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(54) **REACTIVITY ENHANCEMENT IN ION BEAM ETCHER**

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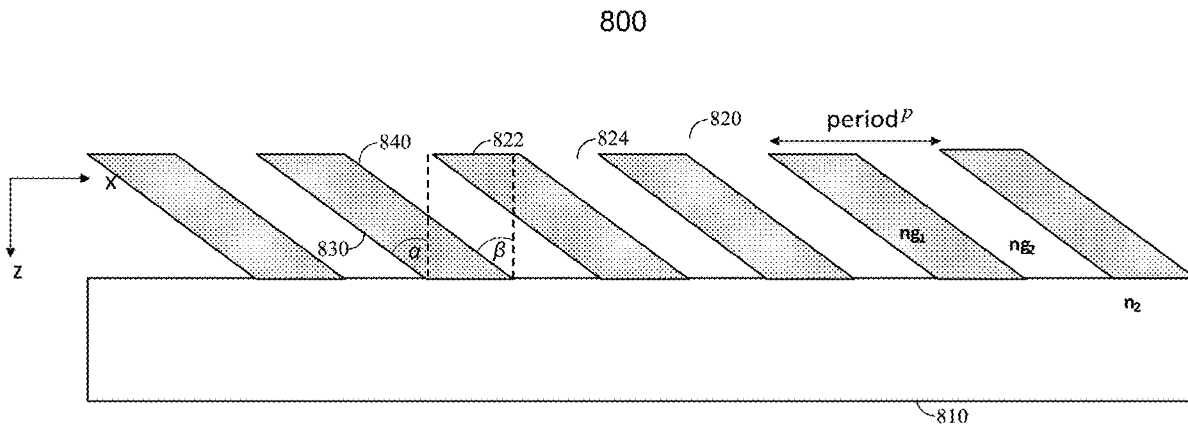
(57) **ABSTRACT**

A chemically assisted reactive ion beam etching (CAME) system for fabricating a slanted surface-relief structure in a material layer includes an reactive ion source generator configured to generate a plasma using a first reactive gas; one or more aligned collimator grids configured to extract and accelerate at least some of the reactive ions in the plasma to form a collimated reactive ion beam towards the material layer; and a gas ring configured to inject a second reactive gas onto the material layer. The plasma includes reactive ions of the first reactive gas that react with the material layer to generate volatile materials. The second reactive gas also reacts with the material layer. The collimated reactive ion beam and the second reactive gas etch the material layer both physically and chemically to form the slanted surface-relief structure in the material layer.



