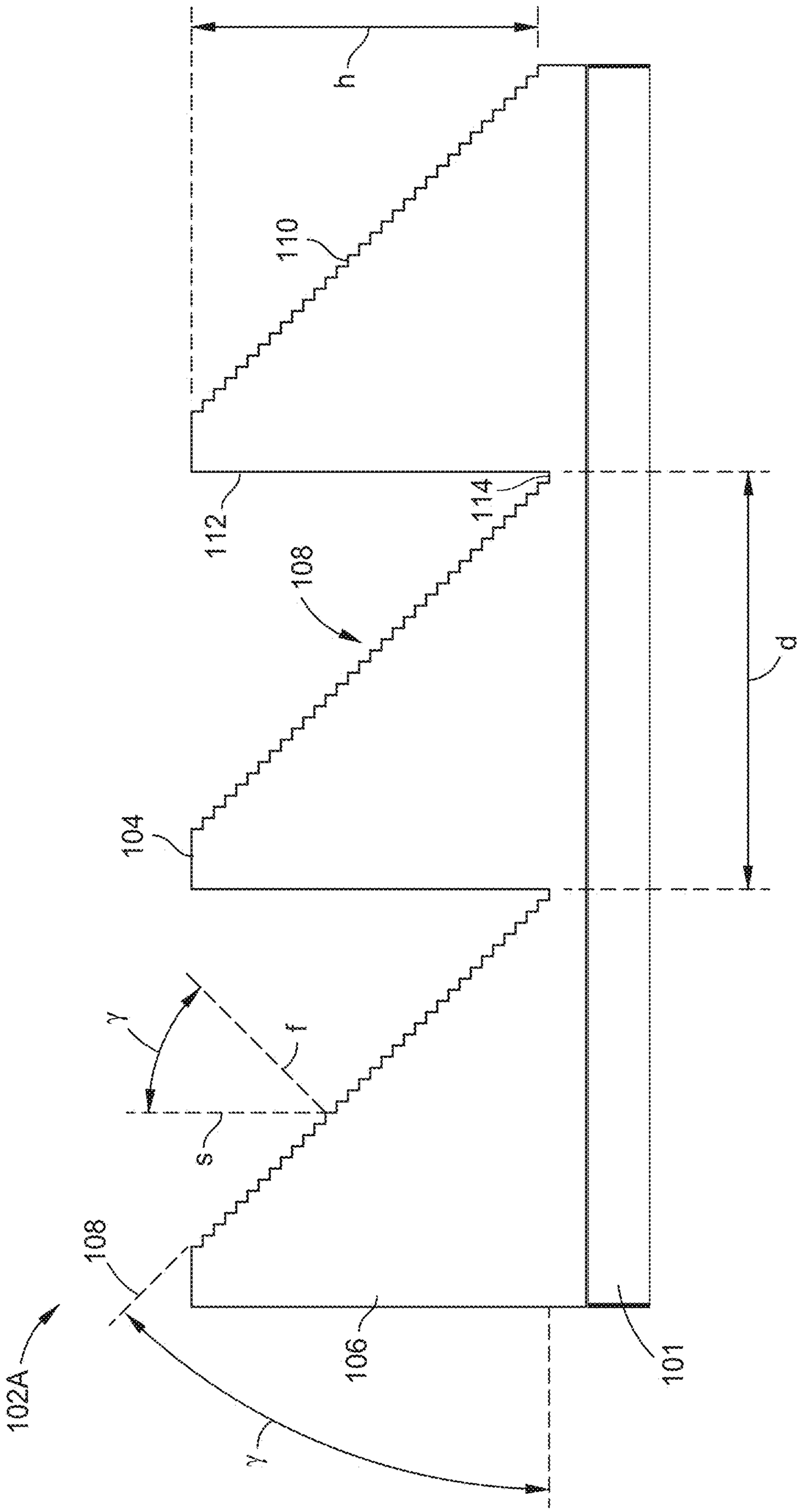


FIG. 1B

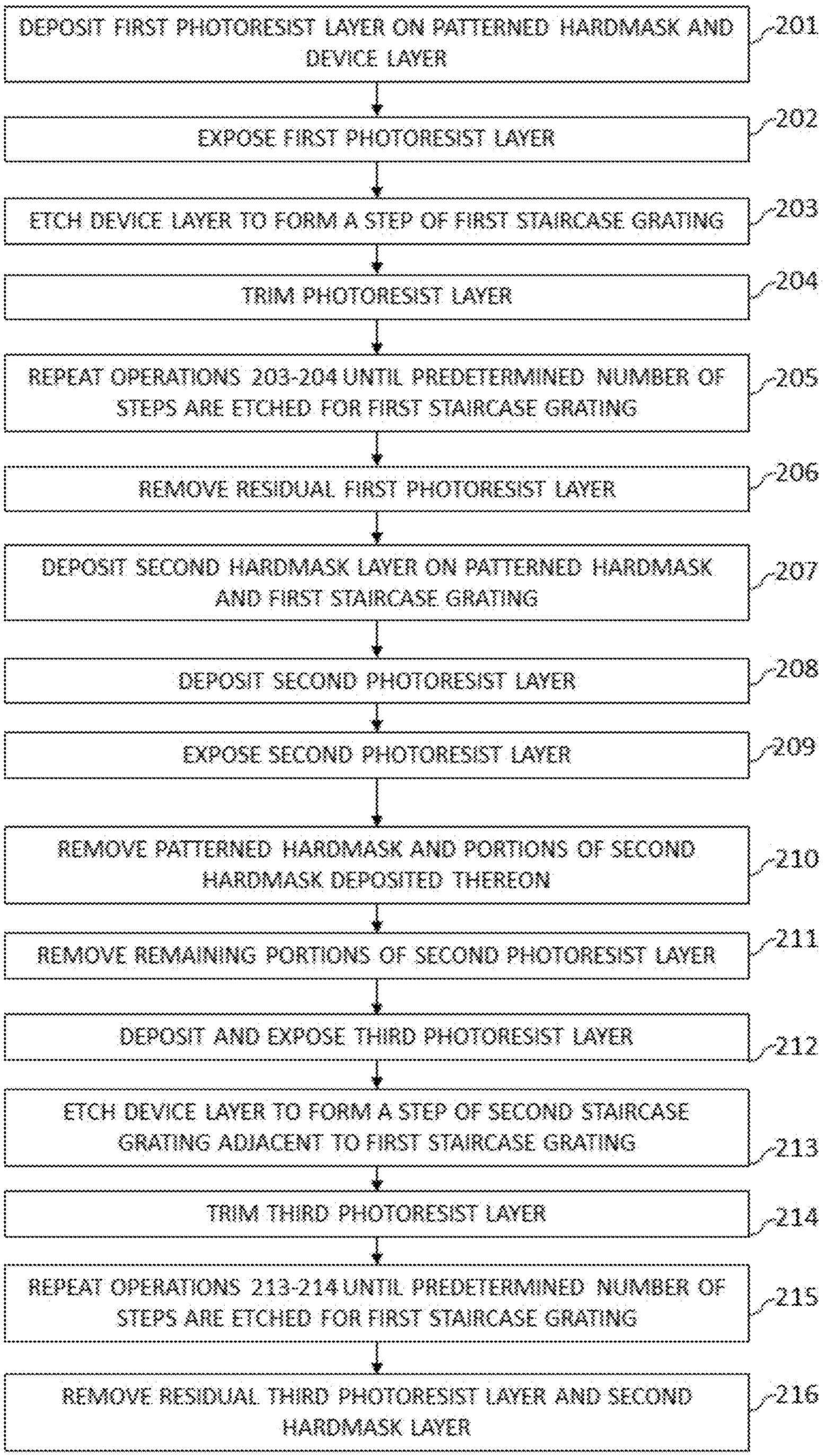

DEPOSIT FIRST PHOTORESIST LAYER ON PATTERNED HARDMASK AND DEVICE LAYER
201
EXPOSE FIRST PHOTORESIST LAYER
202
ETCH DEVICE LAYER TO FORM A STEP OF FIRST STAIRCASE GRATING
203
TRIM PHOTORESIST LAYER
204
REPEAT OPERATIONS 203-204 UNTIL PREDETERMINED NUMBER OF STEPS ARE ETCHED FOR FIRST STAIRCASE GRATING
205
REMOVE RESIDUAL FIRST PHOTORESIST LAYER
206
DEPOSIT SECOND HARDMASK LAYER ON PATTERNED HARDMASK AND FIRST STAIRCASE GRATING
207
DEPOSIT SECOND PHOTORESIST LAYER
208
EXPOSE SECOND PHOTORESIST LAYER
209
REMOVE PATTERNED HARDMASK AND PORTIONS OF SECOND HARDMASK DEPOSITED THEREON
210
REMOVE REMAINING PORTIONS OF SECOND PHOTORESIST LAYER
211
DEPOSIT AND EXPOSE THIRD PHOTORESIST LAYER
212
ETCH DEVICE LAYER TO FORM A STEP OF SECOND STAIRCASE GRATING ADJACENT TO FIRST STAIRCASE GRATING
213
TRIM THIRD PHOTORESIST LAYER
214
REPEAT OPERATIONS 213-214 UNTIL PREDETERMINED NUMBER OF STEPS ARE ETCHED FOR FIRST STAIRCASE GRATING
215
REMOVE RESIDUAL THIRD PHOTORESIST LAYER AND SECOND HARDMASK LAYER
216

