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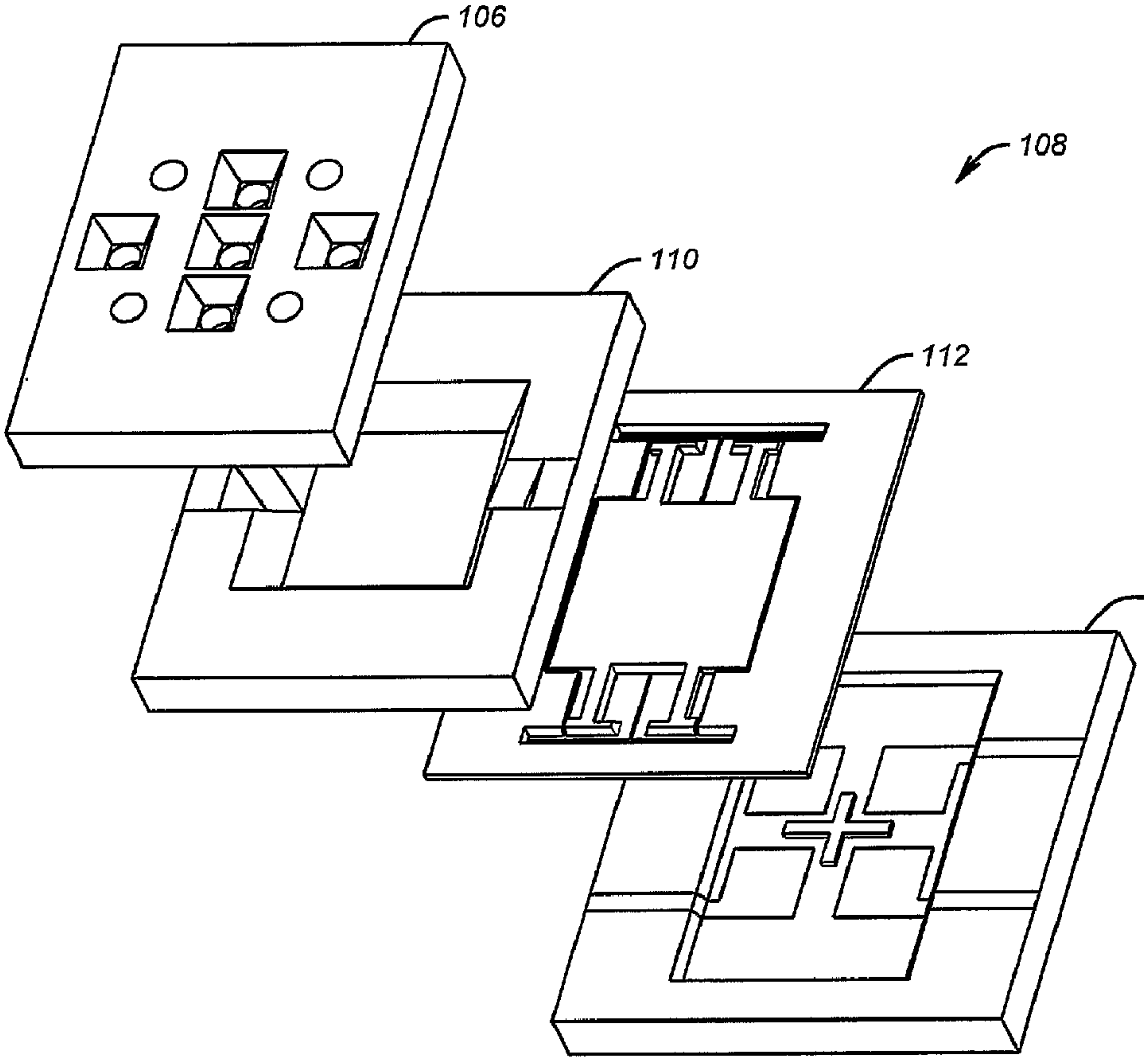

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A digital optical switch apparatus and method for manufacture. The apparatus includes a mirror assembly (112) coupled to a top cap (110) and to a bottom cap (114).

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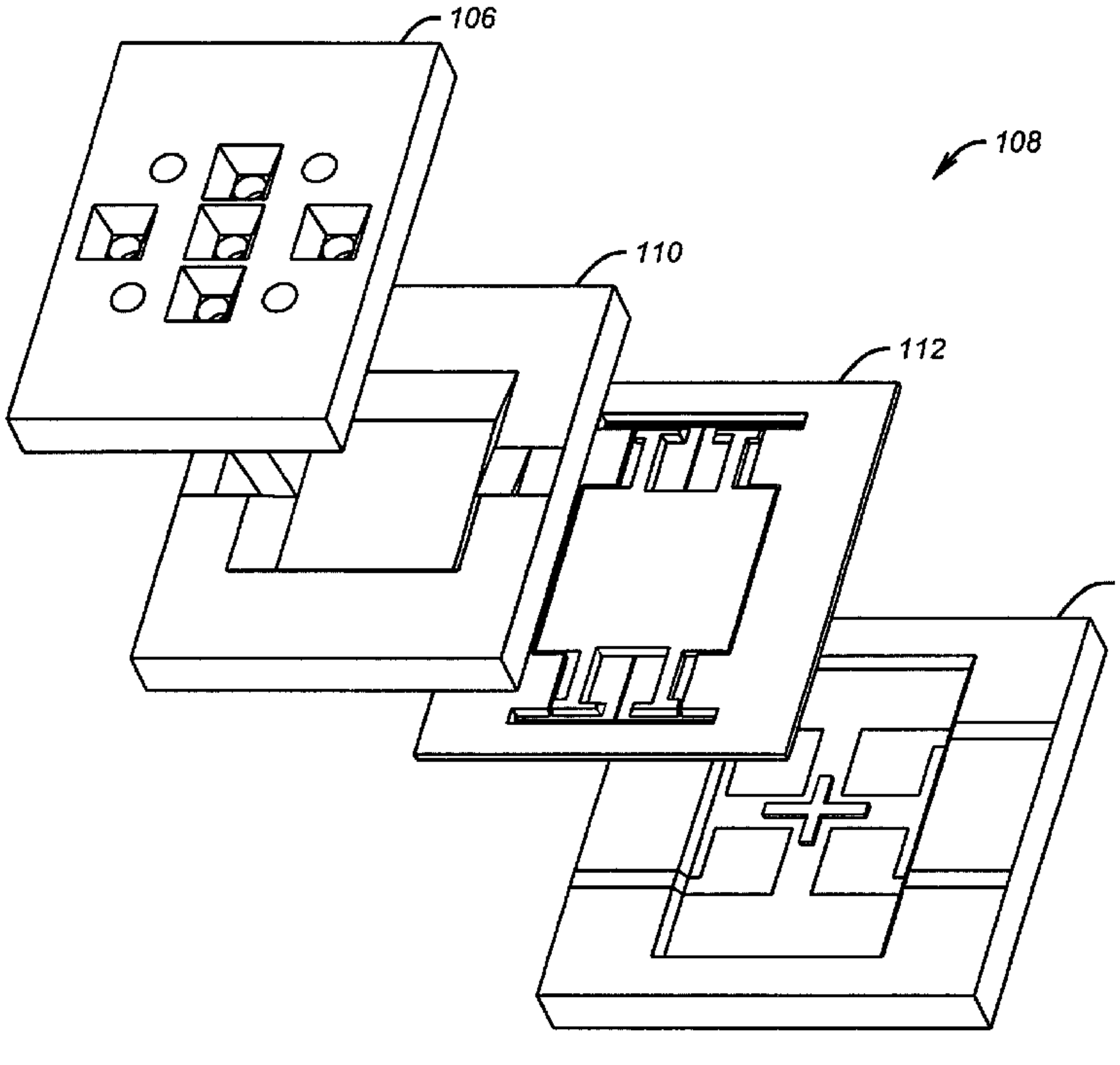

(57) Abstract: A digital optical switch apparatus and method for manufacture. The apparatus includes a mirror assembly (112) coupled to a top cap (110) and to a bottom cap (114).

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APPLICATION FOR LETTERS PATENT

TITLE: **DIGITAL OPTICAL SWITCH APPARATUS AND PROCESS FOR MANUFACTURING SAME**

INVENTORS: **DULI YU; ARJUN SELVAKUMAR; HOWARD GOLDBERG AND TAECHUNG YI**

Background of the Invention

Field of the invention

[0001] The present invention generally relates to three-dimensional micro-machined devices and more particularly to a micro-machined mirror apparatus having multiple axes of rotation and discrete positioning.

Description of the Related Art

[0002] Micro-machined devices have gained widespread use in a variety of applications in recent years. One such application is the use of such devices in optical applications in which a micro-machined mirror structure is used as an optical switch to deflect an incident light beam to redirect the light beam in a plurality of directions.

[0003] The typical MEMS mirror used as an optical switch includes a micro-machined mirror structures that can be deflected by applying electrical energy to one or more electrodes. The energized electrodes provide a force on the mirror thereby inducing an angular change in the surface plane of the mirror.

[0004] It is desirable to have a mirror surface with two axes of angular (i.e. rotational) freedom in these optical switches. Some typical devices provide such freedom by providing a gimbaled coupling between the mirror and a mirror support structure, then providing a gimbaled coupling between the mirror support structure and a second support structure. Other known devices include a pedestal-type mirror structure.

[0005] While these typical devices provide the desired degrees of freedom, they suffer from several disadvantages. These devices provide only analog movement. This movement is a continuous sweeping movement from one angular position to another angular position. As such, any induced mechanical shock during operation may move the mirror thereby disrupting the operation. Moreover, accurate positioning using electrical energy is very difficult. Thus it is desirable to provide a planar mirror surface with multiple axes of rotation, and providing digital positioning. Digital positioning as used herein is defined as one or more discrete planar positions including known angular relationships to a beginning or reference planar angle.

[0006] Another problem with the typical optical switch is that they are relatively difficult to manufacture. MEMS devices are three-dimensional structures. MEMS optical switches typically require at least two stacked layers having electrodes and electrode contacts passing from one layer to the next. The conventional process includes non-planar etching and dicing techniques that increase manufacturing time and reduce the reliability of the final product. Thus, it is desirable to provide a product manufactured using planar processes for etching, bonding and electrode traversal of multiple tiered devices.

Summary of the Invention

[0007] The present invention addresses one or more of the above-identified problems found in conventional MEMS optical switches, such as those conventional devices described above. The present invention provides an optical switch comprising multiple layers of structure including a mirrored surface having digital positioning. Furthermore, the present invention provides a process of manufacturing a MEMS three-dimensional structure using planar methods.

[0008] The present invention provides a micro-machined apparatus including a housing and a support structure coupled to the housing. A mass is coupled to the support structure by a pair of single-gimbaled structures for providing rotational movement of the mass about two axes of rotation. The structures are preferably T-shaped hinges. A plurality of electrodes is coupled to the structure. The electrodes are energized with electrical power for providing a selectable force to the mass that moves the mass in a plurality of angular directions. A plurality of travel stops are positioned within the housing for arresting movement of the mass such that the mass position is one of a plurality of discrete predetermined angular positions.

[0009] Another aspect of the present invention provides a micro-machined cascaded digital optical switch comprising two or more mirror assemblies coupled in cascading relationship. Each mirror assembly includes a mirror coupled to a support structure by a pair of substantially T-shaped hinges for providing rotational movement of the mass about first and second axes of rotation, a top cap having a plurality of first electrodes, the top cap being bonded to the mirror support structure and a bottom cap having a plurality of second electrodes, the bottom cap being bonded to the mirror support structure, wherein the first and second electrodes when energized with electrical power provide a selectable force to the mirror for moving the mirror in a plurality of angular directions, and a plurality of travel stops positioned about the mirror for arresting movement of the mirror such that the mirror position is one of a plurality of discrete predetermined angular positions. The assemblies might be coupled using fiber optics or a fixed reflective surface might be used for reflecting light exiting one mirror to a second mirror.

[0010] Another aspect provides two mirrors in a face-to-face relationship. A first mirror received light through any of a plurality of input ports. The light is reflected an in internal incident light beam to a second mirror by controlling the position of the first mirror. The internal incident light beam enters a second mirror through a port. The second mirror is controllably positioned to reflect the internal incident light beam to exit the assembly through any one of a plurality of exit ports.

[0011] Another aspect of the present invention provides a process of manufacturing a micro-machined apparatus. The process comprises providing a first substrate with a plurality of electrically isolated islands, providing an electrically conductive bond pad on each island, providing at least one second substrate having a plurality of electrical leads, and bonding the first substrate to the second substrate wherein each electrical lead is electrically coupled to one of the bond pads thereby creating a multi-tier device having electrically isolated electrical leads of one tier being accessible at another tier.

[0012] Another aspect of the present invention provides a process of manufacturing a micro-machined apparatus comprising providing a first substrate with an electrically non-conducting surface. An in-situ shadow mask is then provided to shadow one or more predetermined regions of the surface. An electrically conductive material is then deposited over the substrate and shadow mask, wherein the shadowed regions remain electrically non-conductive after the metal deposition.

[0013] These several aspects enable transferring electrical feedthrough from each layer of a three-layer stack to accessible wire bond pads located in the top surface of the bottom and middle layers of the stack. Electrical conduits formed on the underside of the top cap of the stack are coupled to the top surface of the middle layer through isolated bond islands. Electrical paths on the middle layer lead to larger bond pads. Electrical conduits on the bottom layer of the three-wafer stack are accessed through openings formed in the middle layer.

[0014] The present invention allows manufacturing personnel or machinery access to the several bond pads via multiple electrical conduits located on various wafers of the three-wafer stack. The conduits are electrically insulated from each other. The process obviates the need for complicated through-wafer via fabrication, and provides a planar machining process to fabricate the multi-tier MEMS structure.

