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(54) **APPARATUSES AND SYSTEMS INCLUDING ULTRA-THIN ADJUSTABLE LENSES**

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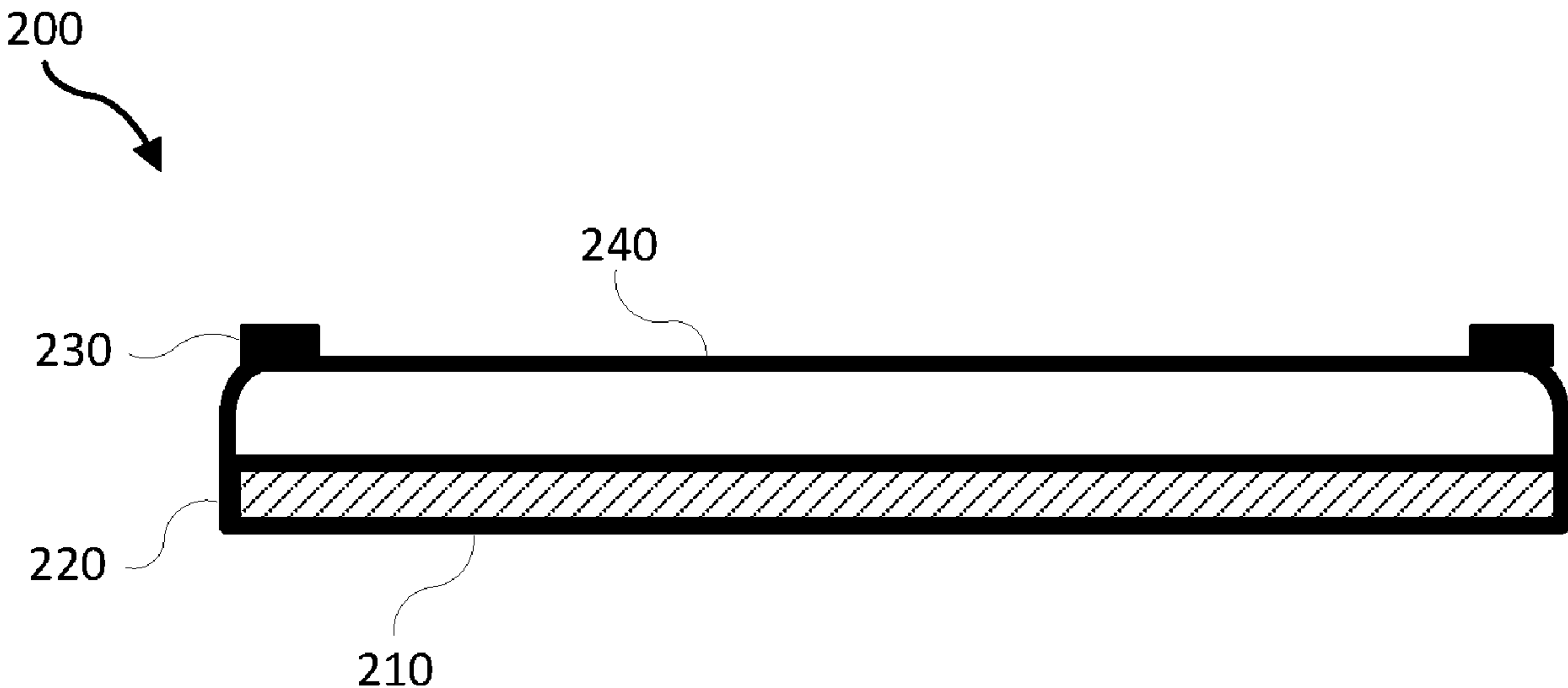
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(57) **ABSTRACT**

A method may include bonding a deformable bounding element to a structural support element in which the deformable bounding element and a cavity-adjacent side of the structural support element define a cavity. The method may further include filling the cavity with a deformable medium by injecting the deformable medium past a cavity-opposite side of the structural support element and toward the cavity-adjacent side of the structural support element. The method may additionally include sealing an entry point of the injection of the deformable medium into the cavity. Various other apparatuses, systems, and methods are also disclosed.



