

BLAZED GRATING FORMATION BY STAIRCASE ETCH**BACKGROUND****Field**

[0001] Embodiments of the present disclosure generally relate to optical waveguides. More specifically, embodiments described herein provide techniques for forming a waveguide having blazed gratings.

Description of the Related Art

[0002] Virtual reality is generally considered to be a computer-generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

[0003] Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

[0004] Blazed grating is desired in AR waveguides for high diffraction efficiency into the targeted order. However, blazed facets are difficult to manufacture using traditional patterning. Currently, there is no scalable industrial solution to form blazed gratings for AR waveguides.

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

SUMMARY

[0006] Embodiments herein are generally directed to methods of forming optical device structures such as blazed gratings.

[0007] In an embodiment, a method of forming an optical device structure is provided. The method includes depositing a photoresist layer on a patterned hardmask disposed over a device layer or a substrate, exposing the photoresist layer to produce a plurality of photoresist segments, etching the device layer or the substrate to produce at least one step, the at least one step forming a blazed grating, trimming the plurality of photoresist segments horizontally, and removing the plurality of photoresist segments and the patterned hardmask.

[0008] In another embodiment, a method of forming an optical device structure is provided. The method includes depositing a photoresist layer on a patterned hardmask having a plurality of hardmask segments disposed over a device layer or a substrate, exposing the photoresist layer to produce a plurality of photoresist segments, and etching the device layer or the substrate to produce a first step of a blazed grating. The method also includes trimming the plurality of photoresist segments horizontally, and repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a second step of the blazed grating. The method may further include repeating etching the device layer and trimming the plurality of photoresist segments horizontally to produce a third step of the blazed grating, and removing the plurality of photoresist segments and the patterned hardmask.

[0009] In a further embodiment, a method of forming an optical device structure is provided. The method includes depositing a photoresist layer on a patterned hardmask disposed over a device layer or a substrate, patterning the photoresist layer to produce a plurality of photoresist segments, etching the device layer or the substrate to produce a first step of a blazed grating at a first linewidth, and trimming the plurality of photoresist segments horizontally. The method also includes repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a second step of the blazed grating at a second linewidth and removing the plurality of photoresist segments and the patterned hardmask. In one aspect, the second linewidth of the second step is non-uniformly greater than the first linewidth of the first step.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] So that the manner in which the above-recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments of the present disclosure and are therefore not to be considered limiting of its scope, and the present disclosure may admit to other equally effective embodiments.

[0011] Figure 1A is a perspective, frontal view of an optical device, according to certain embodiments.

[0012] Figures 1B and 1C are schematic, cross-sectional views of a plurality of device structures, according to certain embodiments.

[0013] Figure 2 is a flow diagram of a method for forming an optical device structure, according to certain embodiments.

[0014] Figures 3A-3I are schematic, cross-sectional views of a waveguide structure undergoing the method for forming the waveguide structure of Figure 2, according to certain embodiments.

[0015] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0016] Embodiments herein are generally directed to methods of forming waveguide structures with blazed gratings. The methods include exposing a device layer disposed over a substrate having a patterned hardmask and offset patterned photoresist to etchant.

[0017] Figure 1A is a front view of an optical device 100. It is to be understood that the optical device 100 described below is an exemplary optical device. In one embodiment, which can be combined with other embodiments described herein, the

optical device 100 is a waveguide combiner, such as an augmented reality waveguide combiner. In another embodiment, which can be combined with other embodiments described herein, the optical device 100 is a flat optical device, such as a metasurface. . The optical device 100 includes a plurality of device structures disposed in (as shown in Figure 1B) or on (as shown in Figure 1C) a substrate 101. As shown in Figure 1C, the device structures are formed in a device layer 103 formed on the substrate 101. The device structures may be nanostructures having sub-micron dimensions, e.g., nano-sized dimensions, such as critical dimensions less than 1 μm . The optical device 100 includes an input coupling region 102A defined by a plurality of gratings 106 (illustrated in Figures 1B and 1C), a waveguide region 102B, and an output coupling region 102C.