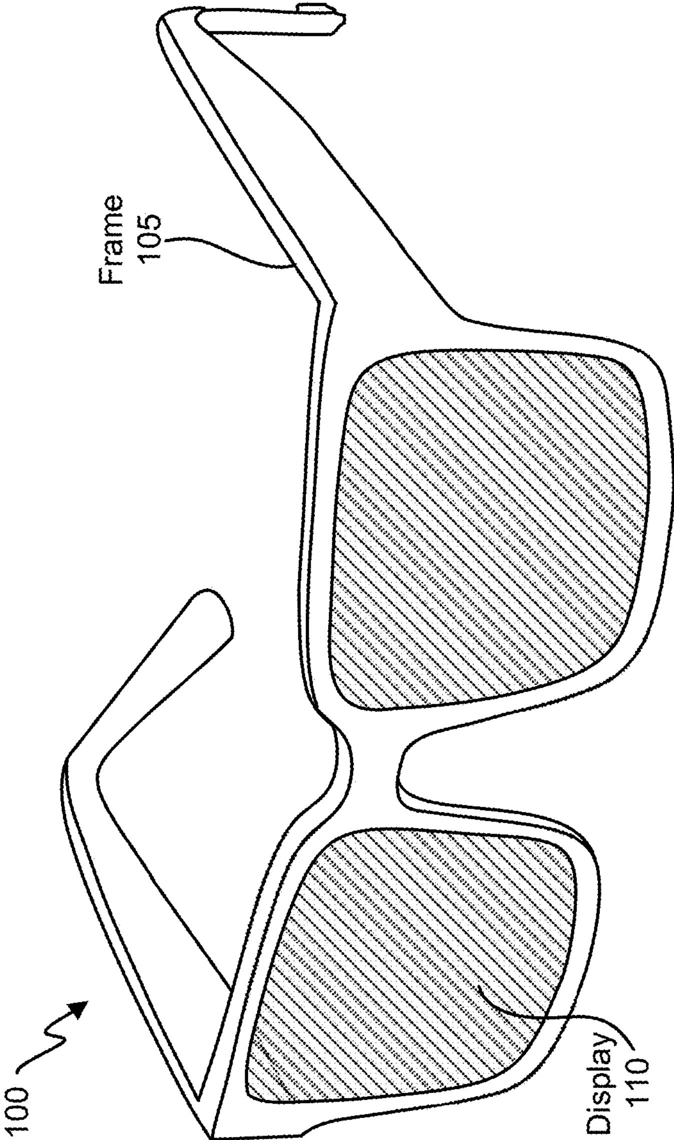


FIG. 1

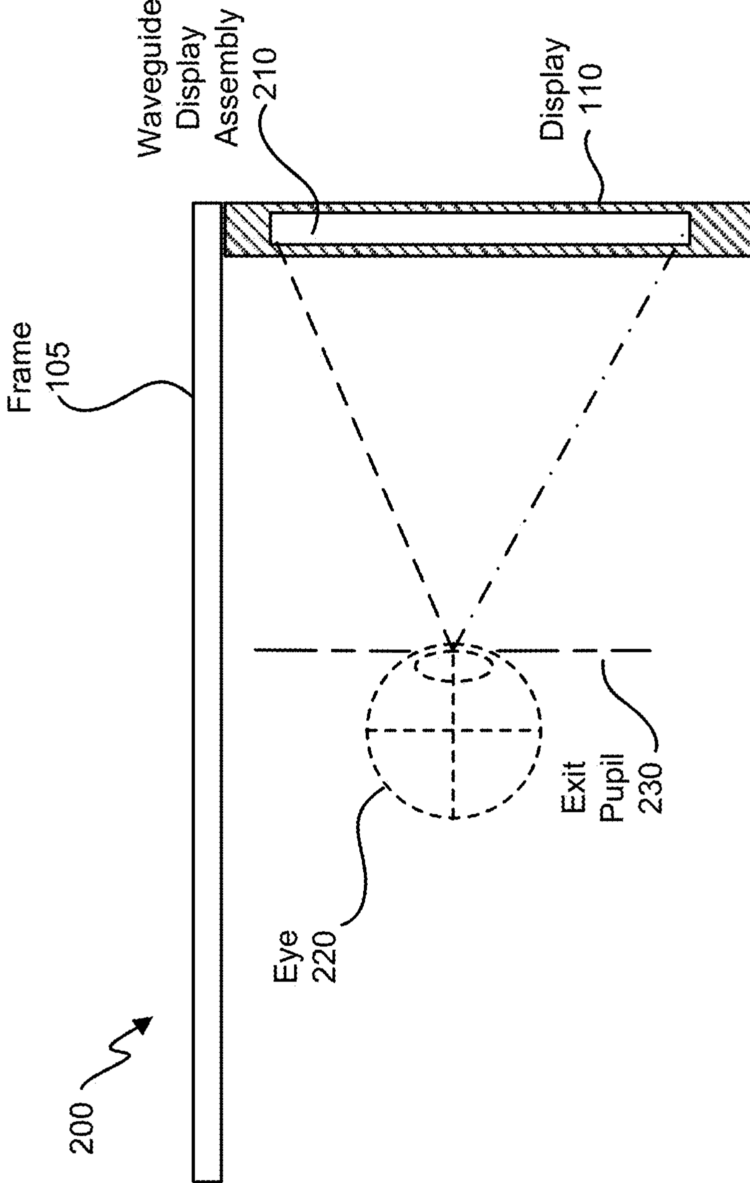


FIG. 2

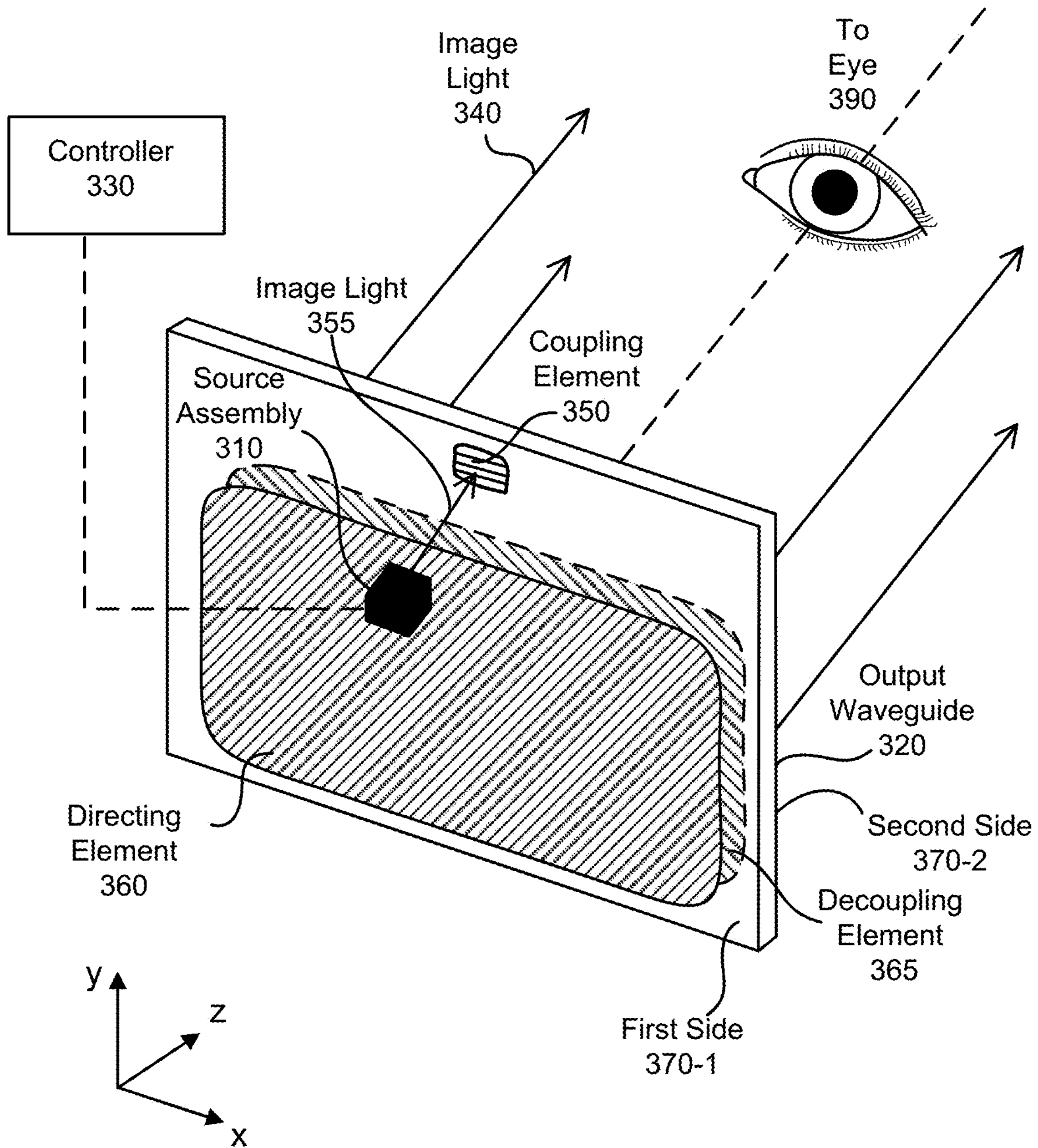


FIG. 3

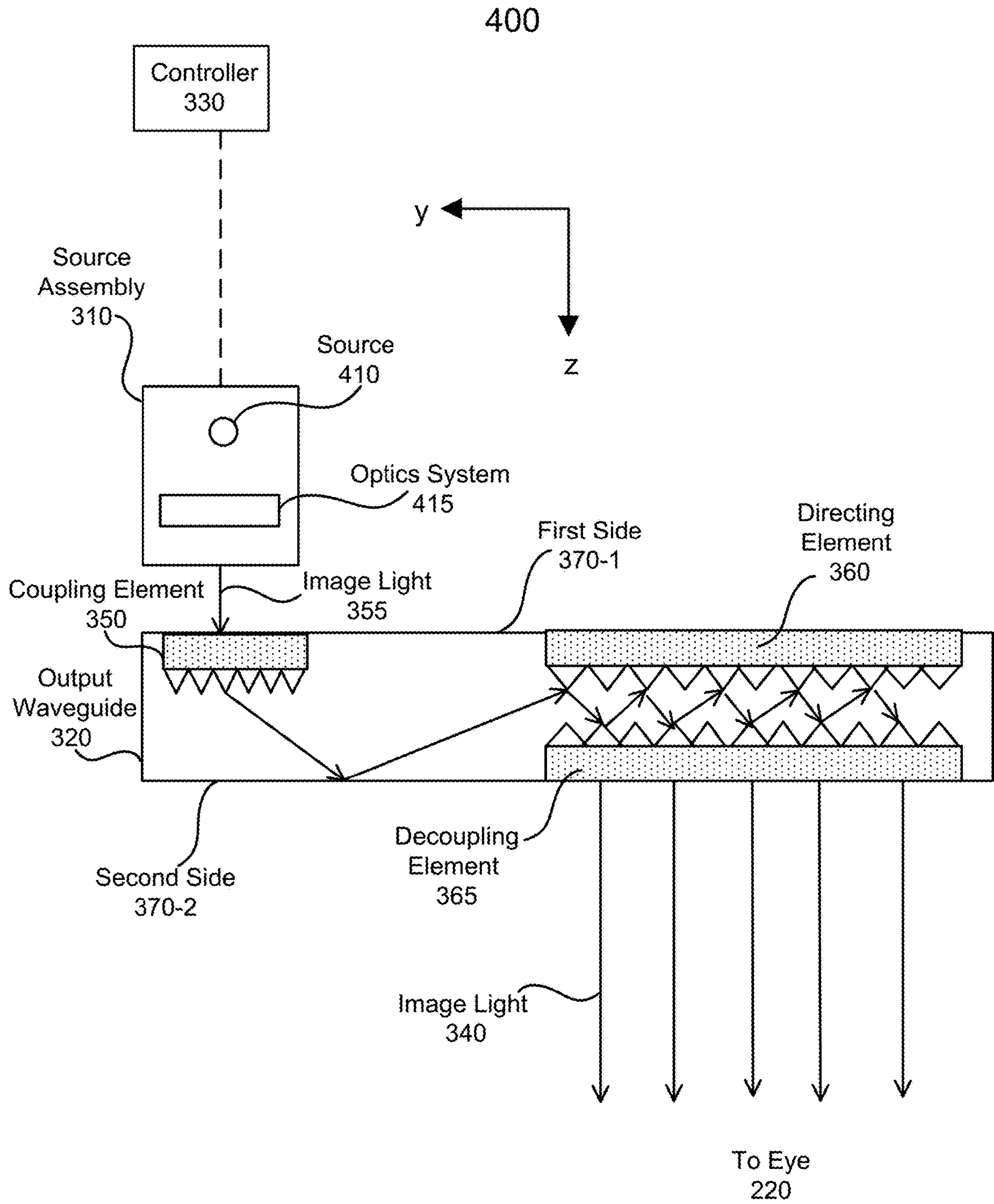


FIG. 4

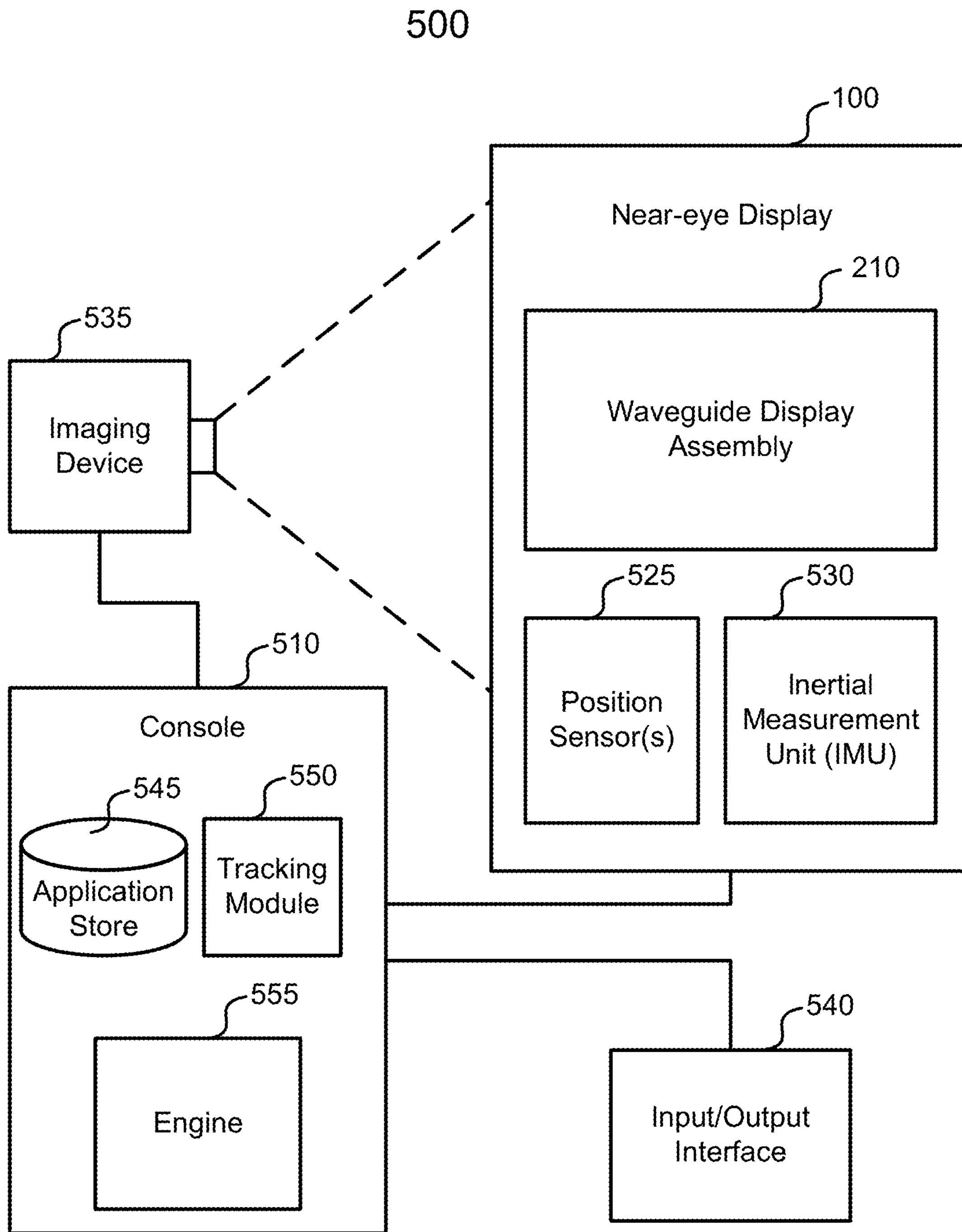


FIG. 5

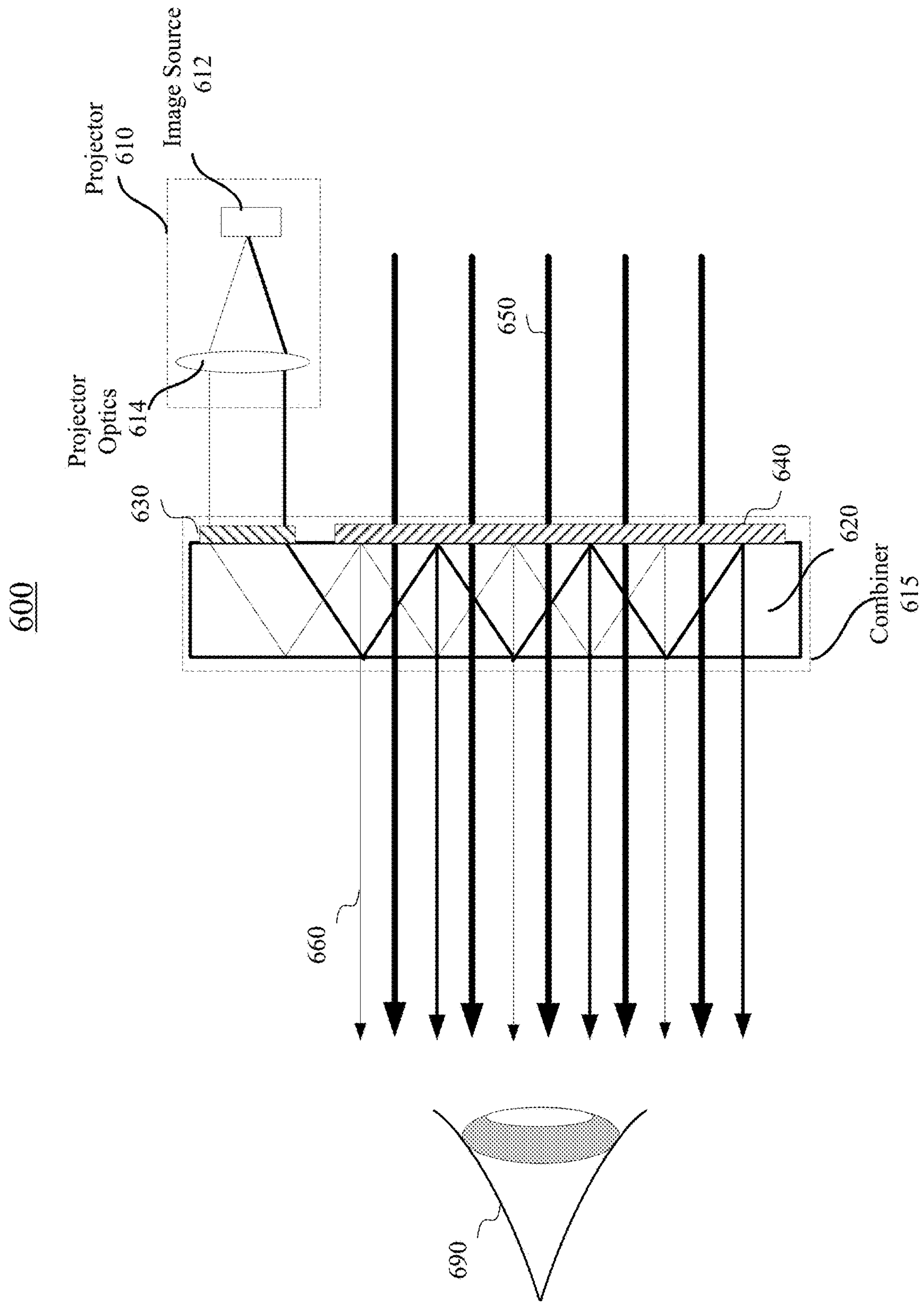


FIG. 6

700

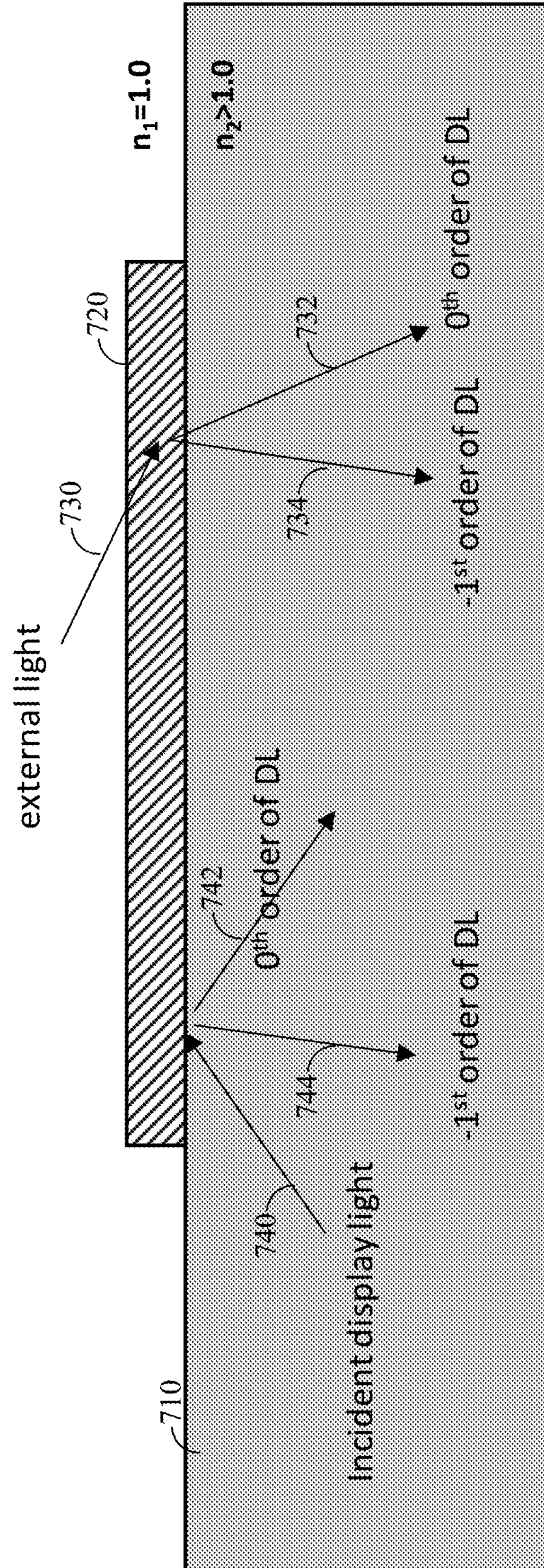


FIG. 7

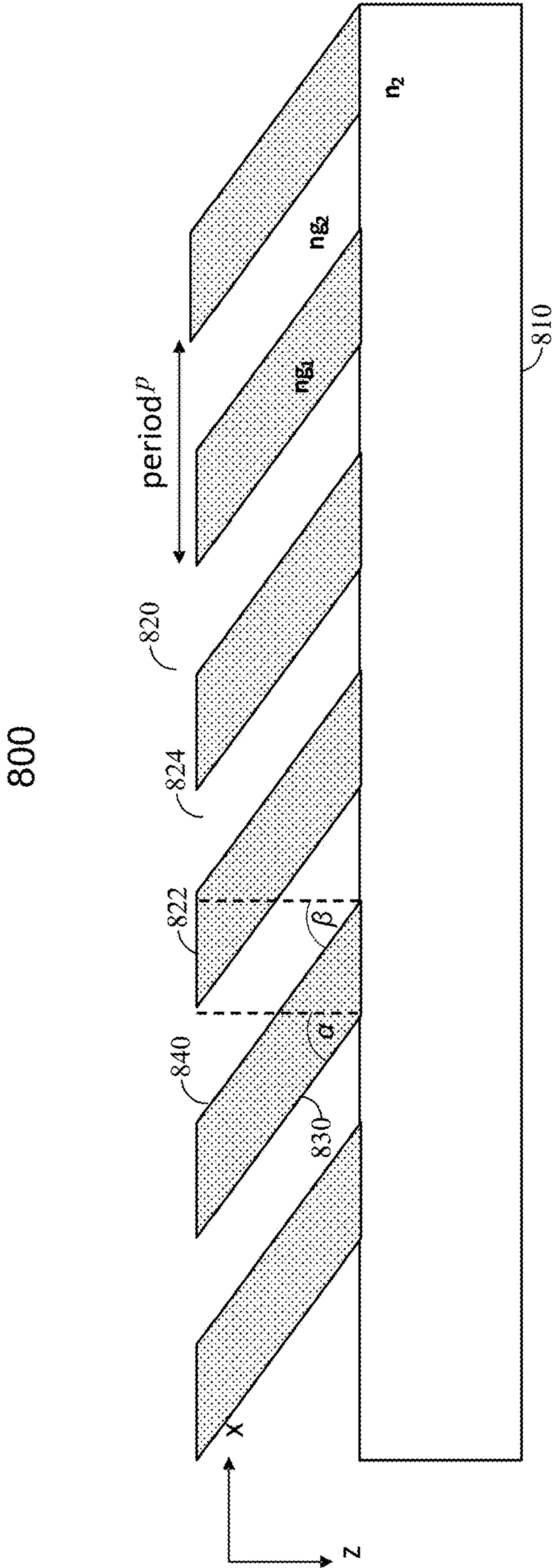


FIG. 8

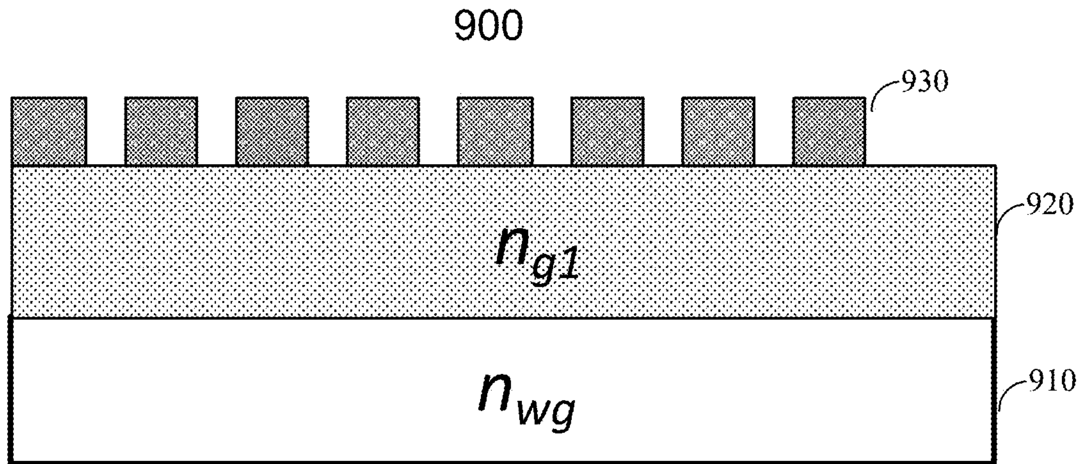


FIG. 9A

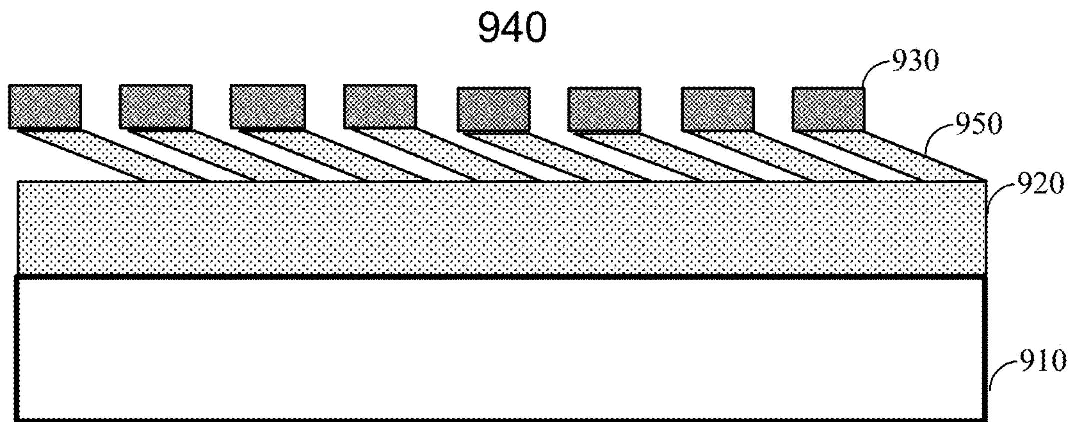


FIG. 9B

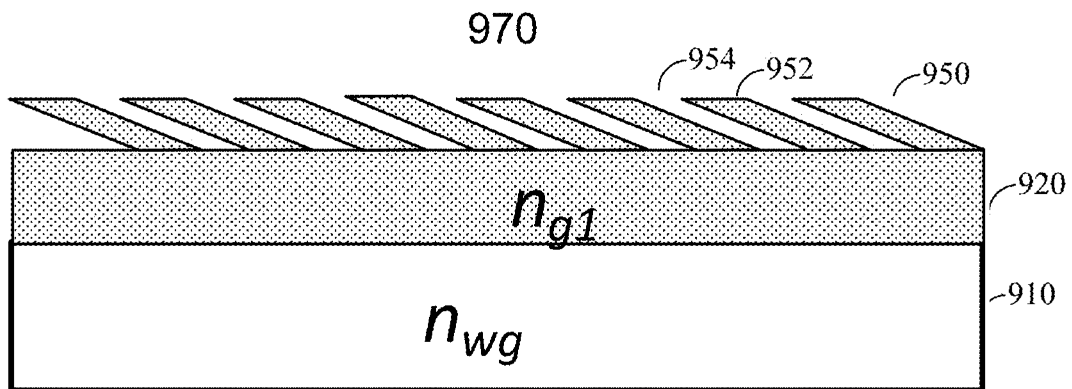


FIG. 9C

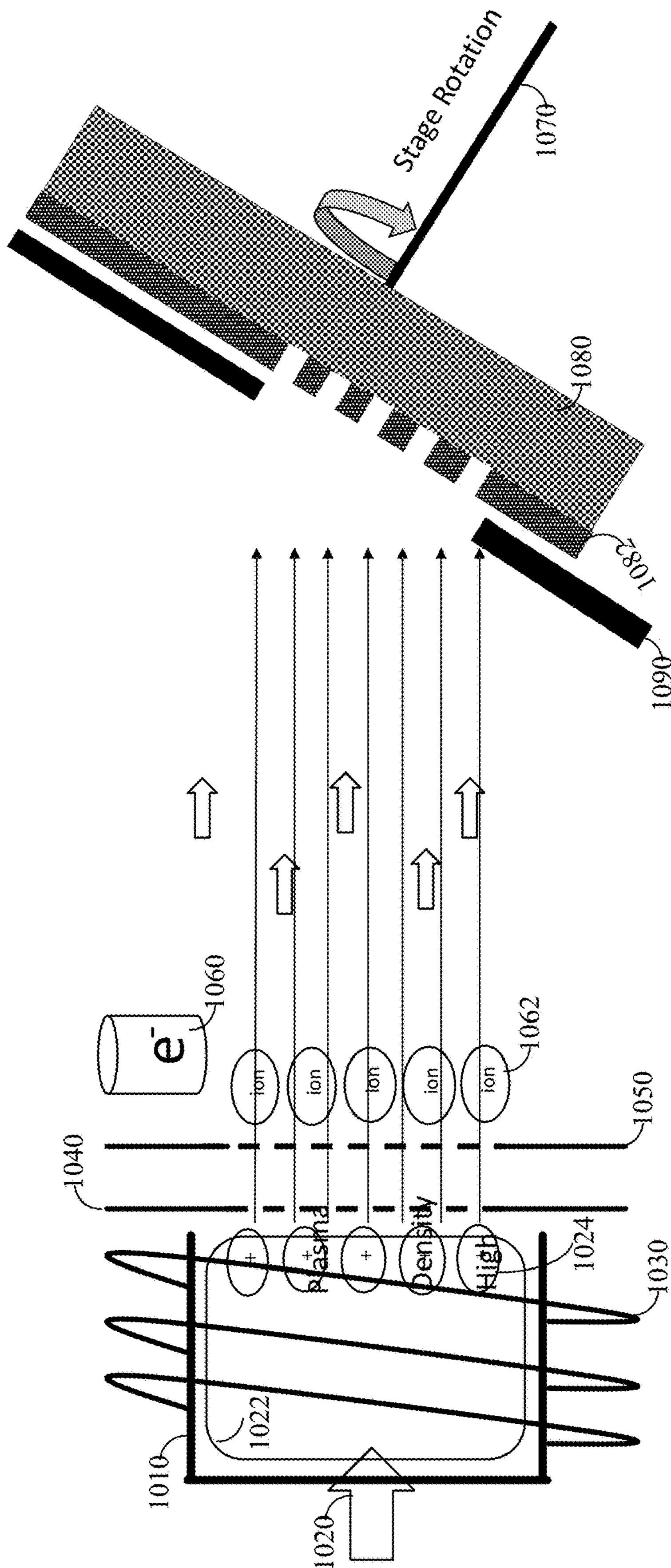


FIG. 10

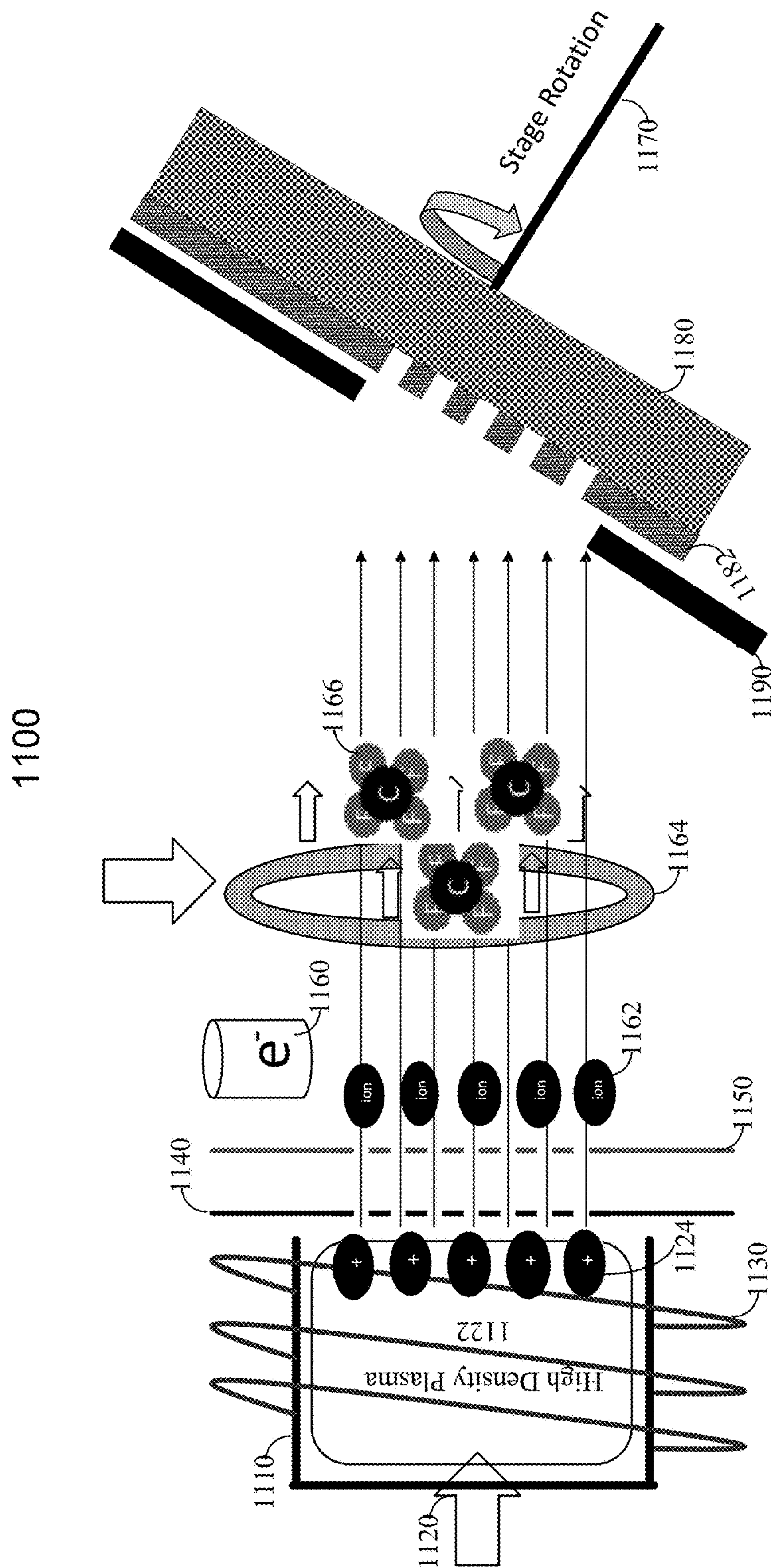


FIG. 11

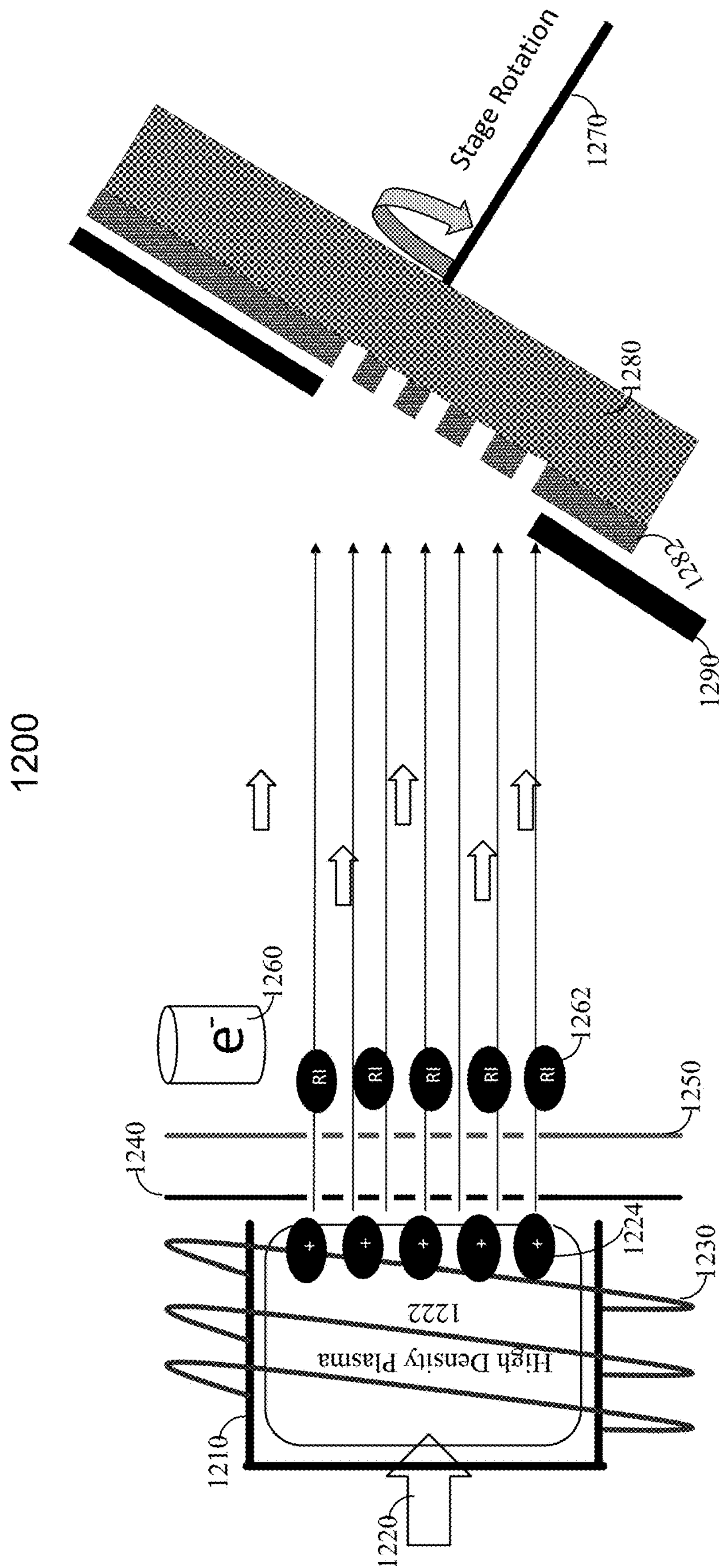


FIG. 12

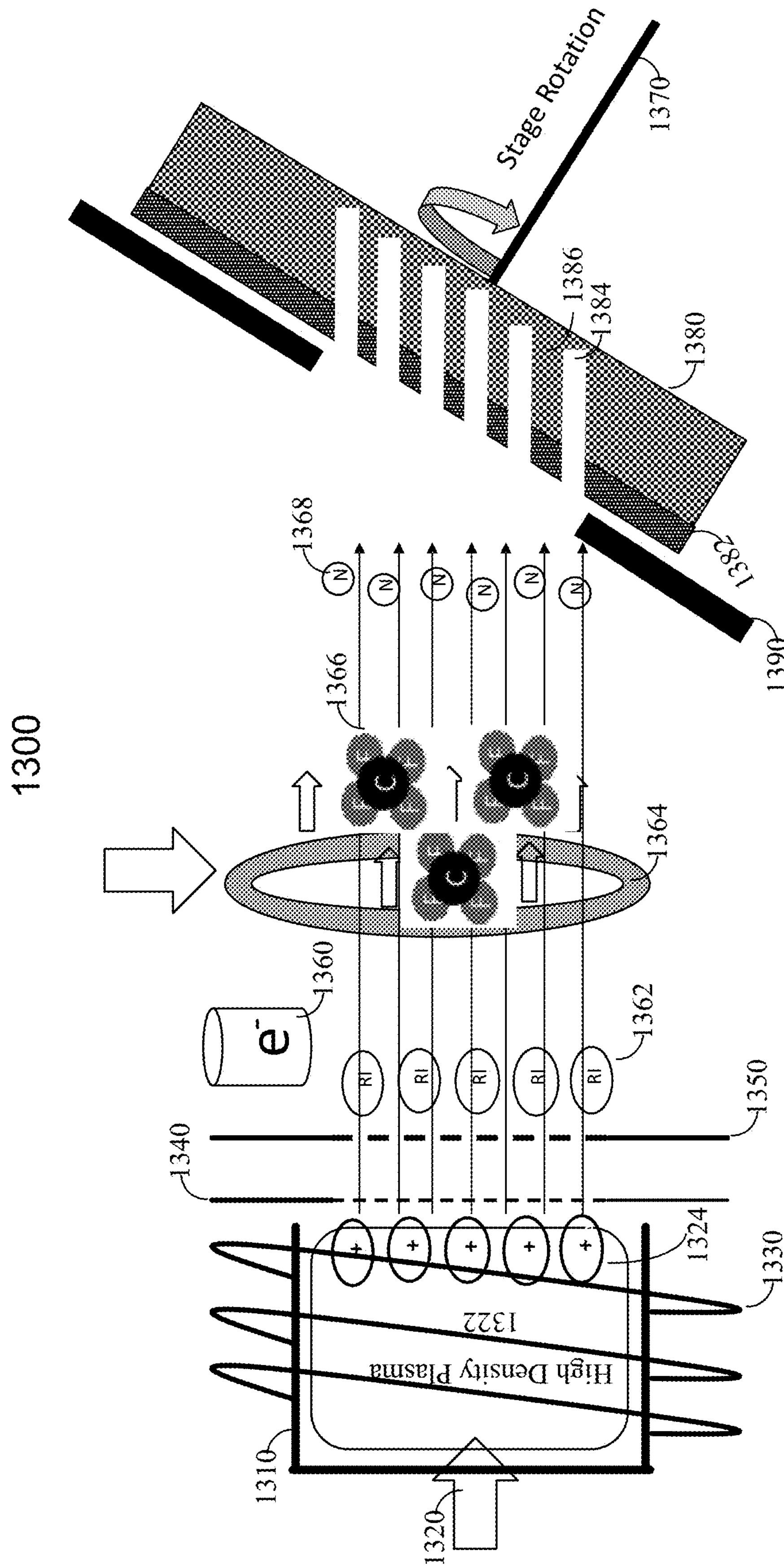


FIG. 13

1450

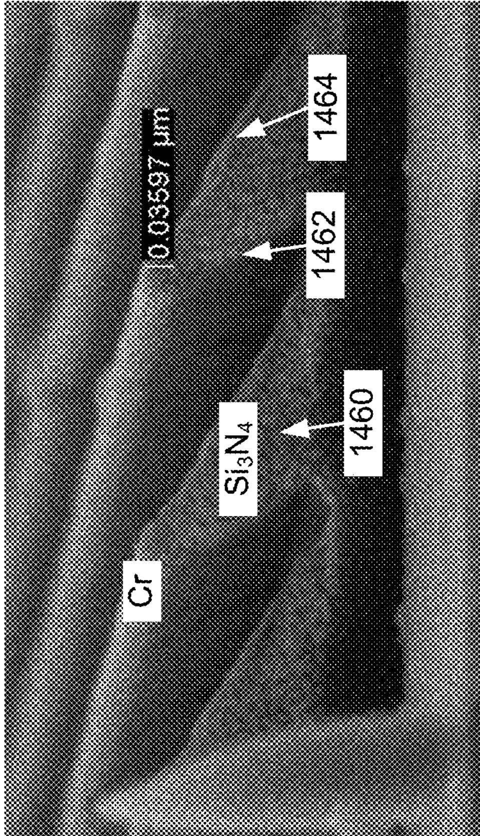


FIG. 14B

1400

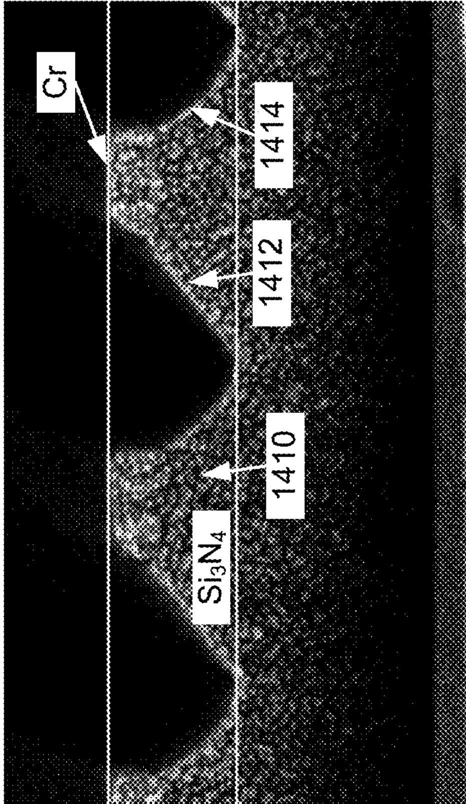


FIG. 14A

1550

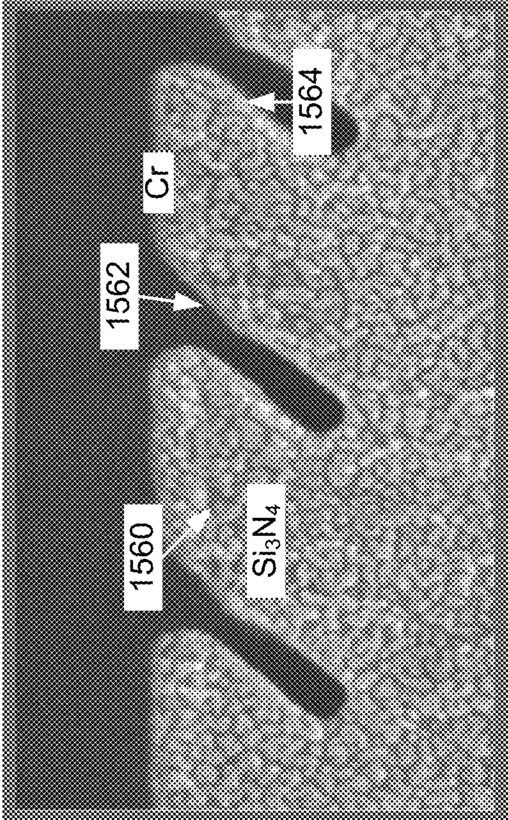


FIG. 15B

1500

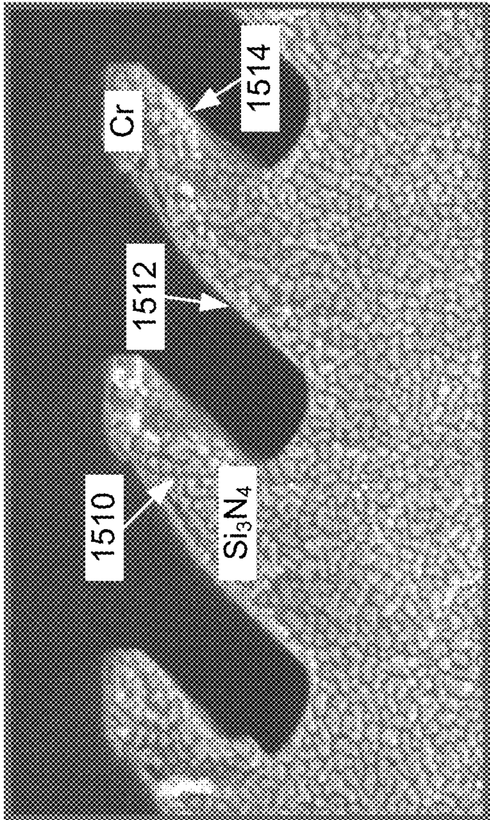


FIG. 15A

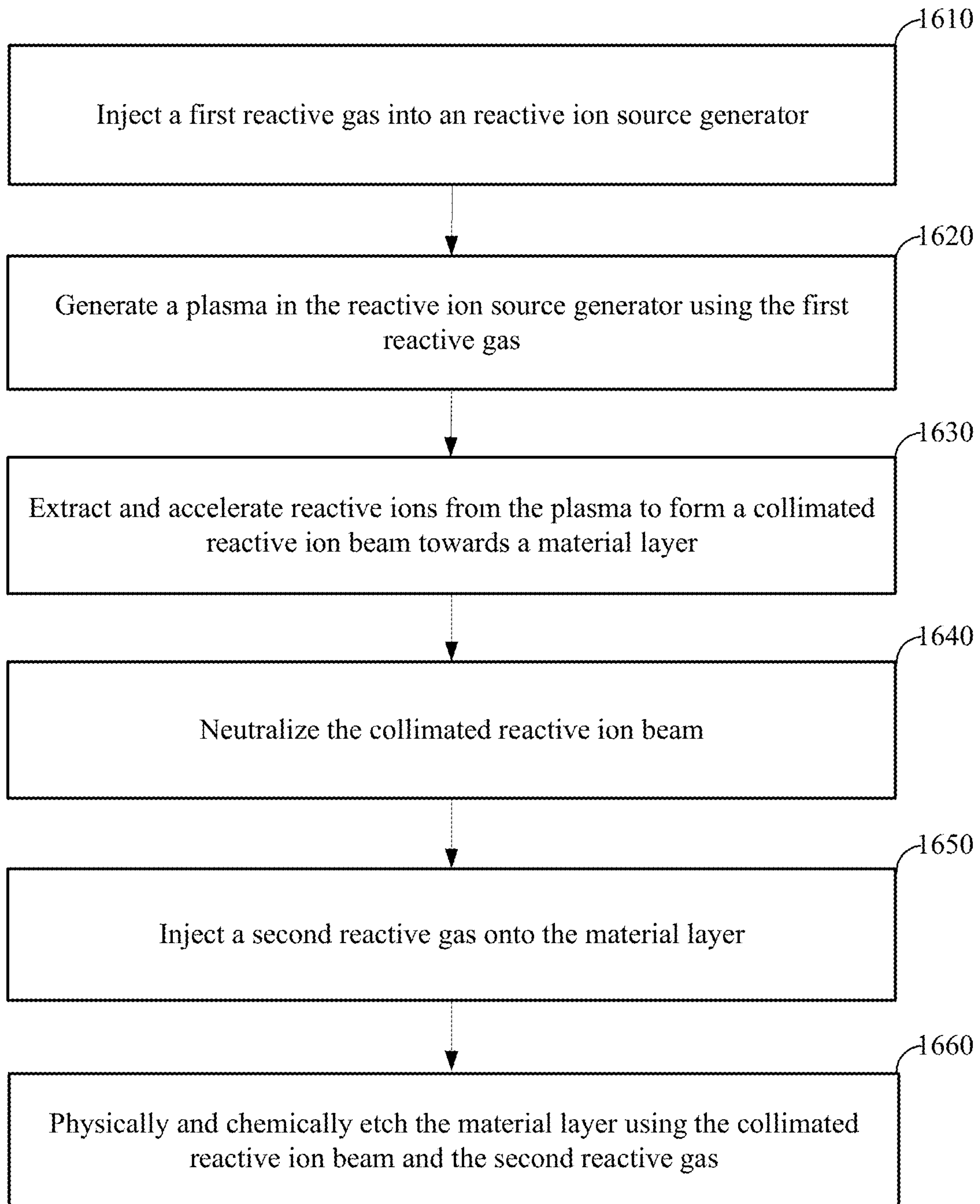


FIG. 16

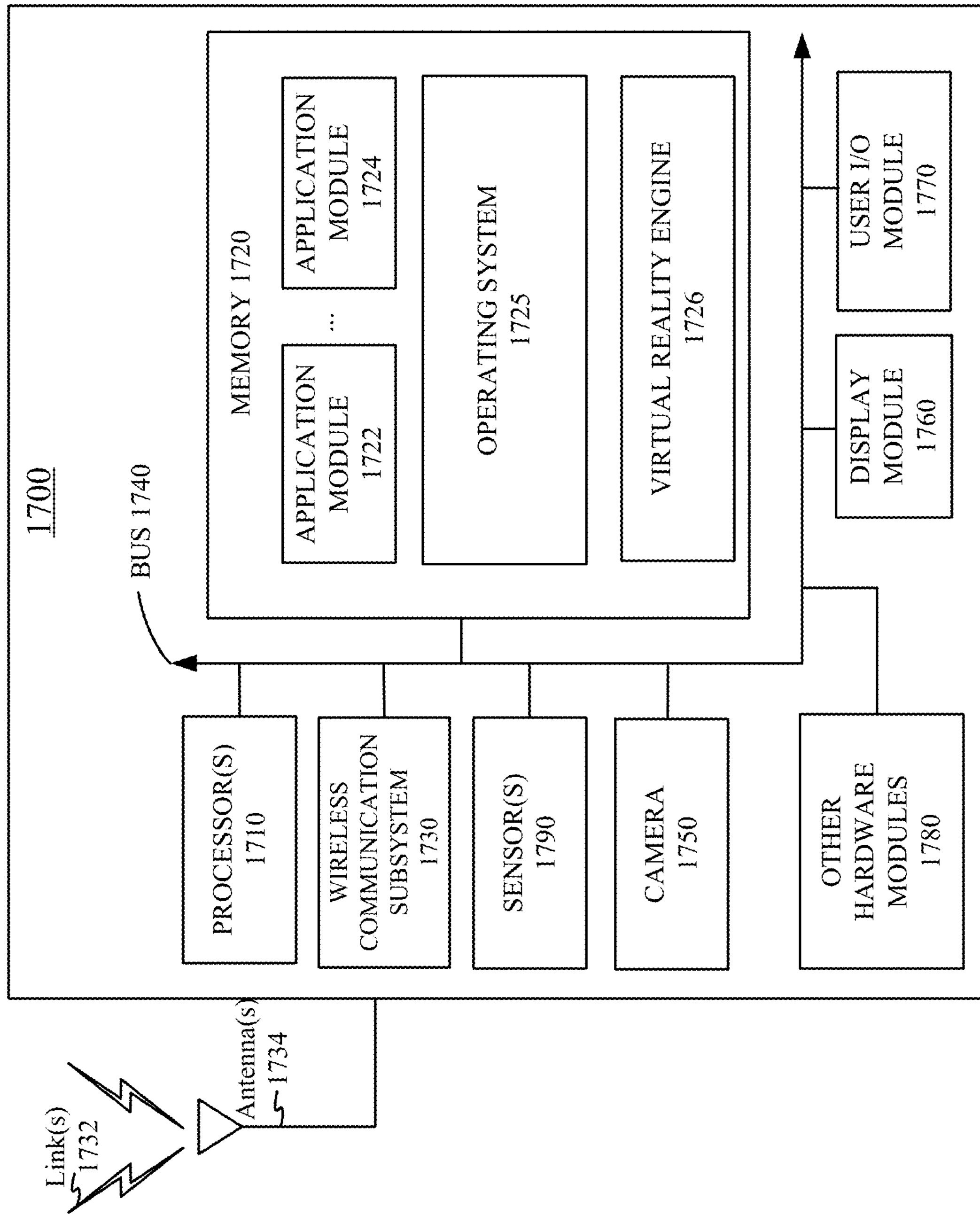


FIG. 17

REACTIVITY ENHANCEMENT IN ION BEAM ETCHER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application is a divisional of U.S. Non-Provisional patent application Ser. No. 16/001,694, filed Jun. 6, 2018, titled "REACTIVITY ENHANCEMENT IN ION BEAM ETCHER," which claims priority to U.S. Provisional Patent Application Ser. No. 62/579,055, filed Oct. 30, 2017, entitled "REACTIVITY ENHANCEMENT IN ION BEAM ETCHER," both of which are assigned to the assignee hereof and are hereby incorporated by reference in their entireties for all purposes.

BACKGROUND

[0002] An artificial reality system, such as a head-mounted display (HMD) or heads-up display (HUD) system, generally includes a display configured to present artificial images that depict objects in a virtual environment. The display may display virtual objects or combine images of real objects with virtual objects, as in virtual reality (VR), augmented reality (AR), or mixed reality (MR) applications. For example, in an AR system, a user may view both images of virtual objects (e.g., computer-generated images (CGIs)) and the surrounding environment by, for example, seeing through transparent display glasses or lenses (often referred to as optical see-through) or viewing displayed images of the surrounding environment captured by a camera (often referred to as video see-through).

[0003] One example optical see-through AR system may use a waveguide-based optical display, where light of projected images may be coupled into a waveguide (e.g., a substrate), propagate within the waveguide, and be coupled out of the waveguide at different locations. In some implementations, the light of the projected images may be coupled into or out of the waveguide using a diffractive optical element, such as a slanted surface-relief grating. In many cases, it may be challenging to fabricate the slanted surface-relief grating with the desired profile at a desirable speed.