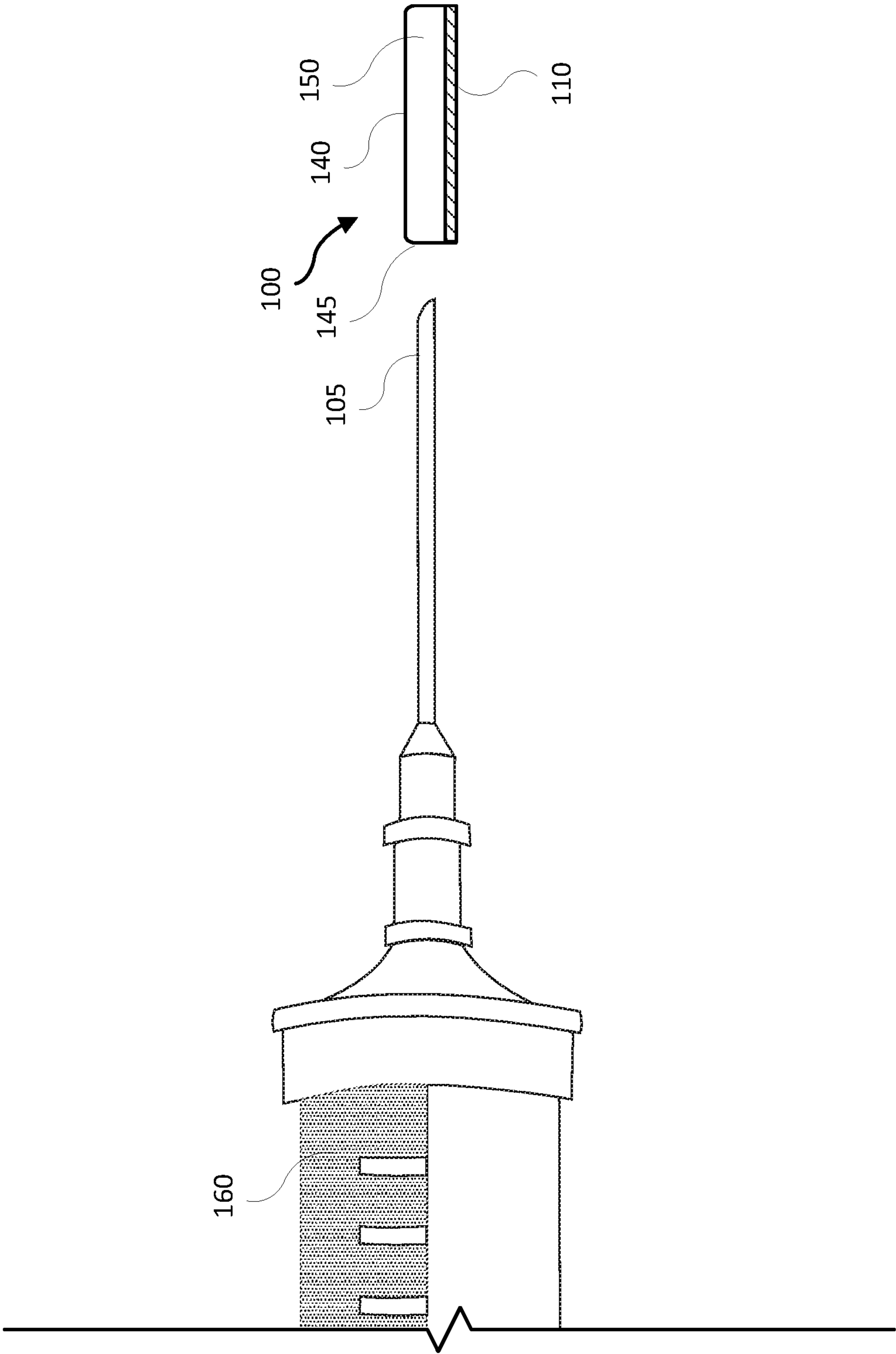


FIG. 1A

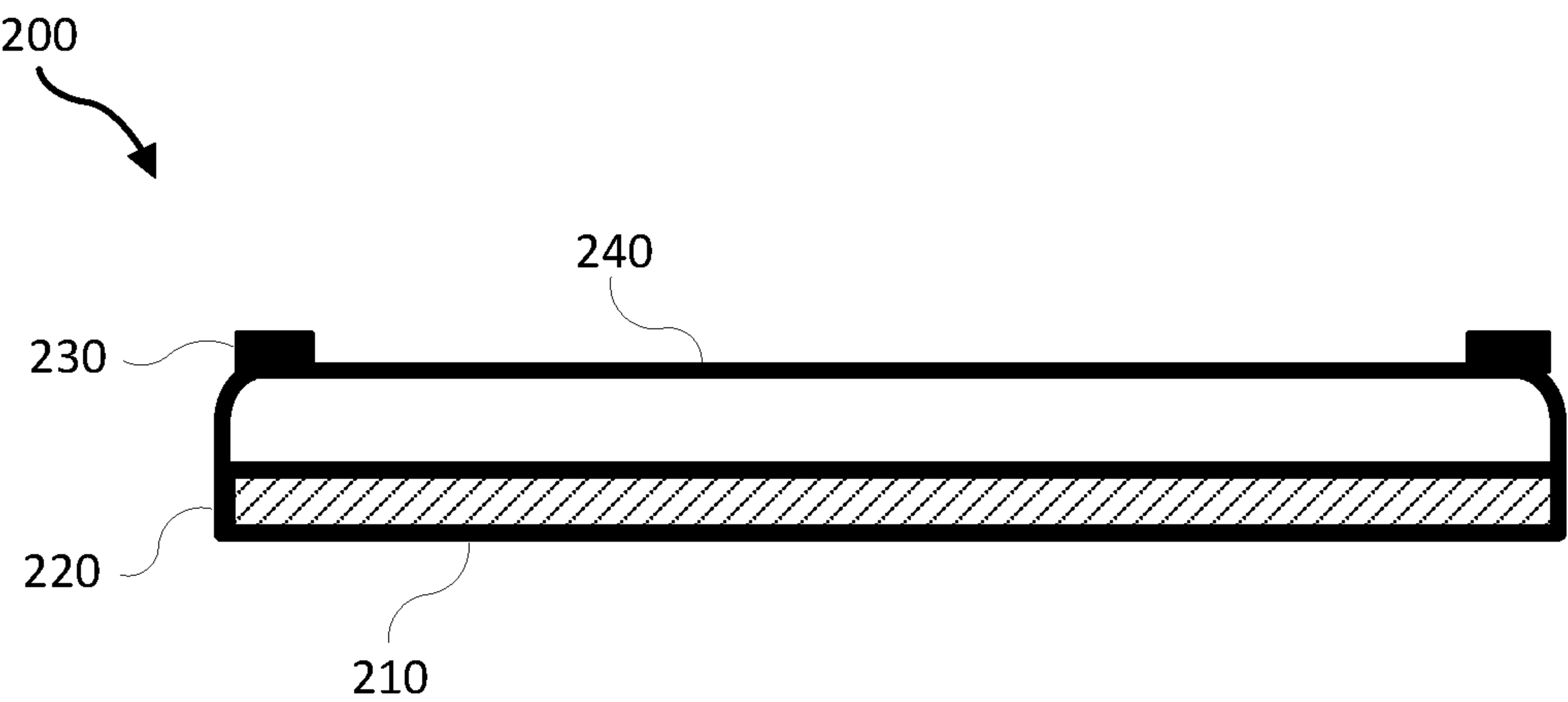


FIG. 2A

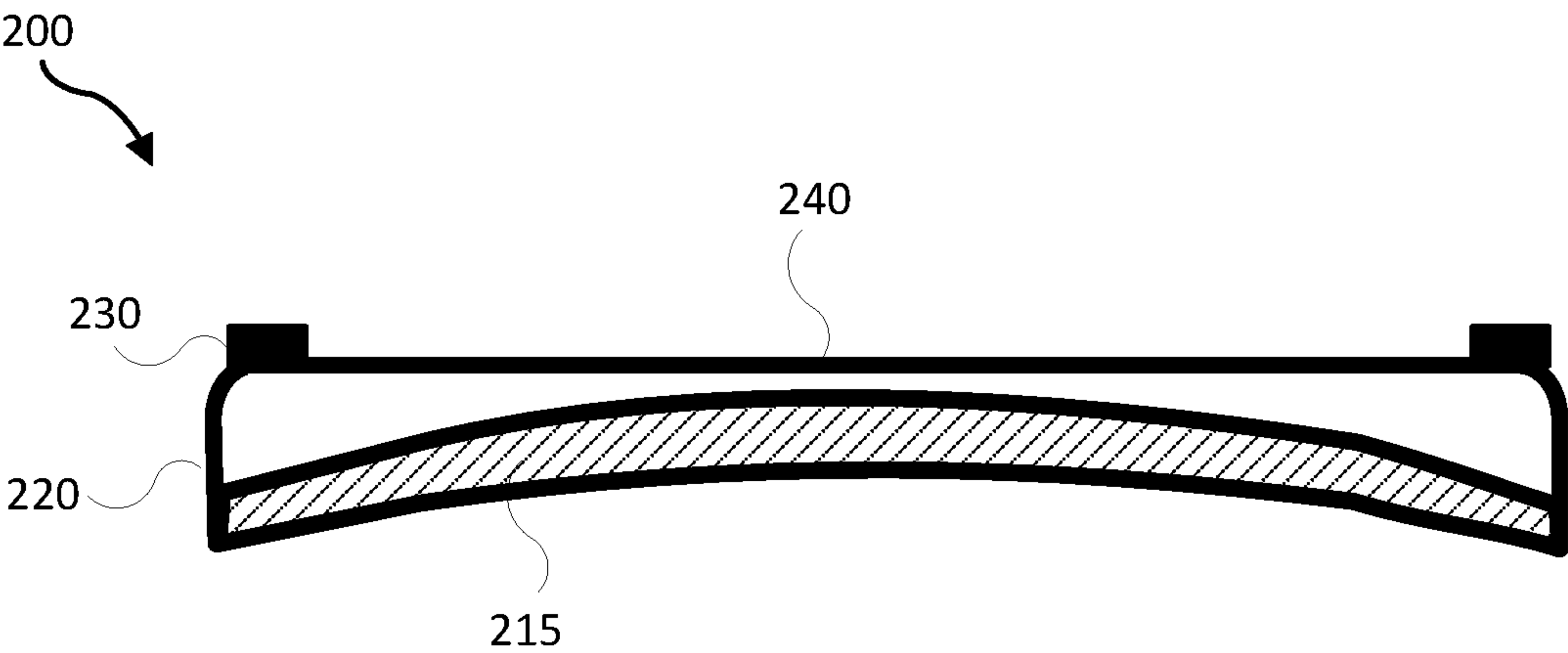


FIG. 2B

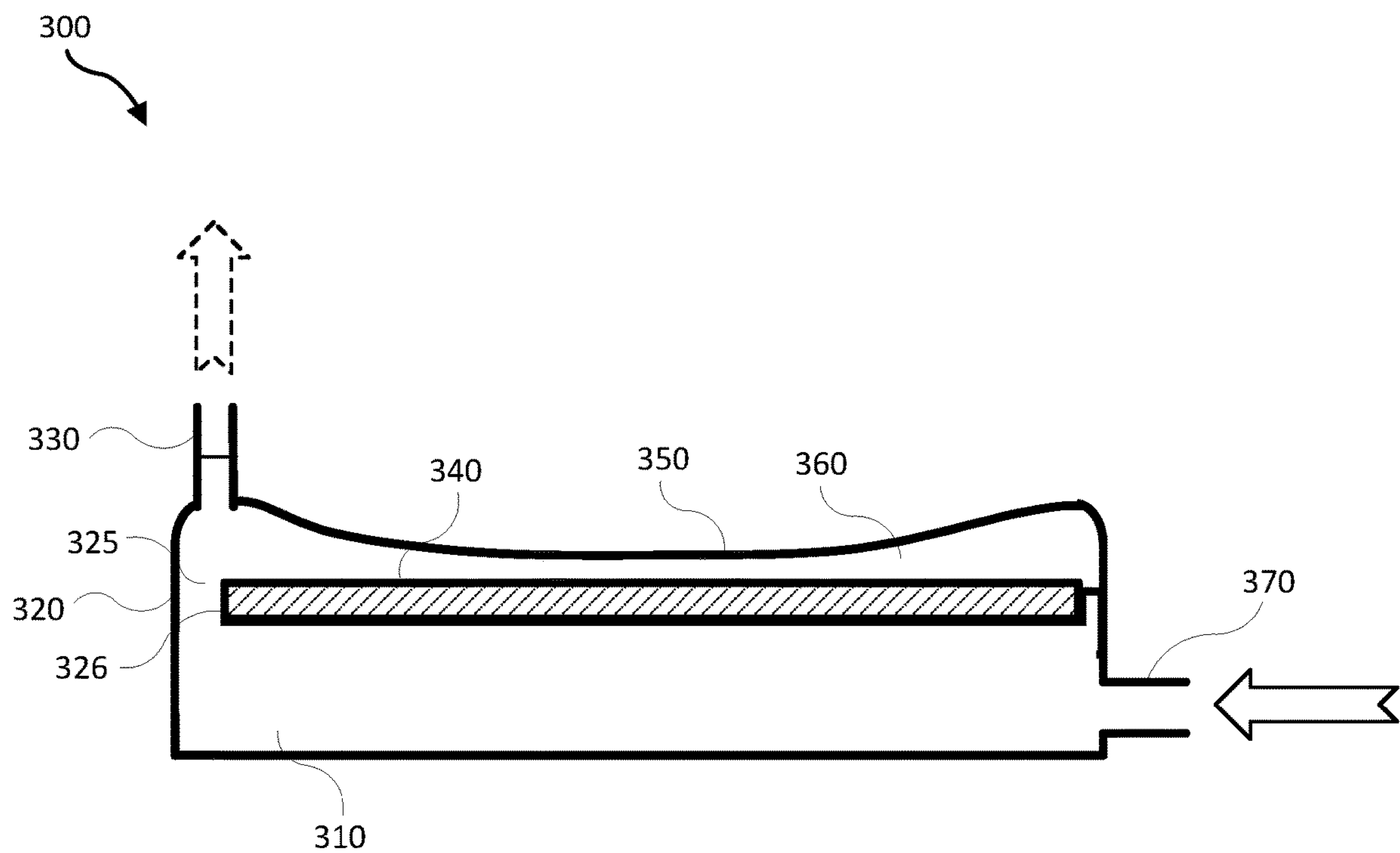


FIG. 3

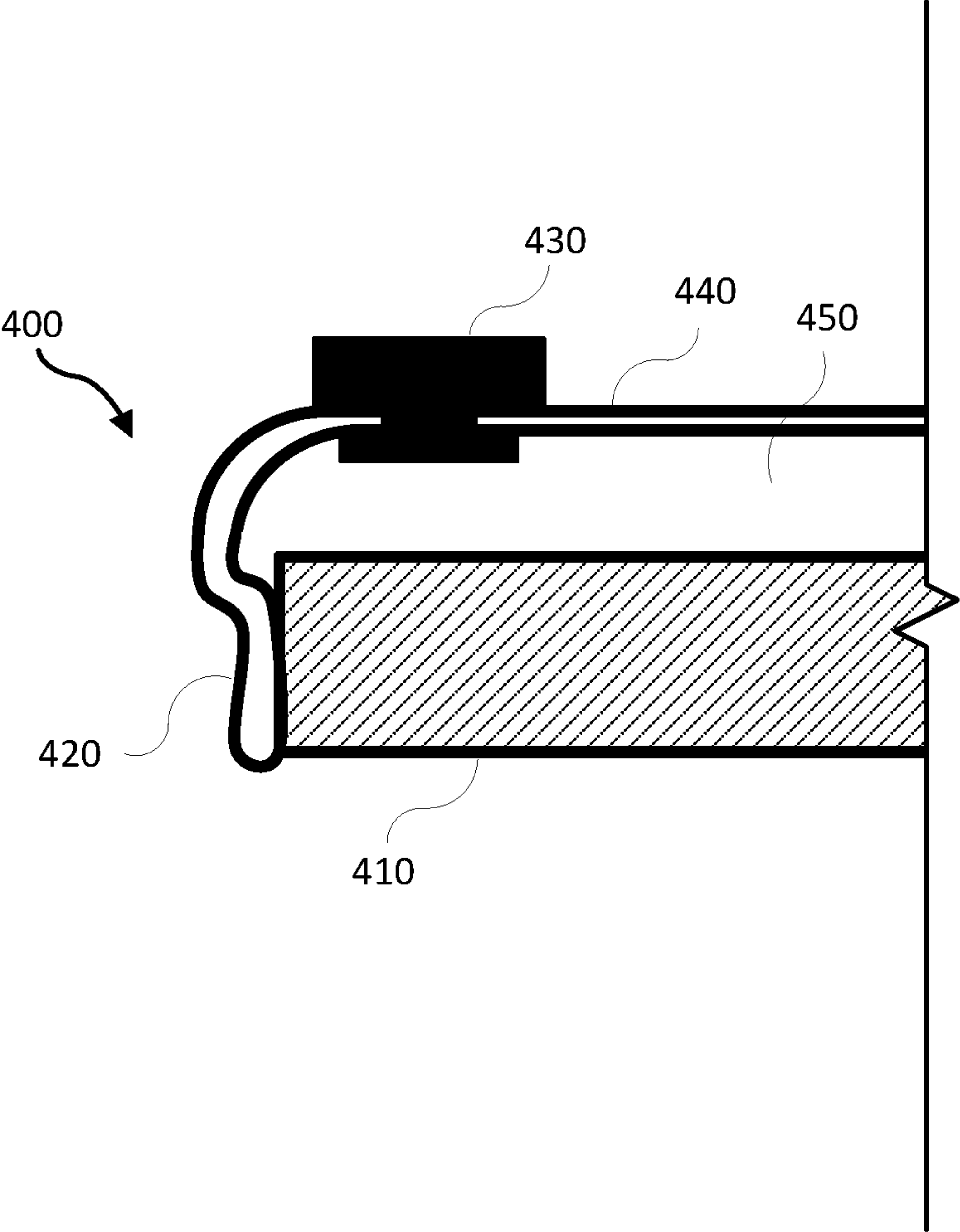


FIG. 4

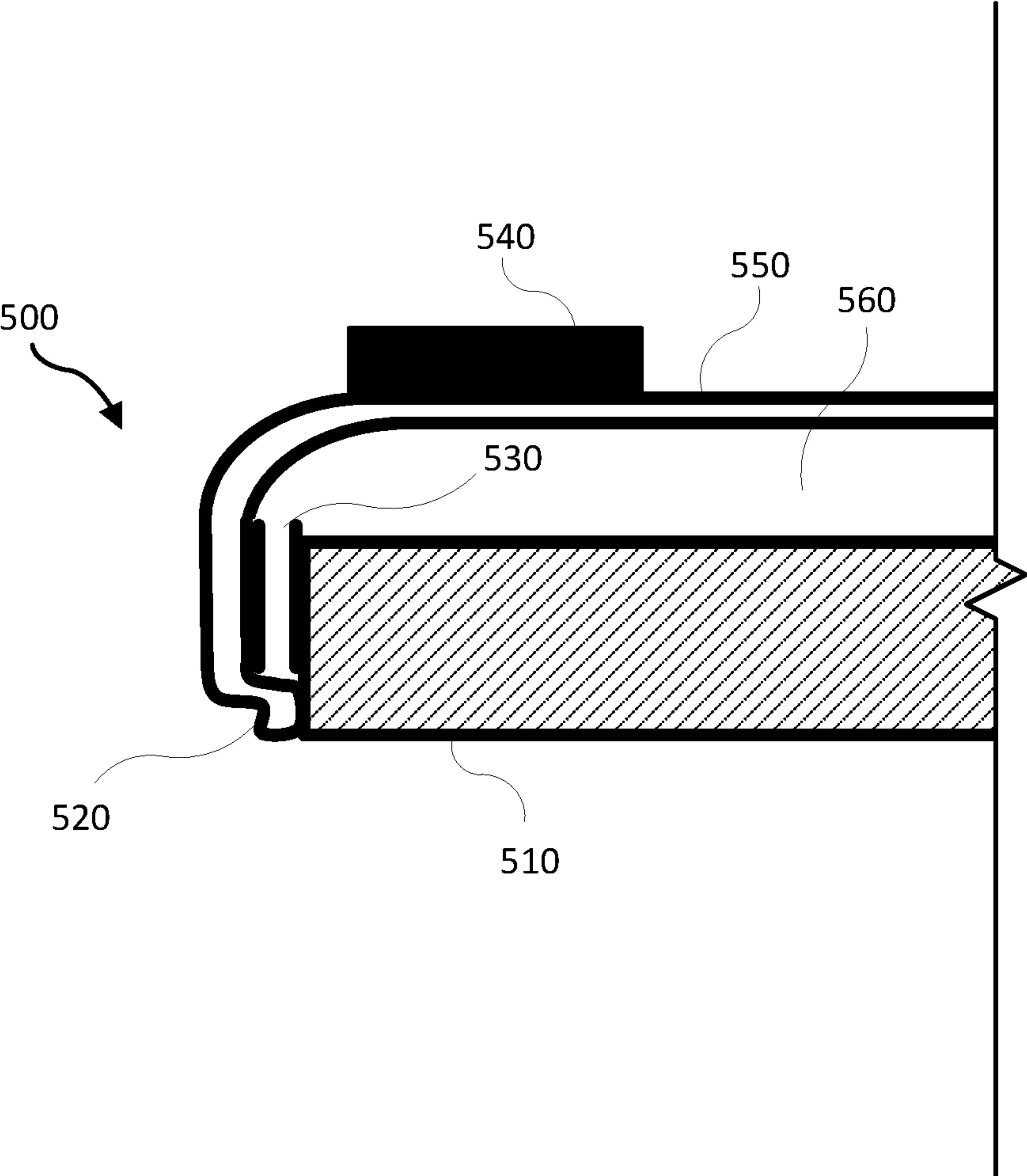


FIG. 5

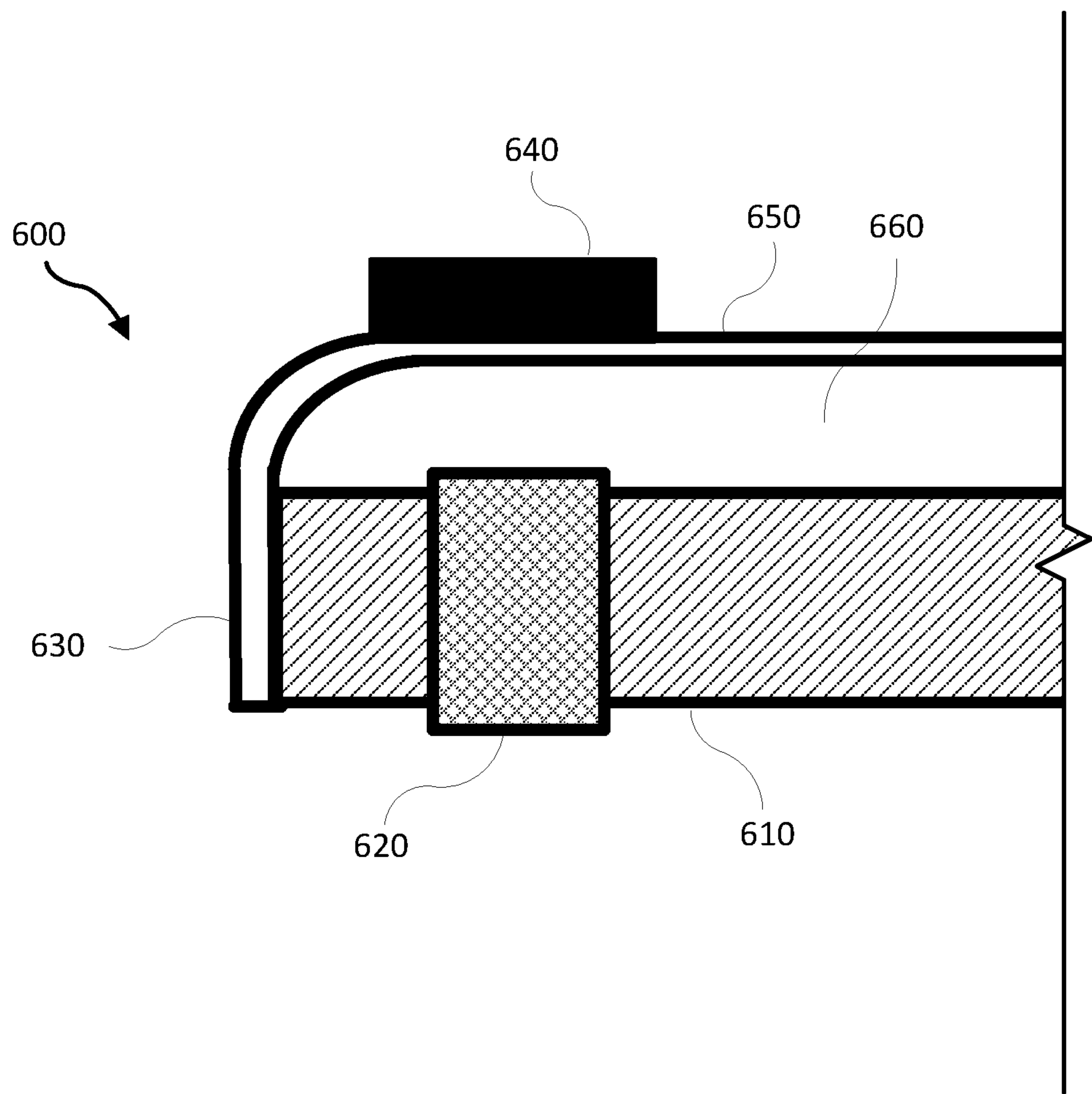


FIG. 6

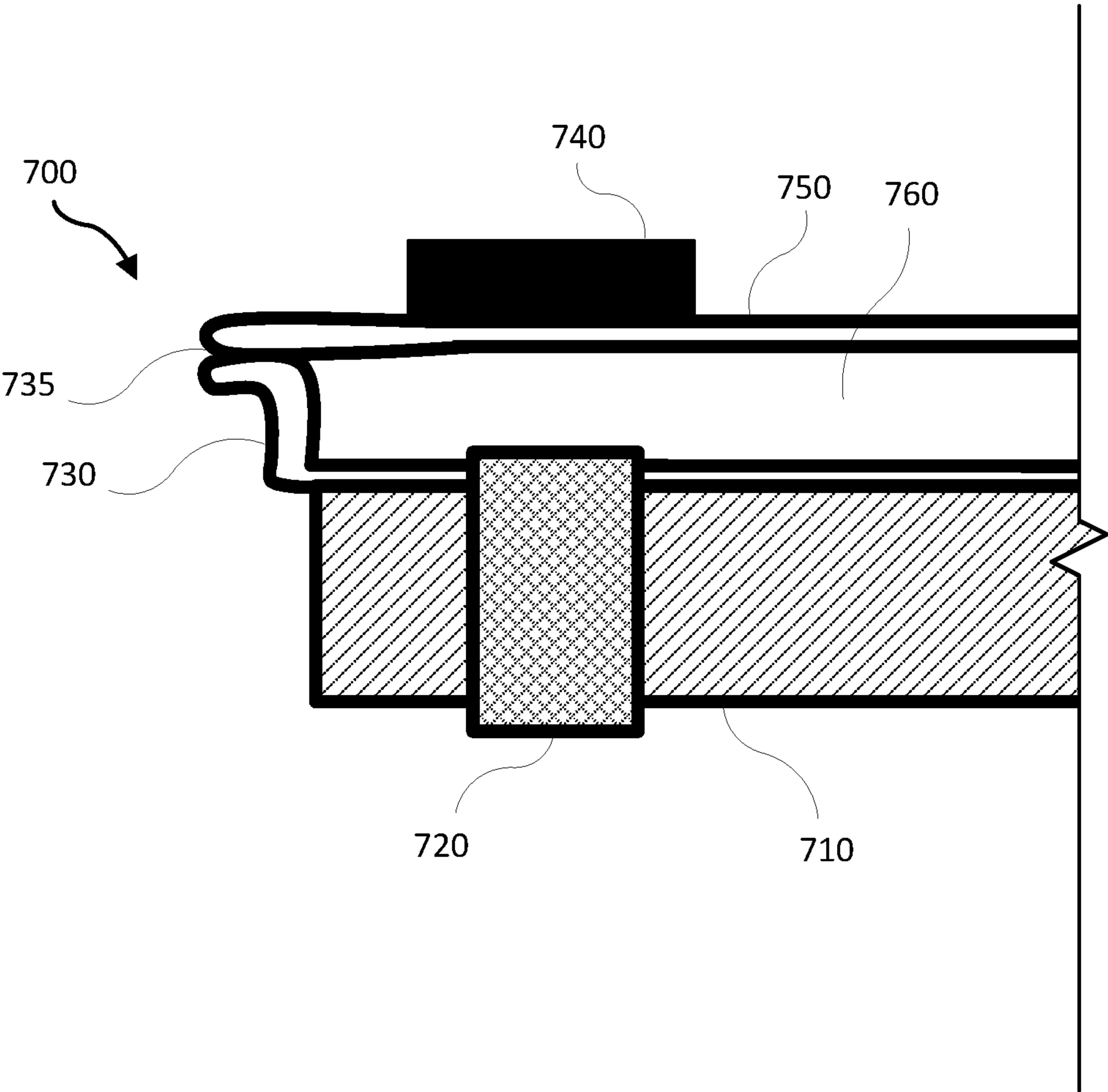


FIG. 7

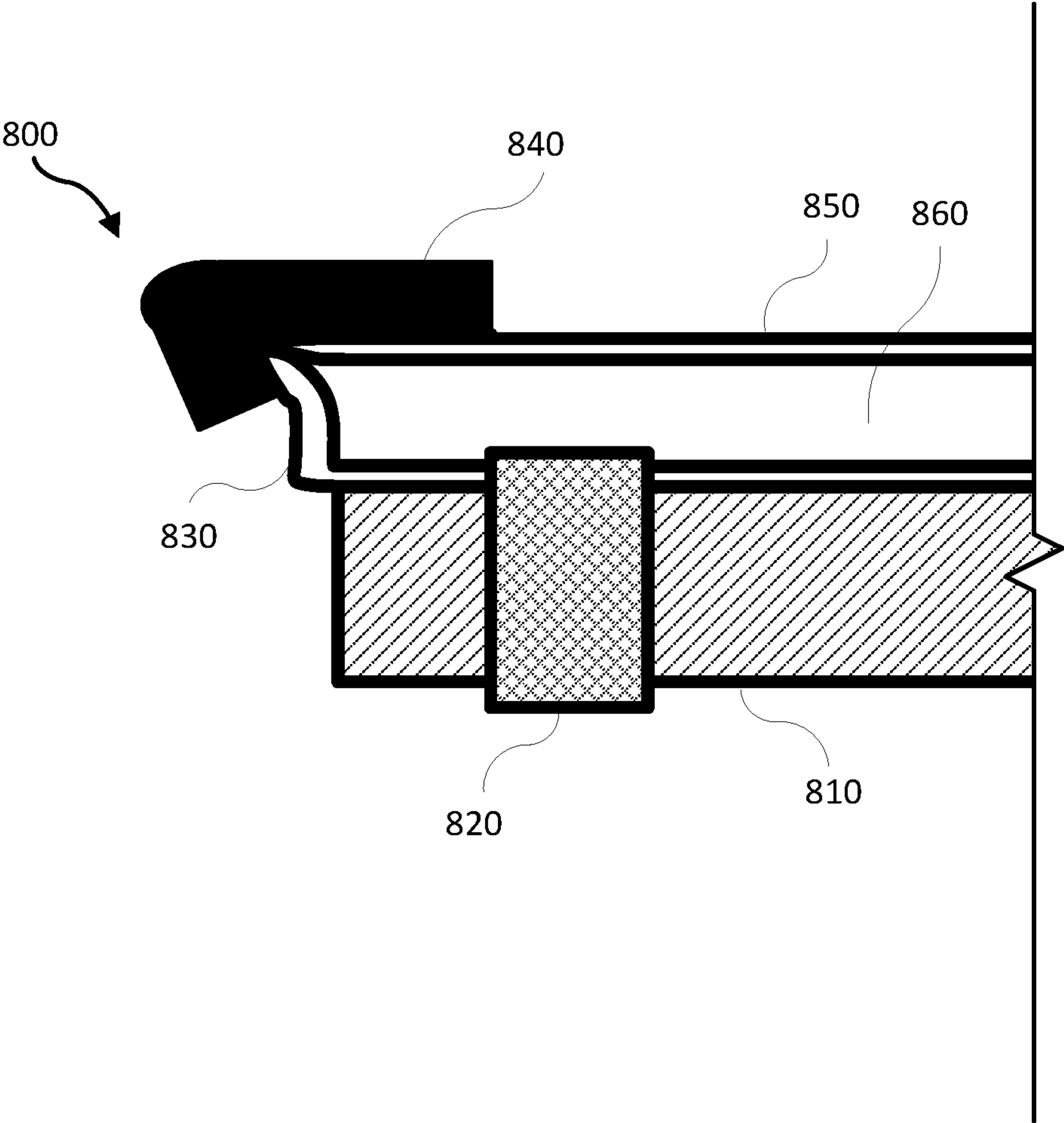


FIG. 8

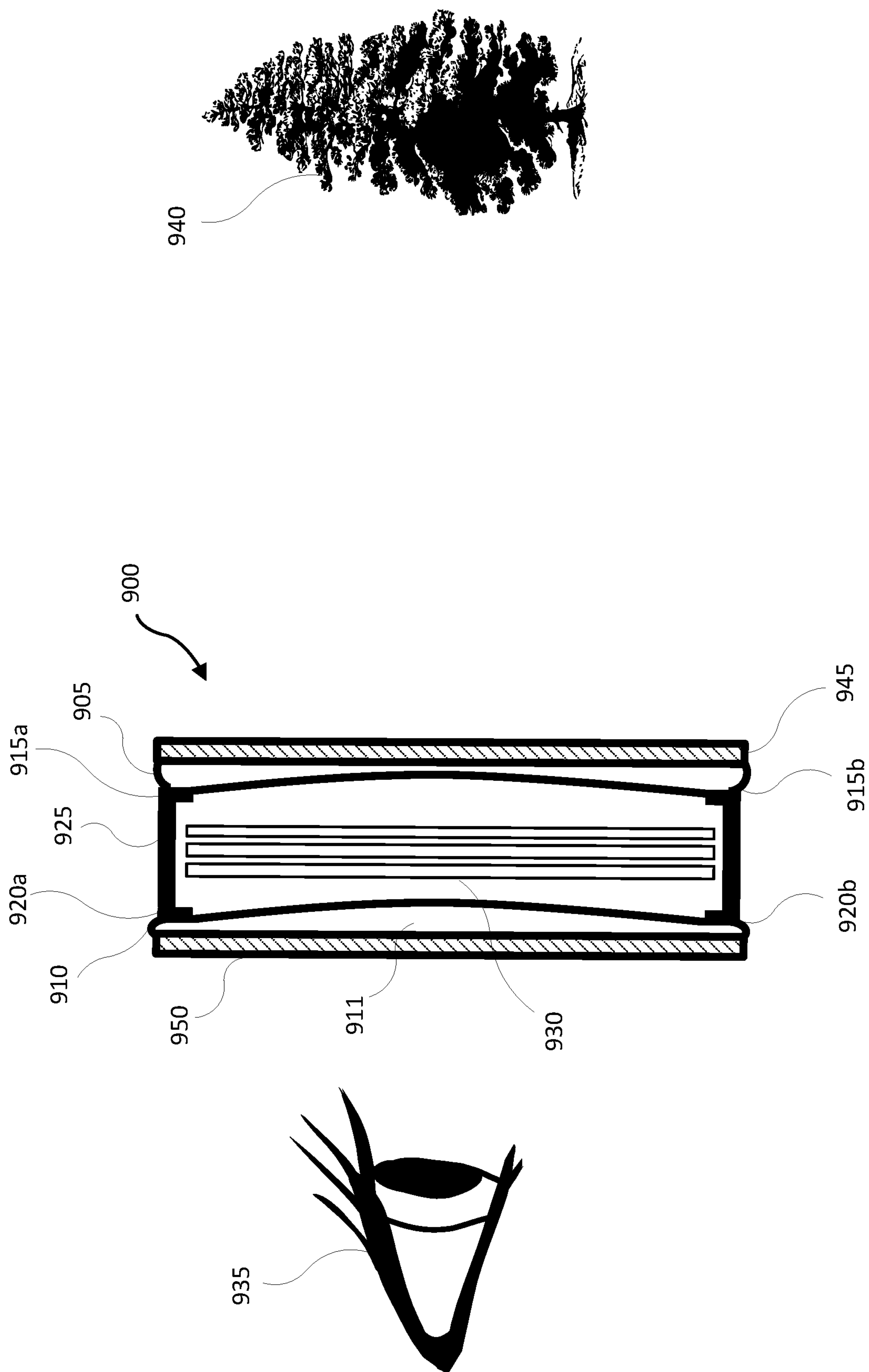


FIG. 9

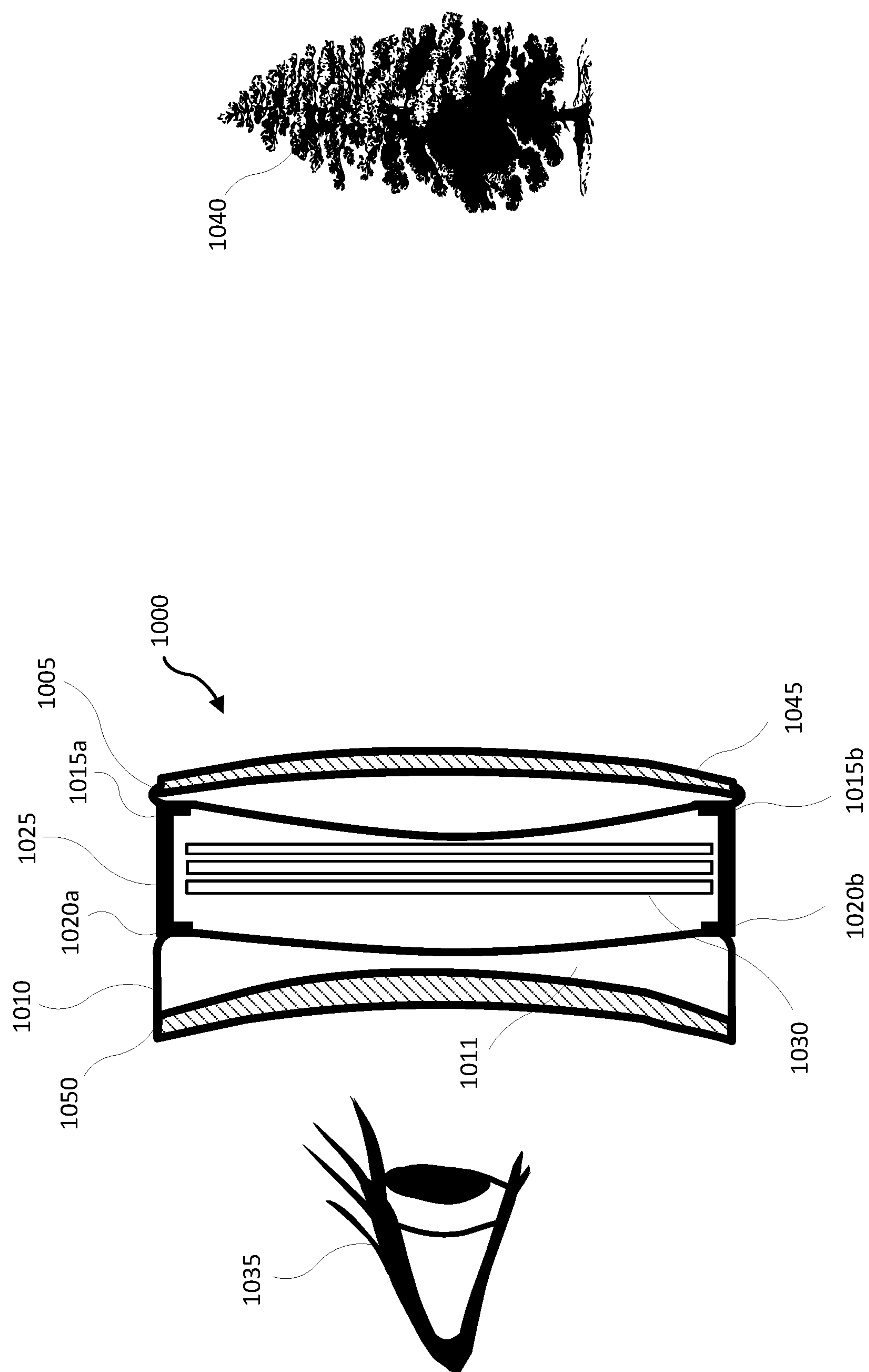


FIG. 10

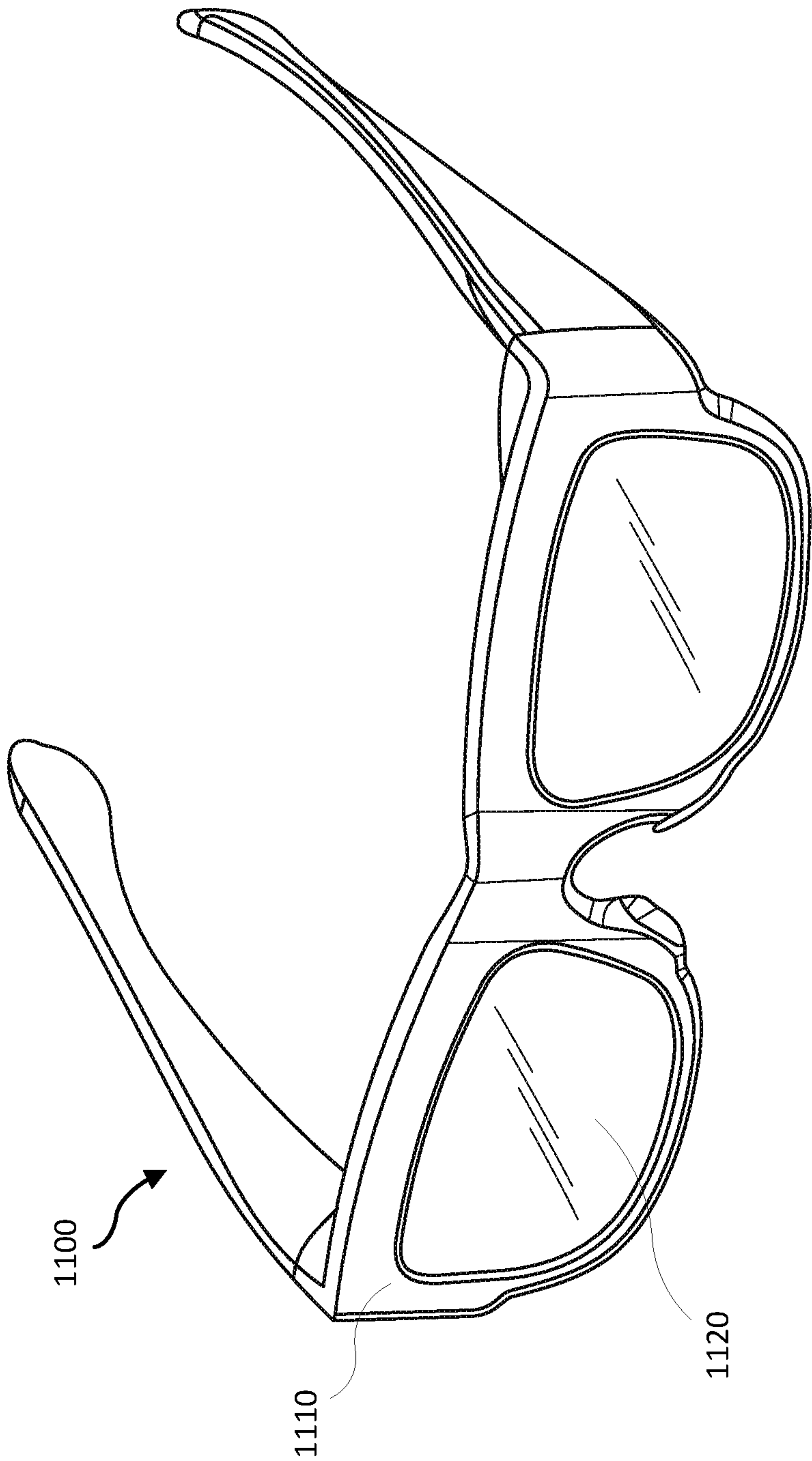


FIG. 11

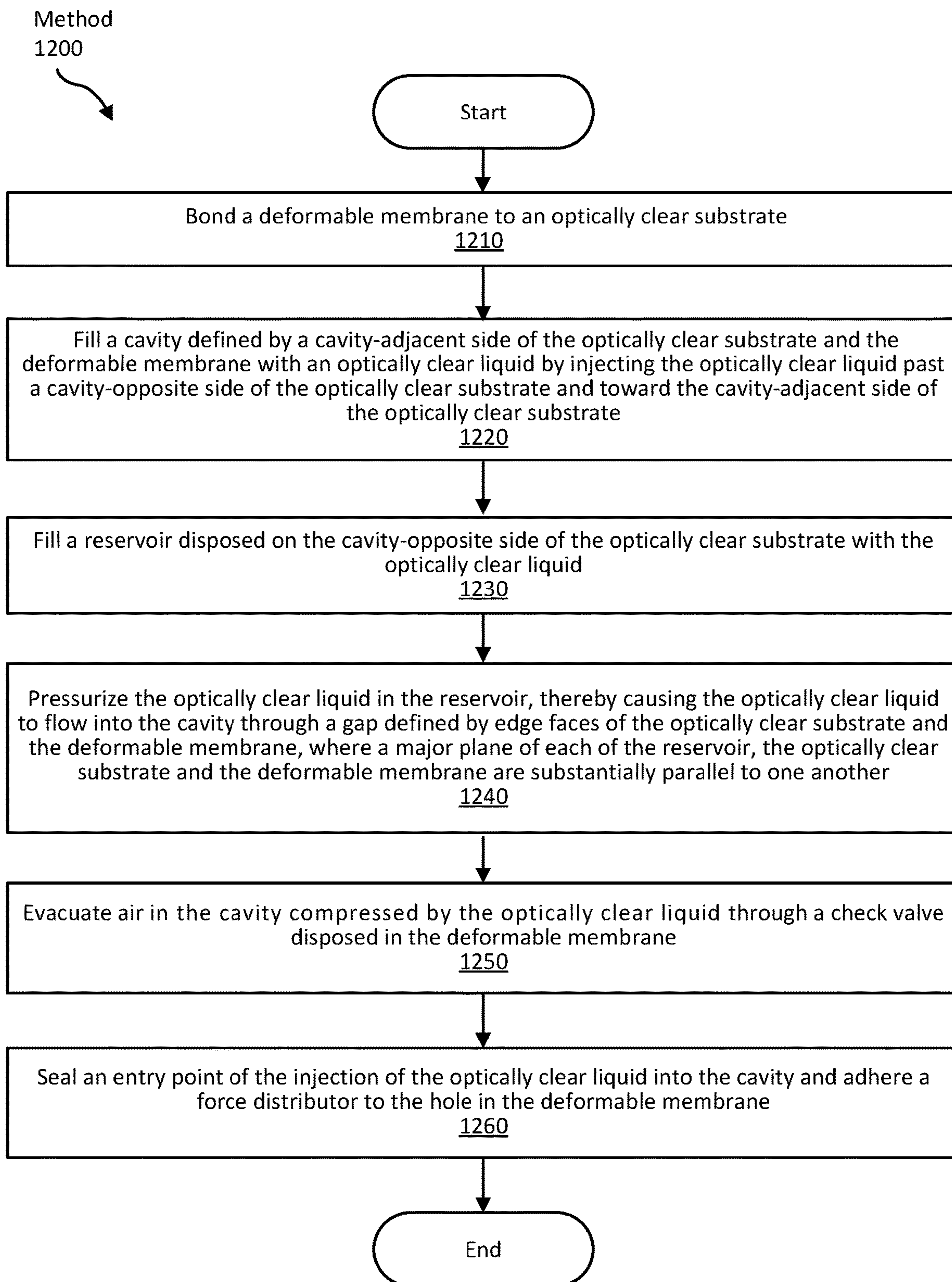


FIG. 12

Method
1300

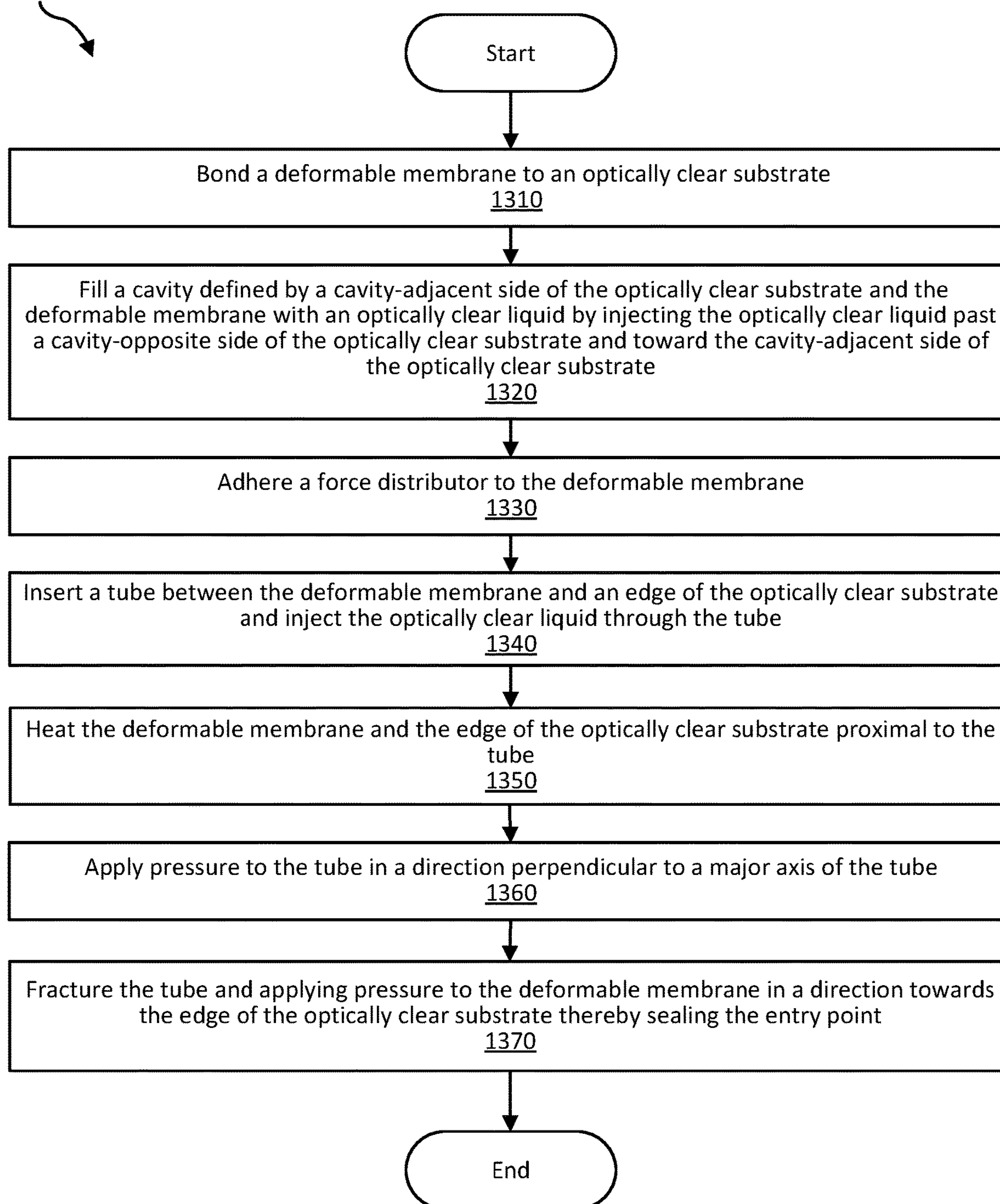


FIG. 13

Method
1400

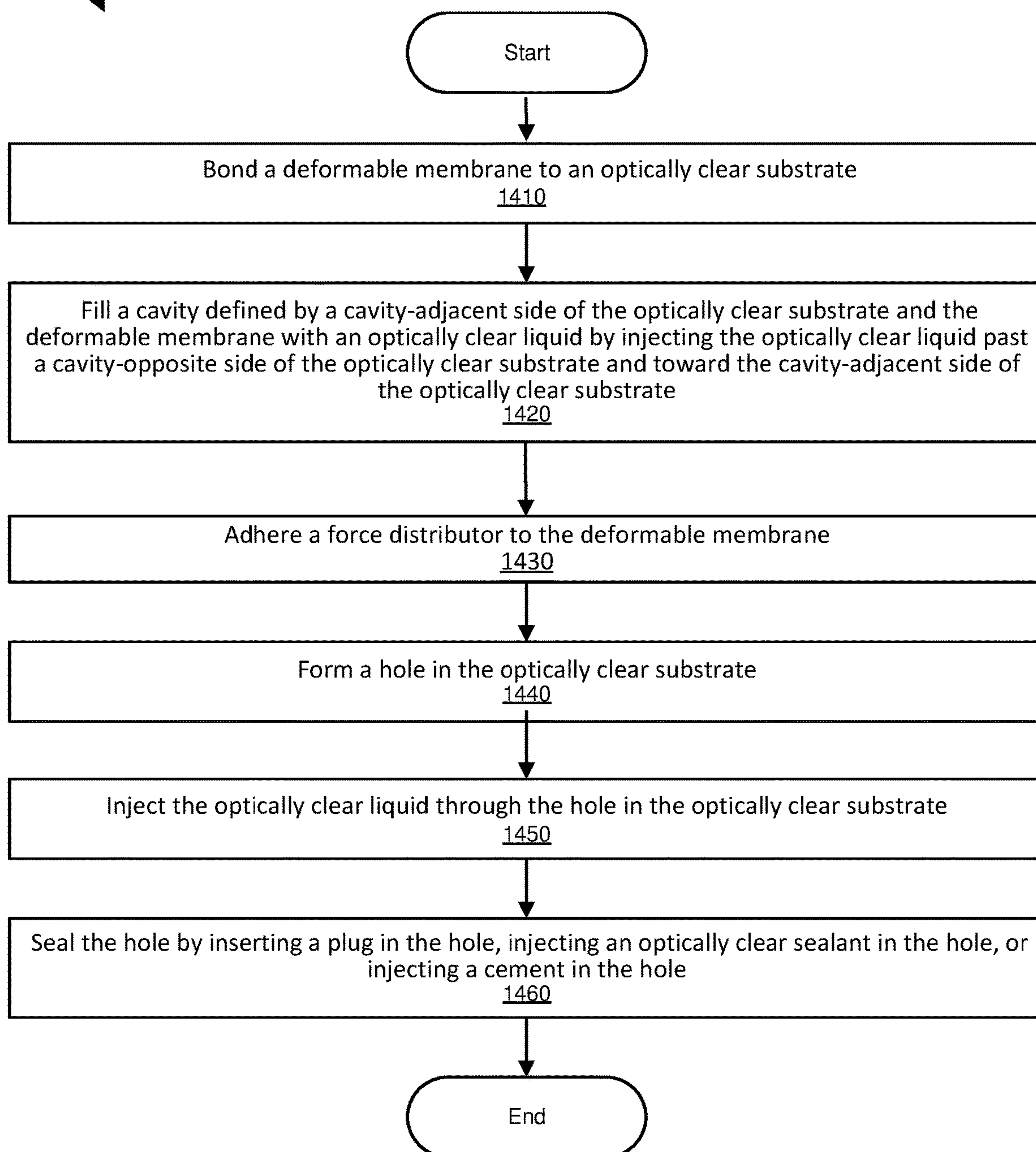


FIG. 14

APPARATUSES AND SYSTEMS INCLUDING ULTRA-THIN ADJUSTABLE LENSES

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. patent application Ser. No. 15/972,794, filed May 7, 2018, titled “APPARATUS, SYSTEM, AND METHOD FOR FABRICATING ULTRA-THIN ADJUSTABLE LENSES,” which claims the benefit of U.S. Provisional Patent Application No. 62/646,900, filed 22 Mar. 2018, titled “OPTICAL DEVICES, SYSTEMS, AND METHODS OF MANUFACTURING.” The entire disclosure of each of these applications is incorporated herein by reference.

BACKGROUND

[0002] Putting on a virtual-reality or augmented-reality head-mounted system may be the beginning of a thrilling experience, one that may be more immersive than almost any other digital entertainment or simulation experience available today. Head-mounted systems may enable users to travel through space and time, interact with friends in a three-dimensional world, or play video games in a radically redefined way. Head-mounted systems may also be used for purposes other than recreation—governments may use them for military training simulations, doctors may use them to practice surgery, and engineers may use them as visualization aids.

[0003] In any use of a virtual-reality or augmented-reality system, making the experience as immersive as possible may be critical. However, many design features of head-mounted systems may potentially interfere with an immersive experience. For example, many head-mounted systems may be relatively heavy with most of their weight distributed toward the front, potentially resulting in significant pressure on a user’s face and leading to discomfort that may make a virtual reality experience less compelling. In addition, attempts to integrate more functionality into head-mounted systems may add thickness and weight, potentially resulting in head-mounted systems that are overly heavy or unwieldy.

SUMMARY

[0004] As will be described in greater detail below, the instant disclosure describes a method, system and apparatus for fabricating ultra-thin optical lens assemblies.

[0005] In one example, a method may include bonding a deformable element to a structural support element. The deformable element and a cavity-adjacent side of the structural support element may define a cavity. The method may further include filling the cavity with a deformable medium by injecting the deformable medium past a cavity-opposite side of the structural support element and toward the cavity-adjacent side of the structural support element. The method may further include sealing an entry point of the injection of the deformable medium into the cavity.

[0006] In some examples, the method may further include filling a reservoir disposed on the cavity-opposite side of the structural support element with the deformable medium. The method may further include pressurizing the deformable medium in the reservoir, thereby causing the deformable medium to flow into the cavity through a gap defined by an edge face of the structural support element and an edge face

of the deformable element. In some examples, a major plane of each of the reservoir, the structural support element and the deformable element may be substantially parallel to one another.

[0007] In some examples, the gap defined by an edge face of the structural support element and an edge face of the deformable element may be sized such that there is substantially no capillary effect on the deformable medium.