FIG. 2

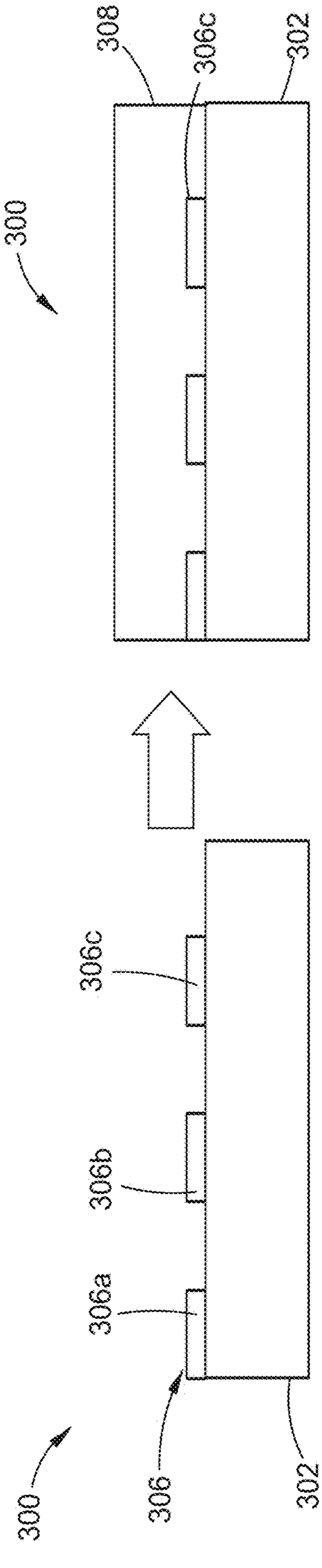


FIG. 3A

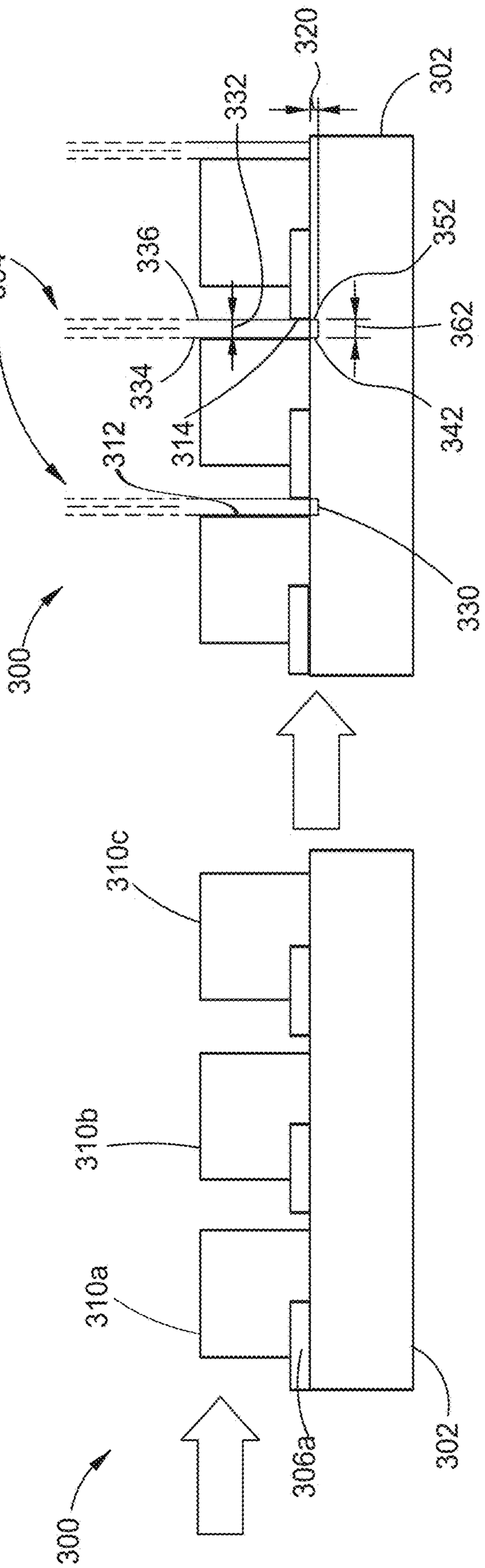


FIG. 3B

FIG. 3C

FIG. 3E

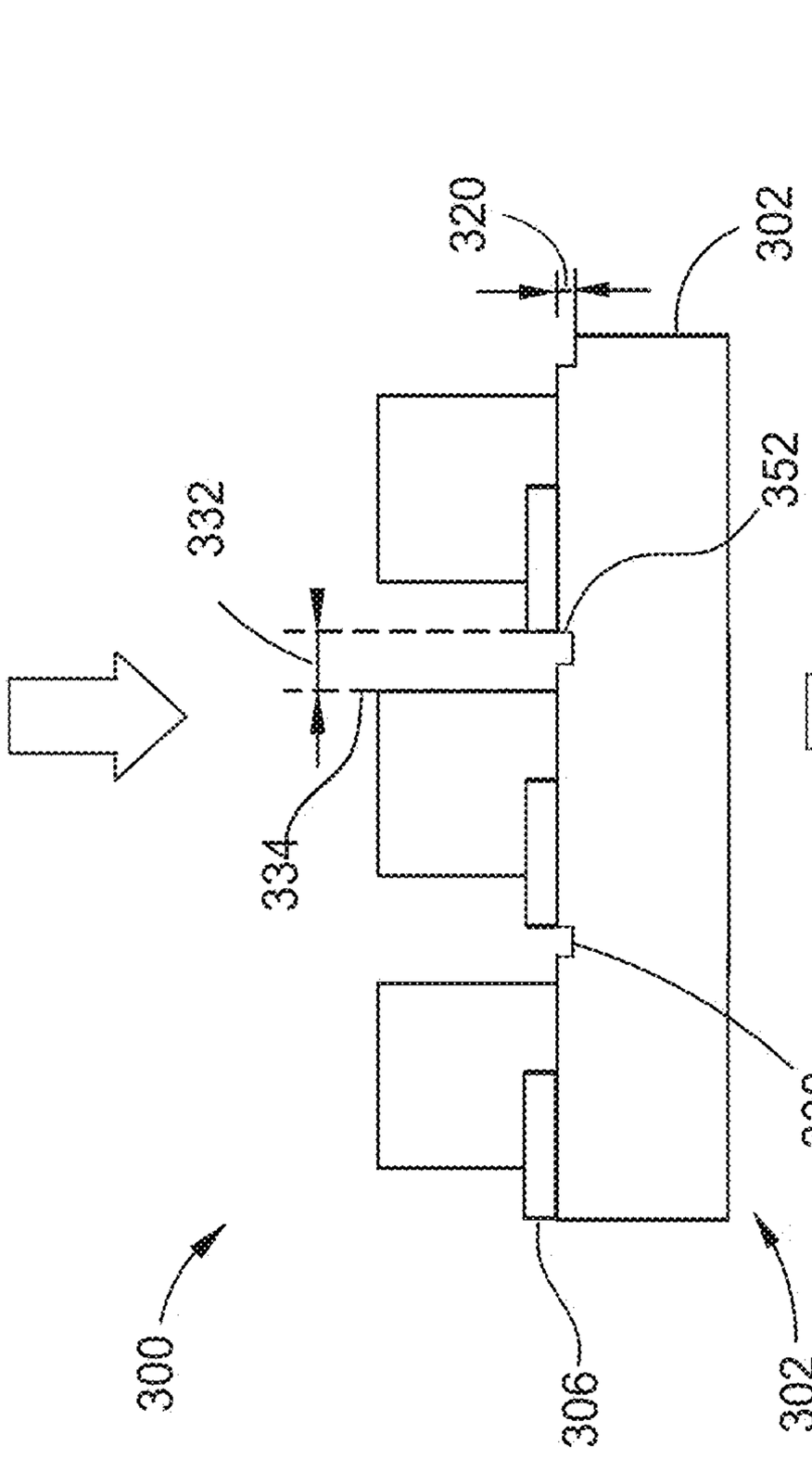
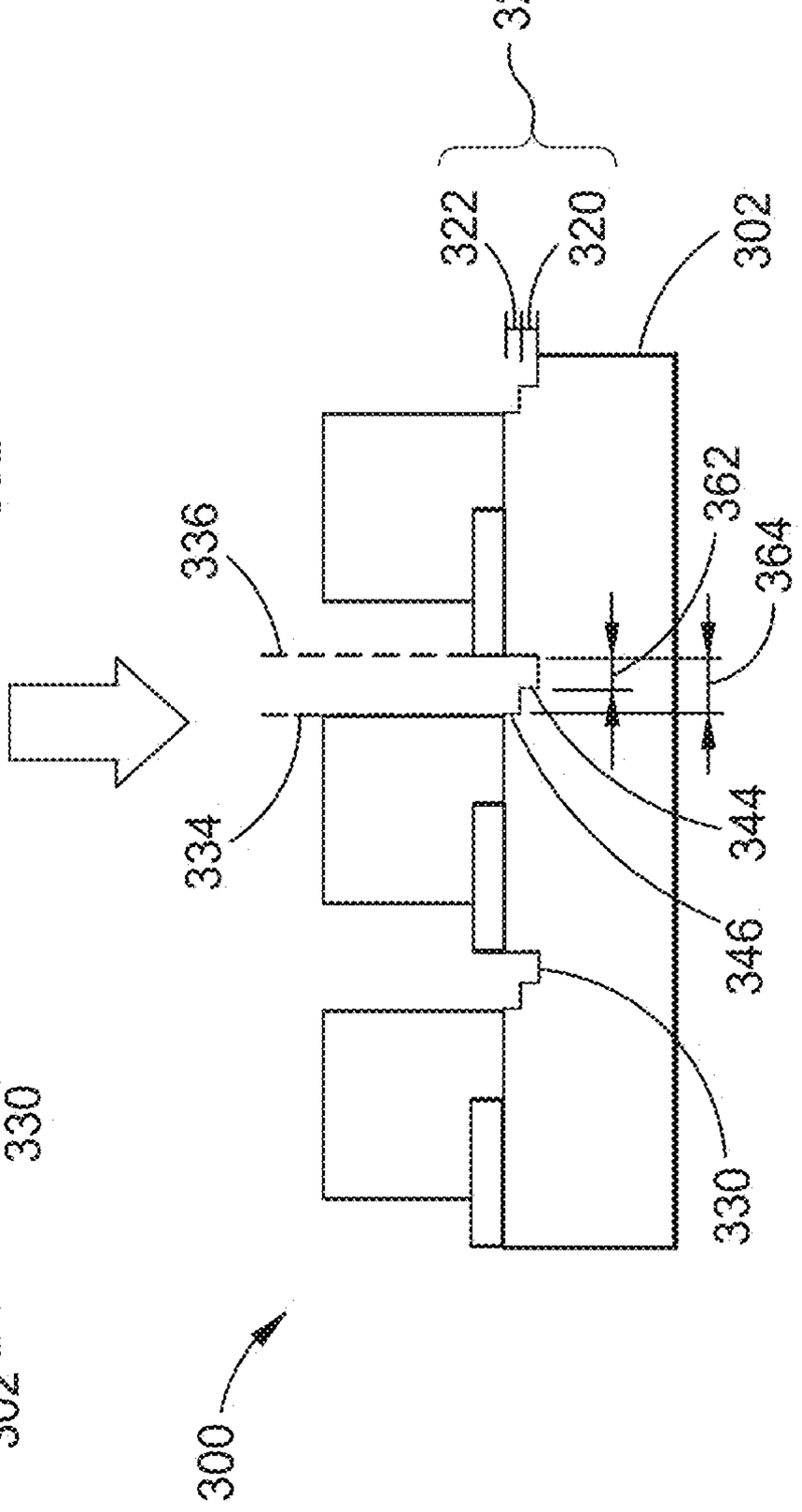

