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Doshay et al.

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(45) **Date of Patent: Aug. 18, 2026**

(54) **PHOTORESIST LOADING SOLUTIONS FOR FLAT OPTICS FABRICATION**

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G02B 5/20 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 5/20*** (2013.01); *G02B 2207/101* (2013.01)

(58) **Field of Classification Search**
CPC G02B 5/20; G02B 2207/101; G02B 1/002; G02B 6/107; G02B 2006/12035;
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(56) **References Cited**

U.S. PATENT DOCUMENTS

9,196,868 B2 * 11/2015 Young H10K 50/85
10,468,623 B2 * 11/2019 Ajiki H10K 59/122
(Continued)

FOREIGN PATENT DOCUMENTS

CN 102259831 A 11/2011
CN 105319832 A 2/2016
(Continued)

OTHER PUBLICATIONS

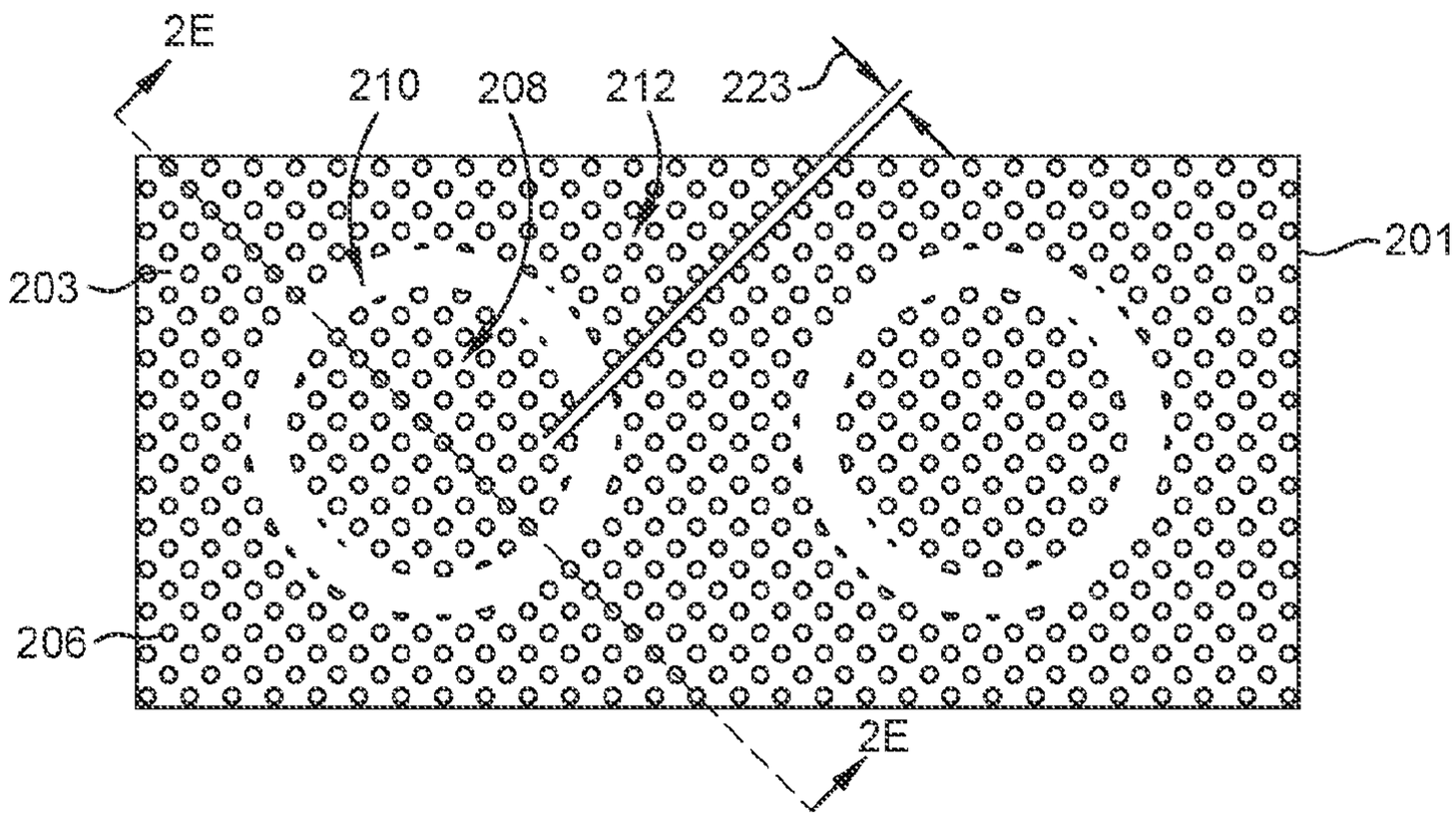
International Search Report and Written Opinion for International Application No. PCT/US2020/034054 dated Sep. 11, 2020.
(Continued)

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(57) **ABSTRACT**

Embodiments of the present disclosure relate to methods for fabricating optical devices. One embodiment of the method includes disposing a structure material layer on a surface of a substrate and disposing a patterned photoresist over the structure material layer. The patterned photoresist has at least one device portion and at least one auxiliary portion. Each device portion and each auxiliary portion exposes unmasked portions of the structure material layer. The unmasked portions of structure material layer corresponding to each device portion and each auxiliary portion are etched. The etching the unmasked portions forms at least one optical device having device structures corresponding to the unmasked portions of at least one device portion and at least one auxiliary region having auxiliary structures corresponding to the unmasked portions of at least one auxiliary portion.

20 Claims, 9 Drawing Sheets



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(60) Provisional application No. 62/858,708, filed on Jun. 7, 2019.

(58) **Field of Classification Search**
CPC G02B 2006/12097; G02B 2006/12176; B82Y 40/00; G03F 7/42
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2007/0285639	A1	12/2007	Liang et al.	
2013/0140269	A1*	6/2013	Chiang	G03F 7/0043 977/887
2014/0001432	A1	1/2014	Hall et al.	
2014/0326988	A1	11/2014	Yamaguchi et al.	
2017/0212285	A1	7/2017	Arbabi et al.	
2018/0231700	A1	8/2018	Ahmed et al.	
2018/0348548	A1	12/2018	Visser et al.	
2019/0033683	A1	1/2019	Ahmed et al.	
2019/0044003	A1	2/2019	Heck et al.	
2019/0318957	A1	10/2019	Godet et al.	
2020/0166783	A1	5/2020	Roy et al.	

FOREIGN PATENT DOCUMENTS

EP	1041405	A1	10/2000
JP	2000-275405	A	10/2000
KR	20100106456	A	10/2010
TW	201333544	A	8/2013
TW	201903472	A	1/2019

OTHER PUBLICATIONS

Taiwan Office Action dated May 21, 2021 re Taiwan Application No. 109118563.
European Search Report for Application No. 20817887.1 dated Jun. 15, 2023.
Japanese Office Action dated Aug. 6, 2024 for Application No. 2021-572417.
Korean Office Action dated Mar. 11, 2024 for Application No. 10-2022-7000325.
Japanese Office Action dated Jan. 9, 2024 for Application No. 2021-572417.
Chinese Office Action dated May 9, 2025 for Application No. 202080040885.1.
European Office Action Dated Oct. 24, 2025 For Application No. 20817887.
Chinese Office Action Dated Sep. 26, 2025 For Application No. 202080040885.

* cited by examiner

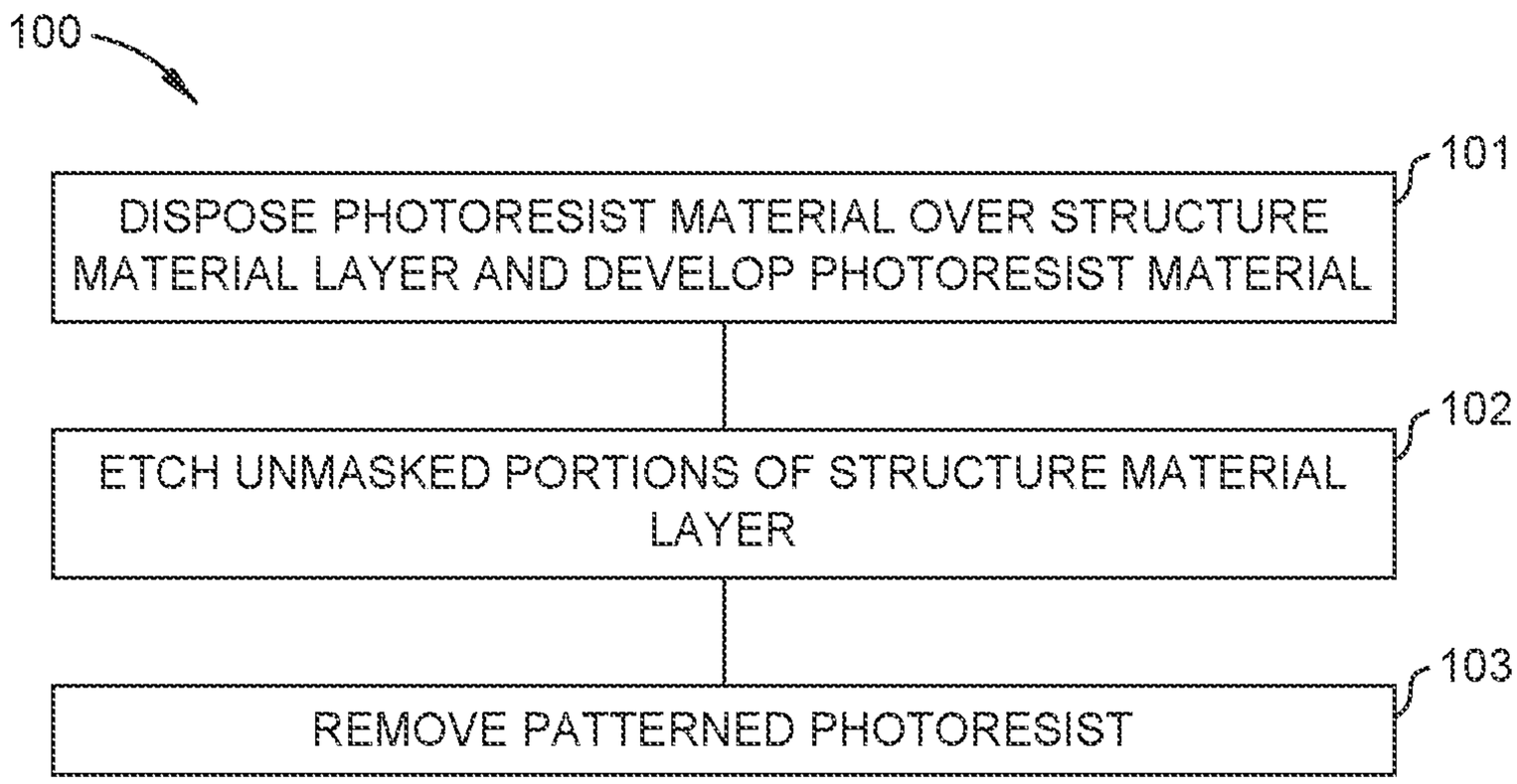

100
DISPOSE PHOTORESIST MATERIAL OVER STRUCTURE MATERIAL LAYER AND DEVELOP PHOTORESIST MATERIAL
101
ETCH UNMASKED PORTIONS OF STRUCTURE MATERIAL LAYER
102
REMOVE PATTERNED PHOTORESIST
103

FIG. 1

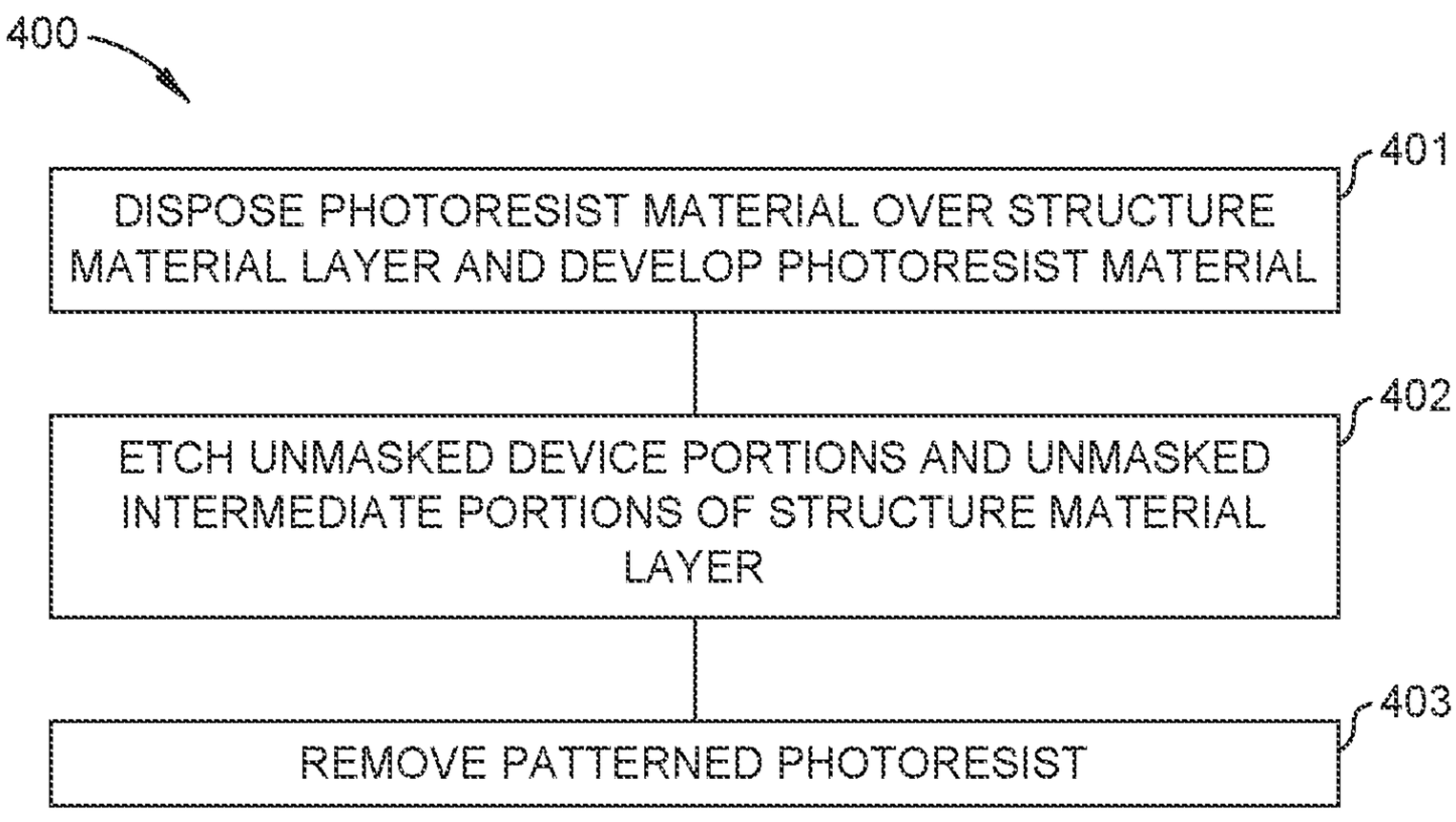

400
DISPOSE PHOTORESIST MATERIAL OVER STRUCTURE MATERIAL LAYER AND DEVELOP PHOTORESIST MATERIAL
401
ETCH UNMASKED DEVICE PORTIONS AND UNMASKED INTERMEDIATE PORTIONS OF STRUCTURE MATERIAL LAYER
402
REMOVE PATTERNED PHOTORESIST
403