[0008] In some examples, the method may further include evacuating air in the cavity compressed by the deformable medium through a check valve disposed in the deformable bounding element having a portion defining a hole. The method may further include removing the check valve disposed in the hole in the deformable bounding element. The method may further include adhering a force distributor to the hole in the deformable bounding element.

[0009] The method may further include sealing the entry point of the injection of the deformable medium into the cavity by coating an edge of the structural support element with an adhesion promoting layer and sealing the gap between the edge face of the structural support element and the edge face of the deformable bounding element.

[0010] In some examples, sealing the gap defined by an edge face of the structural support element and an edge face of the deformable element may include at least one of heat bonding the edge face of the structural support element to the edge face of the deformable bounding element or ultrasonic welding of the edge face of the structural support element to the edge face of the deformable bounding element.

[0011] In some examples, the method may further include adhering a force distributor to the deformable bounding element. In some examples, injecting the deformable medium may include inserting a tube between the deformable bounding element and an edge of the structural support element. The method may further include injecting the deformable medium through the tube.

[0012] In some examples, sealing the entry point of the injection of the deformable medium into the cavity may include heating the deformable bounding element and the edge of the structural support element proximal to the tube. The method may further include applying pressure to the tube in a direction perpendicular to a major axis of the tube and fracturing the tube. The method may further include applying pressure to the deformable bounding element in a direction towards the edge of the structural support element.

[0013] In some examples, the method may further include adhering a force distributor to the deformable bounding element. The method may further include forming a hole in the structural support element. In some examples, injecting the deformable medium may comprise injecting the deformable medium through the hole in the structural support element. The method may further include sealing the entry point of the injection of the deformable medium into the cavity comprises sealing the hole in the structural support element.

[0014] In some examples, the hole in the structural support element may be disposed on a perimeter of the structural support element within a bezel-mounting area, thereby substantially maintaining a clear aperture area afforded by the deformable bounding element and the structural support element.

[0015] In some examples, sealing the hole may comprise sealing the hole with an optically clear sealant.

[0016] In some examples, bonding the deformable bounding element to the structural support element may include forming a first portion of the deformable bounding element into a shape that defines the cavity. The method may further include adhering a surface of the first portion of the deformable bounding element to a surface of the cavity-adjacent side of the structural support element. The method may further include sealing the cavity by bonding a perimeter edge of the first portion of the deformable bounding element to a perimeter edge of a second portion of the deformable bounding element.

[0017] In some examples, bonding the perimeter edge of the first portion of the deformable bounding element to the perimeter edge of the second portion of the deformable bounding element may include crimping the force distributor around the perimeter edges of the first and second portions of the deformable bounding element.

[0018] In some examples, the structural support element may include at least one of an eye tracking element or corrective ophthalmic properties.

[0019] In some examples, bonding the deformable bounding element to the structural support element, filling the cavity with the deformable medium, and sealing the entry point of the injection may produce an optical lens assembly having a thickness of less than two millimeters.