300
302
306
330
332
334
352
320
302

FIG. 3F


300
302
330
334
336
344
346
362
364
320
322
324

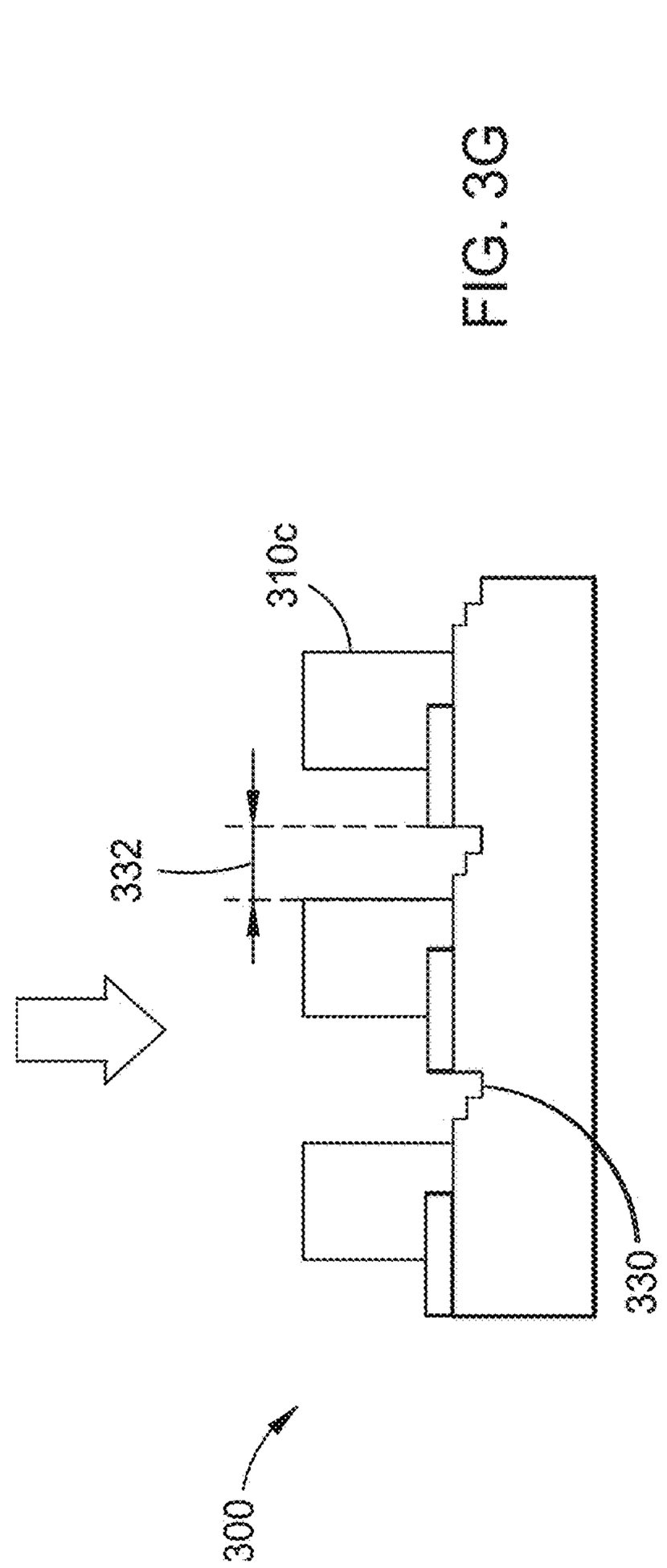

300
310c
332
330

FIG. 3G

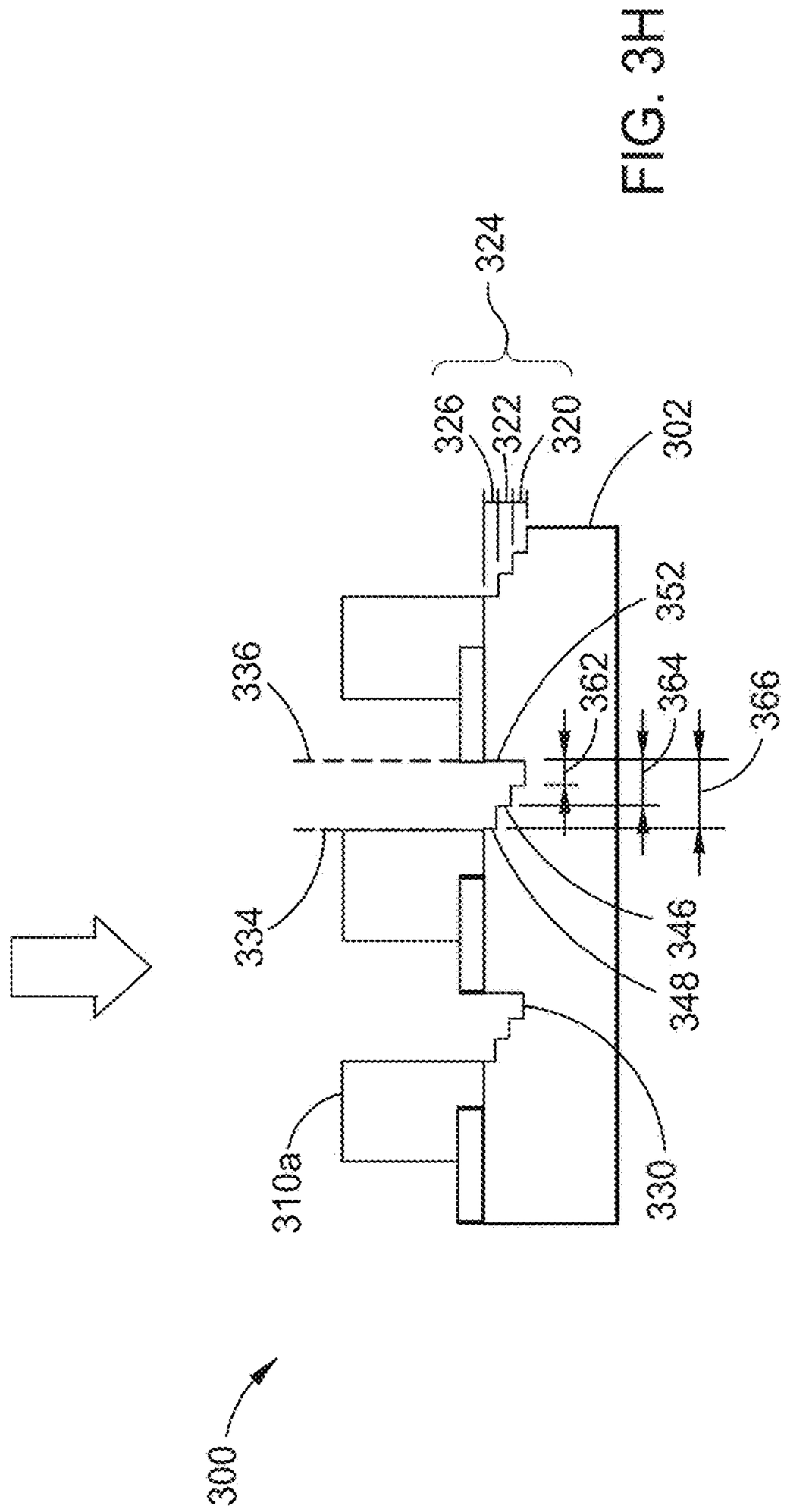

300
310a
324
326
322
320
302
336
334
352
362
364
366
348
346
330

FIG. 3H

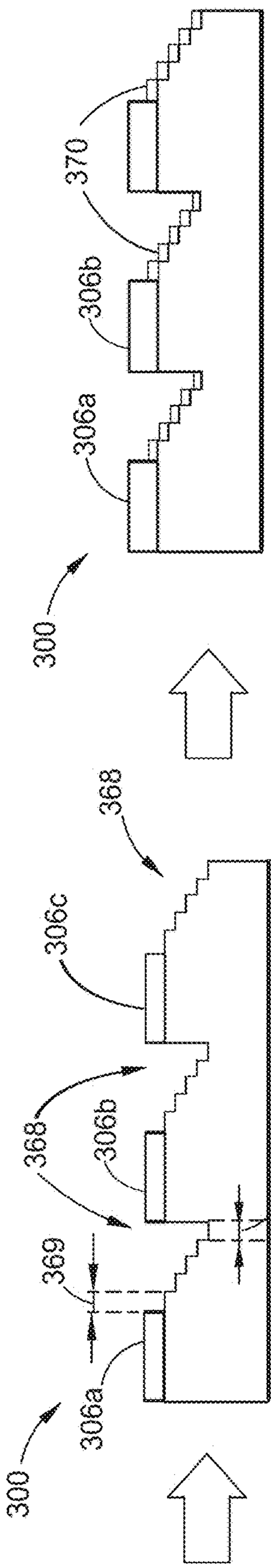


FIG. 3I

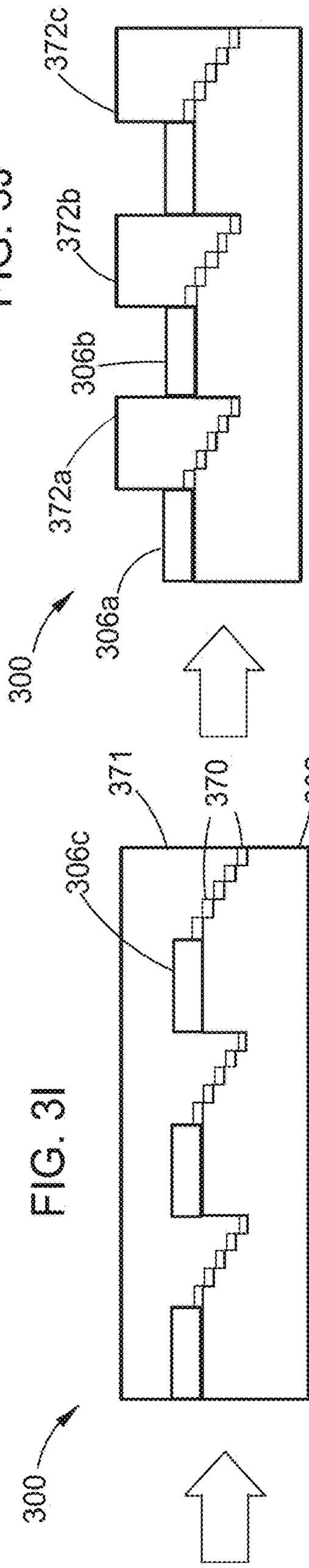


FIG. 3J

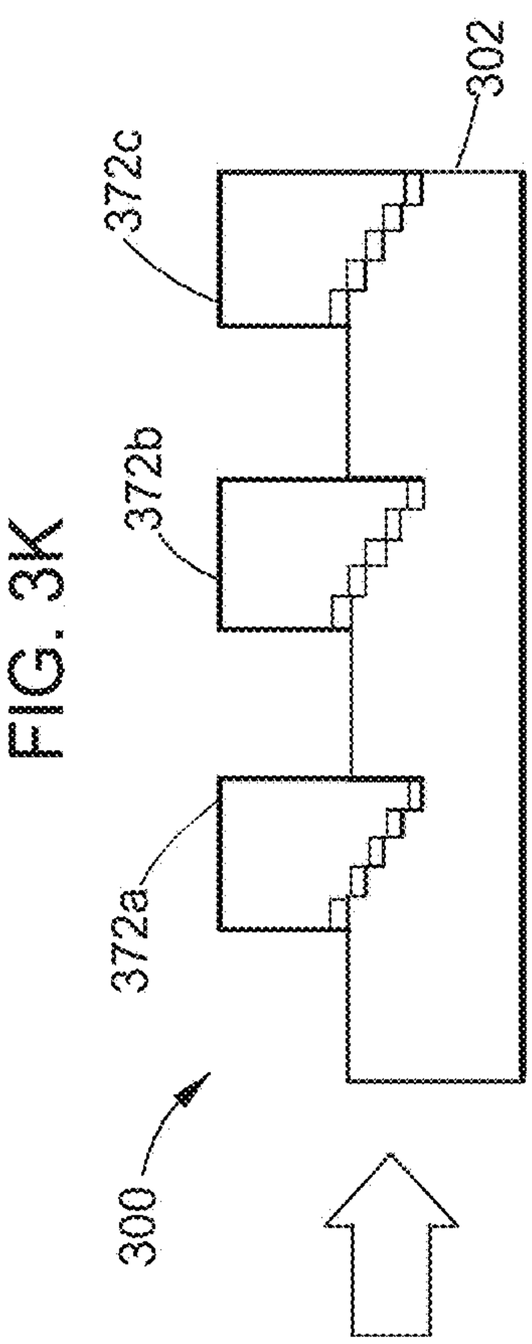


FIG. 3K

FIG. 3L

FIG. 3M

FIG. 3N

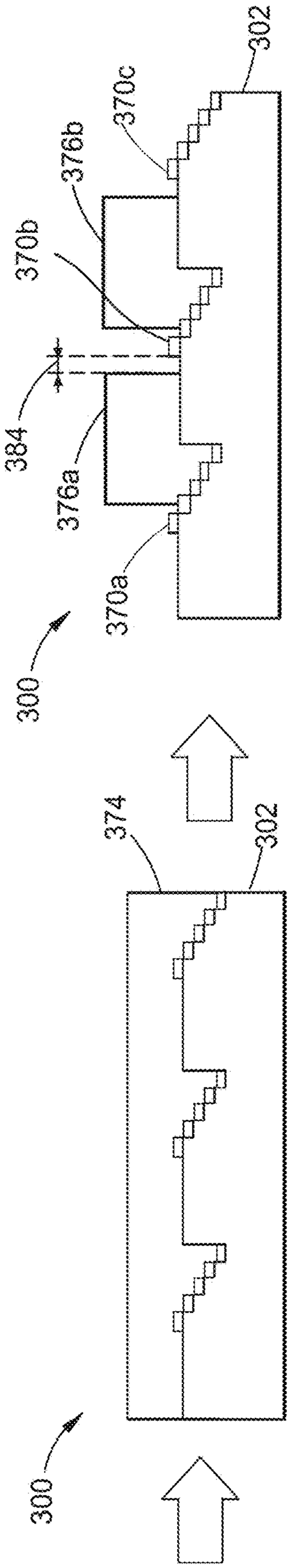


FIG. 3O

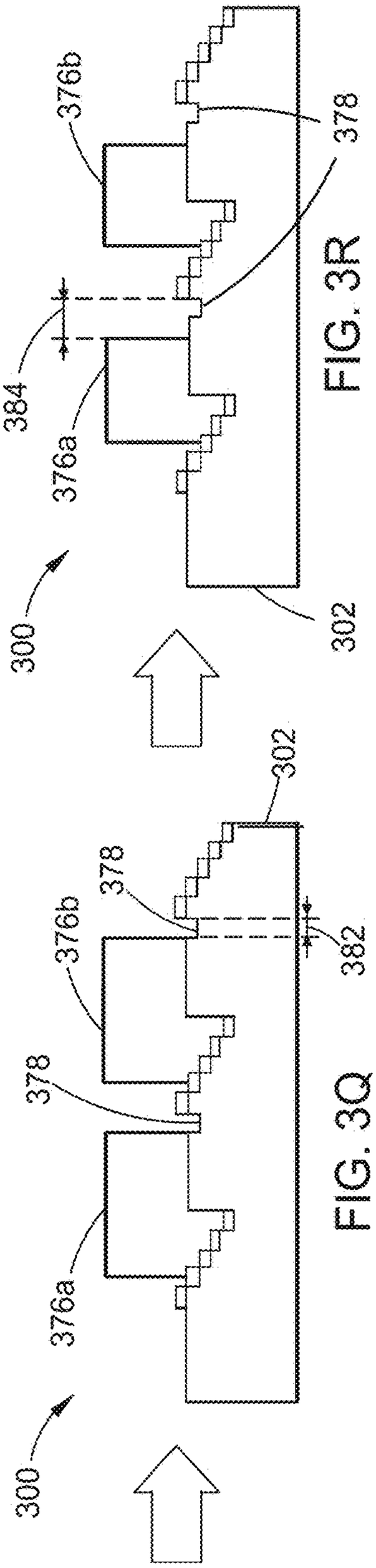


FIG. 3Q

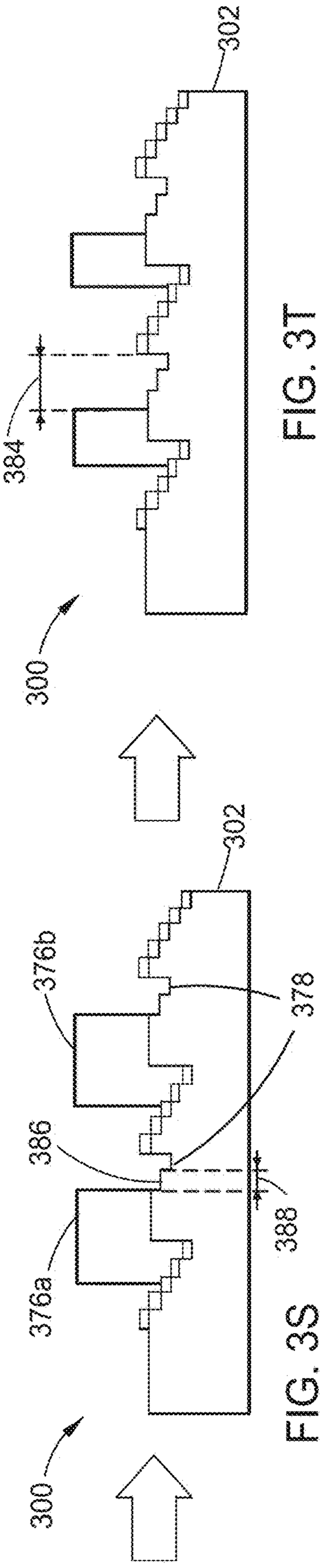


FIG. 3S

FIG. 3P

FIG. 3R

FIG. 3T

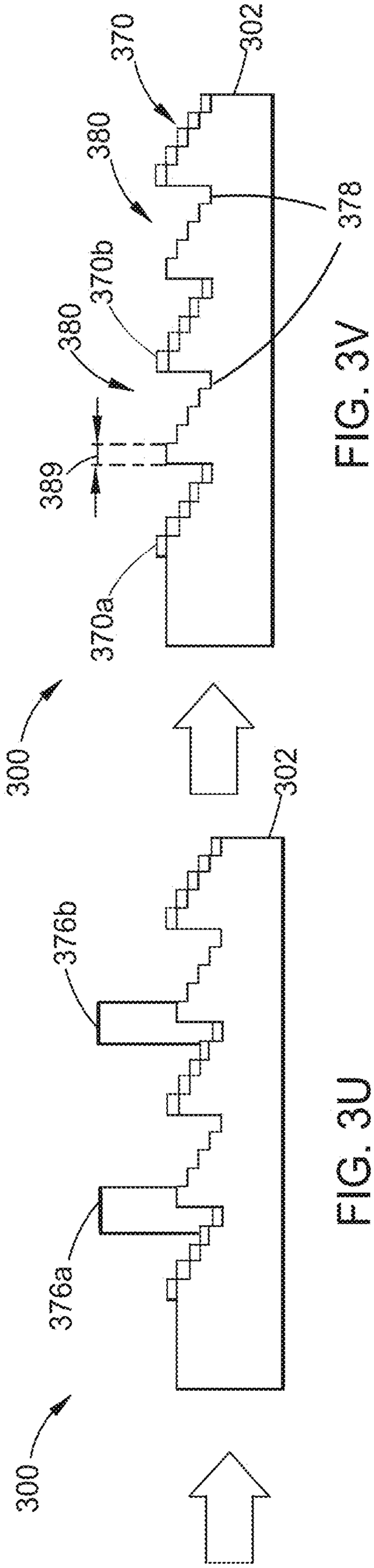


FIG. 3U

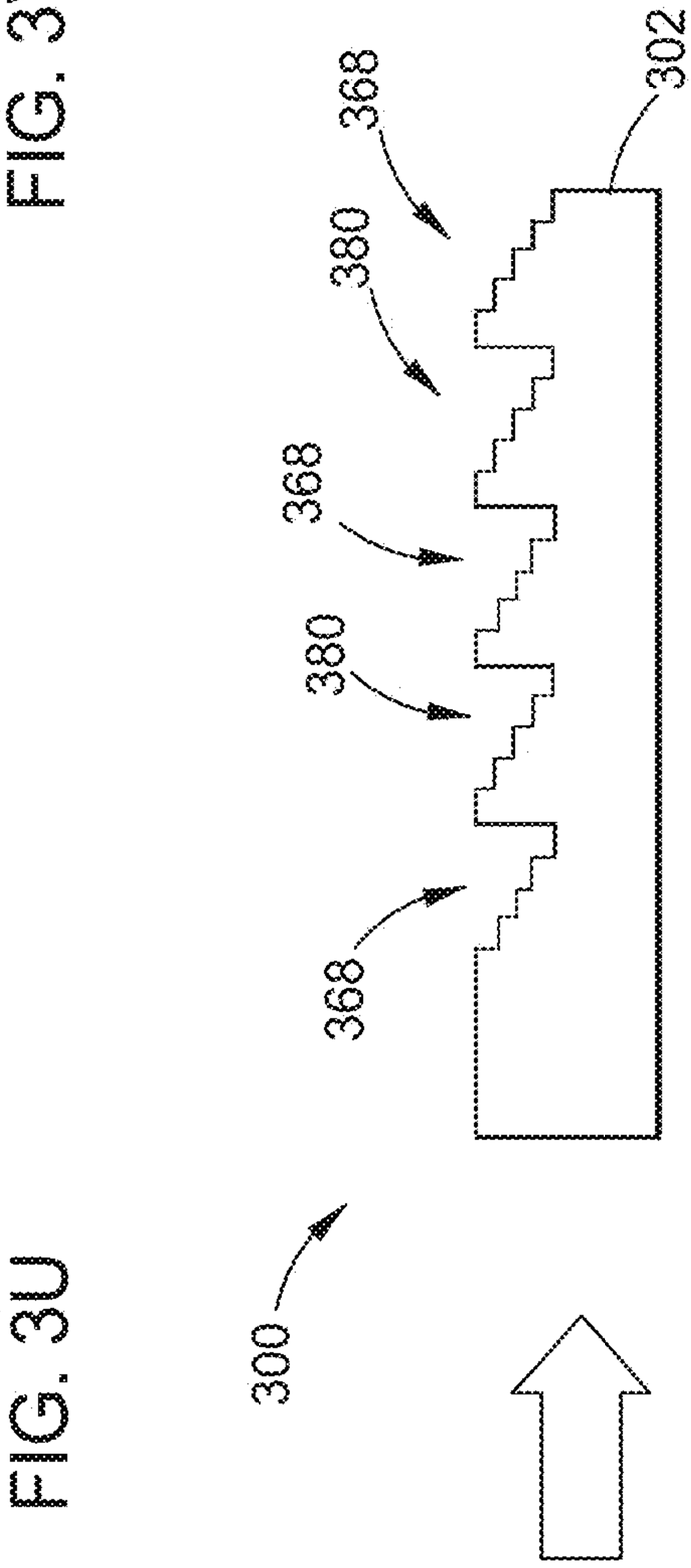


FIG. 3V

FIG. 3W

METHOD FOR FORMING STAIRCASE GRATINGS WITH REDUCED TOP AND BOTTOM CRITICAL DIMENSIONS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application 63/684,028 filed on Aug. 16, 2024, which is herein incorporated by reference in its entirety.

BACKGROUND

Field

[0002] Embodiments of the present disclosure generally relate to optical waveguides. More specifically, embodiments described herein provide techniques for forming a waveguide having staircase gratings.

Description of the Related Art

[0003] Virtual reality is generally considered to be a computer-generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment. Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

[0004] One such challenge is displaying a virtual image overlaid on an ambient environment. Optical devices including waveguide combiners, such as augmented reality waveguide combiners, and flat optical devices, such as metasurfaces, are used to assist in overlaying images. Generated light is propagated through an optical device until the light exits the optical device and is overlaid on the ambient environment. Optical devices may require gratings with staircase stepped structures or structures having blazed angles relative to the surface of the optical device substrate. Blazed angle gratings are desired in AR waveguides for high diffraction efficiency into the targeted order. However, blazed facets are difficult to manufacture using traditional patterning. Staircase stepped structures are close approximations of blazed angle gratings. Current techniques for forming staircase stepped structures however have inherent limitations in the minimum top and bottom critical dimensions (CD) that can be formed for the staircase stepped structures.

[0005] Accordingly, there is a need for improved methods of forming staircase grating structures.

SUMMARY