SUMMARY

[0004] This disclosure relates generally to techniques for fabricating slanted structures, and more specifically, to techniques for etching slant structures on various materials, such as silicon dioxide, silicon nitride, titanium dioxide, or alumina. A chemically assisted reactive ion beam etch (CARIBE) technique is used to etch the slanted structures, such as high symmetrical slanted structures or slanted structures in exotic materials (e.g., silicon nitride, organic materials, or inorganic metal oxides). The CARIBE process (e.g., the chemical compounds, the radicals, or ions) can be more precisely controlled to achieve the desired etching selectivity, etch rate, and profile of the slanted structures.

[0005] In some embodiments, a method of fabricating a slanted surface-relief structure in a material layer includes injecting a first reactive gas into an reactive ion source generator, generating a plasma including reactive ions in the reactive ion source generator, extracting at least some of the reactive ions from the plasma to form a collimated reactive ion beam towards the material layer, and injecting a second reactive gas onto the material layer. The collimated reactive ion beam and the second reactive gas etch the material layer both physically and chemically to form the slanted surface-relief structure. In some embodiments, the method also includes rotating the material layer based on a desired slant angle of the slanted surface-relief structure.

[0006] In some embodiments, a chemically assisted reactive ion beam etching (CARIBE) system for fabricating a slanted surface-relief structure in a material layer is disclosed. The CARIBE system includes an reactive ion source generator configured to generate a plasma using a first reactive gas, where the plasma includes reactive ions. The CARIBE system also includes one or more aligned collimator grids configured to extract and accelerate at least some of the reactive ions in the plasma to form a collimated reactive ion beam towards the material layer. The CARIBE system further includes a gas ring configured to inject a second reactive gas onto the material layer. The collimated reactive ion beam and the second reactive gas etch the material layer both physically and chemically to form the slanted surface-relief structure in the material layer. In some embodiments, the CARIBE system includes a rotation stage configured to hold and rotate a substrate.

