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(54) **DEVICES AND METHODS FOR VARIABLE ETCH DEPTHS**

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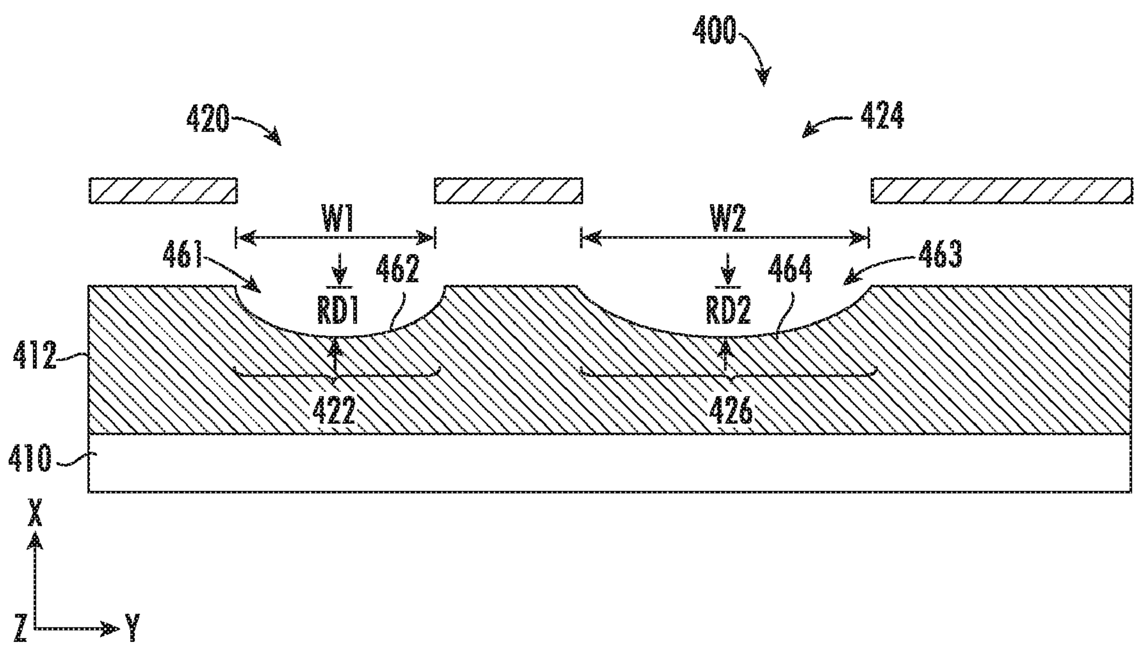
(57) **ABSTRACT**

Methods and devices for producing substrates with variable height features are provided. In one example, a proximity mask may include a plate positioned over a substrate, wherein at least a portion of the plate is separated from the substrate by a distance. The plate may include a first opening and a second opening, wherein the first opening is defined by a first perimeter having a first shape, wherein the second opening is defined by a second perimeter having a second shape, and wherein the first shape is different than the second shape.