[0020] In one example, an apparatus may include an optical lens assembly having a thickness less than 2 millimeters. In some examples, the optical lens assembly may include a deformable bounding element bonded to a structural support element and a deformable medium disposed between the deformable bounding element and the structural support element.

[0021] In some examples, the apparatus may further include a force distributor adhered to the deformable bounding element. In some examples, the force distributor may distribute a force applied by an actuator to a perimeter edge of the deformable bounding element thereby altering the shape of the optical lens assembly and the optical power of the optical lens assembly.

[0022] In one example, a system may include a head-mounted device which may include a pair of optical lens assemblies. In some examples, each of the optical lens assemblies may have a thickness of less than two millimeters. In some examples, each of the optical lens assemblies may include a deformable bounding element bonded to a structural support element. In some examples, each of the optical lens assemblies may include a deformable medium disposed between the deformable bounding element and the structural support element.

[0023] In some examples, the head mounted device may further include a bezel. In some examples, the optical lens assemblies may be mounted in the bezel. In some examples, the deformable medium may be injected through an entry point within a bezel-mounting area, thereby reducing obstruction of the optical lens assemblies.

[0024] In some examples, the ratio of a clear aperture area of the optical lens assemblies to an overall surface area of the optical lens assemblies is greater than 75 percent.

[0025] Features from any of the above-mentioned embodiments may be used in combination with one another in accordance with the general principles described herein. These and other embodiments, features, and advantages will

be more fully understood upon reading the following detailed description in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The accompanying drawings illustrate a number of exemplary embodiments and are a part of the specification. Together with the following description, these drawings demonstrate and explain various principles of the instant disclosure.

[0027] FIG. 1A illustrates a method for filling a deformable optical element.

[0028] FIG. 1B illustrates an attempt to fill an ultra-thin deformable optical element.

[0029] FIG. 2A is an illustration of an optical lens assembly.

[0030] FIG. 2B is an illustration of an optical lens assembly with an ophthalmic substrate.

[0031] FIG. 3 is an illustration of an optical lens assembly fixtured within a deformable medium reservoir.

[0032] FIG. 4 is a partial view of an optical lens assembly with a force distributor adhered to a hole in a deformable bounding element.

[0033] FIG. 5 is a partial view of an optical lens assembly with a filling tube inserted between a deformable bounding element and a structural support element.

[0034] FIG. 6 is a partial view of an optical lens assembly with a hole in a structural support element.

[0035] FIG. 7 is a partial view of an optical lens assembly with a hole in a structural support element and a deformable bounding element with a pre-formed cavity.

[0036] FIG. 8 is a partial view of an optical lens assembly with a hole in a structural support element and a deformable bounding element sealed by a crimped force distribution ring.

[0037] FIG. 9 is a side view of an optical lens assembly.

[0038] FIG. 10 is a side view of an optical lens assembly with an ophthalmic corrective element.

[0039] FIG. 11 is a perspective view of head-mounted device.

[0040] FIG. 12 shows a flow diagram of an example method of filling and sealing an optical lens assembly using a reservoir.

[0041] FIG. 13 shows a flow diagram of an example method of filling and sealing an optical lens assembly using a fill tube.

[0042] FIG. 14 shows a flow diagram of an example method of filling and sealing an optical lens assembly through a hole in a structural support element.

[0043] Throughout the drawings, identical reference characters and descriptions indicate similar, but not necessarily identical, elements. While the exemplary embodiments described herein are susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and will be described in detail herein. However, the exemplary embodiments described herein are not intended to be limited to the particular forms disclosed. Rather, the instant disclosure covers all modifications, equivalents, and alternatives falling within the scope of the appended claims.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