[0007] This summary is neither intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this disclosure, any or all drawings, and each claim. The foregoing, together with other features and examples, will be described in more detail below in the following specification, claims, and accompanying drawings.

[0008] Embodiments according to the invention are in particular disclosed in the attached claims, wherein any feature mentioned in one claim category, e.g. method, can be claimed in another claim category, e.g. system as well. The dependencies or references back in the attached claims are chosen for formal reasons only. However any subject matter resulting from a deliberate reference back to any previous claims (in particular multiple dependencies) can be claimed as well, so that any combination of claims and the features thereof is disclosed and can be claimed regardless of the dependencies chosen in the attached claims. The subject-matter which can be claimed comprises not only the combinations of features as set out in the attached claims but also any other combination of features in the claims, wherein each feature mentioned in the claims can be combined with any other feature or combination of other features in the claims. Furthermore, any of the embodiments and features described or depicted herein can be claimed in a separate claim and/or in any combination with any embodiment or feature described or depicted herein or with any of the features of the attached claims.

[0009] In an embodiment, a method of fabricating a slanted surface-relief structure in a material layer comprises: injecting a first reactive gas into an reactive ion source generator; generating a plasma in the reactive ion source generator, the plasma including reactive ions; extracting at least some of the reactive ions from the plasma to form a collimated reactive ion beam towards the material layer; and injecting a second reactive gas onto the material layer, where the collimated reactive ion beam and the second reactive gas etch the material layer both physically and chemically to form the slanted surface-relief structure.

[0010] In an embodiment, the method further comprises rotating the material layer based on a desired slant angle of the slanted surface-relief structure.

[0011] In an embodiment, the first reactive gas comprises at least one of CF_4, CHF_3, N_2, O_2, SF_6, Cl_2, BCl_3, HBr, H_2, Ar, He, or Ne.

[0012] In an embodiment, the material layer includes a semiconductor substrate, a SiO_2 layer, a Si_3N_4 material layer, a titanium oxide layer, an alumina layer, a SiC layer, a SiO_xN_y layer, an amorphous silicon layer, a spin on carbon (SOC) layer, an amorphous carbon layer (ACL), a diamond like carbon (DLC) layer, a TiO_x layer, an AlO_x layer, a TaO_x layer, or a HFO_x layer.