Brief Description of the Drawings

[0015] For detailed understanding of the present invention, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

Fig. 1A is a packaged mirror array apparatus according to the present invention;

Fig. 1B is a 1xN mirror array stack assembly according to the present invention and used in the packaged apparatus of **Fig. 1A**;

Fig. 1C is an exploded view of a micro-electromechanical systems (MEMS) mirror assembly according to the present invention;

Fig. 2 is a top view of the apparatus **106**;

Fig. 3 is a top view of the top cap **110**;

Fig. 4 is a bottom view of the top cap **110** showing top cap electrodes;

FIG. 5 shows the mirror assembly **112** made according to one embodiment of the present invention;

Fig. 6A is an isometric view of the bottom cap **114**;

Figs. 6B-D are schematic illustrations of alternative embodiments of the apparatus;

Fig. 7A-C show a process according to the present invention for manufacturing the apparatus of Figs. 1-6;

Figs. 8A-B show views of a bond pad region of a device made using the process of **Figs. 7A-C**;

Figs. 9A-9C show a shadow-masking method according to the present invention for optional use in the process of **Figs. 7A-C**;

Figs. 10A-B illustrate operation of alternative embodiments of a cascaded digital mirror according to the present invention;

Fig. 10C illustrates operation of an alternative cascade embodiment that forms a face-to-face 8X8 digital optical switch according the present invention;

Fig. 11 illustrates an alternative process embodiment provided by the present invention; and

Fig. 12 is an alternative process embodiment with inverted mirror manufacturing to allow alternate electrode routing.

Description of the Preferred Embodiment

[0016] **Fig. 1A** is a packaged micro-electromechanical system (MEMS) mirror array apparatus **100** according to the present invention. The apparatus **100** includes a package **102** such as a typical printed circuit board (PCB) mountable housing or other frame structure known in the art, and a plurality of electrically conductive leads **104**. As will be described later with reference to **Fig. 1C**, the packaged assembly may include one or more optional overlays

106. The apparatus **100** of the present invention is useful as a digital optical switch for use in fiber optic or optical laser systems.

[0017] Referring to **Fig. 1B**, the apparatus **100** includes an internally mounted 1xN mirror array stack assembly **108** according to the present invention. The term 1XN as used herein describes one or more devices combined in an array, wherein the variable term N is an integer ranging from 1 (for a single device) to a positive value of 8 or more. The array assembly **108** includes a top electrode wafer **110**, a thinned mirror wafer **112** and a bottom electrode wafer **114**.

[0018] The top electrode wafer **110**, also called herein "top cap **110**", includes a mirror window **116** and a bond pad window **118** spaced apart from the mirror window **116**. The mirror window **116** provides an optical path that allows light to pass through the top cap **110** to meet one or more mirrors **120** integral to the mirror wafer **112**. The bond pad window **118** allows easy manufacturing access to a plurality of electrically conductive bond pads **122**. The plurality of bond pads **122** are connected to the electrical leads **104** for final packaging of the apparatus **100**.

[0019] **Fig. 1C** is an exploded view of the 1xN mirror array assembly 108 shown as a 1x1 (single-mirror stack) for simplicity of explanation. Shown is the three-wafer stack assembly **108**, including the bottom cap **114**, the thinned mirror wafer **112**, top cap **110** and the optional light-guide overlay **106**. The mirror wafer **112** is a dual axis moveable mirror assembly, which is bonded between the top cap **110** and bottom cap **114** to create the three-dimensional MEMS assembly **108**. The assembly **108** is then bonded to the frame **102** described above and shown in **Fig. 1A**. The light-guide overlay **106**, when used, is bonded to the frame **102** such that the overlay **106** and top cap **110** are separated by a distance sufficient to allow light to travel through the light guide overlay and mirror window **116** along predetermined light paths.

[0020] **Fig. 2** is a top view of the light-guide overlay **106**. The overlay **106** has a main structure **200**. Formed in the structure are an incident light port **202** and an incident light guide **204** in the approximate center of the structure **200**. Incident light enters the apparatus **100** through the incident light port **202**, with the incident light guide **204** providing angular tolerance for the incident light. The incident light is reflected within the apparatus **100** such that the reflected light travels along one of a plurality of discrete exit paths. The term "discrete" as used herein means substantially motionless when used to describe position. The term further means substantially invariant when used to describe a light path.

[0021] Light following an exit path exits the apparatus through one of a plurality of exit ports **206a-h**. Exit ports **206a-h** may or may not include an exit light guide **208a-d** for allowing interface tolerance between the apparatus **100** and an interfacing device (not shown). Similarly, incident light guide 204 is an optional feature. Furthermore, those skilled in the art with the benefit of the present disclosure would recognize that port **202** illustrates and described herein as incident light port **202** might serve as an exit port in an alternative embodiment. In this alternative embodiment any of the exit ports **206a-h** can be adapted to serve as an incident light port.

[0022] The optional light-guide overlay **106** is not required for an effective embodiment of the present invention. For example, applications having incident light comprising a laser may not need a guide. In such applications, the laser has a substantially invariant beam angle for the distances traveled. Thus the light paths are defined by the incident angle of the laser and the angle of reflection. In one embodiment, digital mirror assemblies are cascaded and the light guide overlay 106 is beneficial for cascading the assemblies. As will be explained later, each of the eight light guide output ports may be coupled to an input port of one of eight cascaded assembly overlays. A preferred coupling is by optic fibers. In this manner, the exit path is not necessarily restricted to a straight-line path.

[0023] The overlay **106** includes one or more mechanical bond pads **210a, 210b** to allow mechanical bonding to the external optical packaging frame **102**.

[0024] **Fig. 3** is a top view of the top cap **110**. The top cap **110** is formed in a substrate **300** such as a silicon wafer and includes a window **302** for allowing light to pass from the overlay **108**, through the top cap **110** to the mirror assembly **112**. Reflected light passes from the mirror assembly **112**, through the window **302** and out of the apparatus **100** through one of the exit ports (see **Fig. 2 at 206a-h**).

[0025] The top cap **110** includes electrically conductive contact pads **304a-b** that provide conductive paths for energizing top cap electrodes (not visible in this view). Each path **304a-b** includes a wedge recess **306a-b** terminating in a groove opening **308a-b**. This allows for a process known as electrical feed-through via for making an electrically conductive path from the contact pads **304a-b** through the top cap **110** to connect the electrodes on the bottom of the top cap. To do this, electrically conductive metal is deposited using later described processes to the top of the top cap. The metal passes into the wedge recesses **306a-b**, through the groves **308a-b** to make contact with lead strips located on the bottom of the top cap.

[0026] **Fig. 4** is a bottom view of the top cap **110** showing a two-electrode configuration. Shown are top cap electrode feed strips **402a-b** that are electrically coupled to the top cap contact pads **304a-b** by the electrical feed-through via process just described. The top cap **110** has a bottom surface **404** in which a recess **406** is formed according to the process of the present invention. Two top cap electrodes **400a-b** are integral to the lead strips **402a-b**, both of which are metal deposited within the recess 406. Metal deposition of electrodes will be described in a process embodiment of the present invention. The electrodes **400a-b** and lead strips **402a-b** are preferably gold, but may be any suitable electrically conductive metal such as silver or aluminum or an alloy.

[0027] It is important to note that electrical feed through via is only one embodiment contemplated by the present invention. Other methods of electrical feed through enabled by the processes of the present invention are isolated-island method of **Figs. 7A-C**. Also, the known technique if drill and fill could be used to provide electrical feed through. Drill and fill methods, however, are more time-consuming and less precise than the isolated island method and thus less desirable.

[0028] **Fig. 5** is an isometric view of the mirror assembly **112**. The assembly **112** is preferably an integral structure formed by micro-machining processes according to the present invention. The mirror assembly **112** is preferably an integral structure having a mass coupled to a support structure by a pair of substantially T-shaped hinges **512**, **514**, which provides a single-gimbaled structure with two axes of rotation. An example of one such mirror assembly is described in detail in U. S. Patent No. 6,315,423 to Yu et al. An example of a mirror assembly having a plurality of bottom cap electrodes for providing two axes of rotational movement is described in detail in U. S. Patent Patent No. 6,454,421 to Yu et al. The present invention provides digital positioning, control of movement damping, and manufacturing processes among other things not provided in these previous applications. Other structures, however, are considered within the scope of this invention. For example, any single- gimbaled hinge structure could replace the T-shaped hinge described herein.

[0029] **FIG. 5** shows the mirror assembly 112 made according to one embodiment of the present invention. The mirror assembly 112 includes a frame or mirror support structure 500 having support members 502,504, 506 and 508. The assembly 112 further comprises a mirror collection plate 510 with a reflective surface 528, a top T-shaped hinge 512, a bottom T-shaped hinge 514, a top left travel stop finger 516, a top right travel stop finger 518, a bottom left travel stop finger 520, and a bottom right travel stop finger 522.

[0030] The advantage of digital positioning of the mirror collection plate 510 is provided by interaction between one or more of the travel stop fingers 518-522 and at least one of the top cap 110 and bottom cap 114. The final position is determined by the interaction along with electrical energy applied to one or more electrodes in the apparatus 100. In this manner a mirror can be created having discrete states #1-#8. Those skilled in the art would appreciate that the mirror collection plate 510 could be used as a multi-point travel stop, thereby eliminating the need for the travel stop fingers 516,518, 520, and 522.

[0031] The 8 individual states of the mirror in each of these alternative embodiments can be described together for brevity. For these embodiments, state #1 is created when the upper travel stop fingers 516 and 518 interact with the bottom cap 114 or when the top edge of the mirror collection plate 510 interacts with the bottom cap 114. State #2 is created when the two lower travel stop fingers 520 and 522 interact with the bottom cap 114 or when the lower edge of the mirror collection plate 510 interacts with the bottom cap **114**. State #3 is created when the left travel stop fingers **516** and **520** interact with the bottom cap **114** or when the left edge of the mirror plate interacts with the bottom cap **114**. State #4 exists when the right travel stop fingers **518** and **522** interact with the bottom cap or when the right edge of the mirror plate interacts with the bottom cap **114**. State # 5 is created when the upper right travel stop finger **518** or the upper right corner of the mirror collection plate **510** contacts the bottom cap **114**. State #6 upper left travel stop finger **516** or the upper left corner of the mirror **528** contacts the bottom cap **114**. State #7 exists when the lower right travel stop finger **522** or the lower right corner of the mirror collection plate **510** contacts the bottom cap **114**. State #8 exists when the lower left travel stop finger **520** or when the lower left corner of the mirror collection plate **510** contacts the bottom cap **114**.

[0032] Those skilled in the art with the benefit of this disclosure would recognize that the present invention is useful in the above-described digital mode or in an analog mode. As the mirror collection plate **510** moves between any two discrete states, the movement is analog in nature. Therefore, one only need to precisely control electrode voltage to operate the mirror in a three-dimensional analog mode. This analog mode of operation preferably uses a critically damped, or overdamped mirror.

[0033] The frame **500** provides the overall support structure for the mirror assembly **112**. The thickness of the collection plate **510** may range, for example, from about 10 to 70 microns depending on desired damping characteristics and to provide a compact structure having a low mass. In a preferred embodiment, beams of the T-shaped hinges **512, 514** have effective beam lengths ranging from about 500-2500 microns and cross sections of about 8,000 microns^2 to 160,000 microns^2 in order to absorb shock loads of about 2000g/0.5 ms half sine wave input.

[0034] The mirror collection plate **510** is coupled to the top T-shaped hinge **512** and the bottom T-shaped hinge **514**. In this manner, the mirror collection plate **510** is provided two axes of rotation **530, 532**. In a preferred embodiment, the axes **530, 532** are substantially perpendicular to one another. One axis **530** being positioned substantially along a first centerline of the mirror collection plate **510** and is coincident with the center of the T-shaped hinges, **512** and **514**, thereby providing a common axis of rotation for the springs. The other axis **532** is position perpendicular to the first axis **530** and runs substantially along a second centerline normal to the first centerline of the assembly **112**.

[0035] The reflective surface **528** is coupled to the top of the mirror collection plate **510**. In this manner, dual-axis rotation of the mirror collection plate **510** about the axes **530, 532** causes incident light from a light source (not shown) to reflect off of the reflective surface **528** in a plurality of directions.

[0036] The reflective surface **528** may be comprised of any number of conventional commercially available optically reflective surfaces such as, for example, gold, silver or aluminum.

[0037] **Fig. 6A** is an isometric view of the bottom cap **114**. The bottom cap **114** includes a plurality of electrodes **604a-d** positioned within a cavity **606** formed in the surface **602** of the bottom cap **114**. Each electrode has an associated conductive lead **608a-d** extending from the electrode to a perimeter location on the bottom cap **114**. In operation, the leads are connected to an electrical power source (not shown) adapted to provide electrical power to any combination of electrodes. The bottom cap also includes an optional damping baffle **610**. The damping baffle is a movement control structure that provides airflow resistance to mirror movement for tuning damping. In one embodiment, the damping baffle acts as a pedestal for arresting vertical movement of the mirror when energy is applied to the electrodes **604a-d** alone. The pedestal assists in converting the vertical movement into rotational movement about one or more axes.

[0038] As discussed above the mirror function is to assume one of several discrete positions upon application of energy to top cap and bottom cap electrodes. Damping is a function of several manufacturing characteristics and parameters. Among these are materials selected, material thickness, hinge shape, viscosity of internal fluid (e.g. amount and purity of air trapped within the assembly) and so forth. A severely underdamped mirror will tend to overshoot the desired position and then settle into the desired position after several oscillations. A severely overdamped mirror will move toward the desired position much too slowly for practical optical switching application. Therefore, damping movement control is desirable. A damping level called critical damping is desired to arrest mirror movement while providing quick response. A critically-damped mirror will quickly move to the selected position without overshooting or oscillation.

[0039] It is important to note that the damping baffle **610** may be constructed as desired to either contact the mirror collection plate **510** during operation or to not contact the mirror collection plate **510**. **Fig. 6B-D** illustrate this point. **Fig. 6B** shows an embodiment wherein the mirror **510** contacts the damping baffle **610** and the bottom cap **114** to effect one of the discrete switching states. **Fig. 6C** shows an alternative embodiment of a mirror assembly in the same switching state, but the mirror **510** only contacts the bottom cap **114**, and does not contact the damping baffle **610** or the top cap **110**. **Fig. 6D** shows a preferred embodiment in which the mirror **510** is in the same switching state and contacting the top cap **110** and the bottom cap **114**, but is not in contact with the damping baffle **610**. Each embodiment is constructed by selecting the dimensions of the damping baffle and mirror to create the desired embodiment.

[0040] In a particularly useful embodiment of the present invention the mirror array assembly **108** may be combined with substantially similar assemblies to effectively multiply the number of digital optical switching states from any number of output paths. Using the exemplary 8-state embodiment of the digital mirror apparatus **100** described above and shown in **Figs. 1A-1C**, a single input or incident beam of light may be digitally switched to 8^n output paths thereby creating a $1x8^n$ digital switch assembly. Here, n is an integer value defined by the number of mirror assemblies cascaded.