[0006] In one embodiment, a method for forming a waveguide structure is provided. The method includes forming a patterned hardmask to produce a first plurality of hardmask segments on a device layer, forming a first plurality of photoresist segments over the plurality of hardmask segments and portions of the device layer exposed between the first plurality of hardmask segments, and forming at least one step in portions of the device layer not covered by any of the plurality of photoresist segments or the plurality of hardmask segments. The at least one step in the device layer for forming a first staircase grating. The method also includes forming a second plurality of hardmask segments on the first staircase grating, removing the first plurality of hardmask segments to expose additional portions of the device layer, forming a second plurality of photoresist segments over the second plurality of hardmask segments and the additional exposed portions of the device layer, and forming at least one step in the additional exposed portions of the device layer not covered by any of the second plurality of photoresist segments or the second plurality of hardmask segments. The at least one step formed in the additional exposed portions of the device layer for forming a second staircase grating.

[0007] In another embodiment, a method for forming a waveguide structure is provided. The method includes forming a patterned hardmask to produce a plurality of hardmask segments on a device layer, depositing a first photoresist layer on the patterned hardmask, exposing the first photoresist layer to produce a first plurality of photoresist segments, and etching the device layer to produce at least one step. The at least one step produced forms a first staircase grating in the device layer. The method also includes trimming the first plurality of photoresist segments horizontally, depositing a second hardmask on the first staircase grating to produce a second plurality of hardmask segments on the first staircase grating, forming a patterned second photoresist on the second hardmask to produce a second plurality of photoresist segments on the first staircase grating, removing the patterned hardmask and the second plurality of photoresist segments, depositing a third photoresist layer on the first staircase grating, exposing the third photoresist layer to produce a third plurality of photoresist segments, and etching the device layer to produce at least one step. The at least one step etched forms a second staircase grating. The method continues with trimming the third plurality of photoresist segments horizontally, and removing the third plurality of photoresist segments and the second plurality of hardmask segments.