[0013] In an embodiment generating the plasma in the reactive ion source generator comprises: applying an RF signal to an inductively coupled plasma generator of the reactive ion source generator.

[0014] In an embodiment extracting at least some of the reactive ions from the plasma to form the collimated reactive ion beam comprises: applying an extraction voltage on an extraction grid adjacent to the reactive ion source generator; and applying an acceleration voltage on an acceleration grid to extract and accelerate at least some of the reactive ions, where the extraction grid and the acceleration grid are aligned; and where the acceleration voltage is lower than the extraction voltage.

[0015] In an embodiment injecting the second reactive gas comprises injecting the second reactive gas onto the material layer using a gas ring.

[0016] In an embodiment the second reactive gas comprises at least one of CF_4, CHF_3, N_2, O_2, SF_6, Cl_2, BCl_3, or HBr.

[0017] In an embodiment the method further comprises neutralizing the collimated reactive ion beam before etching the material layer using the collimated reactive ion beam and the second reactive gas.

[0018] In an embodiment neutralizing the collimated reactive ion beam comprises injecting an electron beam into the collimated reactive ion beam.

[0019] In an embodiment the slanted surface-relief structure comprises a slanted surface-relief optical grating.

[0020] In an embodiment the slanted surface-relief optical grating comprises a plurality of ridges; and a leading edge of each ridge is parallel to a trailing edge of the ridge.

[0021] In an embodiment a slant angle of the leading edge and a slant angle of the trailing edge are greater than 30 degrees with respect to a surface normal of the material layer.

[0022] In an embodiment a depth of the slanted surface-relief optical grating is greater than 100 nm.

[0023] In an embodiment a duty cycle of the slanted surface-relief optical grating is greater than 60%.

[0024] In an embodiment a chemically assisted reactive ion beam etching (CARIBE) system for fabricating a slanted surface-relief structure in a material layer comprises: an reactive ion source generator configured to generate a plasma using a first reactive gas, the plasma including reactive ions; one or more aligned collimator grids configured to extract and accelerate at least some of the reactive ions in the plasma to form a collimated reactive ion beam towards the material layer; and a gas ring configured to inject a second reactive gas onto the material layer, where the collimated reactive ion beam and the second reactive gas etch the material layer both physically and chemically to form the slanted surface-relief structure in the material layer.

[0025] In an embodiment the CARIBE system further comprises a neutralizer configured to inject an electron beam into the collimated reactive ion beam to neutralize the collimated reactive ion beam.

[0026] In an embodiment the CARIBE system further comprises a rotation stage configured to hold and rotate a substrate.

[0027] In an embodiment the reactive ion source generator comprises an inductively coupled plasma generator.

[0028] In an embodiment the first reactive gas comprises at least one of CF_4, CHF_3, N_2, O_2, SF_6, H_2, Cl_2, BCl_3, HBr, Ar, He, or Ne; and the second reactive gas comprises at least one of CF_4, CHF_3, N_2, O_2, SF_6, Cl_2, BCl_3, or HBr.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] Illustrative embodiments are described in detail below with reference to the following figures.

[0030] FIG. **1** is a simplified diagram of an example near-eye display according to certain embodiments.

[0031] FIG. **2** is a cross-sectional view of an example near-eye display according to certain embodiments.

[0032] FIG. **3** is an isometric view of an example waveguide display according to certain embodiments.

[0033] FIG. **4** is a cross-sectional view of an example waveguide display according to certain embodiments.

[0034] FIG. **5** is a simplified block diagram of an example artificial reality system including a waveguide display.

[0035] FIG. **6** illustrates an example optical see-through augmented reality system using a waveguide display according to certain embodiments;

[0036] FIG. **7** illustrates propagations of display light and external light in an example waveguide display.

[0037] FIG. **8** illustrates an example slanted grating coupler in an example waveguide display according to certain embodiments.

[0038] FIGS. **9**A-**9**C illustrate an example process for fabricating a slanted surface-relief structure according to certain embodiments.

[0039] FIG. **10** illustrates an example ion beam etching system for fabricating a slanted surface-relief structure.

[0040] FIG. **11** illustrates an example chemically assisted ion beam etching (CAIBE) system for fabricating a slanted surface-relief structure.

[0041] FIG. **12** illustrates an example reactive ion beam etching (RIBE) system for fabricating a slanted surface-relief structure.

[0042] FIG. **13** illustrates an example chemically assisted reactive ion beam etching (CARIBE) system for fabricating a slanted surface-relief structure according to certain embodiments.

[0043] FIG. **14**A illustrates an example slanted grating fabricated using the RIBE process.

[0044] FIG. **14**B illustrates an example slanted grating fabricated using the CAIBE process.

[0045] FIG. **15**A illustrates an example slanted grating fabricated using the CARIBE process according to certain embodiments.

[0046] FIG. **15**B illustrates an example slanted grating fabricated using the CARIBE process according to certain embodiments.

[0047] FIG. **16** is a simplified flow chart illustrating an example method of fabricating a slanted surface-relief structure according to certain embodiments.

[0048] FIG. **17** is a simplified block diagram of an example electronic system of an example near-eye display for implementing some of the examples disclosed herein.

[0049] The figures depict embodiments of the present disclosure for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated may be employed without departing from the principles, or benefits touted, of this disclosure.

[0050] In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

DETAILED DESCRIPTION

[0051] Techniques disclosed herein relate generally to micro- or nano-structure manufacturing. More specifically, and without limitation, this application relates to techniques for fabricating micro or nano slanted structures. Slanted structures may be used in many optical or electronic devices for manipulating behavior of light and/or electricity. However, it may often be challenging to etch high symmetrical slanted structures (e.g., a ridge with substantially equal leading edge and trailing edge) or slanted structures in exotic materials (e.g., silicon nitride, organic materials, or inorganic metal oxides). According to certain embodiments, slanted surface-relief gratings may be used in some optical devices, such as waveguide displays in artificial reality systems, to create high refractive index variations and high diffraction efficiencies. The slanted structures may not be reliably fabricated using current known etching processes, which may generally be optimized to etch features that are perpendicular to the surface being etched, such as the ion beam etching (IBE), reactive ion beam etching (RIBE), or chemically assisted ion beam etching (CAME) process. According to certain embodiments, a chemically assisted reactive ion beam etch (CARIBE) technique may be used to reliably etch the slanted structures. The CARIBE process parameters, including, for example, the chemical components, radicals, and ions used for the etching, can be more precisely controlled to achieve the desired etching selectivity, desired etch rate, and desired dimensions of the slanted structures.

[0052] In some embodiments, it is found that it is desirable to fabricate slanted structures for manipulating behaviors of light and/or electricity. Some of the benefits of the slanted structures may include a high efficiency of light transfer, a large variation in refractive indices, and/or the like. It is also found that the parallel slanted (with respect to the plane of the surface being etched) structures solve a problem unique to certain applications. Furthermore, it has been found that it may be desirable to form this type of slanted structures in different types of materials (e.g., as silicon dioxide, silicon nitride, titanium dioxide, alumina, etc.).

[0053] In the following description, for the purposes of explanation, specific details are set forth in order to provide a thorough understanding of examples of the disclosure. However, it will be apparent that various examples may be practiced without these specific details. For example, devices, systems, structures, assemblies, methods, and other components may be shown as components in block diagram form in order not to obscure the examples in unnecessary detail. In other instances, well-known devices, processes, systems, structures, and techniques may be shown without necessary detail in order to avoid obscuring the examples. The figures and description are not intended to be restrictive. The terms and expressions that have been employed in this disclosure are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof.

[0054] FIG. **1** is a simplified diagram of an example near-eye display **100** according to certain embodiments. Near-eye display **100** may present media to a user. Examples of media presented by near-eye display **100** may include one or more images, video, and/or audio. In some embodiments, audio may be presented via an external device (e.g., speakers and/or headphones) that receives audio information from near-eye display **100**, a console, or both, and presents audio data based on the audio information. Near-eye display **100** is generally configured to operate as an artificial reality display. In some embodiments, near-eye display **100** may operate as an augmented reality (AR) display or a mixed reality (MR) display.

[0055] Near-eye display **100** may include a frame **105** and a display **110**. Frame **105** may be coupled to one or more optical elements. Display **110** may be configured for the user to see content presented by near-eye display **100**. In some embodiments, display **110** may include a waveguide display assembly for directing light from one or more images to an eye of the user.

[0056] FIG. **2** is a cross-sectional view **200** of near-eye display **100** illustrated in FIG. **1**. Display **110** may include may include at least one waveguide display assembly **210**. An exit pupil **230** may be located at a location where a user's eye **220** is positioned when the user wears near-eye display **100**. For purposes of illustration, FIG. **2** shows cross-section sectional view **200** associated with user's eye **220** and a single waveguide display assembly **210**, but, in some embodiments, a second waveguide display may be used for the second eye of the user.

[0057] Waveguide display assembly **210** may be configured to direct image light (i.e., display light) to an eyebox located at exit pupil **230** and to user's eye **220**. Waveguide display assembly **210** may include one or more materials (e.g., plastic, glass, etc.) with one or more refractive indices. In some embodiments, near-eye display **100** may include one or more optical elements between waveguide display assembly **210** and user's eye **220**.

[0058] In some embodiments, waveguide display assembly **210** may include a stack of one or more waveguide displays including, but not restricted to, a stacked waveguide display, a varifocal waveguide display, etc. The stacked waveguide display is a polychromatic display (e.g., a red-green-blue (RGB) display) created by stacking waveguide displays whose respective monochromatic sources are of different colors. The stacked waveguide display may also be a polychromatic display that can be projected on multiple planes (e.g. multi-planar colored display). In some configurations, the stacked waveguide display may be a monochro-

matic display that can be projected on multiple planes (e.g. multi-planar monochromatic display). The varifocal waveguide display is a display that can adjust a focal position of image light emitted from the waveguide display. In alternate embodiments, waveguide display assembly **210** may include the stacked waveguide display and the varifocal waveguide display.

[0059] FIG. **3** is an isometric view of an embodiment of a waveguide display **300**. In some embodiments, waveguide display **300** may be a component (e.g., waveguide display assembly **210**) of near-eye display **100**. In some embodiments, waveguide display **300** may be part of some other near-eye displays or other systems that may direct image light to a particular location.

[0060] Waveguide display **300** may include a source assembly **310**, an output waveguide **320**, and a controller **330**. For purposes of illustration, FIG. **3** shows waveguide display **300** associated with a user's eye **390**, but in some embodiments, another waveguide display separate, or partially separate, from waveguide display **300** may provide image light to another eye of the user.

[0061] Source assembly **310** may generate image light **355** for display to the user. Source assembly **310** may generate and output image light **355** to a coupling element **350** located on a first side **370-1** of output waveguide **320**. In some embodiments, coupling element **350** may couple image light **355** from source assembly **310** into output waveguide **320**. Coupling element **350** may include, for example, a diffraction grating, a holographic grating, one or more cascaded reflectors, one or more prismatic surface elements, and/or an array of holographic reflectors. Output waveguide **320** may be an optical waveguide that can output expanded image light **340** to user's eye **390**. Output waveguide **320** may receive image light **355** at one or more coupling elements **350** located on first side **370-1** and guide received image light **355** to a directing element **360**.

[0062] Directing element **360** may redirect received input image light **355** to decoupling element **365** such that received input image light **355** may be coupled out of output waveguide **320** via decoupling element **365**. Directing element **360** may be part of, or affixed to, first side **370-1** of output waveguide **320**. Decoupling element **365** may be part of, or affixed to, a second side **370-2** of output waveguide **320**, such that directing element **360** is opposed to decoupling element **365**. Directing element **360** and/or decoupling element **365** may include, for example, a diffraction grating, a holographic grating, a surface-relief grating, one or more cascaded reflectors, one or more prismatic surface elements, and/or an array of holographic reflectors.

[0063] Second side **370-2** of output waveguide **320** may represent a plane along an x-dimension and a y-dimension. Output waveguide **320** may include one or more materials that can facilitate total internal reflection of image light **355**. Output waveguide **320** may include, for example, silicon, plastic, glass, and/or polymers. Output waveguide **320** may have a relatively small form factor. For example, output waveguide **320** may be approximately 50 mm wide along the x-dimension, about 30 mm long along the y-dimension, and about 0.5 to 1 mm thick along a z-dimension.

[0064] Controller **330** may control scanning operations of source assembly **310**. Controller **330** may determine scanning instructions for source assembly **310**. In some embodiments, output waveguide **320** may output expanded image light **340** to user's eye **390** with a large field of view (FOV). For example, expanded image light **340** provided to user's eye **390** may have a diagonal FOV (in x and y) of about 60 degrees or greater and/or about 150 degrees or less. Output waveguide **320** may be configured to provide an eyebox with a length of about 20 mm or greater and/or equal to or less than about 50 mm, and/or a width of about 10 mm or greater and/or equal to or less than about 50 mm.

[0065] FIG. **4** is a cross-sectional view **400** of waveguide display **300**. Waveguide display **300** may include source assembly **310** and output waveguide **320**. Source assembly **310** may generate image light **355** (i.e., display light) in accordance with scanning instructions from controller **330**. Source assembly **310** may include a source **410** and an optics system **415**. Source **410** may include a light source that generates coherent or partially coherent light. Source **410** may include, for example, a laser diode, a vertical cavity surface emitting laser, and/or a light emitting diode.

[0066] Optics system **415** may include one or more optical components that can condition the light from source **410**. Conditioning light from source **410** may include, for example, expanding, collimating, and/or adjusting orientation in accordance with instructions from controller **330**. The one or more optical components may include one or more lenses, liquid lenses, mirrors, apertures, and/or gratings. Light emitted from optics system **415** (and also source assembly **310**) may be referred to as image light **355** or display light.

[0067] Output waveguide **320** may receive image light **355** from source assembly **310**. Coupling element **350** may couple image light **355** from source assembly **310** into output waveguide **320**. In embodiments where coupling element **350** includes a diffraction grating, the diffraction grating may be configured such that total internal reflection may occur within output waveguide **320**, and thus image light **355** coupled into output waveguide **320** may propagate internally within output waveguide **320** (e.g., by total internal reflection) toward decoupling element **365**.

[0068] Directing element **360** may redirect image light **355** toward decoupling element **365** for coupling at least a portion of the image light out of output waveguide **320**. In embodiments where directing element **360** is a diffraction grating, the diffraction grating may be configured to cause incident image light **355** to exit output waveguide **320** at angle(s) of inclination relative to a surface of decoupling element **365**. In some embodiments, directing element **360** and/or the decoupling element **365** may be structurally similar.

[0069] Expanded image light **340** exiting output waveguide **320** may be expanded along one or more dimensions (e.g., elongated along the x-dimension). In some embodiments, waveguide display **300** may include a plurality of source assemblies **310** and a plurality of output waveguides **320**. Each of source assemblies **310** may emit a monochromatic image light corresponding to a primary color (e.g., red, green, or blue). Each of output waveguides **320** may be stacked together to output an expanded image light **340** that may be multi-colored.

[0070] FIG. **5** is a simplified block diagram of an example artificial reality system **500** including waveguide display assembly **210**. System **500** may include near-eye display **100**, an imaging device **535**, and an input/output interface **540** that are each coupled to a console **510**.

[0071] As described above, near-eye display **100** may be a display that presents media to a user. Examples of media

presented by near-eye display **100** may include one or more images, video, and/or audio. In some embodiments, audio may be presented via an external device (e.g., speakers and/or headphones) that may receive audio information from near-eye display **100** and/or console **510** and present audio data based on the audio information to a user. In some embodiments, near-eye display **100** may act as an artificial reality eyewear glass. For example, in some embodiments, near-eye display **100** may augment views of a physical, real-world environment, with computer-generated elements (e.g., images, video, sound, etc.).

[0072] Near-eye display **100** may include waveguide display assembly **210**, one or more position sensors **525**, and/or an inertial measurement unit (IMU) **530**. Waveguide display assembly **210** may include a waveguide display, such as waveguide display **300** that includes source assembly **310**, output waveguide **320**, and controller **330** as described above.

[0073] IMU **530** may include an electronic device that can generate fast calibration data indicating an estimated position of near-eye display **100** relative to an initial position of near-eye display **100** based on measurement signals received from one or more position sensors **525**.

[0074] Imaging device **535** may generate slow calibration data in accordance with calibration parameters received from console **510**. Imaging device **535** may include one or more cameras and/or one or more video cameras.