[0018] The input coupling region 102A receives incident beams of light (a virtual image) having an intensity from a microdisplay. Each grating of the plurality of gratings 106 splits the incident beams into a plurality of modes. Zero-order mode (T0) beams are refracted back or lost in the optical device 100. Positive first-order mode (T1) beams undergo total-internal-reflection (TIR) through the optical device 100 across the waveguide region 102B to the output coupling region 102C and output for display. Negative first-order mode (T-1) beams propagate in the optical device 100 a direction opposite to the T1 beams. Among the diffracted orders, only the T1 beams output to display through output coupling region 102C, while other modes are lost due to different directionality. Therefore, it is crucial to increase T1 beam intensity and decrease other orders beam intensity for higher device optical efficiency. One approach to increase the intensity of the T1 beams and to reduce the intensity of the other order beams is to control the shape of each grating of the plurality of gratings 106. A blazed shape for each grating of the plurality of gratings 106 provides for increased optical efficiency.

[0019] Figure 1B and Figure 1C are schematic, cross-sectional views of a plurality of blazed gratings 106, according to certain embodiments. In one embodiment, which can be combined with other embodiments described herein, the plurality of blazed gratings 106 correspond to the input coupling region 102A of the optical device 100. The method 200 described herein forms the plurality of blazed gratings 106. The waveguide combiner according to one embodiment, which can be combined with other

embodiments described herein, may include blazed gratings 106. Each of the blazed gratings 106 includes a blazed surface 108, a top surface 109, a sidewall 112, a depth h , and a linewidth d . The blazed surface 108 has a plurality of steps 110. In one embodiment, which can be combined with other embodiments described herein, the blazed surface 108 includes at least 3 steps 110, such as greater than 16 steps 110, for example 32 steps 110. The blazed surface 108 has a blazed angle γ and a blazed line width d_2 . The blazed angle γ is the angle between the blazed surface 108 and the surface parallel to the substrate 101 and the angle between the surface normal of the substrate 101 and facet normal f of the blazed surface 108. The depth h corresponds to the height of the sidewall 112 and the linewidth d corresponds to the distances between sidewalls 112 of adjacent blazed gratings 106. The blazed line width d_2 corresponds to a difference between the linewidth d and a width of the top surface 109 of each blazed grating 106.

[0020] In one embodiment, which can be combined with other embodiments described herein, the blazed angle γ of two or more blazed gratings 106 are different. In another embodiment, which can be combined with other embodiments described herein, the blazed angle γ of two or more blazed gratings 106 are the same. In one embodiment, which can be combined with other embodiments described herein, the depth h of two or more blazed gratings 106 are different. In another embodiment, which can be combined with other embodiments described herein, the depth h of two or more blazed gratings 106 are the same. In one embodiment, which can be combined with other embodiments described herein, the linewidths d of two or more blazed gratings 106 are different. In another embodiment, which can be combined with other embodiments described herein, the linewidths d of one or more blazed gratings 106 are the same.

[0021] Figure 2 is a flow diagram of a method 200 for forming a plurality of blazed gratings 106 of an optical device structure 300, as shown in Figures 3A-3I. In one embodiment, the optical device structure 300 corresponds to the input coupling region 102A of the optical device 100 and includes a plurality of blazed gratings etched in a substrate 302 similar to the blazed gratings 106 formed in the substrate 101 shown in Figure 1B.

[0022] The substrate 302 can be any substrate used in the art, and can be either opaque or transparent to a chosen wavelength of light, depending for the use of the substrate 302 as a substrate for a waveguide. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, polymers, or combinations thereof. In some embodiments, the substrate 302 includes, but is not limited to, a silicon-containing material, a silicon and oxygen containing compound, a germanium-containing material, a indium and phosphide containing compound, a gallium and arsenic containing compound, a gallium and nitrogen containing compound, a carbon-containing material, a silicon and carbon containing compound, a silicon, carbon, and oxygen containing compound, a silicon and nitrogen containing compound, a silicon, oxygen, and nitrogen containing compound, a niobium and oxygen containing compound, and lithium, niobium, and oxygen containing compound, an aluminum and oxygen containing compound, a indium, tin, and oxygen containing compound, a titanium and oxygen containing compound, a lanthanum and oxygen containing compound, a gadolinium and oxygen containing compound, a zinc and oxygen containing compound, a yttrium and oxygen containing compound, a tungsten and oxygen containing compound, a potassium, and oxygen containing compound, a phosphorous and oxygen containing compound, a barium and oxygen containing compound, a sodium and oxygen containing compound, or combinations thereof. In other embodiments, which can be combined with other embodiments described herein, the substrate 302 includes an oxide including one or more of gadolinium, silicon, sodium, barium, potassium, tungsten, phosphorus, zinc, calcium, titanium, tantalum, niobium, lanthanum, zirconium, lithium, or yttrium containing-materials. Example materials of the substrate 302 include silicon (Si), silicon monoxide (SiO), silicon dioxide (SiO₂), silicon carbide (SiC), fused silica, diamond, quartz germanium (Ge), silicon germanium (SiGe), indium phosphide (InP), gallium arsenide (GaAs), gallium nitride (GaN), sapphire, sapphire (Al₂O₃), lithium niobate (LiNbO₃), indium tin oxide (ITO), lanthanum oxide (La₂O₃), gadolinium oxide (Gd₂O₃), zinc oxide (ZnO), yttrium oxide (Y₂O₃), tungsten oxide (WO₃), titanium oxide (TiO₂), zirconium oxide (ZrO₃), sodium oxide (Na₂O), niobium oxide (Nb₂O₅), barium oxide (BaO), potassium oxide (K₂O), phosphorus pentoxide (P₂O₅), calcium oxide (CaO), or combinations thereof.