[0008] In another embodiment, a waveguide structure is provided. The waveguide structure includes a substrate, an input coupling region disposed over the substrate and comprising a plurality of staircase gratings. Each of the plurality of staircase gratings comprise a sidewall having a depth, a top surface having a top critical dimension less than about 100 nm, a linewidth between sidewalls of adjacent staircase gratings of the plurality of staircase gratings, and a stepped surface having a staircase angle and at least one step. The at least one step includes a bottom surface having a bottom critical dimension less than about 100 nm.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] So that the manner in which the above-recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate

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

[0010] FIG. **1**A is a perspective, frontal view of an optical device, according to certain embodiments.

[0011] FIG. **1**B is a schematic, cross-sectional view of a plurality of device structures, according to certain embodiments.

[0012] FIG. **2** is a flow diagram of a method for forming a waveguide structure, according to certain embodiments.

[0013] FIGS. **3**A-**3**W are schematic, cross-sectional views of a waveguide structure undergoing the method for forming a waveguide structure of FIG. **2**, according to certain embodiments.

[0014] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0015] Embodiments herein are generally directed to methods of forming waveguide structures with staircase gratings.

[0016] FIG. **1**A is a front view of a waveguide combiner **100**. It is to be understood that the waveguide combiner **100** described below is an exemplary waveguide combiner. The waveguide combiner **100** includes an input coupling region **102**A defined by a plurality of gratings **106** (illustrated in FIG. **1**B), a waveguide region **102**B, and an output coupling region **102**C.

[0017] The input coupling region **102**A receives incident beams of light (a virtual image) having an intensity from a microdisplay. Each grating of the plurality of gratings **106** splits the incident beams into a plurality of modes. Zero-order mode (TO) beams are refracted back or lost in the waveguide combiner **100**. Positive first-order mode (T**1**) beams undergo total-internal-reflection (TIR) through the waveguide combiner **100** across the waveguide region **102**B to the output coupling region **102**C and output for display. Negative first-order mode (T-**1**) beams propagate in the waveguide combiner **100** a direction opposite to the T**1** beams. Among the diffracted orders, only the T**1** beams output to display through output coupling region **102**C, while other modes are lost due to different directionality. Therefore, it is crucial to increase T**1** beam intensity and decrease other orders beam intensity for higher device optical efficiency. One approach to increase the intensity of the T**1** beams and to reduce the intensity of the other order beams is to control the shape of each grating of the plurality of gratings **106**. A staircase shape for each grating of the plurality of gratings **106** provides for increased optical efficiency.