[0044] This disclosure is generally directed to methods, apparatuses, and systems for manufacturing optical lenses. For example, assembling an optical lens may involve bonding a deformable bounding element (e.g., a flexible film) to a structural support element (e.g., a rigid backing), thereby creating a cavity between the deformable bounding element and the structural support element. In order to fill the cavity with a deformable medium (e.g., an optical fluid), methods described herein may involve injecting the deformable medium into the cavity from behind the structural support element (rather than, e.g., laterally injecting the deformable medium into the cavity from a position between the deformable bounding element and the deformable medium). In this manner, as will be explained in greater detail below, methods described herein may be used to produce ultra-thin deformable optical lenses.

[0045] Ultra-thin deformable optical lenses as described herein may provide one or more advantages over other deformable optical lenses. For example, ultra-thin deformable optical lenses may provide adjustable optical power within very small form factors. Furthermore, ultra-thin deformable optical lenses may provide one or more advantages over other ultra-thin optical lenses. For example, as will be described in greater detail below, ultra-thin deformable optical lenses may dynamically adjust (e.g., to change optical power) for any of a wide variety of applications, including vision correction and/or resolving vergence-accommodation conflicts. As will be explained in greater detail below, in some examples the methods for assembling optical lenses described herein may also provide a wide aperture that is substantially free from obstructions. In some examples, an optical lens with a wide aperture that is free from obstructions may be integrated into a device such as a head-mounted display system and may provide an unobstructed wide field of view, thus increasing the performance of the head-mounted display (HMD) and its utility to the user.

[0046] Embodiments presented herein may also provide one or more advantages to head-mounted display systems. For example, a head-mounted display system (e.g., a virtual-reality or augmented-reality display system) that uses ultra-thin deformable optical lenses may provide adjustable optical power while minimizing weight placed on and/or protrusions from a user's face. Additionally or alternatively, such ultra-thin deformable optical lenses may provide room for adding other components to a head-mounted display system within given volume and/or weight design constraints. In one example, ultra-thin deformable optical lenses may be used within devices with minimal form factors, such as head-mounted display devices with an eyeglass form factor. As may be appreciated, head-mounted display systems with reduced weight, reduced volumes and/or profiles, comfortable and/or convenient form factors, and/or integrated functionality may improve user comfort, experience, and/or immersion.

[0047] FIG. 1A illustrates an example approach for filling an optical lens assembly with a deformable medium (e.g., an optical fluid). As shown in FIG. 1A, an optical lens assembly 100 may include a structural support element 110, a deformable bounding element 140, and a cavity 150. A method of filling optical lens assembly 100 may include inserting a needle 105 (or another type of tube), into cavity 150 (e.g.,

before attaching a side portion 145 of deformable bounding element 140 to structural support element 110) and injecting deformable medium 160 through tube 105 into cavity 150. As shown in FIG. 1A, the method may involve injecting deformable medium 160 longitudinally into cavity 150 (e.g., substantially in parallel with optical lens assembly 100) such that needle 105 enters between deformable bounding element 140 and structural support element 110. Although optical lens assembly 100 may have a fairly low profile, needle 105 may be sufficiently thin to enter between deformable bounding element 140 and structural support element 110.

