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# 1 APERTURE SYSTEM FOR PRECERAMIC POLYMER STEREOLITHOGRAPHY

## FIELD

5 [0001] The present disclosure relates generally to polymer stereolithography, and more specifically to an aperture system and device for stereolithography of polymers with high inorganic content.

## BACKGROUND

10 [0002] Additive manufacturing (AM) using stereolithography or three-dimensional (3D) printing of photopolymer resins is of widespread interest as a method of producing structures or parts with complex geometries. These methods typically form a structure by sequentially depositing multiple layers or cross-sections of material in a vertical stack until a desired height and form are achieved.

15 [0003] In stereolithography, layers of solid material are typically formed by polymerizing corresponding liquid photopolymer resin layers held within a reservoir. The controlled transformation of such liquid to solid layers may be accomplished by exposing the resin to a radiation source (e.g. digital projector, laser, LED) capable of curing the resin, e.g., by initiating one or more polymerization reactions in the resin. The volume of liquid photopolymer resin positioned between the radiation source  
20 and the surface of a build platform or previously deposited layer polymerizes upon radiation exposure, thus forming a new layer of solid resin. The layers are stacked during polymerization to thereby form a three-dimensional solid material.

[0004] In a bottom up stereolithography approach, the liquid photopolymer resin held in the reservoir is exposed to a radiation source through a transparent aperture  
25 positioned in the bottom of the reservoir. A build platform or previously deposited layer of material is positioned at a pre-set distance from the aperture, and a layer of solid resin is created between the aperture and the bottom surface of the platform or part. The new solid layer is formed so that it directly contacts (e.g., is in direct contact with) the aperture at the bottom of the reservoir. The new solid layer is  
30 subsequently separated from the aperture, and the layer deposition process may be repeated.

[0005] The aperture used in a bottom-up stereolithography device typically includes a durable, transparent window made of a material such as glass, polyethylene terephthalate (PET), and/or poly(methyl methacrylate) (PMMA).  
35 However, these materials have high hardness values and may readily adhere to any cured resin that is directly deposited on the window. This adherence between the cured resin and the window may prevent or impede removal of the cured photopolymer part, thus prematurely halting or slowing the deposition process.

1 Accordingly, the aperture of a bottom up stereolithography device may further  
include a compliant release layer positioned between the window and the resin to  
reduce adhesive bonding between the resin and the window, thereby avoiding or  
reducing damage associated with removal of adhered resin. Such compliant release  
5 layers are necessarily transparent to the radiation source, and often include silicones  
or fluorinated polymers.

**[0006]** However, such silicon- or fluorine-containing compliant release layers may  
be incompatible with high inorganic content preceramic photopolymer resins (such  
as silicon-containing photopolymer resins), which are desired for manufacturing of  
10 ceramic parts. Specifically, the silicon- or fluorine-containing compliant release layers  
may adhere strongly to the parts made of cured high inorganic content preceramic  
resin, thereby causing damage such as breaking or cracking in the cured part when  
force is applied to separate the part from the aperture. Accordingly, the use of high  
inorganic content preceramic photopolymer resins in additive manufacturing has  
15 been limited.

## SUMMARY

**[0007]** Aspects of embodiments of the present disclosure are directed toward a  
structure to be used in bottom-up stereolithography systems for additive  
20 manufacturing of photopolymer resins with high inorganic content.

**[0008]** Additional aspects will be set forth in part in the description which follows,  
and, in part, will be apparent from the description, or may be learned by practice of  
the presented embodiments.

**[0009]** According to embodiments of the present disclosure, an aperture for  
25 bottom-up stereolithography devices includes a reservoir having a lower opening; an  
aperture, the aperture including a flexible membrane positioned within the reservoir  
and covering the lower opening; and a boundary seal positioned around a periphery  
of the flexible membrane, the boundary seal comprising one or more boundary seal  
components and immobilizing the periphery of the flexible membrane against the  
30 reservoir.

**[0010]** The aperture may further include a transparent window under the flexible  
membrane and in the lower opening of the reservoir, the transparent window  
covering the lower opening; and a compliant release layer between the transparent  
window and the flexible membrane in the lower opening of the reservoir, the  
35 compliant release layer covering the lower opening and having a low affinity for the  
flexible membrane.

**[0011]** The flexible membrane may be configured to have a contact angle greater  
than about 40° with a resin used for stereolithography.

- 1 **[0012]** The flexible membrane may be configured to have an interlayer peel strength of less than about 200 N/m with a cured photopolymer resin part.
- [0013]** The flexible membrane may include polystyrene (PS), polymethylpentene (PMP), cyclic olefin copolymers (COC), fluorinated ethylene propylene (FEP),
- 5 **[0014]** The flexible membrane may have a thickness of about 10  $\mu\text{m}$  to about 750  $\mu\text{m}$ .
- [0015]** The boundary seal components may include a reversible mechanical attachment.
- 10 **[0016]** The reversible mechanical attachment may include a magnet having a magnetic force of about 5 lbs. to about 60 lbs.
- [0017]** The boundary seal components may include an epoxy adhesive, an acrylate adhesive, a silicone sealant, a urethane sealant, or a mixture thereof.
- [0018]** The boundary seal components may include a vacuum chuck to maintain
- 15 contact between the flexible membrane and the reservoir wall.
- [0019]** The boundary seal may extend to a height greater than the aperture within the reservoir and comprises a resin exchange feature.
- [0020]** The transparent window may include glass, polyethylene terephthalate (PET), biaxially-oriented polyethylene terephthalate (BOPET), polymethylpentene
- 20 (PMP), cyclic olefin copolymers (COC), polycarbonate, polymethylmethacrylate (PMMA), or a mixture thereof.
- [0021]** The transparent window may have a thickness of about 0.1 mm to about 16 mm.
- [0022]** The compliant release layer may include silicone, urethane, fluorinated
- 25 polymers, or a mixture thereof.
- [0023]** The compliant release layer may be a gas or fluid, the gas or fluid including air, water, an alcohol, an oil, a resin without a photoinitiator component, or a mixture thereof.
- [0024]** The compliant release layer may have a thickness of about 0.1 mm to
- 30 about 13 mm.
- [0025]** The aperture may further include a transparent window under the flexible membrane, wherein the flexible membrane and the transparent window are integrated and included in the lower opening as a single body without a compliant release layer therebetween.
- 35 **[0026]** The flexible membrane may be suspended above an exposure source under tension without a compliant release layer or a window under the flexible membrane.

1 [0027] The aperture may further include a volume of gas or liquid between the flexible membrane and the compliant release layer. The gas or liquid between the flexible membrane and the compliant release layer may include air, water, an alcohol, an oil, a resin without a photoinitiator component, or a mixture thereof.

5 [0028] The compliant release layer and the transparent window may be integrated and included in the aperture as a single body.

[0029] According to embodiments of the present disclosure, a stereolithography device includes: a build platform; a reservoir positioned below the build platform so that the build platform can be lowered into or raised out of the reservoir; an aperture positioned within and covering at least a portion of a bottom of the reservoir; and an exposure source positioned below the reservoir and configured to emit a light that passes through the aperture; wherein the aperture includes a flexible membrane and a boundary seal positioned around a periphery of the flexible membrane, the boundary seal comprising one or more boundary seal components and immobilizing the periphery of the flexible membrane against the reservoir. The aperture may further include one or more of the following: a transparent window under the flexible membrane and in the lower opening of the reservoir, the transparent window covering the lower opening; and a compliant release layer between the transparent window and the flexible membrane in the lower opening of the reservoir, the compliant release layer covering the lower opening and having a low affinity for the flexible membrane.

## BRIEF DESCRIPTION OF THE DRAWINGS

25 [0030] These and other features and advantages of embodiments of the present disclosure will become more apparent by reference to the following detailed description when considered in conjunction with the following drawings, in which:

[0031] FIG. 1 is a schematic cross-sectional view of a simplified bottom-up stereolithography apparatus, in which a reservoir containing liquid photopolymer resin is exposed to a light output via a transparent window on the bottom of the reservoir;

[0032] FIG. 2 is a schematic cross-sectional view of a bottom-up stereolithography apparatus, in which a compliant release layer is positioned on the transparent window in order to facilitate separation of the cured photopolymer resin (part) from the aperture;

35 [0033] FIG. 3 is a schematic diagram illustrating the contact angle measured for droplets with varying degrees of attraction to a surface.

1 **[0034]** FIG. 4 is a cross-sectional view of an example aperture system including a reservoir, a boundary seal, a flexible membrane, a compliant release layer, and a transparent window, according to embodiments of the present disclosure;

5 **[0035]** FIG. 5 is a schematic cross-sectional view of an example aperture system including only a reservoir, a boundary seal, and a flexible membrane, according to embodiments of the present disclosure;

10 **[0036]** FIG. 6 is a schematic cross-sectional view illustrating the mixed mode separation and release that occurs when the cured photopolymer resin is removed from interfacial contact with the flexible membrane, according to embodiments of the present disclosure;

15 **[0037]** FIG. 7A and FIG. 7B are schematic cross-sectional views illustrating example aperture systems in which (A) a vacuum or (B) a fluid or liquid is present at the interface between the flexible membrane and the compliant release layer during separation and release of the cured photopolymer resin, according to embodiments of the present disclosure;

20 **[0038]** FIG. 8 is a schematic cross-sectional view of an example aperture system in which a sweeper arm is included to facilitate cleaning and repositioning of the flexible membrane following separation and release of the cured photopolymer resin, according to embodiments of the present disclosure;

25 **[0039]** FIG. 9 is a partial schematic cross-sectional view of an example aperture system in which the upper surface of the aperture extends into the liquid photopolymer resin reservoir, and the boundary seal shown in FIG. 3 is replaced by a magnetic clamp with resin exchange features, according to embodiments of the present disclosure;

30 **[0040]** FIG. 10 is a partial schematic cross-sectional view of an example aperture system including a permanent sealant as a boundary seal, in which the upper surface of the aperture shown in FIG. 3 is flush with the lower boundary of the liquid photopolymer resin reservoir, according to embodiments of the present disclosure; and

35 **[0041]** FIG. 11 is a partial schematic cross-sectional view of an example aperture system in which the compliant release layer and the transparent window are combined into a compliant window that is held in place with the flexible membrane by a mechanical attachment boundary seal, according to embodiments of the present disclosure.

## DETAILED DESCRIPTION

**[0042]** In the following detailed description, only certain example embodiments of the subject matter of the present disclosure are shown and described, by way of

1 illustration. As those skilled in the art would recognize, the subject matter of the present disclosure may be embodied in many different forms and should not be construed as being limited to the embodiments set forth herein.

5 **[0043]** In the context of the present application, when a first element is referred to as being "on", "coupled to", or "connected to" a second element, it can be directly on, directly coupled to, or directly connected to the second element, or be indirectly on, indirectly coupled to, or indirectly connected to the second element with one or more intervening elements interposed therebetween. Like reference numerals designate like elements throughout the specification. The thicknesses of layers, films, panels, 10 regions, etc., may be exaggerated in the drawings for clarity. The drawings are not necessarily drawn to scale.

**[0044]** Aspects of embodiments of the present disclosure are directed toward an aperture system and a device including the aperture system to be used in stereolithography of photopolymer resins, including high inorganic content 15 preceramic photopolymer resins. In some embodiments, the aperture system may be included in any commercially available bottom-up stereolithography device to improve the device's versatility and compatibility with high inorganic content preceramic photopolymer resins.

**[0045]** As used herein, the term "photopolymer resin" may refer to: 1) a liquid 20 solution or mixture including one or more monomers, oligomers, and/or crosslinkers that may be polymerized or "cured" to form a solid polymer network upon exposure to light radiation of a suitable wavelength (e.g., UV light); and/or 2) a solid or semi-solid product formed upon polymerization or partial polymerization of the liquid solution or mixture including one or more monomers, oligomers, and/or crosslinkers. 25 In the context of additive manufacturing via stereolithography and/or 3D printing, the liquid, uncured "photopolymer resin" may also be referred to as a "photopolymer ink". Terms such as "cured resin" and "cured photopolymer", etc. may be interchangeably used herein to refer to the solid polymer or printed structure, and to distinguish the cured solid polymer/structure from the liquid, uncured photopolymer resin or ink. 30 However, it will be understood that references to the photopolymer resin, cured resin, or simply the/a "resin" may encompass one or both of the cured and uncured states, and a person of skill in the art is capable of determining the relevant state(s) of the material based on context.

**[0046]** As used herein, the term "preceramic" refers to a material that can be 35 heated, pyrolyzed, and/or oxidized at an elevated temperature (e.g., above 200 °C, for example about 200 °C to about 1,000 °C, or about 500°C to about 1,000 °C) to thereby produce a ceramic material. As used herein, the term "ceramic" refers to an inorganic (e.g., non-organic) and non-metallic solid comprising a network of metal,

1 non-metal, and/or metalloid atoms held together via ionic and/or covalent bonds. Ceramic materials may be crystalline, semi-crystalline, or amorphous. Non-limiting examples of ceramic materials include metal oxides, boride, carbides, and nitrides, such as silicon carbide, silicon nitride, zirconium oxide, and/or the like.