[0075] Input/output interface **540** may be a device that allows a user to send action requests to console **510**. An action request may be a request to perform a particular action. For example, an action request may be to start or end an application or to perform a particular action within the application.

[0076] Console **510** may provide media to near-eye display **100** for presentation to the user in accordance with information received from one or more of: imaging device **535**, near-eye display **100**, and input/output interface **540**. In the example shown in FIG. **5**, console **510** may include an application store **545**, a tracking module **550**, and an engine **555**.

[0077] Application store **545** may store one or more applications for execution by the console **510**. An application may include a group of instructions that, when executed by a processor, may generate content for presentation to the user. Examples of applications may include gaming applications, conferencing applications, video playback application, or other suitable applications.

[0078] Tracking module **550** may calibrate system **500** using one or more calibration parameters and may adjust one or more calibration parameters to reduce error in determination of the position of near-eye display **100**. Tracking module **550** may track movements of near-eye display **100** using slow calibration information from imaging device **535**. Tracking module **550** may also determine positions of a reference point of near-eye display **100** using position information from the fast calibration information.

[0079] Engine **555** may execute applications within system **500** and receives position information, acceleration information, velocity information, and/or predicted future positions of near-eye display **100** from tracking module **550**. In some embodiments, information received by engine **555** may be used for producing a signal (e.g., display instructions) to waveguide display assembly **210**. The signal may determine a type of content to present to the user.

[0080] There may be many different ways to implement the waveguide display. For example, in some implementations, output waveguide **320** may include a slanted surface between first side **370-1** and second side **370-2** for coupling image light **355** into output waveguide **320**. In some implementations, the slanted surface may be coated with a reflective coating to reflect light towards directing element **360**. In some implementations, the angle of the slanted surface may be configured such that image light **355** may be reflected by the slanted surface due to total internal reflection. In some implementations, directing element **360** may not be used, and light may be guided within output waveguide **320** by total internal reflection. In some implementations, decoupling elements **365** may be located near first side **370-1**.

[0081] In some implementations, output waveguide **320** and decoupling element **365** (and directing element **360** if used) may be transparent to light from the environment, and may act as an optical combiner for combining image light **355** and light from the physical, real-world environment in front of near-eye display **100**. As such, the user can view both artificial images of artificial objects from source assembly **310** and real images of real objects in the physical, real-world environment, which may be referred to as optical see-through.

[0082] FIG. **6** illustrates an example optical see-through augmented reality system **600** using a waveguide display according to certain embodiments. Augmented reality system **600** may include a projector **610** and a combiner **615**. Projector **610** may include a light source or image source **612** and projector optics **614**. In some embodiments, image source **612** may include a plurality of pixels that displays virtual objects, such as an LCD display panel or an LED display panel. In some embodiments, image source **612** may include a light source that generates coherent or partially coherent light. For example, image source **612** may include a laser diode, a vertical cavity surface emitting laser, and/or a light emitting diode. In some embodiments, image source **612** may include a plurality of light sources each emitting a monochromatic image light corresponding to a primary color (e.g., red, green, or blue). In some embodiments, image source **612** may include an optical pattern generator, such as a spatial light modulator. Projector optics **614** may include one or more optical components that can condition the light from image source **612**, such as expanding, collimating, scanning, or projecting light from image source **612** to combiner **615**. The one or more optical components may include, for example, one or more lenses, liquid lenses, mirrors, apertures, and/or gratings. In some embodiments, projector optics **614** may include a liquid lens (e.g., a liquid crystal lens) with a plurality of electrodes that allows scanning of the light from image source **612**.

[0083] Combiner **615** may include an input coupler **630** for coupling light from projector **610** into a substrate **620** of combiner **615**. Input coupler **630** may include a volume holographic grating, a diffractive optical elements (DOE) (e.g., a surface-relief grating), or a refractive coupler (e.g., a wedge or a prism). Input coupler **630** may have a coupling efficiency of greater than 30%, 50%, 75%, 90%, or higher for visible light. As used herein, visible light may refer to light with a wavelength between about 380 nm to about 750 nm. Light coupled into substrate **620** may propagate within substrate **620** through, for example, total internal reflection (TIR). Substrate **620** may be in the form of a lens of a pair of eyeglasses. Substrate **620** may have a flat or a curved

surface, and may include one or more types of dielectric materials, such as glass, quartz, plastic, polymer, poly(methyl methacrylate) (PMMA), crystal, or ceramic. A thickness of the substrate may range from, for example, less than about 1 mm to about 10 mm or more. Substrate **620** may be transparent to visible light. A material may be "transparent" to a light beam if the light beam can pass through the material with a high transmission rate, such as larger than 50%, 60%, 75%, 80%, 90%, 95%, or higher, where a small portion of the light beam (e.g., less than 50%, 40%, 25%, 20%, 10%, 5%, or less) may be scattered, reflected, or absorbed by the material. The transmission rate (i.e., transmissivity) may be represented by either a photopically weighted or an unweighted average transmission rate over a range of wavelengths, or the lowest transmission rate over a range of wavelengths, such as the visible wavelength range.

[0084] Substrate **620** may include or may be coupled to a plurality of output couplers **640** configured to extract at least a portion of the light guided by and propagating within substrate **620** from substrate **620**, and direct extracted light **660** to an eye **690** of the user of augmented reality system **600**. As input coupler **630**, output couplers **640** may include grating couplers (e.g., volume holographic gratings or surface-relief gratings), other DOEs, prisms, etc. Output couplers **640** may have different coupling (e.g., diffraction) efficiencies at different locations. Substrate **620** may also allow light **650** from environment in front of combiner **615** to pass through with little or no loss. Output couplers **640** may also allow light **650** to pass through with little loss. For example, in some implementations, output couplers **640** may have a low diffraction efficiency for light **650** such that light **650** may be refracted or otherwise pass through output couplers **640** with little loss. In some implementations, output couplers **640** may have a high diffraction efficiency for light **650** and may diffract light **650** to certain desired directions (i.e., diffraction angles) with little loss. As a result, the user may be able to view combined images of the environment in front of combiner **615** and virtual objects projected by projector **610**.

[0085] FIG. **7** illustrates propagations of incident display light **740** and external light **730** in an example waveguide display **700** including a waveguide **710** and a grating coupler **720**. Waveguide **710** may be a flat or curved transparent substrate with a refractive index n_2 greater than the free space refractive index n_1 (i.e., 1.0). Grating coupler **720** may include, for example, a Bragg grating or a surface-relief grating.

[0086] Incident display light **740** may be coupled into waveguide **710** by, for example, input coupler **630** of FIG. **6** or other couplers (e.g., a prism or slanted surface) described above. Incident display light **740** may propagate within waveguide **710** through, for example, total internal reflection. When incident display light **740** reaches grating coupler **720**, incident display light **740** may be diffracted by grating coupler **720** into, for example, a 0th order diffraction (i.e., reflection) light **742** and a −1st order diffraction light **744**. The 0th order diffraction may continue to propagate within waveguide **710**, and may be reflected by the bottom surface of waveguide **710** towards grating coupler **720** at a different location. The −1st order diffraction light **744** may be coupled (e.g., refracted) out of waveguide **710** towards the user's eye, because a total internal reflection condition may not be met at the bottom surface of waveguide **710** due to the diffraction angle of the -1st order diffraction light **744**.

[0087] External light **730** may also be diffracted by grating coupler **720** into, for example, a 0th order diffraction light **732** or a −1st order diffraction light **734**. The 0th order diffraction light **732** or the −1st order diffraction light **734** may be refracted out of waveguide **710** towards the user's eye. Thus, grating coupler **720** may act as an input coupler for coupling external light **730** into waveguide **710**, and may also act as an output coupler for coupling incident display light **740** out of waveguide **710**. As such, grating coupler **720** may act as a combiner for combining external light **730** and incident display light **740** and send the combined light to the user's eye.

[0088] In order to diffract light at a desired direction towards the user's eye and to achieve a desired diffraction efficiency for certain diffraction orders, grating coupler **720** may include a blazed or slanted grating, such as a slanted Bragg grating or surface-relief grating, where the grating ridges and grooves may be tilted relative to the surface normal of grating coupler **720** or waveguide **710**.

[0089] FIG. **8** illustrates an example slanted grating **820** in an example waveguide display **800** according to certain embodiments. Waveguide display **800** may include slanted grating **820** on a waveguide **810**, such as substrate **620**. Slanted grating **820** may act as a grating coupler for couple light into or out of waveguide **810**. In some embodiments, slanted grating **820** may include a periodic structure with a period p. For example, slanted grating **820** may include a plurality of ridges **822** and grooves **824** between ridges **822**. Each period of slanted grating **820** may include a ridge **822** and a groove **824**, which may be an air gap or a region filled with a material with a refractive index n_{g2}. The ratio between the width of a ridge **822** and the grating period p may be referred to as duty cycle. Slanted grating **820** may have a duty cycle ranging, for example, from about 10% to about 90% or greater. In some embodiments, the duty cycle may vary from period to period. In some embodiments, the period p of the slanted grating may vary from one area to another on slanted grating **820**, or may vary from one period to another (i.e., chirped) on slanted grating **820**.

[0090] Ridges **822** may be made of a material with a refractive index of n_{g1}, such as silicon containing materials (e.g., SiO_2, Si_3N_4, SiC, SiO_xN_y, or amorphous silicon), organic materials (e.g., spin on carbon (SOC) or amorphous carbon layer (ACL) or diamond like carbon (DLC)), or inorganic metal oxide layers (e.g., TiO_x, AlO_x, TaO_x, HfO_x, etc.). Each ridge **822** may include a leading edge **830** with a slant angel α and a trailing edge **840** with a slant angle β. In some embodiments, leading edge **830** and training edge **840** of each ridge **822** may be parallel to each other. In other words, slant angle α is approximately equal to slant angle β. In some embodiments, slant angle α may be different from slant angle β. In some embodiments, slant angle α may be approximately equal to slant angle β. For example, the difference between slant angle α and slant angle β may be less than 20%, 10%, 5%, 1%, or less. In some embodiments, slant angle α and slant angle β may range from, for example, about 30° or less to about 70% or larger.

[0091] In some implementations, grooves **824** between the ridges **822** may be over-coated or filled with a material having a refractive index n_{g2} higher or lower than the refractive index of the material of ridges **822**. For example, in some embodiments, a high refractive index material, such as Hafnia, Titania, Tantalum oxide, Tungsten oxide, Zirconium oxide, Gallium sulfide, Gallium nitride, Gallium phos-

phide, silicon, and a high refractive index polymer, may be used to fill grooves **824**. In some embodiments, a low refractive index material, such as silicon oxide, alumina, porous silica, or fluorinated low index monomer (or polymer), may be used to fill grooves **824**. As a result, the difference between the refractive index of the ridges and the refractive index of the grooves may be greater than 0.1, 0.2, 0.3, 0.5, 1.0, or higher.

[0092] The slanted grating may be fabricated using many different nanofabrication techniques. The nanofabrication techniques generally include a patterning process and a post-patterning (e.g., over-coating) process. The patterning process may be used to form slanted ridges of the slanted grating. There may be many different nanofabrication techniques for forming the slanted ridges. For example, in some implementations, the slanted grating may be fabricated using lithography techniques including slanted etching. In some implementations, the slanted grating may be fabricated using nanoimprint lithography (NIL) molding techniques. The post-patterning process may be used to over-coat the slanted ridges and/or to fill the gaps between the slanted ridges with a material having a different refractive index than the slanted ridges. The post-patterning process may be independent from the patterning process. Thus, a same post-patterning process may be used on slanted gratings fabricated using any pattering technique.

[0093] Techniques and processes for fabricating the slanted grating described below are for illustration purposes only and are not intended to be limiting. A person skilled in the art would understand that various modifications may be made to the techniques described below. For example, in some implementations, some operations described below may be omitted. In some implementations, additional operations may be performed to fabricate the slanted grating. Techniques disclosed herein may also be used to fabricate other slanted structures on various materials.

[0094] FIGS. **9A-9C** illustrate an example simplified process for fabricating a slanted surface-relief grating by slanted etching according to certain embodiments. FIG. **9A** shows a structure **900** after a lithography process, such as a photolithography process. Structure **900** may include a substrate **910** that may be used as the waveguide of a waveguide display described above, such as a glass or quartz substrate. Structure **900** may also include a layer of grating material **920**, such as Si_3N_4 or SiO_2. Substrate **910** may have a refractive index n_{wg}, and the layer of grating material **920** may have a refractive index n_{g1}. In some embodiments, the layer of grating material **920** may be a part of substrate **910**. A mask layer **930** with a desired pattern may be formed on the layer of grating material **920**. Mask layer **930** may include, for example, a photoresist material, a metal (e.g., copper, chrome, titanium, aluminum, or molybdenum), an intermetallic compound (e.g., MoSiON), or a polymer. Mask layer **930** may be formed by, for example, the optical projection or electron beam lithography process, NIL process, or multi-beam interference process.

[0095] FIG. **9B** shows a structure **940** after a slanted etching process, such as a dry etching process (e.g., reactive ion etching (RIE), inductively coupled plasma (ICP), deep silicon etching (DSE), ion beam etching (IBE), or variations of IBE). The slanted etching process may include one or more sub-steps. The slanted etching may be performed by, for example, rotating structure **900** and etching the layer of grating material **920** by the etching beam based on the desired slant angle. After the etching, a slanted grating **950** may be formed in the layer of grating material **920**.

[0096] FIG. **9C** shows a structure **970** after mask layer **930** is removed. Structure **970** may include substrate **910**, the layer of grating material **920**, and slanted grating **950**. Slanted grating **950** may include a plurality of ridges **952** and grooves **954**. Techniques such as plasma or wet etching may be used to strip mask layer **930** with appropriate chemistry. In some implementations, mask layer **930** may not be removed and may be used as part of the slanted grating.

[0097] Subsequently, in some implementations, the post-patterning (e.g., over-coating) process may be performed to over-coat slanted grating **950** with a material having a refractive index higher or lower than the material of ridges **952**. For example, as described above, in some embodiments, a high refractive index material, such as Hafnia, Titania, Tungsten oxide, Zirconium oxide, Gallium sulfide, Gallium nitride, Gallium phosphide, silicon, and a high refractive index polymer, may be used for the over-coating. In some embodiments, a low refractive index material, such as silicon oxide, alumina, porous silica, or fluorinated low index monomer (or polymer), may be used for the over-coating. As a result, the difference between the refractive index of the ridges and the refractive index of the grooves may be greater than 0.1, 0.2, 0.3, 0.5, 1.0, or higher.

[0098] FIG. **10** illustrates an example ion beam etching (IBE) system **1000** for fabricating a slanted surface-relief structure. Ion beam etching is one process enabler in surface relief grating fabrication. Ion beam etching generally uses a highly collimated and highly directional ion beam to physically mill materials from a substrate mounted on a rotation stage with an adjustable rotation angle.

[0099] IBE system **1000** may include an ion source generator **1010**. Ion source generator **1010** may include an inert gas inlet **1020** for receiving an inert gas, such as an Argon gas, into a chamber of ion source generator **1010**. A plasma may be generated in ion source generator **1010** via an RF inductively coupled plasma (ICP) generator **1030**, where highly energetic electrons may ionize neutrals of the injected inert gas (e.g., Ar) through collisions with the neutrals. A high density plasma **1022** may be generated within ion source generator **1010** by the impact ionization. High density plasma **1022** may be considered as a sea of neutrals with positive ions **1024** and negative electrons in charge equilibrium.

[0100] IBE system **1000** may also include one or more aligned collimator grids for extracting a collimated ion beam **1062** from high density plasma **1022** formed within ion source generator **1010**. The aligned collimator grids may be implemented in various ways. For example, as shown in FIG. **10**, the aligned collimator grids may include an extraction grid **1040** that may contact high density plasma **1022** and control its potential, and an acceleration grid **1050** that may be driven by an adjustable negative high voltage supply for accelerating the extracted ions. A beam neutralizer **1060** may be disposed near the aligned collimator grids and may emit an electron beam into collimated ion beam **1062** to achieve a net neutral charge flux associated with collimated ion beam **1062** in order to prevent the buildup of positive charges on the structure to be etched.