[0041] A simple conceptual illustration is provided in **Fig. 10A**. Shown is a cascaded series of mirror assemblies **1002a-c**. An incident light **1004** reflects from a first mirror assembly **1002a** along a first exit path **1006** to meet a reflector **1008**. The reflector **1008** is a fixed reflective surface formed using substantially identical micro-machining process as described in process **700**. A light reflects from the reflector **1008** along a selected 1 of 8 discrete paths to meet another digital optical switch mirror assembly **1002b**. Each one of the 8 paths preferably leads to a substantially similar mirror **1002b**, but only 1 is shown for illustration of the invention. In turn, and limited by the number of cascaded mirror assemblies,.a light reflects from the second mirror along a selected 1 of 8 paths **1012** and so forth to a plurality of cascaded reflectors **1014** and switches **1002c**. Note that the number of states described as 8^n is defined as the maximum number of output states of an 8-state digital optical switch. Although an 8-state digital mirror is a preferred embodiment of the apparatus **100** of the present invention, any digitally-positioned mirror as the term digital is defined herein is contemplated by the present invention. Thus the actual number of digital switching positions is better defined as X^y states, where X is the number of positions possible by a mirror assembly and y is the number of cascaded mirrors. Theoretically, the positioning capability of any one mirror is not determinative of the number of possible positions of any one cascaded mirror. So, any number of digital switch output states is within the scope of the present invention. Thus a 1 x A digital switch apparatus, wherein A is any integer greater than 1 is within scope of the present invention.

[0042] Once cascading is understood, parallel configurations of digital optical switching arrays then logically follow. In this alternative embodiment, a $1X8^n$ cascade may be packaged in parallel with any number of similar array cascades to form an $M \times 8^n$ digital optical switch, where M is an integer formed by the number of cascades packaged in parallel.

[0043] In an alternative cascaded embodiment, the reflectors **1008** and **1014** are not used. In this alternative embodiment, light coupling is accomplished by optic fibers **1018, 1020 and 1022** etc. and light guide overlays **106**. Referring to **Fig. 2** and **Fig. 10B**, incident light travels along path **1004** to enter the first mirror **1002a** via incident light port **202a** of the first mirror overlay **106a**. Note that incident light path **1004** may or may not be an optic fiber. Light exits the first assembly **1002a** via an exit port **206a** and travels along an optic fiber light path **1018** to enter 1 of 8 mirror assemblies **1002b** via an incident light port **202b** of the second mirror overlay **106b**. The light exits the second mirror assembly **1002b** through overlay exit **206b**. Exiting light travels to the next cascaded mirror assembly **1002c** via another optic fiber **1020** to enter incident light port **202c**. The reflection is repeated for cascaded assemblies and any number of fiber optic paths **1022** may be used.

[0044] **Fig. 10C** is a schematic representation of an alternative cascaded embodiment of the present invention. Those skilled in the art would recognize that light is reversible. Therefore, any exit port described hereinabove can also be an incident light port. Shown is an 8X8 optical switch **1050** comprising a first mirror assembly **100** coupled to a second mirror assembly **100'**, which is substantially identical to the first mirror assembly **100**. The mirror assemblies **100** and **100'** are positioned, either separately or in a package, in a face-to-face relationship.

[0045] For simplicity of illustration, input ports are illustrated as a circle with an "X" in the circle, and each output port (internal and external to the package) is represented by a circle with a center dot. Each mirror assembly **100** and **100'** is as described above and shown in Figs. 1A-6. The two mirror assemblies are mounted in a face-to-face relationship to operate as a digital 8X8 optical switch having 8 discrete input ports **206a-206h** and 8 discrete exit ports **206a'-206h'**.

[0046] An incident light beam **1052** enters one of the 8 incident light ports. The beam **1052** is switched according to the present invention within the first assembly **100** by a first mirror collection plate (not separately shown). The reflected beam then exits the first mirror assembly **100** through a first assembly exit port **202** as an internal incident light beam **1054** for the second assembly **100'**. The internal beam **1054** enters the second assembly **100'** through an incident light port **202'**. A not-shown mirror according to the present invention described above disposed in the second assembly **100'** operates according to the present invention to switch the internal beam **1054** toward one of the 8 exit ports **206a'-206h'** as shown to create an exiting light beam **1056**.

[0047] Now that the apparatus of the present invention has been described, a process according to the present invention for manufacturing a three dimensional MEMS apparatus will now be described. **Figs. 7A-7C** show an exemplary micro-machining process **700** according to the present invention used in the manufacture of a three-dimensional MEMS device such as the digital optical switch apparatus **100** described above and shown in **Figs. 1-6** and **10**. For clarity, the apparatus **100** is shown in cross section at several processing stages. This process **700** is separated into a bottom cap process **710**, a top cap process **720** and a three-stack merged mirror process **730**. The process **700** will be explained as a sequence of steps for clarity and ease of understanding. The use of sequential steps for purposes of explanation, however, should not be taken as a limitation of the scope of present invention to any particular manufacturing sequence.

[0048] Those skilled in the art will appreciate the novel processes used without the need for detailed description of known etching techniques. Thus, discussion of the techniques will be limited to direct attention on the process steps, which are the main focus of the invention.

[0049] Those skilled in the art will recognize an etching technique known as deep reactive ion etching, referred to as DRIE or DRIE etch. Also known in the art of MEMS based devices is the use of an epitaxial layer for providing desired electrical properties. Also known in the art is the use of boron doping techniques for providing desired electrical and mechanical properties. Doping is referred to as highly or heavily doped denoted by p++ or doping may be referred to as moderately doped denoted by p+. Doping layers of p++ or p+ are selected depending upon electrical properties desired and is also used as an etch-stop technique during the micro-machining fabrication processes. The high doping of these wafers provides enhanced, ohmic electrical contact between the doped wafers.

[0050] Referring now to **Fig. 7A**, the bottom cap process **710** begins with a substrate **7100** such as a 400 to 700 micron thick single-side polished (SSP) silicon wafer. An oxide insulating layer **7102** is applied, and then KOH etching is performed to create a 1- to 100 micron deep recess **7104** in an upper surface of the wafer.

[0051] Metal electrodes **7106** and metal pads **7108** are formed by known metal disposition techniques. The electrodes are patterned using, for example, thick resist.

[0052] A resistant glass layer **7110** is then applied to the top of the bottom cap in preparation for bonding the bottom cap to the mirror assembly. The glass layer is applied using evaporation, sputter or spin-on techniques known in the art.

[0053] Referring now to **Fig. 7B**, the top cap is formed according to the process **700** by providing a 400 to 700 micron thick double-side polished (DSP) silicon wafer **7202** with an oxide patterned mask **7204**. KOH is then used to etch a top gap **7206** of 10 to 100 microns in the lower surface of the wafer **7202**.

[0054] A second pattern mask **7208** is applied to an upper surface of the wafer **7202**. Timed etching is performed using KOH to create an initial window **7210** in the top cap wafer **7202**. The etching is stopped such that an approximately 1 to 50 micron section **7212** remains to maintain top cap wafer structural integrity for further processing steps. An advantage in this process is that the delicate mirror mechanisms are sealed and protected from potentially damaging process steps such as the dicing operation.

[0055] Top cap or top-side electrodes **7220** are created by depositing electrically conductive metal layers of 50 to 200 angstrom thick chrome (Cr) and then 500 to 800 angstrom thick gold (Au) or of Ti and Au of similar thickness, respectively. These layers also serve as mechanical bonding pads, although it is desirable to keep bond pads and conductive electrodes electrically isolated from each other in multi-electrode multi-tiered devices such as in the present invention.

[0056] **Fig. 7C** shows the process of the mirror assembly and apparatus completion stages, which are collectively referred to as the mirror process **730**. The mirror assembly process begins with a 400 to 700 micron DSP epi silicon wafer **7302**. The wafer **7302** is heavily doped with a p++ epi beam layer **7304** having a preferred thickness of about 1 to 10 microns. A lightly doped p+ structural layer **7306** is then applied over the beam layer **7304**. The structural layer **7306** affects damping and the thickness should be selected along with other parameters to achieve critical damping for the overall structure. The structural layer **7306** is then masked, and etched using KOH etching to expose portions **7308** of the beam layer **7304**. This portion of the process will enable creation of electrically isolated islands **7316a-c**, which will be described in more detail later.

[0057] At **732**, the mirror and bottom electrode wafer are then bonded using anodic bonding. If, however, the electrodes are initially formed by depositing layers of Cr and Au (respective thickness of 50-200 and 500-8000 Angstroms), then the preferred bonding technique is Au eutectic or thermal compression bonding. The mirror wafer **7302** is then thinned using KOH etching to expose an upper surface **7310** of the p++ layer **7304**. Mirror metal **7312** is deposited on the exposed surface **7310**.

[0058] Metal film stress can cause a MEMS mirror to exhibit bowing when thermally stressed, thereby resulting in loss of optical properties. Therefore, in one embodiment, the mirror wafer 7302 is preferably coated with mirror metal 7212 on both sides of the mirror. By coating both sides of the mirror with the same metal, thermal stress is more balanced and the mirror will exhibit less bowing. This embodiment is preferred when expected operational environments include wide temperature range.

[0059] A pattern mask is applied and DRIE etching is used to form beams **7314** and to form bond pad islands **7316**. This provides electrically isolated electrodes, which are now separated by non-conductive air gaps.

[0060] The top cap electrode wafer is then bonded to the mirror wafer using a thermocompression bonding technique to form a three-tier stack **7318**. The stack **7318**, which as described above and shown in **Fig. 1B** comprises a plurality of mirror assemblies, is then diced to the desired number of mirror assemblies e.g. 1 to 8 or more. During the dicing portion of the process **700**, all sensitive cavity areas of the stack are still sealed by remaining wafer portions **7212 and 7213**. This technique provides the advantage of maintaining a non-contaminated environment for the sensitive areas e.g the mirror. After dicing, the remaining sealed cavities are opened, e.g. the window areas, by dry etching. Dicing techniques are well known and thus do not require detailed description here.

[0061] Known techniques such as providing tape over sensitive areas during dicing might be used without eliminating the inventive nature of the present process. These techniques however are more time-consuming and thus less desirable.

[0062] Now, blanket Si etching is performed to open a mirror window **7320** and bond pad window **7321** to expose the bond pads **7316** at the die level. At this point, a three dimensional multi-tier structure having multi-tier electrodes has been formed using planar machining techniques.

[0063] Referring now to **Figs. 7A-C** and **Figs. 8A-B** an important manufacturing advantage will be described. **Fig. 8A** shows a top view of a bond pad region of the present invention. Shown is the bond pad window

7321 and the several bond pad islands **7315** created during the manufacturing processes **730**. It is readily apparent that top cap electrical bond pads **7316a**, mirror bond pad **7316b** and bottom cap electrode bond pads **7316c** are all accessible from a single direction for final packaging and assembly through the bond pad window **7321**. One performing the final manufacturing process simply bonds appropriate electrical leads (such as leads **104** described above and shown in **Fig. 1A** to each bond pad **7316**.

[0064] **Fig. 8B** is a cross section view along the plane **A-A** of **Fig. 8A** to provide a view to clearly show some of the features of the present invention. Shown are the three-tier stack assembly **7318** and the bond pad window **7321**, which provides easy access to pads for final assembly and packaging. For comparison without limitation, the bond pad window **7321** might be manufactured as the bond pad window **118** described above and shown in **Fig. 1B**. Recall that the stack **7318** is manufactured using a fully planar process **700** according to the present invention. That is, there is no requirement in the process to rotate or flip any individual wafer or the stack in order to create the multi stack assembly shown. Moreover, the process provides an assembly having bond pads for each level of the stack accessible from one side through a bond pad window. In the embodiment shown, the bond pad window **7321** is on the top cap side of the assembly. Those skilled in the art having the benefit of the present disclosure would recognize that the top cap bond pad window is merely illustrative of the embodiment shown and does not limit the invention to having access only through a top cap bond pad window.

[0065] The top cap bond pad window **7321** provides access to the bottom cap electrode bond pad **7316c**, to the mirror wafer electrode bond pad **7316b**, and to the top cap electrode bond pad **7316a**.

[0066] The figure also shows how layering is used to provide the three-dimensional structure using a planar process. The glass layer **7110** is shown on top of the bottom cap and between the bottom cap and the mirror wafer. The bottom cap electrode bond pads **7316c** are on the glass layer **7110**. The p++ epi silicon islands **7315** are formed from a layer of p++ epi silicon layer on the mirror wafer as shown. The mirror bond pad **7316b** is substantially co-planar with the top cap electrode bond pad **7316a**. The top cap electrode is connected to the top cap electrode bond pad **7316a** via electrical bonding between the top cap electrical feed through **7220**.

[0067] **Figs. 9A-9C** show a shadow-masking portion of the process 700 according to the present invention. Creating bond pads in typical fashion can be quite complicated, time consuming and costly. A shadow mask is a portion of wafer material having a primary function of covering an area of a wafer surface. During metal deposition, such as for creating electrodes, metal is deposited on all surfaces in a substantially line-of-sight relationship with the direction of deposit. Typically, these are all upper surfaces. Thus, any area covered by a shadow mask does not receive sufficient metal deposits to create unwanted electrical short circuit paths.

[0068] Bond pad deposition according to the present invention may be accomplished using several embodiments of the process **700**. One embodiment provides depositing metal directly to the bond-pad region using an exterior shadow mask **902**. In this manner electrode bond pads are shielded from metal depositions to avoid shorting. The shadow mask **902** is not part of the stack, thus is removed during the manufacturing process immediately after metal deposition.

[0069] In another embodiment, an in-situ shadow mask **904** is created in the mirror assembly during the etching processes **720** that prevents metal from depositing in areas between electrodes. In this embodiment, the shadow mask **904** remains in the completed assembly.

[0070] Still in another embodiment, a frangible beam-like in-situ shadow mask is created in the mirror layer. This shadow mask shields bond pads from metal depositions that can create electrical short circuits. The shadow mask shield **906** are easily broken and removed after metal deposition using a typical manufacturing tool such as a vacuum pick.

[0071] Another embodiment of the process of the present invention provides inverted mirror manufacturing to allow alternate electrode routing and to provide a moderately doped p+ layer on which the mirror surface is formed. This process has the advantage of a smoother mirror surface at the microscopic level. The process **1100** is shown by illustration in **Fig. 11**.

[0072] Shown is the process **1100** beginning with a top cap wafer at **1102**. The 400-700 micron wafer is provided with a Si oxide mask. A pattern mask is applied and a recess **1104** if etched using KOH etching. At **1106** a window mask is applied and top cap electrode bond pads **1108** are attached to the wafer.