5 **[0047]** As used herein to describe a photopolymer resin, the term “high inorganic content” refers to a preceramic material including inorganic atoms, at least a portion of which may be retained upon conversion of the preceramic material to a ceramic material. In some embodiments, greater than about 40% of the mass of the preceramic material may be inorganic and retained upon conversion, for example, 10 about 45% to about 95%, or about 55% to about 80%. In some embodiments, the inorganic content may include silicon (Si) atoms, for example, when the preceramic photopolymer resin or one of its components is based on a derivative of siloxane, silazane, carborane, etc., and/or when the preceramic is used to produce a ceramic material such as silicon carbide (SiC), silicon carbonitride (SiCN), silicon oxycarbide 15 (SiOC), silicon oxycarbonitride (SiOCN), silicon carboboride (SiCB), etc. However, embodiments of the present disclosure are not limited thereto, and other suitable photopolymer resin compositions, e.g., compositions including other inorganic atoms in addition to or in place of Si, are expressly included within the scope of the present disclosure.

20 **[0048]** In some embodiments, the inorganic content may be present as a major component or as a primary component. As used herein, the term “major component” refers to a component that is present in a composition, polymer, or product in an amount greater than an amount of any other single component in the composition or product. In contrast, the term “primary component” refers to a component that makes 25 up at least 50% (wt% or at%) or more of the composition, polymer, or product. However, it will be understood that the Si component may be included in any amount; for example, as a minor component (e.g., in an amount less than that of other materials included in the component), and the practical definition of “high” refers to any amount of inorganic material that causes the photopolymer resin or 30 cured resin to detrimentally adhere to a compliant release layer including silicone-based or fluorinated materials, as will be described herein.

**[0049]** In stereolithography and 3D printing, parts are manufactured *via* layer by layer deposition of a material on a build platform. In stereolithography, the material to be deposited is typically employed as a reservoir of liquid photopolymer resin. Thin 35 layers of the liquid photopolymer resin may be polymerized (e.g., cured) and deposited on the build platform when the liquid resin is exposed to radiation (e.g., light) having a suitable wavelength, for example, UV light. Stereolithography systems can be classified as top-down or bottom-up systems, depending on whether the

1 exposure source is applied from above or below the reservoir, respectively. When the stereolithography system is a bottom-up system, the reservoir should include a transparent aperture to allow the radiation (light) to be transmitted into the liquid photopolymer resin.

5 **[0050]** As used herein, the term “transparent” refers to an ability to transmit radiation (e.g., light) without detrimental amounts of absorption or scattering, and in this context may specifically refer to light having a wavelength in the ultraviolet (UV) range, e.g., between about 200 nm to about 460 nm. The term may refer to transmission of any wavelength (e.g., all wavelengths) falling in this range, or at least  
10 one discrete wavelength within the range. However, embodiments of the present disclosure are not limited thereto, and it will be understood that a person of ordinary skill in the art should be able to select other suitable radiation sources, wavelengths, and transparency characteristics according to the principles described herein.

**[0051]** As used herein, the term “aperture” may refer to a group of one or more  
15 components positioned between the photopolymer resin and the exposure source that facilitate transmission of light output into the photopolymer resin, whereas the term “aperture system” may include additional parts that do not directly participate in light transmission, but may provide other features such as physical support for the parts that directly participate in light transmission. The aperture or aperture system,  
20 as well one or more parts included therein, may be transparent to allow transmission of light into the photopolymer resin, even when not explicitly described as being transparent.

**[0052]** FIG. 1 shows a schematic cross-sectional view of a simplified bottom-up stereolithography system. The system uses an ultraviolet (UV) light output **1** as the  
25 polymerizing radiation, which is produced by an exposure source **2** located below an opaque reservoir **3**. The light output is transmitted through a transparent aperture **4** into a liquid photopolymer resin **5** held within the opaque reservoir so that a layer of the resin adjacent to the aperture may be cured. The aperture may include one or more layers, pieces, or parts, and in some embodiments, may be capable of  
30 disassembly and/or may include disposable and/or replaceable parts, as described below.

**[0053]** In FIG. 1 and the remaining drawings, the entire cross-section of the reservoir **3** is not fully depicted. Instead, the drawings show only a portion of the  
35 bottom floor surrounding the aperture system. However, it will be understood that the reservoir may have any suitable shape, volume, floor area, wall height, etc., as long as the reservoir is configured to accommodate a flat-bottomed aperture system and to hold a volume of liquid resin sufficient for forming at least one cured resin layer.

1 **[0054]** FIG. 2 shows a schematic cross-sectional diagram of a part being  
produced in a typical bottom-up stereolithography system and process. As similarly  
described in FIG. 1, an ultraviolet (UV) light output **1** is produced by an exposure  
source **2** located below an opaque reservoir **3**. The light output is transmitted through  
5 an aperture **4** into a liquid photopolymer resin **5**. A mobile (e.g., movable) build  
platform **6** is provided as a surface or anchor for deposition of a cured photopolymer  
part **7**. In the embodiments described by FIG. 2, the aperture **4** includes a window **8**  
and a compliant release layer **9** on the window **8** (e.g., between the window and the  
liquid photopolymer resin, and/or the window and the cured photopolymer part). The  
10 window and compliant release layer are described in more detail below.

**[0055]** During each deposition of a cured resin layer, the build platform **6** is  
submerged in the liquid photopolymer resin so that the lower surface of the build  
platform and/or the cured photopolymer part **7** attached to the build platform are  
positioned at a suitable distance from the aperture, the distance including a layer of  
15 liquid photopolymer resin with a thickness corresponding to the desired thickness of  
the next cured resin layer. In block **10**, the layer of liquid photopolymer resin  
positioned between the lower facing surface of the build platform or cured  
photopolymer part **7** and the upper facing surface of the aperture **4** is exposed to the  
light output **1** being transmitted through the aperture **4**. The layer of liquid  
20 photopolymer resin is thereby polymerized onto the bottom of the build platform **6** or  
cured photopolymer part **7**. The resulting cumulative cured photopolymer part **7** is  
formed between and adjacent to both the build platform **6** and the aperture **4**.

**[0056]** In block **11**, the build platform moves upward (e.g., away from the  
aperture) to separate the cured photopolymer part from the aperture (e.g., "lift off  
25 from aperture"). The displacement of the build platform enables ingress (e.g.,  
formation) of a new layer of liquid photopolymer resin between the cured  
photopolymer part and the transparent aperture. The new layer of liquid  
photopolymer resin may then be cured in the same manner as above.

**[0057]** A low degree of adhesion (e.g., low adhesive strength) between the  
30 transparent aperture **4** and the photopolymer resin **5** and/or cured resin part **7** is  
associated with a high degree of resolution in the photopolymer parts produced by  
the stereolithography system. For example, a low degree of adhesion facilitates easy  
removal of the cured photopolymer part **7** after each deposition process, such that  
the cured photopolymer part is subjected to minimal force and/or strain upon  
35 separation from the aperture **4**. The degree of adhesion determines or affects the  
size and/or number of successive layers that can be printed on (e.g., cured adjacent  
to) the aperture surface. When the cured photopolymer part **7** adheres to the  
aperture **4**, attempts to remove the photopolymer part from the aperture may result in

1 cohesive failure (e.g., breakage or cracking) of the part, at or prior to which point the aperture should be replaced. In some situations, a gradual increase in adhesion between the cured photopolymer part and the aperture as subsequent layers are deposited and removed may limit the usable lifetime of the aperture.

5 **[0058]** In some embodiments, the aperture **4** may include a window **8**. The window may be formed of a material (such as glass, PET, and/or PMMA) that is transparent to UV light and rigid enough to serve as a stable reservoir bottom. However, such materials often have affinity for (e.g., a tendency to adhere to) the cured and/or uncured preceramic photopolymer, and accordingly, windows formed of  
10 these materials may readily adhere to the cured photopolymer part once formed. Such adhesion between the cured photopolymer part **7** and the window **8** may interfere with removal of the part, which may crack or experience other structural damage when the part is separated from the aperture.

**[0059]** Accordingly, in some embodiments, the aperture **4** may further include a  
15 compliant release layer **9** (as shown in FIG. 2). The compliant release layer **9** promotes adhesive failure at the interface between the cured photopolymer part and the aperture system when a force is applied to separate the part from the aperture system. As used herein, the term “compliant release layer” may be interchangeably used with the terms “compliant membrane”, “release film”, and “interface layer” to  
20 refer to a layer having the function of reducing adhesion at the interface between the cured photopolymer resin and the transparent aperture system. Here, the adjective “compliant” is used to describe the material properties of the layer (e.g., that the layer is flexible), while the term “release” refers to the ability of the layer to encourage release of the cured photopolymer resin from the interface with the  
25 aperture system. The compliant release layer may be formed of a UV-transparent material. Typical compliant release layers **9** in the related art include UV-transparent polymers such as silicones or fluorinated polymers, for example, PDMS and PTFE.

**[0060]** Commercially available examples of bottom-up stereolithography systems that incorporate a consumable UV-transparent compliant release layer include the  
30 FormLabs Form 1, Form 1+, and Form 2; Carbon M1, Autodesk Ember, B9 Creator, Sprint Ray MoonRay, and Kudo3D Titan lithography systems. In these systems, “consumable” refers to the fact that the compliant release layer should be periodically replaced as the compliant release layer degrades or is damaged during use. In some systems, for example, the Kudo3D Titan, the compliant release layer is  
35 included as a stack of disposable release films. The top-most release film that is in contact with the cured photopolymer resin part is removed and disposed of after completion of each part, thus preventing or reducing the need for replacement of the entire aperture system.

1     **[0061]**     The compliant release layers in these commercially available systems  
typically include silicones or fluorinated polymers, which are largely compatible with  
common organic photopolymer resins (e.g., acrylates, methacrylates, urethanes,  
epoxies, etc.) because the adhesive strength at the interface between the compliant  
5     release layer and these polymerized resins is about an order of magnitude lower  
than the interlaminar (internal layer) strength of the cured photopolymer resin part.  
However, compliant release layers including silicones or fluorinated polymers are  
often not suitable for use with high inorganic content photopolymer resins (for  
example, those containing silicon), because the shared silicon content tends to  
10    promote adhesion between the compliant release layer and the cured photopolymer  
part. Silicon-containing photopolymer resins are of particular interest for their ability  
to produce pre-ceramic polymer parts that may be pyrolyzed to produce a silicon-  
containing ceramic material. Such pre-ceramic polymer parts are highly fragile and  
prone to cohesive or internal breakage when adhered to a compliant release layer  
15    including silicones or fluorinated polymers. As such, the use of high inorganic  
content photopolymer resins and other resin compositions that produce fragile parts  
in stereolithography has been limited.

20    **[0062]**     Aspects of embodiments of the present disclosure provide an aperture  
system for a bottom-up stereolithography device. The aperture system may be  
suitable for use with high inorganic content photopolymer resins and other fragile  
resins.

25    **[0063]**     In some embodiments, the aperture system may include a reservoir having  
a lower opening, a flexible membrane positioned within the reservoir and covering  
the lower opening; and a boundary seal positioned around a periphery of the flexible  
membrane, the boundary seal including one or more boundary seal components and  
immobilizing the periphery of the flexible membrane against the reservoir wall. As  
used herein, the term "flexible membrane" refers to a part having a function different  
from that of the "compliant release layer" described above.

30    **[0064]**     In some embodiments, the aperture system may further include a  
transparent window under the flexible membrane and in the lower opening of the  
reservoir, the transparent window covering the lower opening. The aperture system  
may further include a compliant release layer between the transparent window and  
the flexible membrane in the lower opening of the reservoir, the compliant release  
layer covering the lower opening and having a low affinity for the flexible membrane.

35    **[0065]**     The reservoir may be formed of a durable material that does not transmit  
light (e.g., is not transparent) and is unlikely to react with the photopolymer resin or  
any solvent mixed with the photopolymer resin, such as a polycarbonate plastic, a  
metal, glass coated with an opaque coating, etc. The reservoir may have any

1 suitable shape, volume, floor area, wall height, etc., as long as the reservoir is configured to accommodate a flat-bottomed aperture system and to hold a volume of liquid resin sufficient for forming at least one cured resin layer. The reservoir has an opening in its bottom floor or wall that is configured to accommodate the aperture.

5 The aperture may span or substantially span the opening such that there are no gaps in the bottom of the reservoir through which the liquid photopolymer resin may leak. In some embodiments, the aperture or portions of the aperture may be embedded in the opening. The size and shape of the opening and aperture are not particularly limited, and may be similar to those presently used in commercial  
10 systems of the related art, or may be selected by one of ordinary skill in the art according to the desired maximum size (horizontal planar area or footprint) of the manufactured parts, stability of the reservoir, etc.

**[0066]** The flexible membrane may be configured to have any combination of layout, attachment design, material characteristics, etc., that allows the flexible  
15 membrane to be attached to the reservoir *via* the boundary seal and to flex or be deformed during use, as described in example embodiments herein. For example, the flexible membrane may be at least the same shape and size as the opening, and in some embodiments may have a size larger than the opening so that the flexible membrane partially overlaps with the walls of the reservoir around the opening.

20 **[0067]** In addition, the flexible membrane may be transparent to one or more wavelengths corresponding to the radiation wavelength(s) produced by a bottom-mounted exposure source and/or the wavelength(s) required to initiate polymerization of a liquid photopolymer resin held within the reservoir. For example, when the bottom-mounted exposure source produces UV radiation, the flexible  
25 membrane may be transparent to UV radiation between about 200 nm to about 460 nm, or at least one discrete wavelength between about 200 nm to about 460 nm having a suitable energy for polymerizing the resin.

**[0068]** The flexible membrane included in the aperture may be selected or configured to exhibit a low affinity for the photopolymer resin in its cured and uncured  
30 forms so that the part can be easily separated from the flexible membrane and is not prone to formation of a high surface area adhesive interface with the flexible membrane during polymerization. The flexible membrane may also be configured to exhibit a low affinity for any aperture components positioned below the flexible membrane so that the flexible membrane can be easily pulled apart (separated) from  
35 those components during removal of the cured photopolymer part from the flexible membrane. As used herein, the term "low affinity" refers to a degree of interlayer or intermolecular attraction, interlayer bonding, or interlayer adhesion that does not interfere with the functioning of the aperture over 100 or more photopolymerization

1 cycles, for example, 500 or more photopolymerization cycles or 1,000 or more photopolymerization cycles.