[0018] FIG. **1**B is a schematic, cross-sectional view of the input coupling region **102**A. In one embodiment, which can be combined with other embodiments described herein, the input coupling region **102**A includes a plurality of staircase gratings **106** of an optical device. The method **200** described herein forms the plurality of staircase gratings **106** on a substrate **101**. The waveguide combiner **100** according to one embodiment, which can be combined with other embodiments described herein, may include the plurality of staircase gratings **106**. Each of the staircase gratings **106** includes a top surface **104**, a stepped surface **108**, a sidewall **112**, a bottom surface **114**, a depth "h", and a linewidth "d". The stepped surface **108** has a plurality of steps **110**. In one embodiment, which can be combined with other embodiments described herein, the stepped surface **108** includes at least 3 steps **110**, such as greater than 16 steps **110**, for example 32 steps **110**. The stepped surface **108** has a staircase angle "γ". The staircase angle γ is the angle between the stepped surface **108** and the surface parallel to the substrate **101** and the angle between the surface normal "s" of the substrate **101** and the facet normal "f" of the stepped surface **108**. The depth h corresponds to the height of the sidewall **112** and the linewidth d corresponds to the distances between sidewalls **112** of adjacent staircase gratings **106**.

[0019] In one embodiment, which can be combined with other embodiments described herein, the staircase angle γ of two or more staircase gratings **106** are different. In another embodiment, which can be combined with other embodiments described herein, the staircase angle γ of two or more staircase gratings **106** are the same. In one embodiment, which can be combined with other embodiments described herein, the depth h of two or more staircase gratings **106** are different. In another embodiment, which can be combined with other embodiments described herein, the depth h of two or more staircase gratings **106** are the same. In one embodiment, which can be combined with other embodiments described herein, the linewidths d of two or more staircase gratings **106** are different. In another embodiment, which can be combined with other embodiments described herein, the linewidths d of one or more staircase gratings **106** are the same.

[0020] FIG. **2** is a flow diagram of a method **200** for forming a waveguide structure **300** in accordance with one or more embodiments of the present disclosure. FIGS. **3**A-**3**W are views of various stages of forming the waveguide structure **300** in a device layer **302** according to the method **200** of FIG. **2**. In one embodiment, the waveguide structure **300** corresponds to the input coupling region **102**A of the waveguide combiner **100**. In some embodiments, the waveguide structure **300** may be formed from the device layer **302** disposed on the substrate **101**. In other embodiments, the device layer **302** and the substrate **101** may be the same layer.

[0021] The substrate **101** can be any substrate used in the art and can be either opaque or transparent to a chosen wavelength of light, depending on the use of the substrate **101** as a substrate for a waveguide. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, polymers, or combinations thereof. In some embodiments, the substrate **101** includes, but is not limited to, a silicon-containing material, a silicon and oxygen containing compound, a germanium-containing material, a indium and phosphide containing compound, a gallium and arsenic containing compound, a gallium and nitrogen containing compound, a carbon-containing material, a silicon and carbon containing compound, a silicon, carbon, and oxygen containing compound, a silicon and nitrogen containing compound, a silicon, oxygen, and nitrogen containing compound, a niobium and oxygen containing compound, and lithium, niobium, and oxygen containing compound, an aluminum and oxygen containing compound, a indium, tin, and oxygen containing compound, a titanium

and oxygen containing compound, a lanthanum and oxygen containing compound, a gadolinium and oxygen containing compound, a zinc and oxygen containing compound, a yttrium and oxygen containing compound, a tungsten and oxygen containing compound, a potassium, and oxygen containing compound, a phosphorous and oxygen containing compound, a barium and oxygen containing compound, a sodium and oxygen containing compound, or combinations thereof. In other embodiments, which can be combined with other embodiments described herein, the substrate **101** includes an oxide including one or more of gadolinium, silicon, sodium, barium, potassium, tungsten, phosphorus, zinc, calcium, titanium, tantalum, niobium, lanthanum, zirconium, lithium, or yttrium containingmaterials. Example materials of the substrate **101** include silicon (Si), silicon monoxide (SiO), silicon dioxide (SiO_2), silicon carbide (SiC), fused silica, diamond, quartz germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), sapphire, sapphire (Al_2O_3), lithium niobate ($LiNbO_3$), indium tin oxide (ITO), lanthanum oxide (La_2O_3), gadolinium oxide (Gd_2O_5), zinc oxide (ZnO), yttrium oxide (Y_2O_3), tungsten oxide (WO_3), titanium oxide (TiO_2), zirconium oxide (ZrO_3), sodium oxide (Na_2O), niobium oxide (Nb_2O_5), barium oxide (BaO), potassium oxide (K_2O), phosphorus pentoxide (P_2O_5), calcium oxide (CaO), or combinations thereof.

[0022] The device layer **302** may include a different material from the substrate **101**. The device layer **302** includes, but is not limited to, one or more oxides, carbides, or nitrides of silicon, aluminum, zirconium, tin, tantalum, zirconium, barium, titanium, hafnium, lithium, lanthanum, cadmium, niobium, or combinations thereof. Example materials of the device layer **302** include silicon carbide, silicon oxycarbide, titanium oxide, silicon oxide, vanadium oxide, aluminum oxide, aluminum-doped zinc oxide, indium tin oxide, tin oxide, zinc oxide, tantalum oxide, silicon nitride, zirconium oxide, niobium oxide, cadmium stannate, silicon oxynitride, barium titanate, diamond like carbon, hafnium oxide, lithium niobate, silicon carbon-nitride, silver, cadmium selenide, mercury telluride, zinc selenide, silver-indium-gallium-sulfur, silver-indium-sulfur, indium phosphide, gallium phosphide, lead sulfide, lead selenide, zinc sulfide, molybdenum sulfide, tungsten sulfide, or combinations thereof. In an embodiment, the device layer **302** includes at least one of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), indium tin oxide (ITO), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), titanium nitride (TiN), and zirconium dioxide (ZrO_2) containing materials.

[0023] As shown in FIG. **3**A, prior to operation **201**, a hardmask is disposed and patterned on the device layer **302**. The patterned hardmask includes a plurality of hardmask segments, such as a first hardmask segment **306***a*, a second hardmask segment **306***b*, and a third hardmask segment **306***c* that are separated from each other. In certain embodiments, the separation (e.g., distance) between each of the patterned hardmask segments **306***a-c* will determine the width of each staircase grating structure produced in a first plurality of staircase grating structures. In certain embodiments, the width of each of patterned hardmask segments **306***a-c* will determine the width of each staircase grating structure produced in a second plurality of staircase grating structures.

[0024] FIG. **3**B is a schematic cross-sectional view of the device layer. In operation **201**, as shown in FIG. **3**B, a first photoresist layer **308** is deposited or otherwise placed over the hardmask segments **306**. At operation **202** and as shown in FIG. **3**C, the first photoresist layer **308** is exposed by lithography to produce a first plurality of photoresist segments, such as a first photoresist segment **310***a*, a second photoresist segment **310***b*, and a third photoresist segment **310***c*. The first plurality of photoresist segments **310***a-c* directly contacts and cover a portion of the device layer **302** exposed between the hardmask segments **306***a-c*. In some embodiments, the first plurality of photoresist segments **310***a-c* partially cover and are offset from each of the plurality of hardmask segments **306***a-c* such that a portion of each hardmask segment **306***a-c* is exposed. Further, each of the photoresist segments **310***a-c* do not extend to the subsequent and adjacent hardmask segment (e.g., from the first hardmask segment **306***a* to the second hardmask segment **306***b*). Rather, each of the photoresist segments **310***a-c* end a distance from each of the subsequent hardmask segment **306***a-c*.

[0025] At operation **203**, the device layer **302** is etched by plasma etchant **304** as shown in FIG. **3**D. The device layer **302** is exposed to plasma etchant **304**, such as radicals and ion beams, contacting the device layer **302**. Exposing the device layer **302** to the plasma etchant **304** may include etching processes, such as ion etching and reactive ion etching (RIE). The plasma etchant **304** etches a first depth **320** of a plurality of depths **324** (shown in FIG. **3**F) of at least one step **330** formed in the device layer **302**. After operation **203**, in addition to the first depth **320**, the at least one step **330** includes an initial leading sidewall **342** of a leading sidewall **344** (shown in FIG. **3**F), a trailing sidewall **352**, and a first linewidth **362** from the initial leading sidewall **342** to the trailing sidewall **352**. The first linewidth **362** is controlled by a distance **332** between a leading edge plane **334** defined by a first side **312** of each of the first plurality of photoresist segments **310***a-c*, and a trailing edge plane **336** defined by an exposed side **314** of each of the plurality of hardmask segments **306***a-c* contacting the device layer **302**. The distance **332** corresponds to the first linewidth **362** as the plasma etchant **304** is masked from contacting the device layer **302** outside of the distance **332** by the plurality of hardmask segments **306***a-c* and each of the first plurality of photoresist segments **310***a-c*.

[0026] At operation **204**, photoresist segments **310***a*, **310***b*, and **310***c* are trimmed by an isotropic etching process that recesses the photoresist segments vertically and horizontally. The etch process includes an etch chemistry that etches the photoresist segments from all directions (i.e. the top and side surfaces). In one embodiment, which may be combined with other embodiments described herein, operation **204** includes performing a wet etching process or an isotropic dry etching process. This operation increases the distance **332** between the leading edge plane **334** and the trailing edge plane **336**. As shown in FIG. **3**E, the distance **332** is increased from the first linewidth **362** (defined by initial leading sidewall **342** to the trailing sidewall **352** shown in FIG. **3**D) by the distance between the leading sidewall **344** to the trailing edge plane **334** shown in FIG. **3**F.

[0027] At optional operation **205**, operations **203** and **204** may be repeated to etch at least one second depth **322** of a plurality of depths **324** of the at least one step **330** into the device layer **302**. As shown in FIG. **3**E, the first plurality of

photoresist segments **310***a-c* are each trimmed to decrease the width of each of the first plurality of photoresist segments **310***a-c* such that the first side **312** of each of the first plurality of photoresist segments **310***a-c* is shifted along the device layer **302**, increasing the distance **332**.

[0028] As shown in FIG. **3**F, in addition to the second depth **322**, the step **330** includes a second leading sidewall

[0029] **346** and a second linewidth **364** from the second leading sidewall **346** to the trailing sidewall **352**. The second linewidth **364** is controlled by the increased distance **332** between the leading edge plane **334** and the trailing edge plane **336** increased by the optional operations **203** and **204**. As the distance **332** increases with each iteration of operation **204**, the resulting second linewidth **364** is longer than the first linewidth **362** with each subsequent iteration of operation **203**. The distance **332** corresponds to the second linewidth **364** as the plasma etchant **304** does not contact the device layer **302** outside of the distance **332**. Operation **203** and operation **204** are repeated until the waveguide structure **300** is formed when the at least one step **330** has the plurality of depths **324** including the first depth **320** and the at least one second depth **322** corresponding to a step depth. Decreasing the first depth **320** and each second depth **322** will result in a smoother leading sidewall **344** of the at least one step **330**.

