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(54) **PATTERNING OF MULTI-DEPTH OPTICAL DEVICES**

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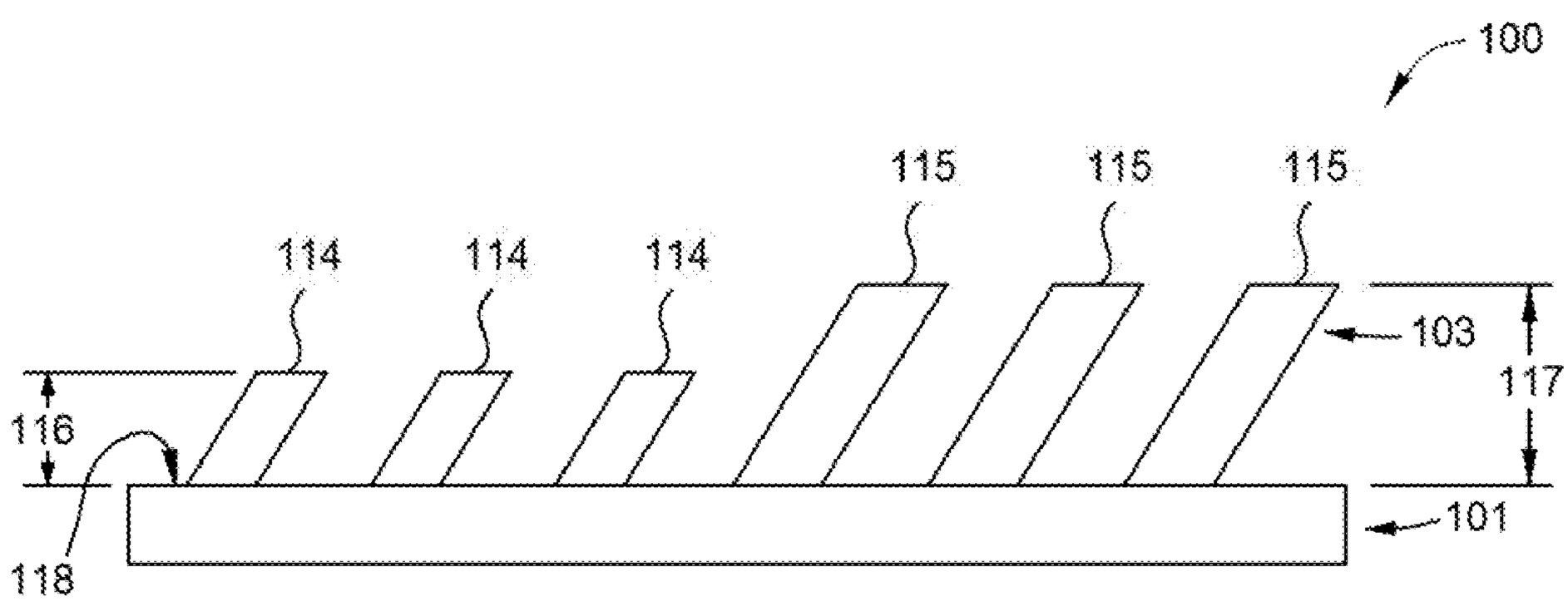
(52) **U.S. Cl.**

CPC ***G03F 7/0005*** (2013.01); ***G02B 6/34*** (2013.01)

(57) **ABSTRACT**

Methods for patterning of multi-depth layers for the fabrication of optical devices are provided. In one embodiment, a method is provided that includes disposing a resist layer over a device layer disposed over a top surface of a substrate, the device layer having a first portion and a second portion, patterning the resist layer to form a first resist layer pattern having a plurality of first openings and a second resist layer pattern having a plurality of second openings, and etching exposed portions of the device layer defined by the plurality of first openings and the plurality of second openings, wherein the plurality of first openings are configured to form at least a portion of a plurality of first structures within the optical device, and the plurality of second openings are configured to form at least a portion of a plurality of second structures within the optical device.