[0073] The bottom cap starts at **1110** with a silicon SSp wafer **1112**. A Si Oxide mask is applied for etching of a recess **1116** and for forming a cross-shaped baffle **1114** in a top surface of the bottom cap. An oxide insulation layer **1118** is then applied to the bottom cap surface.

[0074] Electrodes **1119** are then formed in the recess **1116** at **1120** by metal deposition techniques as described on process **700**.

[0075] The mirror wafer begins at **1122** by providing a DSP wafer **1124**. An epi p++ beam layer **1128** is applied and then a p+ structural layer **1126** is applied. A pad layer is provided using an oxide layer and a nitride layer. The pad layer is then masked and etched.

[0076] The nitride is then stripped and patterned leaving oxide on mirror surfaces **1130**. The mirror oxide is broken up to clear DRIE lanes.

[0077] At **1132**, the top cap and mirror wafers are bonded using fusion bonding, and at **1134** the mirror substrate is thinned to the p++ layer in KOH. The top cap is etched to form the windows **1138** (only mirror window shown in this view). As shown a portion of the window **1138** remains sealed for further processes.

[0078] At **1136** bond metal **1140** is deposited and patterned. The metal is preferably layered Ti and Au as discussed above with process **700**. At **1142** pattern masking and etching is performed with beam-mirror separation mask to separate beams and mirror areas at several locations **1144**.

[0079] The bonded top cap and mirror wafers are then bonded to the bottom cap at **1146** using thermocompression, and at **1148**, the window **1138** is opened using blanket Si etch.

[0080] The stack is completed at **1150** by sputtering layers of Ti and Au **1152** using the shadow masking of **Figs. 9A-C** to shield the bond pad window.

[0081] **Fig. 12** is an alternative process embodiment with inverted mirror manufacturing to allow alternate electrode routing and to provide a moderately doped p+ layer on which the mirror surface in formed. The process **1200** illustrated in **Fig. 12** has the advantage of a smoother mirror surface at the microscopic level. As much of the detailed bonding and depositions are substantially similar to the like processes described above, only the more general steps are described here for brevity.

[0082] Shown is the process **1200** beginning with a top wafer at **1202.** The 400-700 micron wafer is provided with a Si oxide/nitride mask. A pattern mask is applied and a recess **1204** is etched using KOH etching. A window mask is applied **1206**, and top cap electrode **1207** and bond pads **1208** are attached to the wafer.

[0083] A bottom cap starts at **1210** with a silicon SSP wafer **1212**. A Si oxide/nitride mask is applied for etching of a recess **1216** and for forming a cross-shaped baffle **1214** in a top surface of the bottom cap. An oxide/nitride insulation layer **1218** is then applied to the bottom cap surface.

[0084] Electrodes **1219** are then formed in the recess **1216** at **1220** by metal deposition techniques as described on process **700**.

[0085] The insulation layer **1217** on the backside of the wafer **1212** is removed. The metal layer **1221** is then formed in the backside of the wafer **1212** by metal deposition techniques as described above and shown in process **700**.

[0086] The mirror wafer begins at **1222** by providing a DSP wafer **1224**. An epi p++ beam layer **1228** is applied and then a p+ structural layer **1226** is applied. A pad layer **1230** is provided using an oxidation and a nitride layer. The pad layer is then masked and etched.

[0087] The bond metal **1231** is deposited and patterned.

[0088] At **1232** the top cap and mirror wafers are bonded using thermocompression bonding, and at **1234** the mirror substrate is thinned to the p++ layer in KOH. The top cap is etched to form the windows **1238** (only mirror window shown in this view).

[0089] At **1235** portion of the p++ layer on the backside of the mirror **1239** is removed, and, at **1236** metal layer **1241** is deposited on the backside of the mirror. This process minimizes the warping of the mirror.

[0090] At **1236** bond metal **1240** is also deposited and patterned.

[0091] At **1242** pattern masking and etching is performed with beam-mirror separation mask to separate beam and mirror areas at several locations **1244**.

[0092] The process is completed at **1246** by bonding the bond top cap and mirror wafers and the bottom cap using thermocompression.

[0093] The foregoing description is directed to particular embodiments of the present invention for the purpose of illustration and explanation. It will be apparent, however, to one skilled in the art that many modifications and changes to the embodiment set forth above are possible without departing from the scope of the invention and the following claims.

WHAT IS CLAIMED IS:

1. A micro-machined device for controllably directing a beam of light, the device comprising:

   a) a mirror coupled to a support structure by a pair of single-gimbaled dual-axis hinges for providing rotational movement of the mass about first and second axes of rotation;

   b) a top cap bonded to the mirror support structure and having therein a window to allow light to reach the mirror;

   c) a bottom cap bonded to the mirror support structure;

   d) a plurality of electrodes disposed on at least one of the top cap and the bottom cap, the electrodes when energized with electrical energy provide a selectable force to the mirror for moving the mirror in a plurality of angular directions, the mirror including one or more portions contacting at least one of the top cap and the bottom cap during angular movement to stop movement of the mirror such that the mirror position is one of a plurality of discrete predetermined angular positions.

2. The device of claim 1, wherein the plurality of electrodes comprises a first plurality of electrodes positioned on the top cap and a second plurality of electrodes positioned on the bottom cap.

3. The device of claim 1 further comprising an overlay coupled to the top cap, the overlay including a plurality of ports for allowing light to pass through the overlay.

4. The device of claim 3, wherein the plurality of ports include at least one entry port for directing the incident light beam toward the mirrored surface and at least one exit port for directing the reflected light from the mirrored surface.

5. The device of claim 1 further comprising a plurality of optic fibers for directing light into and from the device.

6. The device of claim 4, further comprising a plurality of optic fibers coupled to the ports for directing light.

7. The device of claim 1 further comprising a movement control structure disposed on the bottom cap to control movement of the mirror.

8. The device of claim 7, wherein the movement control structure is adapted to controllably damp movement of the mirror.

9. The device of claim 7, wherein the mirror contacts the movement control structure to reduce vertical mirror movement.

10. The device of claim 1, wherein the mirror further comprises a layer of material on a surface opposite the mirror surface, the material being selected to balance stress across the mirror to reduce mirror bowing.

11. A micro-machined device for controllably directing a beam of light, the device comprising a plurality of mirror assemblies, each mirror assembly comprising:

a) a mirror coupled to a support structure by a pair of single-gimbaled dual-axis hinges for providing rotational movement of the mass about first and second axes of rotation;

b) a top cap bonded to the mirror support structure and having therein a window to allow light to reach the mirror;

c) a bottom cap bonded to the mirror support structure; and

d) a plurality of electrodes disposed on at least one of the top cap and the bottom cap, the electrodes when energized with electrical energy provide a selectable force to the mirror for moving the mirror in a plurality of angular directions, the mirror including one or more portions contacting at least one of the top cap and the bottom cap during angular movement to stop movement of the mirror such that the mirror position is one of a plurality of discrete predetermined angular positions, wherein light exiting a first mirror assembly is directed to enter a second mirror assembly.

12. The device of claim 11 further comprising a mirror fixed in relation to the first mirror assembly and the second mirror assembly to reflect light leaving the first mirror assembly toward the second mirror assembly.

13. The device of claim 11, wherein the first mirror assembly and the second mirror assembly are positioned substantially in a face-to-face relationship to allow light reflected from the first mirror assembly to enter the second mirror assembly.

14. The device of claim 11 further comprising a plurality of optic fibers coupled to the first mirror assembly and to the second mirror assembly for directing light leaving the first mirror assembly toward the second mirror assembly.