[0048] FIG. 1B illustrates an example approach for attempting to fill an ultra-thin optical lens assembly with a deformable medium. As shown in FIG. 1B, an ultra-thin optical lens assembly 101 may include a structural support element 111, a deformable bounding element 141, a deformable bounding element 141 and a cavity 151. As illustrated in FIG. 1B, ultra-thin optical lens assembly 101 has a significantly lower profile in comparison to optical lens assembly 100 in FIG. 1A. As may be appreciated, the method of filling optical lens assembly 100, as described above with reference to FIG. 1A, may be difficult, impractical, and/or ineffective when applied to ultra-thin optical lens assembly 101. For example, the diameter of needle 105 may exceed the height of side portion 146 of deformable bounding element 141 and, therefore, needle 105 may be too large to be inserted in between deformable bounding element 141 and structural support element 111. The relative thinness of optical lens assembly 100 (and, in particular, of cavity 151) may interfere with the use of needle 105 (or similar injection instruments) in any of a variety of ways. In some examples, cavity 151 may be too thin to admit needle 105 between structural support element 111 and deformable bounding element 141. In some examples, attempting to insert needle 105 between structural support element 111 and deformable bounding element 141 into cavity 151 may overstretch and/or damage deformable bounding element 141. Additionally or alternatively, inserting needle 105 and/or injecting the deformable medium 160 laterally between structural support element 111 and deformable bounding element 141 into cavity 151 with sufficient precision to successfully fill cavity 151 with the deformable medium 160 may be difficult and/or impractical. In some examples, attempts to inject deformable medium 160 into cavity 151 may trap air bubbles as air has insufficient room to escape given the thinness of cavity 151. Additionally, inserting the needle may create a defect in the side portion 146 and/or may lead to leakage or failure of at least a part of side portion 146. Accordingly, embodiments discussed in greater detail below may provide alternative methods for manufacturing ultra-thin optical lens assemblies.

[0049] In order to overcome the potential deficiencies of filling the ultra-thin optical lens assembly as described in FIG. 1B (e.g., from the side of the optical lens assembly, via an insertion between the structural support and the deformable bounding element from outside the optical lens assembly into the cavity, and/or via a longitudinal injection), various methods of assembling the ultra-thin optical lens assembly may involve filling the cavity through alternative entry points. For example, methods discussed herein may involve injecting the deformable medium from behind the structural support element, past the structural support element, and into the cavity. Thus, in some examples, methods

discussed herein may inject the deformable medium in a direction substantially parallel to the short axis of the optical lens assembly (e.g., substantially normal to the structural support element and/or the deformable bounding element).

[0050] FIG. 2A illustrates an example of an optical lens assembly. As shown in FIG. 2A, an optical lens assembly **200** may include a structural support element **210**, an edge seal **220**, a force distributor **230**, a deformable bounding element **240**, and a cavity **250**. Edge seal **220** may seal deformable bounding element **240** to the edge of structural support element **210** and cavity **250** may be encapsulated between deformable bounding element **240** and structural support element **210**. Edge seal **220** may thereby contain the deformable medium within cavity **250**. Force distributor **230** may couple deformable bounding element **240** to an external actuation mechanism (not shown). When the external actuation mechanism applies a force or pressure to force distributor **230**, force distributor **230** may distribute the force to the perimeter of deformable bounding element **240**, causing the surface of deformable bounding element **240** to deform and thereby modify one or more optical properties of optical lens assembly **200** (e.g., the optical power of optical lens assembly **200**). Various types of structural support element may be suitable for sealing deformable bounding element **240** to structural support element **210** along edge seal **220**, enabling the use of ophthalmic, eye tracking or other optical elements as the structural support element **210**.

[0051] FIG. 2B illustrates an example of an optical lens assembly with an ophthalmic substrate. As shown in FIG. 2B, an optical lens assembly **200** may include an ophthalmic substrate **215**, an edge seal **220**, a force distributor **230** and a deformable bounding element **240** in a structure analogous to optical lens assembly **100**. Ophthalmic substrate **215** may have corrective optical properties (e.g., correcting a user's vision).

[0052] By way of example, FIGS. 3-5, which will be discussed in greater detail below, show various methods used to produce the optical lens assembly structures shown in FIGS. 1 and 2. The methods described in reference to FIGS. 3-5 are shown with a flat substrate (e.g., similar to structural support element **111**) but may be compatible with other substrate types including ophthalmic substrates and therefore could also be used for assemblies similar to optical lens assembly **200**.

[0053] As discussed earlier, the deformable optical lenses discussed herein may be adjusted (e.g., thereby modifying one or more optical properties of the deformable optical lenses). For example, an optical lens assembly may be integrated with an actuator on or near the perimeter of the deformable bounding element. Actuation along the perimeter of the deformable bounding element may apply a force to the perimeter of the deformable bounding element (e.g., downward onto the deformable bounding element, radially inward onto the deformable bounding element, etc.), thereby increasing the pressure of the deformable medium in the cavity. The increased pressure of the deformable medium may apply a force against the deformable bounding element, thereby changing the curvature of the deformable bounding element and its optical power. The direction and magnitude of the applied force may be variable and thus may determine the variable optical power of a deformable optical element. The deformable optical element may be an element capable of providing variable optical properties through deformation (e.g., the deformable optical element may include a deform-

able lens that provides variable optical power). In some examples, the deformable optical element may include a deformable bounding element, a deformable medium, and/or a structural support element. The deformable bounding element may be any element that, when deformed, changes at least one optical property of the optical lens assembly. The deformable medium may be an optically transparent medium that is capable of being deformed by a deformable bounding element. The structural support element may be an element that provides structural support for the deformable medium. The curvature and focal length of the deformable optical element may be switched from convex to concave. In some examples, optical lens assemblies described herein may be varifocal, have high transmissivity of light, and may achieve low off-axis aberration and distortion for high image display quality over a wide range of optical powers.

[0054] The optical lens assemblies produced by the methods of the instant disclosure may also provide a wide aperture which may be free (or substantially free) from obstructions. An optical lens assembly with a wide aperture which is free from obstructions may be integrated into a device such as an HMD and provide an unobstructed wide field of view, thus increasing the performance of the HMD and its value to the user. Some of the methods for filling optical lens assemblies described herein may be applied by filling the optical lens assembly through a perimeter area of the optical lens assembly and, therefore, one or more components used in the filling process which may contribute to an obstruction may be located in the perimeter area. When the optical lens assembly is integrated into an HMD, the perimeter area may be concealed by a bezel of the HMD, thereby maintaining a clear aperture area of the deformable optical element and increasing the performance and comfort of the HMD.

[0055] The optical lens assembly produced by the methods of the instant disclosure may also be ultra-thin and lightweight. Filling an optical lens assembly through a hole in the structural support element or past the edge of the structural support element may reduce the thickness of the optical lens assembly. Further, the reduced thickness of the optical lens assembly may reduce the weight of the optical lens assembly. For example, the optical lens assembly may have a thickness less than about 3 mm, less than about 2 mm, less than about 1.5 mm, less than 1.0 mm, less than about 0.8 mm, less than about 0.7 mm, less than about 0.6 mm, less than about 0.5 mm, or less than about 0.4 mm. In some examples, the thickness of the optical lens assembly may be measured as the distance from the center of the outer surface of the deformable bounding element to the cavity-adjacent side surface of the structural support element when the optical lens assembly is in an undeformed state. In some examples, the optical lens assembly produced by the methods of the instant disclosure may also use materials which are lightweight. An HMD with ultra-thin and lightweight deformable optical elements may be more comfortable for a user to wear for extended periods of time.

[0056] The optical lens assembly may also be interfaced or integrated with other components such as ophthalmic lens components, eye tracking components, and/or wave guide components. The optical lens assembly may include a structural support element which may be shaped with a curvature that provides an ophthalmic lens which corrects for vision impairment of the user. The optical lens assembly may also be integrated with an eye tracking system which may track

where the user is looking and/or the motion of an eye relative to the head. The eye tracking system may increase functionality and user satisfaction levels in an AR/VR system and may include a selective-transmission element which transmits light having a selected property (e.g., visible light) but does not transmit light that does not have the selected property (e.g., infrared light). The selective-transmission element may be used to facilitate eye tracking in which an infrared light source will be reflected by the selective-transmission element back to an eye-tracking camera. In some examples, when the optical lens assembly includes an ophthalmic lens, light may be reflected and processed differently by the eye-tracking system than when the optical lens assembly does not include an ophthalmic lens. The eye-tracking system may include a controller to control the processing of the eye-tracking system.

[0057] The optical lens assembly may also be integrated with a wave guide, which may provide a virtual display that allows computer generated images to be viewed alongside real images by the user.

[0058] When the optical lens assemblies of the instant disclosure are integrated into an HMD, the HMD may be comfortable to wear for long periods of time due to the lighter weight, be aesthetically pleasing due to the ultra-thinness of the optical lens assembly, provide lower manufacturing costs, provide space for additional functional components, increase manufacturing yield, and provide an improved augmented-reality experience due to the obstruction-free field of view and wide aperture.

[0059] The deformable bounding element may deform, flex and/or stretch in response to pressure from the deformable medium within an adjacent cavity. The deformable bounding element may be any element that, when deformed, changes at least one optical property of the optical lens assembly. For example, the deformable bounding element may be a flexible film. The optical properties may include accommodative properties, such as adjusting optical power, and/or adaptive properties, such as controlling, compensating, or correcting for wavefront errors, such as distortion and aberrations.

[0060] The deformable bounding element may have any of a variety of properties. For example, the deformable bounding element may be substantially optically clear. In some examples, as used herein, the term “substantially optically clear,” as applied to an element, may refer to an element capable of transmitting an image through the element. In various examples, an element that is “substantially optically clear” may be capable of transmitting about 70% or more of incident light, about 80% or more of incident light, about 85% or more of visible light, or about 90% or more of incident light.

[0061] The deformable bounding element may include any of a variety of materials. For example, the deformable bounding element may include one or more flexible materials that may be shaped in response to one or more applied forces. In some examples, the deformable bounding element may include one or more tensioned or non-tensioned linear elastic and hyper-elastic polymers (examples are silicones and thermoplastic polyurethane (TPU), etc.). The deformable bounding element may also be higher modulus polymers such as polyethylene terephthalate (PET), polyethylene naphthalate (PEN) or polyvinylidene fluoride (PVDF). Preferably, the deformable bounding element has a low creep. Higher modulus materials may also be used, such as glass,

crystals, and ceramics. In various examples, the deformable bounding element may have a Young's modulus of less than about 100 gigapascals (GPa), less than about 10 GPa, less than about 2 GPa, or less than about 1 GPa.

[0062] The structural support element may function as a backing for an optical lens assembly when the deformable bounding element is bonded to the structural support element. For example, the structural support element may form a backing of a deformable medium cavity, a deformable bounding element and a deformable medium to form the optical lens assembly shown in FIGS. 2A and 2B. The structural support element may have any of a variety of properties. For example, the structural support element may be substantially optically clear.

[0063] The structural support element may include any of a variety of materials. For example, the structural support element may include glass, sapphire, acrylic, silica, ceramics, polycarbonates. In some examples, the structural support element may include optically clear, thin, and/or rigid substrates. In various examples, the structural support element may include flat or meniscus lens substrates. The structural support element may have a physical stress—strain curve that is linear or non-linear. The structural support element may have a rigidity sufficient to prevent the structural support element from substantially bending, deforming or changing shape during and/or after repeated cycles of deformation of the deformable bounding element due to pressure transmitted by the deformable medium within the cavity between the structural support element and the deformable bounding element.

[0064] In some examples, the composition of the structural support element material may be fairly uniform and may therefore provide a constant index of refraction throughout the material (e.g., in the range of 1.2 to 2.0). According to some examples, structural support element may be substantially flat, contributing no optical power to the optical lens assembly. In some examples, the structural support element may be shaped as a convex-concave or meniscus lens, in which one surface of the structural support element has a radius of curvature and the opposite side of the structural support element has a different radius of curvature. The difference in curvature between the two surfaces may thereby create a corrective power in the structural support element. The difference in curvature between the two surfaces may be constant, providing a constant optical power across the aperture of the structural support element, or the difference in the radius of curvature may be continuously variable across one or both of the surfaces (resulting in different optical powers being provided at different locations on the structural support element).

[0065] As described above, the deformable optical element may be filled with a deformable medium. The deformable medium may function as a medium that transfers pressure in a cavity to a deformable bounding element. The deformable medium may be substantially optically clear. The deformable medium may have a viscosity range of about 0.001 to 1 pascal-seconds which may allow the deformable medium to flow through or past the components used during the process of filling the cavity with the deformable medium. In addition, the viscosity of the deformable medium may allow the deformable medium to flow within the cavity during adjustment of the deformable optical element focusing. The deformable medium may transmit the pressure applied by actuation of the optical lens assembly

(e.g., by actuators on the perimeter of the optical lens assembly) to the deformable bounding element. The actuation may take any of a variety of forms, including, e.g., mechanical and/or electromechanical actuation.

[0066] The deformable medium may include any of a variety of materials. For example, the deformable medium may include water, glycerol, a gel, a polymer-gel, a foam, a polymer, silicone oil, phenyl silicone oil, or a combination thereof. In various examples, pressure applied to the deformable medium may propagate through the deformable medium, affecting a change in curvature of the deformable medium as contained by the deformable bounding element. For example, the deformable medium in the cavity may have a near constant volume and may transmit the pressure as a hydraulic pressure and thus may be an incompressible deformable medium. The viscosity of the deformable medium may allow the pressure to be transmitted quickly, resulting in low latency when adjusting the focal point. Alternatively, the deformable medium may be a gas, which may apply a pneumatic pressure to the deformable bounding element and thereby changes the curvature of the deformable bounding element (and, therefore, the focal point of the optical lens assembly). In some examples, the deformable medium may also include a liquid that extends the operating temperature range of the deformable optical element (e.g., ethylene glycol). In one example, assembling an ultra-thin optical lens assembly may include bonding a deformable bounding element to a structural support element. As mentioned above, the deformable bounding element and the structural support element may form a cavity in a space between the deformable bounding element and the structural support element when bonded together. As an example, the deformable bounding element and a cavity-adjacent side of the structural support element may define a cavity. The cavity-adjacent side of the structural support element may be a side which is adjacent to a cavity, gap, chamber or space formed between the deformable bounding element and the structural support element. The cavity-opposite side of the structural support element may be a side which is opposite to the cavity-adjacent side of the structural support element. As an example, the method of filling the cavity with a deformable medium may include injecting the deformable medium past a cavity-opposite side of the structural support element and toward the cavity-adjacent side of the structural support element.

[0067] As an example, the method of filling the cavity may include flowing or injecting the deformable medium from one side to another side of the substrate, laterally around a side of the substrate, from underneath the substrate to the top of the substrate and/or through a hole, void, channel, duct, groove, pipe, tube and/or slit in the substrate. The shape of the structural support element may be any of a variety of shapes, including, without limitation, substantially planar, biconvex, biconcave, plano-convex, plano-concave, positive meniscus, or negative meniscus.