The affinity between the flexible membrane and the liquid (uncured) photopolymer resin may be described in terms of a contact angle. As used herein, the term  
5 “contact angle” is used in its art-recognized sense to refer to the angle between the floor and wall of a droplet of a test liquid on a test surface (e.g., the angle between a first vector parallel to the liquid-solid interface and a second vector normal to the outer surface of the droplet at and perpendicular to the perimeter of the liquid-solid interface) as a proxy for the amount of intermolecular attraction between the liquid  
10 and solid substances. FIG. 3 is a schematic diagram illustrating contact angles **14** measured for droplets **15** with varying degrees of attraction to a surface **16**. In some embodiments, for example, the flexible membrane may be configured to have a contact angle with the liquid photopolymer resin of greater than about 40°, for example, about 40° to about 90°, about 40° to about 60°, or about 60° to about 90°.  
15 For example, the flexible membrane may be formed of a specific material having a contact angle within the above range, or the flexible membrane may be further surface treated, texturized, etc. to further modify the contact angle to be within the above range with respect to the liquid photopolymer resin being used. The contact angle between the liquid resin and the flexible membrane may depend on several  
20 factors, such as the composition of the resin, surface functional groups of the flexible membrane, and microscale structure of the membrane, and it will be understood that those of ordinary skill in the art are capable of selecting suitable structures and compositions for the flexible membrane and liquid resin part in order to attain an appropriate or desired contact angle. The contact angle may be measured and  
25 quantified using any suitable method available in the art, such as a static or dynamic sessile drop method, a pendant drop method, or a variation of the Wilhelmy method.

**[0069]** The affinity between the flexible membrane and the solid (cured) photopolymer resin part may be described in terms of an interlayer peel strength. As used herein, the term “interlayer peel strength” may refer to the average amount of  
30 force necessary to separate two layers having a commonly shared interfacial surface area. In some embodiments, for example, the flexible membrane may be configured to have an interlayer peel strength with the cured photopolymer resin part of less than about 200 N/m, for example, less than 150 N/m or less than about 100 N/m. For example, the flexible membrane may be formed of a specific material having an  
35 interlayer peel strength within the above range, or the flexible membrane may be further surface treated, texturized, etc. to further modify the interlayer peel strength to be within the above range with respect to the photopolymer resin part being formed. The peel strength between the flexible membrane and cured resin part may

1 depend on several factors including the interfacial surface area, and it will be  
understood that those of ordinary skill in the art are capable of selecting suitable  
structures and materials for the flexible membrane and cured resin part in order to  
attain an appropriate or desired peel strength.

5 **[0070]** The flexible membrane may be formed of a material having a suitable  
elasticity and affinity for the cured photopolymer resin, as described above. In some  
embodiments, for example, the flexible membrane may be formed of an aliphatic  
polymer. Non-limiting examples of aliphatic polymers include polystyrene (PS),  
10 polymethylpentene (PMP), cyclic olefin copolymers (COC), fluorinated ethylene  
propylene (FEP), perfluoroalkoxyalkane (PFA), polytetrafluoroethylene (PTFE), and  
mixtures thereof.

**[0071]** The thickness of the flexible membrane may be selected according to one  
or more considerations, including the desired total thickness of the aperture, the  
durability, stiffness, and refractive index of the flexible membrane, and the presence  
15 or absence of additional aperture components. In some embodiments, the flexible  
membrane may have a thickness of about 10  $\mu\text{m}$  to about 750  $\mu\text{m}$ . For example, the  
flexible membrane may have a thickness of about 50  $\mu\text{m}$  to about 500  $\mu\text{m}$ , or about  
200  $\mu\text{m}$  to about 400  $\mu\text{m}$ . However, embodiments of the present disclosure are not  
limited thereto, and those of ordinary skill in the art are capable of selecting suitable  
20 membrane thicknesses according to the desired configuration of the device and the  
principles described herein.

**[0072]** When the flexible membrane has a thickness that is relatively small (thin)  
in comparison to the thicknesses of the transparent window and/or the compliant  
release layer, the durometer, refractive index, and transparency of the flexible  
25 membrane may have a correspondingly small effect on the overall absorbance and  
scattering of the aperture as a whole. Accordingly, in some embodiments, the flexible  
membrane may include materials typically considered ill-suited or unsuitable for the  
window and/or compliant release layer (e.g., due to its durometer, refractive index,  
and transparency). However, embodiments of the present disclosure are not limited  
30 thereto, and a person of ordinary skill in the art is capable of selecting a suitable  
flexible membrane and/or materials included therein based on the principles  
described herein.

**[0073]** The boundary seal is positioned around the periphery of the flexible  
membrane on the side of the reservoir-membrane interface that is in contact with the  
35 photopolymer resin (e.g., within the reservoir). The boundary seal may perform two  
functions. First, the boundary seal may block or prevent ingress of the liquid  
photopolymer resin below the flexible membrane, thus reducing resin loss as well as  
the chances of resin curing and deposition within the aperture system, for example,

1 when multiple component layers are included in the aperture. In sealing the aperture  
system against photopolymer resin ingress, the boundary seal may thus increase or  
improve the lifetime of the device by reducing the chances that cured photopolymer  
resin (which may be UV-opaque) will adhere to the aperture components and render  
5 the system inoperable by blocking light transmission. Second, the boundary seal  
may apply a suitable amount of tension to the flexible membrane in order to  
constrain its displacement and maintain the position of the flexible membrane in  
relation to other parts of the aperture system, even after the flexible membrane is  
placed in a deformed state (e.g., pulled out of a planar conformation). For example, if  
10 the membrane tension is too high, the membrane may not flex sufficiently and/or  
may tear as the cured part is lifted off of the aperture. However, if the membrane  
tension is too low, release of the part from the membrane may be followed by  
sagging or wrinkling of the flexible membrane, which could lead to subsequent  
distortion and scattering of the light traveling through the aperture from the exposure  
15 source into the resin. It will be understood that those of skill in the art are capable of  
selecting an appropriate membrane tension according to the principles described  
herein.

**[0074]** The boundary seal may be formed of combined multiple components or  
may be formed as a single component. The boundary seal and its components may  
20 be permanent (e.g. an integral part of the aperture system), or may be removable  
(e.g., non-permanent), with the choice being dependent upon the desired properties  
of the aperture system. For example, a permanent boundary seal may be less likely  
to leak, whereas a removable boundary seal may allow access to and replacement  
of the aperture system parts (including the transparent window, compliant release  
25 layer, and/or flexible membrane). In some embodiments, the boundary seal may  
include a combination of permanent and removable elements.

**[0075]** When the boundary seal is permanent, non-limiting examples of  
components that may be included in the boundary seal include chemical seals such  
as adhesives (such as epoxies, acrylates, etc.) and sealants (such as silicones,  
30 urethanes, etc.), and non-reversible mechanical attachments (such as interference  
fits, pawls, etc.). When the boundary seal includes a permanent chemical seal such  
as an adhesive or sealant, the adhesive or sealant may be selected for its  
compatibility (e.g., lack of reactivity) with the liquid photopolymer resin. In some  
embodiments, the boundary seal may include acrylated urethanes, silicones, and/or  
35 cycloaliphatic epoxies.

**[0076]** When the boundary seal is removable, non-limiting examples of  
components that may be included in the boundary seal may include mechanical  
fasteners, magnets, tape, and reversible snap fits. In some embodiments, when the

1 boundary seal includes a mechanical fastener, the mechanical fastener may include a screw, a bolt, a crimp, a clamp, a clip, etc.

**[0077]** In some embodiments, the boundary seal may include magnets or be held in place using a magnetic force. This magnetic attachment method may be particularly suitable when the boundary seal is immersed in photopolymer resin, because the non-interlocking magnetic seal is less prone to becoming jammed with fully or partially cured resin. In some embodiments, the boundary seal may include multiple paired magnets. In some embodiments, the boundary seal include a series of permanent magnets paired with (attracted) to a rail, structure, series of pieces, etc. comprising a ferromagnetic material. However, embodiments are not limited thereto, and a person of ordinary skill in the art should be capable of selecting other suitable magnetic attachments according to the principles described herein.

**[0078]** When the boundary seal is held in place with a magnetic force, the magnets may have any holding power suitable to maintain tension on the membrane and/or to enforce the boundary seal when the cured photopolymer part is removed from the aperture system. In some embodiments, for example, the magnets may have a holding power of about 0.5 lb. to about 1 lb. each, for a total holding power (magnetic attachment force) of at least 5 lbs., and in some embodiments about 5 lbs. to about 60 lbs.

**[0079]** In some embodiments, the removable boundary seal may be achieved by a pressure differential such as that applied by utilizing a vacuum chuck. The vacuum applied by the vacuum chuck may be any suitable level of vacuum that maintains a seal when the cured photopolymer part is separated from the flexible membrane, for example, about 10-30 inches Hg, or about 10-20 inches Hg.

**[0080]** In some embodiments, the boundary seal may be flush or substantially flush with the surface of the aperture within the resin reservoir. For example, when the boundary seal is achieved by a pressure differential instead of a component having a physical height, the surface of the aperture system may be substantially flat. Similarly, when the boundary seal is achieved by a permanent sealant, the profile of the sealant may be low or substantially flat. In some embodiments, the boundary seal may extend to a height greater than that of the aperture system within the reservoir. When the boundary element extends above the surface of aperture system, the boundary seal may incorporate resin exchange features such as vents, channels, baffles, or troughs in order to facilitate fluid exchange or flow between the volume of resin within the aperture system boundary and the volume of resin outside of the aperture system boundary. Schematic descriptions of embodiments including various kinds of boundary seals are provided in the Examples.

1 **[0081]** In some embodiments, the aperture may further include a transparent  
window under the flexible membrane and in the lower opening of the reservoir. The  
transparent window is transparent to one or more wavelengths required to initiate  
polymerization of the liquid photopolymer resin, as described herein in connection  
5 with the flexible membrane. The transparent window may be formed of a material  
having a suitable strength and rigidity to serve as the bottom of the photopolymer  
reservoir. For example, when the bottom-mounted exposure source produces UV  
radiation, the window may be transparent to UV radiation between about 200 nm to  
about 460 nm, or at least one discrete wavelength between about 200 nm to about  
10 460 nm. In some embodiments, for example, the transparent window may be formed  
of a glass (e.g., quartz, fused silica, sapphire), polyethylene terephthalate (PET),  
biaxially-oriented polyethylene terephthalate (BOPET), polymethylpentene (PMP),  
cyclic olefin copolymers (COC), polycarbonate, polymethylmethacrylate (PMMA),  
and mixtures thereof.

15 **[0082]** In some embodiments, the composition and thickness of the window may  
be selected so that the refractive index of the window is matched to that of the  
material occupying the volume between the window and the exposure source (e.g.  
air) as well as that of other materials included in the aperture. When index matching  
is difficult or not feasible, the refractive index difference may be minimized by  
20 reducing the thickness of the window. In some embodiments, the window may have  
a thickness of about 1 mm to about 16 mm. For example, the window may have a  
thickness of about 1 mm to about 10 mm, or about 1 mm to about 5 mm.

**[0083]** When the aperture system includes a compliant release layer, the  
compliant release layer may be between the flexible membrane and the transparent  
25 window. The compliant release layer allows the cured photopolymer part to be  
pressed into intimate contact against the aperture system without being damaged.  
Accordingly, the compliant release layer may be selected to have some compliance  
(e.g., have a low hardness or durometer) to prevent or reduce damage to the cured  
photopolymer part as it is removed from the aperture. If the durometer is too high,  
30 the interface will not deform (e.g., yield) when the part separates from the aperture  
system, and part damage may be induced by this process. In some embodiments,  
the material used to form the compliant release layer may have a durometer of about  
3000 to about 65A. The composition, transparency, and refractive index of the  
material used to form the compliant release layer may be selected to reduce or  
35 minimize light absorption and scattering in a manner similar to the transparent  
window.

**[0084]** Non-limiting examples of materials that satisfy the needs of this compliant  
release layer may include silicones and urethanes having durometers ranging from

1 extra soft to medium hard. In some embodiments, for example, the compliant release  
layer may be formed of a silicone elastomer such as Sylgard® 184 or Lumisil® 7600.  
Since the flexible membrane separates the photopolymer resin from the compliant  
5 release layer, the compliant release layer may include materials which are  
incompatible with the liquid or solid (cured) preceramic photopolymers. As used  
herein, the term “incompatible” refers to a material or composition capable of  
reacting with and/or adhering to the liquid or cured preceramic photopolymers.

**[0085]** In some embodiments, the compliant release layer may have a thickness  
of about 0.1 mm to about 13 mm, for example, about 1 mm to about 10 mm, and in  
10 some embodiments, about 3 mm to about 6 mm. The horizontal planar area of the  
compliant release layer may be any suitable size to cover or protect the transparent  
window, for example, about the same size or larger than the transparent window.

**[0086]** While specific combinations of the above components may be described in  
present disclosure, it will be understood that embodiments of the present disclosure  
15 are not limited thereto. Additional combinations of the above components, including  
those configurations in which two or more components are integrated as a single  
component, are included within the scope of embodiments of the present disclosure.  
Furthermore, unless otherwise stated, aperture systems including one or more of the  
above components are not limited to those components, and may be further  
20 combined with elements and devices not explicitly described herein.