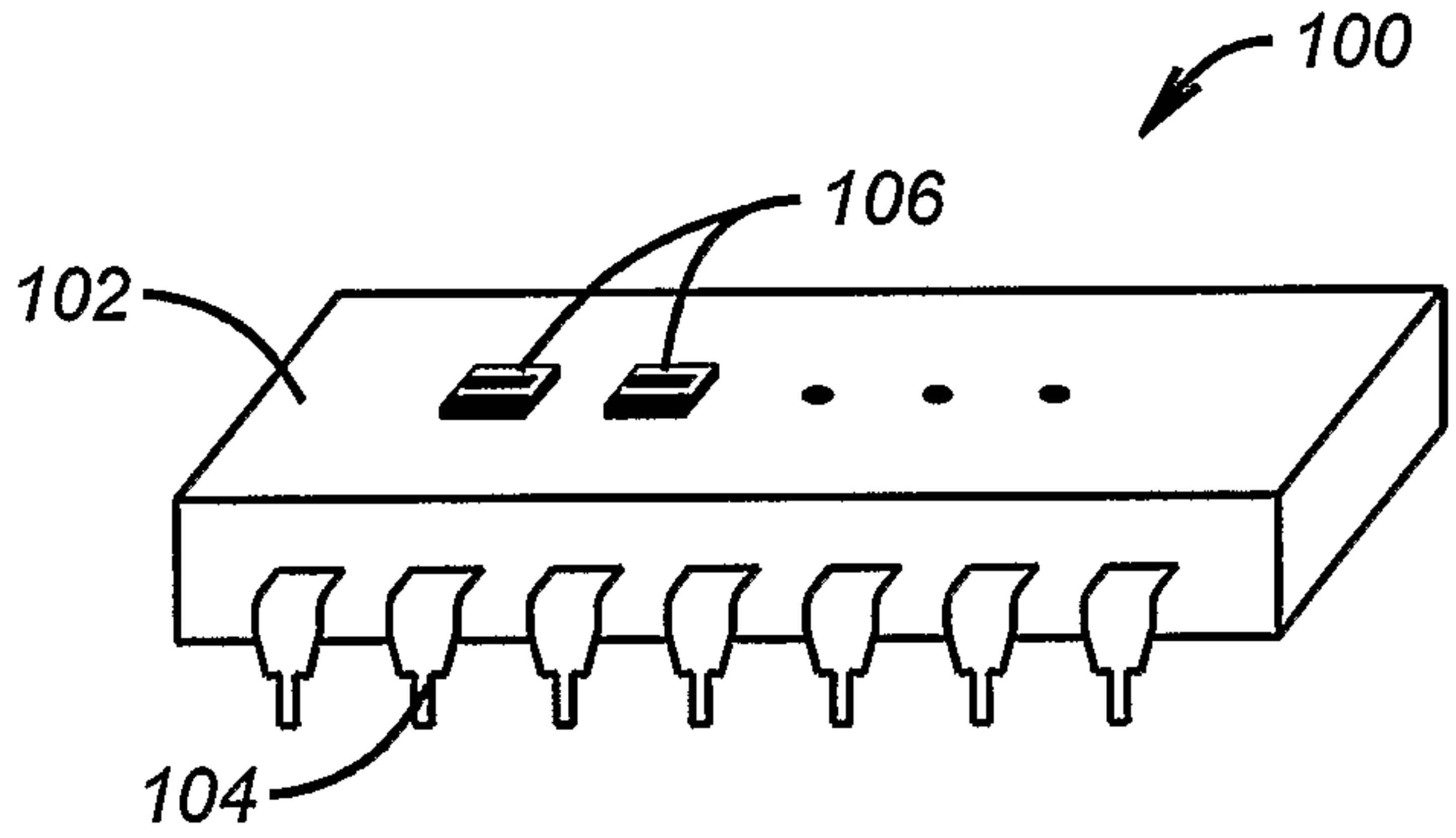


FIG. 1A

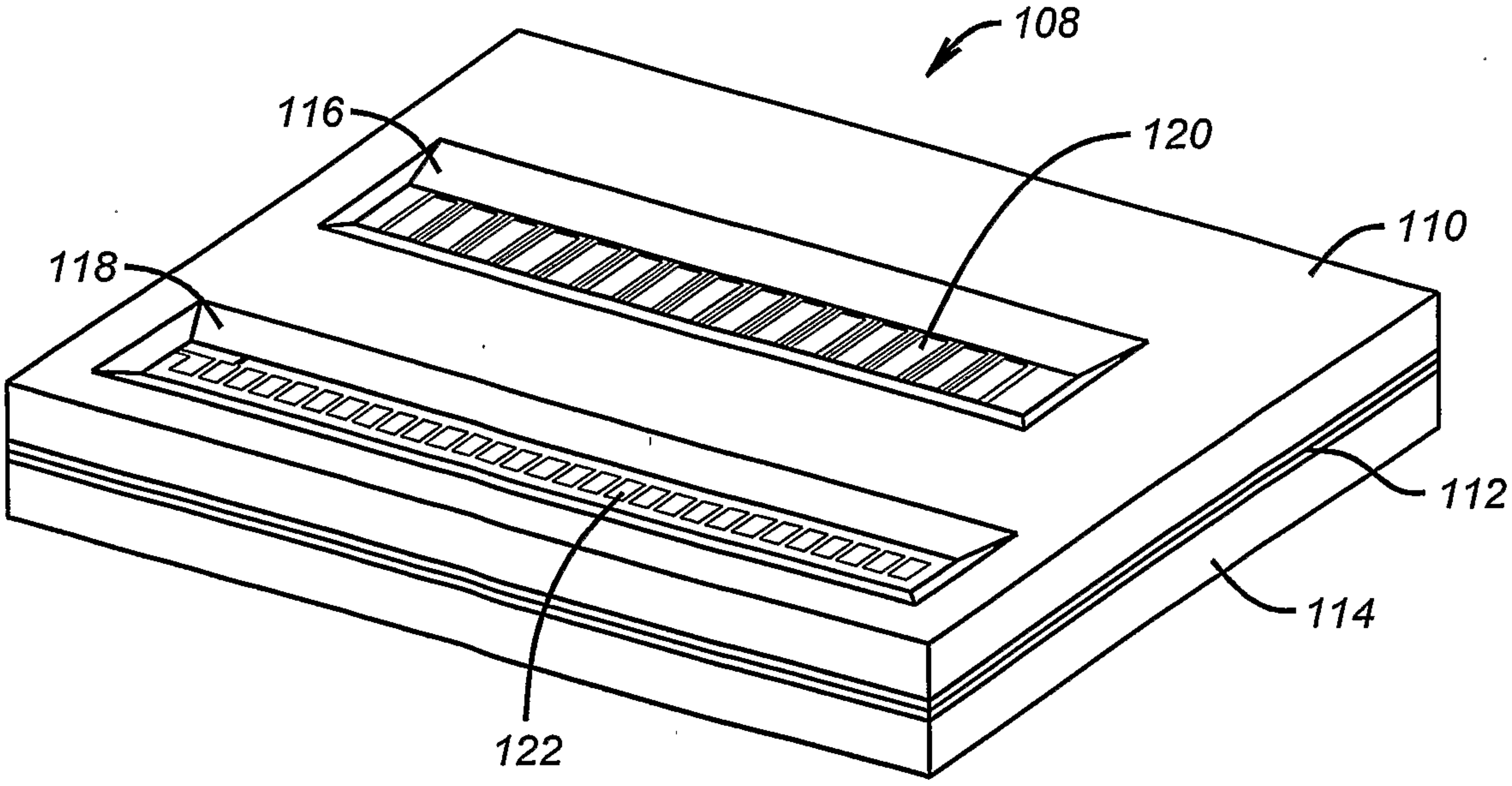


FIG. 1B

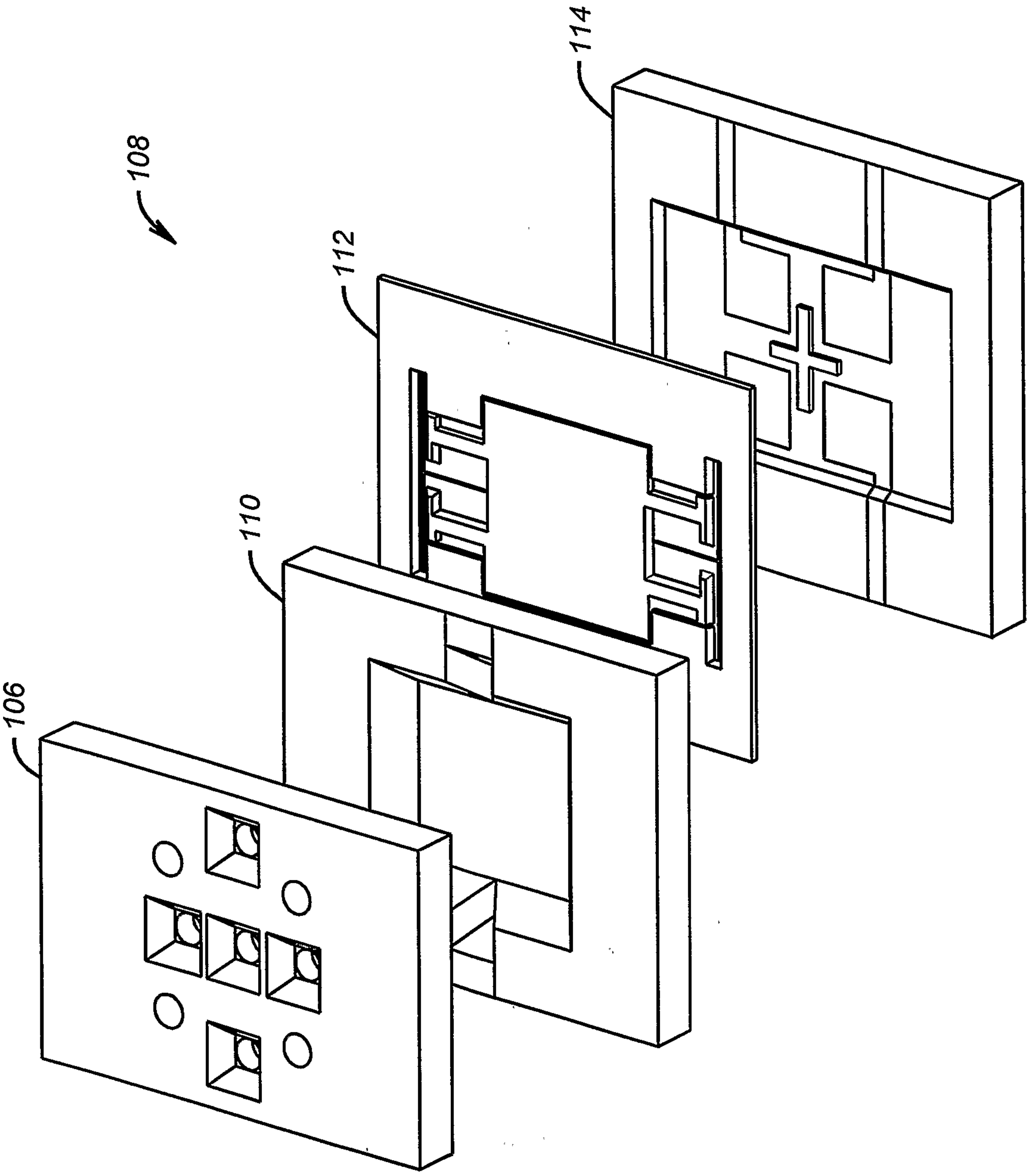
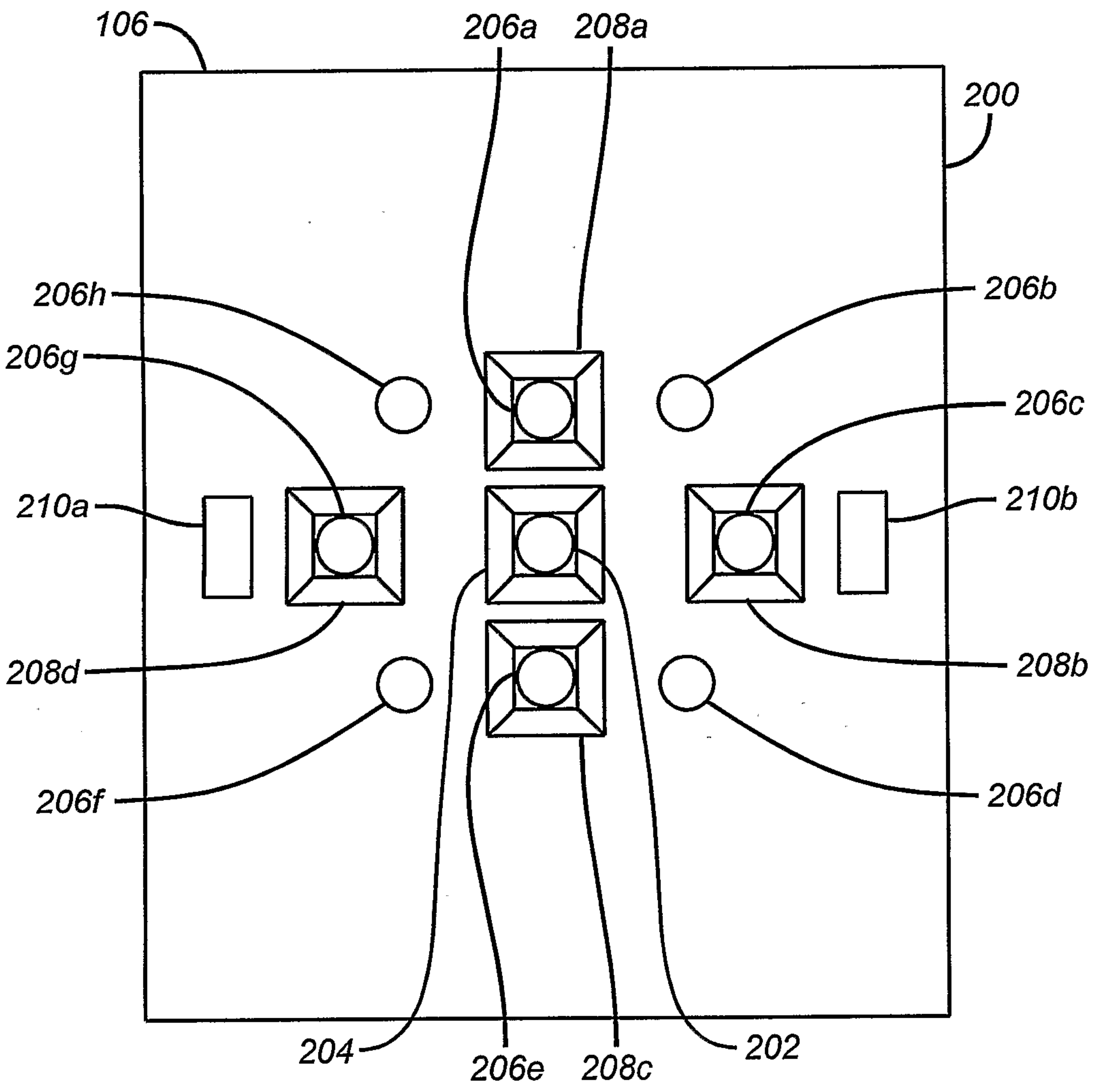


FIG. 1C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206a
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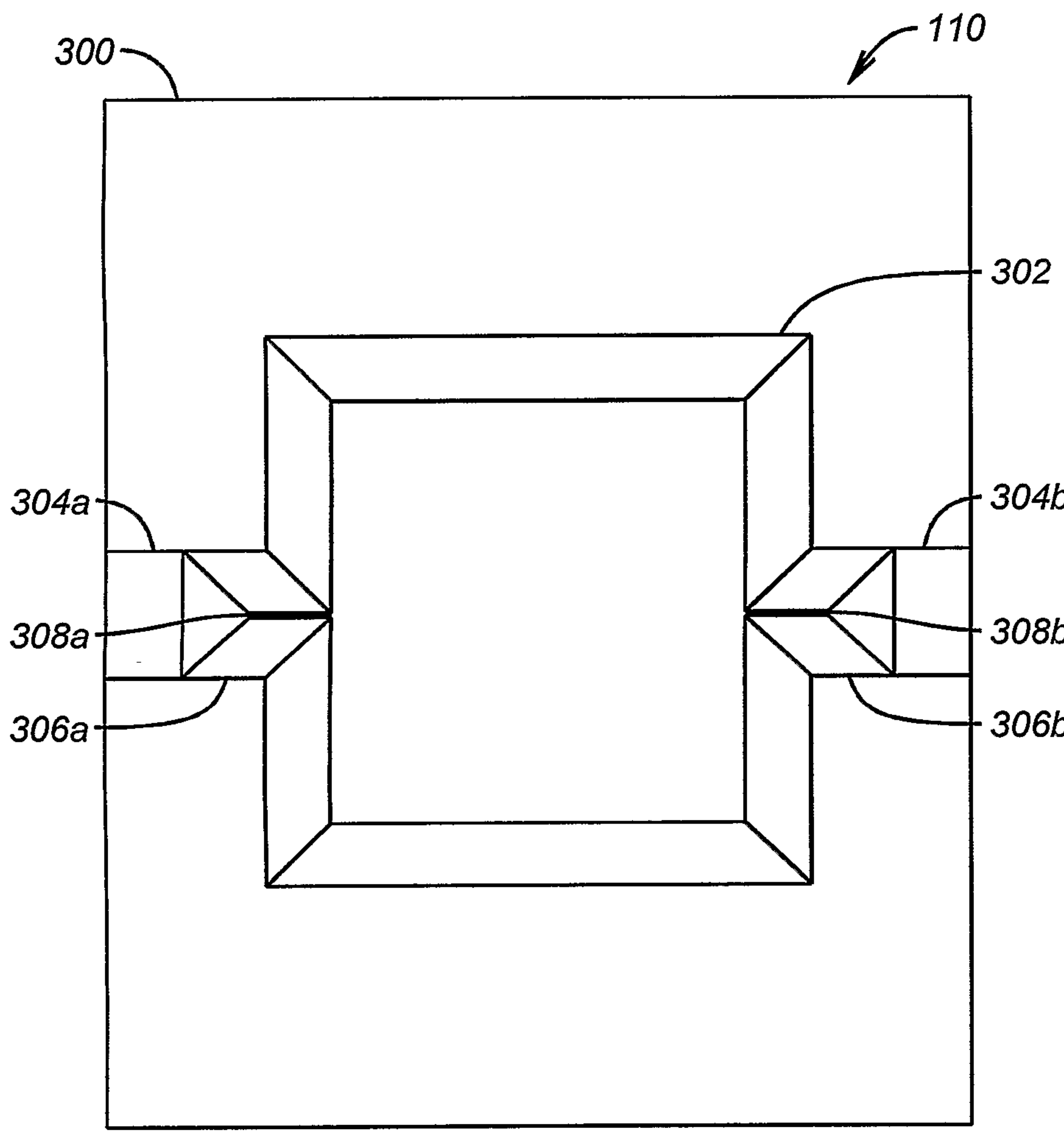
202

FIG. 2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306b

FIG. 3

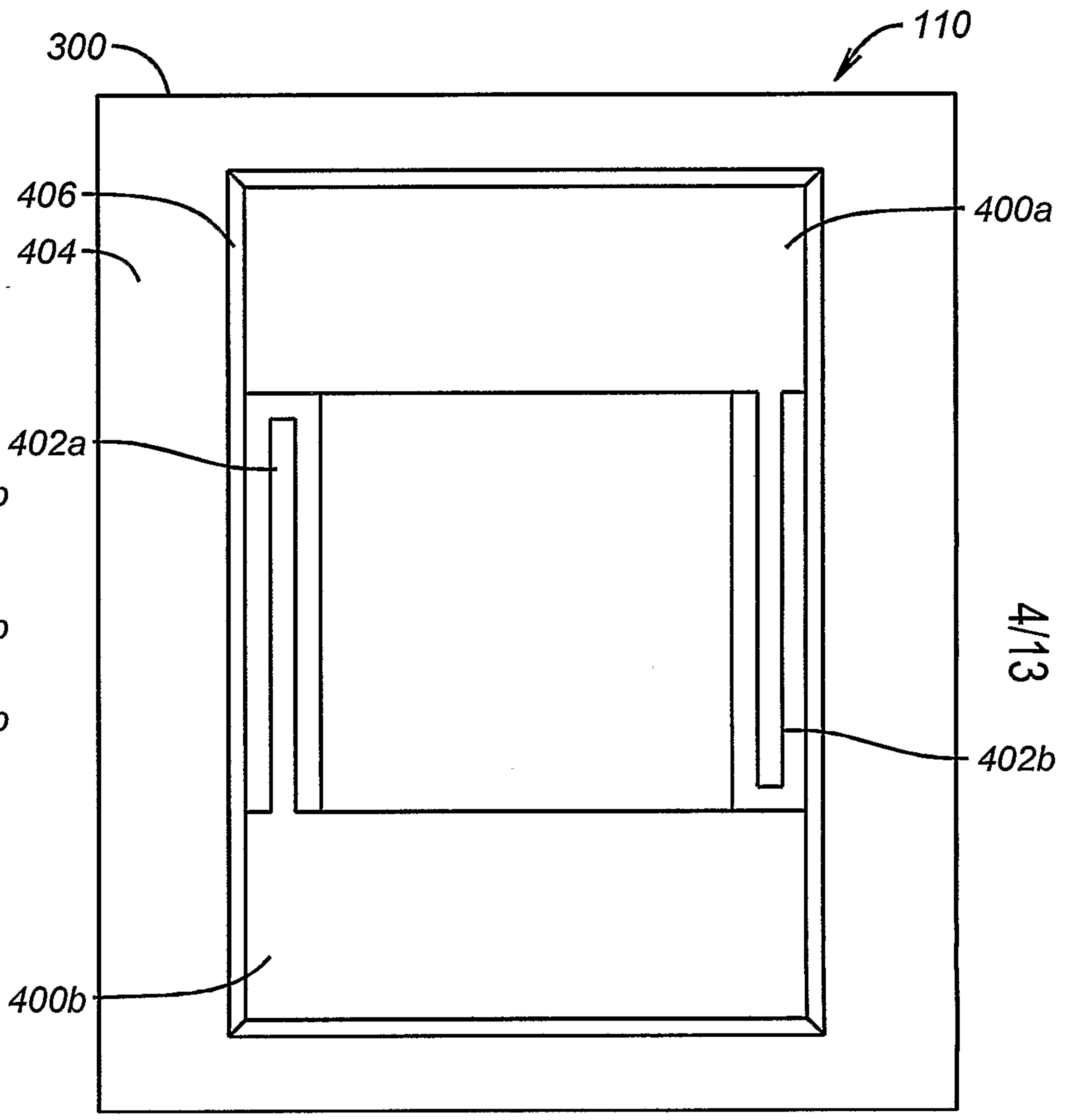
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FIG. 4