FIG. 4

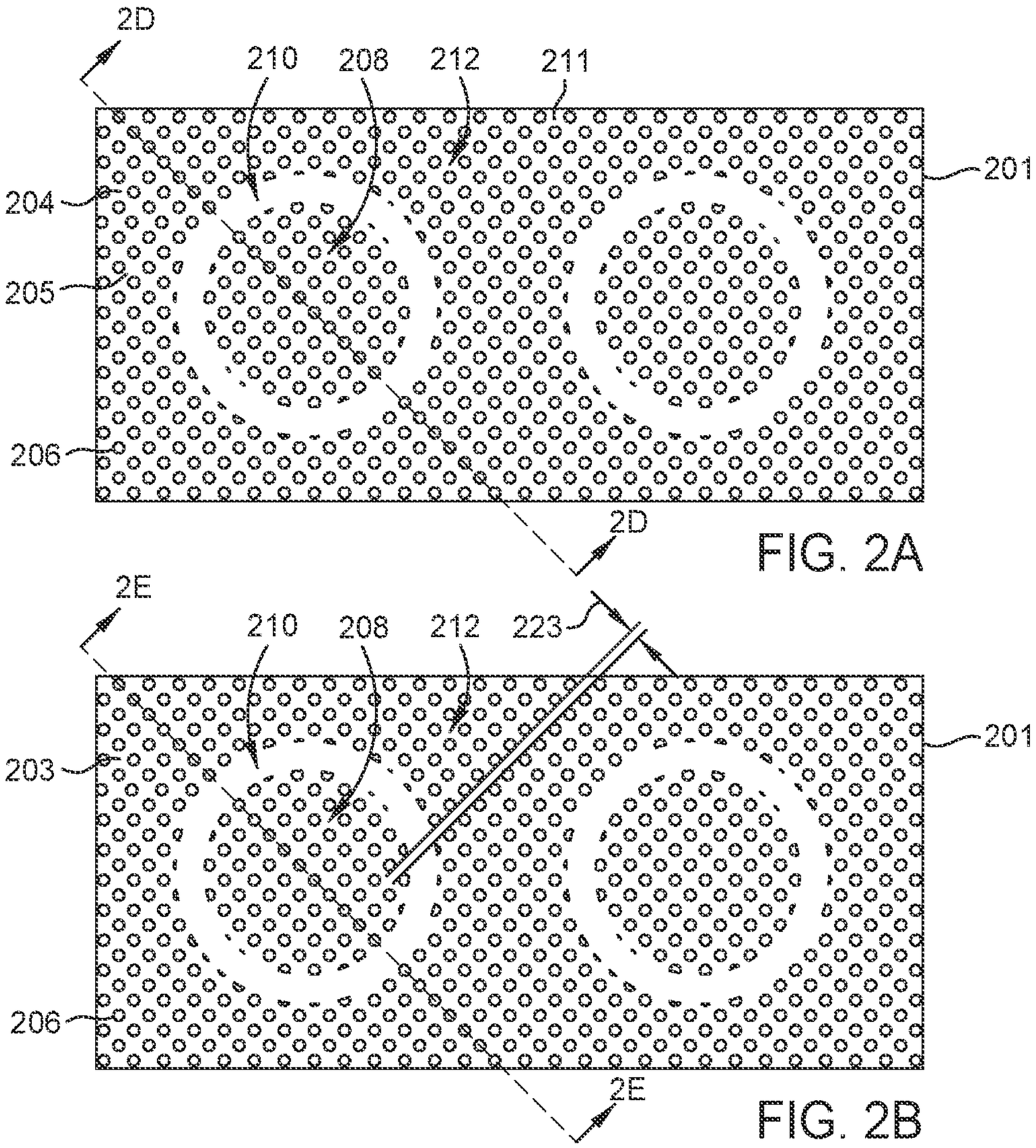


FIG. 2A

FIG. 2B

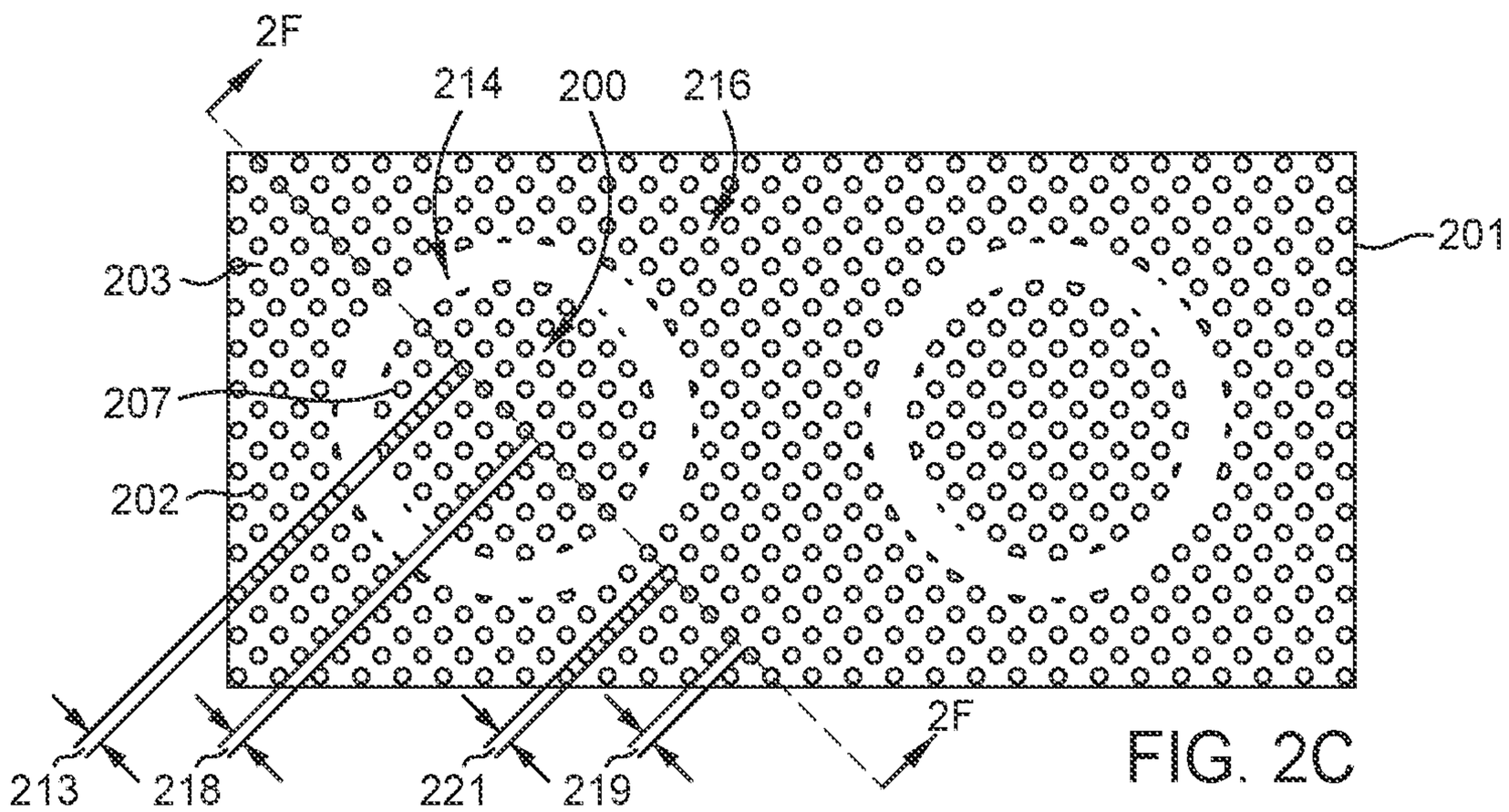


FIG. 2C

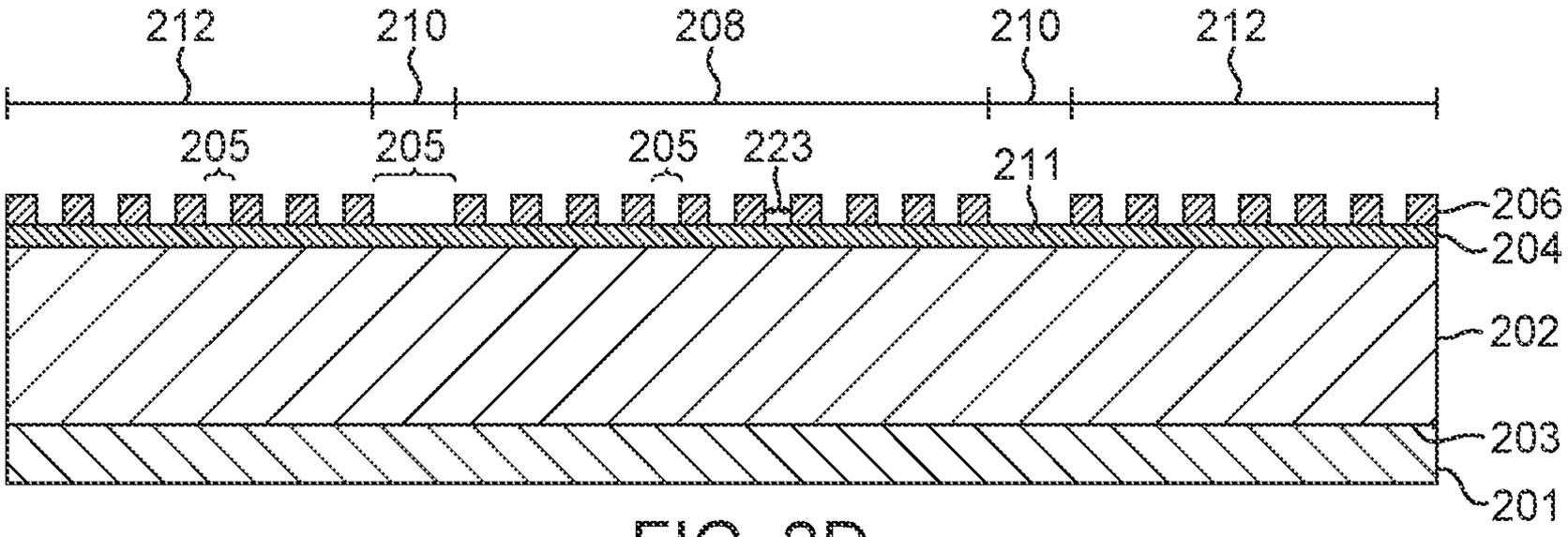


FIG. 2D

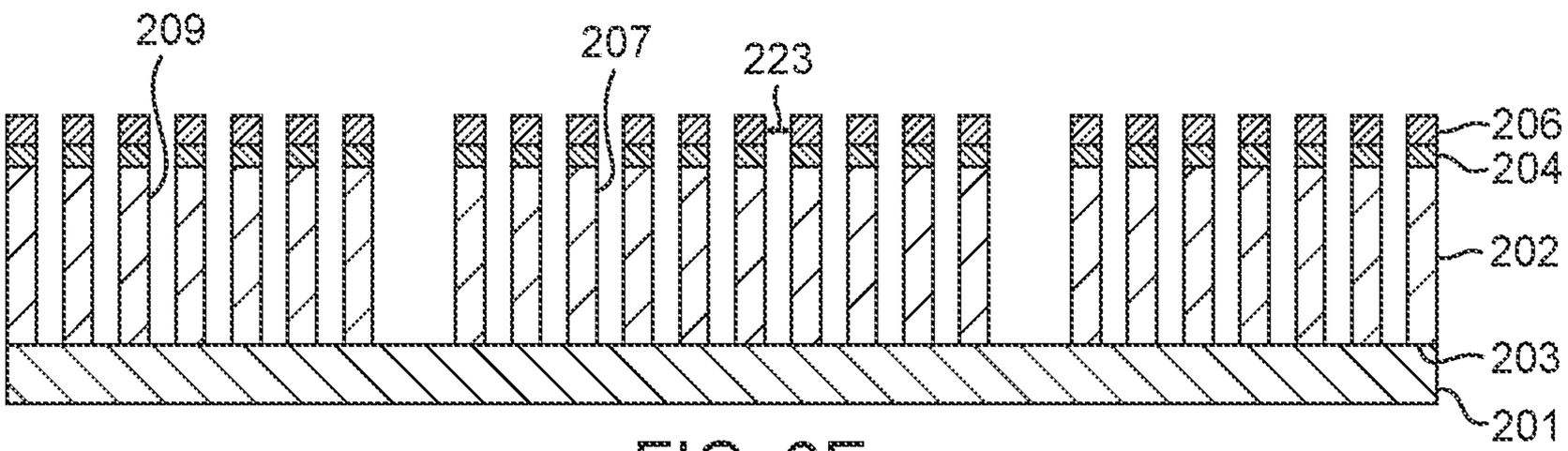


FIG. 2E

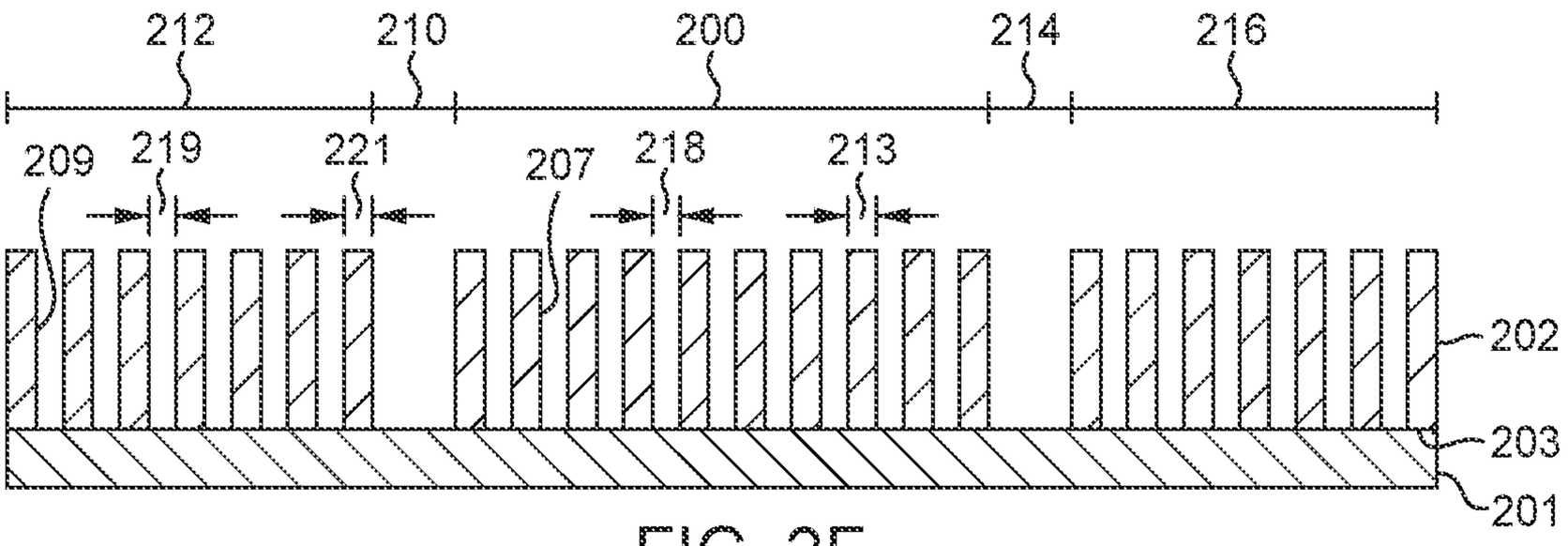


FIG. 2F

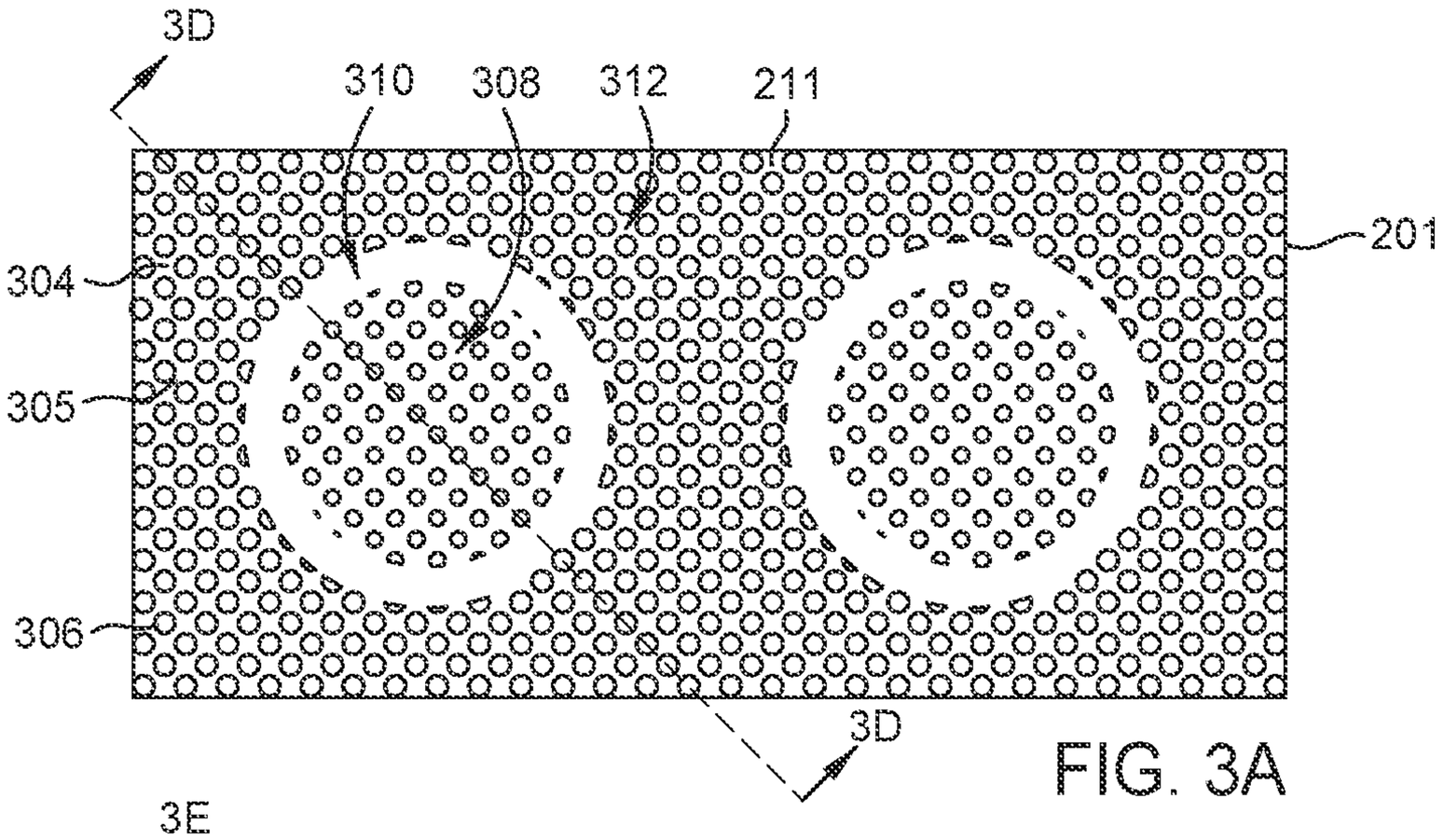


FIG. 3A

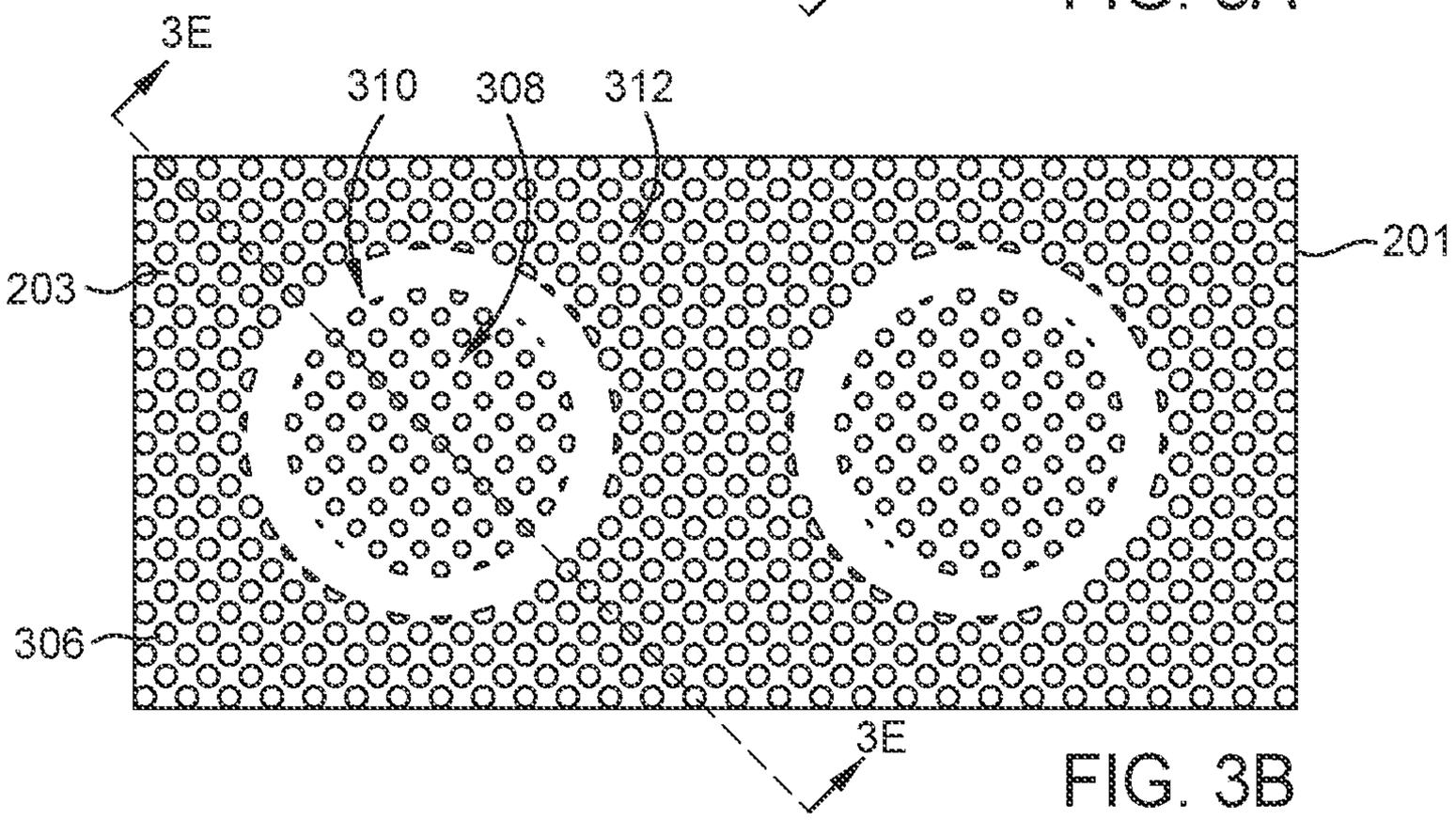


FIG. 3B

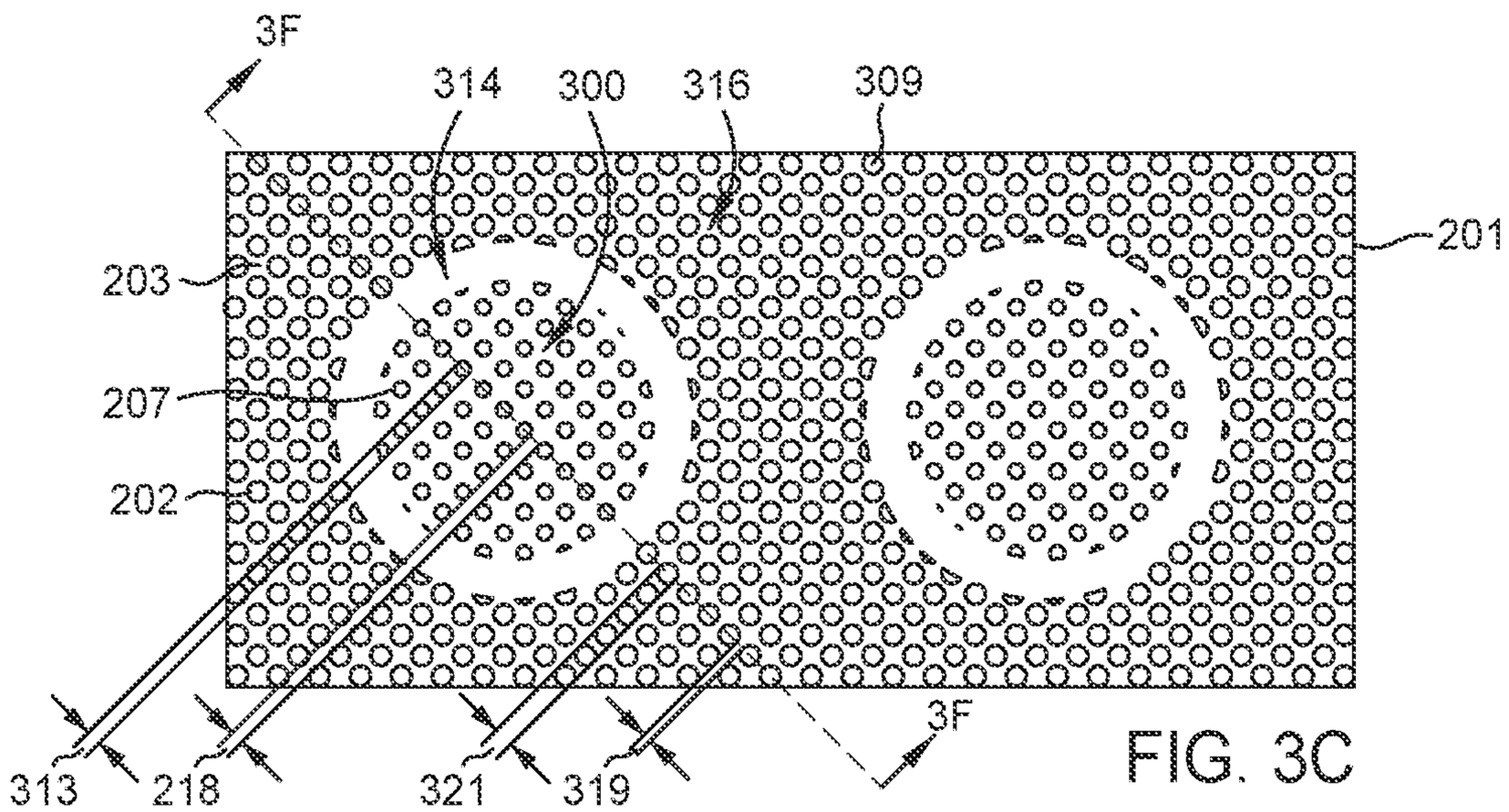


FIG. 3C

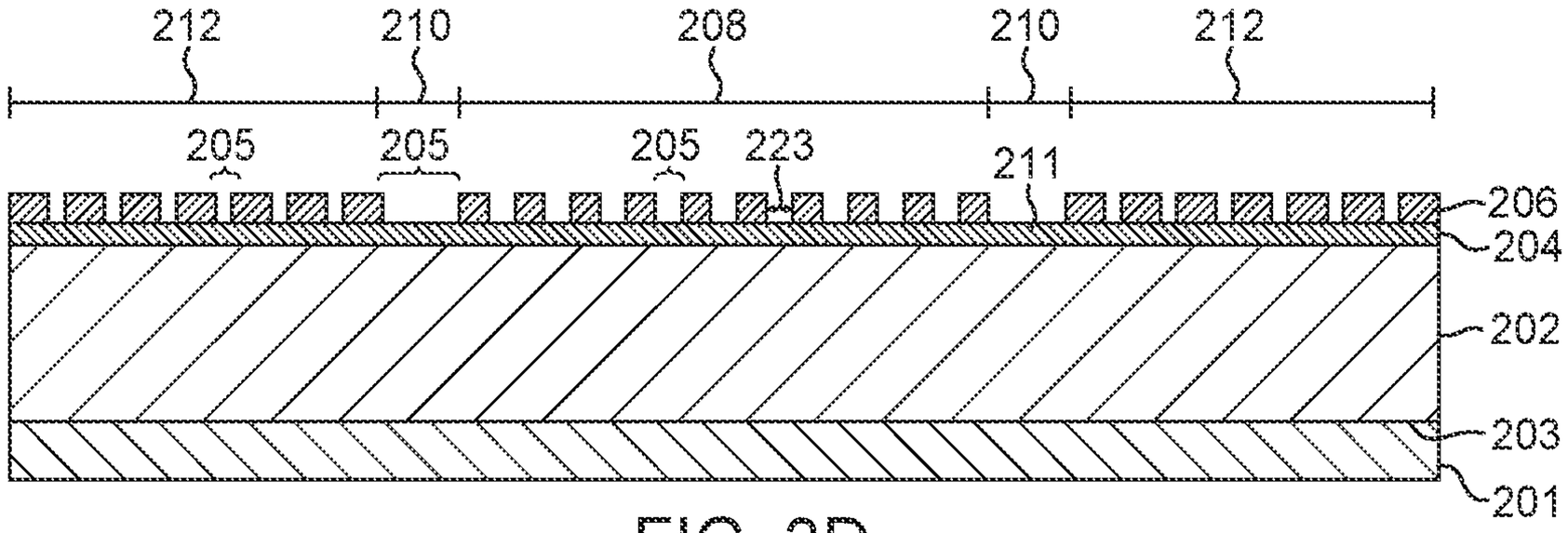


FIG. 3D

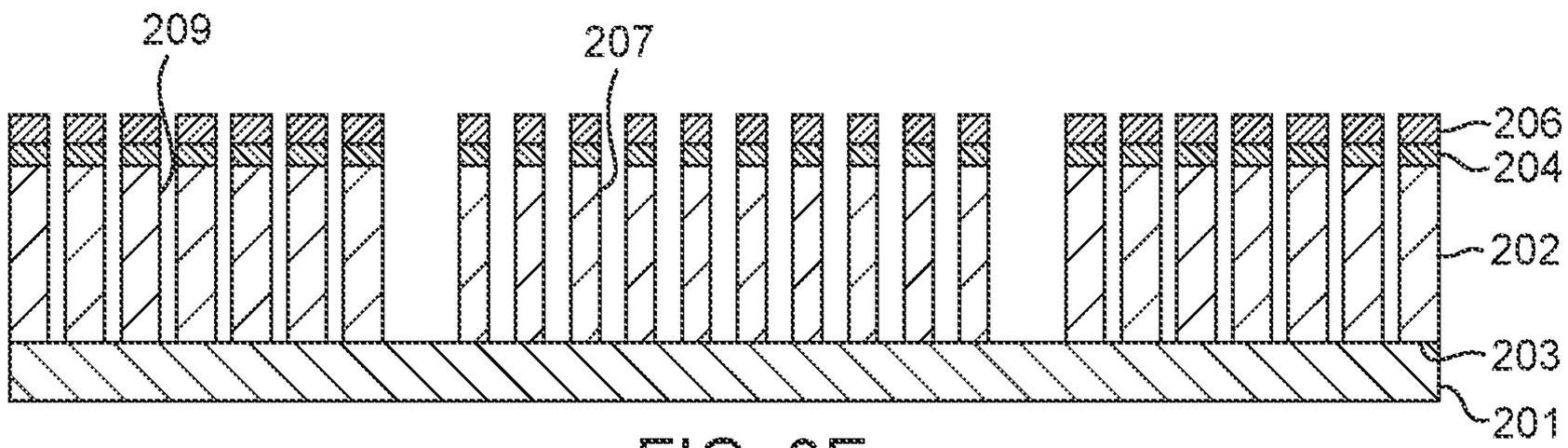


FIG. 3E