[0030] As shown in FIG. **3**E, in various embodiments, the increase in the distance **332** between each of the first plurality of photoresist segments **310***a-c* after trimming is uniform and equal to double the first linewidth **362**, e.g., the second linewidth **364** is double the length of the first linewidth **362**, such that each of the at least one steps **330** are symmetric. In some embodiments, the trimming of each of the photoresist segments **310***a-c* occurs at both ends of each of the respective photoresist segments **310***a-c* such that the side of each of the photoresist segments opposite of the first side **312** is shifted along the respective hardmask segments **306***a-c*. Alternatively, the second linewidth **364** may increase non-uniformly over, e.g., be non-uniformly greater than, the first linewidth **362**. For example, the second linewidth **364** may increase by 1.5 times the first linewidth **362**, producing a non-symmetric staircase or staircase grating. Similarly, subsequent linewidths may increase symmetrically or non-symmetrically.

[0031] As shown in FIGS. **3**G and **3**H, optional operation **205** includes repeating optional operation **204** after each second depth **322** of the at least one step **330** is etched. For example, at optional operation **204**, the photoresist segments **310** are trimmed, further increasing the distance **332**. At optional operation **203**, a third depth **326** of the plurality of depths **324** is created along with a third leading sidewall **348** and a third linewidth **366** from the third leading sidewall **348** to the trailing sidewall **352**. The third linewidth **366** is controlled by distance between the leading edge plane **334** and the trailing edge plane **336**, increased by the subsequent optional operation **204**. The distance **332** corresponds to the third linewidth **366** as the plasma etchant **304** does not contact the device layer **302** outside of the distance **332**.

[0032] FIG. **31** is a schematic, cross-sectional view of the waveguide structure **300** after operation **206** of the method **200**. In one embodiment, remaining residual portions of the at least one first photoresist layer **308** (e.g., remaining non-trimmed portions of the photoresist segments **310**), if present, are removed at operation **206** after a first plurality of staircase grating structures **368** of the waveguide structure **300** is formed between each of the hardmask segments **306***a-c*. As shown in FIG. **31**, each of the first plurality of staircase grating structures **368** formed includes at least one step **330** in which a bottom critical dimension (CD) corresponds with the linewidth **362** and a top critical dimension of each of the first plurality of staircase grating structure **368** corresponding with a linewidth **369**.

[0033] After operation **206**, the at least one step **330** remains and forms the structure of the staircase gratings **106** for each of the first plurality of staircase grating structures **368**. Although only five steps are shown in FIG. **31**, optional operation **204** may be repeated to produce a desired number of steps, such as **3**, such as **10**, such as **25**, or more. As the number of steps increases, it is noted that the linewidth of each step (e.g., **362**, **364**) may decrease, producing a smoother leading sidewall (e.g., **342**, **344**) for each staircase grating **106**. For example, the method **200** may enable the formation of a plurality of staircase gratings **106** that each approximate a continuous blazed profile.

[0034] At operation **207**, a second hardmask is deposited or otherwise disposed over the plurality of hardmask segments **306***a-c* and each of the at least one step **330** of each of the first plurality of staircase grating structures **368**. As shown in FIG. **3**J, a corresponding second plurality of hardmask segments **370** is formed over each of the at least one step **330** in the first plurality of staircase grating structures **368** when the second hardmask is deposited. In an embodiment, the material of the second hardmask may be the same as the material of the first patterned hardmask such that the second hardmask formed over each of the plurality of hardmask segments **306***a-c* causes a thickness of each of each of the hardmask segments **306***a-c* to increase in operation **207**.

[0035] At operation **208**, as shown in FIG. **3**K, a second photoresist layer **371** is deposited or otherwise placed over the patterned hardmask segments **306***a-c* and each of the second hardmask segments **370**. At operation **209** and as shown in FIG. **3**L, the second photoresist layer **371** is exposed by lithography to produce a second plurality of photoresist segments, such as a first photoresist segment **372***a*, a second photoresist segment **372***b*, and a third photoresist segment **372***c*. The second plurality of photoresist segments **372***a-c* directly contact and cover the second plurality of hardmask segments **370** over each of the at least one step **330** of each of the first plurality of staircase grating structures **368** exposed between the hardmask segments **306***a-c*.

[0036] At operation **210**, hardmask segments **306***a-c* are removed exposing a portion of the device layer **302** between the second plurality of photoresist segments **372***a-c*, as shown in FIG. **3**M. In an embodiment in which the material of the hardmask segments **306***a-c* and the second plurality of hardmask segments **370** are made of the same material, the second plurality of photoresist segments **372***a-c* prevents the second plurality of hardmask segments **370** on each of the at least one step **330** from being removed in operation **210**. At operation **211**, the second plurality of photoresist segments **372***a-c* are removed from each of the plurality of first staircase grating structures **368**. As shown in FIG. **3**N, after operation **211**, portions of the device layer **302** previously covered by the patterned hardmask segments **306***a-c* are exposed between each of the first plurality of staircase grating structures **368** and corresponding second hardmask segments **370** disposed thereon.

[0037] At operation **212**, operations similar to operations **201** and **202** are performed to form a plurality of third photoresist segments over the device layer **302**. Operation **212** includes depositing a third photoresist layer **374** over the device layer **302** and the second plurality of hardmask segments **370** and exposing the third photoresist layer **374** to form to produce a third plurality of photoresist segments, such as a first photoresist segment **376***a* and a second photoresist segment **376***b*. The third plurality of photoresist segments **376***a-c* directly contact and cover a portion of the device layer **302** exposed between each of the first plurality of staircase grating structures **368**.

[0038] In some embodiments, as shown in FIG. **3**P, the third plurality of photoresist segments **376***a-c* partially cover and are offset from the second hardmask segments **370** on each of the first plurality of staircase grating structures **368** such that a portion of the second hardmask segments **370** on each of the first plurality of staircase grating structures **368** are exposed. Further, each of the photoresist segments **376***a-c* do not extend to the subsequent and adjacent second hardmask segment **370** on the top surface of the subsequent adjacent staircase grating structure **368** (e.g., from a second hardmask segment **370***a* on the top surface of one of the first plurality of staircase grating structure **368** to a second hardmask segment **370***b* on the top surface of the next staircase grating structure **368** as shown in FIG. **3**P). Rather, each of the photoresist segments **376***a-c* end a distance from each of the subsequent top second hardmask segments **370***a-c*.

[0039] At operation **213**, plasma etchant contacts the device layer **302** similar to that as shown in and discussed for FIG. **3**D with regards to the plasma etchant **304** used in operation **203**. As shown in FIG. **3**Q, at least one step **378** for a second plurality of staircase grating structures **380** (shown in FIGS. **3**V and **3**W) is formed by the plasma etchant in the device layer **302**. After operation **213**, the at least one step **378** of each of the second plurality of staircase grating structures **380** includes a linewidth **382** controlled by a distance **384** between a leading edge plane defined by a first side of the photoresist segments **376***a* disposed directly over the device layer **302**, and a trailing edge plane defined by an exposed side of a second hardmask segment **370***a* disposed on the top surface of an adjacent staircase grating structure **368**. The distance **384** controls the linewidth **382** etched by the plasma etchant in operation **213** for forming each of the at least one step **378** as the plasma etchant is masked from contacting the device layer **302** outside of the distance **384** by the second hardmask segments **370** and the third plurality of photoresist segments **376**.

[0040] At operation **214**, photoresist segments **376***a* and **376***b* of the third photoresist layer **374** are trimmed by an isotropic ion etching process similar to operation **204** discussed above. Operation **214** recesses the photoresist segments vertically and horizontally from both sides of the photoresist segments **376**. As shown in FIG. **3**R, operation **214** increases the distance **384**.

[0041] At optional operation **215**, operations **213** and **214** may be repeated to etch one or more additional steps of the at least one step **378** into the device layer **302**. Operations **213** and **214** for forming the second plurality of staircase grating structures **380** may be repeated similarly to operations **203** and **204** described above for optional operation **205** when forming the at least one step **330** for the first plurality of staircase grating structures **368**. As shown in FIG. **3**S-**3**U, after the third plurality of photoresist segments **376***a-c* are trimmed such that the distance **384** increases, operation **213** may be repeated to etch exposed portions of the device layer **302** and form a second step **386** adjacent to the at least one step **378**. A linewidth **388** of the second step **386** is controlled by the change in distance **384** due to the trimming of the third plurality of photoresist segments **376***a-c* in prior operation **214**. As the second step **386** is etched in operation **213**, the at least one step **378** previously etched is similarly further etched such that a depth of the at least one step **378** is increased by an etched depth of the second step **386**.

[0042] FIGS. **3**T and **3**U show a schematic, cross-sectional view of the waveguide structure **300** after additional iterations of operations **213** and **214** is performed to form additional steps of the at least one step **378** in the device layer **302**. As the distance **384** increases with each iteration of operation **214**, the resulting linewidth **382** increases with each subsequent iteration of operation **213**. Similarly, as additional steps are etched with each subsequent iteration of operation **213**, the depth of each of the at least one step **378** previously etched is increased by a depth corresponding to the most recently formed at least one step **378**. Decreasing the depth of each subsequently formed step in the device layer **302** may in turn result in a smoother leading sidewall of the at least one step **378**. In an embodiment, each of the second plurality of staircase grating structures **380** may be formed the same as each of the first plurality of staircase grating structures **368**. In other embodiments, the second plurality of staircase grating structures **380** may be formed different from the first plurality of staircase grating structures **368**.

[0043] After the waveguide structure **300** is formed in operation **215**, the second hardmask segments **370** and the remaining portions of the third plurality of photoresist segments **376***a-c* may be removed at operation **216**. In one embodiment, which can be combined with other embodiments described herein, the second hardmask segments **370** and the remaining portions of the third plurality of photoresist segments **376***a-c* include non-transparent materials that are removed at operation **216** to form the waveguide structure **300** shown in FIG. **3**W. Removing the second hardmask segments **370** may include ion etching, RIE, or selective wet chemical etching. Removing the remaining portions of the third plurality of photoresist segments **376***a-c* may include a lithography process or etching process described herein.