[0068] After the cavity is filled with the deformable medium, the entry point of the injection of the deformable medium into the cavity may be sealed to contain the deformable medium in the cavity. As an example, the entry point of the injection of the deformable medium into the cavity may be a point on the side of the structural support element which is opposite the cavity, a point on the side of the structural support element adjacent to the cavity or a point on the perimeter or near the edge of the structural support element.

The entry point seal may prevent the deformable medium from leaking out of the cavity and may be capable of withstanding the hydraulic or pneumatic pressure of the deformable medium when the deformable bounding element is deformed.

[0069] Sealing the entry point may include bonding an edge face of the deformable bounding element which may be a side of the deformable bounding element along the perimeter of the deformable bounding element to an edge face of the structural support element which may be a side of the structural support element along the perimeter of the structural support element.

[0070] Before sealing the entry point, the method may include coating an edge of the structural support element with an adhesion promoting layer or primer which increases the strength of the seal. Sealing the entry point may include using adhesives, heat bonding, ultrasonic welding, a plug, an optically clear sealant, and/or a cement compatible with the material of the structural support element. Sealing the entry point between the edge of the deformable bounding element and the structural support element may include heat bonding or ultrasonic welding or adhesives (e.g., glue, paste, resin, sealant, cement, or epoxy) which are compatible with the materials used in the deformable bounding element and the structural support element. Additionally or alternatively, sealing the entry point in a hole in the structural support element may include inserting a plug into the hole.

[0071] FIG. 3 illustrates an example of an optical lens assembly fixtured within a deformable medium reservoir. As shown in FIG. 3, an optical lens assembly 300 may include a deformable medium reservoir 310, an edge face of a deformable bounding element 320, a gap 325, an edge face of a structural support element 326, a check valve 330, a structural support element 340, a deformable bounding element 350, a cavity 360 and an inlet 370. As an example, deformable bounding element 350 may be stretched, molded, and/or formed out of, for example, a thermoplastic polyurethane (TPU), and the edge of structural support element 340 may be optionally coated with an adhesion-promoting layer or treatment, for example, a TPU-based coating. Deformable bounding element 350 and structural support element 340 may be separately fixtured within deformable medium reservoir 310 to create gap 325 in at least one region between the edge face of structural support element 326 and the edge face of deformable bounding element 320. Deformable medium reservoir 310 may include any type of container, receptacle, basin, pan, bowl, or tub capable of fixturing deformable bounding element 350 and structural support element 340 and containing the deformable medium.

[0072] Pressurized deformable medium may enter deformable medium reservoir 310 through inlet 370. The deformable medium pressure may be generated from any suitable pressure source (e.g., a source of hydraulic or pneumatic pressure). For example, the pressure may be supplied via a pump for the deformable medium. The cavity of the deformable optical element may be filled from the cavity-opposite side of the substrate (i.e., a side of the substrate opposite to a side of the substrate adjacent to the cavity). The pressure of the deformable medium in deformable medium reservoir 310 may cause the deformable medium to flow through gap 325 in a direction from the cavity-opposite side of structural support element 340 to the cavity-adjacent side of structural support element 340. In

some examples, the deformable medium entering the cavity-adjacent side of structural support element **340** may displace air in cavity **360**, thereby causing an increase in air pressure in cavity **360**. The increase in air pressure in cavity **360** may cause the air to exhaust from cavity **360** through check valve **330**. Check valve **330** may be a device which operates as a one-way valve allowing a substance (e.g., air and/or the deformable medium) to exit cavity **360** but not enter cavity **360**. Check valve **330** may include any suitable valve mechanism including, without limitation, a spring-loaded ball check valve, a diaphragm check valve, a swing check valve, or a microelectromechanical (MEMS) check valve.

[0073] The deformable medium may continue to enter cavity **360** and displace the air, which may be exhausted through check valve **330**, until the air is completely evacuated from cavity **360**. The deformable medium filling operation may include the priming and operation of a diaphragm or deformable bounding element pump. Once cavity **360** is filled with deformable medium, pressure may be applied to the edge face of deformable bounding element **320**, in proximity to gap **325** and in a direction towards the edge face of structural support element **326**, to form a seal between the edge face of deformable bounding element **320** and the edge face of structural support element **326**. The size of gap **325** may be designed to minimize deformation to the edge face of deformable bounding element **320** during pressure contact while preventing capillary effects or action on the deformable medium during the filling process. In some examples, capillary effects on the deformable medium may occur due to intermolecular forces between the deformable medium and the solid surfaces surrounding the gap. If the diameter of the gap is sufficiently small, then the combination of surface tension (which is caused by cohesion within the deformable medium) and adhesive forces between the deformable medium and the surfaces surrounding the gap act to propel the deformable medium. Accordingly, in some examples, the gap may be sized sufficiently to prevent or reduce capillary action. The seal between the edge face of deformable bounding element **320** and the edge face of structural support element **326** may be formed with heat bonding, adhesives, or ultrasonic welding.

[0074] FIG. 4 provides a partial view of an example optical lens assembly with a force distributor adhered to a hole in a deformable bounding element. As shown in FIG. 4, an optical lens assembly **400** may include a structural support element **410**, an edge seal **420**, a force distributor **430**, a deformable bounding element **440**, and a cavity **450**. In some examples, FIG. 4 shows a partial view of optical lens assembly **400** after the process described with respect to FIG. 3 is complete. Edge seal **420** formed between structural support element **410** and deformable bounding element **440** encapsulates cavity **450**. The check valve may be removed from deformable bounding element **440** and the hole left in deformable bounding element **440** caused by the removal of the check valve may be plugged by adhering force distributor **430** to the hole. Force distributor **430** may be adhered to deformable bounding element **440** using any suitable method, including, without limitation, adhesives, heat bonding, ultrasonic bonding, mechanical locking and/or adherence, or anodic bonding. The optical lens assembly formed by the above described method may be seamless as edge seal **420** may be uniform along the perimeter of structural support element **410**. There may be minimal and non-visible

obstruction where the check valve was removed from the hole in structural support element **410** and is obscured by force distributor **430**.

[0075] FIG. 5 provides a partial view of an example optical lens assembly with a filling tube inserted between a deformable bounding element and a structural support element. As shown in FIG. 5, an optical lens assembly **500** may include a structural support element **510**, an edge seal **520**, a fill tube **530**, a force distributor **540**, a deformable bounding element **550**, and a cavity **560**. FIG. 5 shows a partial view of an optical lens assembly **500** produced by a method which may include an edge seal filling process that may be used to create deformable optical element assemblies **100** and **200**. Similar to the method described with respect to FIG. 3, deformable bounding element **550** may be stretched, molded, and/or formed out of thermoplastic polyurethane (TPU) and the edge of structural support element **510** may be coated with TPU-based coating. Force distributor **540** may be adhered to deformable bounding element **550** before or after filling cavity **560**.

[0076] A notched or non-uniform compressive strength fill tube **530** or needle may be inserted at the interface between deformable bounding element **550** and structural support element **510**. The assembly may be heated to form a sealing bond between deformable bounding element **550** and structural support element **510**. Fill tube **530** may be any device capable of transporting the deformable medium from a deformable medium source into cavity **560**. Examples of fill tube **560** include, without limitation, a tube, a duct, a pipe, a hose, an instrument, a needle, a cylinder, or a channel which acts as a conduit for transporting the deformable medium into cavity **560**. Cavity **560** may be filled by injecting the deformable medium through fill tube **530** at the interface between deformable bounding element **550** and structural support element **510**. When the assembly has reached a set temperature and after cavity **560** is filled with deformable medium, pressure may be applied to fill tube **530** in a direction perpendicular to a major axis of fill tube **530** (e.g., a force applied to fill tube **530** may include a component that is perpendicular to the major axis of fill tube **530**). The applied pressure may thereby cause fill tube **530** to fracture, shear, or break at the notch on fill tube **530** or the region of lowest compressive strength on fill tube **530**. The applied pressure may then cause a portion of the edge of deformable bounding element **550** near the point of insertion of fill tube **530** to contact the adhesive along the edge of structural support element **510** forming edge seal **520**. The seal may be formed via heat bonding of the adhesive or through any of the above-mentioned methods.

[0077] In FIG. 5, a partial view of optical lens assembly **500** near fill tube **530** insertion point is shown after a portion of the edge of deformable bounding element **550** is sealed to the edge of structural support element **510**. The applied perpendicular pressure and heat bonding of the adhesive forms edge seal **520** under fractured fill tube **530**. A portion of fractured fill tube **530** and deformable medium in cavity **560** may be sealed between the edge of structural support element **510** and deformable bounding element **550**. Adhering force distributor **540** to an outer surface of deformable bounding element **550** may further augment the optical lens assembly.

[0078] FIG. 6 provides a partial view of an optical lens assembly with a hole in a structural support element. As shown in FIG. 6, an optical lens assembly **600** may include

a structural support element **610**, a hole **620**, an edge seal **630**, a force distributor **640**, a deformable bounding element **650**, and a cavity **660**. FIG. 6 shows a partial view of an optical lens assembly **600** produced by a method which introduces minimal obstruction. The deformable medium filling and sealing process may be performed on an empty, pre-sealed cavity **660** through a perimeter region of optical lens assembly **600** along a frame bezel (not shown) that may be obscured by elements of the optical lens assembly frame or other structural assembly elements.

[0079] FIG. 6 provides a partial view of optical lens assembly **600** after filling the deformable medium through hole **620**. Hole **620** in structural support element **610** may be etched or cut into a perimeter region of structural support element **610**. Structural support element **610** and deformable bounding element **650** may be pre-sealed along edge seal **630** using adhesives, heat bonding or ultrasonic welding. Hole **620** may be disposed beneath force distributor **640** and is therefore not visible in optical lens assembly **600**. A tube, needle or other suitable filling device may be inserted in hole **620** and the deformable medium may be injected into cavity **660** until cavity **660** is filled. After cavity **660** is filled, the tube, needle or other suitable filling device may be removed from hole **620** and hole **620** may be sealed (e.g., with a plug, an optically clear sealant, or cement compatible with the material of structural support element **610**).

[0080] FIG. 7 provides a partial view of an example optical lens assembly with a hole in a structural support element and a deformable bounding element with a pre-formed cavity. As shown in FIG. 7, an optical lens assembly **700** may include a structural support element **710**, a hole **720**, a first portion of a deformable bounding element **730**, an edge seal **735**, a force distributor **740**, a second portion of a deformable bounding element **750**, and a cavity **760**. FIG. 7 shows a partial view of an optical lens assembly **700** produced by a method which introduces minimal obstruction. The first portion of deformable bounding element **730** may be pre-formed to produce cavity **760**. Cavity **760** may be formed into a shape capable of containing the deformable medium. Cavity **760** may be formed by injection molding, compression molding, thermoforming, rotational molding, blow molding or film insert molding. The first portion of deformable bounding element **730** formed into cavity **760** may be bonded to the cavity-adjacent surface of structural support element **710**. The first portion of deformable bounding element **730** may be bonded to structural support element **710** using adhesives, heat bonding, ultrasonic bonding, or anodic bonding. Hole **720** may be etched or cut through a perimeter region of structural support element **710** and the first portion of deformable bounding element **730** thereby creating an entry point for the deformable medium to be injected into cavity **760**. Hole **720** may be cut in any suitable manner (e.g., using a drill, a hot knife, a router, liquid pressure, pneumatic press, ultrasonic cutting, or a laser). The second portion of deformable bounding element **750** may be bonded to the first portion of deformable bounding element **730** on the perimeter edge surfaces of the first and second portions forming edge seal **735** and thereby sealing cavity **760**. The bonding of the surfaces may be performed in any suitable manner (e.g., via compression, ultrasonic welding, adhesives, heat, or anodic bonding). Excess material on the outer perimeter of deformable bounding element **730** created during the bonding process may be trimmed using a knife blade, laser cutting, ultrasonic cutting or die cutting.

[0081] Hole **720** may be disposed beneath force distributor **740** and may not be visible in optical lens assembly **700**. A tube, needle, or other suitable filling device as described above with respect to FIG. 5 may be inserted in hole **720** and the deformable medium may be injected into cavity **760** until cavity **760** is filled. After cavity **760** is filled, hole **720** may be sealed with a plug, an optically clear sealant, or cement compatible with the material of structural support element **710**. Force distributor **740** may be adhered to a cavity-opposite side of the second portion of deformable bounding element **750**.

[0082] FIG. 8 provides a partial view of an optical lens assembly with a hole in a structural support element and a deformable bounding element sealed by a crimped force distribution ring. As shown in FIG. 8, an optical lens assembly **800** may include a structural support element **810**, a hole **820**, a first portion of a deformable bounding element **830**, a force distributor **840**, a second portion of a deformable bounding element **850**, and a cavity **860**. As will be explained in greater detail below, optical lens assembly **800**, as shown in FIG. 8, may be produced by a method which introduces minimal obstruction. The first portion of deformable bounding element **830** may be pre-formed to produce cavity **860**. The first portion of deformable bounding element **830** may be bonded to the cavity-adjacent surface of structural support element **810**. Hole **820** may be etched or cut through a perimeter region of structural support element **810** and the first portion of deformable bounding element **830** thereby creating an entry point for the deformable medium to be injected into cavity **860**. Force distribution ring **840** may be adhered to the second portion of deformable bounding element **850**. The second portion of deformable bounding element **850** may be bonded to the first portion of deformable bounding element **830** on the perimeter edge surfaces of the first and second portions by applying a compression force to a portion of force distribution ring **840** thereby crimping the first and second portions together and forming the edge seal which creates sealed cavity **860**. A tube, needle, or other suitable filling device as described above with respect to FIG. 5 may be inserted in hole **820** and the deformable medium may be injected into cavity **860** until cavity **860** is filled. After cavity **860** is filled, hole **820** may be sealed with a plug, an optically clear sealant, or cement compatible with the material of structural support element **810**.

[0083] FIGS. 1-8 show methods and structures of a single optical lens assembly in which an actuator is interfaced with a force distributor that applies a force resulting in the deformable bounding element changing an optical power. In some examples, optical lens assemblies for a single eye of an HMD are shown in FIGS. 9 and 10 and represent an example of an application for the varifocal accommodation capability of the optical lens assembly.