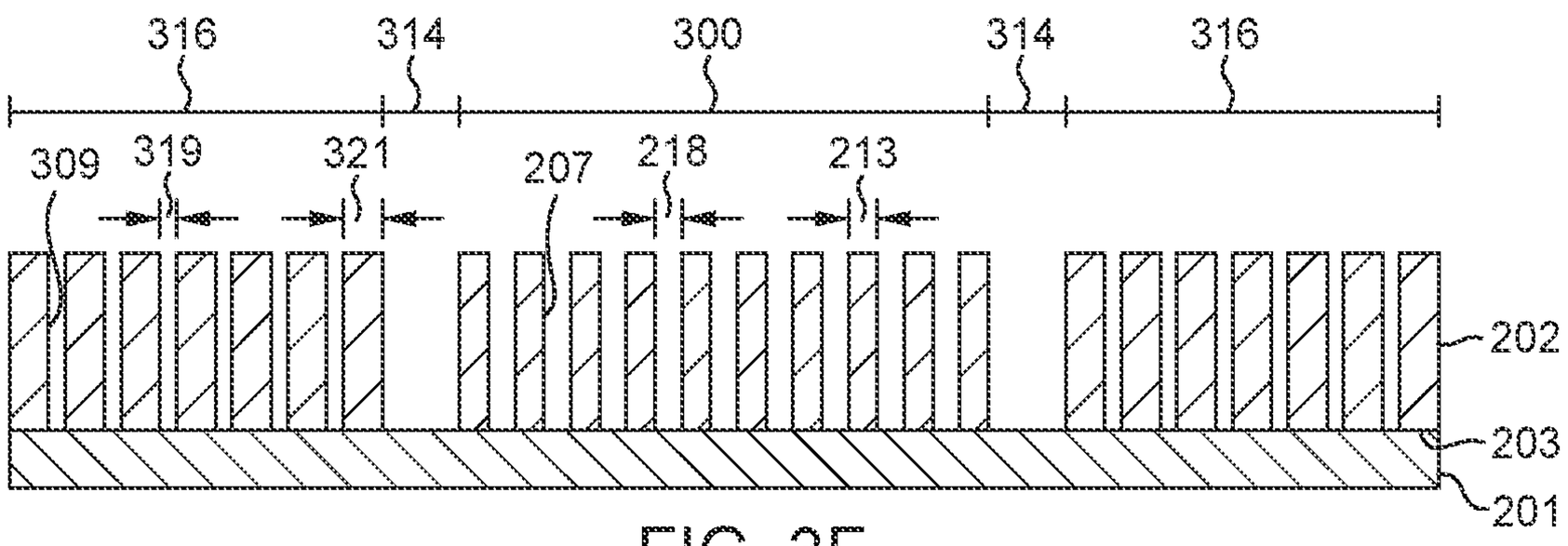


FIG. 3F

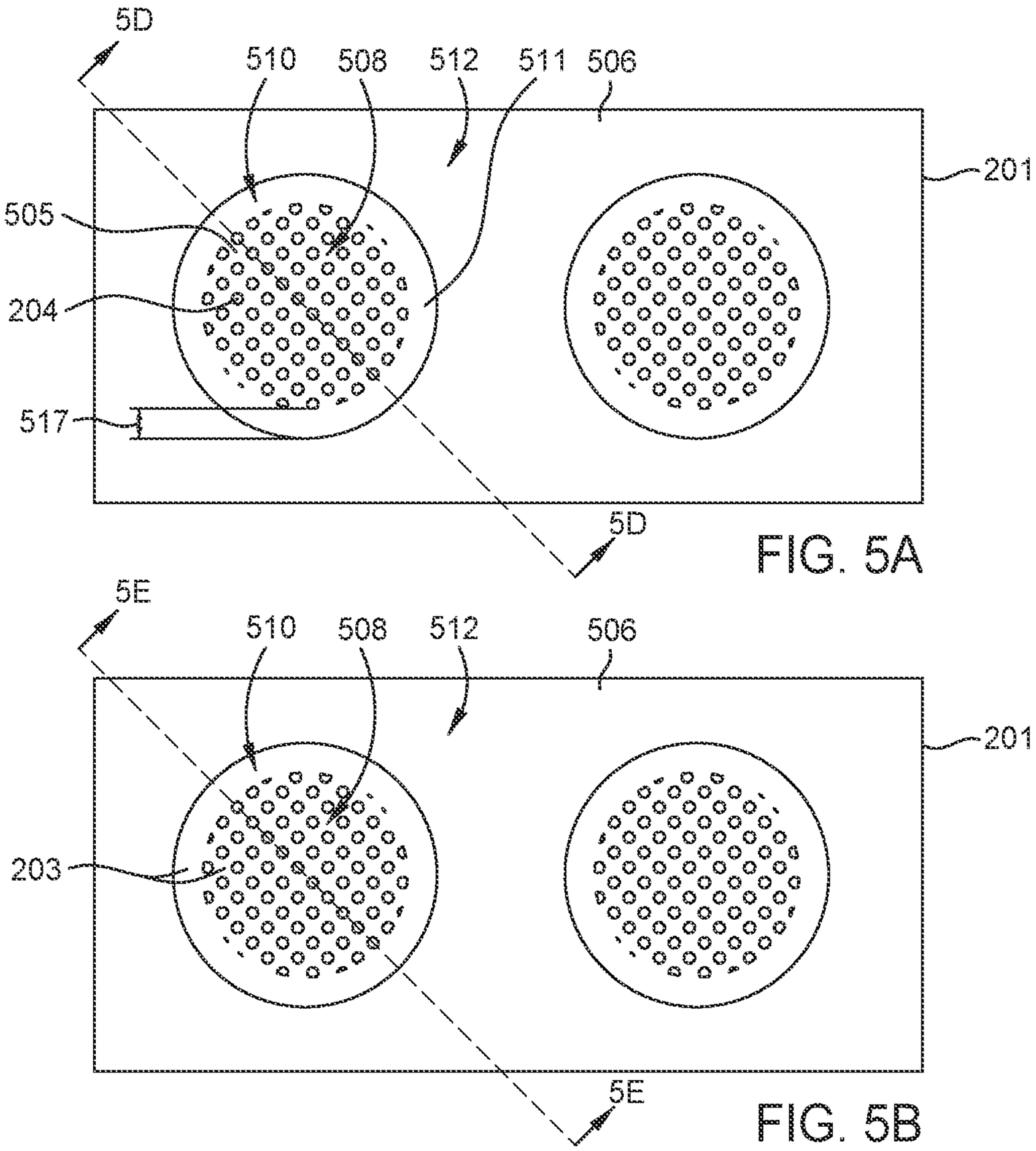


FIG. 5A

FIG. 5B

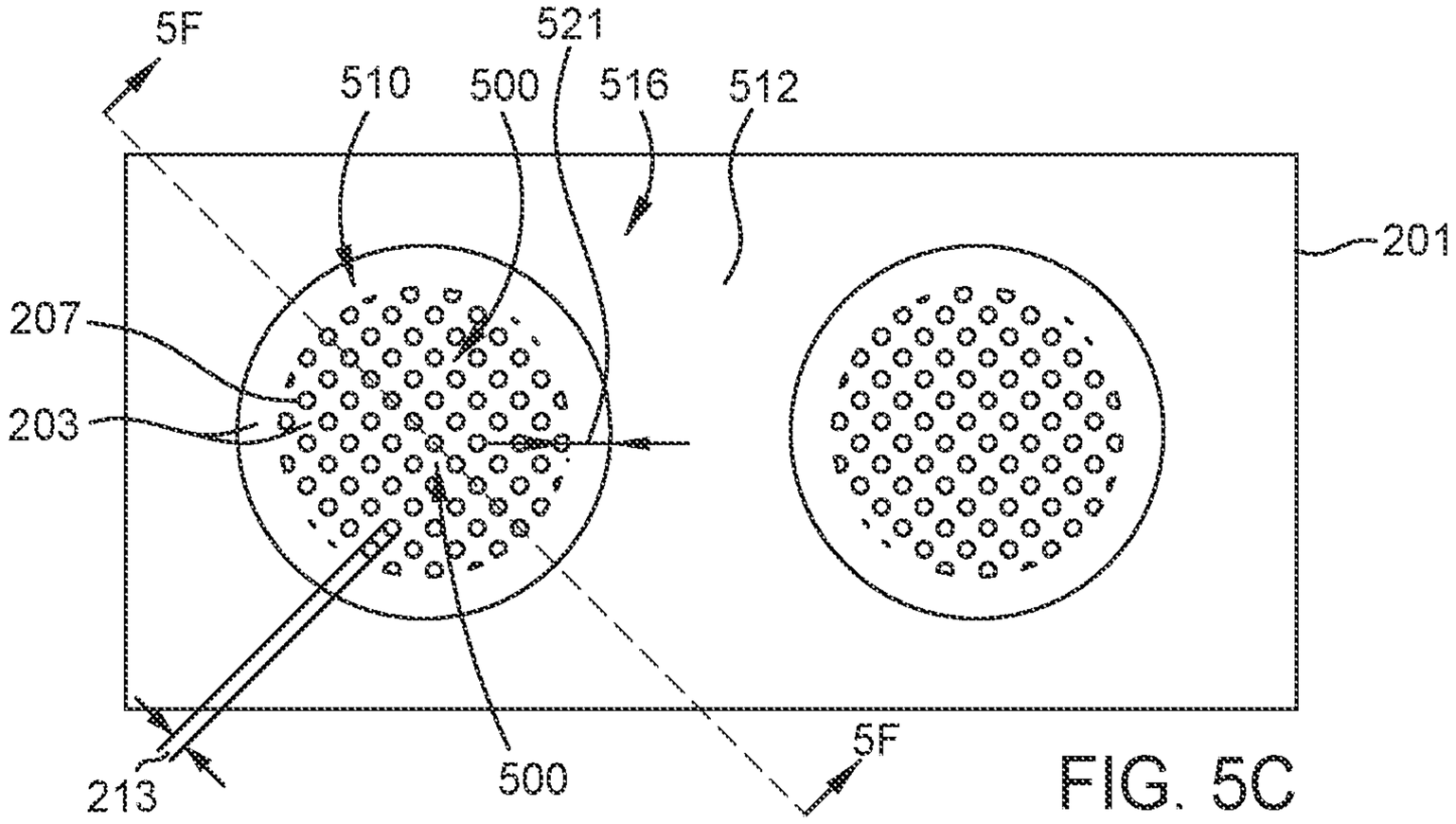


FIG. 5C

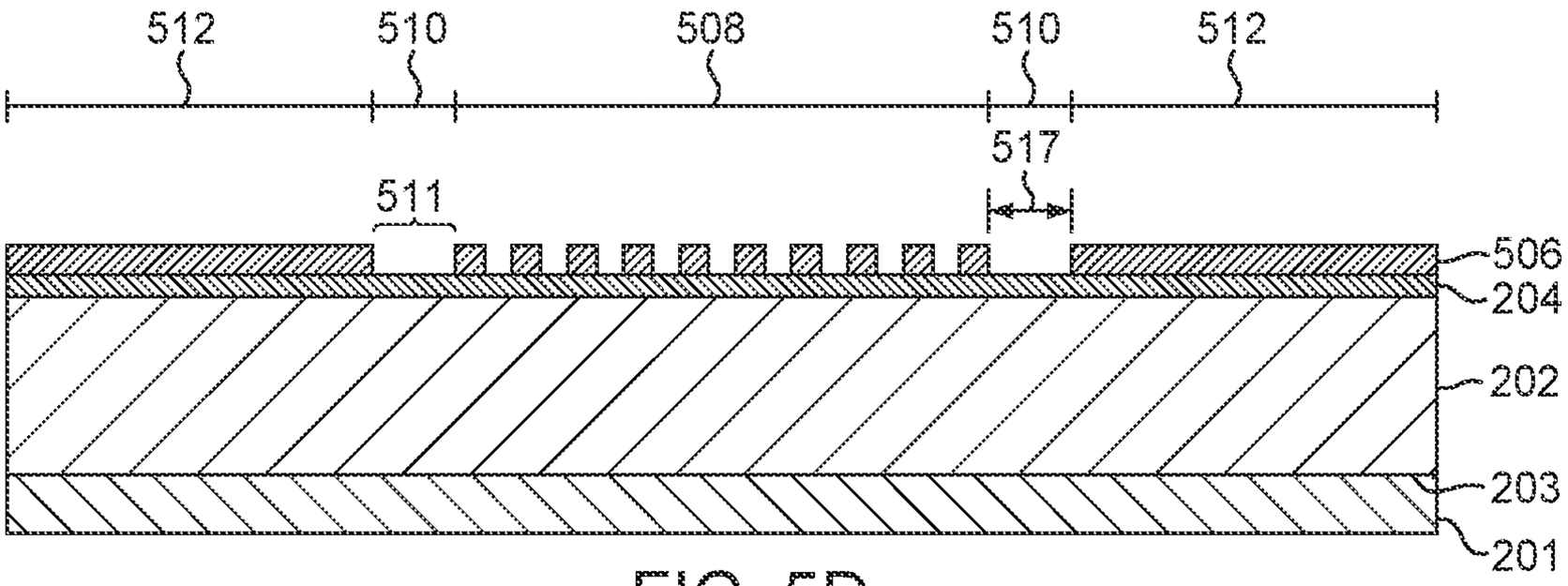


FIG. 5D

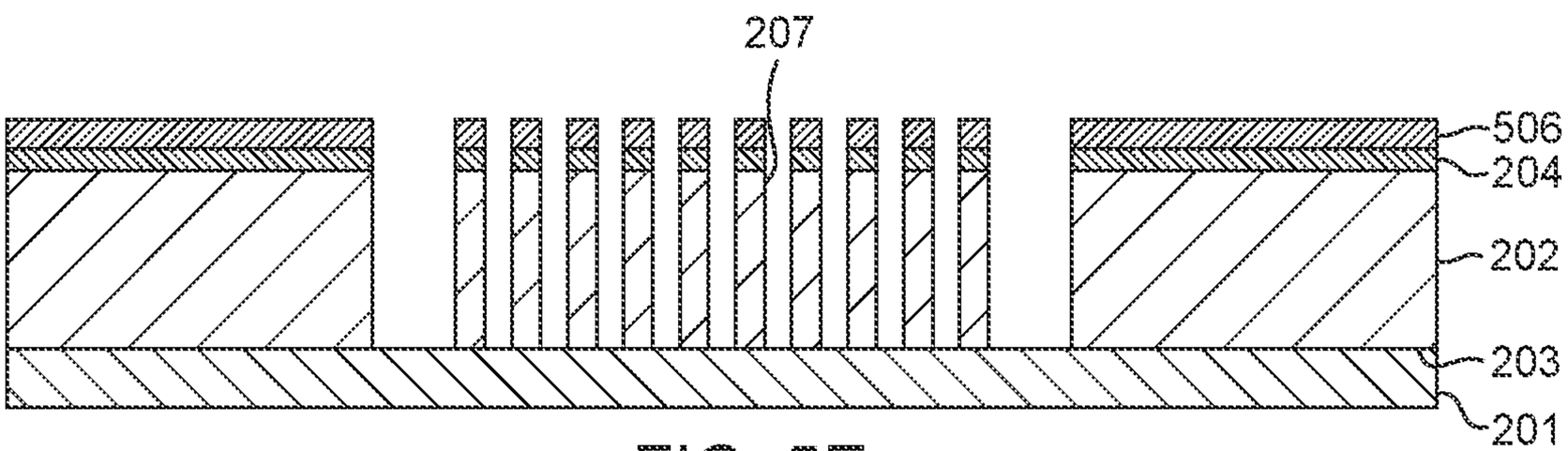


FIG. 5E

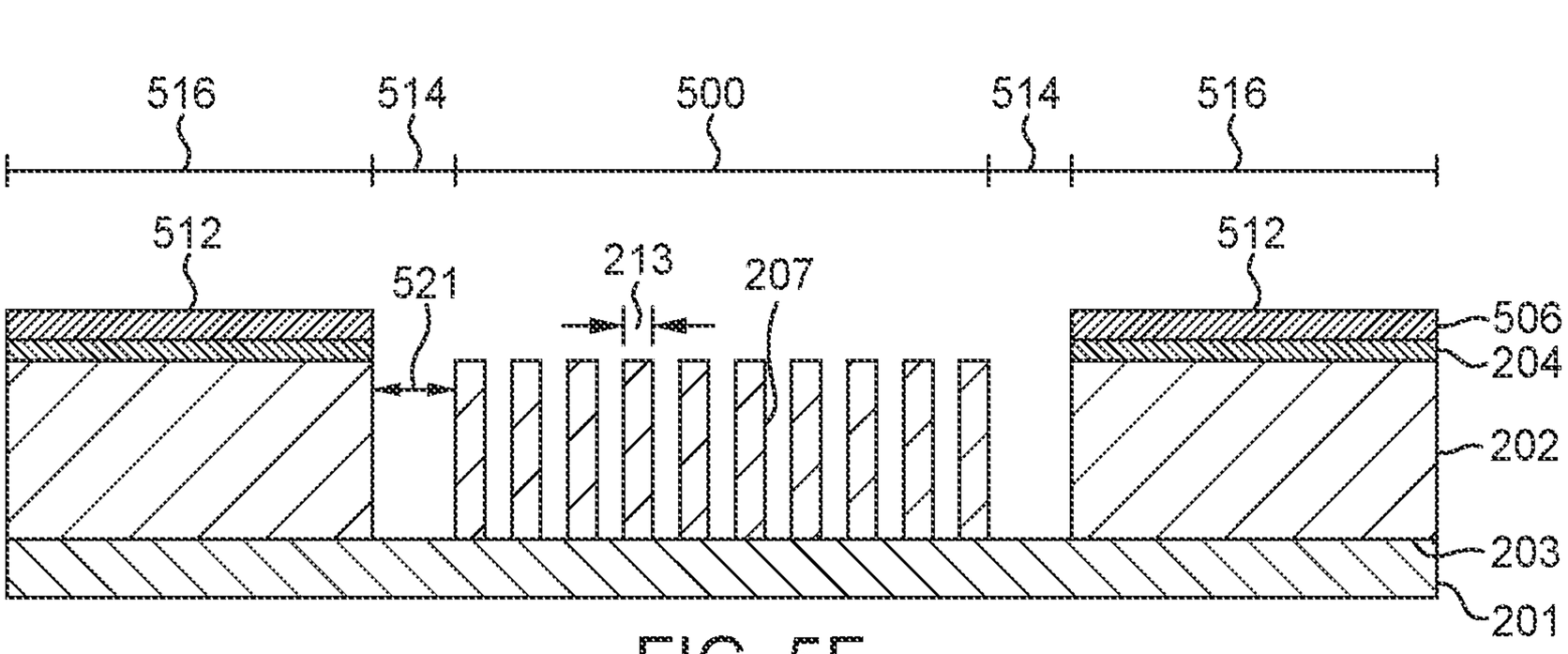


FIG. 5F

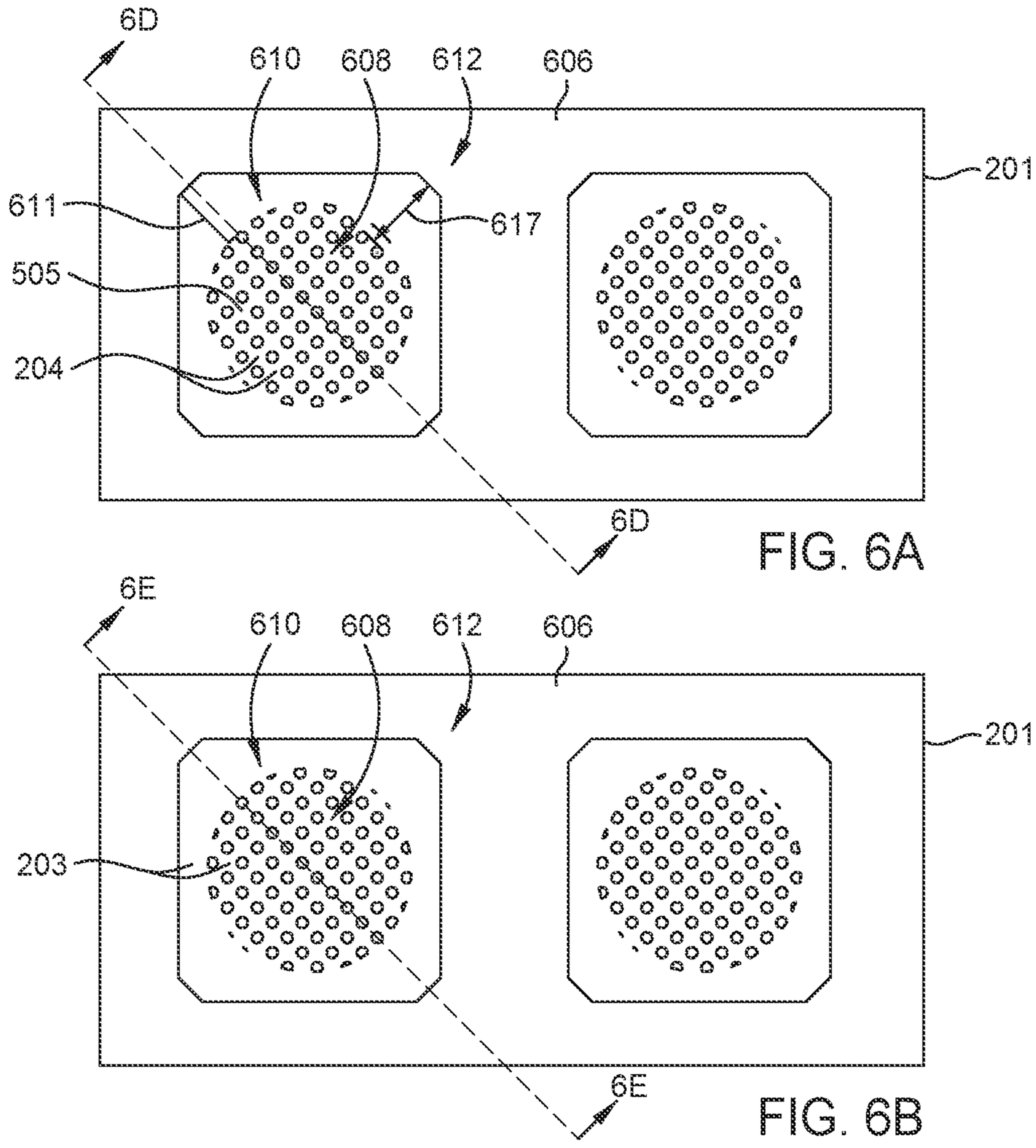


FIG. 6A

FIG. 6B

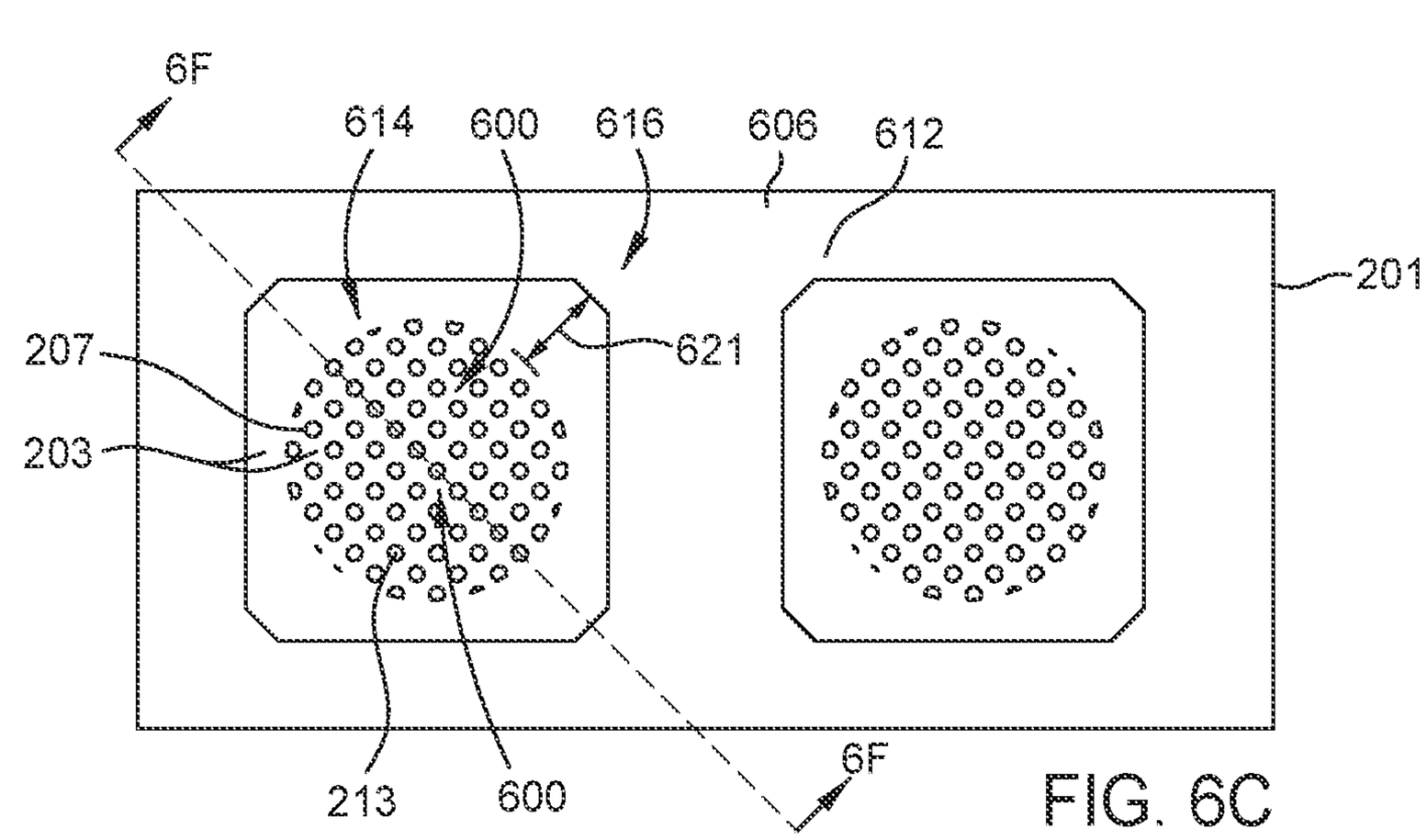


FIG. 6C

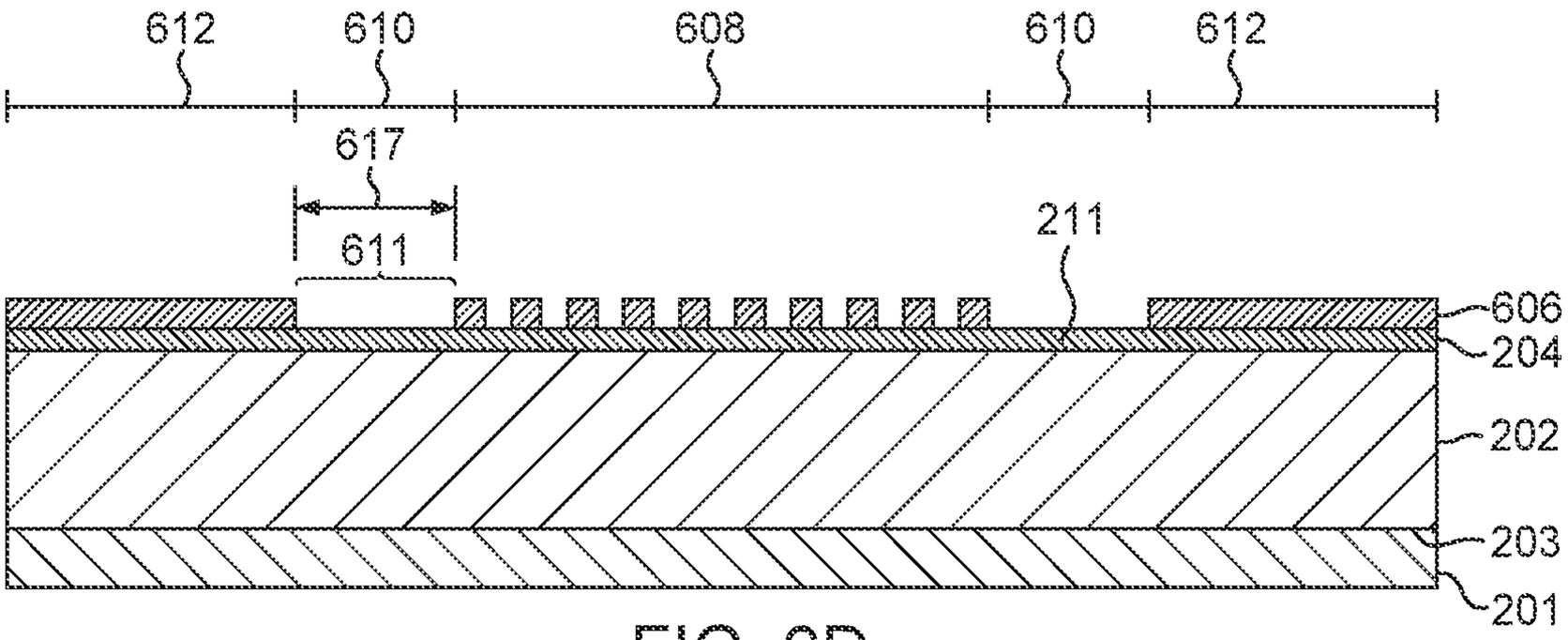


FIG. 6D

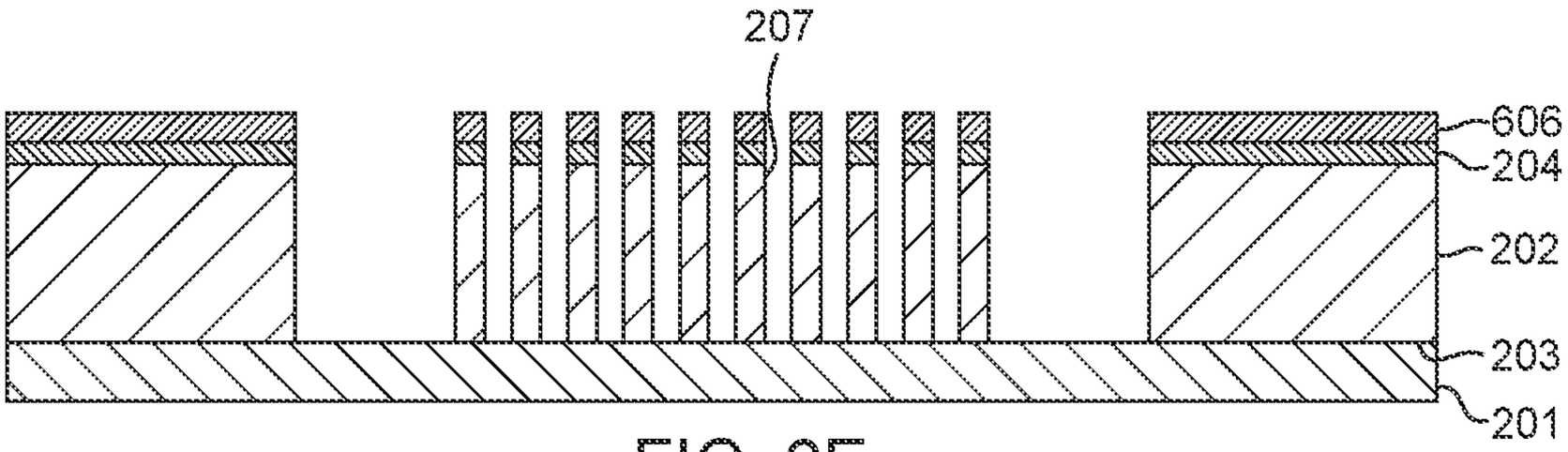