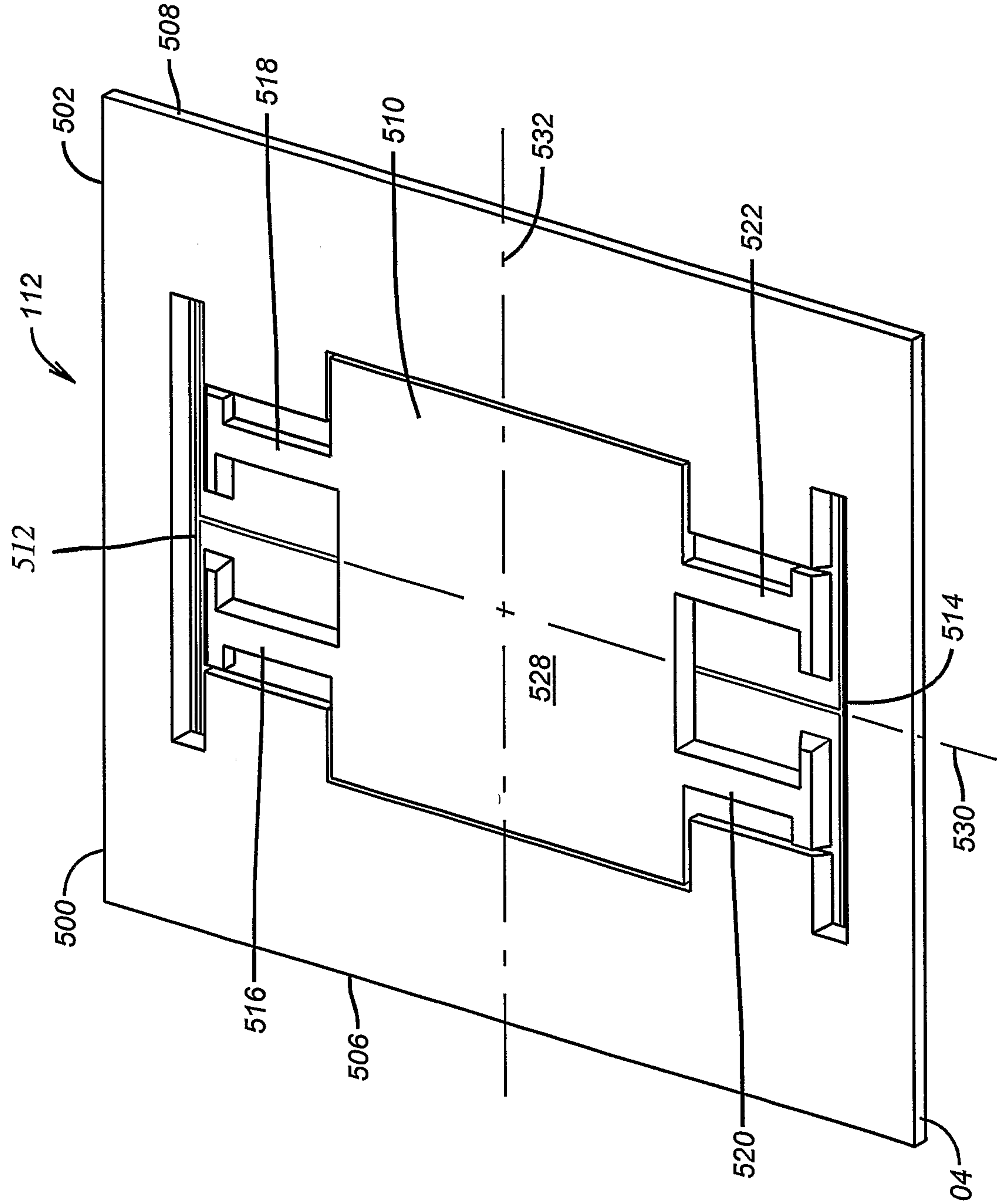


FIG. 5

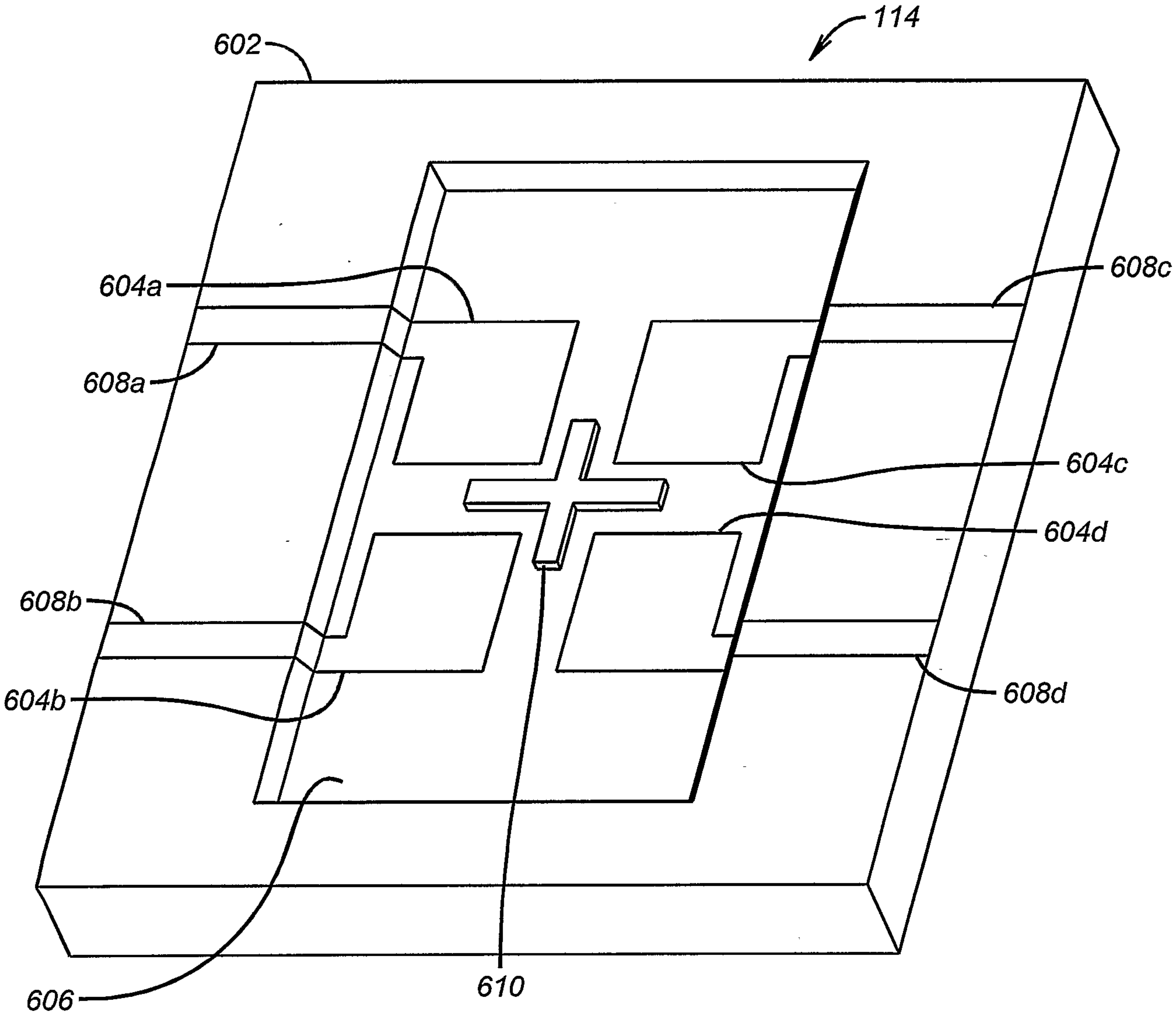


FIG. 6A

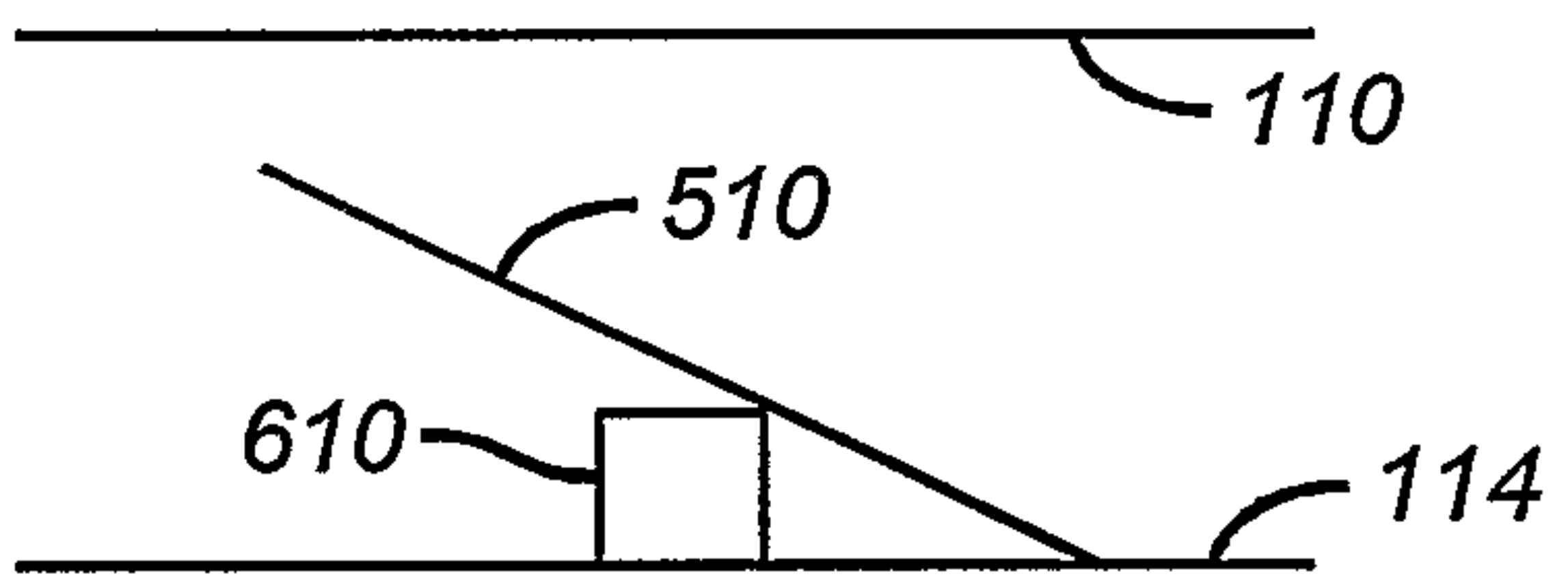


FIG. 6B

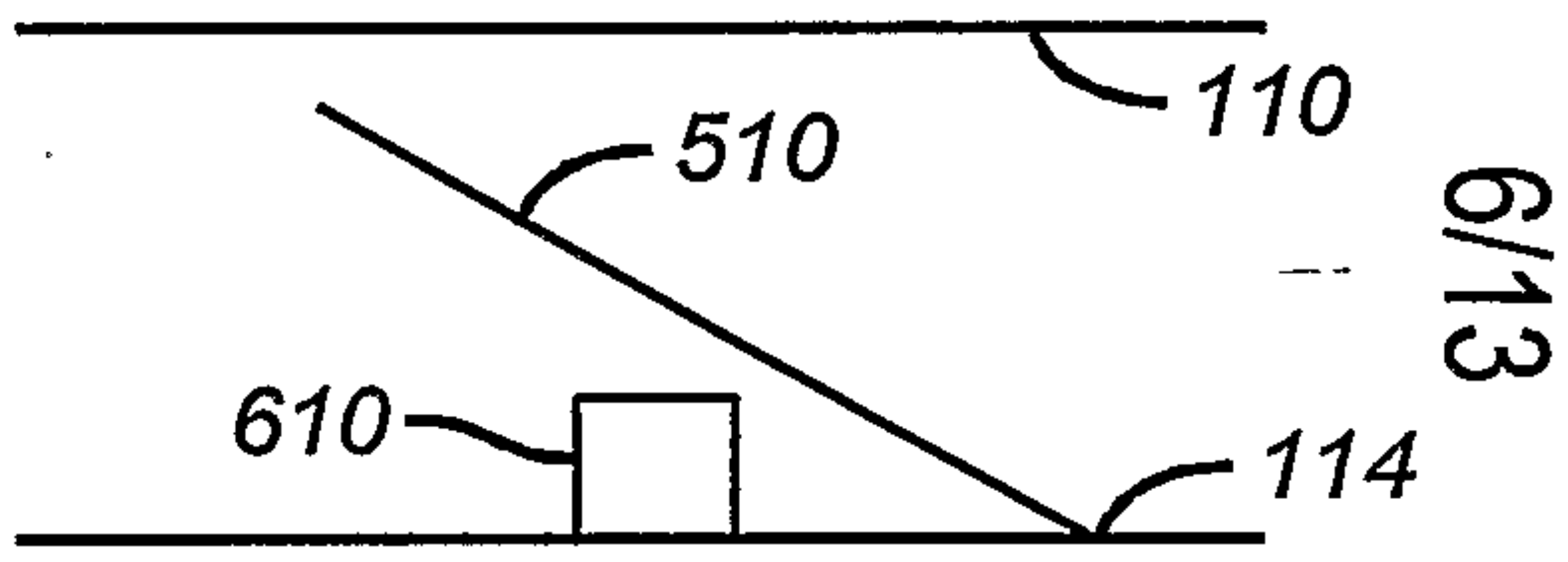


FIG. 6C

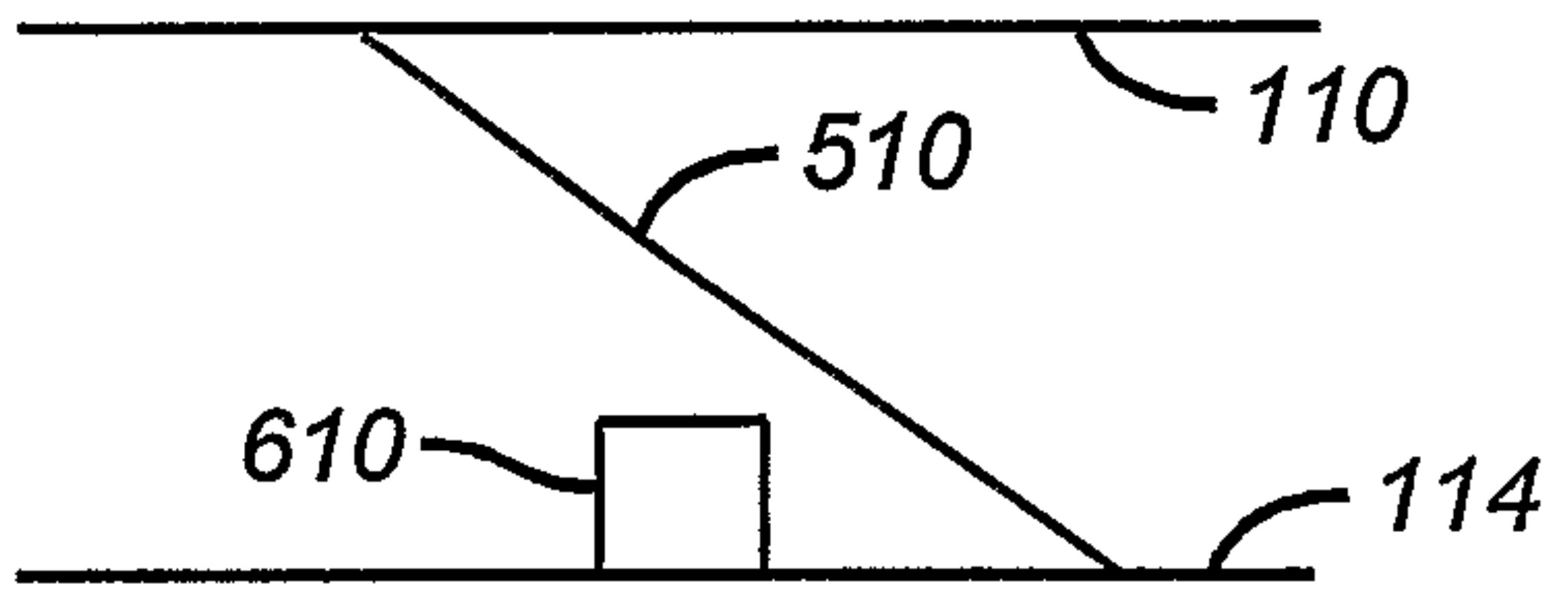
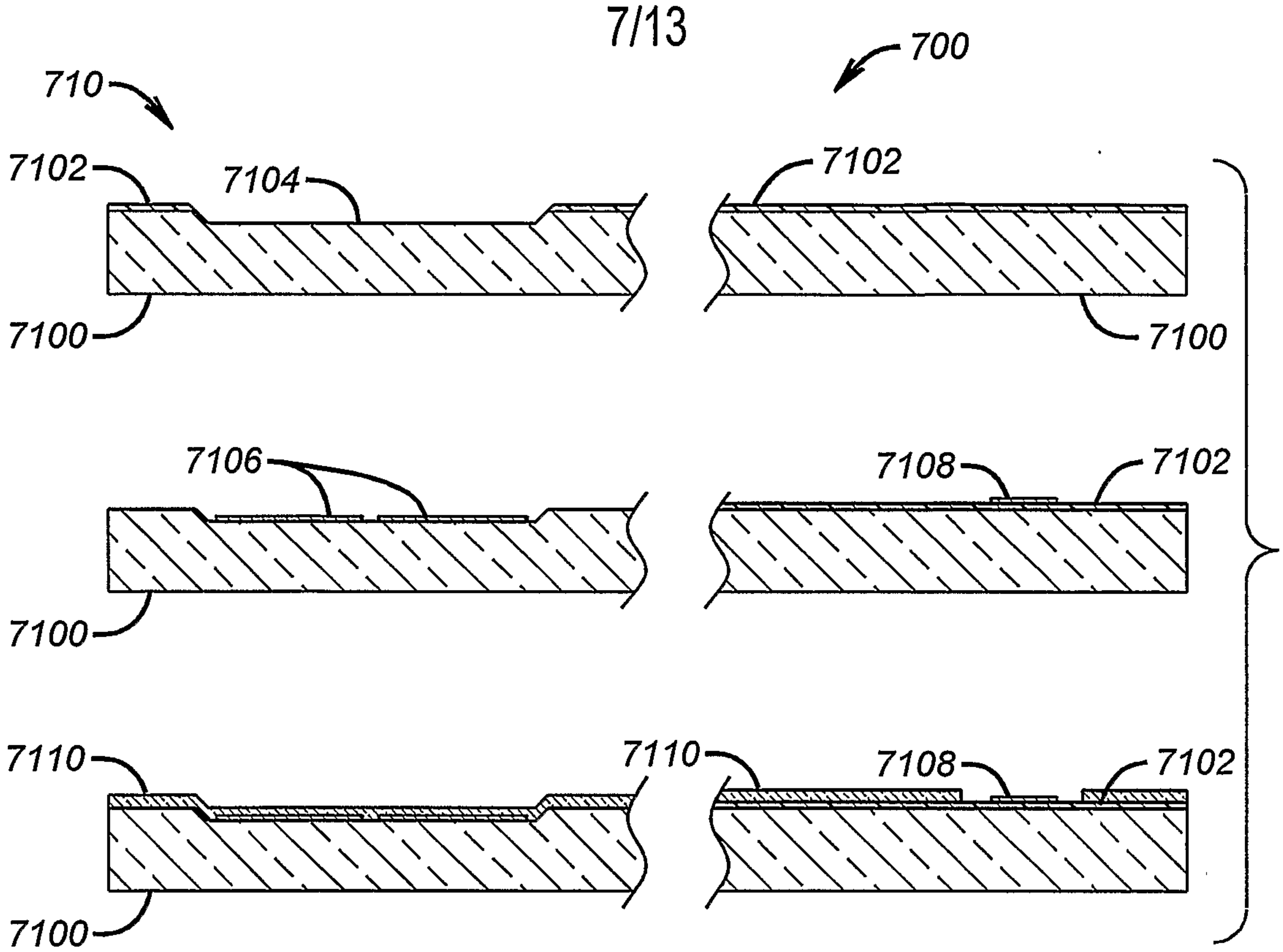