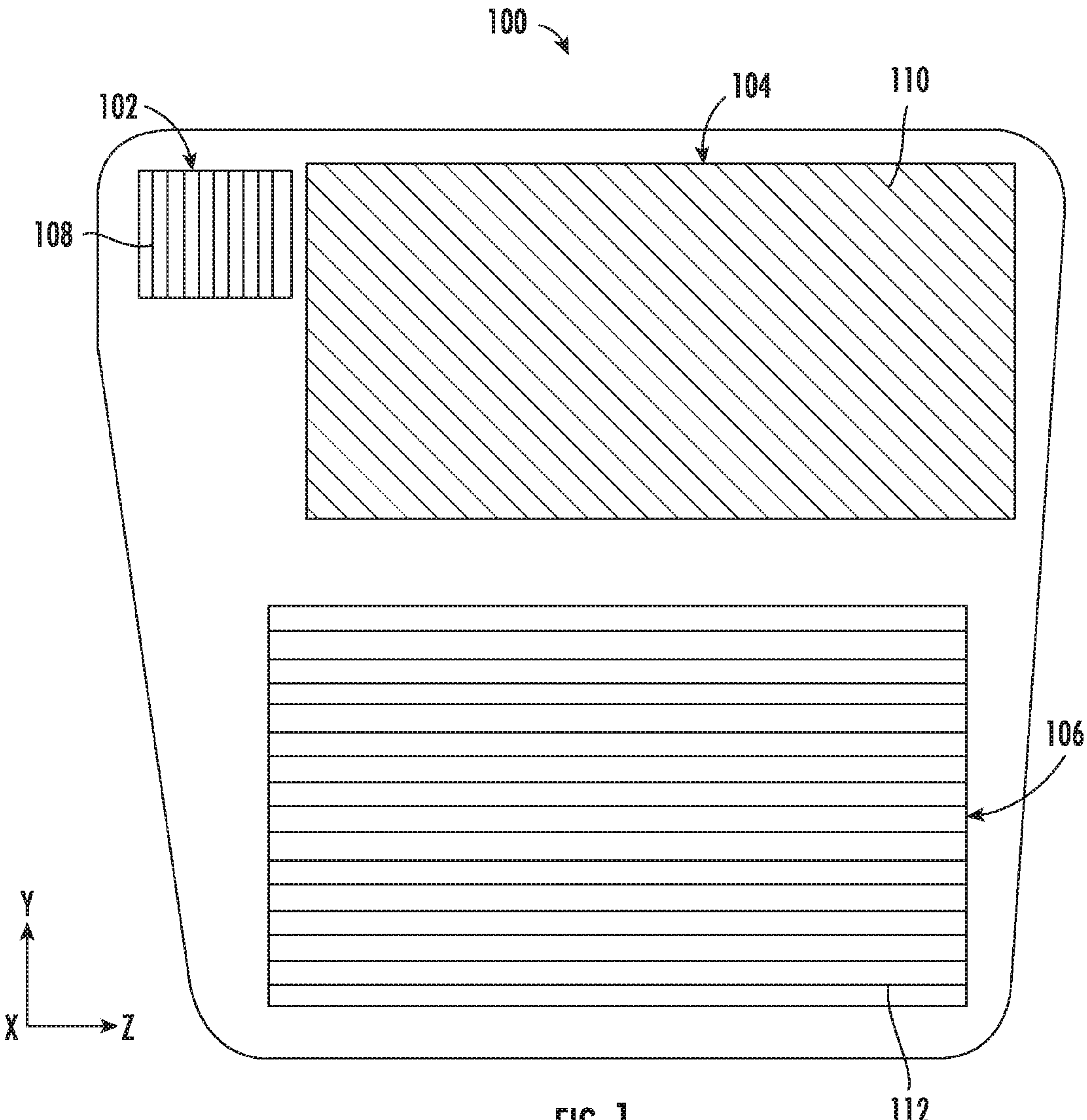


FIG. 1

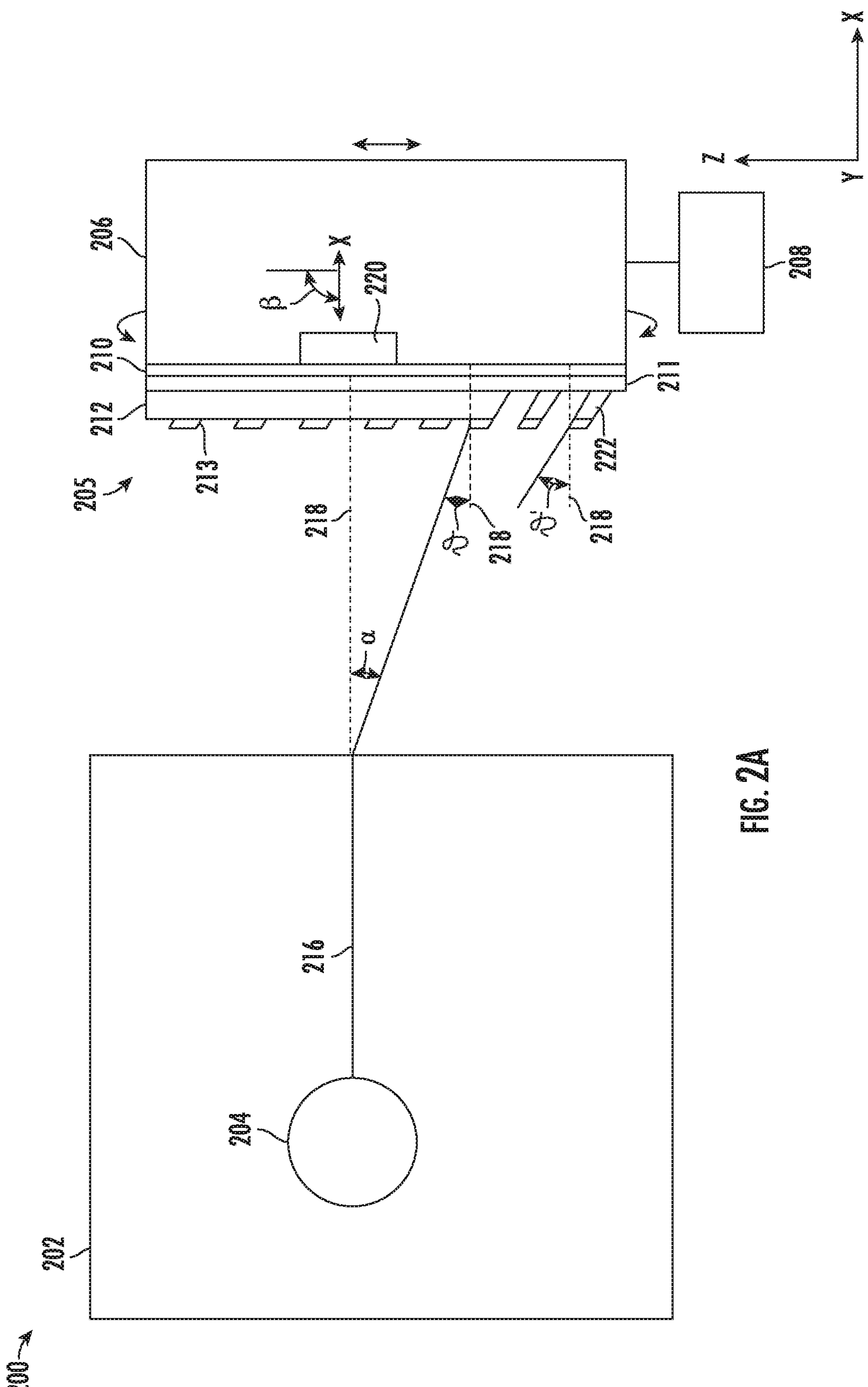


FIG. 2A

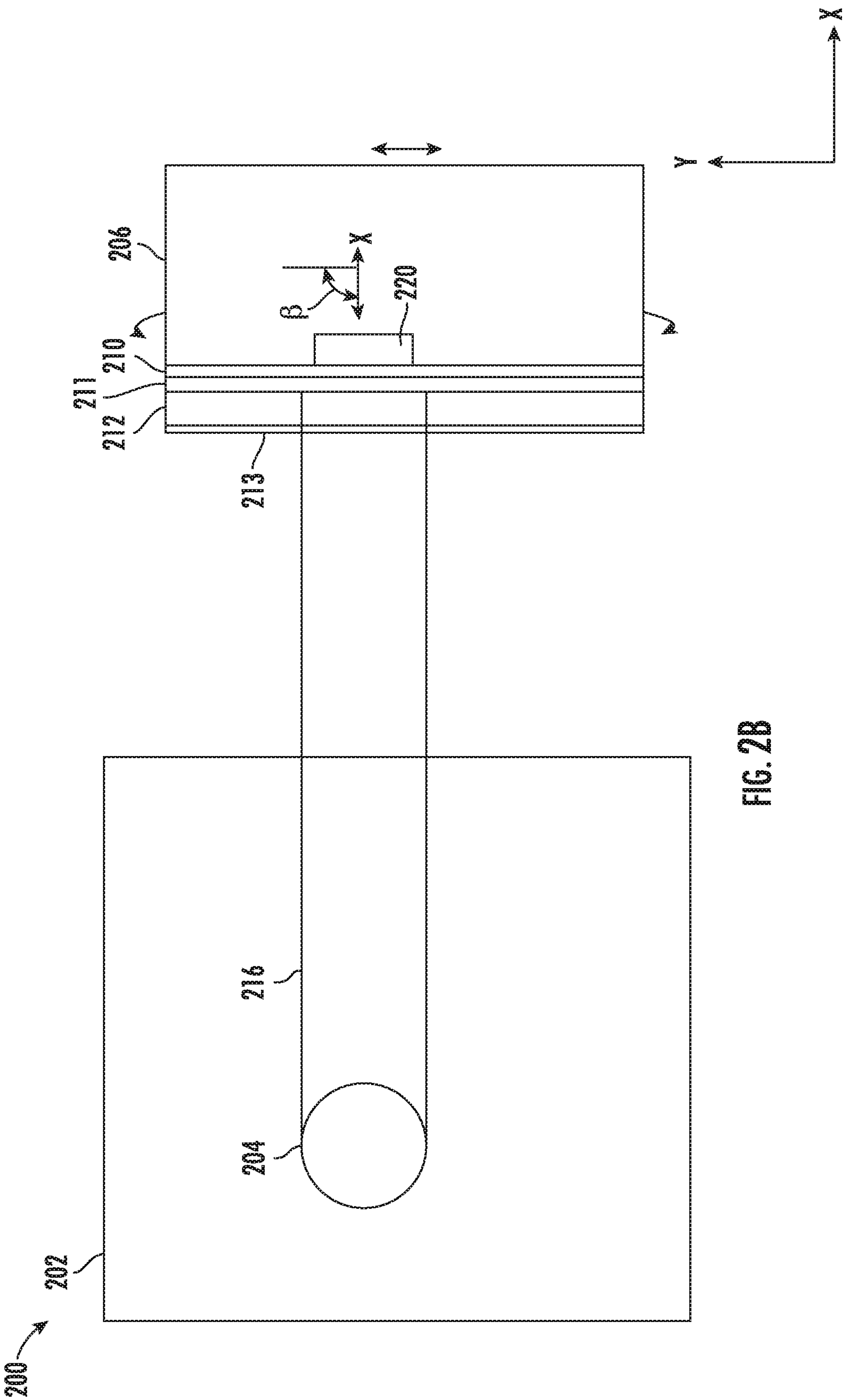


FIG. 2B

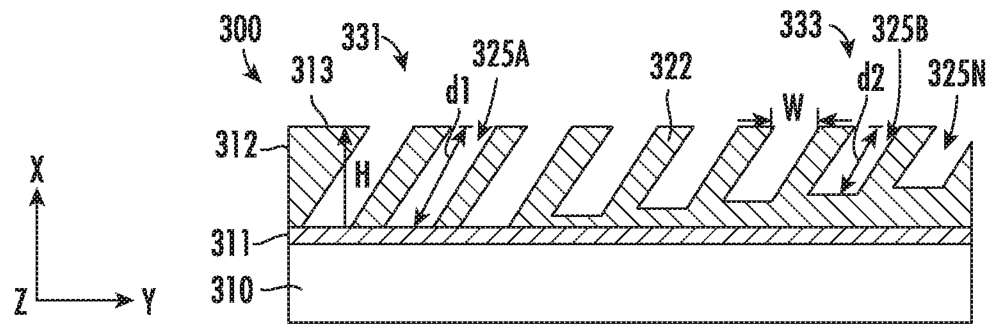

300
331
313
325A
d1
322
333
325B
W
d2
325N
312
H
X
311
Z
Y
310

FIG. 3A

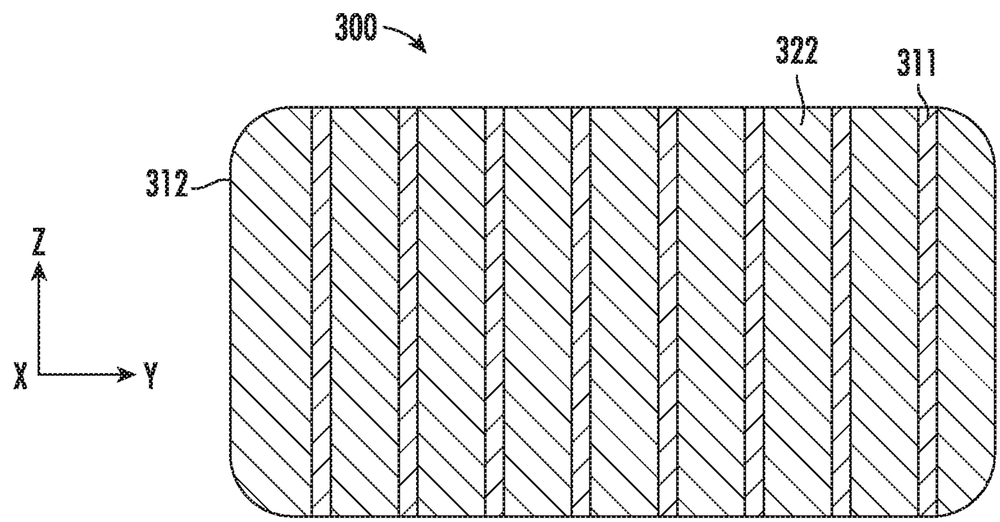

300
322
311
312
Z
X
Y

FIG. 3B

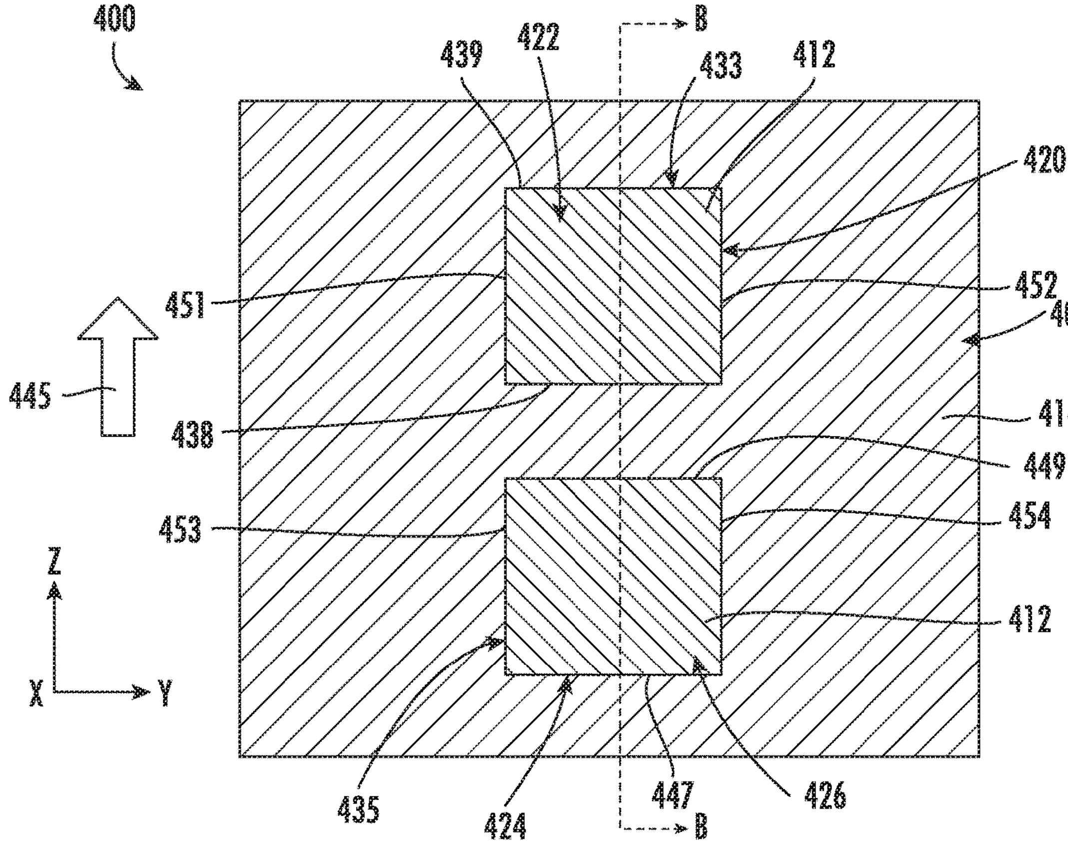

400
439
422
B
433
412
420
451
452
404
445
438
414
449
453
454
Z
412
X
Y
435
424
447
426
B

FIG. 4A

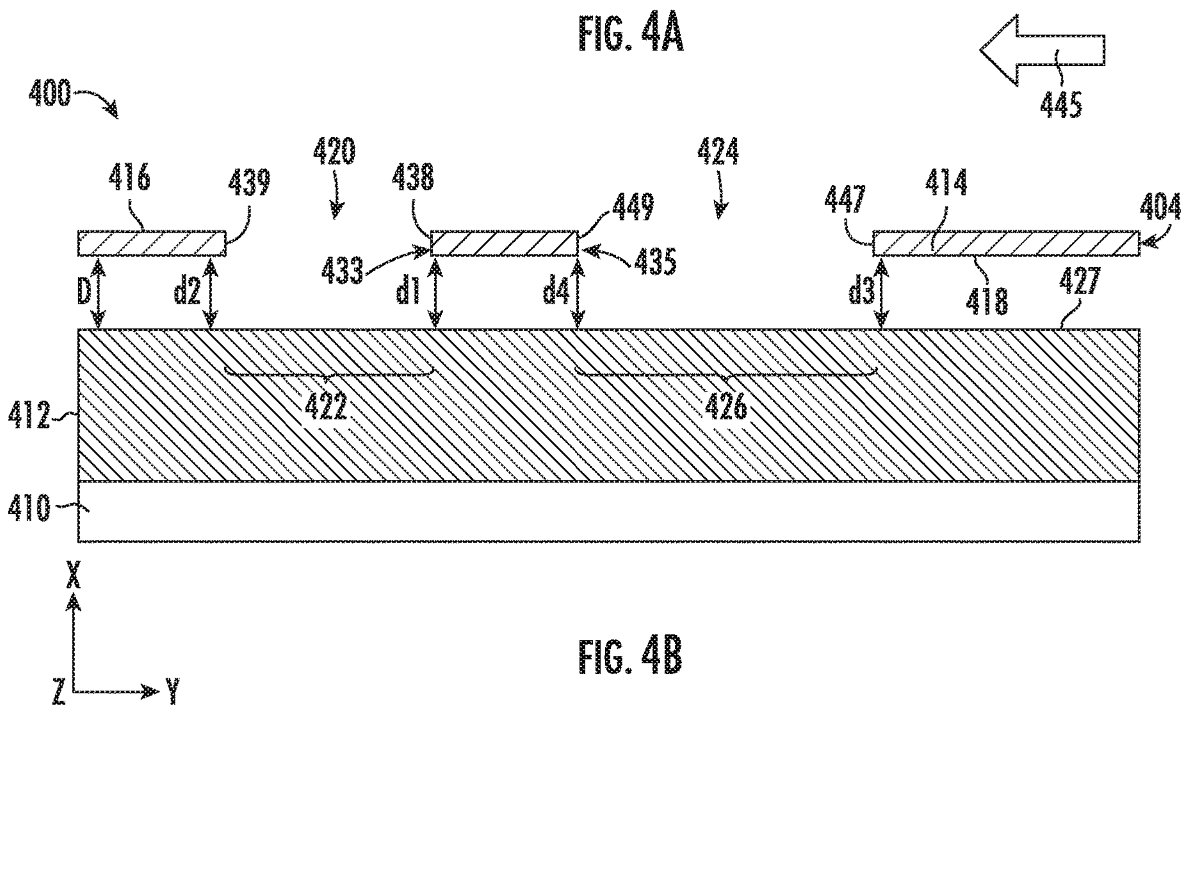
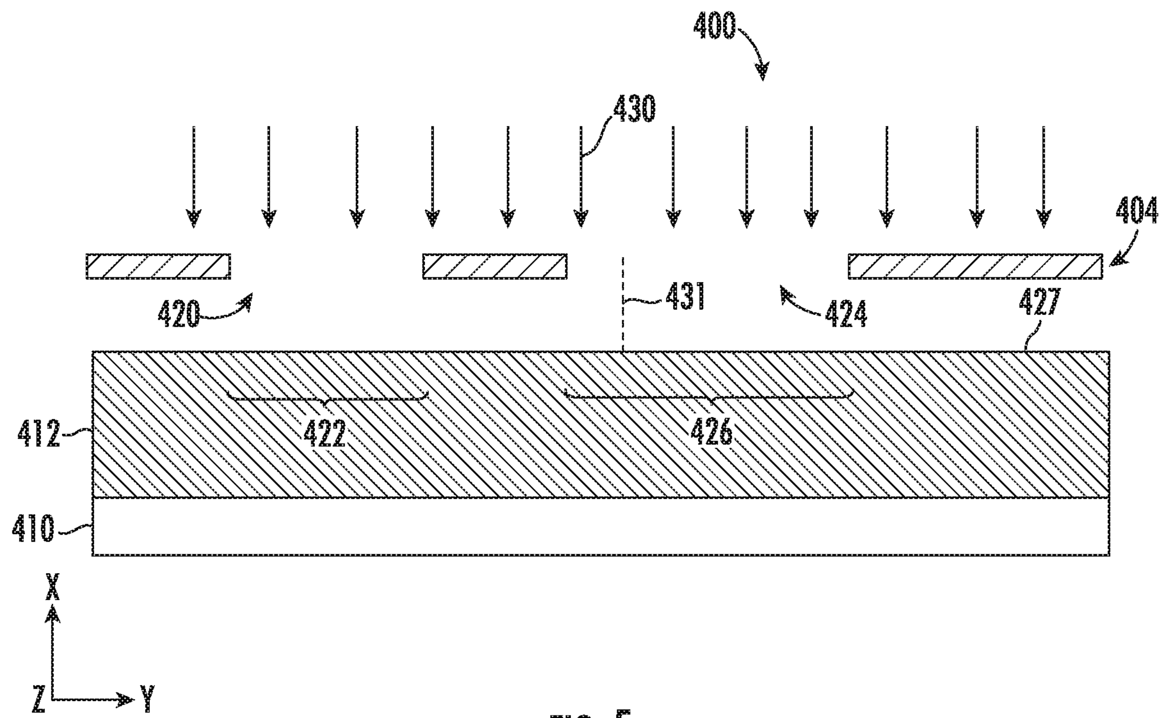

400
445
416
439
420
438
449
424
447
414
404
433
435
D
d2
d1
d4
d3
418
427
422
426
412
410
X
Z
Y

FIG. 4B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430
404
420
431
424
427
412
422
426
410
X
Z
Y