FIG. 6E

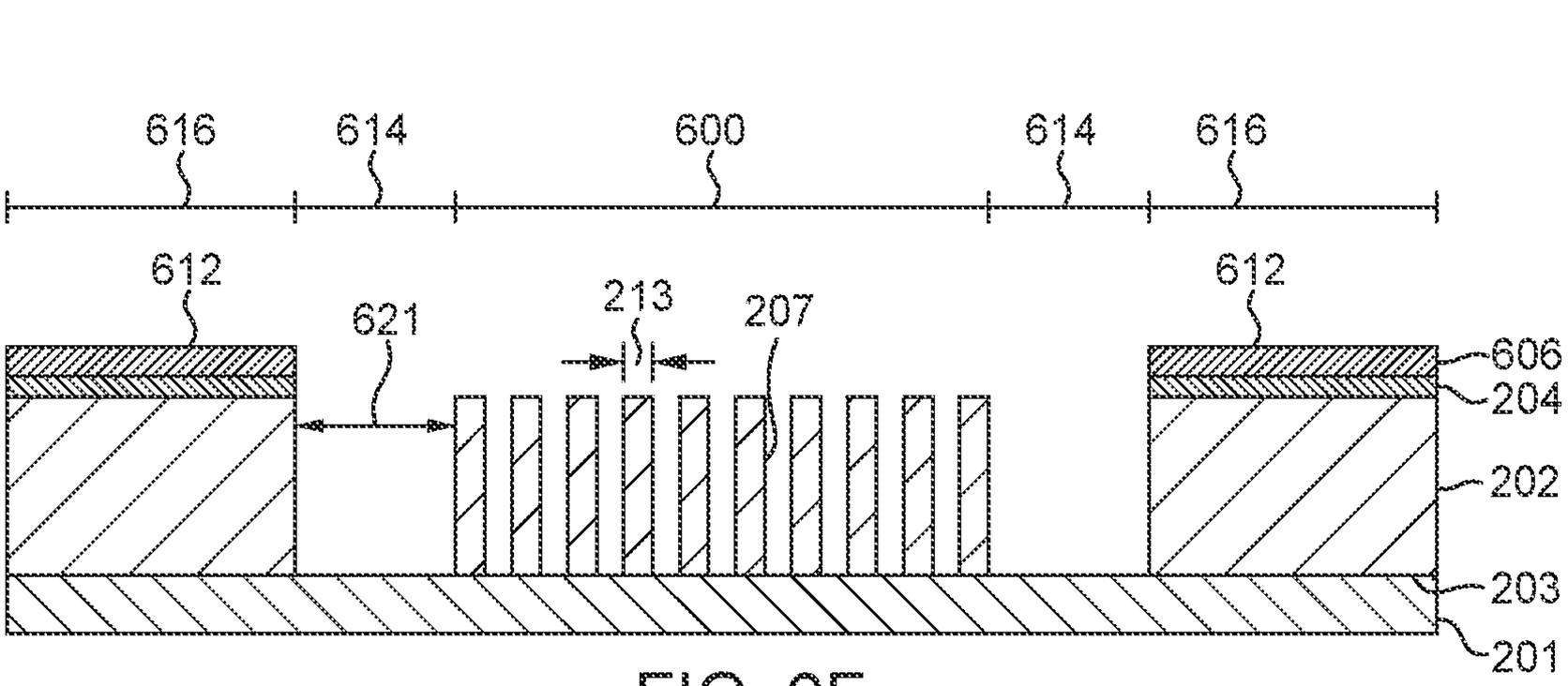


FIG. 6F

PHOTORESIST LOADING SOLUTIONS FOR FLAT OPTICS FABRICATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional application of U.S. patent application Ser. No. 16/880,846, filed May 21, 2020, which claims priority to U.S. Provisional Patent Application Ser. No. 62/858,708, filed on Jun. 7, 2019. Each of the aforementioned related patent applications is herein incorporated by reference.

BACKGROUND

Field

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein provide for the fabrication of one or more optical devices.

Description of the Related Art

Optical devices may be used to manipulate the propagation of light. One example of optical devices is flat optical devices. Flat optical devices in the visible and near-infrared spectrum may require transparent substrates having structures, such as nanostructures, disposed thereon. However, processing transparent substrates to form optical devices is both complex and challenging as an emerging technology. For example, large areas of the structure material may be etched away in the areas between adjacent optical devices and between the optical devices and a periphery of the substrate, such that the optical devices are only surrounded by the surface of the substrate. Surrounding the optical devices only by the surface of the substrate results in an inability to determine the endpoint of etch processes which can result in an undesirable critical dimension of the structures.

Accordingly, what is needed in the art are improved methods for fabricating optical devices.