FIG. 6D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700
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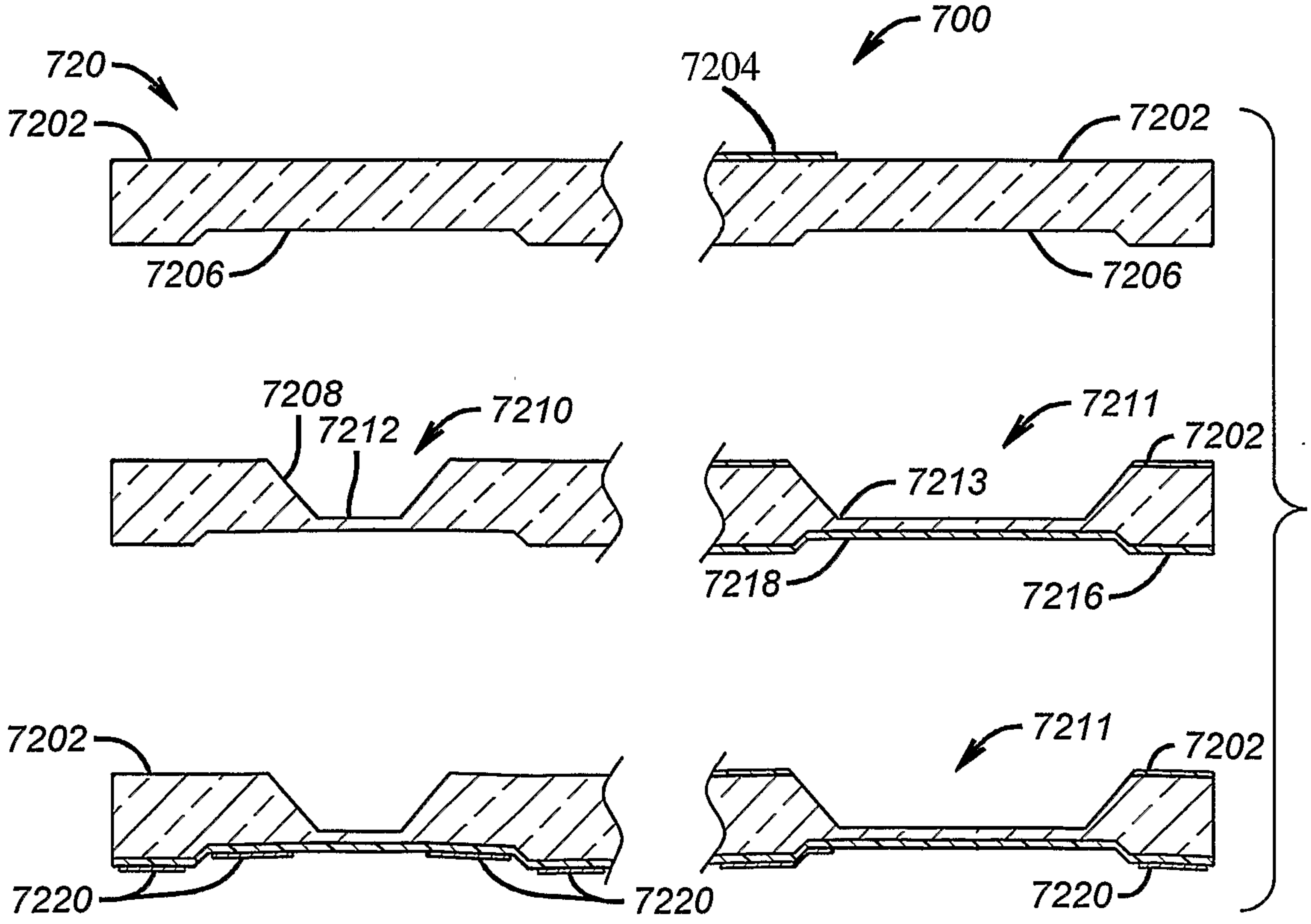
FIG. 7A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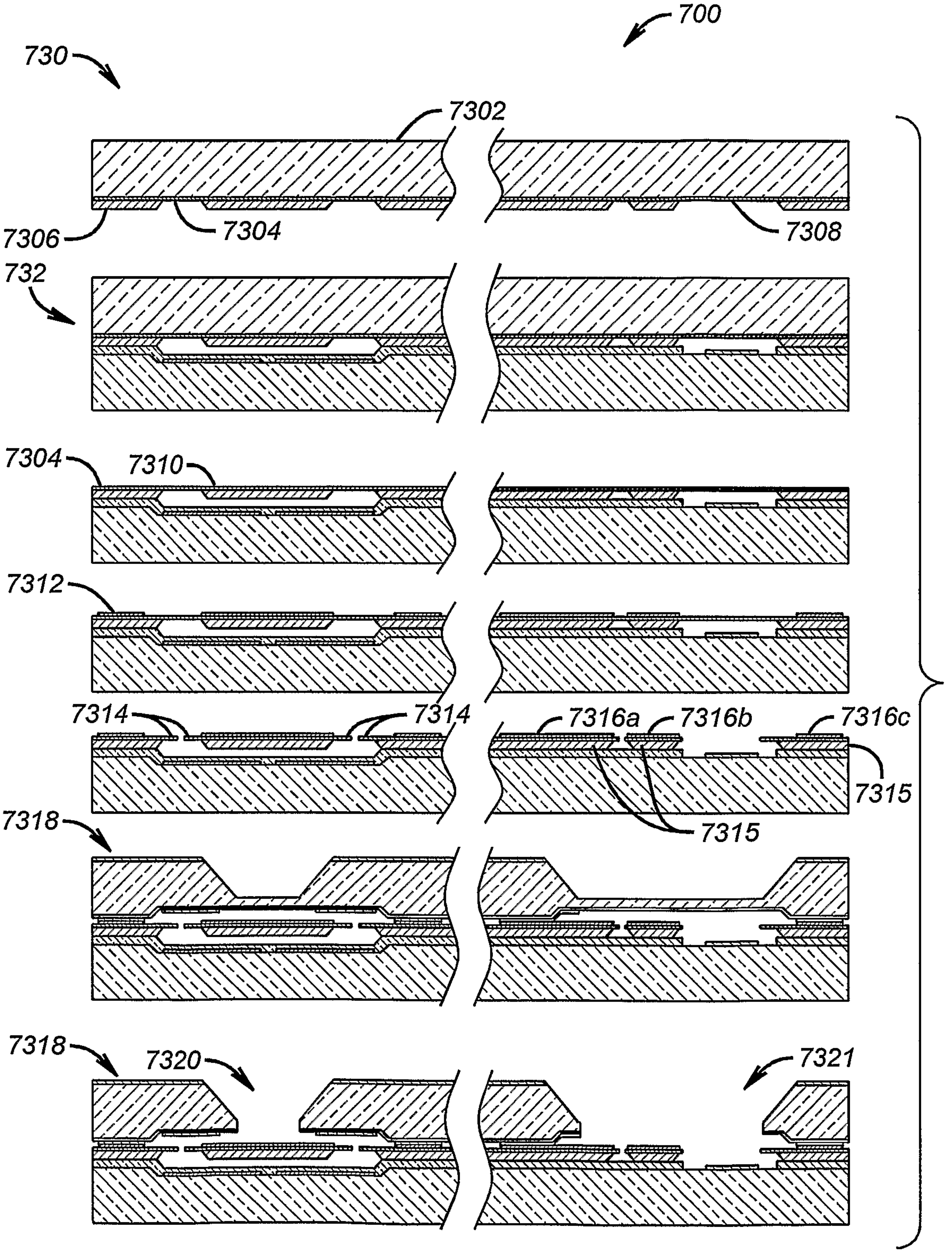
7220
7220