[0044] In another embodiment, which can be combined with other embodiments described herein, the second hardmask segments **370** may include transparent materials such that the second hardmask segments **370** is left on after the waveguide structure **300** is formed in operation **215**. FIG. **3**V is a schematic, cross-sectional view of the waveguide structure **300** after operation **216** is only partially performed to remove the remaining portions of the third plurality of photoresist segments **376***a-c*. The second hardmask segments **370** may include, but is not limited to, chromium (Cr), silver (Ag). Si_3N_4. SiO_2, TIN, and carbon (C) containing materials. In a further embodiment, both the third plurality of photoresist segments **376***a-c* and the second hardmask segments **370** may include transparent materials such that both the second hardmask segments **370** and the remaining

portions of the third plurality of photoresist segments **376***a-c* remain on the waveguide structure **300** after operation **215**, as shown in FIG. **3**U.

[0045] After operation **216**, the at least one step **378** between each of the first plurality of staircase grating structures **368** forms the second plurality of staircase grating structures **380** in the device layer **302**, as shown in FIG. **3**W. Each of the second plurality of staircase grating structures **380** includes at least one step **378** in which a bottom critical dimension (CD) of each of the second plurality of staircase grating structures **380** corresponds with the linewidth **382** of a bottom surface of each of the second plurality of staircase grating structures **380**, and a top critical dimension of corresponding with a linewidth **389** of a top surface of the staircase grating structure **380**, as shown in FIGS. **3**Q and **3**V. Although only five steps are shown in FIG. **3**W, optional operation **215** may be repeated to produce a desired number of steps, such as **3**, such as **10**, such as **25**, or more. As the number of steps increases, it is noted that the linewidth of each step (e.g., **362**, **364**) may decrease, producing a smoother leading sidewall (e.g., **342**, **344**) for each staircase grating structure. For example, the method **200** may enable the formation of a plurality of staircase gratings **106** that each approximate a continuous blazed profile.

[0046] Advantages of the present disclosure provide for forming staircase grating structures having reduced top critical dimension (CD_{Top}) and reduced bottom critical dimension (CD_{Bottom}), as compared to staircase grating structures formed utilizing conventional means. In staircase grating structures for waveguides, large CD_{Top} and CD_{Bottom} are generally undesired as they may negatively impact optical performance. In staircase grating structures formed using conventional techniques, the minimum CD_{Bottom} of staircase grating structures are generally limited to 100 nm, which is the minimum gap CD achievable by dry lithography when etching the photoresist segments. Under such limitations, it observed that the bottom and top CDs are in turn limited to the following restriction function (I) below based on the pitch P (i.e. period) of the staircase grating structure to be formed.

$$CD_{Bottom} + CD_{Top} \geq \frac{(P+100)}{2} \quad \text{(I)}$$

[0047] The above function provides that in an example of a conventionally formed staircase grating structure in which P is about 400 nm and the minimum gap CD achievable by lithography is about 100 nm, the CD_{Bottom} is about 100 nm for such staircase gratings as mentioned above, and the CD_{Top} in turn must be ≥150 nm.

[0048] Conversely, it was observed that for staircase grating structures formed using the techniques of the present disclosure, the bottom and top CDs are limited to the more relaxed restriction function (ii) below:

$$2 \times CD_{Bottom} + CD_{Top} \geq 100 \text{ nm} \quad \text{(II)}$$

[0049] Based on the above, for an exemplary staircase grating structure formed using the techniques of the present disclosure and in which the minimum gap CD achievable by lithography is about 100 nm and CD_{Bottom}=CD_{Top}, the present disclosures provides for staircase grating structures in which CD_{Top}≥33 nm and CD_{Bottom}≥33 nm. Accordingly, the present disclosure provides for forming staircase grating structures with much smaller bottom and top CDs.

[0050] When introducing elements of the present disclosure or exemplary aspects or embodiments thereof, the articles "a," "an," "the" and "said" are intended to mean that there are one or more of the elements.

[0051] The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0052] The term "coupled" is used herein to refer to the direct or indirect coupling between two objects. For example, if object A physically touches object B and object B touches object C, the objects A and C may still be considered coupled to one another-even if objects A and C do not directly physically touch each other. For instance, a first object may be coupled to a second object even though the first object is never directly in physical contact with the second object.

[0053] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method of forming a waveguide structure, comprising:

forming a patterned hardmask to produce a first plurality of hardmask segments on a device layer;

forming a first plurality of photoresist segments over the plurality of hardmask segments and portions of the device layer exposed between the first plurality of hardmask segments;

forming at least one step in portions of the device layer not covered by any of the plurality of photoresist segments or the plurality of hardmask segments, the at least one step forming a first staircase grating;

forming a second plurality of hardmask segments on the first staircase grating;

removing the first plurality of hardmask segments to expose additional portions of the device layer;

forming a second plurality of photoresist segments over the second plurality of hardmask segments and the additional exposed portions of the device layer; and

forming at least one step in the additional exposed portions of the device layer not covered by any of the second plurality of photoresist segments or the second plurality of hardmask segments, the at least one step forming a second staircase grating.

2. The method of claim **1**, further comprising removing the second plurality of photoresist segments and the second plurality of hardmask segments after the second staircase grating is formed.

3. The method of claim **1**, wherein forming the at least one step for the first staircase grating comprises:

etching the device layer to produce a first step;

trimming the first plurality of photoresist segments horizontally to increase portions of the device layer not covered by any of the plurality of photoresist segments and the plurality of hardmask segments; and

repeating etching the device layer and trimming the first plurality of photoresist segments horizontally to produce a second step of the first staircase grating.

4. The method of claim **1**, wherein forming the at least one step for the second staircase grating comprises:

etching the additional exposed portions of the device layer device layer to produce a first step;

trimming the second plurality of photoresist segments horizontally to increase the additional exposed portions of the device layer; and

repeating etching the additional exposed portions of the device layer and trimming the second plurality of photoresist segments horizontally to produce a second step of the second staircase grating.

5. The method of claim **1**, further comprising removing the first plurality of photoresist segments prior to forming the second plurality of hardmask segments.

6. The method of claim **1**, further comprising wherein removing the first plurality of hardmask segments comprises:

forming a photoresist layer on the patterned hardmask and the second plurality of hardmask segments on the first staircase grating;

exposing the photoresist layer to produce a third plurality of photoresist segments over the second plurality of hardmask segments on the first staircase grating; and

etching the first plurality of hardmask segments exposed between the third plurality of photoresist segments.

7. A method of forming a waveguide structure, comprising:

forming a patterned hardmask to produce a plurality of hardmask segments on a device layer;

depositing a first photoresist layer on the patterned hardmask;

exposing the first photoresist layer to produce a first plurality of photoresist segments;

etching the device layer to produce at least one step, the at least one step forming a first staircase grating;

trimming the first plurality of photoresist segments horizontally;

depositing a second hardmask on the first staircase grating to produce a second plurality of hardmask segments on the first staircase grating;

forming a patterned second photoresist on the second hardmask to produce a second plurality of photoresist segments on the first staircase grating;

removing the patterned hardmask and the second plurality of photoresist segments;

depositing a third photoresist layer on the first staircase grating;

exposing the third photoresist layer to produce a third plurality of photoresist segments;

etching the device layer to produce at least one step, the at least one step forming a second staircase grating;

trimming the third plurality of photoresist segments horizontally; and

removing the third plurality of photoresist segments and the second plurality of hardmask segments.

8. The method of claim **7**, further comprising:

before depositing the second hardmask, repeating etching the device layer and trimming the first plurality of photoresist segments horizontally to produce a second step of the first staircase grating.

9. The method of claim **7**, further comprising:

before removing the third plurality of photoresist segments and the remaining portion of the second hardmask, repeating etching the device layer and trimming the third plurality of photoresist segments horizontally to produce a second step of the second staircase grating.

10. The method of claim **7**, wherein the at least one step of the first grating structure includes a first depth into the device layer.

11. The method of claim **8**, wherein the at least one step of the first staircase grating includes a first depth into the device layer and the second step includes a second depth into the device layer, the first depth being greater than the second depth.

12. The method of claim **9**, wherein the at least one step of the second staircase grating includes a first depth into the device layer and the second step includes a second depth into the device layer, the first depth being greater than the second depth.

13. The method of claim **7**, further comprising removing residual portions of the first plurality of photoresist segments before depositing the second hardmask.

14. The method of claim **7**, wherein a linewidth of the first staircase grating is determined by a distance between each of the plurality of hardmask segments.

15. The method of claim **7**, wherein a linewidth of the second staircase grating is determined by a width of each of the plurality of hardmask segments.

16. The method of claim **7**, wherein the first plurality of photoresist segments are offset from the plurality of hardmask segments of the patterned hardmask such that a portion of each of the first plurality of photoresist segments directly contact a portion of the device layer.

17. The method of claim **7**, wherein depositing the second hardmask on the first staircase grating produces a second plurality of hardmask segments on the at least one step of the first staircase grating, and the third plurality of photoresist segments are offset from the second hardmask segments of the second hardmask such that a portion of each of the third plurality of photoresist segments directly contact a portion of the device layer.

18. The method of claim **7**, wherein the at least one step of the first staircase grating includes a first linewidth controlled by a distance between a leading edge plane defined by a first side of a photoresist segment of the first plurality of photoresist segments and a trailing edge plane defined by an exposed side of a hardmask segment of the plurality of hardmask segments.

19. The method of claim **7**, wherein the at least one step of the second staircase grating includes a first linewidth controlled by a distance between a leading edge plane defined by a first side of a photoresist segment of the third plurality of photoresist segments and a trailing edge plane defined by an exposed side of a second hardmask segment disposed over a top surface of the first staircase grating.

20. A waveguide structure, comprising:

a substrate;

an input coupling region disposed over the substrate and comprising a plurality of staircase gratings, each of the plurality of staircase gratings comprising:

a sidewall having a depth;

a top surface having a top critical dimension less than about 100 nm;

a linewidth between sidewalls of adjacent staircase gratings of the plurality of staircase gratings; and

a stepped surface having a staircase angle and at least one step, the at least one step comprising a bottom surface having a bottom critical dimension less than about 100 nm.

* * * * *