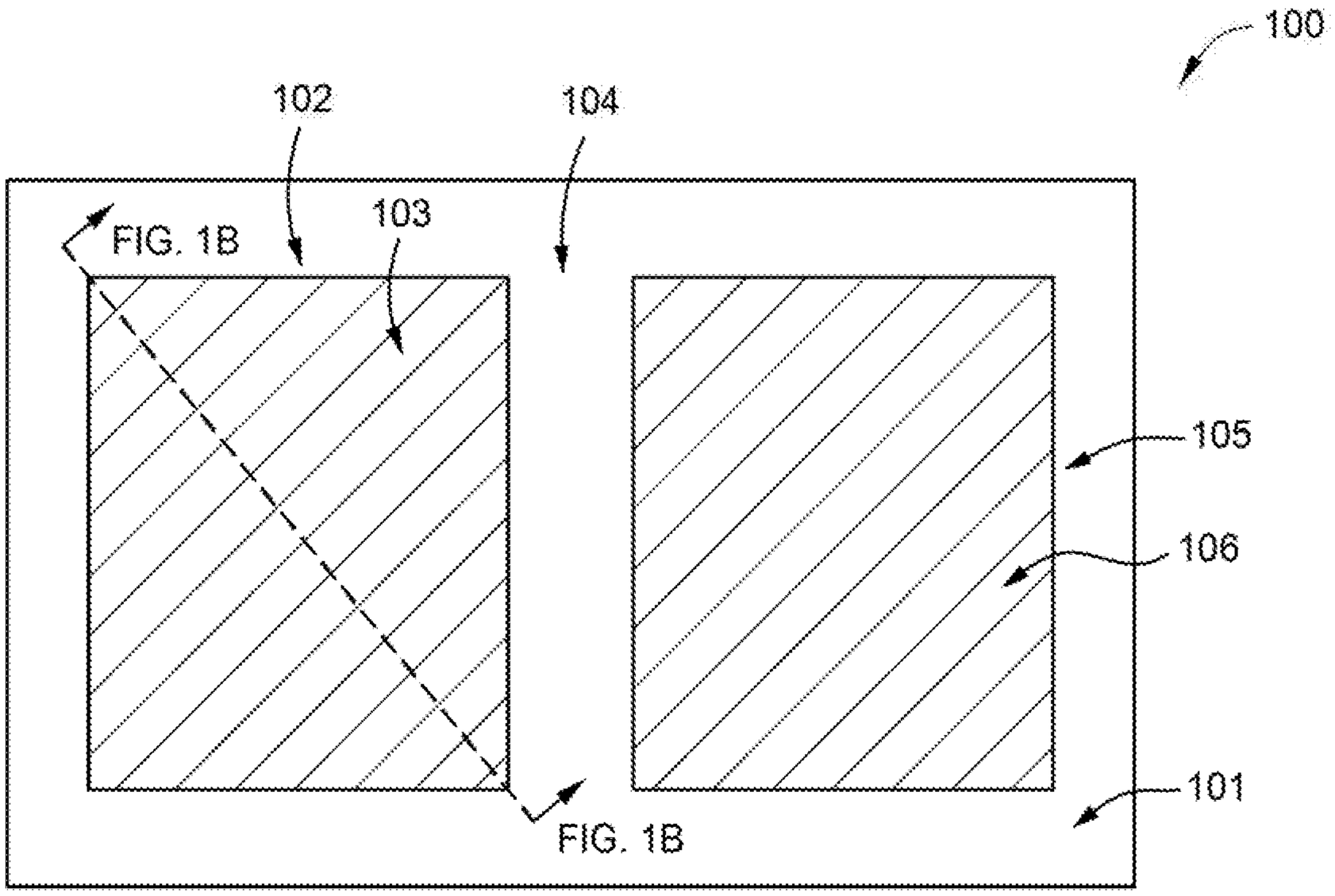

100
102
104
103
FIG. 1B
105
106
101
FIG. 1B

FIG. 1A

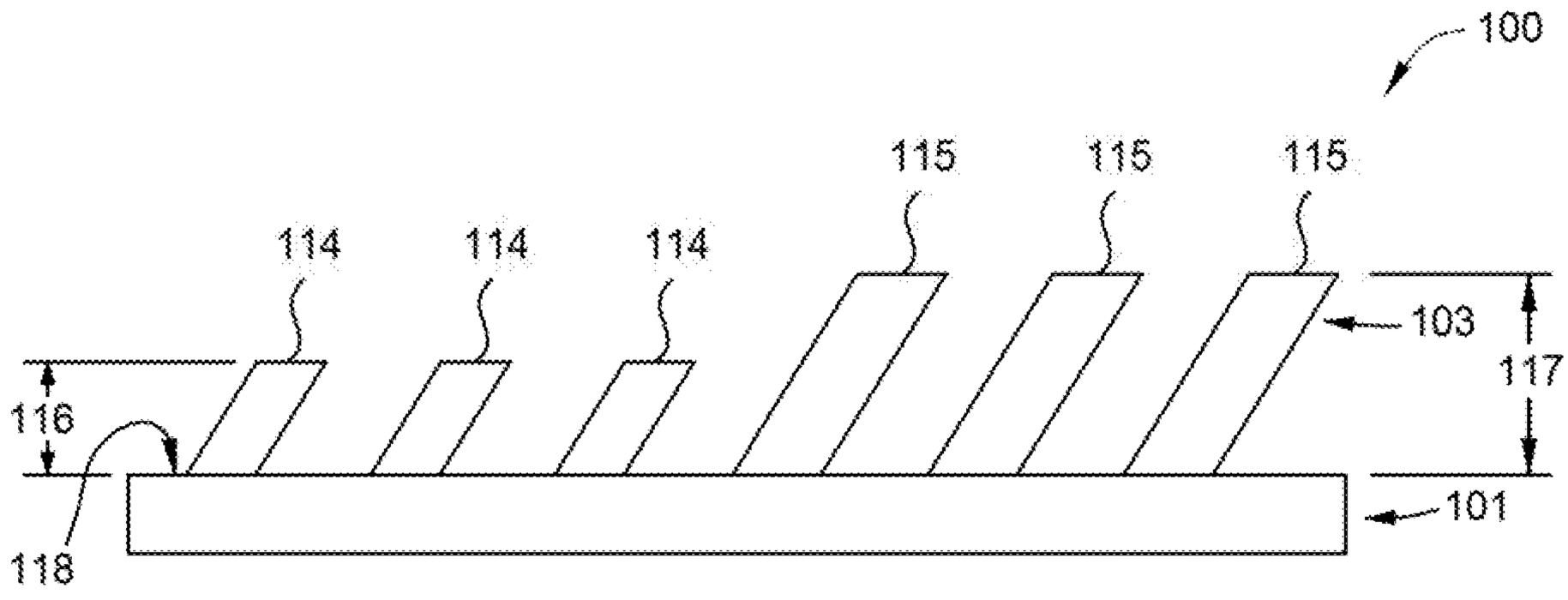

100
115
115
115
114
114
114
103
117
116
101
118

FIG. 1B

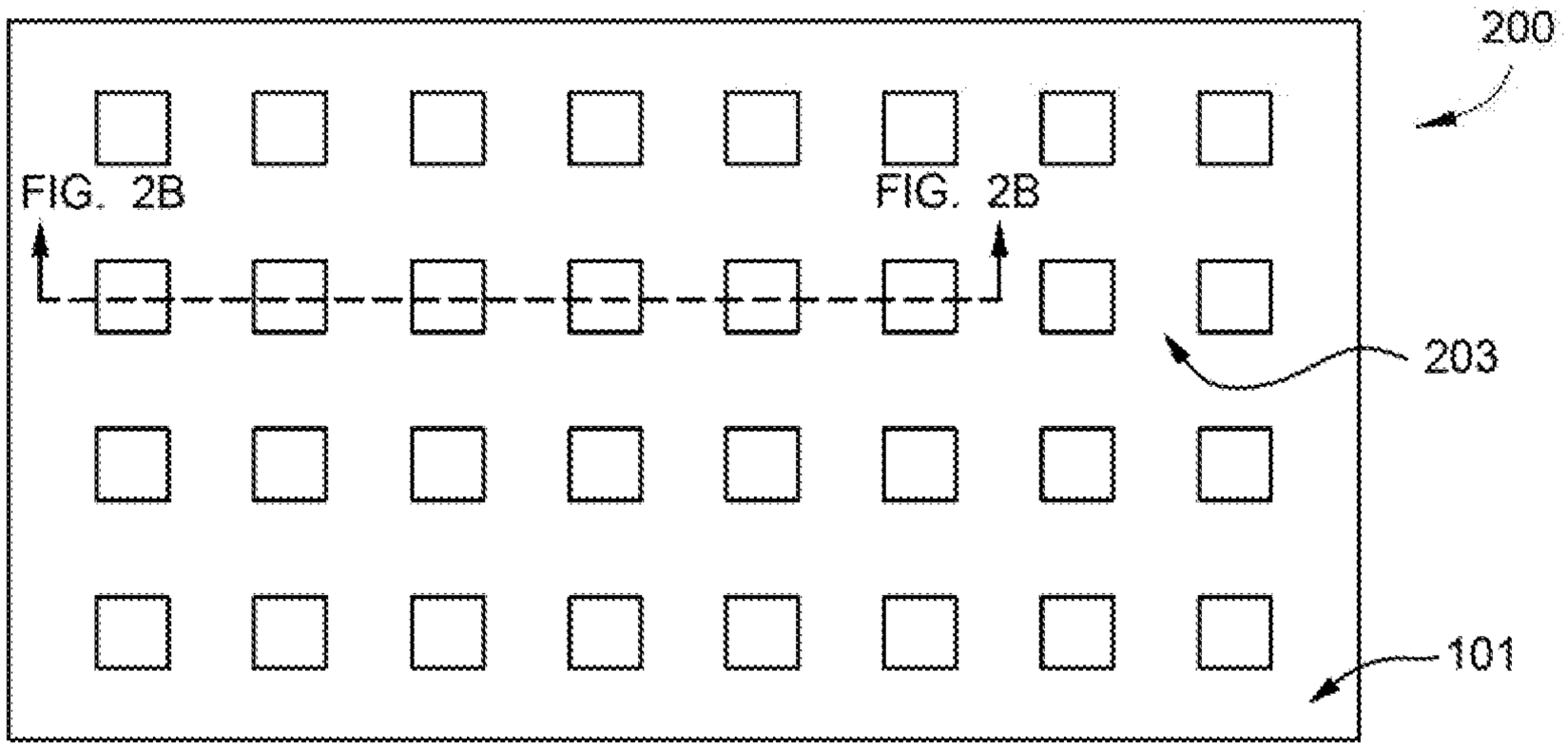

200
FIG. 2B
FIG. 2B
203
101

FIG. 2A

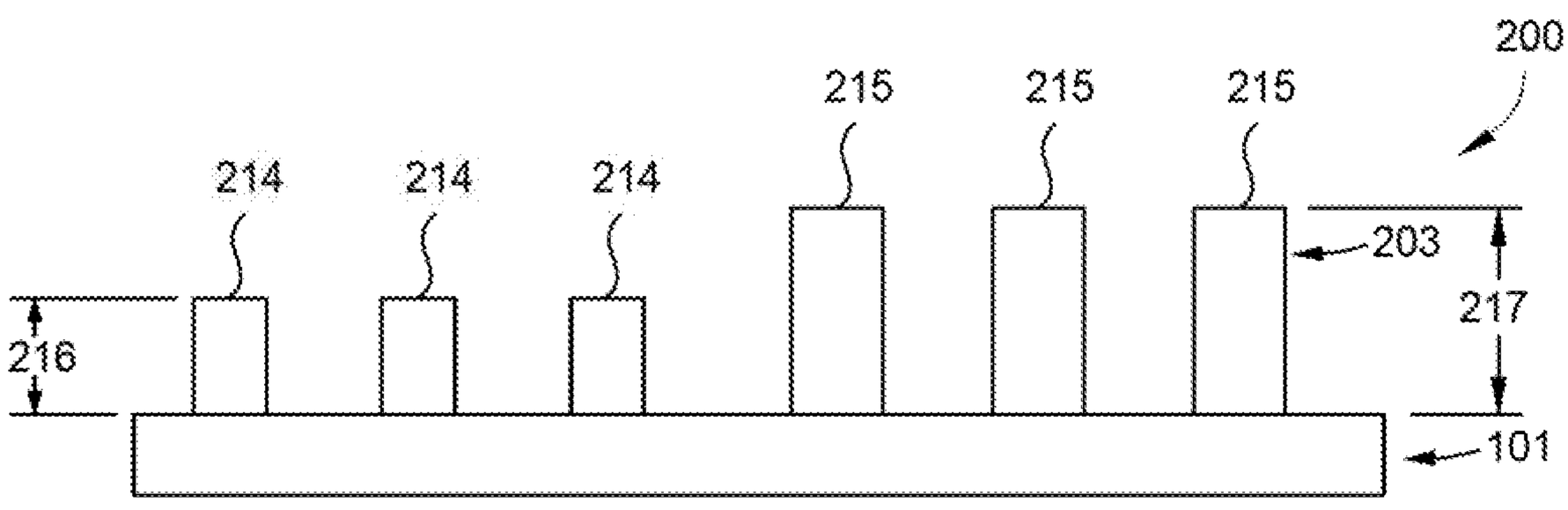

200
215
215
215
214
214
214
203
217
216
101

FIG. 2B

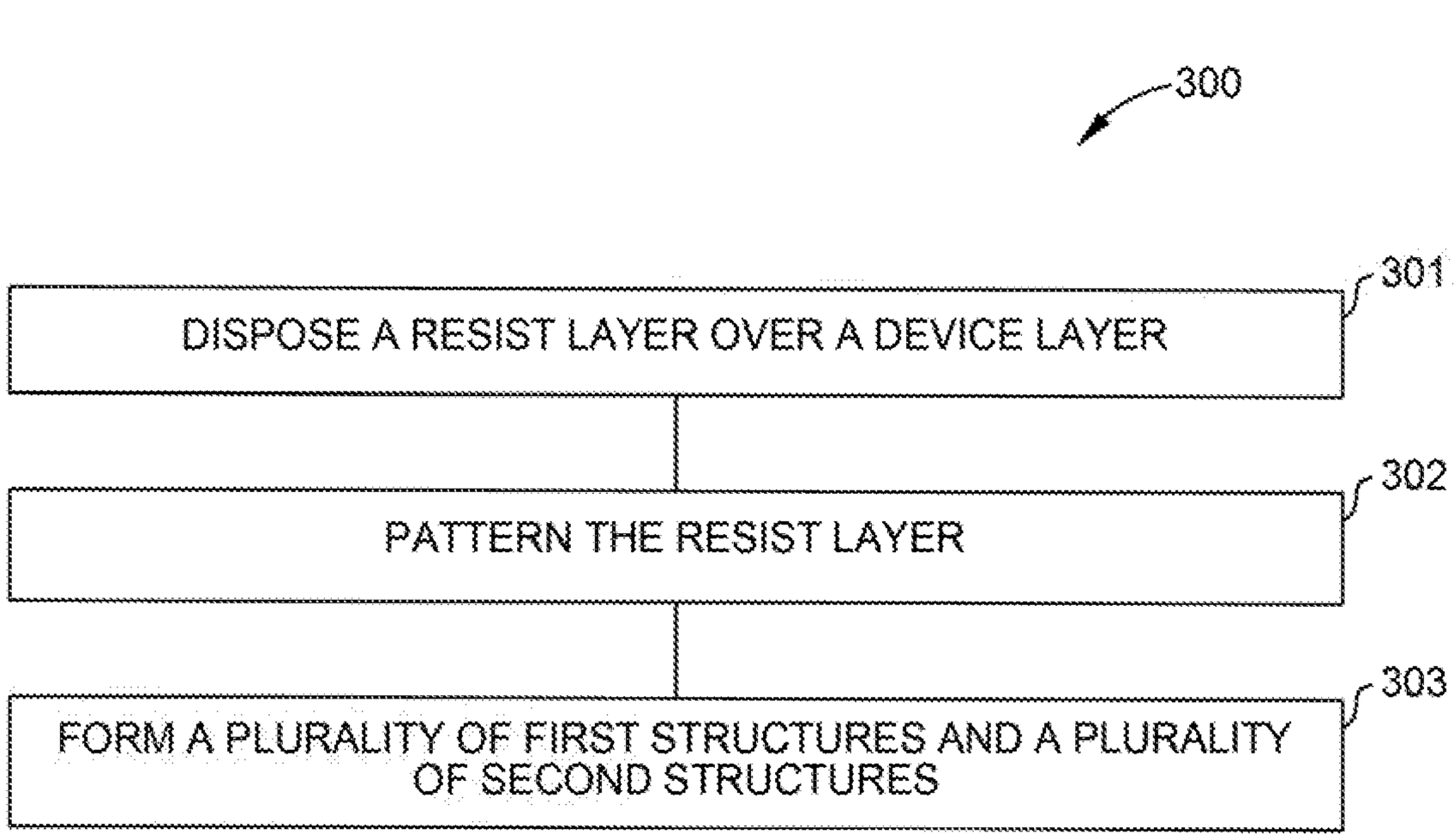

300
DISPOSE A RESIST LAYER OVER A DEVICE LAYER
301
PATTERN THE RESIST LAYER
302
FORM A PLURALITY OF FIRST STRUCTURES AND A PLURALITY OF SECOND STRUCTURES
303