**[0087]** In some embodiments, the aperture may include a flexible membrane, a  
compliant release layer, and a transparent window. FIG. 4 is a simplified schematic  
cross-sectional diagram of an aperture system including a reservoir **3**, a flexible  
25 membrane **12**, a boundary seal **13**, a transparent window **8**, and a compliant release  
layer **9**, according to embodiments of the present disclosure. The reservoir **3** holds a  
volume of liquid photopolymer resin **5** above an exposure source **2**. The flexible  
membrane **12** is positioned between the liquid photopolymer resin **5** and the  
compliant release layer **9**, while the compliant release layer **9** is positioned on the  
transparent window **8**. The flexible membrane **12** is held in place around its  
30 periphery by the adhesive boundary seal **13**, which blocks or prevents ingress of the  
photopolymer resin **5** between the flexible membrane **12** and the compliant release  
layer **9**.

**[0088]** In some embodiments, the aperture may omit one or both of the compliant  
release layer **9** or the transparent window **8**, such that the flexible membrane **12** is  
35 suspended under tension. For example, the flexible membrane **12** may be combined  
with a transparent window **8** without (e.g., in the absence of) the compliant release  
layer **9**, such that a gap is formed between the flexible membrane **12** and the window  
**8**. Alternatively, the flexible membrane **12** may be suspended directly above an

1 exposure source (e.g., without a transparent window or compliant release layer  
supporting the bottom surface of the flexible membrane). In either design, the  
tension on the flexible membrane **12** is configured to be sufficiently high enough to  
prevent or reduce wrinkling or buckling. Furthermore, the thickness and tension of  
5 the flexible membrane may be selected such that it is not significantly deformed by  
the weight of the photopolymer resin on the unsupported flexible membrane layer,  
but still maintains flexibility during peeling.

**[0089]** FIG. 5 is a schematic cross-sectional view of an example aperture system  
including only a reservoir **3**, a boundary seal **13**, and a flexible membrane **12**,  
10 according to embodiments of the present disclosure. Here, the aperture is simplified  
so that only the flexible membrane **12** directly contacting the photopolymer resin **5**  
and **7** is present.

**[0090]** Conventional bottom-up stereolithography systems in the related art  
typically include an aperture including a transparent window and a compliant release  
15 layer, such that the photopolymer resin is in contact with the compliant release layer.  
In these systems, the compliant release layer is configured to perform two functions.  
First, the compliant release layer is configured to prevent or reduce adhesion  
between the cured photopolymer part and the transparent aperture. Second, the  
compliant release layer is configured to allow the cured photopolymer part to be  
20 pressed into intimate contact against the aperture without being damaged. Both  
functions are directly or indirectly dependent on the composition of the compliant  
release layer, as described herein. As such, the composition of the compliant release  
layer is limited to materials that are suitable for both functions.

**[0091]** The combination of a flexible membrane and a compliant release layer,  
25 with the flexible membrane being on or above the compliant release layer, may  
enable decoupling of these two functions. As a result, two different materials may be  
used for each component and function. In some embodiments, for example, the  
flexible membrane may serve as the surface that contacts the resin and reduces  
adhesion between the part and aperture, while the compliant release layer may  
30 serve as a foundation that enables the part to be pressed against the aperture, but is  
not exposed to the resin. As such, the flexible membrane may be formed of a hard  
(e.g., high durometer) and non-adhesive material, while the compliant release layer  
may be formed of low durometer material having high adhesion potential with the  
cured photopolymer part. As such, the flexible membrane and compliant release  
35 layer may each be selected from a wider range of materials, and may be separately  
optimized for their respective functions.

**[0092]** Because the flexible membrane can stretch and deform towards the cured  
photopolymer part and/or build platform (e.g., in the direction of movement) as the

1 cured part is lifted off (e.g., moved away from the aperture), an aperture including a  
flexible membrane exhibits different separation behavior from an aperture in which  
parts are deposited directly on a compliant release layer. As the flexible membrane  
deforms from a planar shape to a bell curve shape, the adhesive failure mode at the  
5 interface between the cured photopolymer part and the flexible membrane changes  
from being purely Mode I (peel) to being mixed mode (e.g., Mode I (peel) + Mode II  
(shear)). The modified (mixed) adhesive failure mode requires less energy to  
separate the cured photopolymer part from the aperture. As such, the cured  
photopolymer part can be removed using a reduced amount of force compared to  
10 the amount of force required for separation according to any pure mode (e.g., purely  
Mode I, purely Mode II, etc.). This mixed mode interface separation may enable thick  
( $> 75$  mm thickness) or fine-featured ( $< 50$   $\mu\text{m}$  resolution) preceramic polymer  
components to be fabricated without damage induced by excessive strain placed on  
the cured resin during attempts at separation. The combination of reduced adhesion  
15 potential between the two surfaces (e.g., the cured photopolymer part and the  
flexible membrane) and a lower energy adhesive failure mode may enable more  
efficient and reproducible production of preceramic polymer components in bottom-  
up stereolithography devices.

**[0093]** FIG. 6 is a cross-sectional schematic diagram illustrating the mixed mode  
20 interface separation enabled by inclusion of the flexible membrane in the example  
aperture system of FIG. 4. In block **20**, the photopolymer resin **5** is exposed to UV  
light output **1** so that a layer of the cured photopolymer resin part **7** is formed (e.g.,  
cured/deposited) adjacent to the flexible membrane **12**. In block **21**, the build  
platform **6** moves away from the flexible membrane **12** and aperture system, pulling  
25 the cured photopolymer resin part **7** and the attached portion of the flexible  
membrane **12** away from the compliant release layer **9** positioned below it. As the  
cured photopolymer resin part **7** pulls on the flexible membrane **12**, the shape of the  
membrane is distorted from a planar surface to that of a concave down parabolic  
function or bell curve, with the peak of the curve corresponding to the center of the  
30 attached portion and the zeroes of the curve corresponding to the edges of the  
flexible membrane. Upon deformation of the flexible membrane **12**, the adhesive  
failure mechanism at the interface between the flexible membrane **12** and the cured  
photopolymer resin part **7** shifts from pure Mode I (peel) to a lower energy mixed  
mode ("Mixed mode interface separation") so that separation of the flexible  
35 membrane **12** and the cured photopolymer resin part **7** occurs ("Flexible membrane  
release"). In block **22**, the build platform is then positioned a suitable distance away  
from the flexible membrane corresponding to the desired thickness of the next

1 deposited layer. The photopolymer resin is again exposed to UV light output **1** in  
block **20** so that the next layer is formed adjacent to the flexible membrane.

**[0094]** In some embodiments of the aperture system, the flexible membrane and  
the compliant release layer are in intimate (e.g., direct) contact over an area  
5 corresponding to the surface area of the photopolymer resin being exposed to the  
UV exposure source. The flexible membrane is pulled away from the compliant  
release layer during removal of the cured photopolymer part from the aperture, such  
that the flexible membrane deforms near its center while remaining fixed at the  
boundary seal. The resulting displacement between the flexible membrane and the  
10 boundary seal leads to creation and/or deformation of an intervening volume. FIG.  
7A is a schematic diagram highlighting the creation of a volume **23** between the  
compliant release layer **9** and the flexible membrane **12** upon deformation of the  
flexible membrane, which is occupied by a low pressure air gap or vacuum. The low  
pressure within this volume **23** relative to the photopolymer resin material **5** in the  
15 surrounding reservoir exerts a restoring force on the flexible membrane **12**, and  
causes the flexible membrane to “hiccup” or jump back toward a flat geometry upon  
release of the cured photopolymer resin part **7**. This movement may cause damage  
to the part and/or require additional energy input for release.

**[0095]** In some embodiments, this pull back force may be attenuated by adding  
20 an additional gas or fluid to the interface between the flexible membrane and  
compliant release layer. Accordingly, in some embodiments, the aperture system  
may further comprise a gas and/or liquid between the compliant release layer and  
the flexible membrane. FIG. 7B is a schematic cross-sectional view of an  
embodiment in which the volume between the flexible membrane **12** and the  
25 compliant release layer **9** is occupied by a fluid interface **24**, which is deformed upon  
lifting of the cured photopolymer part **7**. The presence of this fluid interface **24** may  
facilitate mixed mode interface separation by reducing the amount of energy input  
needed to deform the flexible membrane **12**. However, in some embodiments, the  
presence of the fluid interface **24** may also impede the membrane from returning to a  
30 uniformly flat surface, which may negatively affect level disposition of additional  
layers.

**[0096]** In some embodiments, when the fluid interface **24** includes a gas, the gas  
may include nitrogen, argon, helium, air, carbon dioxide, or a mixture thereof, etc. In  
some embodiments, the gas may be included at a pressure of about 1 atm, for  
35 example 1 atm to 0.8 atm.

**[0097]** In some embodiments, when the fluid interface **24** includes a liquid, the  
liquid may include water, an alcohol, an oil, a photopolymer resin without a  
photoinitiator component, or a mixture thereof. Any suitable gas and/or liquid may be

1 used as long as it does not interfere with or reduce transmittance of the light output  
into the resin and is suitably index-matched to the other components of the aperture  
system.

5 **[0098]** In some embodiments, a fixed amount of the gas and/or liquid may be  
injected and sealed within the interface prior to use of the aperture system, for  
example with a hypodermic needle, and may therefore be present in the interface at  
all times. When the cured resin is pulled away from the flexible membrane, the  
volume of the gas and/or liquid in the interface may increase and the vapor pressure  
may decrease. In some embodiments, a portion or all of the gas and/or liquid may be  
10 injected or pulled into the interfacial space during membrane deformation, e.g., from  
a separate coupled reservoir, and returned or pushed back to the separate reservoir  
when the membrane is allowed to fall back into place. However, the gas or liquid is  
not an exchange fluid with the photopolymer resin, and is not coupled to the  
reservoir containing the photopolymer resin.

15 **[0099]** In some embodiments, the aperture system may further include a sweeper  
arm. The sweeper arm may be positioned on the top surface of the flexible  
membrane and may be used to clean and position the membrane surface between  
successive exposures. FIG. 8 is a schematic diagram of an embodiment including a  
sweeper arm **25**, which traverses the exposure surface of the aperture system to  
20 clear any residual resin and/or to remove any wrinkles in the flexible membrane **12**.  
While not required for operation of the aperture system, the sweeper arm may  
enable the use of thinner flexible membranes, which are more prone to wrinkling, or  
the wider use of flexible membrane materials with greater adhesive strength to the  
cured preceramic photopolymer. In addition, the sweeper arm **25** may be suitably  
25 used to flatten the flexible membrane **12** in embodiments in which a fluid is included  
in the flexible membrane/compliant release layer interface, as described above.

**[00100]** In some embodiments, the compliant release layer and transparent  
window are integrated, and may be included in the aperture system as a single body  
(e.g., a “compliant window”). As used herein, the term “integrated” may refer to a  
30 state in which the physical forms and functions of the previously separate parts (e.g.,  
the compliant release layer and the transparent window) are combined into a single  
part or body having the combined functions of both. The physical form or footprint of  
the single body may be similar to or substantially the same as the combined volume  
or footprint of the previously separate parts; however, embodiments of the present  
35 disclosure are not limited thereto.

**[00101]** In some embodiments, the flexible membrane and transparent window are  
integrated, and may be included in the aperture system as a single body without a  
compliant release layer therebetween. The physical form or footprint of the single

1 body may be similar to or substantially the same as the combined volume or footprint  
of the previously separate parts; however, embodiments of the present disclosure  
are not limited thereto.

5 **[00102]** In some embodiments, the compliant release layer is removed (e.g., the  
aperture includes a flexible membrane and transparent windows, but does not  
include a compliant release layer) and an intervening volume or thickness between  
the flexible membrane and the transparent window is enlarged and filled with gas or  
fluid. For example, the compliant release layer may be replaced by a gas or fluid that  
10 carries out the same functions of enabling the cured photopolymer part to be  
pressed against the aperture, and facilitating easy separation of the flexible  
membrane from the aperture system. The gas or fluid may be the same as described  
above regarding the gas or fluid interface between the flexible membrane and  
compliant release layer. When the compliant release layer is replaced by a gas or  
15 fluid, the thickness of the intervening volume may be about 0.1 mm to about 13 mm,  
for example, about 1 mm to about 10 mm; and in some embodiments, about 3 mm to  
about 7 mm.

**[00103]** Aspects of embodiments of the present disclosure provide a  
stereolithography device including: a build platform, a reservoir positioned below the  
build platform so that the build platform can be lowered into or raised out of the  
20 reservoir, an aperture positioned within and covering at least a portion of a bottom of  
the reservoir, and an exposure source positioned below the reservoir and configured  
to emit light (e.g., patterned light) so that the light passes through the aperture.

**[00104]** The build platform, reservoir, and exposure source are not particularly  
limited, and may be similar to commercially available elements in terms of suitable  
25 materials and sizes.

**[00105]** The light may be any form of light capable of initiating a  
photopolymerization reaction in any resin that may be used within the  
stereolithography device, e.g., by generating a reactive species capable of one or  
more bond-forming reactions. In some embodiments, the light may be ultraviolet  
30 (UV) light, e.g., light having a wavelength of about 200 nm to about 460 nm. The light  
may be generated by any suitable exposure source, such as a digital projector, a  
lamp, an LED, a laser, etc. The light may be in any suitable form, and for example,  
may be collimated (coherent) or non-coherent. However, embodiments of the  
present disclosure are not limited thereto, and a person of skill in the art is capable of  
35 selecting an appropriate light and exposure source based on the principles described  
herein.