[0023] In another embodiment, the plurality of blazed gratings are etched in a device layer (not shown) formed over the substrate 302, similar to the blazed gratings 106 formed in the device layer 103 formed over the substrate 101 shown in Figure 1C. In such an embodiment, the device layer 103 and the substrate 101 include a different material. The device layer 103 includes, but is not limited to, one or more oxides, carbides, or nitrides of silicon, aluminum, zirconium, tin, tantalum, zirconium, barium, titanium, hafnium, lithium, lanthanum, cadmium, niobium, or combinations thereof. Example materials of the device layer 103 include silicon carbide, silicon oxycarbide, titanium oxide, titanium dioxide, silicon oxide, silicon dioxide, vanadium oxide, aluminum oxide, aluminum-doped zinc oxide, indium tin oxide, tin oxide, zinc oxide, tantalum oxide, tantalum pentoxide, silicon nitride, titanium nitride, zirconium oxide, zirconium dioxide, niobium oxide, cadmium stannate, silicon oxynitride, barium titanate, diamond like carbon, hafnium oxide, lithium niobate, silicon carbon-nitride, silver, cadmium selenide, mercury telluride, zinc selenide, silver-indium-gallium-sulfur, silver-indium-sulfur, indium phosphide, gallium phosphide, lead sulfide, lead selenide, zinc sulfide, molybdenum sulfide, tungsten sulfide, or combinations thereof.

[0024] In an embodiment, prior to performing the method 200, the device layer 103 can be deposited on the substrate 101 for forming the blazed gratings 106 shown in Figure 1C. Any suitable method for deposition of the device layer 103 can be used. Examples of suitable thin film deposition methods include a physical vapor deposition (PVD) process (e.g., ion beam sputtering, magnetron sputtering, e-beam evaporation), a chemical vapor deposition (CVD) process, a plasma enhanced chemical vapor deposition (PECVD) process, an atomic layer deposition (ALD) process, an inkjet printing process, or a three-dimensional (3D) printing process.

[0025] As shown in Figure 3A, prior to operation 201, a hardmask 306 is disposed and patterned on the substrate 302 (or the device layer 103 of Figure 1C, if present). The patterned hardmask 306 includes a plurality of hardmask segments, such as a first hardmask segment 306a, a second hardmask segment 306b, and a third hardmask segment 306c separated from each other. The separation (e.g., distance) between the segments of the patterned hardmask 306 will determine a maximum width of the stepped surface 108 of each blazed grating structure produced. Portions of the substrate 302 (or the device layer 103 of Figure 1C, if present) are in turn exposed by

the separation between the segments of the patterned hardmask 306. Figure 3B is a schematic, cross-sectional view of the substrate 302 at operation 201. In operation 201, as shown in Figure 3B, a photoresist layer 308 is deposited or otherwise disposed over the hardmask segments 306 and exposed portions of the substrate 302 (or the device layer 103 of Figure 1C, if present). A material of the photoresist layer 308 is selected based on the substrate 302 etch chemistry (in embodiments in which the substrate 302 is etched to form the blazed grating structures as shown in Figure 1B) or the device layer 103 etch chemistry (in embodiments in which the device layer 103 is etched to form the blazed grating structures as shown in Figure 1C).