FIG. 3

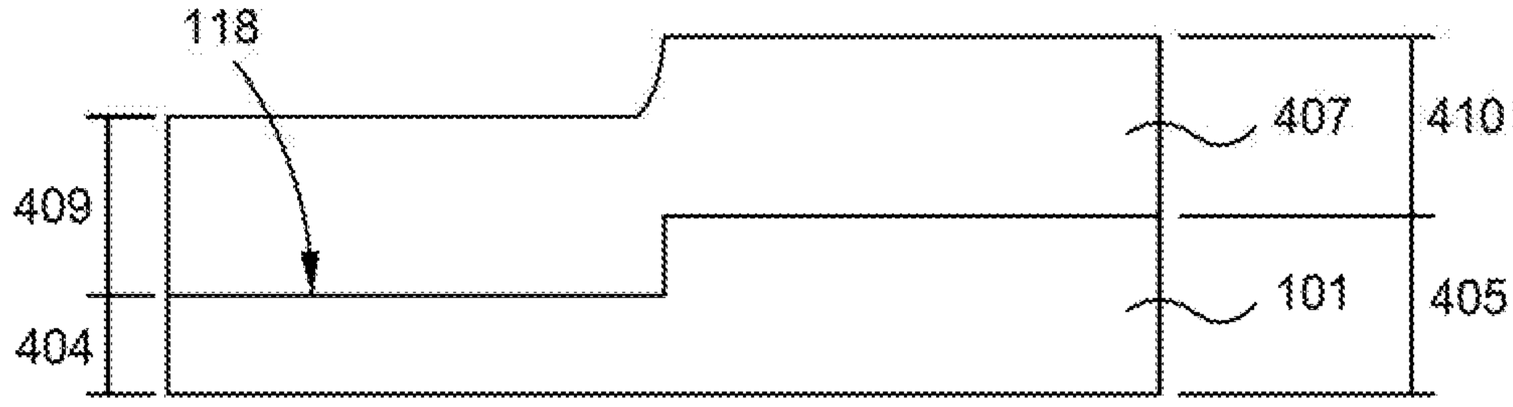


FIG. 4A

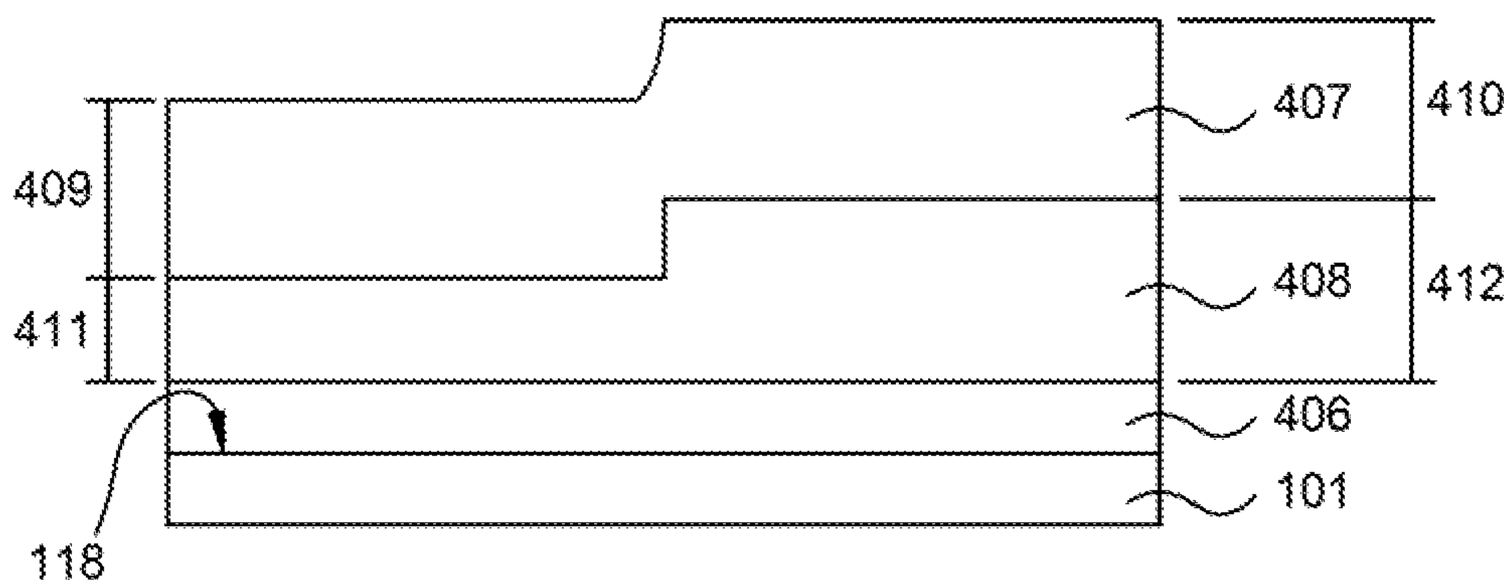


FIG. 4B

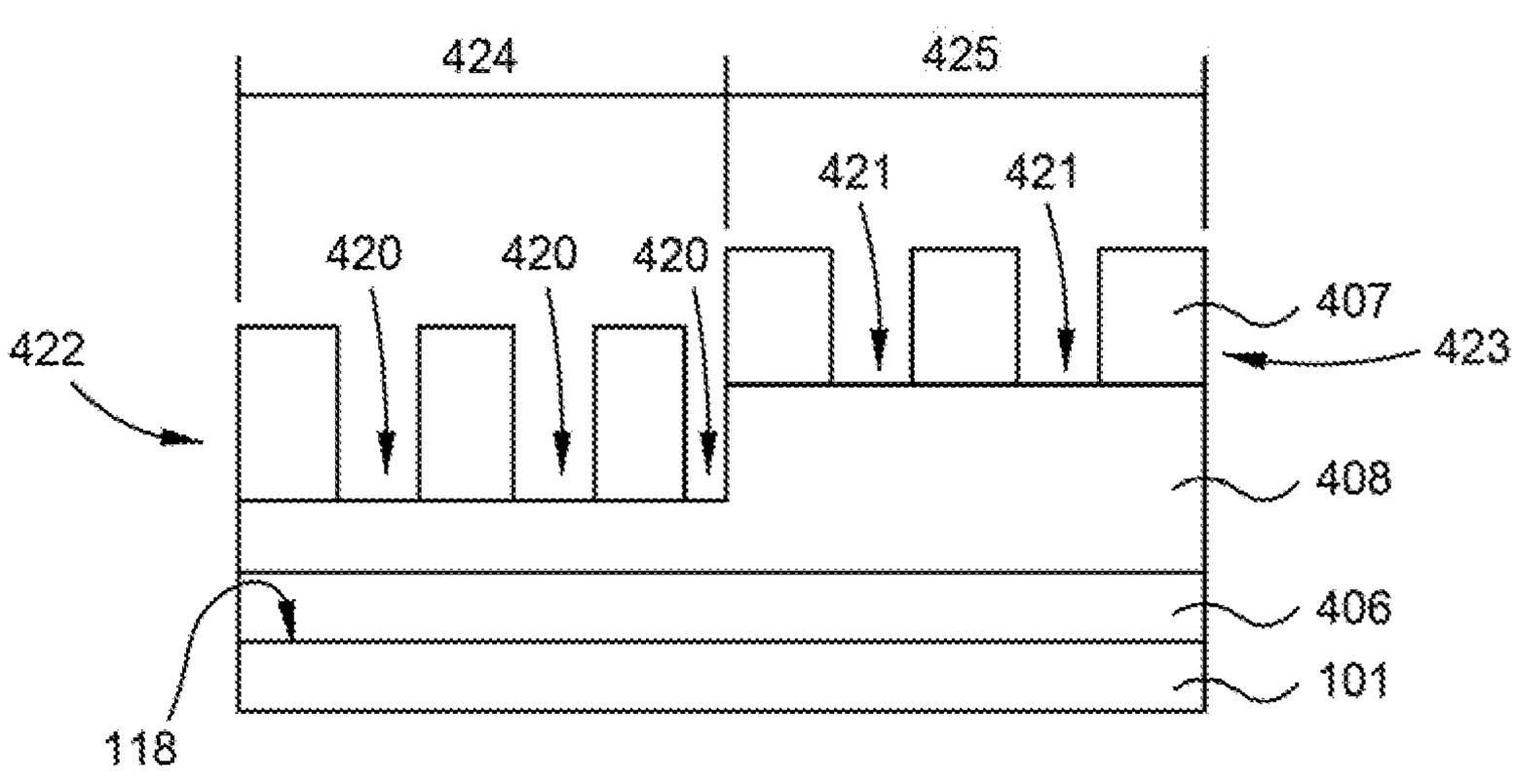


FIG. 4C

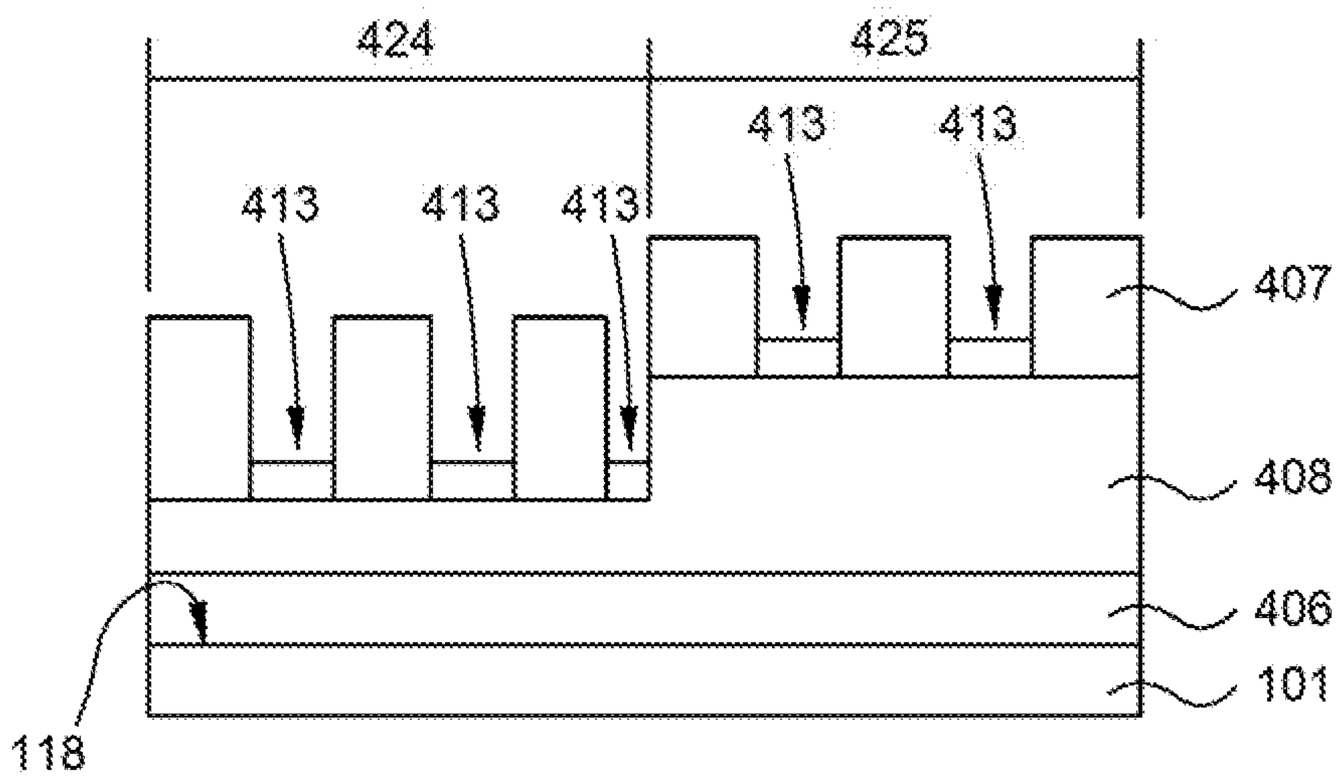

424
425
413
413
413
413
413
407
408
406
101
118

FIG. 4D

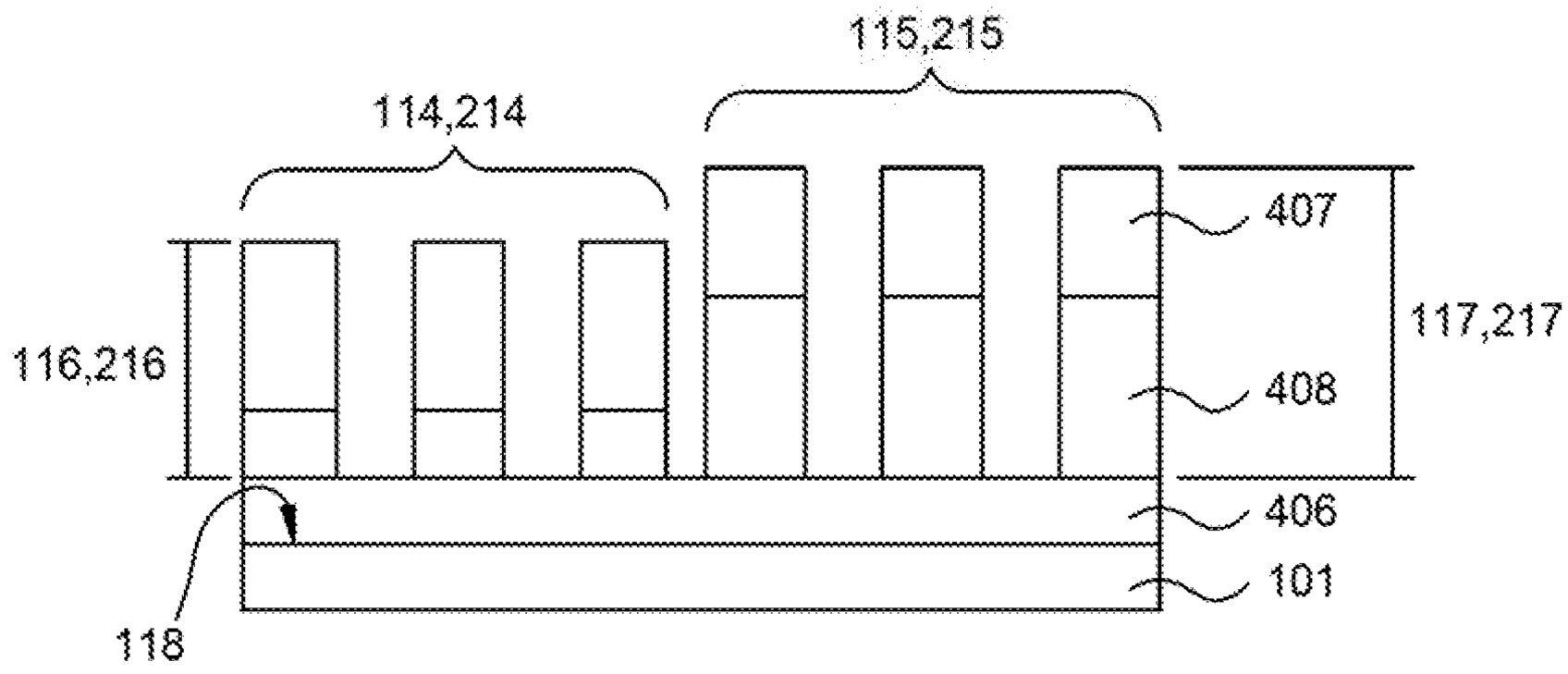