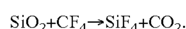
[0101] The highly directional collimated ion beam **1062** may physically mill materials from a material layer **1080** to be etched, such as, for example, a semiconductor wafer, a

glass substrate, a Si_3N_4 material layer, a titanium oxide layer, an alumina layer, etc. Material layer **1080** may be partially covered by a mask **1082**, which may be formed on material layer **1080** by, for example, a photolithography process. Mask **1082** may include, for example, a photoresist material, a metal (e.g., copper, chrome, aluminum, or molybdenum), an intermetallic compound (e.g., $MoSi_2$), or a polymer. In some embodiments, a shutter **1090** (or blade) may be used to control the etch time and/or the etch region. Material layer **1080** may be mounted on a rotation stage **1070** that can be rotated to modify the angle of material layer **1080** with respect to the highly directional collimated ion beam **1062**. The ability to modify the angle of material layer **1080** may allow for the creation of tailored sidewall profiles with minimal sputtered redeposition on mask **1082**. Since the IBE mechanism is purely physical, the etch rate may not be as fast as desired. In addition, the energetic ions may cause stoichiometric damage to the material layer and introduce defects, and thus may lead to degraded performance of the etched slanted structure.

[0102] FIG. **11** illustrates an example chemically assisted ion beam etching (CAIBE) system **1100** for fabricating a slanted surface-relief structure. In the chemically assisted ion beam etching, reactive species, such as a reactive gas (e.g., CF_4, CHF_3, N_2, O_2, SF_6, Cl_2, BCl_3, HBr, etc.) may be introduced into the process independent of the ion beam. Thus, the material layer to be etched may be etched both physically and chemically.

[0103] As IBE system **1000**, CAIBE system **1100** may include an ion source generator **1110**. Ion source generator **1110** may be similar to ion source generator **1010** described above with respect to FIG. **10**. Ion source generator **1110** may include an inert gas inlet **1120** for receiving an inert gas, such as an Argon gas, into a chamber of ion source generator **1110**. A plasma may be generated in ion source generator **1110** via an RF inductively coupled plasma (ICP) generator **1130**. A high density plasma **1122** may be generated within ion source generator **1110** by impact ionization. One or more aligned collimator grids may be used to extract a collimated ion beam **1162** from high density plasma **1122**. For example, as shown in FIG. **11**, the aligned collimator grids may include an extraction grid **1140** that may contact high density plasma **1122** and control its potential, and an acceleration grid **1150** that may be driven by an adjustable negative high voltage supply for accelerating the extracted ions. A beam neutralizer **1160** may be disposed near the aligned collimator grids and may emit an electron beam into collimated ion beam **1162** to achieve a net neutral charge flux associated with collimated ion beam **1162** in order to prevent the buildup of positive charges on the structure to be etched.

[0104] In addition, an reactive gas **1166** (e.g., CF_4, CHF_3, N_2, O_2, SF_6, Cl_2 or BCl_3 or HBr etc.) may be injected onto a material layer **1180** to be etched using a gas ring **1164**. In general, reactive gas **1166** may be injected at a location close to material layer **1180**. Reactive gas and collimated ion beam **1162** may reach areas of material layer **1180** uncovered by a mask **1182**, and both physically (as in IBE) and chemically etch the uncovered area. For example, a glass substrate may be chemically etched by a reactive gas CF_4 according to:



$$SiO_2+CF_4 \rightarrow SiF_4+CO_2.$$

SiF_4 and CO_2 are volatile materials that may be easily removed. As IBE system **1000**, CAIBE system **1100** may include a shutter **1190** (or blade) for controlling the etch time and/or the etch region. Material layer **1180** may be mounted on a rotation stage **1170** that can be rotated to modify the angle of material layer **1180** with respect to the highly directional collimated ion beam **1162**. For certain materials, an CAIBE system may offer additional control of etch anisotropy, sputter redeposition, and etch rate over an IBE system.

[0105] FIG. **12** illustrates an example reactive ion beam etching (RIBE) system **1200** for fabricating a slanted surface-relief structure. Reactive ion beam etching system **1200** may be similar to IBE system **1000**, except that a reactive gas (e.g., CF_4, CHF_3, N_2, O_2, SF_6, etc.) may also be injected into the ion source generator to form a reactive ion beam that can both physically and chemically etch the material layer to be etched.

[0106] RIBE system **1200** may be similar to IBE system **1000**, and may include an ion source generator **1210** for generating a high density plasma **1222**. Ion source generator **1210** may include an gas inlet **1220** for receiving a reactive gas (e.g., CF_4, CHF_3, N_2, O_2, SF_6, Cl_2, BCl_3, or HBr, etc.) and, in some cases, an inert gas (e.g., Argon gas, Helium gas, or Neon gas) into a chamber of ion source generator **1210**. High density plasma **1222** may be generated by impact ionization in ion source generator **1210** via an RF inductively coupled plasma (ICP) generator **1230**. One or more aligned collimator grids may be used to extract a collimated reactive ion beam **1262** from high density plasma **1222**. For example, as shown in FIG. **12**, the aligned collimator grids may include an extraction grid **1240** that may contact high density plasma **1222** and control its potential, and an acceleration grid **1250** that may be driven by an adjustable negative high voltage supply for accelerating the extracted reactive ions. A beam neutralizer **1260** may be disposed near the aligned collimator grids and may emit an electron beam into collimated reactive ion beam **1262** to achieve a net neutral charge flux associated with collimated reactive ion beam **1262** in order to prevent the buildup of positive charges on the structure to be etched.

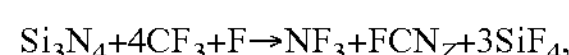
[0107] Collimated reactive ion beam **1262** may reach areas of a material layer **1280** uncovered by a mask **1282**, and physically and chemically etched the uncovered area. As IBE system **1000** and CAIBE system **1100**, RIBE system **1200** may also include a shutter **1290** (or blade) for controlling the etch time and/or the etch region. Material layer **1280** may be mounted on a rotation stage **1270** that can be rotated to modify the angle of material layer **1280** with respect to the highly directional collimated reactive ion beam **1262**. For certain materials, an RIBE system may offer additional control of etch anisotropy, sputter redeposition, and etch rate over an IBE system.

[0108] For many materials (e.g., silicon nitride, organic materials, or inorganic metal oxides) and/or certain desired slanted features (e.g., grating ridge with substantially equal leading edge and trailing edge), these known etching processes, such as the IBE process, RIBE process, and CAIBE process, may not be used to reliably fabricate the slanted structures. One reason is that these processes may not provide appropriate combinations of reactants and/or process parameters for etching the desired slanted structures on the desired materials. According to certain embodiments, a chemically assisted reactive ion beam etch (CARIBE) process can be used to fabricate slanted surface-relief structures on various materials. The CARIBE process disclosed herein

may provide more effective control of radicals and ions by providing appropriate chemical components in the ion source and the gas ring, and thus may enable improved profile and mask selectivity for materials requiring a higher amount of chemical component for etching and may also help in increasing the etch stop margin. Using the CARIBE process, the features of the slanted structure can be more accurately fabricated on various materials, including materials that may need a higher amount of chemical components. In some embodiments, the process described herein may be used to fabricate a grating on an object that controls the behavior of light as the light reflects, refracts, and/or diffracts due to the interactions with the gratings and/or the interferences between light that interacts with the gratings. In some embodiments, the grating may be slanted and the object may be an optical element, such as a waveguide for waveguide display.

[0109] FIG. **13** illustrates an example chemically assisted reactive ion beam etching (CARIBE) system **1300** for fabricating a slanted surface-relief structure according to certain embodiments. CARIBE system **1300** may include a reactive ion source generator **1310**. Reactive ion source generator **1310** may include an gas inlet **1320** for receiving a reactive gas (e.g., CF_4, CHF_3, N_2, O_2, SF_6, H_2, etc.) and, in some cases, an inert gas (e.g., Argon gas) into a chamber of reactive ion source generator **1310**. A high density plasma **1322** may be generated by impact ionization in reactive ion source generator **1310** via an RF inductively coupled plasma (ICP) generator **1330**. One or more aligned collimator grids may be used to extract a collimated reactive ion beam **1362** from high density plasma **1322**. For example, as shown in FIG. **13**, the aligned collimator grids may include a extraction grid **1340** that may contact high density plasma **1322** and control its potential, and an acceleration grid **1350** that may be driven by an adjustable negative high voltage supply for accelerating the extracted reactive ions. A beam neutralizer **1360** may be disposed near the aligned collimator grids and may emit an electron beam into collimated reactive ion beam **1362** to achieve a net neutral charge flux associated with collimated reactive ion beam **1362** in order to prevent the buildup of positive charges on the structure to be etched.

[0110] In addition, CARIBE system **1300** may include a gas ring **1364** for injecting an reactive gas **1366** (e.g., CF_4, CHF_3, N_2, O_2, SF_6, etc.) onto the material layer to be etched at a location close to the material layer. Collimated reactive ion beam **1362** (or neutrals **1368** after neutralization) and reactive gas **1366** may reach areas of a material layer **1380** uncovered by a mask **1382**, and may physically and chemically etched the uncovered area due to physical milling and chemical reactions. For example, a Si_3N_4 layer may be chemically etched by a reactive gas CF_4 according to:



$$Si_3N_4+4CF_3+F\rightarrow NF_3+FCN_Z+3SiF_4,$$

where the NF_3, FCN_z, and SiF_4 may be volatile material and can be relatively easily removed to form the slanted structures in the Si_3N_4 layer. The neutral to ion ratio in the beam that reaches material layer **1380** in the CARIBE process may be higher than that in the RIBE or CAME process.

[0111] CARIBE system **1300** may include a shutter **1390** (or blade) for controlling the etch time and/or the etch region. Material layer **1380** may be mounted on a rotation stage **1370** that can be rotated to modify the angle of material layer **1380** with respect to the highly directional collimated reactive ion beam **1362**. As a result, a slanted structure including a plurality of grooves **1384** and a plurality of ridges **1386** may be formed in material layer **1380**. The width and the slant angle of ridges **1386** may be more precisely controlled, compare with the IBE, RIBE, or CAIBE process.

[0112] FIG. **14**A illustrates an example slanted grating **1400** fabricated using the RIBE process. Slanted grating **1400** may be fabricated on a Si_3N_4 layer using a chrome mask. As described above, in many applications according to certain embodiments, it is often desirable that the leading edge and the trailing edge of the ridge of the slanted grating are substantially parallel to each other to achieve certain desired performance. As shown in FIG. **14**A, the slant angle of a leading edge **1412** of a ridge **1410** of slanted grating **1400** may be very different from the slant angle of a trailing edge **1414** of ridge **1410** of slanted grating **1400**. This may be caused by the accumulation of certain materials (e.g., carbon) generated during the etching process. Thus, slanted grating **1400** fabricated using the RIBE process may not have the desired features of the slanted gratings for certain applications.

[0113] FIG. **14**B illustrates an example slanted grating **1450** fabricated using the CAIBE process. Similarly to slanted grating **1400**, slanted grating **1450** may be fabricated on a Si_3N_4 layer using a chrome mask. As shown in FIG. **14**B, the slant angle of a leading edge **1462** of a ridge **1460** of slanted grating **1450** may be very different from the slant angle of a trailing edge **1464** of ridge **1460** of slanted grating **1450**. This may be caused by the accumulation of certain materials (e.g., carbon) generated during the etching process. Thus, slanted grating **1450** fabricated using the CAIBE process may not have the desired features of the slanted gratings for certain applications either.

[0114] FIG. **15**A illustrates an example slanted grating **1500** fabricated using the CARIBE process according to certain embodiments. Slanted grating **1500** may be fabricated on a Si_3N_4 layer using a chrome mask. As shown in FIG. **15**A, the slant angle of a leading edge **1512** of a ridge **1510** of slanted grating **1500** may be similar to the slant angle of a trailing edge **1514** of ridge **1510** of slanted grating **1500**. More specifically, in the example shown in FIG. **15**A, the slant angle of leading edge **1512** may be measured to be about 44°, the slant angle of trailing edge **1514** may be about 43°, the duty cycle of slanted grating **1500** may be about 50%, and the depth of ridge **1510** may be about 200 nm.

[0115] FIG. **15**B illustrates another example slanted grating **1550** fabricated using the CARIBE process according to certain embodiments. Slanted grating **1550** may also be fabricated on a Si_3N_4 layer using a chrome mask. As shown in FIG. **15**B, the slant angle of a leading edge **1562** of a ridge **1560** of slanted grating **1550** may be similar to the slant angle of a trailing edge **1564** of ridge **1560** of slanted grating **1550**. In the example shown in FIG. **15**B, the depth of ridge **1510** may be about 200 nm, and the duty cycle of slanted grating **1550** may be greater than 80%. In other words, a narrow and deep slanted groove with the leading edge parallel to the trailing edge may be fabricated using the CARIBE process disclosed herein.

[0116] FIGS. **15**A and **15**B show that the CARIBE process disclosed herein can achieve symmetric profiles and target depths for materials such as Si_3N_4. The CARIBE process can be used to reliably fabricated a slanted structure with a leading edge and a trailing edge parallel or substantially parallel to each other (e.g., with a slant angle difference less

than about 1, 2, 3, 5, or 10 degrees). In some embodiments, the symmetric profile may lead to an improved performance (e.g., as compared to gratings formed using the IBE, RIBE, or CAIBE process) of an output coupler of a waveguide display used in an augmented-reality system. Furthermore, the CARIBE process can be used to fabricate deep and accurate surface relief structures while maintaining the parallel relationship between the leading edge and the trailing edge.

[0117] FIG. **16** is a simplified flow chart **1600** illustrating an example method of fabricating a slanted surface-relief structure according to certain embodiments. The operations described in flow chart **1600** are for illustration purposes only and are not intended to be limiting. In various implementations, modifications may be made to flow chart **1600** to add additional operations or to omit some operations. The operations described in flow chart **1600** may be performed using, for example, CARIBE system **1300** described above.

[0118] At block **1610**, a first reactive gas may be injected into a chamber of an reactive ion source generator, such as reactive ion source generator **1310** shown in FIG. **13**. The first reactive gas may include, for example, CF_4, CHF_3, N_2, O_2, SF_6, H_2, Cl_2, BCl_3, HBr, etc. In some embodiments, an inert gas, such as Argon, He, or Ne, may also be injected into the reactive ion source generator.

[0119] At block **1620**, the reactive ion source generator may generate a high density plasma in the chamber of the reactive ion source generator. For example, a time-varying electric current (e.g., an RF current signal) may be passed through a coil that may create a time-varying magnetic field around it, which may in turn induce an electric field in the chamber of the reactive ion source generator and lead to the discharge of electrons. The discharged electrons may impact the gas in the chamber of the reactive ion source generator to generate reactive ions (e.g., CF_3^+ and Ar^+). Thus, the chamber of the reactive ion source generator may include neutrals, ions, and electrons.

[0120] At block **1630**, the reactive ions may be extracted from the high density plasma and may be accelerated to form a collimated reactive ion beam towards a material layer to be etched. For example, as described above, one or more aligned collimator grids may be used to extract and accelerate the reactive ions to form a highly directive, highly energetic collimated reactive ion beam. In some embodiments, the one or more aligned collimator grids may include an extraction grid that may contact the high density plasma and control its potential, and an acceleration grid that may be driven by an adjustable negative high voltage supply for accelerating the ions.

[0121] Optionally, at block **1640**, the collimated reactive ion beam extracted from the reactive ion source generator by the aligned collimator grids may be neutralized by an electron beam to form a collimated beam that may include neutrals and/or ions and electrons that are approximately in charge equilibrium. Therefore, the collimated beam may be electronically neutral, thus preventing the buildup of positive charges on the material layer to be etched.

[0122] At block **1650**, a second reactive gas may be injected onto the material layer to be etched using a gas ring as described above. The second reactive gas may include, for example, CF_4, CHF_3, N_2, O_2, SF_6, Cl_2, BCl_3. HBr, etc. The second reactive gas may be injected at a location closed to the material layer to be etched.

[0123] At block **1660**, the collimated beam and the second reactive gas may both physically mill and chemically etch the material layer as described above. As also described above, the material layer to be etched, such as a silicon wafer, a glass substrate, a titanium oxide layer, an alumina layer, or a Si_3N_4 material layer, may be mounted on a rotation stage that may rotate with respect to the direction of the collimated beam based on the desired slant angle of the slanted structure to be etched on the material layer. The material layer may be partially covered by a patterned mask including a pattern similar to the desired pattern of a cross-section of the slanted structure. In some embodiments, a shutter or blade may be used to control the etch time and/or etch region on the material layer.