[0026] At operation 202 and as shown in Figure 3C, the photoresist layer 308 is patterned by a lithography process, such as photolithography or digital lithography, or by laser ablation process to form a plurality of photoresist segments 310. In an embodiment, the plurality of photoresist segments 310 includes a first photoresist segment 310a, a second photoresist segment 310b, and a third photoresist segment 310c formed over the patterned hardmask 306 and the substrate 302 (or the device layer 103 of Figure 1C, if present). While only three photoresist segments 310a-310c and three hardmask segments 306a-306c are shown, the entire photoresist layer 308 and the hardmask 306 can be etched such that a desired number of blazed gratings 106 are formed in the substrate 302 (or the device layer 103 of Figure 1C, if present) depending on the predetermined design for the optical device structure 300.

[0027] The plurality of photoresist segments 310 are offset from the hardmask segments 306 such that the photoresist segments 310 directly contact and cover a portion of the substrate 302 (or the device layer 103 of Figure 1C, if present) while exposing a portion of each hardmask segments 306a, 306b, and 306c. Further, the photoresist segments 310 do not extend to subsequent hardmask segments (e.g., from the first hardmask segment 306a to the second hardmask segment 306b). Rather, each photoresist segment 310 ends a distance from the adjacent subsequent hardmask segment 306.

[0028] At operation 203, plasma etchant 304 contacts the substrate 302 as shown in Figure 3D. The substrate 302 is exposed to plasma etchant 304, such as radicals and ion beams, contacting the substrate 302. Exposing the substrate 302 (or the device layer 103 of Figure 1C, if present) to the plasma etchant 304 may include

etching processes, such as ion etching and reactive ion etching (RIE). The plasma etchant 304 etches a first depth 320 of a plurality of depths 324 (shown in Figures 3F-3I) of at least one step 330 into portions of the substrate 302 (or the device layer 103 of Figure 1C, if present) exposed between the patterned hardmask segments 306a-c and the plurality of photoresist segments 310. After operation 203, in addition to the first depth 320, the at least one step 330 includes an initial leading sidewall portion 342 of a leading sidewall 344 (shown in Figure 3D), a trailing sidewall 352, and a first linewidth 362 from the initial leading sidewall portion 342 to the trailing sidewall 352. The first linewidth 362 is controlled by a distance 332 between a leading edge plane 334 defined by a first side 312 of each photoresist segment 310 and a trailing edge plane 336 defined by an exposed side 314 of each hardmask segment 306 contacting the substrate 302 (or the device layer 103 of Figure 1C, if present). The distance 332 corresponds to the first linewidth 362 as the plasma etchant 304 does not contact the substrate 302 (or the device layer 103 of Figure 1C, if present) outside of the distance 332.

[0029] At operation 204, photoresist segments 310a, 310b, and 310c are trimmed by an isotropic ion etching process that recesses the photoresist segments vertically and horizontally. This operation increases the distance from the first linewidth 362 (defined by initial leading sidewall portion 342 to the trailing sidewall portion 352 shown in Figure 3D) to the distance 332 between the leading sidewall 344 to the trailing edge plane 334 shown in Figure 3F.

[0030] At optional operation 205, operations 203 and 204 may be repeated to etch at least one second depth 322 of a plurality of depths 324 of the at least one step 330 into the substrate 302 (or the device layer 103 of Figure 1C, if present). As shown in Figure 3E, each photoresist segment 310 is trimmed to decrease the width of each photoresist segment 310 such that the first side 312 of each photoresist segment 310 is shifted along the substrate 302, increasing the distance 332.

[0031] As shown in Figure 3F, in addition to the second depth 322, the step 330 includes a second leading sidewall portion 346 and a second linewidth 364 from the second leading sidewall portion 346 to the trailing sidewall portion 352. The second linewidth 364 is controlled by the distance 332 between a leading edge plane 334 and a trailing edge plane 336 increased by the optional operation 204. As the distance

332 increases with each iteration of operation 204, the second linewidth 364 is longer than the first linewidth 362. The distance 332 corresponds to the second linewidth 364 as the plasma etchant 304 does not contact the substrate 302 (or the device layer 103 of Figure 1C, if present) outside of the distance 332. As shown in Figure 3E, in various embodiments, the increase in the distance 332 between each photoresist segment 310 after trimming is uniform and equal to double the first linewidth 362, e.g., the second linewidth 364 is double the length of the first linewidth 362, such that each of the at least one steps 330 are symmetric. Alternatively, the second linewidth 364 may increase non-uniformly over, e.g., be non-uniformly greater than, the first linewidth 362. For example, the second linewidth 364 may increase by 1.5 times the first linewidth 362, producing a non-symmetric staircase or blazed grating. Similarly, subsequent linewidths may increase symmetrically or non-symmetrically.