115,215
114,214
407
117,217
116,216
408
406
101
118

FIG. 4E

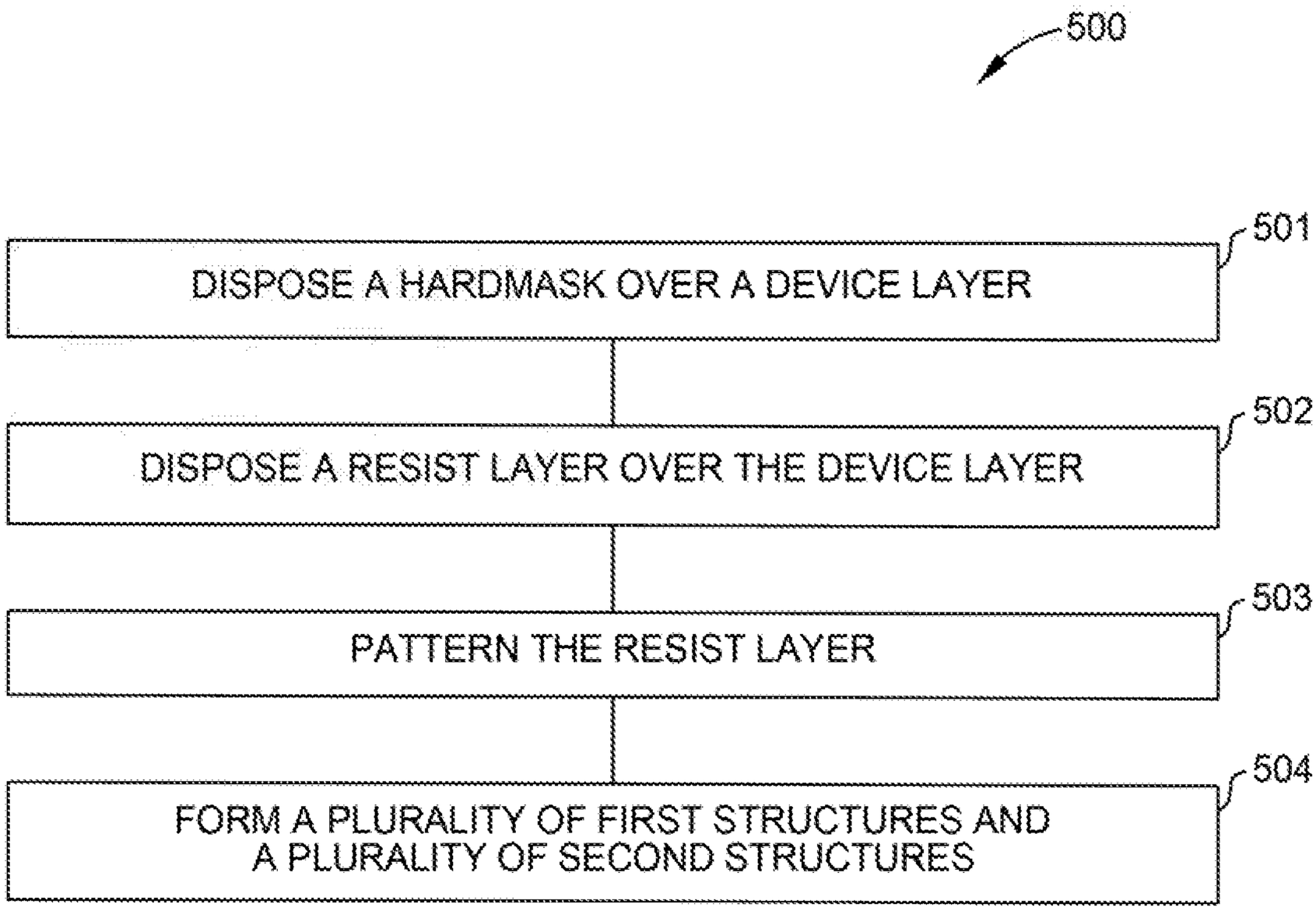

500
DISPOSE A HARDMASK OVER A DEVICE LAYER
501
DISPOSE A RESIST LAYER OVER THE DEVICE LAYER
502
PATTERN THE RESIST LAYER
503
FORM A PLURALITY OF FIRST STRUCTURES AND A PLURALITY OF SECOND STRUCTURES
504