**[00106]** The aperture system may be the same as any one of the embodiments  
described in the present disclosure, or may have any compatible combination of

1 features of the above-described embodiments, as long as the aperture system includes a flexible membrane as described herein.

**[00107]** The stereolithography device may further include a liquid photopolymer resin within the reservoir. The resin may be any UV-curable photopolymer resin. The  
5 UV-curable photopolymer resin may include a photoinitiator compound and one or more monomers or oligomers. Upon exposure to UV light energy, the compounds included in the UV-curable polymer precursor mixture may undergo one or more photoinitiated polymerization (photopolymerization) reactions to form a solid material including a polymer network.

10 **[00108]** The monomers, oligomers, and photoinitiators included in the liquid photopolymer resin are not particularly limited as long as they are compatible with each other (e.g., include mutually reactive functional groups) and are compatible with the exposure source (e.g., are activated at the UV wavelength produced by the exposure source). When the UV-curable photopolymer resin is a pre-ceramic  
15 photopolymer resin, the monomers and oligomers may include high amounts of inorganic atoms (such as Si), as described above, and may be substituted with cross-reactive functional groups. However, embodiments of the present disclosure are not limited thereto, and a person of skill in the art should be capable of selecting an appropriate resin mixture or composition according to the principles described  
20 herein.

**[00109]** Aspects of embodiments of the present disclosure provide a method of additively manufacturing preceramic parts, the method including: securing a volume of photopolymer resin in a bottom-up stereolithography device equipped with an aperture system, exposing the photopolymer resin to a exposure source positioned  
25 below the aperture system to cure a layer of the resin; and pulling the cured layer of resin apart from the aperture system so that the flexible membrane separates from the compliant release layer and the cured layer separates from the flexible membrane. The aperture system may be the same as any one of the embodiments described in the present disclosure, or may have any compatible combination of  
30 features of the above-described embodiments, as long as the aperture system includes a flexible membrane as described herein.

**[00110]** In some embodiments, for example, the aperture system may include: a reservoir having a lower opening, a flexible membrane positioned within the reservoir and covering the lower opening; and a boundary seal positioned around a periphery  
35 of the flexible membrane, the boundary seal including one or more boundary seal components and immobilizing the periphery of the flexible membrane against the reservoir wall. In some embodiments, the aperture system may further include a transparent window under the flexible membrane and in the lower opening of the

1 reservoir, the transparent window covering the lower opening. The aperture system  
may further include a compliant release layer between the transparent window and  
the flexible membrane in the lower opening of the reservoir, the compliant release  
layer covering the lower opening and having a low affinity for the flexible membrane.

5 **[00111]** Additional example embodiments of aperture systems of the present  
disclosure are shown in FIGS. 9 to 11 for reference. FIG. 9 shows an example  
embodiment of a aperture system incorporating a transparent window **8**, a compliant  
release layer **9**, a flexible membrane **12**, and a boundary seal **13**. The boundary seal  
10 **13** is broken into four separate components for ease of repair/replacement of the  
membrane and interface elements: a magnetic clamp (N) **30** embedded in an upper  
boundary seal **31** positioned above the surface of the flexible membrane, and a  
magnetic clamp (S) **32** embedded in a lower boundary seal **33** positioned below the  
flexible membrane **12** and on the bottom inner surface of the reservoir **3**. Because  
15 the boundary seal **13** and aperture surface (i.e., the profile of the flexible membrane  
**12**) extend above the resin reservoir wall, a resin exchange feature **34** (flow  
channels) are included in the upper boundary seal component **31** to allow for  
exchange of resin between the outer resin volume **35** and the inner resin volume **36**,  
the two volumes being demarcated by the boundary seal **13**. In the embodiment  
described by FIG. 9, the lower boundary seal **33** is permanently affixed (e.g., using  
20 an adhesive bond **37**) to the reservoir wall **3**, while a non-permanent attractive force  
between the magnetic clamps **30** and **32** is used to enforce contact of the upper  
boundary seal **31** against the flexible membrane **12**. FIG. 9 illustrates an  
embodiment in which the two boundary elements **31** and **33** include paired  
permanent magnets as removable clamps. In some embodiments, mechanical  
25 fasteners or integral interlocking features could be used to seal the boundary as well.

**[00112]** FIG. 10 shows an example embodiment in which the surface of the  
aperture (i.e., the profile of the flexible membrane **12**) is flush or nearly level with the  
lower boundary of the photopolymer reservoir **3**. Accordingly, no exchange features  
are needed to connect and exchange the resin adjacent to the aperture with resin in  
30 the rest of the reservoir (collectively shown as photopolymer resin **5**). In this design,  
a small inset in the reservoir **3** is used to mount the transparent window **8** and  
compliant release layer **9**, while the flexible membrane **12** is affixed to the reservoir **3**  
by a boundary seal **13** including a permanent sealant, such as a chemical bond,  
silicon based tape, etc., applied around its periphery. This design does not allow for  
35 repair or replacement of the flexible membrane element, and the entire aperture  
system is consumable.

**[00113]** FIG. 11 shows an example embodiment including combined elements of  
the first and second designs in FIGS. 9 to 10. In the example embodiment of FIG.

1 11, the compliant release layer and transparent window have been combined into  
(e.g., replaced by) a single "compliant window" component **40** that is sealed against  
the reservoir **3** by a boundary seal **13** around its periphery. The flexible membrane  
**12** is positioned within the reservoir **3** in direct contact with the compliant window **40**,  
5 and is held in place by a rigid boundary frame mechanically attached to the reservoir  
**3** via a mechanical attachment **41** (e.g., a screw coupled with a boundary seal).  
Because the boundary seal **13** does not deeply extend into the reservoir, no resin  
exchange features are added.

**[00114]** Although embodiments of the present disclosure have been described in  
10 relation to silicon-containing preceramic polymers, embodiments of the present  
disclosure are not limited thereto, and it will be understood that embodiments of the  
aperture system described herein may be beneficially used in conjunction with other  
types of polymer and photopolymer resins. For example, embodiments of the  
present disclosure may facilitate manufacturing of parts with a larger number of  
15 layers or delicate features such as bottlenecks that are more susceptible to cohesive  
failure.

**[00115]** Embodiments of the disclosure described herein may be applied to a  
variety of additive manufacturing methods and devices in order to reduce part count,  
scrap, non-recurring engineering, etc. In addition, embodiments of the present  
20 disclosure may be applied to additive manufacturing of components and parts used  
in high wear or high temperature applications that would necessitate ceramic  
materials, including propulsion structures (vanes, impellers, nacelles, thrusters),  
control surfaces (fins, leading edges), hypersonic structures (thermal protection  
systems, heat shields), high wear components (brakes, clutches, rotors), catalyst  
25 support structures, pump components, and filters. There is high commercial demand  
for additively manufactured ceramics in a variety of fields, including: automotive and  
aerospace, industrial filtration (molten metal filters, flow separators), metal  
processing (casting molds/blanks), implantable dental and medical devices, and  
semiconductor processing. Accordingly, embodiments of the present disclosure may  
30 be used in bottom-up stereolithography systems to enable additive manufacturing in  
diverse industries and applications.

**[00116]** As used herein, unless otherwise expressly specified, all numbers such as  
those expressing values, ranges, amounts or percentages may be read as if  
prefaced by the word "about," even if the term does not expressly appear. As used  
35 herein, the terms "substantially", "about", and similar terms are used as terms of  
approximation and not as terms of degree, and are intended to account for the  
inherent deviations in measured or calculated values that would be recognized by  
those of ordinary skill in the art. Also, any numerical range recited herein is intended

1 to include all sub-ranges of the same numerical precision subsumed within the  
recited range. For example, a range of "1.0 to 10.0" is intended to include all  
subranges between (and including) the recited minimum value of 1.0 and the recited  
5 maximum value of 10.0, that is, having a minimum value equal to or greater than 1.0  
and a maximum value equal to or less than 10.0, such as, for example, 2.4 to 7.6.  
Any maximum numerical limitation recited herein is intended to include all lower  
numerical limitations subsumed therein and any minimum numerical limitation recited  
in this specification is intended to include all higher numerical limitations subsumed  
therein. Accordingly, Applicant reserves the right to amend this specification,  
10 including the claims, to expressly recite any sub-range subsumed within the ranges  
expressly recited herein. As used herein, the terms "combination thereof" and  
"combinations thereof" may refer to a chemical combination (e.g., an alloy or  
chemical compound), a mixture, or a laminated structure of components.

**[00117]** It will be understood that, although the terms "first", "second", "third", etc.,  
15 may be used herein to describe various elements, components, regions, layers  
and/or sections, these elements, components, regions, layers and/or sections should  
not be limited by these terms. These terms are used to distinguish one element,  
component, region, layer or section from another element, component, region, layer  
or section. Thus, a first element, component, region, layer or section described  
20 below could be termed a second element, component, region, layer or section,  
without departing from the spirit and scope of the present disclosure.

**[00118]** Spatially relative terms, such as "beneath", "below", "lower", "under",  
"above", "upper", and the like, may be used herein for ease of explanation to  
describe one element or feature's relationship to another element(s) or feature(s) as  
25 illustrated in the accompanying drawings. It will be understood that the spatially  
relative terms are intended to encompass different orientations of the device in use  
or in operation, in addition to the orientations depicted in the accompanying  
drawings. For example, if the structures in the accompanying drawings are turned  
over, elements described as "below" or "beneath" or "under" other elements or  
30 features would then be oriented "above" the other elements or features. Thus, the  
example terms "below" and "under" can encompass both an orientation of above and  
below. The device may be otherwise oriented (e.g., rotated 90 degrees or at other  
orientations) and the spatially relative descriptors used herein should be interpreted  
accordingly.

35 **[00119]** The terminology used herein is for the purpose of describing particular  
embodiments only and is not intended to be limiting of the present disclosure. Plural  
encompasses singular and vice versa. As used herein, the singular forms "a" and  
"an" are intended to include the plural forms as well, unless the context clearly

1 indicates otherwise. It will be further understood that the terms "comprises",  
"comprising", "includes", and "including," when used in this specification, specify the  
presence of the stated features, integers, acts, operations, elements, and/or  
components, but do not preclude the presence or addition of one or more other  
5 features, integers, acts, operations, elements, components, and/or groups thereof.  
As used herein, the term "and/or" includes any and all combinations of one or more  
of the associated listed items. Expressions such as "at least one of", when preceding  
a list of elements, modify the entire list of elements and do not modify the individual  
elements of the list.

10 **[00120]** While the subject matter of the present disclosure has been described in  
connection with certain embodiments, it is to be understood that the subject matter of  
the present disclosure is not limited to the disclosed embodiments, but, on the  
contrary, the present disclosure is intended to cover various modifications and  
equivalent arrangements included within the spirit and scope of the appended  
15 claims, and equivalents thereof.

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1 **WHAT IS CLAIMED IS:**

1. An aperture system for a bottom-up stereolithography device, the aperture system comprising:

a reservoir having a lower opening;

5 an aperture, the aperture comprising:

a flexible membrane positioned within the reservoir and covering the lower opening; and

a boundary seal positioned around a periphery of the flexible membrane, the boundary seal comprising one or more boundary seal components and immobilizing  
10 the periphery of the flexible membrane against the reservoir.

2. The aperture system of claim 1, the aperture further comprising:

a transparent window under the flexible membrane and in the lower opening of the reservoir, the transparent window covering the lower opening; and

15 a compliant release layer between the transparent window and the flexible membrane in the lower opening of the reservoir, the compliant release layer covering the lower opening and having a low affinity for the flexible membrane.

3. The aperture system of claim 1, wherein the flexible membrane is  
20 configured to have a contact angle greater than about 40° with a resin used for stereolithography.

4. The aperture system of claim 1, wherein the flexible membrane is  
25 configured to have an interlayer peel strength of less than about 200 N/m with a cured photopolymer resin part.

5. The aperture system of claim 1, wherein the flexible membrane  
30 comprises polystyrene (PS), polymethylpentene (PMP), cyclic olefin copolymers (COC), fluorinated ethylene propylene (FEP), perfluoroalkoxyalkane (PFA), polytetrafluoroethylene (PTFE), or a mixture thereof.

6. The aperture system of claim 1, wherein the flexible membrane has a thickness of about 10 μm to about 750 μm.

35 7. The aperture system of claim 1, wherein the boundary seal components comprise a reversible mechanical attachment.

1           8.     The aperture system of claim 7, wherein the reversible mechanical attachment comprises a magnet having a magnetic force of about 5 lbs. to about 60 lbs.

5           9.     The aperture system of claim 1, wherein the boundary seal components comprise an epoxy adhesive, an acrylate adhesive, a silicone sealant, a urethane sealant, or a mixture thereof.

10          10.    The aperture system of claim 1, wherein the boundary seal components comprise a vacuum chuck to maintain contact between the flexible membrane and the reservoir.

15          11.    The aperture system of claim 1, wherein the boundary seal comprises a resin exchange feature.

20          12.    The aperture system of claim 2, wherein the transparent window comprises glass, polyethylene terephthalate (PET), biaxially-oriented polyethylene terephthalate (BOPET), polymethylpentene (PMP), cyclic olefin copolymers (COC), polycarbonate, polymethylmethacrylate (PMMA), or a mixture thereof.

25          13.    The aperture system of claim 2, wherein the transparent window has a thickness of about 0.1 mm to about 16 mm.

30          14.    The aperture system of claim 2, wherein the compliant release layer comprises silicone, urethane, fluorinated polymers, or a mixture thereof.

35          15.    The aperture system of claim 2, wherein the compliant release layer comprises a gas or fluid, the gas or fluid comprising nitrogen, argon, air, water, an alcohol, an oil, a resin without a photoinitiator component, or a mixture thereof.