FIG. 5

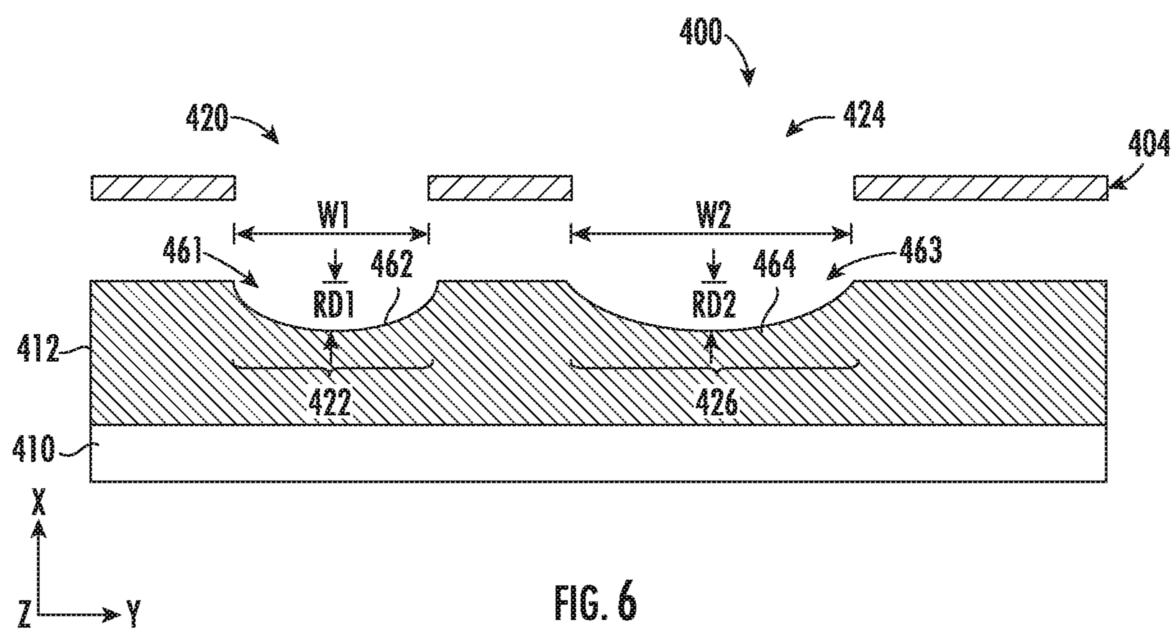
400
420
424
404
W1
W2
461
462
RD1
RD2
464
463
412
422
426
410
X
Z
Y

FIG. 6

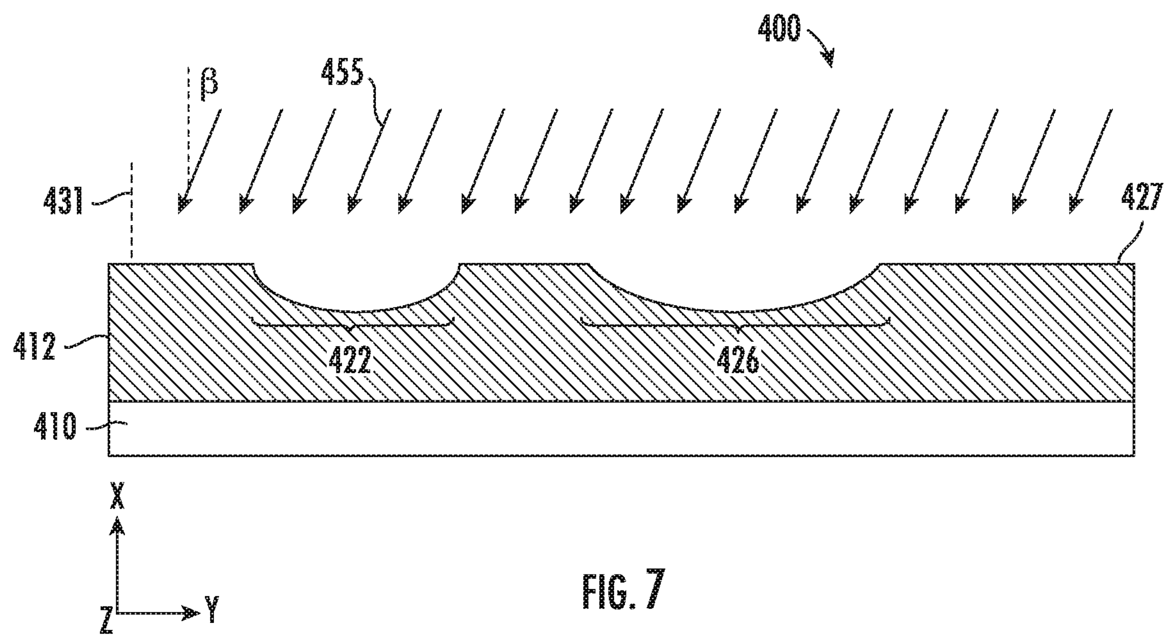
400
β
455
431
427
412
422
426
410
X
Z
Y

FIG. 7

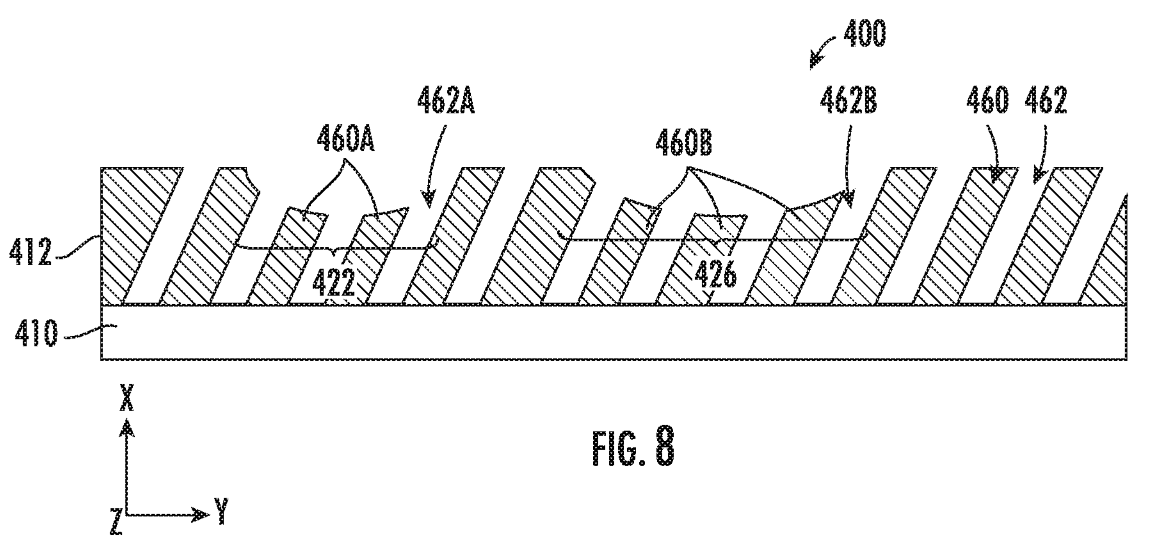
400
462A
462B
460
462
460A
460B
412
422
426
410
X
Z
Y

FIG. 8

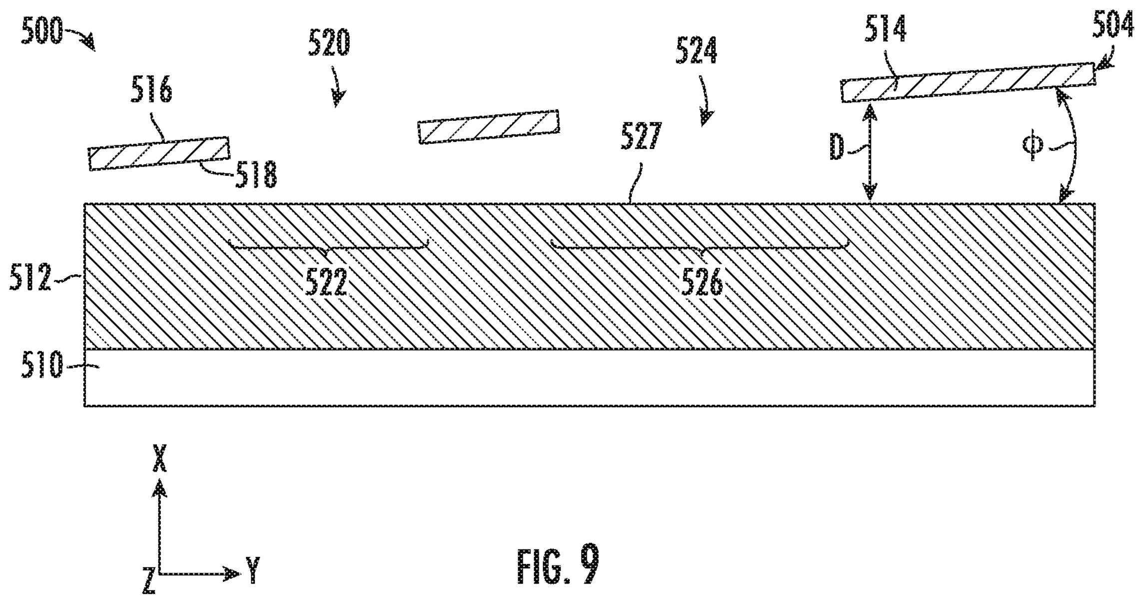
500
520
524
514
504
516
518
527
D
φ
512
522
526
510
X
Z
Y

FIG. 9

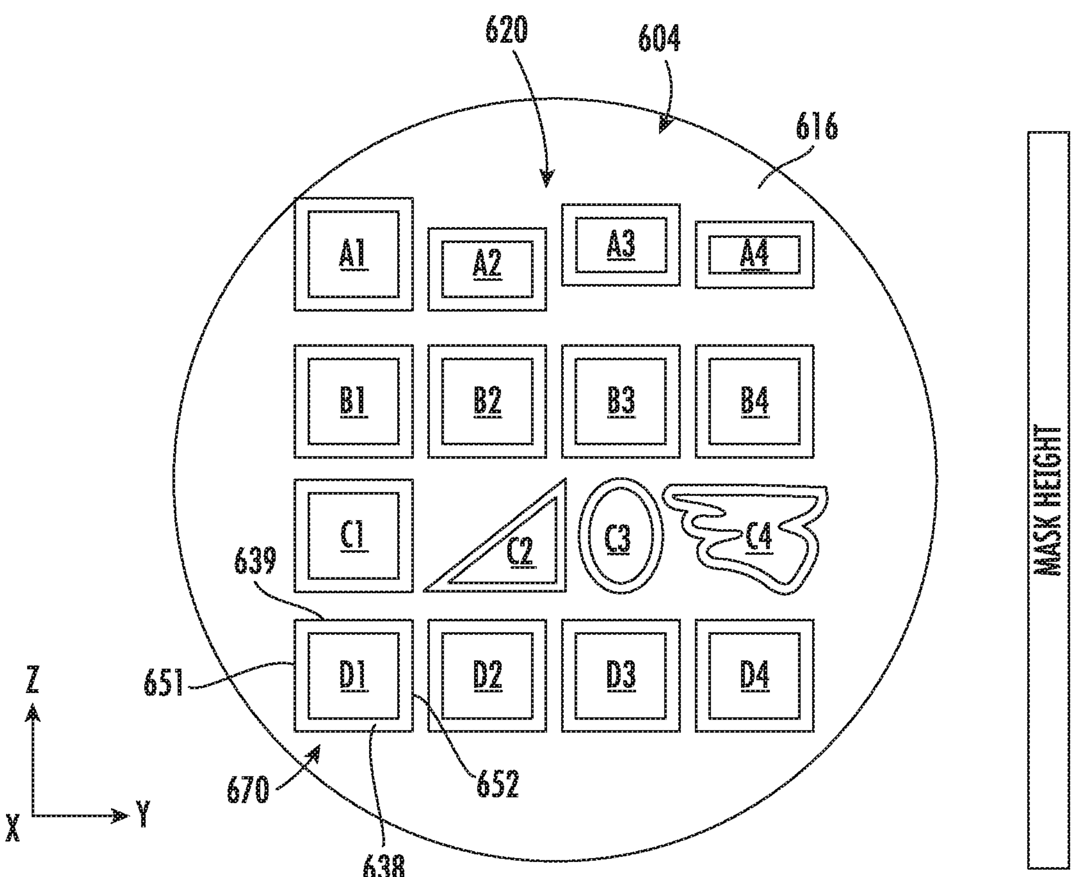
620
604
616
A1
A2
A3
A4
B1
B2
B3
B4
C1
C2
C3
C4
639
651
D1
D2
D3
D4
670
652
638
Z
X
Y
MASK HEIGHT