FIG. 5

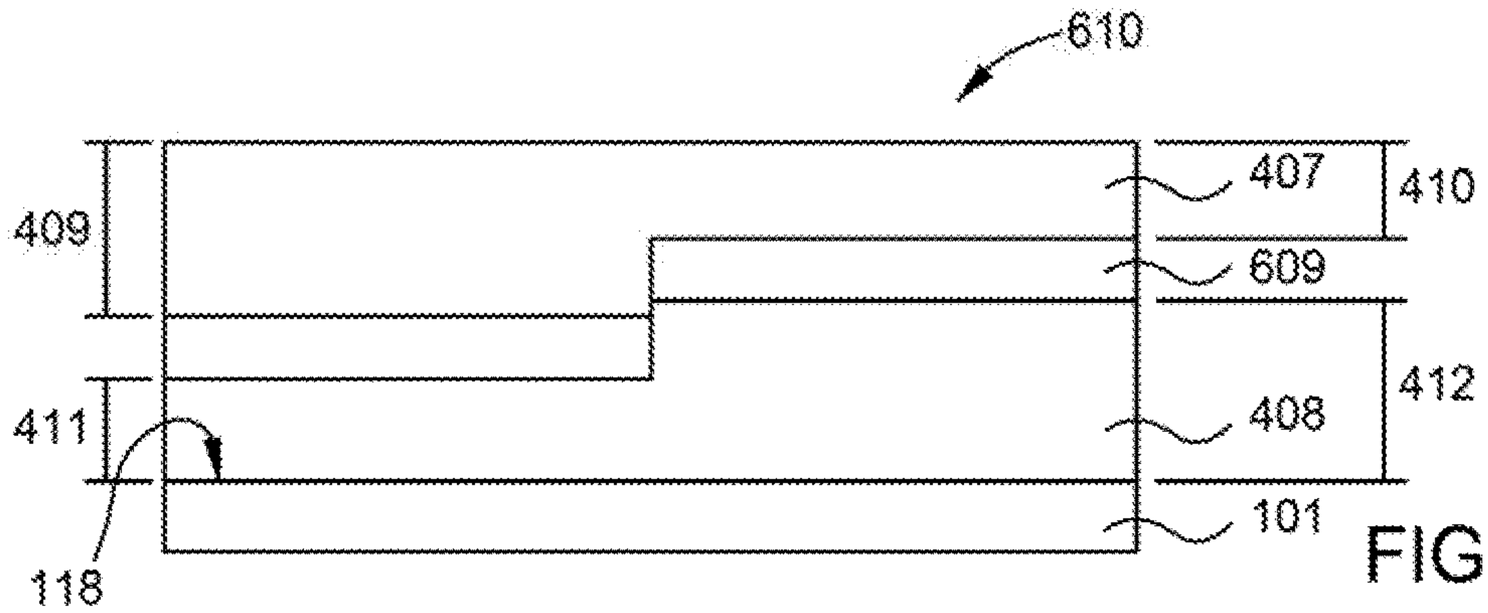


FIG. 6A

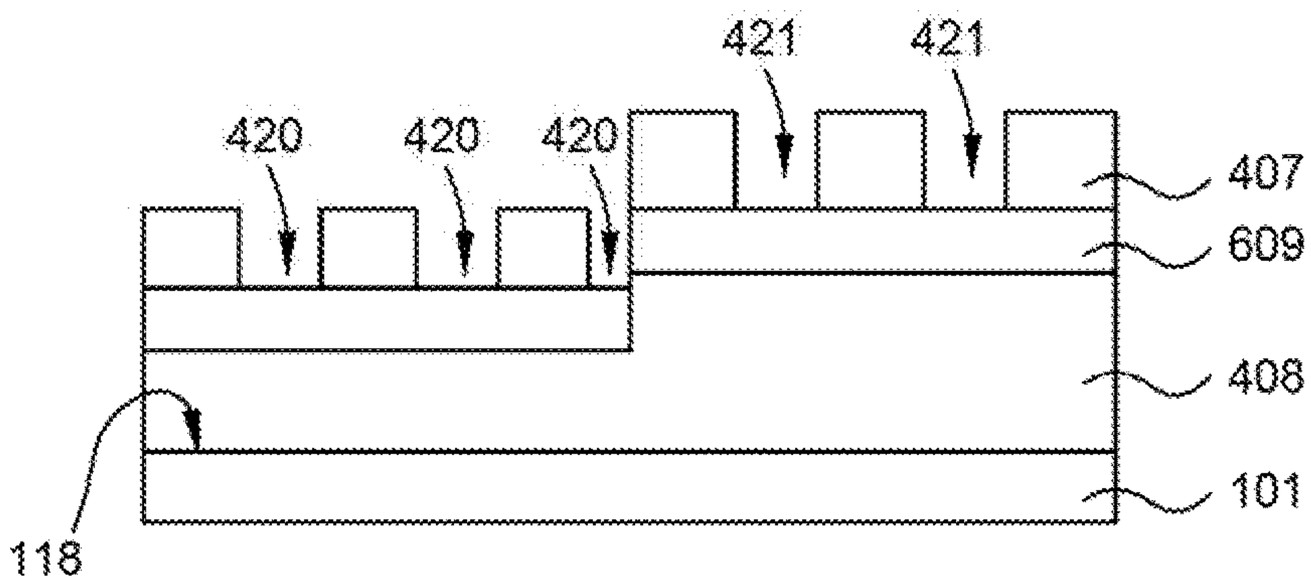


FIG. 6B

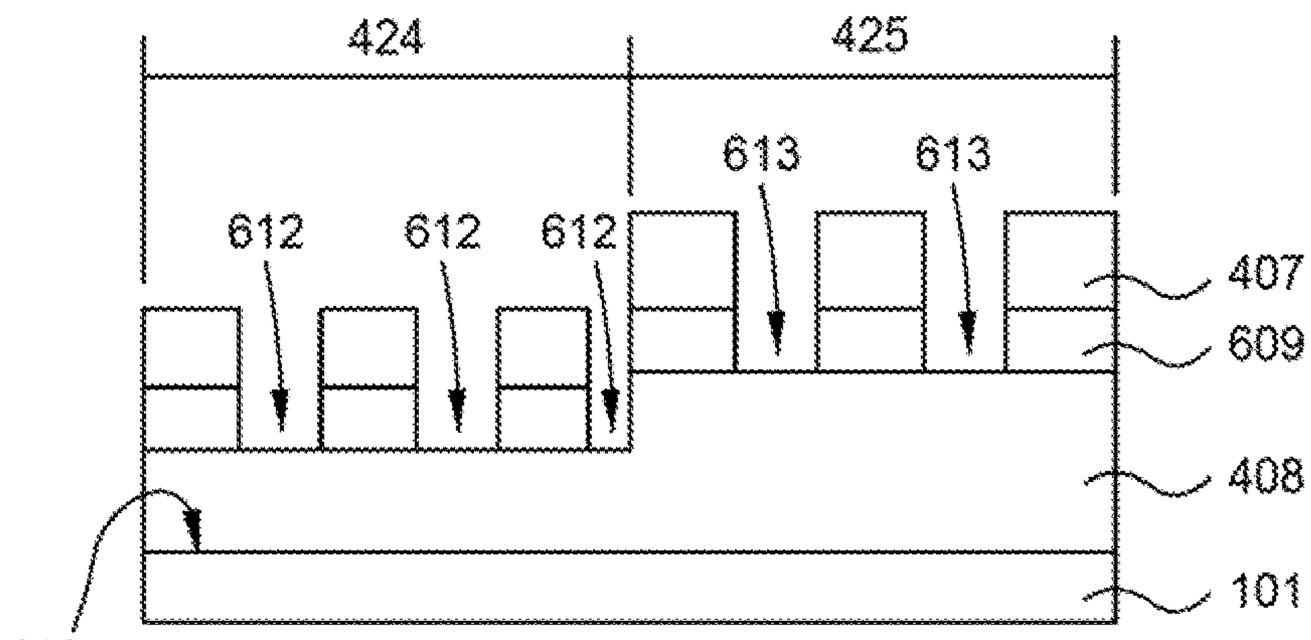


FIG. 6C

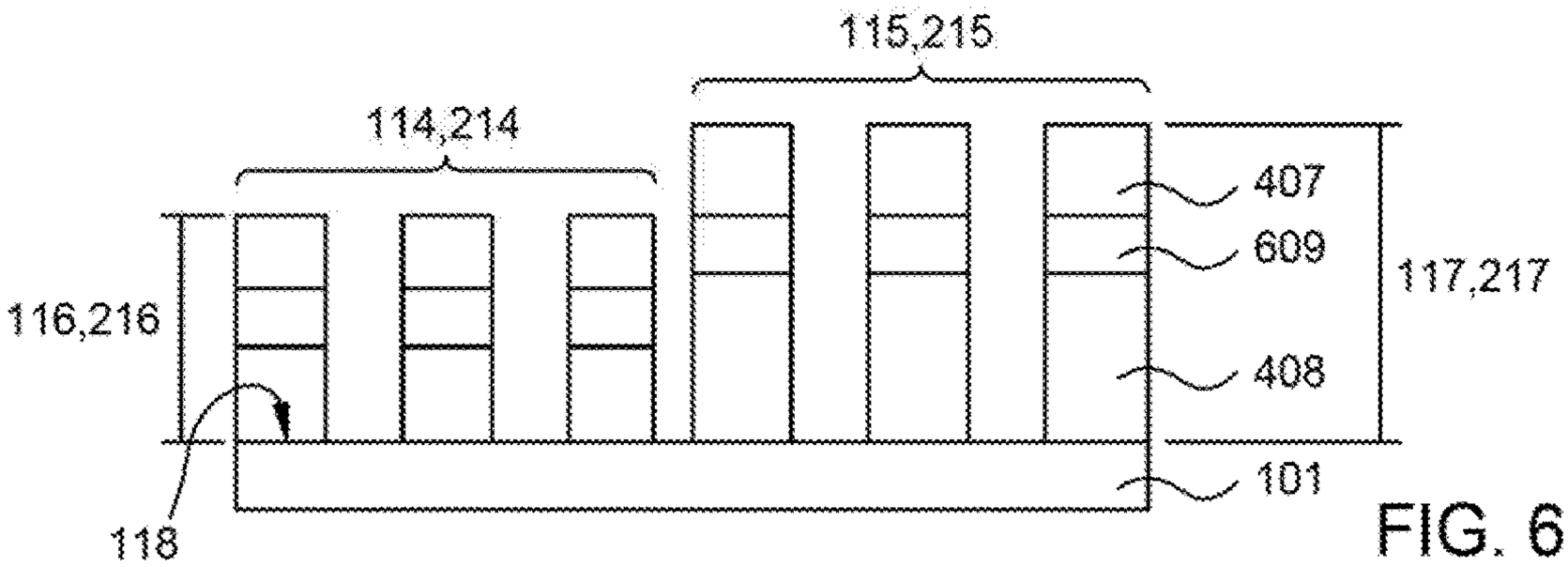


FIG. 6D

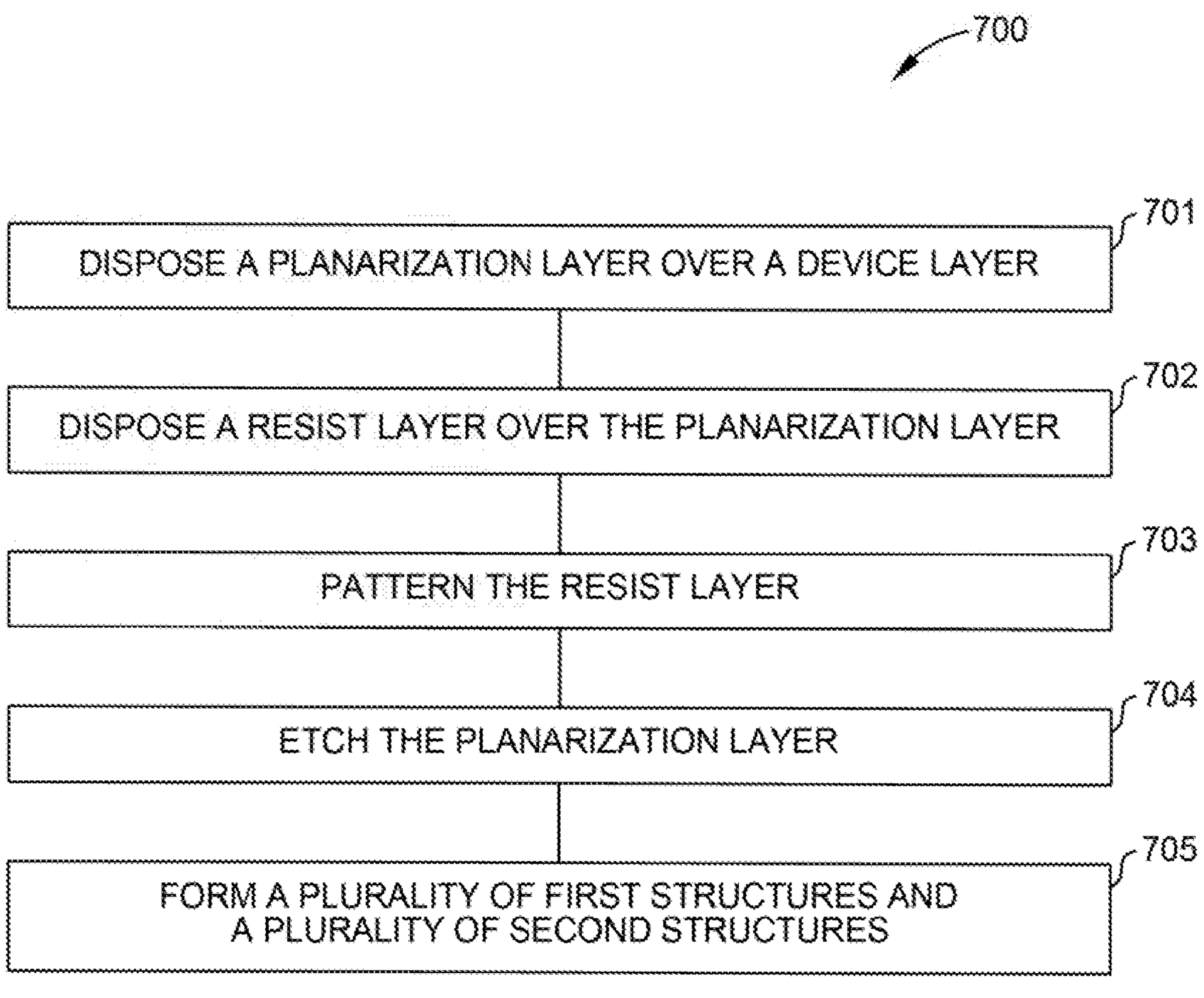

700
DISPOSE A PLANARIZATION LAYER OVER A DEVICE LAYER
701
DISPOSE A RESIST LAYER OVER THE PLANARIZATION LAYER
702
PATTERN THE RESIST LAYER
703
ETCH THE PLANARIZATION LAYER
704
FORM A PLURALITY OF FIRST STRUCTURES AND A PLURALITY OF SECOND STRUCTURES
705