[0124] In some embodiments, the slanted grating fabricated using the method described in flow chart **1600** may be over-coated with a material having a refractive index different from the grating material layer. For example, in some embodiments, a high refractive index material, such as Hafnia, Titania, Tungsten oxide, Zirconium oxide, Gallium sulfide, Gallium nitride, Gallium phosphide, silicon, or a high refractive index polymer, may be used to over-coat the slanted grating and/or fill the gaps between the ridges of the slanted grating. In some embodiments, a low refractive index material, such as silicon oxide, alumina, porous silica, or fluorinated low index monomer (or polymer), may be used to over-coat the slanted grating and/or fill the gaps between the ridges of the slanted grating. As a result, the difference between the refractive index of the ridges and the refractive index of the grooves of the slanted grating may be greater than 0.1, 0.2, 0.3, 0.5, 1.0, or higher.

[0125] Embodiments of the invention may include or be implemented in conjunction with an artificial reality system. Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, for example, a virtual reality (VR), an augmented reality (AR), a mixed reality (MR), a hybrid reality, or some combination and/or derivatives thereof. Artificial reality content may include completely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, haptic feedback, or some combination thereof, and any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional effect to the viewer). Additionally, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, for example, create content in an artificial reality and/or are otherwise used in (e.g., perform activities in) an artificial reality. The artificial reality system that provides the artificial reality content may be implemented on various platforms, including a head-mounted display (HMD) connected to a host computer system, a standalone HMD, a mobile device or computing system, or any other hardware platform capable of providing artificial reality content to one or more viewers.

[0126] FIG. **17** is a simplified block diagram of an example electronic system **1700** of an example near-eye display (e.g., HMD device) for implementing some of the examples disclosed herein. Electronic system **1700** may be used as the electronic system of an HMD device or other near-eye displays described above. In this example, electronic system **1700** may include one or more processor(s) **1710** and a memory **1720**. Processor(s) **1710** may be con-

figured to execute instructions for performing operations at a number of components, and can be, for example, a general-purpose processor or microprocessor suitable for implementation within a portable electronic device. Processor(s) **1710** may be communicatively coupled with a plurality of components within electronic system **1700**. To realize this communicative coupling, processor(s) **1710** may communicate with the other illustrated components across a bus **1740**. Bus **1740** may be any subsystem adapted to transfer data within electronic system **1700**. Bus **1740** may include a plurality of computer buses and additional circuitry to transfer data.

[0127] Memory **1720** may be coupled to processor(s) **1710**. In some embodiments, memory **1720** may offer both short-term and long-term storage and may be divided into several units. Memory **1720** may be volatile, such as static random access memory (SRAM) and/or dynamic random access memory (DRAM) and/or non-volatile, such as read-only memory (ROM), flash memory, and the like. Furthermore, memory **1720** may include removable storage devices, such as secure digital (SD) cards. Memory **1720** may provide storage of computer-readable instructions, data structures, program modules, and other data for electronic system **1700**. In some embodiments, memory **1720** may be distributed into different hardware modules. A set of instructions and/or code might be stored on memory **1720**. The instructions might take the form of executable code that may be executable by electronic system **1700**, and/or might take the form of source and/or installable code, which, upon compilation and/or installation on electronic system **1700** (e.g., using any of a variety of generally available compilers, installation programs, compression/decompression utilities, etc.), may take the form of executable code.

[0128] In some embodiments, memory **1720** may store a plurality of application modules **1722** through **1724**, which may include any number of applications. Examples of applications may include gaming applications, conferencing applications, video playback applications, or other suitable applications. The applications may include a depth sensing function or eye tracking function. Application modules **1722-1724** may include particular instructions to be executed by processor(s) **1710**. In some embodiments, certain applications or parts of application modules **1722-1724** may be executable by other hardware modules **1780**. In certain embodiments, memory **1720** may additionally include secure memory, which may include additional security controls to prevent copying or other unauthorized access to secure information.

[0129] In some embodiments, memory **1720** may include an operating system **1725** loaded therein. Operating system **1725** may be operable to initiate the execution of the instructions provided by application modules **1722-1724** and/or manage other hardware modules **1780** as well as interfaces with a wireless communication subsystem **1730** which may include one or more wireless transceivers. Operating system **1725** may be adapted to perform other operations across the components of electronic system **1700** including threading, resource management, data storage control and other similar functionality.

[0130] Wireless communication subsystem **1730** may include, for example, an infrared communication device, a wireless communication device and/or chipset (such as a Bluetooth® device, an IEEE 802.11 device, a Wi-Fi device, a WiMax device, cellular communication facilities, etc.), and/or similar communication interfaces. Electronic system **1700** may include one or more antennas **1734** for wireless communication as part of wireless communication subsystem **1730** or as a separate component coupled to any portion of the system. Depending on desired functionality, wireless communication subsystem **1730** may include separate transceivers to communicate with base transceiver stations and other wireless devices and access points, which may include communicating with different data networks and/or network types, such as wireless wide-area networks (WWANs), wireless local area networks (WLANs), or wireless personal area networks (WPANs). A WWAN may be, for example, a WiMax (IEEE 802.16) network. A WLAN may be, for example, an IEEE 802.11x network. A WPAN may be, for example, a Bluetooth network, an IEEE 802.15x, or some other types of network. The techniques described herein may also be used for any combination of WWAN, WLAN, and/or WPAN. Wireless communications subsystem **1730** may permit data to be exchanged with a network, other computer systems, and/or any other devices described herein. Wireless communication subsystem **1730** may include a means for transmitting or receiving data, such as identifiers of HMD devices, position data, a geographic map, a heat map, photos, or videos, using antenna(s) **1734** and wireless link(s) **1732**. Wireless communication subsystem **1730**, processor (s) **1710**, and memory **1720** may together comprise at least a part of one or more of a means for performing some functions disclosed herein.

[0131] Embodiments of electronic system **1700** may also include one or more sensors **1790**. Sensor(s) **1790** may include, for example, an image sensor, an accelerometer, a pressure sensor, a temperature sensor, a proximity sensor, a magnetometer, a gyroscope, an inertial sensor (e.g., a module that combines an accelerometer and a gyroscope), an ambient light sensor, or any other similar module operable to provide sensory output and/or receive sensory input, such as a depth sensor or a position sensor. For example, in some implementations, sensor(s) **1790** may include one or more inertial measurement units (IMUs) and/or one or more position sensors. An IMU may generate calibration data indicating an estimated position of the HMD device relative to an initial position of the HMD device, based on measurement signals received from one or more of the position sensors. A position sensor may generate one or more measurement signals in response to motion of the HMD device. Examples of the position sensors may include, but are not limited to, one or more accelerometers, one or more gyroscopes, one or more magnetometers, another suitable type of sensor that detects motion, a type of sensor used for error correction of the IMU, or some combination thereof. The position sensors may be located external to the IMU, internal to the IMU, or some combination thereof. At least some sensors may use a structured light pattern for sensing.

[0132] Electronic system **1700** may include a display module **1760**. Display module **1760** may be a near-eye display, and may graphically present information, such as images, videos, and various instructions, from electronic system **1700** to a user. Such information may be derived from one or more application modules **1722-1724**, virtual reality engine **1726**, one or more other hardware modules **1780**, a combination thereof, or any other suitable means for resolving graphical content for the user (e.g., by operating system **1725**). Display module **1760** may use liquid crystal display (LCD) technology, light-emitting diode (LED) tech-

nology (including, for example, OLED, ILED, mLED, AMOLED, TOLED, etc.), light emitting polymer display (LPD) technology, or some other display technology.

[0133] Electronic system **1700** may include a user input/output module **1770**. User input/output module **1770** may allow a user to send action requests to electronic system **1700**. An action request may be a request to perform a particular action. For example, an action request may be to start or end an application or to perform a particular action within the application. User input/output module **1770** may include one or more input devices. Example input devices may include a touchscreen, a touch pad, microphone(s), button(s), dial(s), switch(es), a keyboard, a mouse, a game controller, or any other suitable device for receiving action requests and communicating the received action requests to electronic system **1700**. In some embodiments, user input/output module **1770** may provide haptic feedback to the user in accordance with instructions received from electronic system **1700**. For example, the haptic feedback may be provided when an action request is received or has been performed.

[0134] Electronic system **1700** may include a camera **1750** that may be used to take photos or videos of a user, for example, for tracking the user's eye position. Camera **1750** may also be used to take photos or videos of the environment, for example, for VR, AR, or MR applications. Camera **1750** may include, for example, a complementary metal-oxide-semiconductor (CMOS) image sensor with a few millions or tens of millions of pixels. In some implementations, camera **1750** may include two or more cameras that may be used to capture 3-D images.

[0135] In some embodiments, electronic system **1700** may include a plurality of other hardware modules **1780**. Each of other hardware modules **1780** may be a physical module within electronic system **1700**. While each of other hardware modules **1780** may be permanently configured as a structure, some of other hardware modules **1780** may be temporarily configured to perform specific functions or temporarily activated. Examples of other hardware modules **1780** may include, for example, an audio output and/or input module (e.g., a microphone or speaker), a near field communication (NFC) module, a rechargeable battery, a battery management system, a wired/wireless battery charging system, etc. In some embodiments, one or more functions of other hardware modules **1780** may be implemented in software.

[0136] In some embodiments, memory **1720** of electronic system **1700** may also store a virtual reality engine **1726**. Virtual reality engine **1726** may execute applications within electronic system **1700** and receive position information, acceleration information, velocity information, predicted future positions, or some combination thereof of the HMD device from the various sensors. In some embodiments, the information received by virtual reality engine **1726** may be used for producing a signal (e.g., display instructions) to display module **1760**. For example, if the received information indicates that the user has looked to the left, virtual reality engine **1726** may generate content for the HMD device that mirrors the user's movement in a virtual environment. Additionally, virtual reality engine **1726** may perform an action within an application in response to an action request received from user input/output module **1770** and provide feedback to the user. The provided feedback may be visual, audible, or haptic feedback. In some implementations, processor(s) **1710** may include one or more GPUs that may execute virtual reality engine **1726**.

[0137] In various implementations, the above-described hardware and modules may be implemented on a single device or on multiple devices that can communicate with one another using wired or wireless connections. For example, in some implementations, some components or modules, such as GPUs, virtual reality engine **1726**, and applications (e.g., tracking application), may be implemented on a console separate from the head-mounted display device. In some implementations, one console may be connected to or support more than one HMD.

[0138] In alternative configurations, different and/or additional components may be included in electronic system **1700**. Similarly, functionality of one or more of the components can be distributed among the components in a manner different from the manner described above. For example, in some embodiments, electronic system **1700** may be modified to include other system environments, such as an AR system environment and/or an MR environment.

[0139] The methods, systems, and devices discussed above are examples. Various embodiments may omit, substitute, or add various procedures or components as appropriate. For instance, in alternative configurations, the methods described may be performed in an order different from that described, and/or various stages may be added, omitted, and/or combined. Also, features described with respect to certain embodiments may be combined in various other embodiments. Different aspects and elements of the embodiments may be combined in a similar manner. Also, technology evolves and, thus, many of the elements are examples that do not limit the scope of the disclosure to those specific examples.

[0140] Specific details are given in the description to provide a thorough understanding of the embodiments. However, embodiments may be practiced without these specific details. For example, well-known circuits, processes, systems, structures, and techniques have been shown without unnecessary detail in order to avoid obscuring the embodiments. This description provides example embodiments only, and is not intended to limit the scope, applicability, or configuration of the invention. Rather, the preceding description of the embodiments will provide those skilled in the art with an enabling description for implementing various embodiments. Various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the present disclosure.

[0141] Also, some embodiments were described as processes depicted as flow diagrams or block diagrams. Although each may describe the operations as a sequential process, many of the operations may be performed in parallel or concurrently. In addition, the order of the operations may be rearranged. A process may have additional steps not included in the figure. Furthermore, embodiments of the methods may be implemented by hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware, or microcode, the program code or code segments to perform the associated tasks may be stored in a computer-readable medium such as a storage medium. Processors may perform the associated tasks.

[0142] It will be apparent to those skilled in the art that substantial variations may be made in accordance with

specific requirements. For example, customized or special-purpose hardware might also be used, and/or particular elements might be implemented in hardware, software (including portable software, such as applets, etc.), or both. Further, connection to other computing devices such as network input/output devices may be employed.

[0143] With reference to the appended figures, components that can include memory can include non-transitory machine-readable media. The term "machine-readable medium" and "computer-readable medium" may refer to any storage medium that participates in providing data that causes a machine to operate in a specific fashion. In embodiments provided hereinabove, various machine-readable media might be involved in providing instructions/code to processing units and/or other device(s) for execution. Additionally or alternatively, the machine-readable media might be used to store and/or carry such instructions/code. In many implementations, a computer-readable medium is a physical and/or tangible storage medium. Such a medium may take many forms, including, but not limited to, non-volatile media, volatile media, and transmission media. Common forms of computer-readable media include, for example, magnetic and/or optical media such as compact disk (CD) or digital versatile disk (DVD), punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a programmable read-only memory (PROM), an erasable programmable read-only memory (EPROM), a FLASH-EPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read instructions and/or code. A computer program product may include code and/or machine-executable instructions that may represent a procedure, a function, a subprogram, a program, a routine, an application (App), a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements.

[0144] Those of skill in the art will appreciate that information and signals used to communicate the messages described herein may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0145] Terms, "and" and "or" as used herein, may include a variety of meanings that are also expected to depend at least in part upon the context in which such terms are used. Typically, "or" if used to associate a list, such as A, B, or C, is intended to mean A, B, and C, here used in the inclusive sense, as well as A, B, or C, here used in the exclusive sense. In addition, the term "one or more" as used herein may be used to describe any feature, structure, or characteristic in the singular or may be used to describe some combination of features, structures, or characteristics. However, it should be noted that this is merely an illustrative example and claimed subject matter is not limited to this example. Furthermore, the term "at least one of" if used to associate a list, such as A, B, or C, can be interpreted to mean any combination of A, B, and/or C, such as A, AB, AC, BC, AA, ABC, AAB, AABBCCC, etc.

[0146] Further, while certain embodiments have been described using a particular combination of hardware and software, it should be recognized that other combinations of hardware and software are also possible. Certain embodiments may be implemented only in hardware, or only in software, or using combinations thereof. In one example, software may be implemented with a computer program product containing computer program code or instructions executable by one or more processors for performing any or all of the steps, operations, or processes described in this disclosure, where the computer program may be stored on a non-transitory computer readable medium. The various processes described herein can be implemented on the same processor or different processors in any combination.

[0147] Where devices, systems, components or modules are described as being configured to perform certain operations or functions, such configuration can be accomplished, for example, by designing electronic circuits to perform the operation, by programming programmable electronic circuits (such as microprocessors) to perform the operation such as by executing computer instructions or code, or processors or cores programmed to execute code or instructions stored on a non-transitory memory medium, or any combination thereof. Processes can communicate using a variety of techniques, including, but not limited to, conventional techniques for inter-process communications, and different pairs of processes may use different techniques, or the same pair of processes may use different techniques at different times.

[0148] The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. It will, however, be evident that additions, subtractions, deletions, and other modifications and changes may be made thereunto without departing from the broader spirit and scope as set forth in the claims. Thus, although specific embodiments have been described, these are not intended to be limiting. Various modifications and equivalents are within the scope of the following claims.

What is claimed is:

1. A chemically assisted reactive ion beam etching (CARIBE) system for fabricating a slanted surface-relief structure in a material layer, the CARIBE system comprising:

an reactive ion source generator configured to generate a plasma using a first reactive gas, the plasma including reactive ions of the first reactive gas that are configured to react with the material layer to generate volatile materials;

one or more aligned collimator grids configured to extract and accelerate at least some of the reactive ions in the plasma to form a collimated reactive ion beam towards the material layer; and

a gas ring configured to inject a second reactive gas onto the material layer, the second reactive gas configured to react with the material layer,

wherein the collimated reactive ion beam and the second reactive gas etch the material layer both physically and chemically to form the slanted surface-relief structure in the material layer.

2. The CARIBE system of claim **1**, further comprising a neutralizer configured to inject an electron beam into the collimated reactive ion beam to neutralize the collimated reactive ion beam.

3. The CARIBE system of claim **1**, further comprising a rotation stage configured to hold and rotate a substrate that include the material layer.

4. The CARIBE system of claim **1**, wherein the reactive ion source generator comprises an inductively coupled plasma generator.

5. The CARIBE system of claim **1**, wherein:
the first reactive gas comprises at least one of CF_4, CHF_3, N_2, O_2, SF_6, H_2, Cl_2, BCl_3, HBr, Ar, He, or Ne; and
the second reactive gas comprises at least one of CF_4, CHF_3, N_2, O_2, SF_6, Cl_2, BCl_3, or HBr.

6. The CARIBE system of claim **1**, further comprising a gas inlet for receiving the first reactive gas.

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