FIG. 10

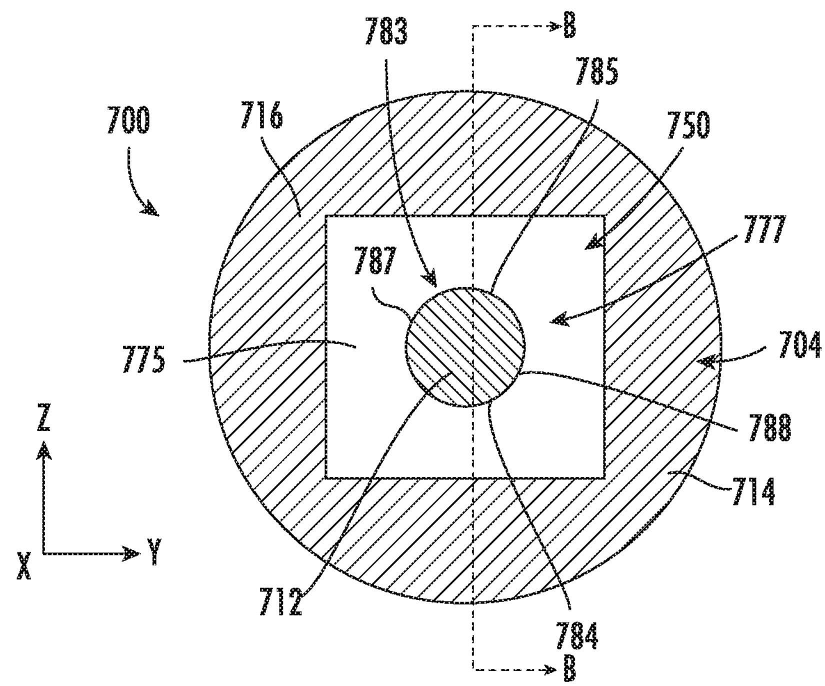

FIG. 11A

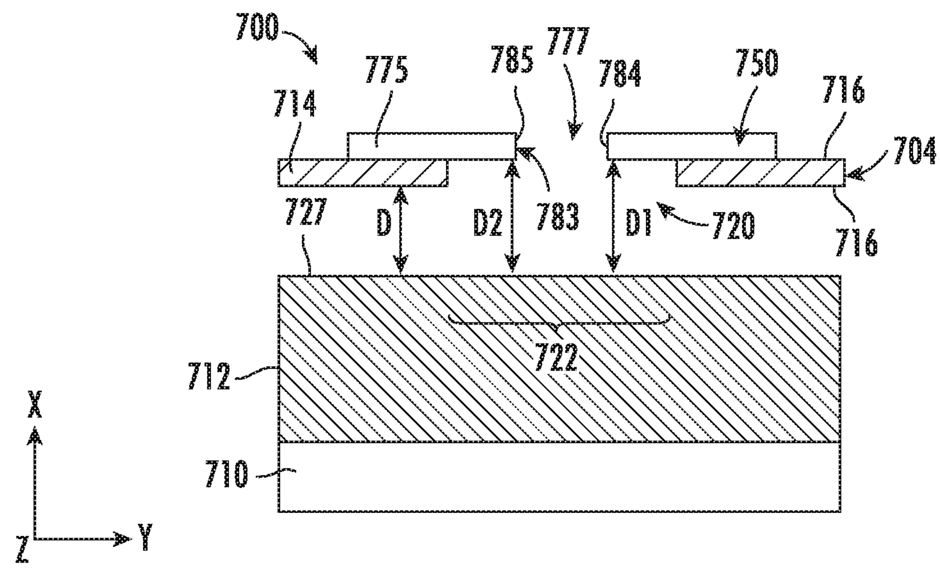

FIG. 11B

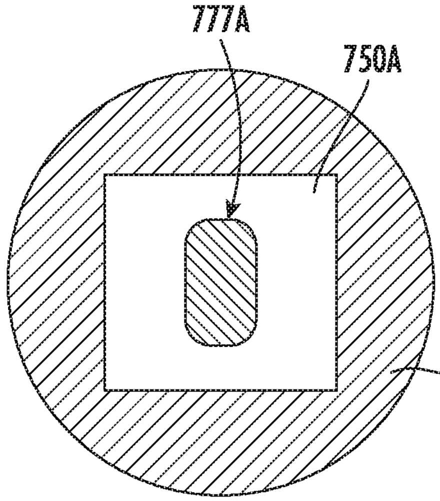

FIG. 12A

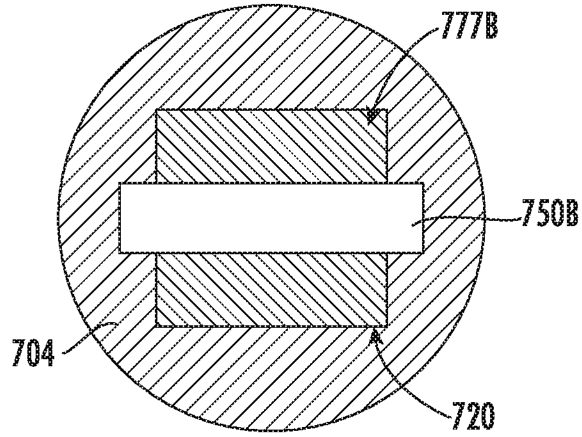

FIG. 12B

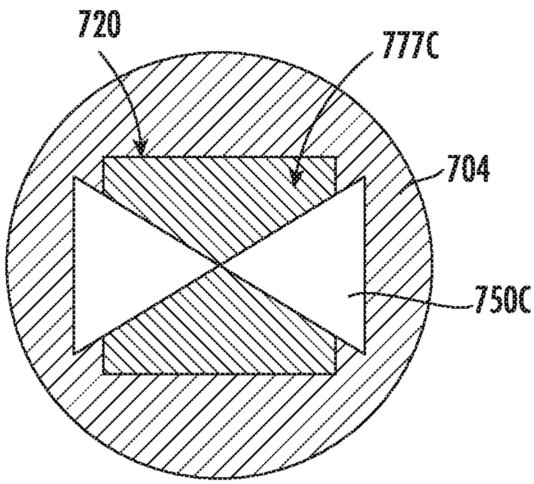

FIG. 12C

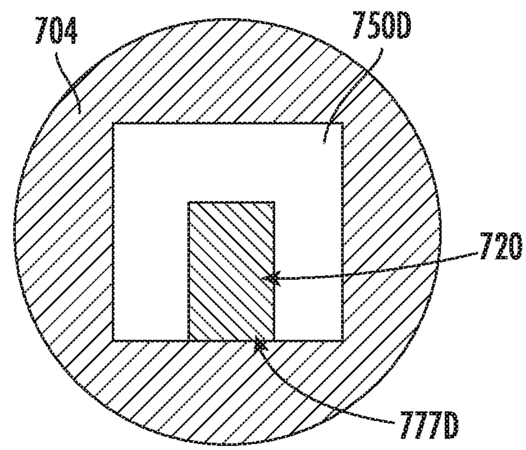

FIG. 12D

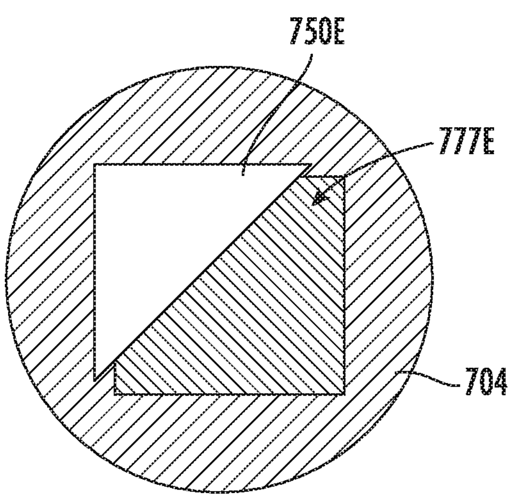

FIG. 12E

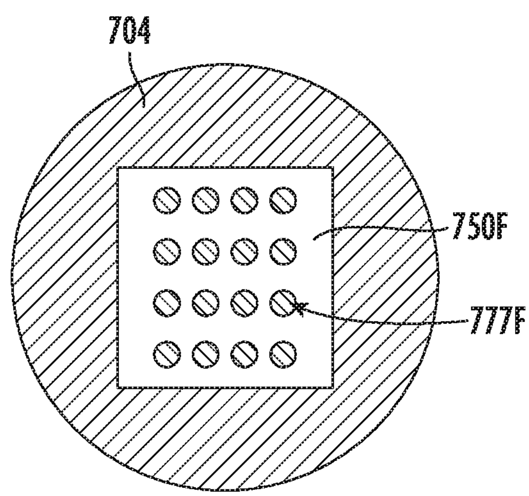

FIG. 12F

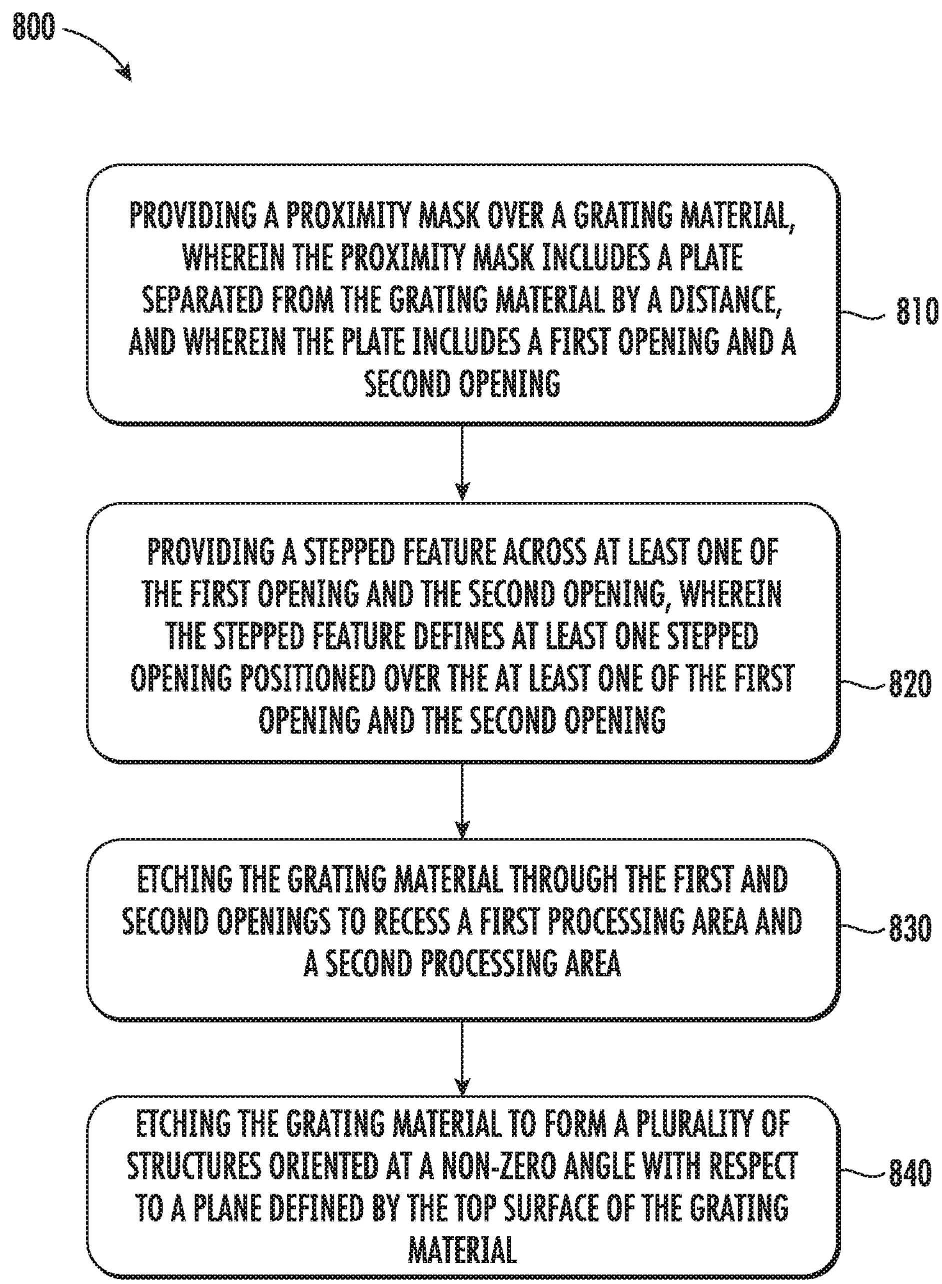
800
PROVIDING A PROXIMITY MASK OVER A GRATING MATERIAL, WHEREIN THE PROXIMITY MASK INCLUDES A PLATE SEPARATED FROM THE GRATING MATERIAL BY A DISTANCE, AND WHEREIN THE PLATE INCLUDES A FIRST OPENING AND A SECOND OPENING
810
PROVIDING A STEPPED FEATURE ACROSS AT LEAST ONE OF THE FIRST OPENING AND THE SECOND OPENING, WHEREIN THE STEPPED FEATURE DEFINES AT LEAST ONE STEPPED OPENING POSITIONED OVER THE AT LEAST ONE OF THE FIRST OPENING AND THE SECOND OPENING
820
ETCHING THE GRATING MATERIAL THROUGH THE FIRST AND SECOND OPENINGS TO RECESS A FIRST PROCESSING AREA AND A SECOND PROCESSING AREA
830
ETCHING THE GRATING MATERIAL TO FORM A PLURALITY OF STRUCTURES ORIENTED AT A NON-ZERO ANGLE WITH RESPECT TO A PLANE DEFINED BY THE TOP SURFACE OF THE GRATING MATERIAL
840