FIG. 7

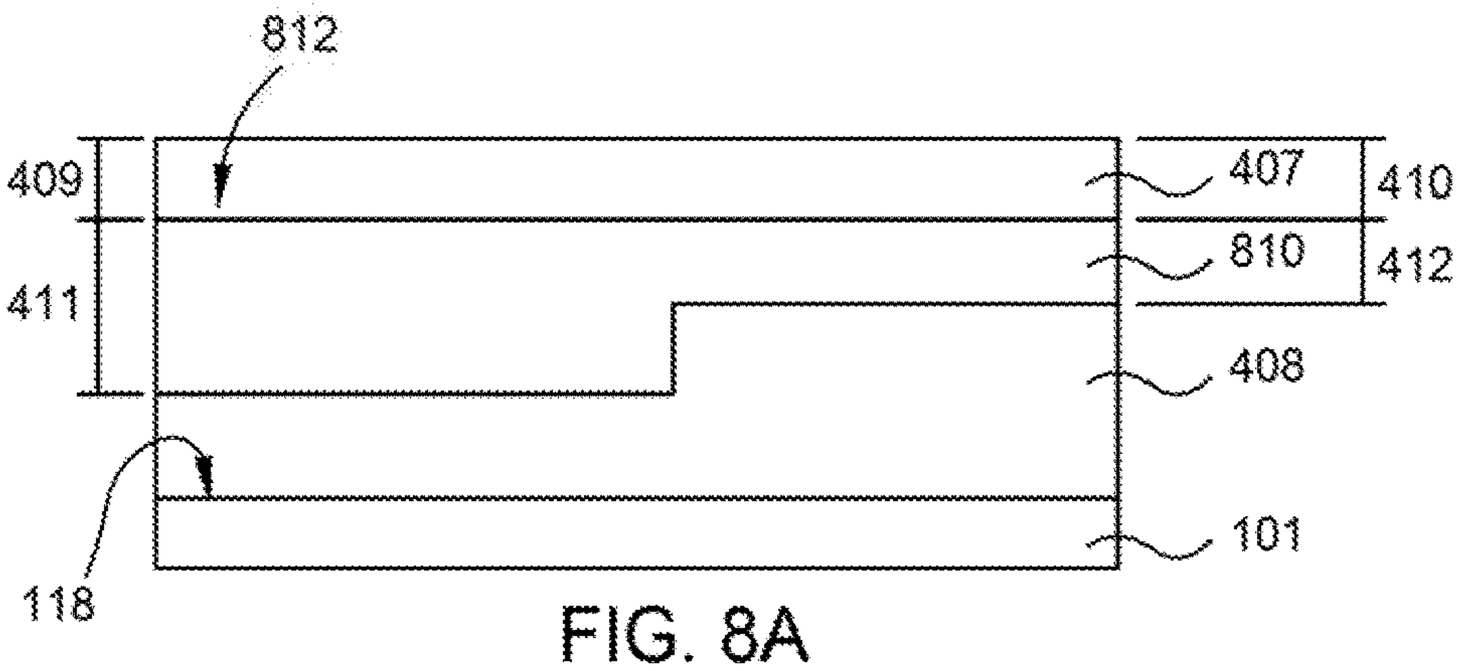


FIG. 8A

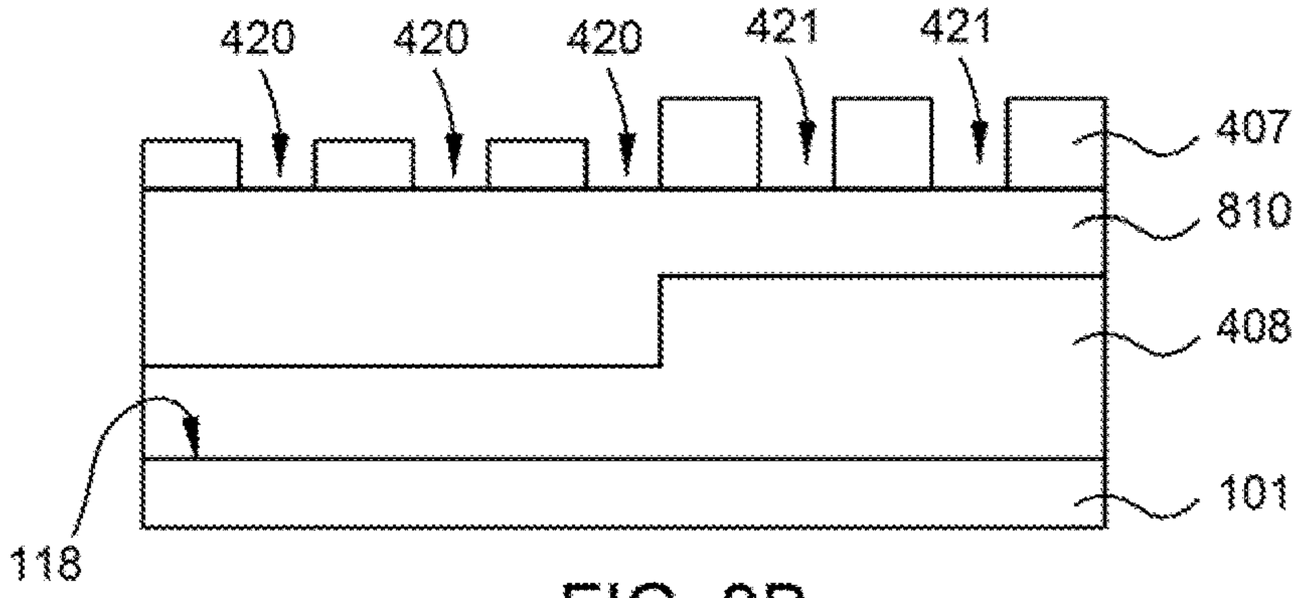


FIG. 8B

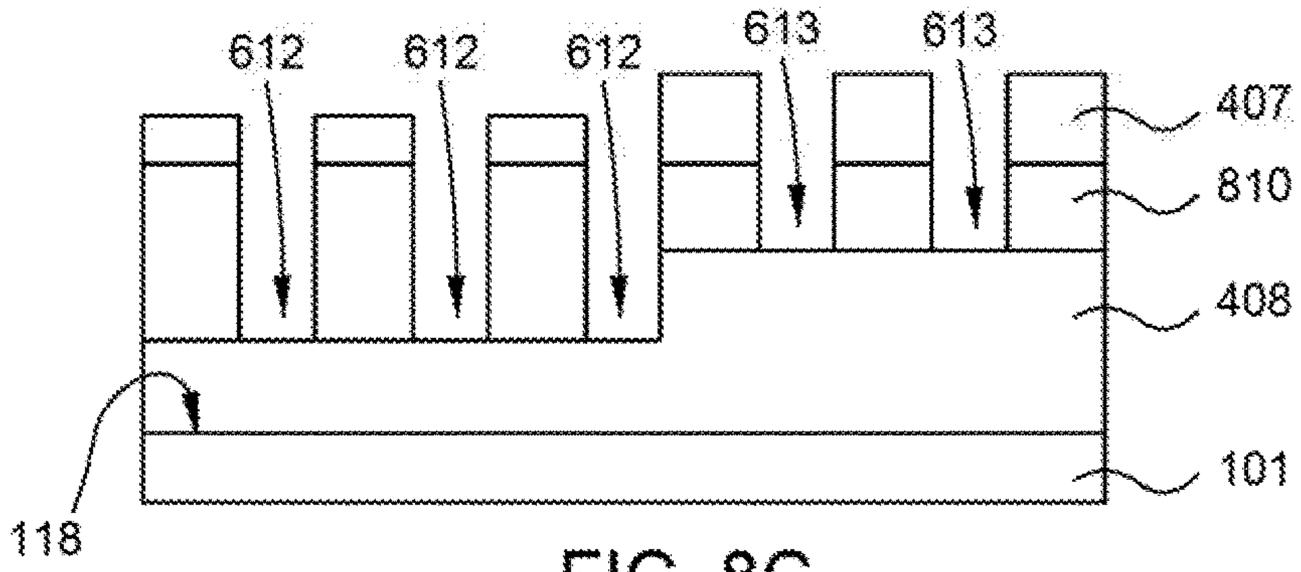


FIG. 8C

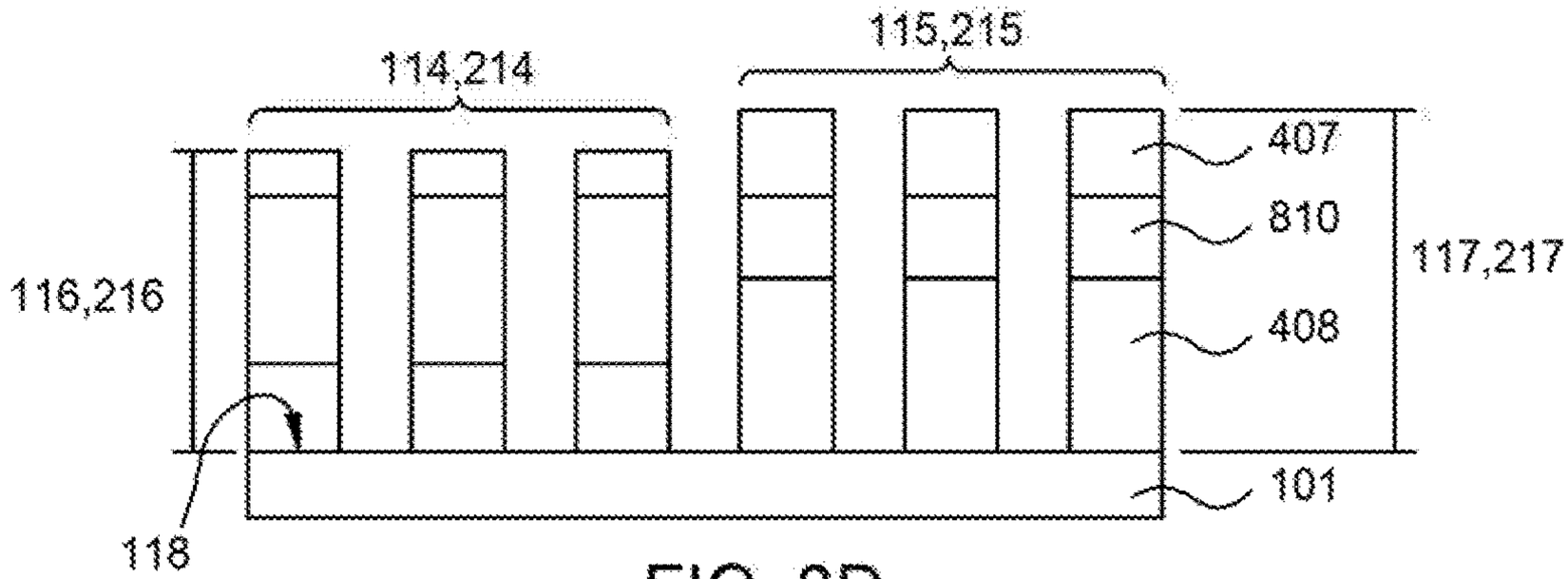


FIG. 8D

PATTERNING OF MULTI-DEPTH OPTICAL DEVICES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Ser. No. 62/832,807, filed on Apr. 11, 2019, which herein is incorporated by reference.

BACKGROUND

Field

[0002] Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein provide for patterning multi-depth layers for the fabrication of optical devices.

Description of the Related Art

[0003] Optical devices may be used to manipulate the propagation of light by spatially varying structural parameters (e.g., shape, size, orientation) of structures of the optical devices formed on a substrate. The optical devices provide a spatially varying optical response that molds optical wavefronts as desired. These structures of the optical devices alter light propagation by inducing localized phase discontinuities (i.e., abrupt changes of phase over a distance smaller than the wavelength of the light). These structures may be composed of different types of materials, shapes, or configurations on the substrate and may operate based upon different physical principles.

[0004] Fabricating optical devices requires forming structures from a device layer disposed on the substrate. However, the desired properties of an optical device to be fabricated may necessitate structures having various depths. Forming structures with various depths from may require patterning multiple layers disposed adjacently over the substrate. Accordingly, what is needed in the art are methods for patterning of multi-depth layers for the fabrication of optical devices.

SUMMARY

[0005] Methods for patterning of multi-depth layers for the fabrication of optical devices are provided. In one embodiment, a method is provided that includes disposing a resist layer over a device layer disposed over a top surface of a substrate, the device layer having a first portion having a first height from the top surface of the substrate and a second portion having a second height from the top surface of the substrate, patterning the resist layer to form a first resist layer pattern having a plurality of first openings formed therein over the first portion of the device layer and form a second resist layer pattern having a plurality of second openings formed therein over the second portion of the device layer, and etching exposed portions of the device layer defined by the plurality of first openings and the plurality of second openings, wherein the plurality of first openings in the first resist layer pattern are configured to form at least a portion of a plurality of first structures within the optical device, and the first structures have a first depth relative to the top surface of the substrate, and the plurality of second openings in the second resist layer pattern are configured to form at least a portion of a plurality of second structures within the optical device, and the second structures have a second depth relative to the top surface of the substrate.

[0006] In another embodiment, a method is provided that includes disposing a hardmask over a device layer disposed over a top surface of a substrate, the device layer having a first portion having a first height from the top surface of the substrate and a second portion having a second height from the top surface of the substrate, disposing a resist layer over the hardmask, the resist layer having a top surface parallel to the top surface of the substrate, patterning the resist layer to form a first resist layer pattern having a plurality of first openings formed therein over the first portion of the device layer and form a second resist layer pattern having a plurality of second openings formed therein over the second portion of the device layer, etching exposed portions of the hardmask defined by the plurality of first openings and the plurality of second openings to expose unmasked first device layer segments of the first portion of the device layer and expose unmasked second device layer segments of the second portion of the device layer, and etching the first device layer segments and the second device layer segments, wherein the first device layer segments are configured to form at least a portion of a plurality of first structures within the optical device, and the first structures have a first depth relative to the top surface of the substrate and the second device layer segments are configured to form at least a portion of a plurality of second structures within the optical device, and the second structures have a second depth relative to the top surface of the substrate.

[0007] In yet another embodiment, a method is provided that includes disposing a planarization layer over a device layer disposed over a top surface of a substrate, the device layer having a first portion having a first height from the top surface of the substrate and a second portion having a second height from the top surface of the substrate, disposing a resist layer over the planarization layer, patterning the resist layer to form a first resist layer pattern having a plurality of first openings formed therein over the first portion of the device layer and form a second resist layer pattern having a plurality of second openings formed therein over the second portion of the device layer, etching exposed portions of the planarization layer defined by the plurality of first openings and the plurality of second openings to expose unmasked first device layer segments of the first portion of the device layer and expose unmasked second device layer segments of the second portion of the device layer, and etching the first device layer segments and the second device layer segments, wherein the first device layer segments are configured to form at least a portion of a plurality of first structures within the optical device, and the first structures have a first depth relative to the top surface of the substrate, and the second device layer segments are configured to form at least a plurality of second structures within the optical device, and the second structures have a second depth relative to the top surface of the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] So that the manner in which the above recited structures 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.

[0009] FIG. **1**A is a schematic, perspective view of an optical device according to one embodiment.

[0010] FIG. **1**B is a schematic, cross-sectional view of the optical device of FIG. **1**A.

[0011] FIG. **2**A is a schematic, perspective view of an optical device according to one embodiment.

[0012] FIG. **2**B is a schematic, cross-sectional view of the optical device of FIG. **2**A.

[0013] FIG. **3** is a flow diagram of a method for forming an optical device according to an embodiment.

[0014] FIGS. **4**A-**4**E are schematic, cross-sectional views of a substrate during a method of forming an optical device according to an embodiment.