SUMMARY

In one embodiment, a method is provided. The method includes disposing a structure material layer on a surface of a substrate and disposing a patterned photoresist over the structure material layer. The patterned photoresist has at least one device portion and at least one auxiliary portion. Each device portion and each auxiliary portion exposes unmasked portions of the structure material layer. The unmasked portions of structure material layer corresponding to each device portion and each auxiliary portion are etched. The etching the unmasked portions forms at least one optical device having device structures corresponding to the unmasked portions of at least one device portion and at least one auxiliary region having auxiliary structures corresponding to the unmasked portions of at least one auxiliary portion.

In another embodiment, a method is provided. The method includes disposing a structure material layer on a surface of a substrate and disposing a patterned photoresist over the structure material layer. The patterned photoresist has at least one device portion exposing unmasked device portions of the structure material layer, at least one auxiliary portion masking at least one auxiliary region of the substrate, the auxiliary region defined by an intermediate region to be formed and a periphery of the substrate, and at least one intermediate portion exposing unmasked intermediate portions of the structure material layer between each device portion and each auxiliary portion. The unmasked device portions and unmasked intermediate portions of the structure material layer corresponding to each device portion and each intermediate portion are etched. The etching the unmasked device portions and unmasked intermediate portions forms at least one optical device having device structures corresponding to the unmasked portions of at least one device portion and at least one intermediate region between each optical device and each auxiliary region exposing the surface of the substrate. The auxiliary region is masked by each auxiliary portion.

In yet another embodiment, a method is provided. The method includes disposing a structure material layer on a surface of a substrate and disposing a patterned photoresist over the structure material layer. The patterned photoresist has at least one device portion exposing unmasked device portions of the structure material layer and at least one auxiliary portion masking at least one auxiliary region of the substrate. The auxiliary region is defined by an intermediate region to be formed and a periphery of the substrate, and at least one intermediate portion exposing unmasked intermediate portions of the structure material layer between each device portion and each auxiliary portion. An unmasked distance between each device portion and each auxiliary portion is varied. The unmasked device portions and unmasked intermediate portions of the structure material layer corresponding to each device portion and each intermediate portion is etched. The etching the unmasked device portions and unmasked intermediate portions forms at least one optical device having device structures corresponding to the unmasked portions of at least one device portion and at least one intermediate region between each optical device and each auxiliary region exposing the surface of the substrate. The auxiliary region is masked by each auxiliary portion and an exposed distance between each intermediate region and each auxiliary portion is varied.

BRIEF DESCRIPTION OF THE DRAWINGS

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

FIG. **1** is a flow diagram illustrating operations of a method for fabricating one or more optical devices according to embodiments.

FIGS. **2**A-**2**C are schematic, top views of a substrate during the method for fabricating the optical devices according to an embodiment.

FIGS. **2**D-**2**F are schematic, cross-sectional views of a substrate during the method for fabricating the optical devices according to an embodiment.

FIGS. **3**A-**3**C are schematic, top views of a substrate during the method for fabricating the optical devices according to an embodiment.

FIGS. **3**D-**3**F are schematic, cross-sectional views of a substrate during the method for fabricating the optical devices according to an embodiment.

FIG. **4** is a flow diagram illustrating operations of a method for fabricating one or more optical devices according to embodiments.

FIGS. **5**A-**5**C are schematic, top views of a substrate during the method for fabricating the optical devices according to an embodiment.

FIGS. **5**D-**5**F are schematic, cross-sectional views of a substrate during the method for fabricating the optical devices according to an embodiment.

FIGS. **6**A-**6**C are schematic, top views of a substrate during the method for fabricating the optical devices according to an embodiment.

FIGS. **6**D-**6**F are schematic, cross-sectional views of a substrate during the method for fabricating the optical devices according to an embodiment.

DETAILED DESCRIPTION

Embodiments of the present disclosure relate to methods for fabricating optical devices. One embodiment of the method includes disposing a structure material layer on a surface of a substrate and disposing a patterned photoresist over the structure material layer. The patterned photoresist has at least one device portion and at least one auxiliary portion. Each device portion and each auxiliary portion exposes unmasked portions of the structure material layer. The unmasked portions of structure material layer corresponding to each device portion and each auxiliary portion are etched. The etching the unmasked portions forms at least one optical device having device structures corresponding to the unmasked portions of at least one device portion and at least one auxiliary region having auxiliary structures corresponding to the unmasked portions of at least one auxiliary portion.

FIG. **1** is a flow diagram illustrating operations of a method **100** for fabricating one or more optical devices **200**, **300**. FIGS. **2**A-**2**C are schematic, top views of a substrate **201**, and FIGS. **2**D-**2**F are schematic, cross-sectional views of a substrate **201** during the method **100** for fabricating the optical devices **200** according to one embodiment, which can be combined with other embodiments described herein. FIGS. **3**A-**3**C are schematic, top views of a substrate **201**, and FIGS. **3**D-**3**F are schematic, cross-sectional views of a substrate **201** during the method **100** for fabricating the optical devices **300** according to another embodiment, which can be combined with other embodiments described herein.

At operation **101**, as shown in FIGS. **2**A and **2**D, and FIGS. **3**A and **3**D, a photoresist material is disposed over a structure material layer **202**. The structure material layer **202** is disposed over a surface **203** of the substrate **201**. The photoresist material is developed to form patterned photoresist **206**, **306**. The photoresist material may be disposed over the structure material layer **202** using a spin-on coating process. The patterned photoresist **206**, **306** may include, but is not limited to, light-sensitive polymer containing materials. Developing the photoresist material may include performing a lithography process, such as photolithography and digital lithography.

The substrate **201** may also be selected to transmit a suitable amount of light of a desired wavelength or wavelength range, such as one or more wavelengths from about 100 to about 3000 nanometers. Without limitation, in some embodiments, the substrate **201** is configured such that the substrate **201** transmits greater than or equal to about 50%, 60%, 70%, 80%, 90%, 95%, 99%, of an IR to UV region of the light spectrum. The substrate **201** may be formed from any suitable material, provided that the substrate **201** 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, which can be combined with other embodiments described herein, the material of substrate **201** has a refractive index that is relatively low, as compared to the refractive index of the structure material layer **202**. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, and combinations thereof. In some embodiments, which can be combined with other embodiments described herein, the substrate **201** includes a transparent material. In one embodiment, which can be combined with other embodiments described herein, the substrate **201** is transparent with absorption coefficient smaller than 0.001. Suitable examples may include an oxide, sulfide, phosphide, telluride or combinations thereof. In one example, the substrate **201** includes silicon (Si), silicon dioxide (SiO_2), sapphire, and high-index transparent materials containing materials.

The structure material layer **202** may be disposed over the surface **203** of the substrate **201** using 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 plasma-enhanced (PECVD) process, a flowable CVD (FCVD) process, an atomic layer deposition (ALD) process, evaporation process, or sputtering process. In one embodiment, which can be combined with other embodiments described herein, the structure material layer **202**, includes metal-containing dielectric materials not limited to 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) ($SnZnO_3$) containing materials. In another embodiment, which can be combined with other embodiments described herein, the structure material includes non-conductive non-crystalline materials, such as dielectric materials. The dielectric materials may include amorphous dielectrics, non-amorphous dielectrics, and crystalline dielectrics. Examples of the dielectric materials include, but are not limited to, Si containing materials, such as silicon nitride (Si_3N_4) and amorphous silicon (a-Si).

In one embodiment, which can be combined with other embodiments described herein, at operation **101**, the patterned photoresist **206**, **306** is disposed over one or more etch layers **204**, such as hardmasks or etch stop layers, disposed over the structure material layer **202**. The hardmasks may be disposed over the structure material layer **202** using 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, an ALD process, evaporation process, or sputtering process. In one embodiment, the hardmasks are non-transparent hardmasks that are removed after the one or more optical devices **200** are formed. In another embodiment, the hardmasks are transparent hardmasks. Examples of the hardmasks include, but are not limited to, chromium (Cr), silver (Ag), Si_3N_4, SiO_2, TiN and carbon (C) containing materials.

In one embodiment, which can be combined with other embodiments described herein, the patterned photoresist **206**, **306** includes at least one device portion **208**, **308** and

at least one auxiliary portion **212**, **312**. In another embodiment, which can be combined with other embodiments described herein, the patterned photoresist **206**, **306** includes at least one device portion **208**, **308**, at least one intermediate portion **210**, **310**, and at least one auxiliary portion **212**, **312**. Each intermediate portion **210**, **310** is between the device portion **208**, **308** and the auxiliary portion **212**, **312**. Each of the least one device portion **208**, **308**, the at least one intermediate portion **210**, **310**, and the at least one auxiliary portion **212**, **312**, exposes unmasked portions **205**, **305** of the structure material layer **202**. As shown in FIGS. **2**C and **2**F, and FIGS. **3**C and **3**F, each device portion **208**, **308** corresponds to one of the optical devices **200**, **300** having arrays of device structures **207** formed on or are integral with a surface **203** of substrate **201**. Each intermediate portion **210**, **310** corresponds to an intermediate region **214**, **314** between the optical devices **200**, **300** and an auxiliary region **216**, **316**. Each auxiliary portion **212**, **312** corresponds to the auxiliary region **216**, **316** of the substrate **201** having arrays of auxiliary structures **209**, **309** also known as dummy structures described in detail herein, formed on or are integral with a surface **203** of substrate **201**. The auxiliary region **216**, **316** is defined by a space defined by each intermediate region **214**, **314** and a periphery of the substrate **201**.

At operation **102**, as shown in FIGS. **2**B and **2**E, and FIGS. **3**B and **3**E, the unmasked portions **205**, **305** of the structure material layer **202** are etched. The etching the unmasked portions **205**, **305** of the structure material layer **202** includes at least one a dry etching process not limited to at least one of ion implantation, ion etching, reactive ion etching (RIE), directional RIE, plasma etching, and wet etching. Etching the unmasked portions **205**, **305** forms the device structures **207** of the optical device **200**, **300**, exposes the surface **203** of substrate **201** in the intermediate region **214**, **314**, and auxiliary structures **209**, **309** of the auxiliary region **216**, **316**. In one embodiment, which can be combined with other embodiments described herein, unmasked portions **211** of the one or more etch layers **204** are etched prior to the unmasked portions **205**, **305** of the structure material layer **202**. In one embodiment, which can be combined with other embodiments described herein, at least one of the etch layers **204** has a greater etch selectivity than the structure material layer **202**. At operation **103**, as shown in FIGS. **2**C and **2**F, and FIGS. **3**C and **3**F, the patterned photoresist **206**, **306** is removed. Removing the patterned photoresist **206**, **306** may include a lithography process or etching process described herein. In the embodiments with the one or more etch layers **204**, the one or more etch layers **204** are removed. Removing the one or more etch layers **204** may include ion etching, RIE, or selective wet chemical etching.

In one embodiment, which can be combined with other embodiments described herein, the device structures **207** may have the same dimensions, such as height and width. In another embodiment, which can be combined with other embodiments described herein, at least one of the device structures **207** may have at least one different dimension, such as one of height and width, from the dimensions of additional structures of the device structures **207**. In some embodiments described herein, the width of each of the device structures **207** is a critical dimension **213**. In some embodiments described herein, the width of each of the auxiliary structures **209**, **309** is a critical dimension **221**, **321**. In one embodiment, which can be combined with other embodiments described herein, the device structures **207** may have the same refractive index. In another embodiment, which can be combined with other embodiments described herein, at least one of the device structures **207** may have a different refractive index than the refractive index of additional structures of the device structures **207**. In some embodiments, which can be combined with other embodiments described herein, the optical devices **200**, **300** are metasurfaces having the device structures **207** that are nanostructures in the form of nanoscale features. In one example, the nanostructures has a critical dimension **213**, **313** less than about 1000 nm, for example, less than about 500 nm, less than about 200 nm, less than about 100 nm or even less than about 20 nm.

The device structures **207** have a device gap **218** defined as a distance between adjacent device structures **207**. In one embodiment, which can be combined with other embodiments described herein, the device gap **218** of each of device structures **207** may be substantially the same. In another embodiment, which can be combined with other embodiments described herein, at least one of the device structures **207** may have at least one different device gap **218**. The auxiliary structures **209**, **309** have an auxiliary gap **219**, **319** defined as a distance between adjacent auxiliary structures **307**, **309**. In one embodiment, which can be combined with other embodiments described herein, the auxiliary gap **219**, **319** of each of auxiliary structures **209**, **309** may be substantially the same. In another embodiment, which can be combined with other embodiments described herein, at least one of the auxiliary structures **209**, **309** may have at least one different auxiliary gap **219**, **319**.

The method **100** forms one or more optical devices **200** over the substrate **201** separated from the auxiliary region **216** by the intermediate region **214**. The optical devices **200** have a relationship between the critical dimension **213** of the device structures **207** and of the critical dimension **221** of the auxiliary structures **209**. For portions of the optical devices **200** and the auxiliary region **216** having a device gap **218** and auxiliary gap **219** that are substantially the same, the critical dimension **213** of the device structures **207** and of the critical dimension **221** of the auxiliary structures **209** are substantially the same. The substantially equal critical dimension **213** and critical dimension **221** of portions having the substantially equal device gap **218** and auxiliary gap **219** provides control of load dependence during the etching of the unmasked portions **205** of the structure material layer **202**. Load dependence denotes the relationship between loading of the patterned photoresist **206**, **306**, i.e., exposure area of the unmasked portions **205**, and the etch rate of the structure material layer **202**.