FIG. 13

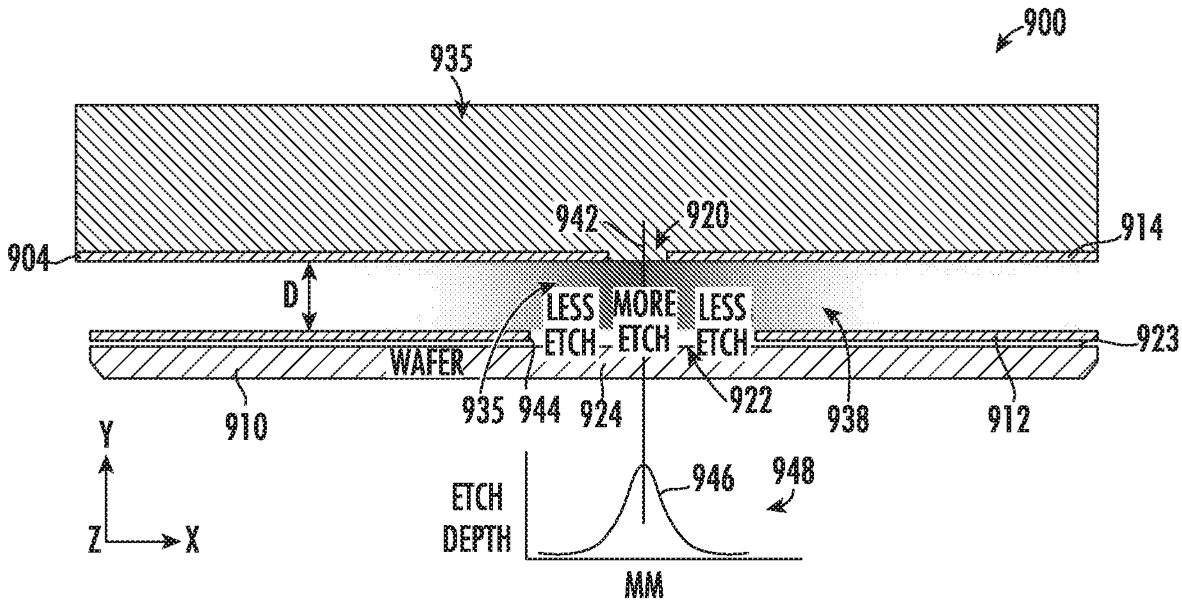

FIG. 14A

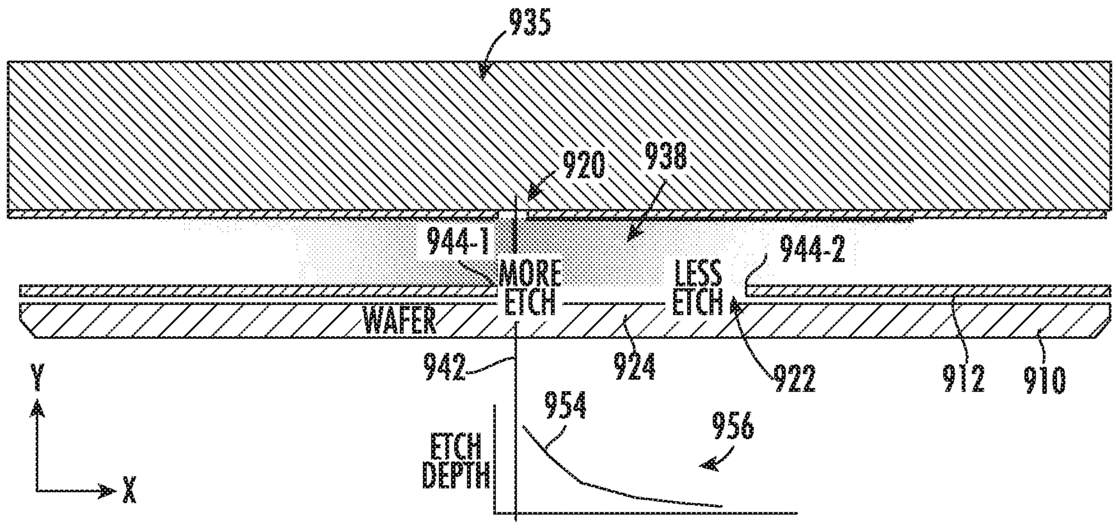

FIG. 14B

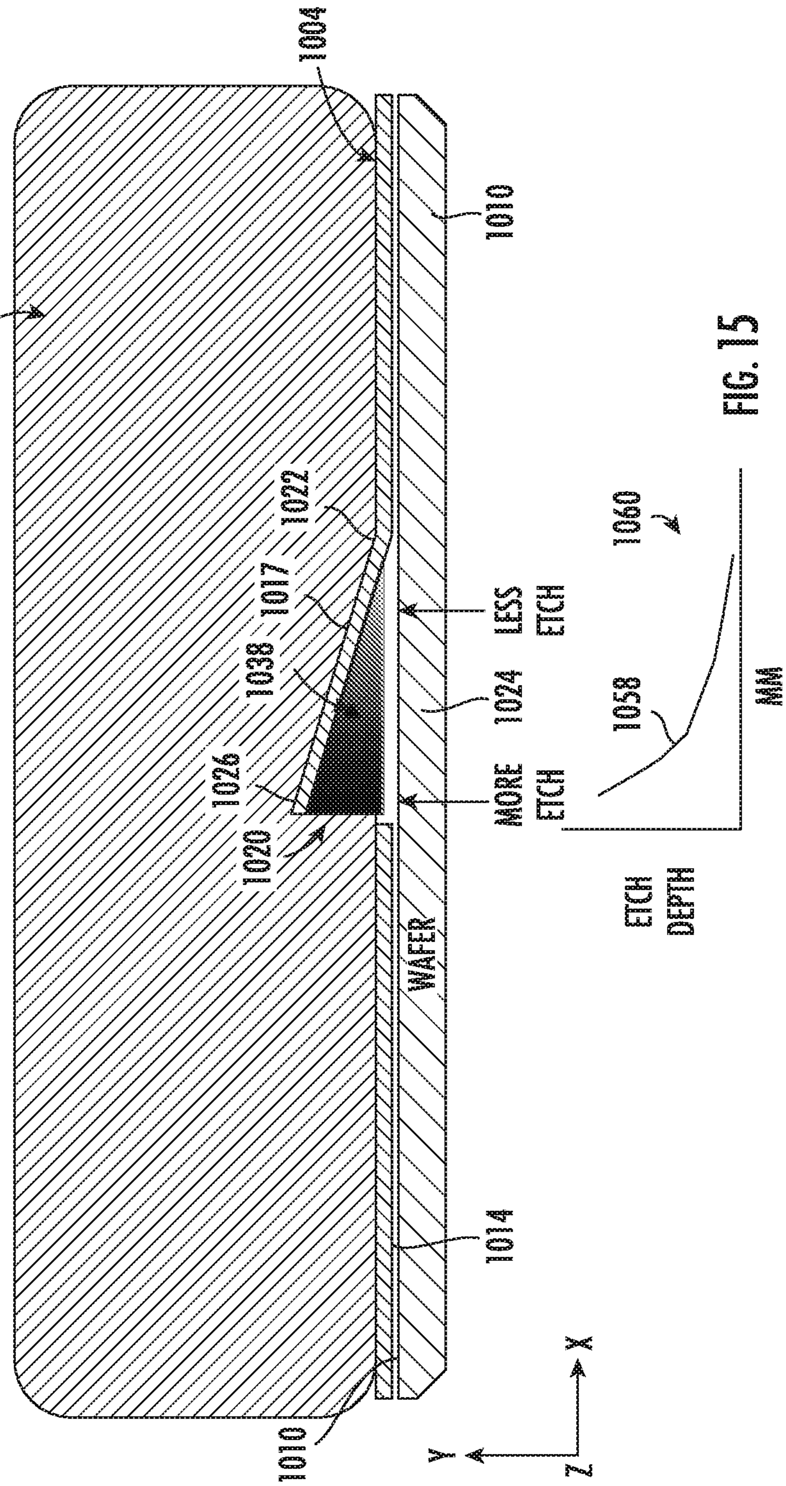
1000
1035
1004
1010
1022
1017
1038
1026
1020
1024
LESS ETCH
MORE ETCH
WAFER
1014
1010
1060
1058
ETCH DEPTH
MM
X
Y
Z

FIG. 15

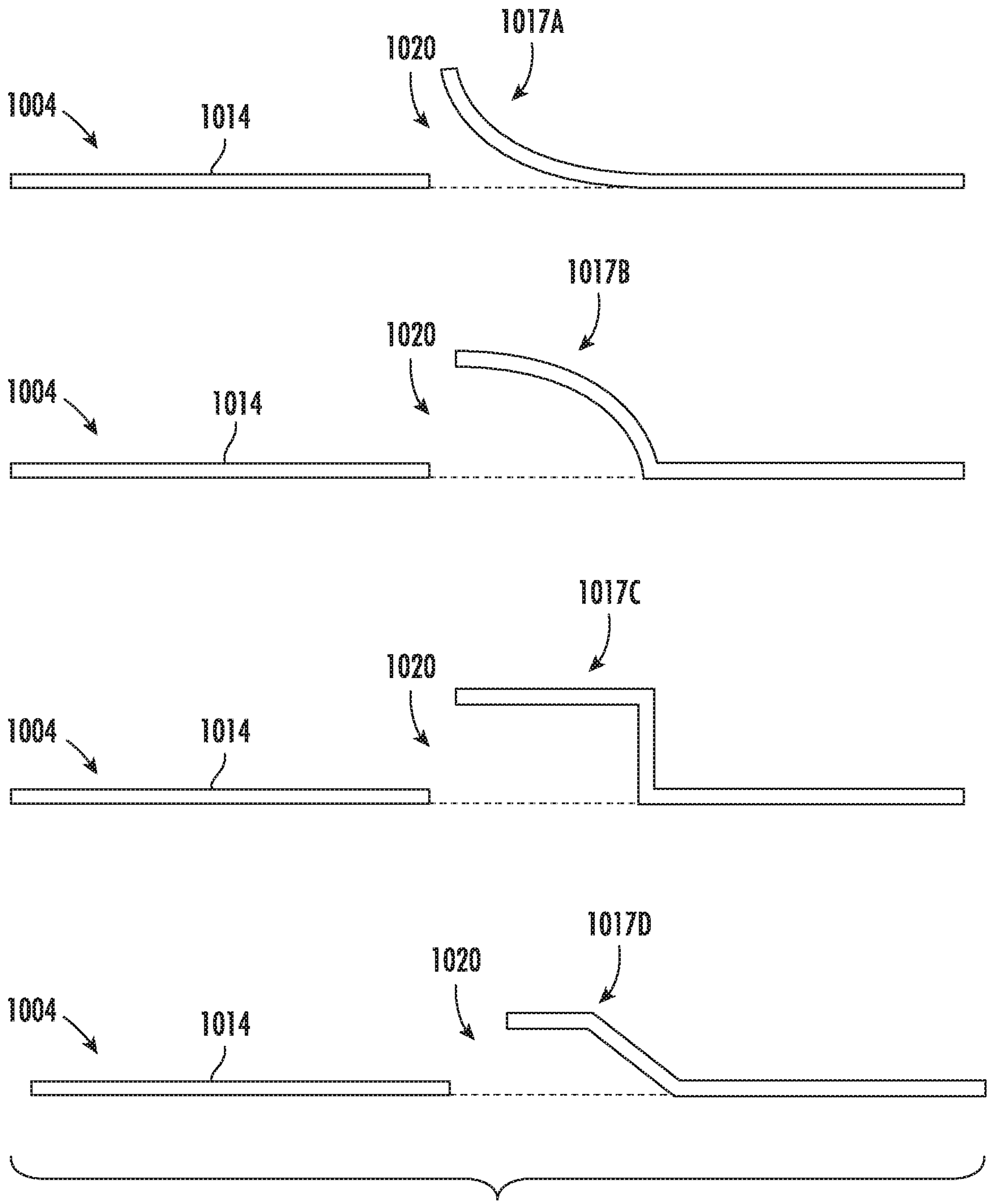
1017A
1020
1004
1014
1017B
1020
1004
1014
1017C
1020
1004
1014
1017D
1020
1004
1014

FIG. 16

DEVICES AND METHODS FOR VARIABLE ETCH DEPTHS

FIELD OF THE DISCLOSURE

[0001] The present disclosure generally relates to processing of substrates. More specifically, the disclosure relates to devices and methods for producing variable-depth grating materials.

BACKGROUND OF THE DISCLOSURE

[0002] Optical elements such as optical lenses have long been used to manipulate light for various advantages. Recently, micro-diffraction gratings have been utilized in holographic and augmented/virtual reality (AR and VR) devices. One particular AR and VR device is a wearable display system, such as a headset, arranged to display an image within a short distance from a human eye. Such wearable headsets are sometimes referred to as head mounted displays, and are provided with a frame displaying an image within a few centimeters of the user's eyes. The image can be a computer-generated image on a display, such as a micro display. The optical components are arranged to transport light of the desired image, where the light is generated on the display to the user's eye to make the image visible to the user. The display where the image is generated can form part of a light engine, so the image generates collimated light beams guided by the optical component to provide an image visible to the user.

[0003] The optical components may include structures with different slant angles, such as fins of one or more gratings, on a substrate, formed using an angled etch system. One example of an angled etch system is an ion beam chamber that houses an ion beam source. The ion beam source is configured to generate an ion beam, such as a ribbon beam, a spot beam, or full substrate-size beam. The ion beam chamber is configured to direct the ion beam at an angle relative to a surface normal of a substrate to generate a structure having a specific slant angle. Changing the slant angle of the structure to be generated by the ion beam requires substantial hardware reconfiguration of the of the ion beam chamber.

[0004] Forming optical devices that include different structures having different depths across the surface of the substrate has conventionally been performed using gray-tone lithography. However, gray-tone lithography is a time-consuming and complex process, which adds considerable costs to devices fabricated using the process.

[0005] Accordingly, improved methods and related equipment are needed for forming optical devices that include different structures with different slant angles and/or different depths across a single substrate.

SUMMARY

[0006] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended as an aid in determining the scope of the claimed subject matter.

[0007] According to one embodiment, a proximity mask may include a plate positioned over a substrate, wherein at least a portion of the plate is separated from the substrate by a distance, and a first opening and a second opening formed through the plate. The first opening may be defined by a first perimeter having a first shape, wherein the second opening is defined by a second perimeter having a second shape, and wherein the first shape is different than the second shape.

[0008] According to another embodiment, a method may include providing a proximity mask over a substrate, wherein the proximity mask includes a plate separated from the substrate by a distance, and wherein the plate includes a first opening and a second opening. The method may further include etching the substrate through the first and second openings to recess a first processing area and a second processing area, and etching the substrate to form a plurality of structures oriented at a non-zero angle with respect to a perpendicular to a plane defined by a top surface of the substrate.