[0015] FIG. **5** is a flow diagram of a method for forming an optical device according to an embodiment.

[0016] FIGS. **6**A-**6**D are schematic, cross-sectional views of a substrate during a method of forming an optical device according to an embodiment.

[0017] FIG. **7** is a flow diagram of a method for forming an optical device according to an embodiment.

[0018] FIGS. **8**A-**8**D are schematic, cross-sectional views of a substrate during a method of forming an optical device according to an embodiment.

[0019] 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 structures of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0020] Embodiments of the present disclosure relate to patterning multi-depth layers for the fabrication of optical devices.

[0021] FIG. **1**A is a schematic, perspective view of an optical device **100**. In one embodiment, the optical device **100** is a waveguide combiner, for example an augmented reality waveguide combiner. It is to be understood that the optical device **100** described below is an exemplary waveguide combiner. The optical device **100** includes a substrate **101**, a first grating **102** defined by a plurality of structures **103**, and a second grating **105** defined by a plurality of structures **106**. In one embodiment, the structures **103** and the structures **106** are nanostructures having sub-micron critical dimensions, e.g., nano-sized critical dimensions.

[0022] FIG. **1**B is a schematic, cross-sectional view of the optical device **100** according to FIG. **1**A. The optical device **100** includes a plurality of structures **103** having two or more depths. As shown in FIG. **1**B, a plurality of first structures **114** have a first depth **116** to a top surface **118** of the substrate **101**, and a plurality of second structures **115** have a second depth **117** to the top surface **118** of the substrate **101**. The first depth **116** and the second depth **117** are different. For example, as shown in FIG. **1**B, the first depth **116** is less than the second depth **117**. In one embodiment, the structures **103** are at an angle with regard to the top surface **118** of the substrate **101**. In another embodiment, the structures **103** are perpendicular to the top surface **118** of the substrate **101**.

[0023] FIG. **2**A is a schematic, perspective view of an optical device **200** having one or more structures **203** according to embodiments described herein. In some embodiments, the optical device **200** is a flat optical device, such as a metasurface. The one or more structures **203** are disposed on the substrate **101**. While FIG. **2**A depicts the one or more structures **203** as having square or rectangular cross-sections, the cross-sections of the one or more structures **203** may have other shapes including, but not limited to, circular, triangular, and/or irregular shaped cross-sections. In one embodiment, the structures **203** are nanostructures having sub-micron critical dimensions, e.g., nano-sized critical dimensions.

[0024] FIG. **2**B is a schematic, cross-sectional view of the optical device **200** according to FIG. **2**A. The optical devices **200** includes one or more structures **203**, such as one or more first structures **214** and one or more second structures **215** disposed on the substrate **101**. The one or more first structures **214** have a first depth **216** to the top surface **118** of the substrate **101**. The one or more second structures **215** have a second depth **217** to the top surface **188** of the substrate **101**. The first depth **216** and the second depth **217** are different. For example, as shown in FIG. **2**B, the first depth **216** is less than the second depth **217**. In one embodiment, the structures **203** are at an angle with regard to the top surface **118** of the substrate **101**. In another embodiment, the structures **203** are perpendicular to the top surface **118** of the substrate **101**.

[0025] The substrate **101** may be selected to transmit a suitable amount of light of a desired wavelength or wavelength range, such as one or more wavelengths in the infrared region to UV region (i.e., from about 700 to about 1500 nanometers). Without limitation, in some embodiments, the substrate **101** is configured such that the substrate **101** transmits greater than or equal to about 50%, 60%, 70%, 80%, 90%, 95%, 99%, to UV region of the light spectrum. The substrate **101** may be formed from any suitable material, provided that the substrate **101** can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the optical devices. In some embodiments, the material of substrate **101** has a refractive index that is relatively low, as compared to the refractive index of the device material. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, and combinations thereof. In some embodiments, the substrate **101** includes a transparent material. In one embodiment, the substrate **101** is transparent with absorption coefficient smaller than 0.001. Suitable examples may include an oxide, sulfide, phosphide, telluride, or combinations thereof.

[0026] In some embodiments, the optical devices **100**, **200** described herein include first structures **114**, **214** having first depths **116**, **216** and second structures **115**, **215** having second depths **117**, **217** disposed in the substrate **101**. In the embodiments described herein of the methods **300**, **500**, and **700** for the forming optical devices **100**, **200**, the substrate **101** has a first height **404** and a second height **405** (shown in FIG. **4**A). The first height **404** corresponds to the first depth **116**, **216** of the first structures **114**, **214** to be formed, and the second height **405** corresponding to the second depth **117**, **217** of the plurality of second structures **115**, **215** to be formed in the substrate **101**.

[0027] In other embodiments, the optical devices **100**, **200** described herein include first structures **114**, **214** having first depths **116**, **216** and second structures **115**, **215** having

second depths **117**, **217** are disposed over the substrate **101**. The first structures **114**, **214** and the second structures **115**, **215** are formed from a device layer **408**. Prior to the methods **300**, **500**, and **700**, the device layer **408** has a first height **411** and a second height **412**. The first height **411** corresponds to the first depth **116**, **216** of the first structures **114**, **214** to be formed, and the second height **412** corresponds to the second depth **117**, **217** of the plurality of second structures **115**, **215** to be formed.

[0028] FIG. **3** is a flow diagram of a method **300** for forming a portion of an optical device **100**, **200** according to embodiments described herein. FIGS. **4**A-**4**E are schematic, cross-sectional views of the substrate **101** during a method of forming a portion of an optical device **100** or an optical device **200** according to an embodiment. The portion may correspond to one grating, such as the first grating **102** or second grating **105**, or the portion may correspond to the entirety of the optical device **100** or optical device **200**.

[0029] FIG. **4**A illustrates an embodiment, in which a resist layer **407** is disposed on the substrate **101**. In one embodiment, the substrate **101** is patterned, the substrate **101** having first height **404** and second height **405** for achieving first structures **114**, **214** and second structures **115**, **215** of various heights. FIG. **4**B illustrates an embodiment in which the resist layer **407** is disposed on a device layer **408** and the device layer **408** is disposed on the top surface **118** of the substrate **101**. In one embodiment, the device layer **408** is patterned, the device layer having first height **411** and second height **412** for achieving first structures **114**, **214** and second structures **115**, **215** of various heights.

[0030] In one embodiment, the resist layer **407** includes a silicon-containing material. In another embodiment, the resist layer **407** includes an organic material. The resist layer **407** is deposited on the substrate **101** through any suitable method, such as a liquid material pour casting process, a spin-on coating process, a liquid spray coating process, a dry powder coating process, a screen printing process, a doctor blading process, a physical vapor deposition (PVD) process, a chemical vapor deposition (CVD) process, a flowable CVD (FCVD) process, or an atomic layer deposition (ALD) process. The thickness of the resist layer **407** is selected in order to tune the etch process and the resulting critical dimensions of the plurality of structures **103**. For example, a greater thickness of the resist layer **407** can result in smaller critical dimensions of the plurality of structures **103**. In one embodiment, the thickness of the resist layer **407** ranges from about 50 nm to about 300 nm. In one embodiment, the resist layer **407** has a first thickness **409** and a second thickness **410**. The first thickness **409** may be greater or less than the second thickness **410**. The first thickness **409** will result in the first structures **114**, **214** having the first depths **116**, **216**. The second thickness **410** will result in the second structures **115**, **215** having the second depths **117**, **217**.

[0031] According to one embodiment, the device layer **408** includes, but is not limited to, one or more of titanium dioxide (TiO_2), zinc oxide (ZnO), tin dioxide (SnO_2), aluminum-doped zinc oxide (AZO), fluorine-doped tin oxide (FTO), cadmium stannate (tin oxide) (CTO), niobium oxide (Nb_2O_5), and zinc stannate (tin oxide) ($SnZnO_3$), silicon nitride (Si_3N_4), and amorphous silicon (a-Si) containing materials. In one embodiment, the height of the device layer **408** ranges from about 20 nm to about 200 nm. As shown in FIG. **3**, the resist layer **407** is disposed on the device layer **408** at step **301**. The device layer **408** includes a first portion **424** having first height **411** from the surface of the substrate and a second portion **425** having second height **412** from the surface of the substrate. The first height **411** corresponds to the first structures **114**, **214** to be formed, and the second height **412** corresponds to the second structures **115**, **215** to be formed.

[0032] The embodiment of FIG. **4**A illustrates a 1:1 etch rate in which the resist layer **407** is etched at approximately the same rate as the device layer **408**. The embodiment of FIG. **4**D illustrates an etch rate other than 1:1. At step **301**, as shown in FIG. **4**A, a resist layer **407** is disposed over the device layer **408**, the device layer **408** corresponding to the plurality of first structures **114**, **214** and the plurality of second structures **115**, **215** to be formed. In one embodiment, as shown in FIG. **4**B, the resist layer **407** is disposed over the substrate **101**.

[0033] At step **302**, the resist layer **407** is patterned to expose unmasked portions of the device layer **408** as depicted in FIGS. **4**C and **4**D. Patterning the resist layer **407** includes forming a first resist layer pattern **422** having a plurality of first openings **420** formed therein over the first portion **424** of the device layer **408**, and forming a second resist layer pattern **423** having a plurality of second openings **421** formed therein over the second portion **425** of the device layer **408**. The resist layer **407** may be patterned by processes including, but not limited to, nanoimprint lithography, photoimprint lithography, or any suitable process to expose unmasked portions of the device layer **408**. In the embodiment depicted in FIG. **4**D, a residual layer **413** remains after the resist layer **407** is patterned. In one embodiment, the residual layer **413** is removed through a dry etch process.

[0034] FIG. **4**D illustrates an embodiment, in which an etch stop layer **406** is disposed on the substrate **101**. The etch stop layer **406** prevents over-etching into the substrate **101**. The etch stop layer **406** may be disposed by one or PVD, CVD, plasma-enhanced (PECVD), FCVD, ALD, and spin-on processes. The etch stop layer **406** is formed from any suitable material, provided that the etch stop layer **406** is resistant to the etching processes described herein. In one embodiment, the etch stop layer **406** includes a nitrogen-containing material. In one embodiment, the etch stop layer **406** is a non-transparent etch stop layer that is removed after the waveguide combiner is formed. In another embodiment, the etch stop layer **406** is a transparent etch stop layer. The etch stop layer **406** has a depth of about 5 nm to about 50 nm. Although an etch stop layer **406** is depicted herein, one or more embodiments without an etch stop layer **406** is contemplated.

[0035] At step **303** and as shown in FIGS. **4**C and **4**D, the exposed portions of the device layer **408** defined by the plurality of first openings **420** and the plurality of second openings **421** are etched to form the plurality of first structures **114**, **214** and the plurality of second structures **115**, **215**. The plurality of first openings **420** in the first resist layer pattern **422** are configured to form at least a portion of the plurality of first structures **114**, **214** within the optical device **100**, **200**. The plurality of second openings **421** in the second resist layer pattern **423** are configured to form at least a portion of the plurality of second structures **115**, **215** within the optical device **100**, **200**. The etch process may include, but is not limited to, at least one of ion implantation, ion beam etching (IBE), reactive ion etching (RIE), direc-

tional RIE, plasma etching, and thermal atomic layer etching. In some embodiments, the etch process utilizes oxidizing etch chemistries. In other embodiments, the etch process utilizes reducing etch chemistries. In one embodiment, the etch process utilizes one or more oxygen, nitrogen gas (N_2), SiO_2, chlorine, and ammonia (NH_3) containing gases. In another embodiment, a fluorine containing gas, such as fluoromethane (CH_3F), sulfur hexafluoride (SF_6), tetrafluoromethane (CF_4), fluoroform (CHF_3), and nitrogen trifluoride (NF_3), is used as an etchant. The fluorine containing gas is optionally delivered to a processing environment with a methane containing gas, such as methane (CH_4) and dichlorodifluoromethane (CCl_2F_2).