[0032] As shown in Figures 3G and 3H, optional operation 205 includes repeating optional operation 204 after each second depth 322 of the at least one step 330 is etched. For example, at optional operation 204, the photoresist segments 310 are trimmed, further increasing the distance 332. At optional operation 203, a third depth 326 of the plurality of depths 324 is created along with a third leading sidewall portion 348 and a third linewidth 366 from the third leading sidewall portion 348 to the trailing sidewall 352. The third linewidth 366 is controlled by the distance between the leading edge plane 334 and the trailing edge plane 336, increased by the subsequent optional operation 202. The distance 332 corresponds to the third linewidth 366 as the plasma etchant 304 do not contact the substrate 302 (or the device layer 103 of Figure 1C, if present) outside of the distance 332.

[0033] Figure 3F is a schematic, cross-sectional view of the optical device structure 300. Operation 203 and operation 204 are repeated until the optical device structure 300 is formed when the at least one step 330 has the plurality of depths 324 including the first depth 320 and the at least one second depth 322 corresponding to a step depth. Decreasing the first depth 320 and each second depth 322 will result in a smoother leading sidewall 344 of the at least one step 330.

[0034] Figure 3I is a schematic, cross-sectional view of the optical device structure 300 after operation 206 of the method 200. In one embodiment, the patterned hardmask 306 and the at least one photoresist layer 308 include non-transparent

materials and are removed at operation 206 after the optical device structure 300 is formed, as shown in Figure 3I. For example, the patterned hardmask 306 and the at least one photoresist layer 308 include reflective materials, such as Cr or silver (Ag). In another embodiment, the patterned hardmask 306 and the photoresist layer 308 include transparent materials such that the patterned hardmask 306 and the at least one photoresist layer 308 remain after the optical device structure 300 is formed.

[0035] After operation 206, the at least one step 330 remains and forms the structure of the blazed gratings 106. Although only three steps are shown in Figure 3I, optional operation 204 may be repeated to produce a desired amount of steps, such as 5, such as 10, such as 25. As the number of steps increases, it is noted that the linewidth of each step (e.g., 362, 364) may decrease, producing a smoother leading sidewall portion (e.g., 342, 344) or blazed surface 108 for each blazed grating 106.

[0036] Advantages of the present disclosure provide a scalable method for forming blazed gratings for AR waveguide using standard lithography and etch processes. For example, the method 200 may enable the formation of a plurality of blazed gratings 106 by etching a plurality of staircase steps to form the blazed surface 108 of each blazed grating 106 that in turn, each approximate a continuous blazed profile. Blazed gratings are generally desired in AR waveguides for increased diffraction efficiency.

[0037] When introducing elements of the present disclosure or exemplary aspects or embodiments thereof, the articles “a,” “an,” “the” and “said” are intended to mean that there are one or more of the elements.

[0038] The terms “comprising,” “including,” and “having” are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0039] The term “coupled” is used herein to refer to the direct or indirect coupling between two objects. For example, if object A physically touches object B and object B touches object C, the objects A and C may still be considered coupled to one another—even if objects A and C do not directly physically touch each other. For

instance, a first object may be coupled to a second object even though the first object is never directly in physical contact with the second object.