[0009] According to another embodiment, a method may include providing an ion beam source within a chamber, wherein the chamber is operable to deliver an ion beam to a substrate, and providing a proximity mask over the substrate, wherein the proximity mask includes a plate separated from the substrate by a distance, and wherein the plate includes a first opening and a second opening. The method may further include etching the substrate through the first and second openings to recess a first processing area and a second processing area, and etching the substrate to form a plurality of structures oriented at a non-zero angle with respect to a perpendicular to a plane defined by a top surface of the substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The accompanying drawings illustrate exemplary approaches of the disclosure, including the practical application of the principles thereof, as follows:

[0011] FIG. **1** is a perspective, frontal view of an optical device, according to embodiments of the present disclosure;

[0012] FIG. **2**A is a side, schematic cross-sectional view of an angled etch system, according to embodiments of the present disclosure;

[0013] FIG. **2**B is a top, schematic cross-sectional view of the angled etch system shown in FIG. **2**A, according to embodiments of the present disclosure;

[0014] FIG. **3**A depicts a side, cross sectional view of an optical grating component formed from a substrate, according to embodiments of the disclosure;

[0015] FIG. **3**B depicts a frontal view of the optical grating component of FIG. **3**A, according to embodiments of the present disclosure;

[0016] FIG. **4**A is a top view of an optical grating device and proximity mask according to embodiments of the present disclosure;

[0017] FIG. **4**B is a side cross-sectional view of the optical grating device and proximity mask, taken along cutline B-B of FIG. **4**A, according to embodiments of the present disclosure;

[0018] FIG. **5** is a side cross-sectional view of the optical grating device during an etch process according to embodiments of the present disclosure;

[0019] FIG. **6** is a side cross-sectional view of the optical grating device after the etch process according to embodiments of the present disclosure;

[0020] FIG. **7** is a side cross-sectional view of the optical grating device during an etch process according to embodiments of the present disclosure;

[0021] FIG. **8** is a side cross-sectional view of the optical grating device after the etch process according to embodiments of the present disclosure;

[0022] FIG. **9** is a side cross-sectional view of an optical grating device after the etch process according to embodiments of the present disclosure;

[0023] FIG. **10** depicts a proximity mask according to embodiments of the present disclosure;

[0024] FIG. **11**A depicts a top view of a portion of a device including a stepped feature according to embodiments of the present disclosure;

[0025] FIG. **11**B is a side cross-sectional view of the device and stepped feature, taken along cutline B-B of FIG. **11**A, according to embodiments of the present disclosure;

[0026] FIGS. **12**A-**12**F depict various stepped features according to embodiments of the present disclosure;

[0027] FIG. **13** is a flowchart of a method according to embodiments of the present disclosure;

[0028] FIG. **14**A demonstrates a proximity mask, with a centered opening, provided over a mask layer and a wafer, according to embodiments of the present disclosure;

[0029] FIG. **14**B demonstrates a proximity mask, with an off-centered opening, provided over a mask layer and a wafer, according to embodiments of the present disclosure;

[0030] FIG. **15** depicts a proximity mask of a device according to another embodiment of the present disclosure; and

[0031] FIG. **16** demonstrates various features of proximity masks according to embodiments of the present disclosure.

[0032] The drawings are not necessarily to scale. The drawings are merely representations, not intended to portray specific parameters of the disclosure. The drawings are intended to depict exemplary embodiments of the disclosure, and therefore are not be considered as limiting in scope. In the drawings, like numbering represents like elements.

[0033] Furthermore, certain elements in some of the figures may be omitted, or illustrated not-to-scale, for illustrative clarity. The cross-sectional views may be in the form of "slices", or "near-sighted" cross-sectional views, omitting certain background lines otherwise visible in a "true" cross-sectional view, for illustrative clarity. Furthermore, for clarity, some reference numbers may be omitted in certain drawings.

DETAILED DESCRIPTION

[0034] Devices, systems, and methods in accordance with the present disclosure will now be described more fully hereinafter with reference to the accompanying drawings, where various embodiments are shown. The devices, systems, methods may be embodied in many different forms and are not to be construed as being limited to the embodiments set forth herein. Instead, these embodiments are provided so the disclosure will be thorough and complete, and will fully convey the scope of the apparatuses, systems, and methods to those skilled in the art.

[0035] FIG. **1** is a perspective, frontal view of a device **100**, such as an optical device, according to embodiments of the present disclosure. Examples of the optical device **100** include, but are not limited to, a flat optical device and a waveguide (e.g., a waveguide combiner). The optical device **100** includes one or more structures, such as gratings. In one embodiment, which can be combined with other embodiments described herein, the optical device **100** includes an input grating **102**, an intermediate grating **104**, and an output grating **106**. Each of the gratings **102**, **104**, **106** includes corresponding structures **108**, **110**, **112** (e.g., fins). In one embodiment, which can be combined with other embodiments described herein, the structures **108**, **110**, **112** and depths between the structures include sub-micron critical dimensions (e.g., nano-sized critical dimensions), which may vary in one or more dimensions across the optical device **100**.

[0036] FIG. **2**A is a side, schematic cross-sectional view and FIG. **2**B is a top, schematic cross-sectional view of an angled etch system (hereinafter "system") **200**, such as the Varian VIISta® system available from Applied Materials, Inc. located in Santa Clara, Calif. It is to be understood that the system **200** described below is an exemplary angled etch system and other angled etch systems, including angled etch systems from other manufacturers, may be used to or modified to form the structures described herein on a substrate.

[0037] FIGS. **2**A-**2**B show a device **205** disposed on a platen **206**. The device **205** may include a substrate **210**, an etch stop layer **211** disposed over the substrate **210**, an etching layer to be etched, such as a grating material **212** disposed over the etch stop layer **211**, and a hardmask **213** disposed over the grating material **212**. It will be appreciated that the device **205** may include different layering materials and/or combinations in other embodiments. For example, the hardmask **213** may not be present in some cases. In another example, the etching layer may be a blanket film to be processed, such as a photoresist-type material or an optically transparent material (e.g., silicon or silicon nitride). The blanket film may be processed using a selective area processing (SAP) etch cycle(s) to form one or more sloped or curved surfaces of the device **205**. In another embodiment, the etch stop layer **211** may not be present.

[0038] To form structures (e.g., fins) **222** having slant angles, the grating material **212** may be etched by the system **200**. In one embodiment, the grating material **212** is disposed on the etch stop layer **211** disposed on the substrate **210**. In one embodiment, the one or more materials of the grating material **212** are selected based on the slant angle of each structure to be formed and the refractive index of the substrate **210**. In some embodiments, the grating material **212** includes one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), indium tin oxide (ITO), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), titanium nitride (TiN), and/or zirconium dioxide (ZrO_2) containing materials. The grating material **212** can have a refractive index between about 1.5 and about 2.65.

[0039] In some embodiments, the hardmask **213** is a non-transparent hardmask that is removed after the device **205** is formed. For example, the non-transparent hardmask **213** can include reflective materials, such as chromium (Cr) or silver (Ag). In another embodiment, the patterned hardmask **213** is a transparent hardmask. In one embodiment, the etch stop layer **211** is a non-transparent etch stop layer that is removed after the device **205** is formed. In another embodiment, the etch stop layer **211** is a transparent etch stop layer.

[0040] The system **200** may include an ion beam chamber **202** that houses an ion beam source **204**. The ion beam source **204** is configured to generate an ion beam **216**, such as a ribbon beam, a spot beam, or full substrate-size beam. The ion beam chamber **202** is configured to direct the ion beam **216** at a first ion beam angle α relative to a surface normal **218** of the substrate **210**. Changing the first ion beam angle α may require reconfiguration of the hardware of the ion beam chamber **202**. The substrate **210** is retained on a platen **206** coupled to a first actuator **208**. The first actuator **208** is configured to move the platen **206** in a scanning motion along a y-direction and/or a z-direction. In one embodiment, the first actuator **208** is further configured to tilt the platen **206**, such that the substrate **210** is positioned at a tilt angle β relative to the x-axis of the ion beam chamber **202**. In some embodiments, the first actuator **208** can further be configured to tilt the platen **206** relative to the y-axis and/or z-axis.

[0041] The first ion beam angle α and the tilt angle β result in a second ion beam angle ϑ relative to the surface normal **218** of the substrate **210** after the substrate **210** is tilted. To form structures having a slant angle ϑ' relative to the surface normal **218**, the ion beam source **204** generates an ion beam **216** and the ion beam chamber **202** directs the ion beam **216** towards the substrate **210** at the first ion beam angle α. The first actuator **208** positions the platen **206**, so that the ion beam **216** contacts the grating material **212** at the second ion beam angle ϑ and etches the grating material **212** to form the structures having a slant angle ϑ' on desired portions of the grating material **212**.

[0042] Conventionally, to form a portion of structures with a slant angle ϑ' different than the slant angle ϑ' of an adjacent portion of structures, or to form structures having a different slant angle ϑ' on successive substrates, the first ion beam angle α is changed, the tilt angle β is changed, and/or multiple angled etch systems are used. Reconfiguring the hardware of the ion beam chamber **202** to change the first ion beam angle α is complex and time-consuming. Adjusting tilt angle β to modify the ion beam angle ϑ results in non-uniform depths of structures across portions of the substrate **210** as the ion beam **216** contacts the grating material **212** with different energy levels. For example, a portion positioned closer to the ion beam chamber **202** will have structures with a greater depth than structures of an adjacent potion positioned further away from the ion beam chamber **202**. Using multiple angled etch systems increases the fabrication time and increases costs due the need of multiple chambers. To avoid reconfiguring the ion beam chamber **202**, adjusting the tilt angle β to modify the ion beam angle ϑ, and using multiple angled etch systems, the angled etch system **200** may include a second actuator **220** coupled to the platen **206** to rotate the substrate **210** about the x-axis of the platen **206** to control the slant angle ϑ' of structures.

[0043] During use, the ion beam **216** may be extracted when a voltage difference is applied using a bias supply between the ion beam chamber **202** and substrate **210**, or substrate platen, as in known systems. The bias supply may be coupled to the ion beam chamber **202**, for example, where the ion beam chamber **202** and substrate **210** are held at the same potential.

[0044] The trajectories of ions within the ion beam **216** may be mutually parallel to one another or may lie within a narrow angular spread range, such as within 10 degrees of one another or less. In other embodiments, the trajectory of ions within the ion beam **216** may converge or diverge from one another, for example, in a fan shape. In various embodiments, the ion beam **216** may be provided as a ribbon reactive ion beam extracted as a continuous beam or as a pulsed ion beam, as in known systems.

[0045] In various embodiments, gas, such as reactive gas, may be supplied by a source to the ion beam chamber **202**. The plasma may generate various etching species or depositing species, depending upon the exact composition of species provided to the ion beam chamber **202**. The ion beam **216** may be composed of any convenient gas mixture, including inert gas, reactive gas, and may be provided in conjunction with other gaseous species in some embodiments. In some embodiments, the ion beam **216** and other reactive species may be provided as an etch recipe to the substrate **210** so as to perform a directed reactive ion etching (RIE) of a layer, such as the grating material **212**. Such an etch recipe may use known reactive ion etch chemistries for etching materials such as oxide or other material, as known in the art. In other embodiments, the ion beam **216** may be formed of inert species where the ion beam **216** is provided to etch the substrate **210** or more particularly, the grating material **212**, by physical sputtering, as the substrate **210** is scanned with respect to ion beam **216**.

[0046] FIG. **3**A depicts a side cross sectional view of an optical grating component **300** formed from the grating material **312** according to embodiments of the disclosure. FIG. **3**B depicts a frontal view of the optical grating component **300**. As shown, the optical grating component **300** includes a substrate **310**, and the optical grating material **312** disposed on the substrate **310**. The optical grating component **300** may be the same or similar to the input grating **102**, the intermediate grating **104**, and/or the output grating **106** of FIG. **1**. In some embodiments, the substrate **310** is an optically transparent material, such as a known glass. In some embodiments, the substrate **310** is silicon. In the latter case, the substrate **310** is silicon, and another process is used to transfer grating patterns to a film on the surface of another optical substrate, such as glass or quartz. The embodiments are not limited in this context. In the non-limiting embodiment of FIG. **3**A and FIG. **3**B, the optical grating component **300** further includes an etch stop layer **311**, disposed between the substrate **310** and the grating material **312**. In other embodiments, no etch stop layer is present between the substrate **310** and the grating material **312**.

[0047] In some embodiments, the optical grating component **300** may include a plurality of angled structures, shown as angled components or structures **322** separated by trenches **325**A-**325**N. The structures **322** may be disposed at a non-zero angle of inclination (ϕ) with respect to a perpendicular to a plane (e.g., y-z plane) of the substrate **310** and the top surface **313** of the grating material **312**. The angled structures **322** may be included within one or more fields of slanted gratings, the slanted grating together forming "micro-lenses."

[0048] In the example of FIG. **3**A, the angled structures **322** and the trenches **325**A-**325**N define a variable height along the direction parallel to the y-axis. For example, a depth 'd**1**' of a first trench **325**A in a first portion **331** of the optical grating component **300** may be different than a depth 'd**2**' of a second trench **325**B in a second portion **333** of the optical grating component **300**. In some embodiments, a width of the angled structures **322** and/or the trenches **325** may also vary, e.g., along the y-direction.