[0036] While FIG. **4**E depicts first structures **114**, **214** and second structures **115**, **215** formed in the device layer **408**, steps **301-303** are applicable to patterning the substrate **101**. In one embodiment, as shown in FIGS. **3** and **4**D, the device layer **408** is etched by the etch process to remove portions of the device layer **408** and form the first structures **114**, **214** and the second structures **115**, **215** in step **303**. In another embodiment, the substrate **101** is etched by the etch process to remove portions of the substrate **101** and form the first structures **114**, **214** and the second structures **115**, **215** in step **303**.

[0037] FIG. **5** is a flow diagram of a method **500** for forming a portion of an optical device **100**, **200** according to embodiments described herein. FIGS. **6**A-**6**D are schematic, cross-sectional views of the optical device **100**, **200** formed according to the method **500**. The portion of the optical device **100**, **200** may correspond to one grating, such as the first grating **102** or second grating **105**, or the portion may correspond to the entirety of the optical device **100** or optical device **200**.

[0038] At step **501**, the hardmask **609** is disposed on the device layer **408** as shown in FIG. **6**A. The hardmask **609** may be disposed over the device layer **408** by one or more liquid material pour casting, spin-on coating, liquid spray coating, dry powder coating, screen printing, doctor blading, PVD, CVD, PECVD, FCVD, ALD, evaporation, and sputtering processes. In one embodiment, the hardmask **609** is non-transparent and is removed after the optical device **100** or optical device **200** is formed. In another embodiment, the hardmask **609** is transparent. In some embodiments, the hardmask **609** includes any suitable imprint-resist material, for example chromium (Cr), silver (Ag), Si_3N_4, SiO_2, TiN, aluminum, and carbon containing materials.

[0039] At step **502**, the resist layer **407** is disposed on the hardmask **609**, and the device layer **408** corresponds to a plurality of first structures **114**, **214** and a plurality of second structures **115**, **215** to be formed. The device layer **408** has first height **411** and second height **412**. In one embodiment, the first thickness **409** and the second thickness **410** of the resist layer **407** are different such that the top surface **610** of the resist layer **407** is parallel to the top surface **118** of the substrate **101**. The top surface **610** of the resist layer **407** parallel to the top surface **118** of the substrate **101** provides a planarized surface to improve the uniformity of the patterning and/or etch process of steps **503** and **504**.

[0040] At step **503** and as shown in FIG. **6**B, the resist layer **407** is patterned to expose portions of the hardmask **609**. Patterning the resist layer **407** includes forming the first resist layer pattern **422** having the plurality of first openings **420** formed therein over the first portion **424** of the device layer **408**, and forming the second resist layer pattern **423** having the plurality of second openings **421** formed therein over the second portion **425** of the device layer **408**. At step **504** and as shown in FIG. **6**C, the exposed portions of the hardmask **609** are etched to expose unmasked first device layer segments **612** of the first portion **424** of the device layer **408** and to expose unmasked second device layer segments **613** of the second portion **425** of the device layer **408**. As shown in FIG. **6**D, the first device layer segments **612** and the second device layer segments **613** of the device layer **408** are etched to form the plurality of first structures **114**, **214** and the plurality of second structures **115**, **215**. The first device layer segments **612** are configured to form at least a portion of the plurality of first structures **114**, **214** within the optical device **100**, **200**. The second device layer segments **613** are configured to form at least a portion of the plurality of second structures **115**, **215** within the optical device **100**, **200**.

[0041] In one embodiment, the hardmask **609** is removed after the device layer **408** is etched. In another embodiment, the hardmask **609** remains on the device layer **408** after the device layer **408** is etched. While FIG. **6**D depicts first structures **114**, **214** and second structures **115**, **215** formed in the device layer **408**, steps **501-504** are applicable to patterning the substrate **101**. In one embodiment, as shown in FIGS. **5** and **6**D, the device layer **408** is etched by the etch process to remove portions of the device layer **408** and form the first structures **114**, **214** and the second structures **115**, **215** in step **504**. In another embodiment, the substrate **101** is etched by the etch process to remove portions of the substrate **101** and form the first structures **114**, **214** and the second structures **115**, **215** in step **504**.

[0042] FIG. **7** is a flow diagram of a method **700** for forming a portion of an optical device **100**, **200** according to embodiments described herein. FIGS. **8**A-**8**D are schematic, cross-sectional views of the optical device **100**, **200** formed according to the method **700**. The portion of the optical device **100**, **200** may correspond to one grating, such as the first grating **102** or second grating **105**, or the portion may correspond to the entirety of the optical device **100** or optical device **200**.

[0043] At step **701**, the planarization layer **810** is disposed over the device layer **408** as shown in FIG. **8**A, the device layer **408** corresponding to a plurality of first structures **114**, **214** and a plurality of second structures **115**, **215** to be formed. In one embodiment, the planarization layer **810** includes a-Si containing materials. The planarization layer **810** may be deposited through any suitable process, including, but not limited to, a liquid material pour casting process, a spin-on coating process, a liquid spray coating process, a dry powder coating process, a screen printing process, a doctor blading process, a PVD process, a CVD process, a PECVD process, a FCVD process, or an ALD process. The planarization layer **810** forms a top surface **812** parallel to the substrate **101** so that the planarization layer **810** prevents over-etching of the device layer **408** in the etch process. At step **702**, a resist layer **407** is disposed over the planarization layer **810**.

[0044] At step **703** and as shown in FIG. **8**B, the resist layer **407** is patterned to expose portions of the planarization layer **810**. Patterning the resist layer **407** includes forming the first resist layer pattern **422** having the plurality of first openings **420** formed therein over the first portion **424** of the device layer **408**, and forming the second resist layer pattern **423** having the plurality of second openings **421** formed

therein over the second portion **425** of the device layer **408**. At step **704** and as shown in FIG. **8**C, the exposed portions of the planarization layer **810** defined by the plurality of first openings **420** and the plurality of second openings **421** are etched to expose unmasked first device layer segments **612** of the first portion **424** of the device layer **408** and second device layer segments **613** of the second portion **425** of the device layer **408**.

[0045] In step **705** and as shown in FIG. **8**D, the first device layer segments **612** and the second device layer segments **613** of the device layer **408** are etched to form the plurality of first structures **114**, **214** and the plurality of second structures **115**, **215**. The first device layer segments **612** are configured to form at least a portion of the plurality of first structures **114**, **214** within the optical device **100**, **200**. The second device layer segments **613** are configured to form at least a portion of the plurality of second structures **115**, **215** within the optical device **100**, **200**.

[0046] The etching includes, but is not limited to, one or more of ion implantation, ion etching, reactive ion etching (RIE), directional RIE, and plasma etching. In one embodiment, planarization layer **810** has a greater etch selectivity than the device layer **408**. While FIG. **8**D depicts first structures **114**, **214** and second structures **115**, **215** formed in the device layer **408**, steps **701-705** are applicable to patterning the substrate **101**. In one embodiment, the device layer **408** is etched by the etch process to remove portions of the device layer **408** and form the first structures **114**, **214** and the second structures **115**, **215** in step **705**. In another embodiment, the substrate **101** is etched by the etch process to remove portions of the substrate **101** and form the first structures **114**, **214** and the second structures **115**, **215** in step **705**.

[0047] The embodiments described herein provide methods for multi-depth optical devices while minimizing defects associated with over-etching and nonuniformity.

[0048] 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 an optical device, comprising:
disposing a resist layer over a device layer disposed over a top surface of a substrate, the device layer having:
a first portion having a first height from the top surface of the substrate; and
a second portion having a second height from the top surface of the substrate;
patterning the resist layer to:
form a first resist layer pattern having a plurality of first openings formed therein over the first portion of the device layer; and
form a second resist layer pattern having a plurality of second openings formed therein over the second portion of the device layer; and
etching exposed portions of the device layer defined by the plurality of first openings and the plurality of second openings, wherein
the plurality of first openings in the first resist layer pattern are configured to form at least a portion of a plurality of first structures within the optical device, and the first structures have a first depth relative to the top surface of the substrate, and
the plurality of second openings in the second resist layer pattern are configured to form at least a portion of a plurality of second structures within the optical device, and the second structures have a second depth relative to the top surface of the substrate.

2. The method of claim **1**, wherein the etching the exposed portions of the device layer defined by the plurality of first openings and the plurality of second openings comprises at least one of ion implantation, ion beam etching (IBE), reactive ion etching (RIE), directional RIE, plasma etching, and thermal atomic layer etching.

3. The method of claim **2**, wherein the device layer comprises one or more of titanium dioxide, zinc oxide, tin dioxide, aluminum-doped zinc oxide, fluorine-doped tin oxide, cadmium stannate, niobium oxide, zinc stannate, silicon nitride, and amorphous silicon containing materials.

4. The method of claim **1**, wherein an etch stop layer is disposed on the substrate.

5. The method of claim **4**, wherein the etch stop layer is non-transparent.

6. The method of claim **1**, wherein the first depth is less than the second depth.

7. The method of claim **1**, wherein the plurality of first structures and the plurality of second structures are perpendicular to the top surface of the substrate.

8. The method of claim **1**, wherein the plurality of first structures and the plurality of second structures are at an angle relative to the top surface of the substrate.

9. A method of forming an optical device, comprising:
disposing a hardmask over a device layer disposed over a top surface of a substrate, the device layer having:
a first portion having a first height from the top surface of the substrate; and
a second portion having a second height from the top surface of the substrate;
disposing a resist layer over the hardmask, the resist layer having a top surface parallel to the top surface of the substrate;
patterning the resist layer to:
form a first resist layer pattern having a plurality of first openings formed therein over the first portion of the device layer; and
form a second resist layer pattern having a plurality of second openings formed therein over the second portion of the device layer;
etching exposed portions of the hardmask defined by the plurality of first openings and the plurality of second openings to:
expose unmasked first device layer segments of the first portion of the device layer; and
expose unmasked second device layer segments of the second portion of the device layer; and
etching the first device layer segments and the second device layer segments, wherein
the first device layer segments are configured to form at least a portion of a plurality of first structures within the optical device, and the first structures have a first depth relative to the top surface of the substrate; and
the second device layer segments are configured to form at least a portion of a plurality of second structures within the optical device, and the second structures have a second depth relative to the top surface of the substrate.

10. The method of claim **9**, wherein the first depth is less than the second depth.

11. The method of claim **9**, wherein the plurality of first structures and the plurality of second structures are perpendicular to the top surface of the substrate.

12. The method of claim **9**, wherein the plurality of first structures and the plurality of second structures are at an angle relative to the top surface of the substrate.

13. The method of claim **9**, wherein the hardmask is non-transparent.

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

removing the hardmask.

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

disposing a planarization layer over a device layer disposed over a top surface of a substrate, the device layer having:

a first portion having a first height from the top surface of the substrate; and

a second portion having a second height from the top surface of the substrate;

disposing a resist layer over the planarization layer;

patterning the resist layer to:

form a first resist layer pattern having a plurality of first openings formed therein over the first portion of the device layer; and;

form a second resist layer pattern having a plurality of second openings formed therein over the second portion of the device layer;

etching exposed portions of the planarization layer defined by the plurality of first openings and the plurality of second openings to:

expose unmasked first device layer segments of the first portion of the device layer; and

expose unmasked second device layer segments of the second portion of the device layer; and

etching the first device layer segments and the second device layer segments, wherein

the first device layer segments are configured to form at least a portion of a plurality of first structures within the optical device, and the first structures have a first depth relative to the top surface of the substrate, and

the second device layer segments are configured to form at least a plurality of second structures within the optical device, and the second structures have a second depth relative to the top surface of the substrate.

16. The method of claim **15**, wherein an etch stop layer is disposed on the substrate.

17. The method of claim **16**, wherein the etch stop layer comprises a nitrogen-containing material.

18. The method of claim **15**, wherein the first depth is less than the second depth.

19. The method of claim **15**, wherein the plurality of first structures and the plurality of second structures are perpendicular to the top surface of the substrate.

20. The method of claim **15**, wherein the plurality of first structures and the plurality of second structures are at an angle relative to the top surface of the substrate.

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