[0040] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method of forming an optical device structure, comprising:
depositing a photoresist layer on a patterned hardmask having a plurality of hardmask segments disposed over a device layer or a substrate;
patterning the photoresist layer to produce a plurality of photoresist segments;
etching the device layer or the substrate to produce at least one step, the at least one step forming a blazed grating;
trimming the plurality of photoresist segments horizontally; and
removing the plurality of photoresist segments and the patterned hardmask.
2. The method of claim 1, further comprising:
before removing the plurality of photoresist segments and the patterned hardmask, repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a second step of the blazed grating.
3. The method of claim 2, further comprising:
before removing the plurality of photoresist segments and the patterned hardmask but after producing a second step of the blazed grating, repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a third step of the blazed grating.
4. The method of claim 1, wherein the plurality of photoresist segments are offset from a plurality of hardmask segments of the patterned hardmask such that a portion of each of the plurality of photoresist segments directly contact a portion of the device layer or the substrate.
5. The method of claim 1, wherein the at least one step includes a first linewidth controlled by a distance between a leading edge plane defined by a first side of a photoresist segment of the plurality of photoresist segments and a trailing edge plane defined by an exposed side of a hardmask segment of the plurality of hardmask segments.
6. The method of claim 5, wherein the at least one step further comprising a second step, the second step including a second linewidth controlled by a distance

between a leading edge plane defined by the first side of each of the plurality of photoresist segments after trimming the plurality of photoresists a second time and the trailing edge plane, the second linewidth being longer than the first linewidth.

7. The method of claim 1, wherein etching the device layer or the substrate comprises using reactive ion etching.

8. The method of claim 1, wherein the at least one step includes a first depth into the device layer or the substrate.

9. The method of claim 2, wherein the at least one step includes a first depth into the device layer or the substrate and the second step includes a second depth into the device layer or the substrate, the first depth being greater than the second depth.

10. The method of claim 3, wherein the at least one step includes an first depth into the device layer or the substrate, the second step includes a second depth into the device layer or the substrate, and the third step includes a third depth into the device layer or the substrate, the first depth being greater than the second depth and the second depth greater than the third depth.

11. A method of forming an optical device structure, comprising:
depositing a photoresist layer on a patterned hardmask having a plurality of hardmask segments disposed over a device layer or a substrate;
patterning the photoresist layer to produce a plurality of photoresist segments;
etching the device layer or the substrate to produce a first step of a blazed grating;
trimming the plurality of photoresist segments horizontally;
repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a second step of the blazed grating;
repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a third step of the blazed grating; and
removing the plurality of photoresist segments and the patterned hardmask.

12. The method of claim 11, wherein the plurality of photoresist segments are offset from a plurality of hardmask segments of the patterned hardmask such that a portion

of each of the plurality of photoresist segments directly contact a portion of the device layer or the substrate.

13. The method of claim 11, wherein the first step includes a first linewidth controlled by a distance between a leading edge plane defined by a first side of a photoresist segment of the plurality of photoresist segments and a trailing edge plane defined by an exposed side of a hardmask segment of the plurality of hardmask segments.

14. The method of claim 13, wherein the second step includes a second linewidth controlled by a distance between a leading edge plane defined by the first side of a photoresist segment of the plurality of photoresist segments and the trailing edge plane, the second linewidth greater than the first linewidth.

15. The method of claim 14, wherein the third step includes a third linewidth controlled by a distance between a leading edge plane defined by the first side of a photoresist segment of the plurality of photoresist segments and the trailing edge plane, the third linewidth greater than the second linewidth.

16. A method of forming an optical device structure, comprising:
depositing a photoresist layer on a patterned hardmask disposed over a device layer or a substrate;
patterning the photoresist layer to produce a plurality of photoresist segments;
etching the device layer or the substrate to produce a first step of a blazed grating at a first linewidth;
trimming the plurality of photoresist segments horizontally;
repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a second step of the blazed grating at a second linewidth, the second linewidth being non-uniformly greater than the first linewidth; and
removing the plurality of photoresist segments and the patterned hardmask.

17. The method of claim 16, wherein the plurality of photoresist segments are offset from a plurality of hardmask segments of the patterned hardmask such that a portion

of each of the plurality of photoresist segments directly contact a portion of the device layer or the substrate.

18. The method of claim 16, wherein the first step includes a first depth into the device layer or the substrate and the second step includes a second depth into the device layer or the substrate, the first depth being greater than the second depth.

19. The method of claim 16, further comprising repeating etching the device layer or the substrate and trimming the plurality of photoresist segments horizontally to produce a third step of the blazed grating at a third linewidth, the third linewidth being non-uniformly greater than the second linewidth.

20. The method of claim 19, wherein the first step includes a first depth into the device layer or the substrate, the second step includes a second depth into the device layer or the substrate, and the third step includes a third depth into the device layer or the substrate, the first depth being greater than the second depth and the second depth greater than the third depth.