[0049] The angled structures **322** may be accomplished by scanning the substrate **310** with respect to the ion beam using a processing recipe. In brief, the processing recipe may entail varying at least one process parameter of a set of process parameters, having the effect of changing, e.g., the etch rate or deposition rate caused by the ion beam during scanning of the substrate **310**. Such process parameters may include the scan rate of the substrate **310**, the ion energy of the ion beam, duty cycle of the ion beam when provided as a pulsed ion beam, the spread angle of the ion beam, and rotational position of the substrate **310**. The etch profile may be further altered by varying the ion beam quality across the mask. Quality may include intensity/etch rate such as varying current with duty cycle or beam shape for different angles. In at least some embodiments herein, the processing recipe may further include the material(s) of the grating material **312**, and the chemistry of the etching ions of the ion beam. In yet other embodiments, the processing recipe may include starting geometry of the grating material **312**, including dimensions and aspect ratios. The embodiments are not limited in this context.

[0050] Turning now to FIGS. **4A-8**, a process for forming an optical grating device (hereinafter "device") **400** according to embodiments of the present disclosure will be described in greater detail. As shown in FIGS. **4A-4B**, a proximity mask **404** is provided over a substrate layer **412** and a base substrate **410**. In some embodiments, the proximity mask **404** may be formed directly atop the base substrate **410** when the substrate layer **412** is not present. The proximity mask **404** may include a plate **414** patterned or otherwise processed to include to a first opening **420**, which is positioned over a first processing area **422** of the substrate layer **412**, and a second opening **424**, which is positioned over a second processing area **426** of the substrate layer **412**. It will be appreciated that the first and second processing areas **422**, **426** may correspond to areas of the substrate layer **412** where optical gratings or other semiconductor trenches/structures are to be formed. Although not shown, the proximity mask **404** may further include a third opening defining a third processing area.

[0051] In some embodiments, the substrate layer **412** may be an optical grating material made from one or more of silicon oxycarbide (SiOC), titanium dioxide (TiO_2), silicon dioxide (SiO_2), vanadium (IV) oxide (VOx), aluminum oxide (Al_2O_3), indium tin oxide (ITO), zinc oxide (ZnO), tantalum pentoxide (Ta_2O_5), silicon nitride (Si_3N_4), titanium nitride (TiN), and/or zirconium dioxide (ZrO_2) containing materials. Although not shown, the substrate layer **412** may be formed over an etch stop layer, which is formed atop the base substrate **410**.

[0052] The plate **414** may include a first main side **416** opposite a second main side **418**, wherein the second main side **418** faces the substrate layer **412**. In some embodiments, a plane defined by the first main side **416** may be substantially parallel to a plane defined by the second main side **418**. The plate **414** may be separated from a top surface **427** of the substrate layer **412** by a distance 'D' (e.g., along the x-direction). The distance D may be constant across the plate **414**, or the distance D may vary at different spots along the plate **414**. In some embodiments, the plate **414** may be in direct physical contact with the substrate layer **412** at one or more points.

[0053] The first opening **420** may be defined by a first perimeter **433** having a first shape, and the second opening **424** may be defined by a second perimeter **435** having a second shape. As will be described in greater detail herein, the first and second shapes may be the same or different. The first perimeter **433** may include a first leading edge **438** and a first trailing edge **439**, e.g., relative to a scan direction **445**. The first leading edge **438** may be separated from the top surface **427** of the substrate layer **412** by a distance 'd**1**' (e.g., in the x-direction), while the first trailing edge **439** may be separated from the top surface **427** of the substrate layer **412** by a distance 'd**2**'. In various embodiments d**1** and d**2** are the same or different. Similarly, the second perimeter **435** may include a second leading edge **447** and a second trailing edge **449**. The second leading edge **447** may be separated from the top surface **427** of the substrate layer **412** by a distance 'd**3**', while the second trailing edge **449** may be separated from the top surface **427** of the substrate layer **412** by a distance 'd**4**'. In various embodiments d**3** and d**4** are the same or different. Furthermore, in various embodiments, d**1**, d**2**, d**3**, and d**4** may be the same or different.

[0054] As best shown in FIG. **4A**, the first perimeter **433** may further include a first side edge **451** and a second side edge **452**, while the second perimeter **435** may further include a first side edge **453** and a second side edge **454**. Although not shown, the distance between the top surface **427** of the substrate layer **412** and the first and second side edges **452**, **453** may be the same or different. Furthermore, the distance between the top surface **427** and any of the edges **451**, **452**, **453**, and **454** may be the same or different. It will be appreciated that the first perimeter **433** and/or the second perimeter **435** may be curved, sloped, stepped, etc. Embodiments herein are not limited in this context.

[0055] Next, as shown in FIG. **5**, the device **400** may be etched **430** for the purpose of recessing the substrate layer **412** in the first processing area **422** and the second processing area **426**. In some embodiments, the etch **430** may be an inductively coupled plasma (ICP) RIE performed/delivered through the first and second openings **420**, **424** of the proximity mask **404** at an angle substantially perpendicular to the top surface **427** of the substrate layer **412**. In other embodiments, the etch **430** may be performed at a non-zero angle relative to a vertical **431** extending from the top surface **427** of the substrate layer **412**. Furthermore, it will be appreciated that the etch **430** may represent one or multiple etch cycles. A density of the plasma may be greatest towards a center of each of the first and second openings **420**, **424** resulting in a variable etch rate across the first and second processing areas **422**, **426**.

[0056] As shown in FIG. **6**, as a result of the etch **430**, the first processing area **422** may be recessed to a first depth 'RD**1**' to form a first processing trench **461**. As shown, a bottom surface **462** of the first processing trench **461** may be curved/non-uniform due to the varied plasma density in the area beneath the first opening **420**, which results in a faster etch towards the center/bottommost point of the concave shaped bottom surface **462**. The second processing area **426** may be recessed to a second depth 'RD**2**' to form a second processing trench **463**. As shown, a bottom surface **464** of the second processing trench **463** may be curved/non-uniform, again due to the varied plasma density in the area beneath the second opening **424**, which results in a faster etch towards the center/bottommost point of the concave shaped bottom surface **464**. In various embodiments, RD**1** and RD**2** are the same or different. Furthermore, the first processing trench **461** may have a width '**W1**', which may be the same or different than a width '**W2**' of the second processing trench **463**.

[0057] The device **400** may then be etched **455**, as shown in FIG. **7**, to form a plurality of structures **460** and a plurality of trenches **462**A and **462**B, as shown in FIG. **8**. In some embodiments, the proximity mask **404** is removed prior to the etch **455**. In some embodiments, a patterned hardmask (not shown) may be formed over the substrate layer **412** prior to the etching **455**. As shown, the substrate layer **412** may be etched at a non-zero angle 'β' relative to the perpendicular **431** extending from the top surface **427** of the substrate layer **412** to form a first set of angled structures **460**A in the first processing area **422** and a second set of angled structures **460**B in the second processing area **426**. As shown, a depth between two or more trenches of the first plurality of trenches **462**A may vary. Similarly, a depth between two or more trenches of the second plurality of trenches **462**B may vary. In various embodiments, an average width of the first set of structures **460**A may be the same or different than an average width of the second set of structures **460**B. Furthermore, an angle of the first set of structures **460**A may be the same or different than an angle of the second set of structures **460**B. Once the first and second sets of structures **460**A-**460**B are complete, the device **400** contains a plurality of diffracted optical elements. Although non-limiting, the first set of structures **460**A may correspond to an input grating, while the second set of structures **460**B may correspond to an intermediate grating or an output grating.

[0058] In FIG. **9**, a device **500** according to another embodiment of the present disclosure is shown. A proximity mask **504** is provided over a substrate layer **512**, such as an optical grating material, and a base substrate **510**. The proximity mask **504** may include a plate **514** patterned or otherwise processed to include to a first opening **520**, which is positioned over a first processing area **522** of the substrate layer **512**, and a second opening **524**, which is positioned over a second processing area **526** of the substrate layer **512**.

[0059] The plate **514** may include a first main side **516** opposite a second main side **518**, wherein the second main side **518** faces the substrate layer **512**. In some embodiments, a plane defined by the first main side **516** may be substantially parallel to a plane defined by the second main side **518**. The plate **514** may be separated from a top surface **527** of the substrate layer **512** by a distance 'D'. The distance D may vary at different spots along the plate **514**. For example, the plane defined by the second main side **518** may be oriented at a non-zero angle 'ϕ' relative to a plane defined by the top surface **527** of the substrate layer **512**. As such, the first opening **520** may be positioned closer to the substrate layer **512** than the second opening **524**.

[0060] Turning now to FIG. **10**, a proximity mask **604** according to embodiments of the present disclosure will be described. The proximity mask **604** may be positioned over a grating material (not shown). The proximity mask **604** may include a plurality of openings **620** formed therein. For the sake of explanation, the openings **620** may be arranged in a series of rows (e.g., A**1**-**14**, B**1**-B**4**, C**1**-C**4**, and D**1**-D**4**). It'll be appreciated that the number, arrangement, and/or shape of the openings **620** can vary and is non-limiting. For example, a perimeter defining each of openings A**1**-A**4** may have a constant height/distance (e.g., along the x-direction) relative to the grating material but differ in perimeter size and/or alignment. Conversely, a perimeter defining each of openings B**1**-B**4** may have uniform size/alignment, but differ in distance relative to the grating material. For example, B**1** may be positioned closest to the grating material, while B**4** may be the farthest. Furthermore, a perimeter defining each of openings C**1**-C**4** may have a constant height/distance relative to the grating material but differ in perimeter shape. Still furthermore, a perimeter defining one or more of openings D**1**-D**4** may have the same size/shape but differ in height/distance relative to the grating material. For example, opening D**1** may include a perimeter **670** including a leading edge **638**, a trailing edge **639**, a first side edge **651**, and a second side edge **652**. One or more of the leading edge **638**, the trailing edge **639**, the first side edge **651**, and/or the second side edge **652** may vary in height/distance relative to the grating material. Said another way, different portions of the perimeter **670** may be curved, sloped, notched, etc., as desired.

[0061] Although not shown, the proximity mask **604** may further include one or more raised surface features along the leading, trailing, and/or side edges of one or more of the openings **620**. The raised surface features may extend above a plane defined by a first main side **616** of the proximity mask **604**. In some embodiments, the proximity mask **604** may additionally, or alternatively, include surface features extending below a plane defined by a second main side (not shown) of the proximity mask **604**. It will be appreciated that the surface features may partially block ion beams, thus influencing an amount, angle, and/or depth the ion beams passing through the openings **610** and impacting the grating material.

[0062] Turning now to FIGS. **11**A-**11**B, a portion of a device **700** including an example stepped feature **750** according to embodiments of the present disclosure will be described. The device **700** may be the same or similar to the devices **400** and **500** described above. As such, only certain aspects of the device **700** will hereinafter be described for the sake of brevity. As shown, a proximity mask **704** is provided over a substrate layer **712**, such as an optical grating material, and a base substrate **710**. The proximity mask **704** may include a plate **714** patterned or otherwise processed to include to an opening **720**, which is positioned over a processing area **722** of the substrate layer **712**. Although only a single opening **720** and processing area **722** are demonstrated, it will be appreciated that multiple additional openings and processing areas may be present across the device **700**.

[0063] The plate **714** may include a first main side **716** opposite a second main side **718**, wherein the second main side **718** faces the substrate layer **712**. In some embodiments, a plane defined by the first main side **716** may be substantially parallel to a plane defined by the second main side **718**. The plate **714** may be separated from a top surface **727** of the substrate layer **712** by a distance 'D'.

[0064] As shown, the proximity mask **704** may include the stepped feature **750** extending across the opening **720**. Although non-limiting, the stepped feature **750** may extend from the first main side **716** of the plate **714** (e.g., in the x-direction), and include a planar body **775** extending parallel to the first main side **716**. Extending through the planar body **775** is a stepped opening **777**. As shown, the stepped opening **777** is generally aligned above the opening **720** of the plate **714**. In some embodiments, the stepped feature **750** is directly coupled to the plate **714**. In other embodiments, the stepped feature **750** may extend above the plate **714** by some distance. It will be appreciated that the stepped feature **750** may partially block ions, such as ions of an ICP RIE, thus influencing an amount, angle, and/or depth of the ions passing through the stepped opening **777** and the opening **720**.

[0065] In some embodiments, the stepped opening **777** may be defined by a perimeter **783** including a leading edge **784** and a trailing edge **785**, e.g., relative to a scanning direction. The leading edge **784** may be separated from the top surface **727** of the substrate layer **712** by a distance 'D**1**', while the trailing edge **785** may be separated from the top surface **727** of the substrate layer **712** by a distance 'D**2**'. In various embodiments D**1** and D**2** are the same or different. The perimeter **783** may further include a first side edge **787** and a second side edge **788**. Although not shown, the distance between the top surface **727** of the substrate layer **712** and the first and second side edges **787**, **788** may be the same or different. Furthermore, the distance between the top surface **727** and any of the edges **784**, **785**, **787**, and **788** of the perimeter **783** may be the same or different. Still furthermore, any of the edges **784**, **785**, **787**, and **788** of the perimeter **783** may be curved, sloped, stepped, etc. Embodiments herein are not limited in this context.

[0066] It will be appreciated that the stepped feature **750** may take on a number of shapes, configurations, sizes, etc. For example, FIGS. **12**A-**12**F demonstrate a variety of possible implementations for the stepped feature **750** formed over the opening **720** of the proximity mask **704**. In FIG. **12**A, stepped feature **750**A may generally be rectangular, with stepped opening **777**A being oval or a rectangle with rounded corners. In FIG. **12**B, stepped feature **750**B may be a band or rectangle extending across the opening **720**, thus defining multiple stepped openings **777**B. In FIG. **12**C, stepped feature **750**C may take on a dual-triangle or bowtie configuration extending across the opening **720**, thus defining multiple stepped openings **777**C. In FIG. **12**D, stepped feature **750**D may include a rectangular stepped opening **777**D extending from one side of the opening **720**. In FIG. **12**E, stepped feature **750**E may generally be triangular, leaving a relatively large stepped opening **777**E. Finally, in FIG. **12**F, stepped feature **750**F may be a mesh mask including a plurality of stepped openings **777**F. Although non-limiting, the stepped openings **777**F may be uniformly positioned across the stepped feature **750**F.