[0084] As shown in FIGS. 9 and 10, respectively, optical lens apparatus **900** (or **1000**) of the HMD stack may consist of an RGB waveguide **930** (or **1030**) for the display, with two optical lens assemblies mounted on HMD frame **925** (or **1025**). One optical lens assembly may be positioned in front of the display and the second optical lens assembly may be positioned behind the display. The optical lens assembly positioned in front of the display and located nearest to eye **935** (or **1035**) may include a structural support element **950** (or **1050**), a deformable bounding element **910** (or **1010**) and a deformable-medium-filled cavity which may be actuated

through applied force and displacement at force distributor **920a** and **920b** (or **1020a** and **1020b**) to adjust the focus of the virtual image created by RGB waveguide **930** (or **1030**). The optical lens assembly behind RGB waveguide **930** (or **1030**) may include structural support element **945** (or **1045**), deformable bounding element **905** (or **1005**) and deformable medium filled cavity **911** (or **1011**) which may be simultaneously actuated by force distributor **915a** and **915b** (or **1015a** and **1015b**) to create a zero-power image of real world **940** (or **1040**).

[0085] As an example, in FIG. 9, optical lens apparatus **900** may include structural support elements **945** and **950** which include planar surfaces on both the cavity-adjacent side and the cavity-opposite side. The combination of optical lens apparatus **900** with additional components such as eye tracking element(s), an outer protective/anti-reflective lens, and corrective ophthalmic optics may be included in the functional elements of the HMD. Deformable bounding elements **905** and **910** of optical lens apparatus **900** may be coated with an anti-reflective treatment. The anti-reflective treatment may withstand repeated deformations without degradation, yield strain or yield failure. The anti-reflective treatment may be applied to the deformable bounding elements **905** and **910** using multiple methods including chemical vapor deposition, thermal evaporation and spin coating. The materials used to coat deformable bounding elements **905** and **910** which provide the anti-reflective properties may include various types of polymers and/or nanoparticles. The anti-reflective material may be applied to a pre-stretched or unstretched deformable bounding element during the coating process which may increase actuation speed when adjusting an optical focus. The anti-reflective material and the methods of applying the anti-reflective material may reduce production costs. Applying multiple layers of anti-reflective material, each having a different index of refraction between adjacent layers, results in an anti-reflective treatment which reduces unwanted reflected light from entering the optical lens assembly.

[0086] To adjust an optical focus, the adjustment mechanism may modify the optical power provided for an image originating from RGB waveguide **930** between deformable optical elements **905** and **910** without modifying the optical power provided for an image originating beyond deformable optical elements **905** and **910** (e.g., from a real-world object). In some examples, this may allow apparatuses and systems described herein to reduce, minimize, or eliminate accommodation-vergence conflict caused by augmented reality displays by modifying the apparent accommodation distance of images while minimizing any distortion to real-world images. Furthermore, in some examples, by using a single actuator to drive carriage element **925** connecting deformable optical elements **905** and **910**, these apparatuses and systems may reduce the amount of actuating force applied to deform deformable optical elements **905** and **910**. In addition, the use of a single adjustment mechanism may reduce the form factor, the cost of manufacture, and/or the potential points of failure of an optical lens assembly.

[0087] In some examples, carriage **925** may be driven by one or more actuators. For example, the actuator may include a mechanical or an electromechanical actuator. Examples of actuators that may drive carriage **925** may include, without limitation, a piezoelectric, an electroactive polymer, a piezo electric polymer, a dielectric elastomer, an electrostrictive polymer, a shape memory alloy, a voice coil,

a pneumatic actuator, an electromagnetic motor (e.g., a servo motor, a stepper motor, a DC motor, etc.), a hydraulic actuator, or a combination thereof. The actuator may be augmented with secondary passive actuators such as cams, springs, etc. to efficiently drive carriage **925**. The actuator may move carriage **925** in a radial direction which is defined as normal to a major plane of the optical lens assembly, axially which is defined as perpendicular to the radial direction, or a combination thereof. Each of the optical lens assemblies in the HMD may be simultaneously actuated or individually actuated.

[0088] In some examples, the actuator may be driven by a controller which measures the ambient and internal temperatures of the HMD and adjusts the speed of the actuators as a function of the ambient and internal temperatures.

[0089] As another example of multiple optical lens assemblies used in tandem, FIG. 10 illustrates an optical lens apparatus **1000** with structural support elements **1045** and **1050** that include non-planar surfaces on both the cavity-adjacent side and the cavity-opposite side. Accordingly, the description of FIG. 9 above may also apply to FIG. 10, with the exception that structural support elements **1045** and **1050** are non-planar (and may therefore, e.g., provide a corrective optical function and/or modify the range of optical power for viewing display **1030** achieved by adjusting the optical lens assemblies). In some examples, the structural support elements in optical lens apparatus **1000** may be functionally integrated with additional elements. For example, in the more integrated optical lens assembly **1000**, the structural support element may include an ophthalmic corrective optic and/or an eye tracking element. The curvature of structural support element **1045**, which may be furthest from eye **1035**, may result in improved anti-reflective properties and therefore may have a high optical quality as an outer protective lens element.

[0090] For realization of a sub-assembly with similar functionality to optical lens assembly **900**, structural support elements **1050** and **1045** may be zero power meniscus lens elements for improved anti-reflective properties and easier integration with non-planar optical eye tracking and/or ophthalmic optical elements at structural support element **1050**.

[0091] FIG. 11 shows an HMD **1100** which may include the deformable optical element and RGB waveguide assemblies **900** and/or **1000** integrated into eye piece **1120** and mounted within bezel **1110**. Any features or defects related to the filling and/or sealing of the deformable optical element assemblies during the filling and sealing process may be located within bezel **1110** area and therefore may not be visible through clear aperture of eye piece **1120**. For example, the ratio of a clear aperture area of the eye piece **1120** to an overall surface area of the deformable optical element may be at least about 70 percent, at least about 75 percent, at least about 80 percent, at least about 85 percent, at least about 90 percent, or at least about 95 percent.

[0092] FIG. 12 shows a flow diagram of an example method **1200** for filling and sealing an optical lens assembly using a reservoir as described herein. As shown in FIG. 12, the method may include, at step **1210**, bonding a deformable bounding element to a structural support element. At step **1220**, the method may include filling a cavity defined by a cavity-adjacent side of the structural support element and the deformable bounding element with a deformable medium by injecting the deformable medium past a cavity-opposite side of the structural support element and toward the cavity-

adjacent side of the structural support element. At step **1230**, the method may include filling a reservoir disposed on the cavity-opposite side of the structural support element with the deformable medium. At step **1240**, the method may include pressurizing the deformable medium in the reservoir, thereby causing the deformable medium to flow into the cavity through a gap defined by edge faces of the structural support element and the deformable bounding element. In some examples, a major plane of each of the reservoir, the structural support element, and the deformable bounding element may be substantially parallel to one another. At step **1250**, the method may include evacuating air in the cavity displaced by the deformable medium through a check valve disposed in the deformable bounding element having a portion defining a hole. At step **1260**, the method may include sealing an entry point of the injection of the deformable medium into the cavity and adhering a force distributor to the hole in the deformable bounding element.

[0093] FIG. **13** shows a flow diagram of an example method **1300** for filling and sealing an optical lens assembly using a fill tube as described herein. As shown in FIG. **13**, the method may include at step **1310**, bonding a deformable bounding element to a structural support element. At step **1320**, the method may include filling a cavity defined by a cavity-adjacent side of the structural support element and the deformable bounding element with a deformable medium by injecting the deformable medium past a cavity-opposite side of the structural support element and toward the cavity-adjacent side of the structural support element. At step **1330**, the method may include adhering a force distributor to the deformable bounding element. At step **1340**, the method may include inserting a tube between the deformable bounding element and an edge of the structural support element and injecting the deformable medium through the tube. At step **1350**, the method may include heating the deformable bounding element and the edge of the structural support element proximal to the tube. At step **1360**, the method may include applying pressure to the tube in a direction perpendicular to a major axis of the tube. At step **1370**, the method may include fracturing the tube and applying pressure to the deformable bounding element in a direction towards the edge of the structural support element sealing the entry point.

[0094] FIG. **14** shows a flow diagram of an example method **1400** for filling and sealing an optical lens assembly through a hole in a structural support element as described herein. As shown in FIG. **14**, the method may include at step **1410**, bonding a deformable bounding element to a structural support element. At step **1420**, the method may include filling a cavity defined by a cavity-adjacent side of the structural support element and the deformable bounding element with a deformable medium by injecting the deformable medium past a cavity-opposite side of the structural support element and toward the cavity-adjacent side of the structural support element. At step **1430**, the method may include adhering a force distributor to the deformable bounding element. At step **1440**, the method may include forming a hole defined in the structural support element. At step **1450**, the method may include injecting the deformable medium through the hole in the structural support element. At step **1460**, the method may include sealing the hole by inserting a plug in the hole, injecting an optically clear sealant in the hole or injecting a cement in the hole.

[0095] As described in detail above, the instant disclosure describes methods, systems, and apparatuses for fabricating ultra-thin, large-aperture optical lens assemblies. In some examples, the cavity of an optical lens assembly may be filled with a deformable medium from the cavity-opposite side of the substrate to the cavity-adjacent side of the substrate. In some examples, optical lens assemblies produced by the methods of the instant disclosure may provide a wide range of optical power, may have a wide aperture free from obstructions, and may be ultra-thin and lightweight. The optical lens assembly may also be interfaced or integrated with other components (i.e. ophthalmic lens, eye tracking, wave guides, etc.) in the AR/VR optical lens assembly. An HMD may incorporate the ultra-thin, large aperture optical lens assemblies resulting in a lighter weight and an aesthetically pleasing design.

[0096] Embodiments of the instant disclosure 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, e.g., 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, 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, e.g., 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.

[0097] The process parameters and sequence of the steps described and/or illustrated herein are given by way of example only and may be varied as desired. For example, while the steps illustrated and/or described herein may be shown or discussed in a particular order, these steps do not necessarily need to be performed in the order illustrated or discussed. The various exemplary methods described and/or illustrated herein may also omit one or more of the steps described or illustrated herein or include additional steps in addition to those disclosed.

[0098] The preceding description has been provided to enable others skilled in the art to best utilize various aspects of the exemplary embodiments disclosed herein. This exemplary description is not intended to be exhaustive or to be limited to any precise form disclosed. Many modifications and variations are possible without departing from the spirit and scope of the instant disclosure. The embodiments disclosed herein should be considered in all respects illustrative and not restrictive. Reference should be made to the appended claims and their equivalents in determining the scope of the instant disclosure.

[0099] Unless otherwise noted, the terms “connected to” and “coupled to” (and their derivatives), as used in the

specification and claims, are to be construed as permitting both direct and indirect (i.e., via other elements or components) connection. In addition, the terms “a” or “an,” as used in the specification and claims, are to be construed as meaning “at least one of.” Finally, for ease of use, the terms “including” and “having” (and their derivatives), as used in the specification and claims, are interchangeable with and have the same meaning as the word “comprising.”

1. An apparatus comprising:
an optical lens assembly having a thickness less than three millimeters, wherein the optical lens assembly comprises:
a deformable bounding element bonded to a structural support element; and
a deformable medium disposed between the deformable bounding element and the structural support element.
2. The apparatus of claim 1, further comprising:
a force distributor adhered to the deformable bounding element, wherein the force distributor distributes a force applied by an actuator to a perimeter edge of the deformable bounding element thereby altering the shape of the optical lens assembly and the optical power of the optical lens assembly.
3. A system comprising:
a head-mounted device comprising a pair of optical lens assemblies, wherein each of the optical lens assemblies has a thickness of less than three millimeters and comprises:
a deformable bounding element bonded to a structural support element; and
a deformable medium disposed between the deformable bounding element and the structural support element.
4. The system of claim 3, wherein:
the head mounted device further comprises a bezel;
the optical lens assemblies are mounted in the bezel; and
the deformable medium is injected through an entry point within a bezel-mounting area, thereby reducing obstruction of the optical lens assemblies.
5. The system of claim 4, wherein the ratio of a clear aperture area of the optical lens assemblies to an overall surface area of the optical lens assemblies is greater than 75 percent.
6. The system of claim 3, wherein each of the optical lens assemblies has a thickness of less than two millimeters.
7. The system of claim 3, wherein each of the optical lens assemblies further comprises a force distributor coupled to a perimeter region of the deformable bounding element, the force distributor being configured to distribute a force from an external actuation mechanism to the deformable bounding element.
8. The system of claim 7, wherein the force distributor covers at least one hole in the deformable bounding element.
9. The system of claim 3, wherein:
the pair of optical lens assemblies comprises a right proximal optical lens assembly and a left proximal optical lens assembly; and

the head-mounted device further comprises:

- a right waveguide positioned adjacent to the right proximal optical lens assembly in a position to be viewed by a user through the right proximal optical lens assembly; and
- a left waveguide positioned adjacent to the left proximal optical lens assembly in a position to be viewed by the user through the left proximal optical lens assembly.
10. The system of claim 9, the head-mounted device further comprises:
a right distal optical lens assembly positioned an opposite side of the right waveguide relative to the right proximal optical lens assembly; and
a left distal optical lens assembly positioned an opposite side of the right left relative to the left proximal optical lens assembly.
11. The system of claim 10, wherein each of the right distal optical lens assembly and the left distal optical lens assembly has a thickness of less than three millimeters.
12. The system of claim 3, wherein the head-mounted device has an eyeglass form factor.
13. The apparatus of claim 1, wherein the structural support element comprises a substantially flat element that contributes substantially no optical power to the optical lens assembly.
14. The apparatus of claim 1, wherein the structural support element comprises an ophthalmic substrate that contributes an optical power to the optical lens assembly.
15. The apparatus of claim 1, wherein the thickness of the optical lens assembly is measured as a distance from a center of an outer surface of the deformable bounding element to a side surface of the structural support element adjacent to the deformable medium when the optical lens assembly is in an undeformed state.
16. The apparatus of claim 1, wherein the deformable bounding element is configured to transmit about 70% or more of incident light.
17. The apparatus of claim 1, wherein the optical lens assembly comprises an entry point seal blocking a hole in the structural support element used for introducing the deformable medium between the deformable bounding element and the structural support element.
18. The apparatus of claim 1, wherein 1 the optical lens assembly comprises an entry point seal blocking an entry point between an edge face of the structural support element and the deformable bounding element, wherein the entry point is used for introducing the deformable medium between the deformable bounding element and the structural support element.
19. The apparatus of claim 1, wherein the deformable bounding element comprises:
a first portion of the deformable bounding element bonded to the structural support element; and
a second portion of the deformable bounding element coupled to a perimeter region of the first portion of the deformable element, forming an edge seal between the first portion and second portion of the deformable bounding element.
20. The apparatus of claim 19, wherein the first portion and second portion of the deformable bounding element are coupled to each other with a crimped force distribution ring.

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