40          16.    The aperture system of claim 2, wherein the compliant release layer has a thickness of about 0.1 mm to about 13 mm.

45          17.    The aperture system of claim 1, the aperture further comprising a transparent window under the flexible membrane, wherein the flexible membrane and the transparent window are integrated and included in the lower opening as a single body without a compliant release layer therebetween.

1           18.    The aperture system of claim 1, wherein the flexible membrane is  
suspended above an exposure source under tension without a compliant release  
layer or a window under the flexible membrane.

5           19.    The aperture system of claim 2, the aperture further comprising a  
volume of gas or liquid between the flexible membrane and the compliant release  
layer.

10           20.    The aperture system of claim 2, wherein the compliant release layer  
and transparent window are integrated and included in the lower opening as a single  
body.

15           21.    A stereolithography device comprising:  
a build platform;  
a reservoir positioned below the build platform so that the build platform can  
be lowered into or raised out of the reservoir;  
an aperture positioned within and covering a lower opening in a bottom floor  
of the reservoir;  
and  
20           an exposure source positioned below the reservoir and configured to emit a  
light that passes through the aperture;  
wherein the aperture comprises:  
a flexible membrane; and  
a boundary seal positioned around a periphery of the flexible  
25           membrane, the boundary seal comprising one or more boundary seal  
components and immobilizing the periphery of the flexible membrane against  
the reservoir.

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## AMENDED CLAIMS

received by the International Bureau on 07 March 2018 (07.03.2018)

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1. An aperture system for a bottom-up stereolithography device, the aperture system comprising:

a reservoir having a lower opening;

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an aperture, the aperture comprising:

a flexible membrane positioned within the reservoir and covering the lower opening;

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a compliant release layer in the lower opening of the reservoir under the flexible membrane, the compliant release layer covering the lower opening and having a low affinity for the flexible membrane; and

a boundary seal positioned around a periphery of the flexible membrane, the boundary seal comprising one or more boundary seal components and immobilizing the periphery of the flexible membrane against the reservoir.

15

2. The aperture system of claim 1, the aperture further comprising:

a transparent window under the flexible membrane and in the lower opening of the reservoir, the transparent window covering the lower opening.

20

3. The aperture system of claim 1, wherein the flexible membrane is configured to have a contact angle greater than about 40° with a resin used for stereolithography.

25

4. The aperture system of claim 1, wherein the flexible membrane is configured to have an interlayer peel strength of less than about 200 N/m with a cured photopolymer resin part.

30

5. The aperture system of claim 1, wherein the flexible membrane comprises polystyrene (PS), polymethylpentene (PMP), cyclic olefin copolymers (COC), fluorinated ethylene propylene (FEP), perfluoroalkoxyalkane (PFA), polytetrafluoroethylene (PTFE), or a mixture thereof.

35

6. The aperture system of claim 1, wherein the flexible membrane has a thickness of about 10 µm to about 750 µm.

7. The aperture system of claim 1, wherein the boundary seal components comprise a reversible mechanical attachment.

1           8.     The aperture system of claim 7, wherein the reversible mechanical attachment comprises a magnet having a magnetic force of about 5 lbs. to about 60 lbs.

5           9.     The aperture system of claim 1, wherein the boundary seal components comprise an epoxy adhesive, an acrylate adhesive, a silicone sealant, a urethane sealant, or a mixture thereof.

10          10.    The aperture system of claim 1, wherein the boundary seal components comprise a vacuum chuck to maintain contact between the flexible membrane and the reservoir.

15          11.    The aperture system of claim 1, wherein the boundary seal comprises a resin exchange feature.

20          12.    The aperture system of claim 2 , wherein the transparent window comprises glass, polyethylene terephthalate (PET), biaxially-oriented polyethylene terephthalate (BOPET), polymethylpentene (PMP), cyclic olefin copolymers (COC), polycarbonate, polymethylmethacrylate (PMMA), or a mixture thereof.

25          13.    The aperture system of claim 2, wherein the transparent window has a thickness of about 0.1 mm to about 16 mm.

30          14.    The aperture system of claim 1, wherein the compliant release layer comprises silicone, urethane, fluorinated polymers, or a mixture thereof.

35          16.    The aperture system of claim 1, wherein the compliant release layer has a thickness of about 0.1 mm to about 13 mm.

40          19.    The aperture system of claim 1, the aperture further comprising a volume of gas or liquid between the flexible membrane and the compliant release layer.

45          20.    The aperture system of claim 2, wherein the compliant release layer and transparent window are integrated and included in the lower opening as a single body.

21.    A stereolithography device comprising:

- 1 a build platform;  
a reservoir positioned below the build platform so that the build platform can  
be lowered into or raised out of the reservoir;  
an aperture positioned within and covering a lower opening in a bottom floor  
5 of the reservoir; and  
an exposure source positioned below the reservoir and configured to emit a  
light that passes through the aperture;  
wherein the aperture comprises:  
a flexible membrane;  
10 a transparent window under the flexible membrane;  
a compliant release layer between the transparent window and the flexible  
membrane in the lower opening of the reservoir, the compliant release layer having a  
low affinity for the flexible membrane; and  
a boundary seal positioned around a periphery of the flexible membrane, the  
15 boundary seal comprising one or more boundary seal components and immobilizing  
the periphery of the flexible membrane against the reservoir.

22. The aperture system of claim 1, wherein the compliant release layer  
has a lower durometer than the flexible membrane, and the flexible membrane has a  
20 lower adhesion potential with a cured photopolymer part than the compliant release  
layer.

23. The aperture system of claim 1, wherein the boundary seal is within the  
reservoir and apart from the vertical walls of the reservoir.

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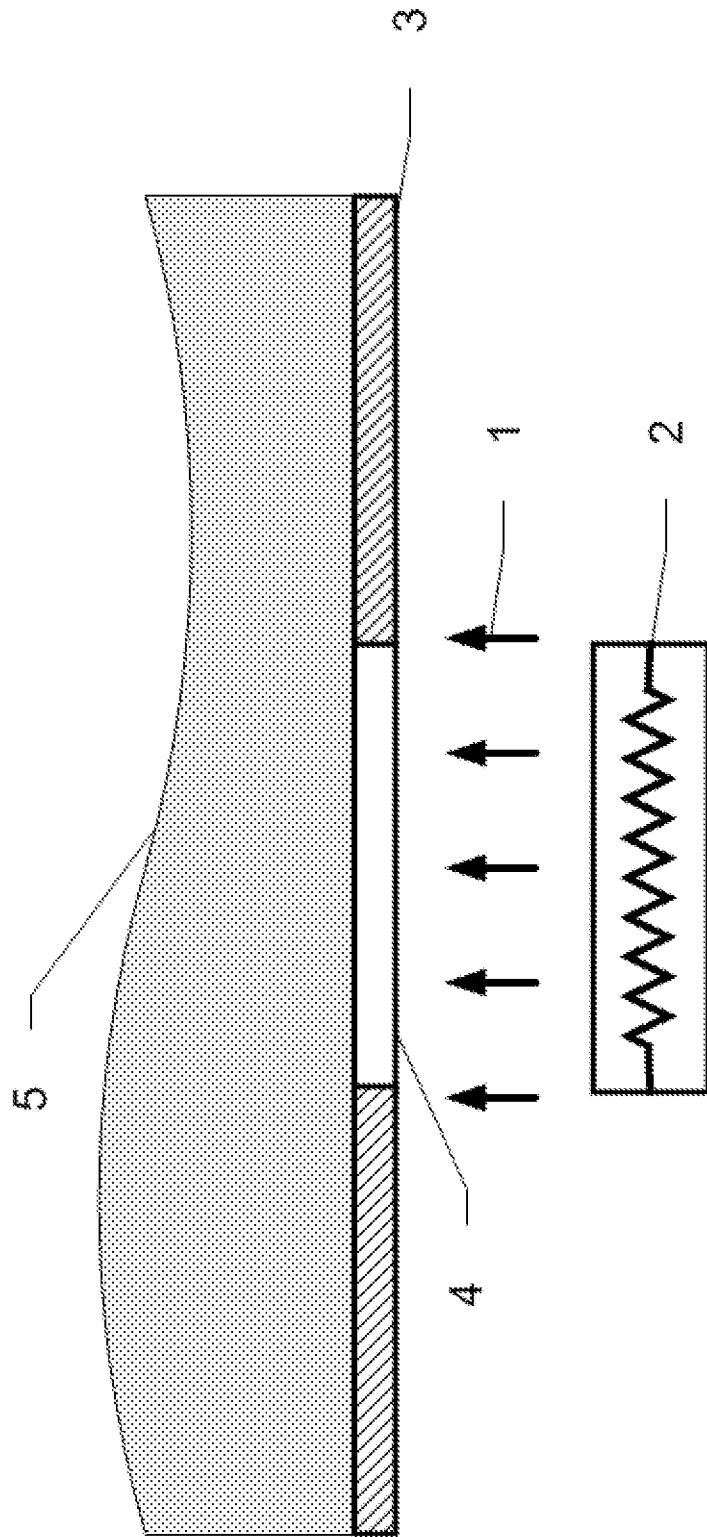