For the critical dimension **213** of the device structures **207** and of the critical dimension **221** of the auxiliary structures **209** to be substantially equal, a width **223** of the unmasked portions **205** is substantially the same for both the device portion **208** and the auxiliary portion **212** corresponding to portions of the optical devices **200** and the auxiliary region **216** having the device gap **218** and auxiliary gap **219** that are substantially the same. The device portion **208** and the auxiliary portion **212** having the substantially equal width **223** of the unmasked portions **205** provides constant loading of the patterned photoresist **206**. The constant loading provides for endpoint detection during the etching of operation **102** and provides for a critical dimension **213** of the device structures **207** less than about 1000 nm, for example, less than about 500 nm, less than about 200 nm, less than about 100 nm or even less than about 20 nm. Endpoint detection provides the ability to end the etching of operation **102** as soon as the device structures **207** are formed such that the critical dimension **213** and sidewall profile of the device

structures **207** is maintained. As a result of the constant loading of the patterned photoresist **206**, **306**, the critical dimension **213** is substantially the same for the device structures **207** and auxiliary structures **209**. The critical dimension **213** is controlled such that auxiliary structures **209** reduce or obstruct optical interaction of beams with the substrate and the optical devices **200**.

The method **100** forms one or more optical devices **300** over the substrate **201** separated from the auxiliary region **316** by the intermediate region **314**. The optical devices **300** have a relationship between the critical dimension **213** of the device structures **207** and of the critical dimension **321** of the auxiliary structures **309**. For portions of the optical devices **300** and the auxiliary region **316** having a device gap **218** and auxiliary gap **319** that are substantially the same, the critical dimension **213** of the device structures **207** is less than the critical dimension **321** of the auxiliary structures **309**. The critical dimension **213** of the device structures **207** less than the critical dimension **321** of the auxiliary structures **309** provides substantially constant loading of the patterned photoresist **306**. The substantially constant loading provides for endpoint detection during the etching of operation **102** and provides for a critical dimension **213** of the device structures **207** less than about 1000 nm, for example, less than about 500 nm, less than about 200 nm, less than about 100 nm or even less than about 20 nm. As a result of the substantially constant loading of the patterned photoresist **306**, the critical dimension **213** of the device structures **207** is less than a critical dimension **315** of the auxiliary structures **309** and sidewall profile of the device structures **207** is maintained. The critical dimension **315** is controlled such that auxiliary structures **309** reduce or obstruct optical interaction of beams with the substrate and the optical devices **300**.

FIG. **4** is a flow diagram illustrating operations of a method **400** for fabricating one or more optical devices **500**, **600**. FIGS. **5**A-**5**C are schematic, top views of a substrate **201**, and FIGS. **5**D-**5**F are schematic, cross-sectional views of a substrate **201** during the method **400** for fabricating the optical devices **500** according to one embodiment, which can be combined with other embodiments described herein. FIGS. **6**A-**6**C are schematic, top views of a substrate **201**, and FIGS. **6**D-**6**F are schematic, cross-sectional views of a substrate **201** during the method **400** for fabricating the optical devices **600** according to another embodiment, which can be combined with other embodiments described herein.

At operation **401**, as shown in FIGS. **5**A and **5**D, and FIGS. **6**A and **6**D, a photoresist material is disposed over the structure material layer **202**. The structure material layer **202** is disposed over the surface **203** of the substrate **201**. The photoresist material is developed to form a pattered photoresist **506**, **606**. The photoresist material may be disposed over the structure material layer **202** using a spin-on coating process. The photoresist material may include, but is not limited to, light-sensitive polymer containing materials. In one embodiment, which can be combined with other embodiments described herein, at operation **401**, the pattered photoresist **506**, **606** is disposed over one or more etch layers **204**, such as hardmasks or etch stop layers, disposed over the structure material layer **202**. Developing the photoresist material may include performing a lithography process, such as photolithography and digital lithography.

In one embodiment, which can be combined with other embodiments described herein, the patterned photoresist **506**, **606** includes at least one device portion **508**, **608** and at least one auxiliary portion **512**, **612**. In another embodiment, which can be combined with other embodiments described herein, the patterned photoresist **506**, **606** includes at least one device portion **508**, **608**, at least one intermediate portion **510**, **610**, and at least one auxiliary portion **512**, **612**. Each intermediate portion **510**, **610** is between the device portion **508**, **608** and the auxiliary portion **512**, **612**. The at least one device portion **508**, **608** exposes unmasked device portions **505** of the structure material layer **202**. The auxiliary portion **512**, **612** masks, i.e., covers, the structure material layer **202**. The at least one intermediate portion **510**, **610** exposes unmasked intermediate portions **511**, **611** of the structure material layer **202** between the device portion **508**, **608** and the auxiliary portion **512**, **612**. Each of the unmasked intermediate portions **511**, **611** has an unmasked distance **517**, **617** from the device portion **508**, **608** to the auxiliary portion **512**, **612**. In one embodiment, which can be combined with other embodiments described herein, the unmasked distance **517** between each device portion **508** and each auxiliary portion **512** is constant. In another embodiment, which can be combined with other embodiments described herein, the unmasked distance **617** between each device portion **608** and each auxiliary portion **612** is varied.

At operation **402**, as shown in FIGS. **5**B and **5**E, and FIGS. **6**B and **6**E, the unmasked device portions **505** and unmasked intermediate portions **511**, **611** of the structure material layer **202** are etched. The etching the unmasked device portions **505** and unmasked intermediate portions **511**, **611** of the structure material layer **202** includes at least one a dry etching process not limited to at least one of ion implantation, ion etching, reactive ion etching (RIE), directional RIE, plasma etching, and wet etching. Etching the unmasked device portions **505** and unmasked intermediate portions **511**, **611** forms the device structures **207** of the optical device **500**, **600**, and exposes the surface **203** of substrate **201** in an intermediate region **514**, **614** The auxiliary portion **512**, **612** of the patterned photoresist **506**, **606** remains over the structure material layer **202**.

As shown in FIGS. **5**C and **5**D, and FIGS. **6**C and **6**F, each device portion **508**, **608** corresponds to one of the optical devices **500**, **600** having arrays of device structures **207** formed on or are integral with a surface **203** of substrate **201**. Each intermediate portion **510**, **610** corresponds to an intermediate region **514**, **614** between the optical devices **500**, **600** and an auxiliary region **516**, **616**. Each auxiliary portion **512**, **612** corresponds to the auxiliary region **516**, **616** of the substrate **201**. The auxiliary region **516**, **616** is defined by a space defined by each intermediate region **514**, **614** and a periphery of the substrate **201**. The auxiliary portion **512**, **612** of the patterned photoresist **506**, **606** is a dark-field mask over the auxiliary portion **512**, **612**.

In one embodiment, which can be combined with other embodiments described herein, unmasked portions **211** of the one or more etch layers **204** are etched prior to the unmasked device portions **505** and unmasked intermediate portions **511**, **611** of the structure material layer **202**. At operation **403**, as shown in FIGS. **5**C and **5**D, and FIGS. **6**C and **6**F, the device portion **508**, **608** of the patterned photoresist **506**, **506** is removed. Removing the device portion **508**, **608** may include a lithography process or etching process described herein. In the embodiments with the one or more etch layers **204**, the one or more etch layers **204** are removed.

The unmasked distance **517** between each device portion **508** and each auxiliary portion **512** being constant provides loading of the patterned photoresist **506**. The loading provides for endpoint detection during the etching of operation

402 and provides for a critical dimension 213 of the device structures 207 less than about 1000 nm, for example, less than about 500 nm, less than about 200 nm, less than about 100 nm or even less than about 20 nm. The unmasked distance 517 between each device portion 508 and each auxiliary portion 512 corresponds to an exposed distance 521 of the surface 203 between each intermediate region 514 and each auxiliary portion 512 that is constant. The constant exposed distance 521 provides control of optical interaction of the auxiliary portion 512 with light incident on the optical devices 500. The unmasked distance 617 between each device portion 608 and each auxiliary portion 612 being varied provides loading of the patterned photoresist 606. The loading provides for endpoint detection during the etching of operation 402 and provides for a critical dimension 213 of the device structures 207 less than about 1000 nm, for example, less than about 500 nm, less than about 200 nm, less than about 100 nm or even less than about 20 nm. The unmasked distance 617 between each device portion 608 and each auxiliary portion 612 corresponds to an exposed distance 621 of the surface 203 between each intermediate region 614 and each auxiliary portion 612 that is varied. The varied exposed distance 621 provides control of optical interaction of the auxiliary portion 612 with light incident on the optical devices 600. The dark-field mask of the auxiliary portion 512, 612 over the auxiliary portion 512, 612 functions as apertures that prevent beams from degrading the functionality and efficiency of the optical devices 500, 600 by prevention optical interaction of beams with the substrate outside of the optical devices 500, 600.

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.

The invention claimed is:

1. A method, comprising:
disposing a structure material layer on a surface of a substrate;
forming a patterned photoresist over the structure material layer, the patterned photoresist having:
at least one device portion; and
at least one auxiliary portion, wherein each device portion and each auxiliary portion exposes unmasked portions of the structure material layer; and
etching the unmasked portions of structure material layer corresponding to each device portion and each auxiliary portion, wherein the etching the unmasked portions forms:
at least one optical device having one or more arrays of nanostructures disposed on or integral with a surface of a substrate, each of the nanostructures having:
a device critical dimension defined by a width of the nanostructures; and
a device gap defined as a distance between adjacent nanostructures; and
an intermediate region surrounding each optical device, the intermediate region exposing the surface of the substrate, the intermediate region extending a distance greater than the device critical dimension and the device gap, the intermediate region void of nanostructures.

2. The method of claim 1, wherein the device critical dimension is less than 1000 nanometers (nm).

3. The method of claim 1, wherein the at least one auxiliary portion has a dark-field mask disposed on or integral with the surface of the substrate.

4. The method of claim 3, wherein the dark-field mask is at least one of a photoresist or hardmask disposed over an auxiliary structure disposed on the surface of the substrate.

5. The method of claim 4, wherein the hardmask includes at least one of chromium (Cr), silver (Ag), silicon nitride (Si_3N_4), silicon dioxide (SiO_2), titanium nitride (TiN), or carbon (C) containing materials.

6. The method of claim 4, wherein the nanostructures and the auxiliary structure consist of a same material.

7. The method of claim 1, wherein the intermediate region surrounding each optical device is equal in size.

8. The method of claim 1, wherein the intermediate region surrounding each optical device is inconsistent in size.

9. The method of claim 1, wherein the nanostructures comprise 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), zinc stannate (tin oxide) ($SnZnO_3$), silicon nitride (Si_3N_4), niobium oxide (Nb_2O_5), or silicon containing materials.

10. A method, comprising:
disposing a structure material layer on a surface of a substrate;
forming a patterned photoresist over the structure material layer, the patterned photoresist having:
at least one device portion; and
at least one auxiliary portion, wherein each device portion of the at least one device portion and each auxiliary portion of the at least one auxiliary portion exposes unmasked portions of the structure material layer; and
etching the unmasked portions of the structure material layer corresponding to the each device portion and the each auxiliary portion, wherein the etching the unmasked portions forms:
at least one optical device having one or more arrays of device structures corresponding to each device portion disposed on or integral with a surface of the substrate, wherein each device structure comprises:
a device critical dimension defined by a width of the device structures the device critical dimension less than 1000 nanometers (nm); and
a device gap defined as a distance between adjacent device structures; and
the at least one auxiliary portion defined by an intermediate region, the intermediate region disposed around a periphery of each optical device, the at least one auxiliary portion having auxiliary structures corresponding to the each auxiliary portion, the at least one auxiliary portion having a distance greater than a width of the device structures and a width of the auxiliary structures.

11. The method of claim 10, wherein a width of the unmasked portions is the same for both the at least one device portion and the at least one auxiliary portion.

12. The method of claim 11, wherein a device critical dimension of the device structures is equal to an auxiliary critical dimension of the auxiliary structures.

13. The method of claim 10, wherein a width of the unmasked portions of the auxiliary portion is greater than the width of the unmasked portions of the at least one device portion.

14. The method of claim 13, wherein an auxiliary critical dimension of the 14 auxiliary structures is greater than a device critical dimension of the device structures.

15. The method of claim 10, wherein the structure material layer comprises one or more titanium dioxide (TiO2), zinc oxide (ZnO), tin dioxide (SnO2), aluminum-doped zinc oxide (AZO), fluorine-doped tin oxide (FTO), cadmium stannate (tin oxide) (CTO), zinc stannate (tin oxide) (SnZnO3), silicon nitride (Si3N4) and silicon a-Si containing materials.

16. The method of claim 10, wherein the etching the unmasked portions comprises one or more of ion implantation, ion etching, reactive ion etching (RIE), directional RIE, plasma etching, and wet etching.

17. A method, comprising:

disposing a structure material layer on a surface of a substrate;

forming a patterned photoresist over the structure material layer, the patterned photoresist having:

at least one device portion; and

at least one auxiliary portion, wherein each device portion and each auxiliary portion exposes unmasked portions of the structure material layer; and

etching the unmasked portions of structure material layer corresponding to each device portion and each auxiliary portion, wherein the etching the unmasked portions forms:

at least one optical device having one or more arrays of nanostructures disposed on or integral with a surface of a substrate, each of the nanostructures having:

a device critical dimension defined by a width of the nanostructures, the device critical dimension less than 1000 nanometers (nm); and

a device gap defined as a distance between adjacent nanostructures; and

an auxiliary region defined by an intermediate region disposed around a periphery of each optical device, the intermediate region having a width greater than the device critical dimension and the device gap, the auxiliary region void of nanostructures, the auxiliary region having one or more arrays of auxiliary structures disposed on or integral with the surface of the substrate; each of the auxiliary structures having:

an auxiliary critical dimension defined by a width of the auxiliary structures, the auxiliary critical dimension being smaller than the width of the intermediate region; and

an auxiliary gap defined as a distance between adjacent auxiliary structures, the auxiliary gap being smaller than the width of the intermediate region.

18. The method of claim 17, wherein the device critical dimension is less than the auxiliary critical dimension.

19. The method of claim 17, wherein the device critical dimension is equal to the auxiliary critical dimension.

20. The method of claim 17, wherein at least one of the nanostructures or the auxiliary structures comprise one or more of titanium dioxide (TiO2), zinc oxide (ZnO), tin dioxide (SnO2), aluminum-doped zinc oxide (AZO), fluorine-doped tin oxide (FTO), cadmium stannate (tin oxide) (CTO), zinc stannate (tin oxide) (SnZnO3), silicon nitride (Si3N4), niobium oxide (Nb2O5), or silicon containing materials.

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