[0067] Turning to FIG. **13**, a method **800** according to embodiments of the present disclosure will be described. As shown, at block **810**, the method **800** may include providing a proximity mask over a substrate and/or grating material, wherein the proximity mask includes a plate separated from the grating material by a distance, and wherein the plate includes a first opening and a second opening. In some embodiments, the plate may include a first main side opposite a second main side, wherein the second main side faces the grating material. In some embodiments, a plane defined by the first main side may be substantially parallel to a plane defined by the second main side. In some embodiments, the plate may be separated from a top surface of the grating material by a constant or varied amount. In some embodiments, the plate may be in direct physical contact with the grating material at one or more points. In some embodiments, the plate at a second non-zero angle relative to the plane defined by the top surface of the grating material.

[0068] At block **820**, the method **800** may optionally include providing a stepped feature across at least one of the first opening and the second opening, wherein the stepped feature defines at least one stepped opening positioned over the at least one of the first opening and the second opening. In some embodiments, the stepped feature may extend from the first main side of the plate, and include a planar body extending parallel to the first main side. Through the planar body may be a stepped opening. In some embodiments, the stepped feature is directly coupled to the plate. In other embodiments, the stepped feature may extend above the plate by some distance.

[0069] At block **830**, the method **800** may include etching the grating material through the first and second openings to recess a first processing area and a second processing area. In some embodiments, the etching process may be an ICP RIE process.

[0070] At block **840**, the method **800** may further include etching the grating material to form a plurality of structures oriented at a non-zero angle with respect to a plane defined by the top surface of the grating material. In some embodiments, the method includes etching the grating material to form a first plurality of trenches in the first processing area and a second plurality of trenches in the second processing area. In some embodiments, the method includes varying an etch depth between two or more trenches of the first plurality of trenches, and varying an etch depth between two or more trenches of the second plurality of trenches. In some embodiments, the method includes removing before the grating material is etched to form the plurality of structures.

[0071] Turning now to FIG. **14**A, a portion of a device **900** according to embodiments of the present disclosure will be described. As shown, a proximity mask **904** is provided over a mask layer **912** and a wafer **910**. Although not shown, the wafer **910** may include one or more layers, such as an optical grating material. The proximity mask **904** may include a plate **914** patterned or otherwise processed to include to an opening **920**, which is positioned over a second opening **922** of the mask layer **912**. The second opening **922** may define a processing area **924** of the wafer **910**. The plate **914** may be separated from the mask layer **912** by a distance 'D'. In some embodiments, the mask layer **912** may be further separated from a top surface **923** of the wafer **910** by a space/distance. In other embodiments, the mask layer **912** is formed atop the top surface **923** of the wafer **910**. It will be appreciated that the distance 'D' may be varied. In some embodiments, the opening **920** and/or the second opening **922** allow for a curved plasma sheath that causes ions of a plasma **935** to converge towards a location on the wafer **910**, such as an intended location of the processing area **924**.

[0072] As shown, density of the plasma **935** above the proximity mask **904** is uniform or substantially uniform. However, in an area **938** between the proximity mask **904** and the mask layer **912**, the density of the plasma **935** may vary. For example, density of the plasma **935** may be greatest near an approximate center of the opening **920**, as represented by centerline **942**. The farther from the centerline **942** (e.g., along +x, −x), the less dense the plasma **935** in the area **938** becomes. As a result, etch rate and/or intensity may be greatest near the centerline **942** and generally less near edges **944** of the second opening **922**. The resultant etch depth is demonstrated by gradient profile **946** in graph **948**.

[0073] As shown in FIG. **14**B, the opening **920** through the proximity mask **904** may be varied, e.g., along the x-axis, relative to the second opening **922** and the processing area **924** of the wafer **910**. Density of the plasma **935** in the area **938** may be greatest proximate the centerline **942**. In this embodiment, density decreases from a first edge **944-1** to a second edge **944-2** of the second opening **922**. As a result, etch rate and/or intensity may be greatest near the centerline **942** and the first edge **944-1**, and generally less near the second edge **944-2**. The resultant etch depth is demonstrated by gradient profile **954** in graph **956**.

[0074] Turning now to FIG. **15**, a proximity mask **1004** of a device **1000** according to another embodiment of the present disclosure will be described. As shown, the proximity mask **1004** is provided over a wafer **1010**. The proximity mask **1004** may include a plate **1014** patterned or otherwise processed to include to an opening **1020**, which is positioned over a processing area **1024** of the wafer **1010**. The plate **1014** may be separated from the wafer **1010** or may be formed directly atop a top surface **1023** of the wafer **1010**.

[0075] As further shown, the proximity mask **1004** may include a protruding structure or feature **1017**, such as a flap, covering, overhang, tab, etc., which extends away from the plate **1014**, e.g., in the y-direction. Although non-limiting, the feature **1017** may include a fixed end **1022** coupled to the plate **1014** and a free end **1026** angling away from the plate **1014**. As a result, a plasma **1035**, which may have a uniform density above the plate **1014**, may have a gradient density in an area **1038** beneath the feature **1017** and above the processing area **1024**. Said another way, the plasma **1035** in the area **1038** may be denser near the free end **1026** and less dense near the fixed end **1022**. As a result, etch rate and/or intensity may be greatest near the entrance to the opening **1020**, decreasing towards the fixed end **1022**. The resultant etch depth is demonstrated by gradient profile **1058** in graph **1060**.

[0076] It will be appreciated that the feature **1017** of the proximity mask **1004** may take on a variety of shapes and configurations in various embodiments. Some non-limiting examples of the feature (i.e., **1017**A-**1017**D) are demonstrated in FIG. **16**. By varying the shape, configuration, and/or distance of the feature **1017** from the plate **1014**, as well as by varying a width, height and/or size of the opening **1020**, the plasma density gradient in the area beneath the feature **1017** and above the processing area may also be varied.

[0077] In sum, by utilizing the embodiments described herein, a substrate (e.g., waveguide) with regions of variable etch depth is formed. A first technical advantage of the waveguide of the present embodiments includes improved manufacturing efficiency by eliminating more time consuming and difficult processes. Further, a second technical advantage of the grating structures of the present embodiments includes providing a two dimensional or a three-dimensional shape, enabling use of the waveguide in an increased range of applications.

[0078] For the sake of convenience and clarity, terms such as "top," "bottom," "upper," "lower," "vertical," "horizontal," "lateral," and "longitudinal" will be used herein to describe the relative placement and orientation of components and their constituent parts as appearing in the figures. The terminology will include the words specifically mentioned, derivatives thereof, and words of similar import.

[0079] As used herein, an element or operation recited in the singular and proceeded with the word "a" or "an" is to be understood as including plural elements or operations, until such exclusion is explicitly recited. Furthermore, references to "one embodiment" of the present disclosure are not intended as limiting. Additional embodiments may also incorporate the recited features.

[0080] Furthermore, the terms "substantial" or "substantially," as well as the terms "approximate" or "approximately," can be used interchangeably in some embodiments, and can be described using any relative measures acceptable by one of ordinary skill in the art. For example, these terms can serve as a comparison to a reference parameter, to indicate a deviation capable of providing the intended function. Although non-limiting, the deviation from the reference parameter can be, for example, in an amount of less than 1%, less than 3%, less than 5%, less than 10%, less than 15%, less than 20%, and so on.

[0081] Still furthermore, one of ordinary skill will understand when an element such as a layer, region, or substrate is referred to as being formed on, deposited on, or disposed "on," "over" or "atop" another element, the element can be directly on the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly on," "directly over" or "directly atop" another element, no intervening elements are present.

[0082] In various embodiments, design tools can be provided and configured to create the datasets used to pattern the layers of the grating material and the diffracted optical elements described herein. For example, data sets can be created to generate photomasks used during lithography operations to pattern the layers for structures as described herein. Such design tools can include a collection of one or more modules and can also be comprised of hardware, software or a combination thereof. Thus, for example, a tool can be a collection of one or more software modules, hardware modules, software/hardware modules or any combination or permutation thereof. As another example, a tool can be a computing device or other appliance running software, or implemented in hardware.

[0083] As used herein, a module might be implemented utilizing any form of hardware, software, or a combination thereof. For example, one or more processors, controllers, ASICs, PLAs, logical components, software routines or other mechanisms might be implemented to make up a module. In implementation, the various modules described herein might be implemented as discrete modules or the functions and features described can be shared in part or in total among one or more modules. In other words, as would be apparent to one of ordinary skill in the art after reading the description, the various features and functionality described herein may be implemented in any given application. Furthermore, the various features and functionality can be implemented in one or more separate or shared modules in various combinations and permutations. Although various features or elements of functionality may be individually described or claimed as separate modules, one of ordinary skill in the art will understand these features and functionality can be shared among one or more common software and hardware elements.

[0084] The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, other various embodiments of and modifications to the present disclosure, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such other embodiments and modifications are intended to fall within the scope of the present disclosure. Furthermore, the present disclosure has been described herein in the context of a particular implementation in a particular environment for a particular purpose. Those of ordinary skill in the art will recognize the usefulness is not limited thereto and the present disclosure may be beneficially implemented in any number of environments for any number of purposes. Thus, the claims set forth below are to be construed in view of the full breadth and spirit of the present disclosure as described herein.

What is claimed is:

1. A proximity mask, comprising:

a plate positioned over a substrate, wherein at least a portion of the plate is separated from the substrate by a distance; and

a first opening and a second opening formed through the plate, wherein the first opening is defined by a first perimeter having a first shape, wherein the second opening is defined by a second perimeter having a second shape, and wherein the first shape is different than the second shape.

2. The proximity mask of claim **1**, further comprising a stepped feature extending across at least one of the first opening and the second opening.

3. The proximity mask of claim **2**, wherein the stepped feature defines at least one stepped opening positioned over the at least one of the first opening and the second opening.

4. The proximity mask of claim **2**, wherein the plate includes a first main side opposite a second main side, wherein the stepped feature extends from the first main side, and wherein the second main side of the plate faces the substrate.

5. The proximity mask of claim **4**, wherein a plane defined by the second main side of the plate is oriented at a non-zero angle relative to a plane defined by a top surface of the substrate.

6. The proximity mask of claim **4**, wherein the stepped feature includes a leading edge and a trailing edge, and wherein a step distance between the first main side of the plate and the stepped feature varies between the leading and trailing edges.

7. The proximity mask of claim **1**, wherein the first perimeter includes a first leading edge and a first trailing edge, wherein a first distance between the first leading edge and the substrate is different than a second distance between the first trailing edge and the substrate.

8. The proximity mask of claim **7**, wherein the first perimeter further includes a first side edge and a second side edge, wherein a third distance between the first side edge and the substrate is different than fourth distance between the second side edge and the substrate.

9. The proximity mask of claim **1**, further comprising a structure extending across at least one of the first opening and the second opening, wherein the structure extends away from the plate.

10. A method, comprising:

providing a proximity mask over a substrate, wherein the proximity mask includes a plate separated from the substrate by a distance, and wherein the plate includes a first opening and a second opening;

etching the substrate through the first and second openings to recess a first processing area and a second processing area; and

etching the substrate to form a plurality of structures oriented at a non-zero angle with respect to a perpendicular to a plane defined by a top surface of the substrate.

11. The method of claim **10**, further comprising extending a stepped feature across at least one of the first opening and the second opening, wherein the stepped feature defines at least one stepped opening positioned over the at least one of the first opening and the second opening.

12. The method of claim **10**, further comprising orienting the plate at a second non-zero angle relative to the plane defined by the top surface of the substrate.

13. The method of claim **10**, further comprising etching the substrate through the first and second openings to form the first processing area or the second processing area with a variable depth.

14. The method of claim **13**, further comprising varying an etch depth between two or more trenches of the first plurality of trenches, and varying an etch depth between two or more trenches of the second plurality of trenches.

15. The method of claim **10**, further comprising varying an etch depth across the first processing area and a second processing area.

16. A method, comprising:

providing an ion beam source within a chamber, wherein the chamber is operable to deliver an ion beam to a substrate;

providing a proximity mask over the substrate, wherein the proximity mask includes a plate separated from the substrate by a distance, and wherein the plate includes a first opening and a second opening;

etching the substrate through the first and second openings to recess a first processing area and a second processing area; and

etching the substrate to form a plurality of structures oriented at a non-zero angle with respect to a perpendicular to a plane defined by a top surface of the substrate.

17. The method of claim **16**, further comprising extending a stepped feature across at least one of the first opening and the second opening, wherein the stepped feature defines at least one stepped opening positioned over the at least one of the first opening and the second opening.

18. The method of claim **16**, further comprising orienting the plate at a second non-zero angle relative to the plane defined by the top surface of the substrate.

19. The method of claim **16**, further comprising etching the substrate to form a first plurality of trenches in the first processing area and a second plurality of trenches in the second processing area, wherein an etch depth between two or more trenches of the first plurality of trenches is different, and wherein an etch depth between two or more trenches of the second plurality of trenches is different.

20. The method of claim **19**, further comprising removing the proximity mask after the first and second processing areas are recessed and before the substrate is etched to form the first plurality of trenches in the first processing area and the second plurality of trenches in the second processing area.

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