FIG. 1

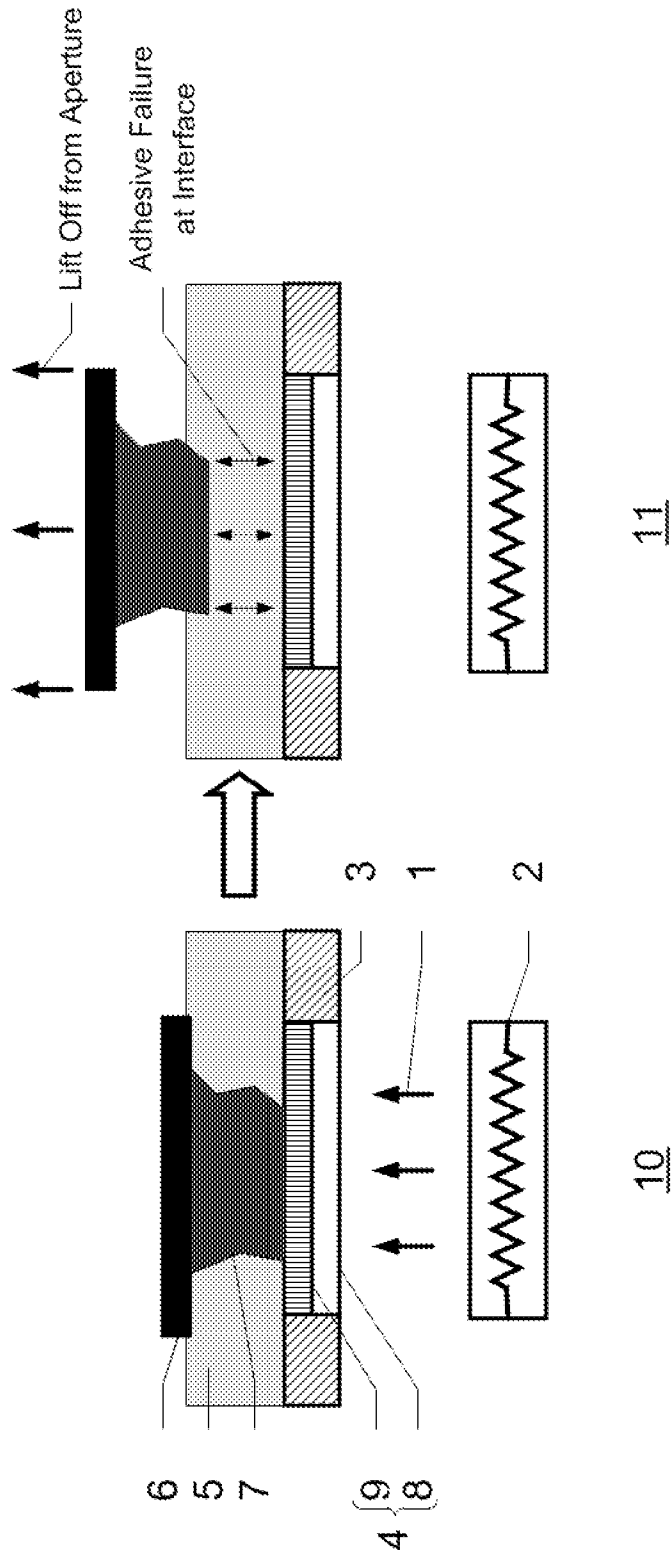


FIG. 2

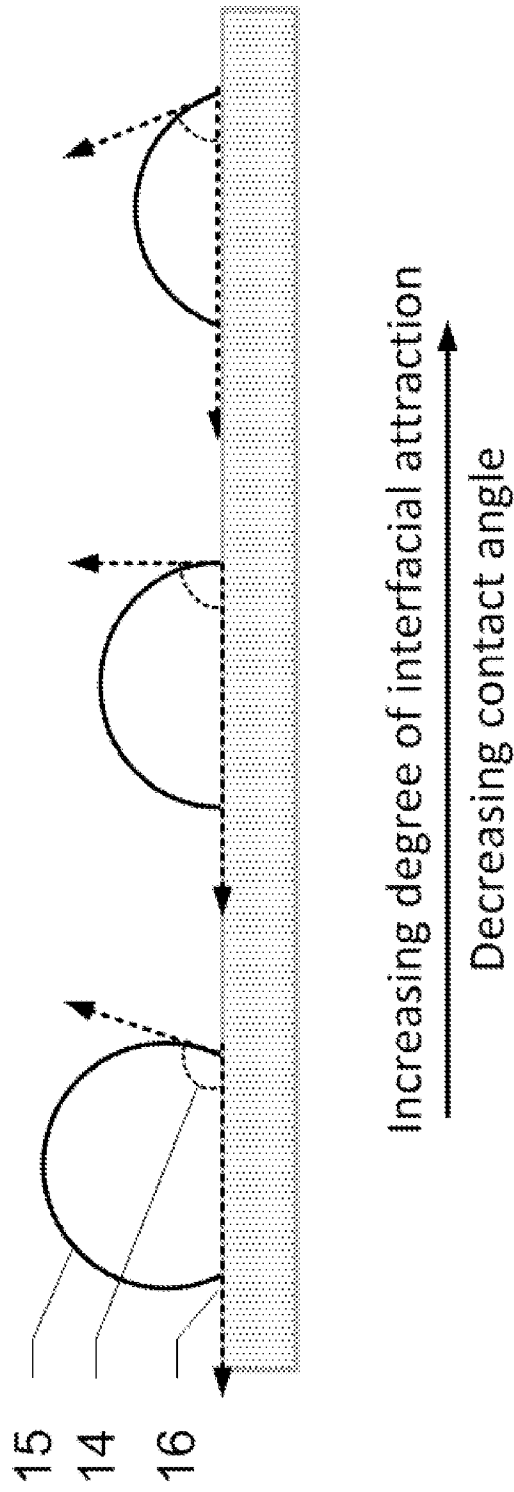


FIG. 3

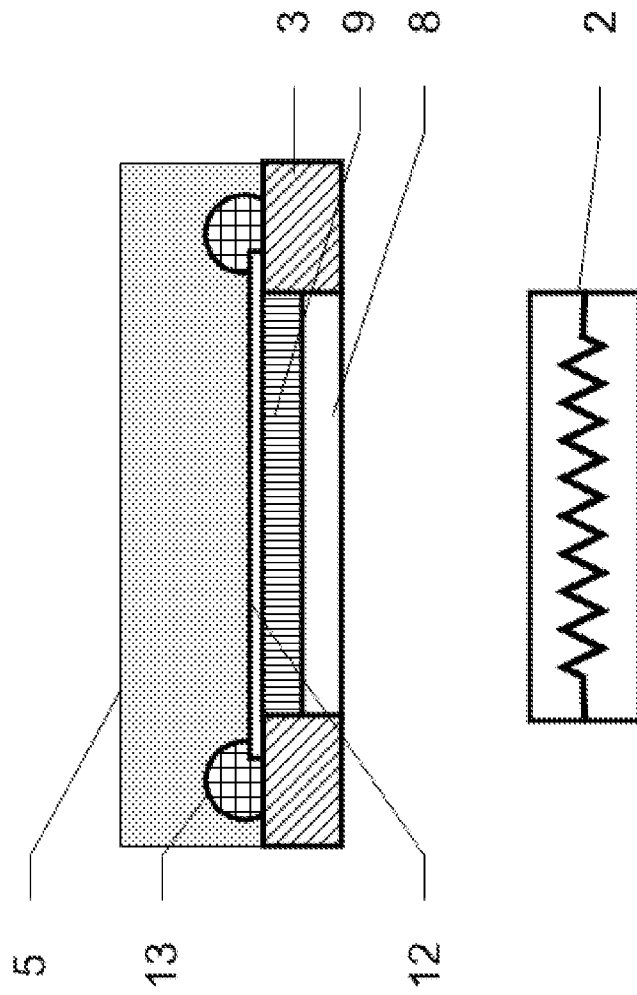


FIG. 4

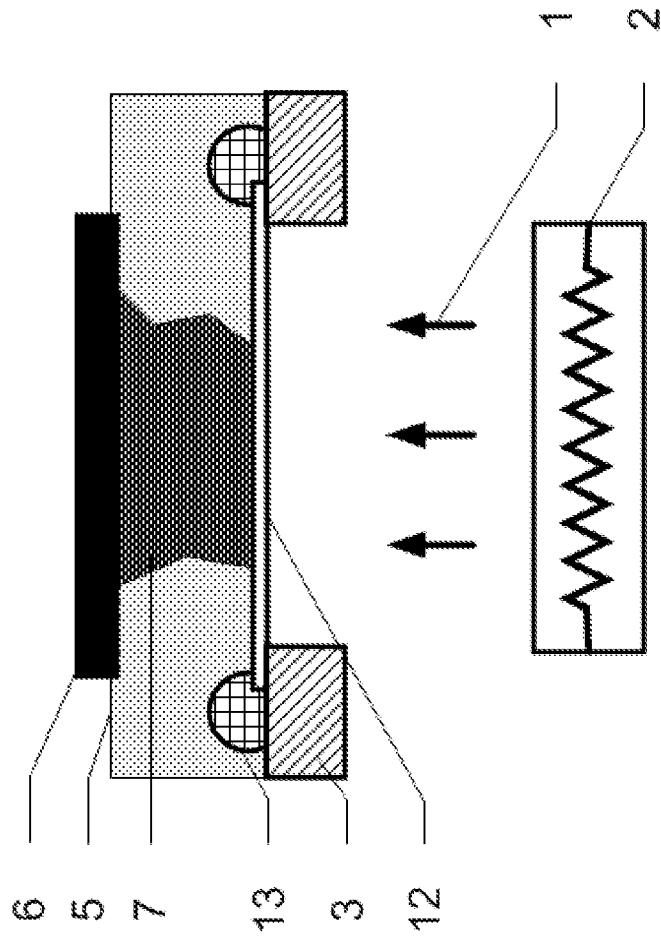


FIG. 5

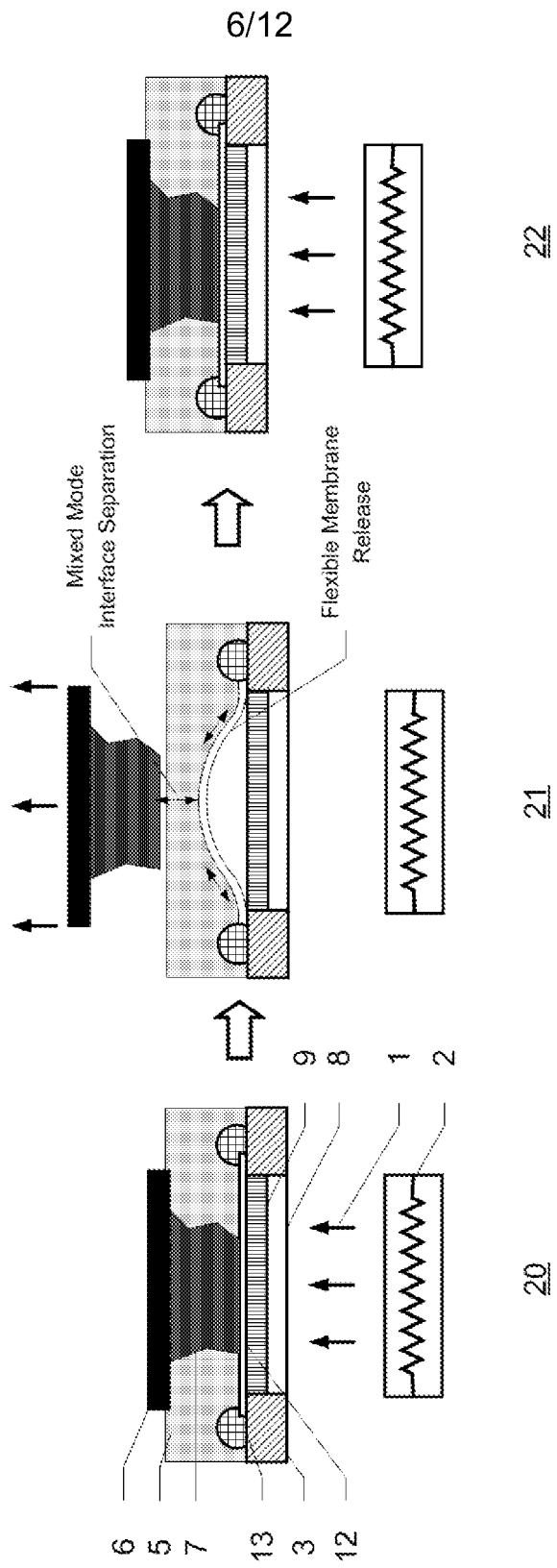


FIG. 6



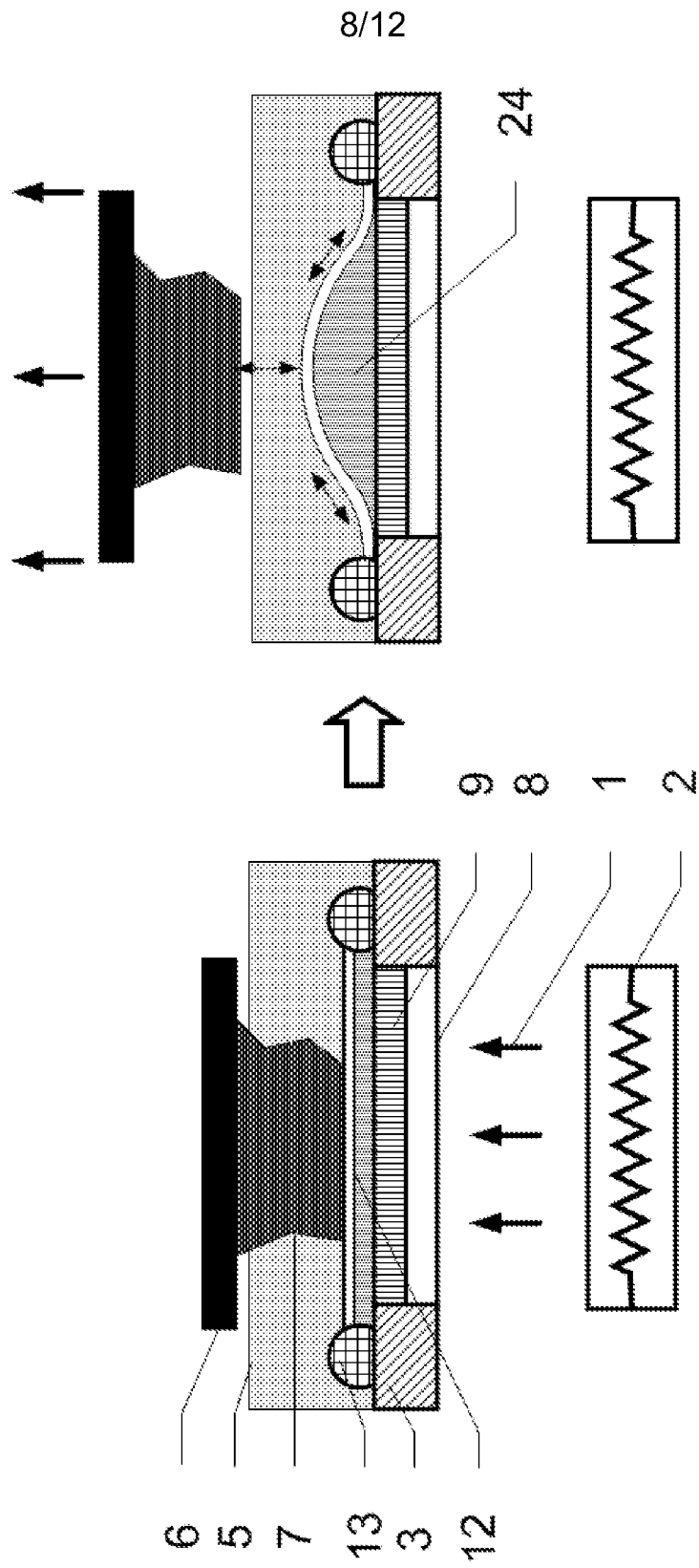


FIG. 7B

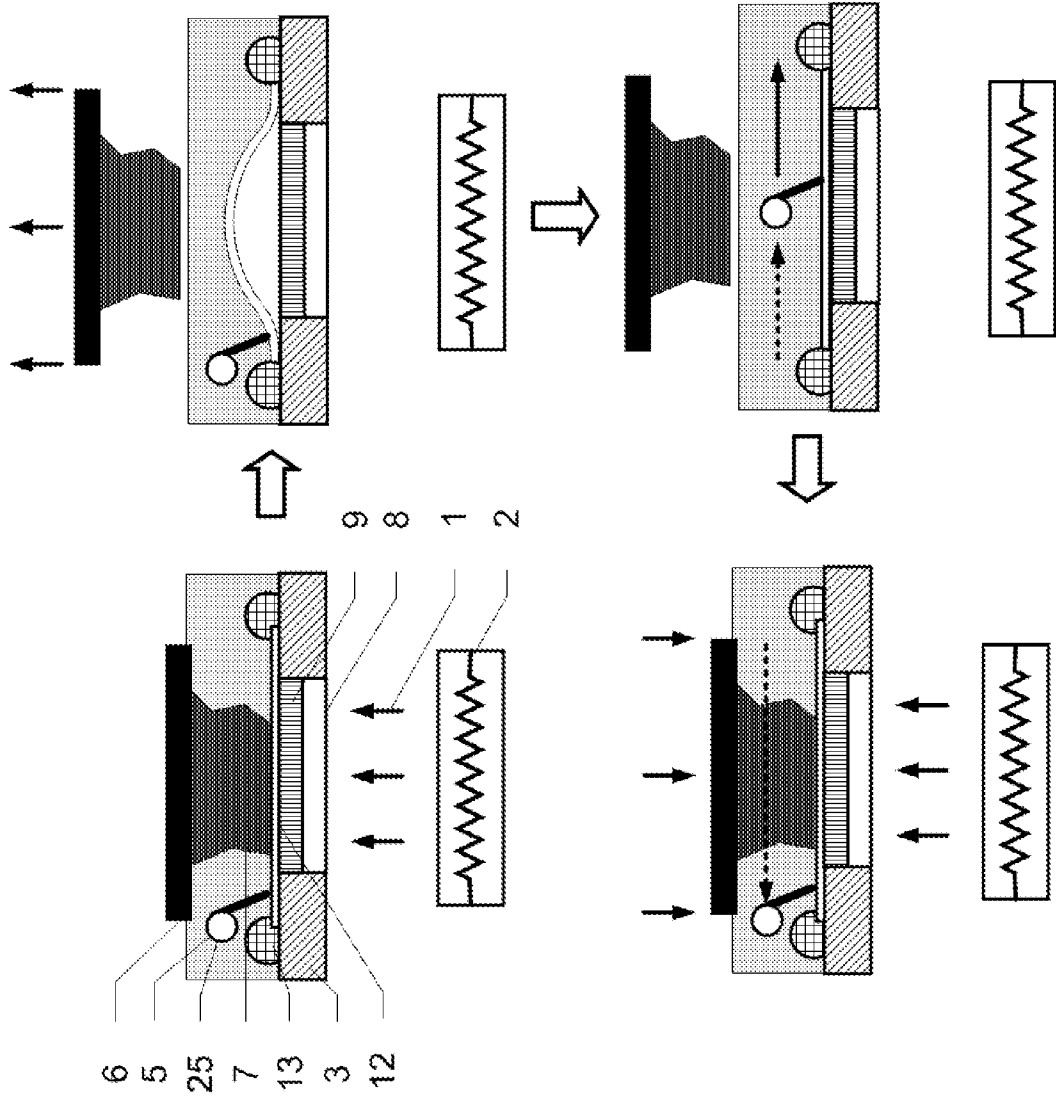


FIG. 8

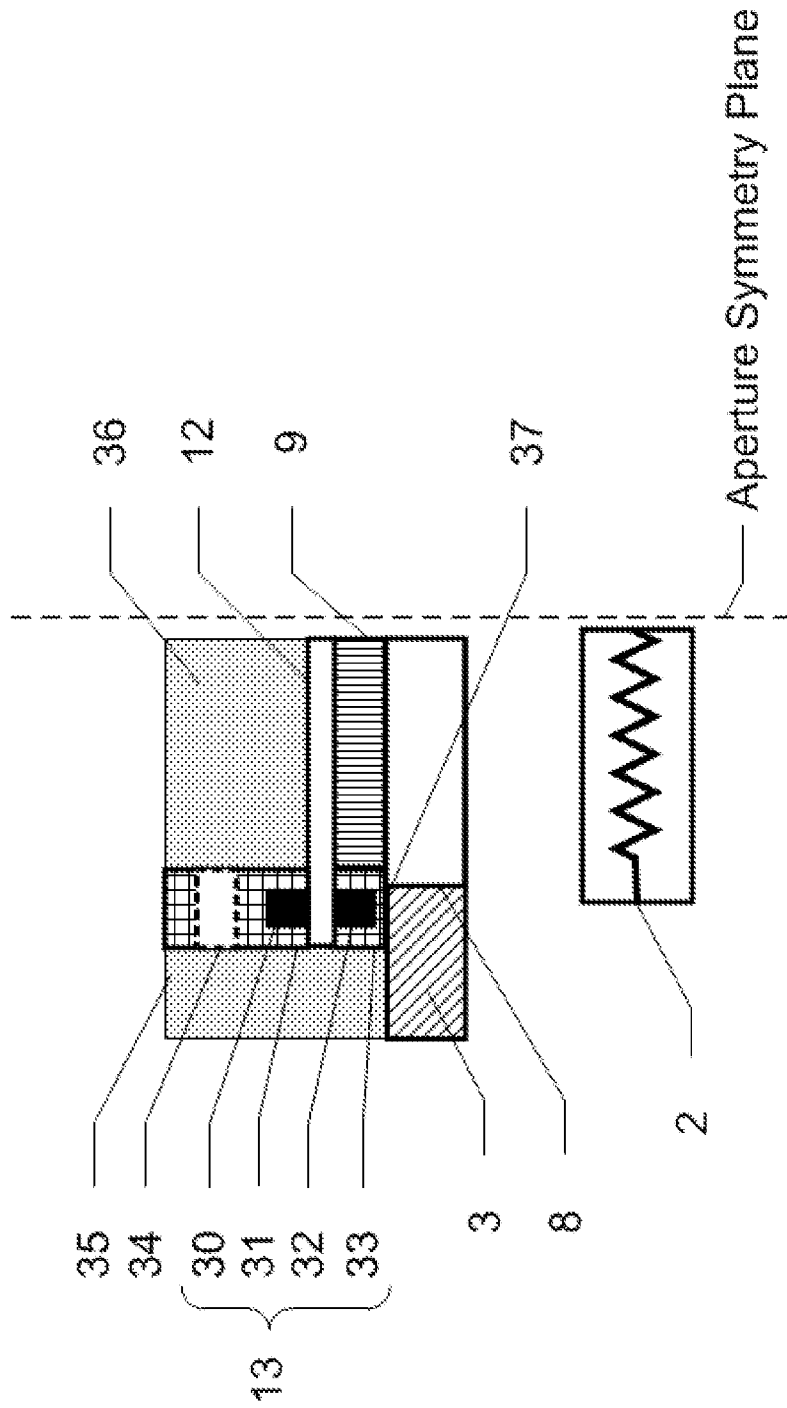


FIG. 9

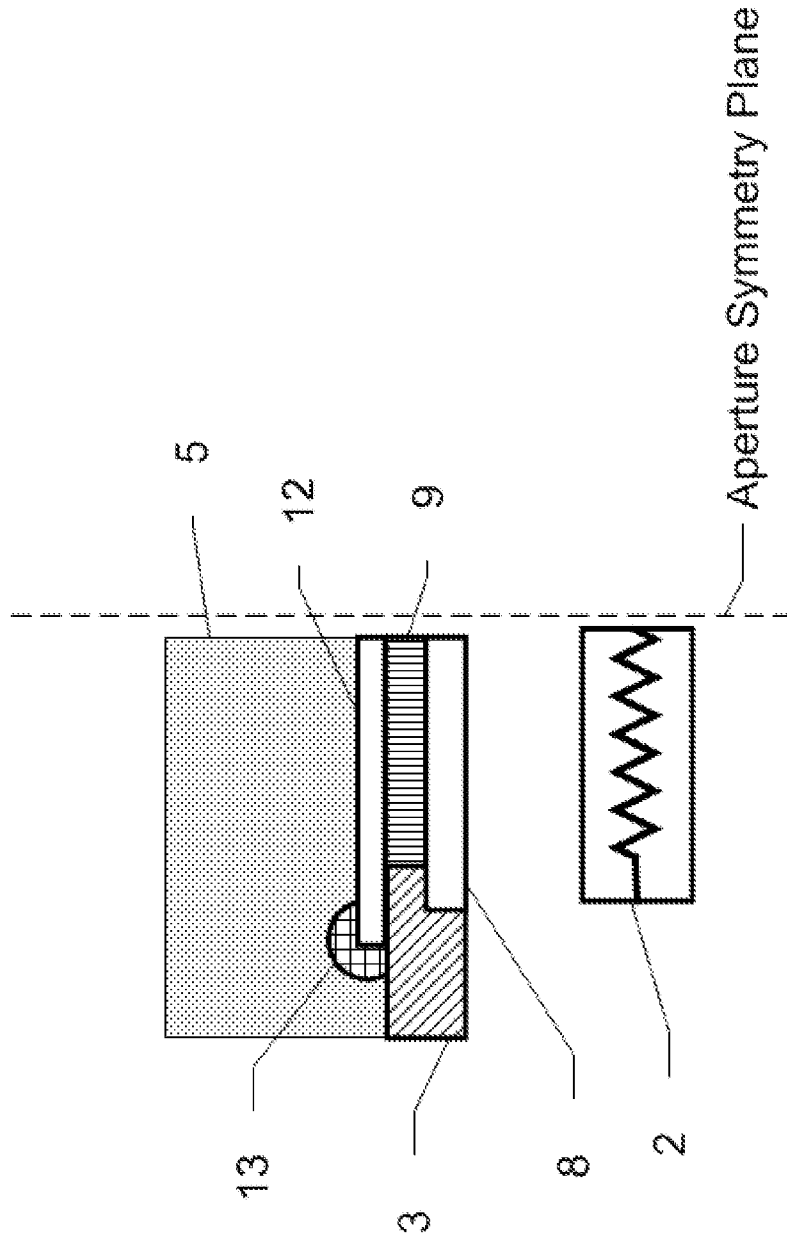


FIG. 10

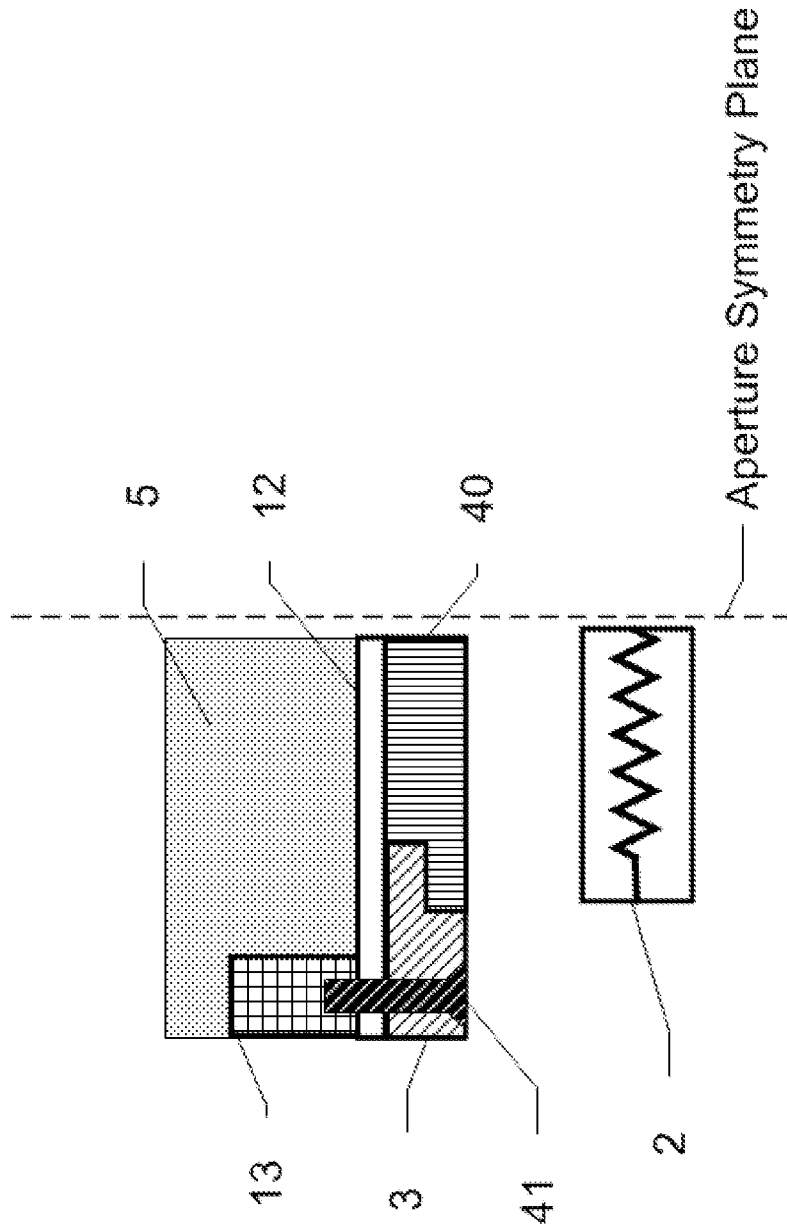


FIG. 11

## INTERNATIONAL SEARCH REPORT

International application No.  
**PCT/US2017/046609****A. CLASSIFICATION OF SUBJECT MATTER****B29C 64/286(2017.01)i, B29C 64/129(2017.01)i, G03F 7/20(2006.01)i, B33Y 40/00(2015.01)i, B33Y 30/00(2015.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

B29C 64/286; B65B 7/00; B29C 67/00; B28B 7/36; B29C 35/08; B29C 64/129; G03F 7/20; B33Y 40/00; B33Y 30/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) &amp; Keywords: bottom, stereolithography, adherence, damage, flexible, reservoir

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 7438846 B2 (HENDRIK JOHN) 21 October 2008 See column 1, lines 8-9, 20-25; column 2, lines 30-33, 55-57; column 3, lines 27-34, 42-48; column 4, lines 36-38; claims 1, 7; and figures 1C, 3A-3C.	1-21
Y	US 2015-0064298 A1 (KAO-CHIH SYAO) 05 March 2015 See paragraphs 51, 64; and figures 2B, 8A.	1-21
A	US 2015-0056320 A1 (DWS S.R.L.) 26 February 2015 See the entire document.	1-21
A	US 2012-0328726 A1 (SERGIO ZENERE) 27 December 2012 See the entire document.	1-21
A	US 2013-0295212 A1 (YONG CHEN et al.) 07 November 2013 See the entire document.	1-21

 Further documents are listed in the continuation of Box C. See patent family annex.

\* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

19 January 2018 (19.01.2018)

Date of mailing of the international search report

**22 January 2018 (22.01.2018)**

Name and mailing address of the ISA/KR

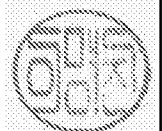
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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.

**PCT/US2017/046609**

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Information on patent family members

International application No.

**PCT/US2017/046609**

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