FIG. 7B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7308
732
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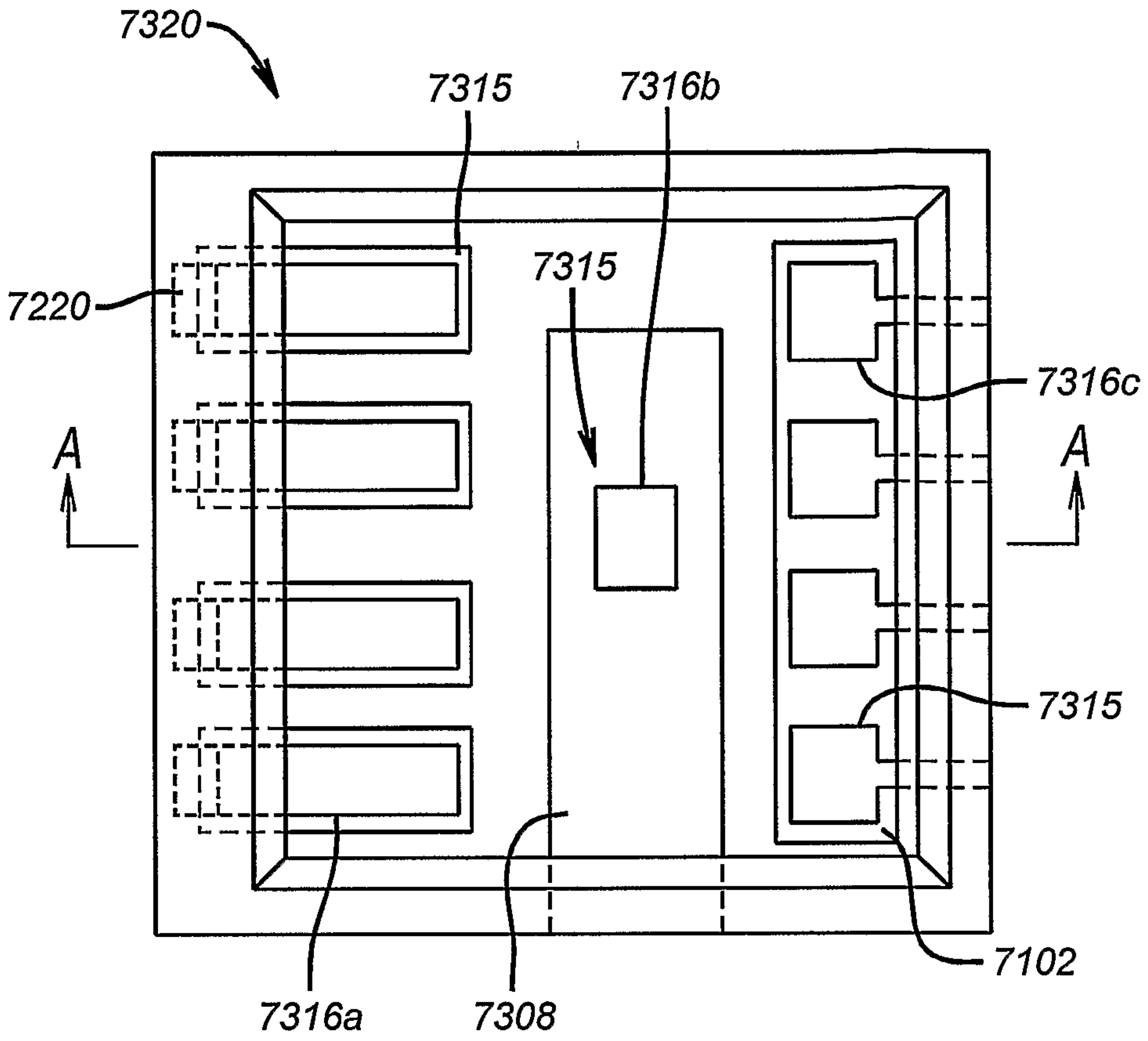
7316c
7315
7315
7318
7318
7320
7321

FIG. 7C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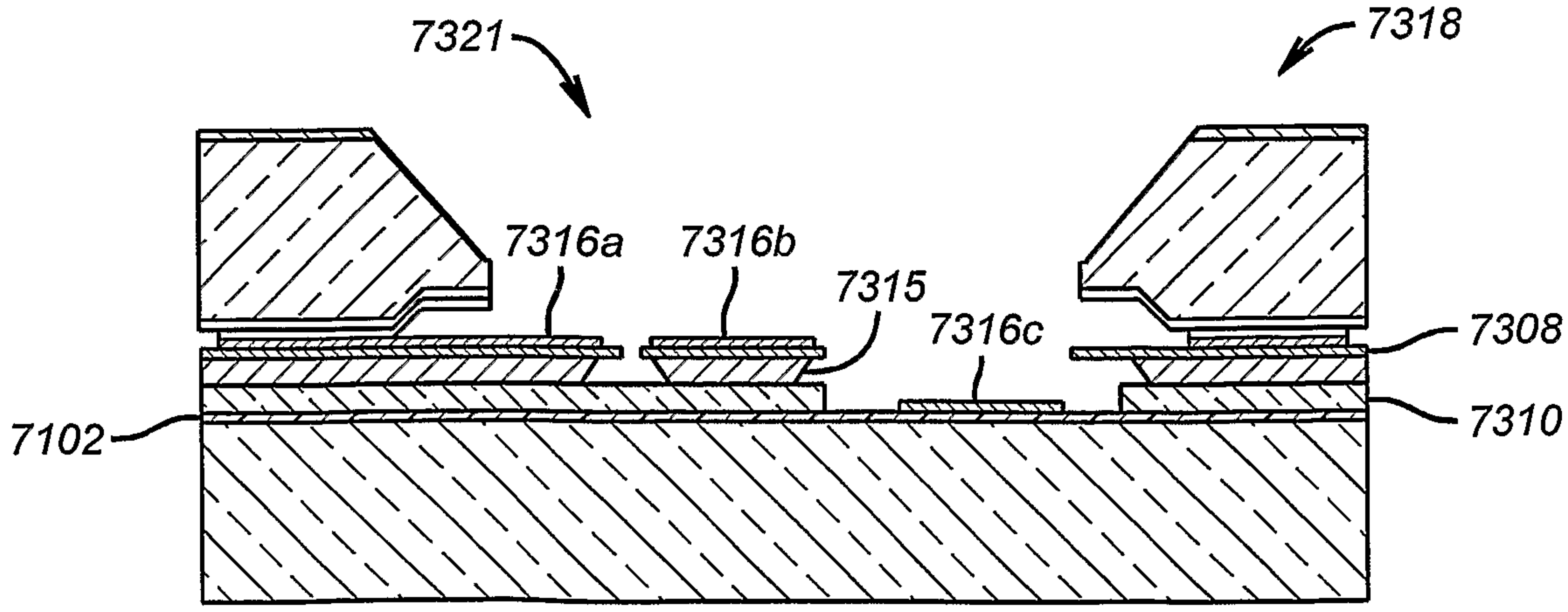
7316a
7308

FIG. 8A


7321
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7102
7310

FIG. 8B

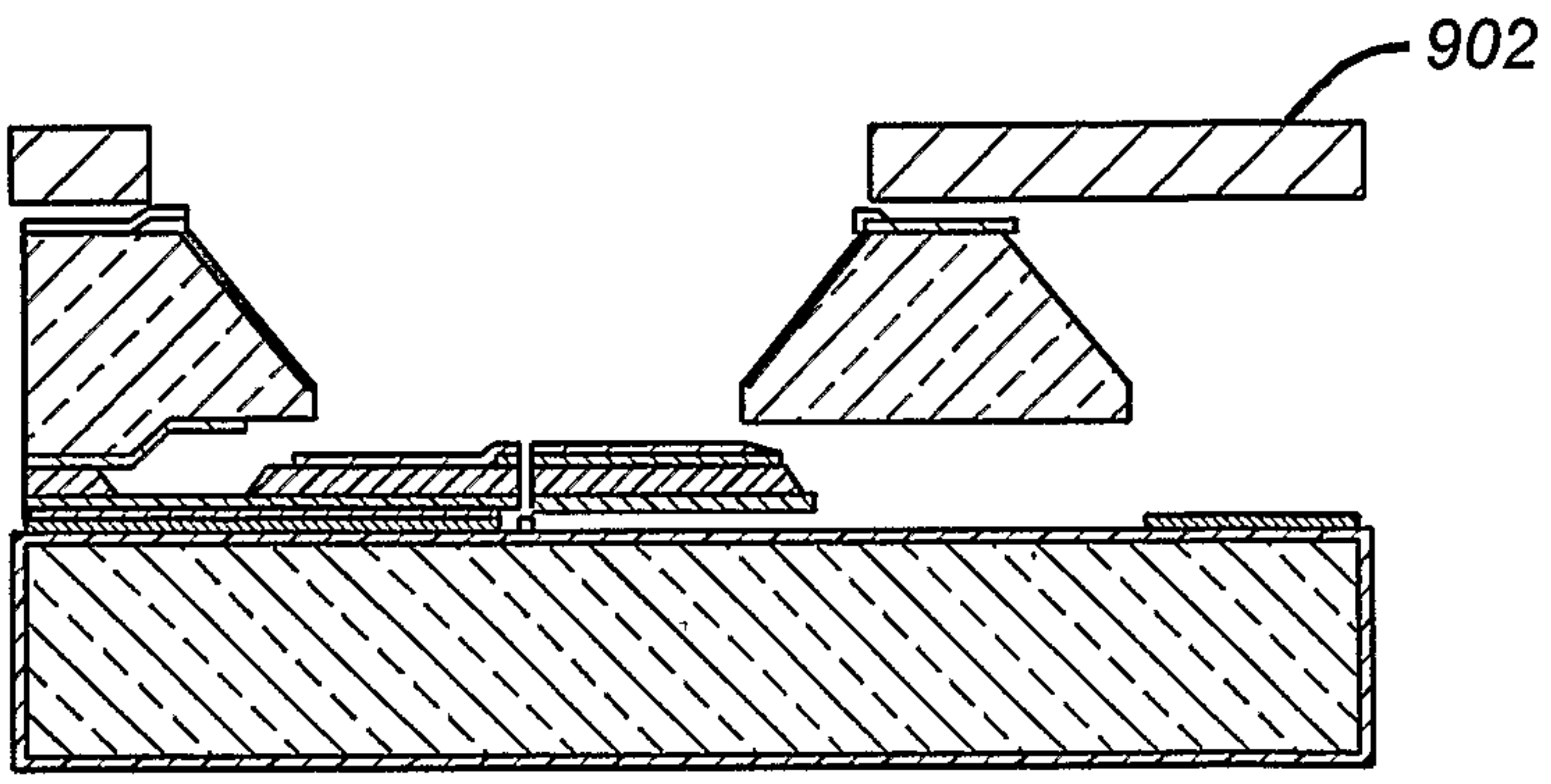

FIG. 9A

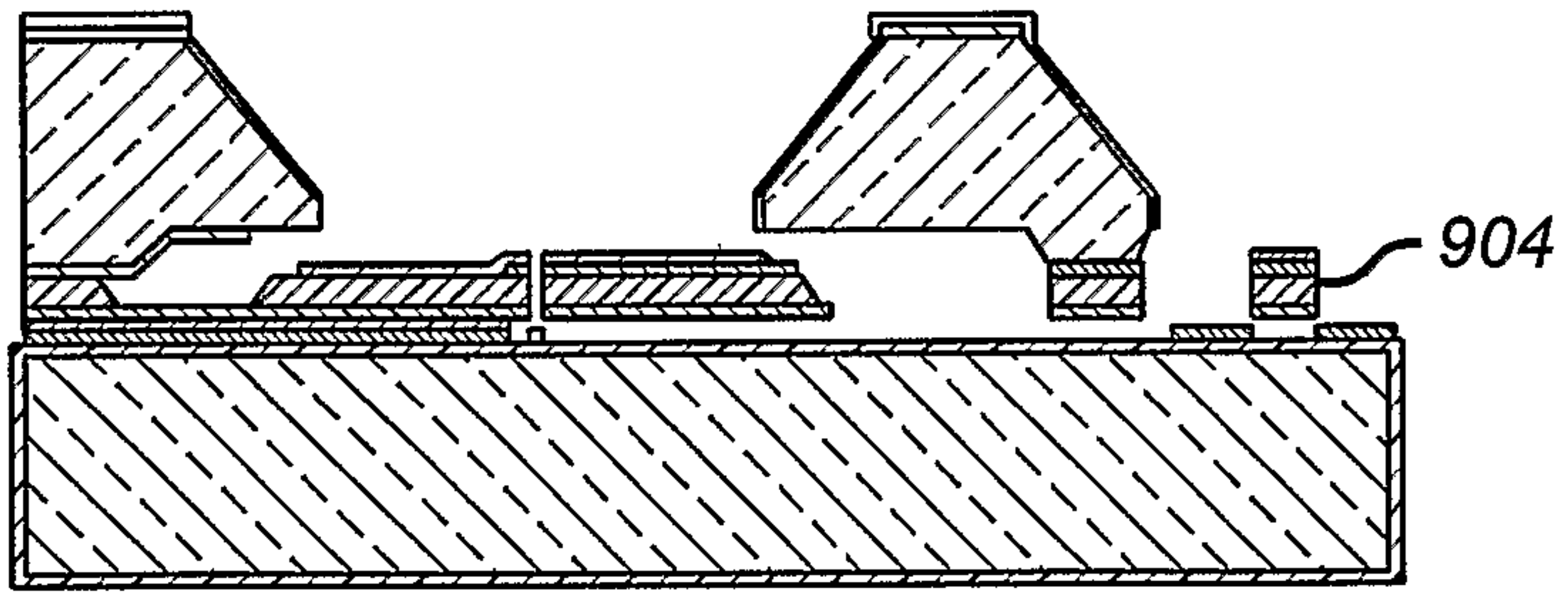

FIG. 9B

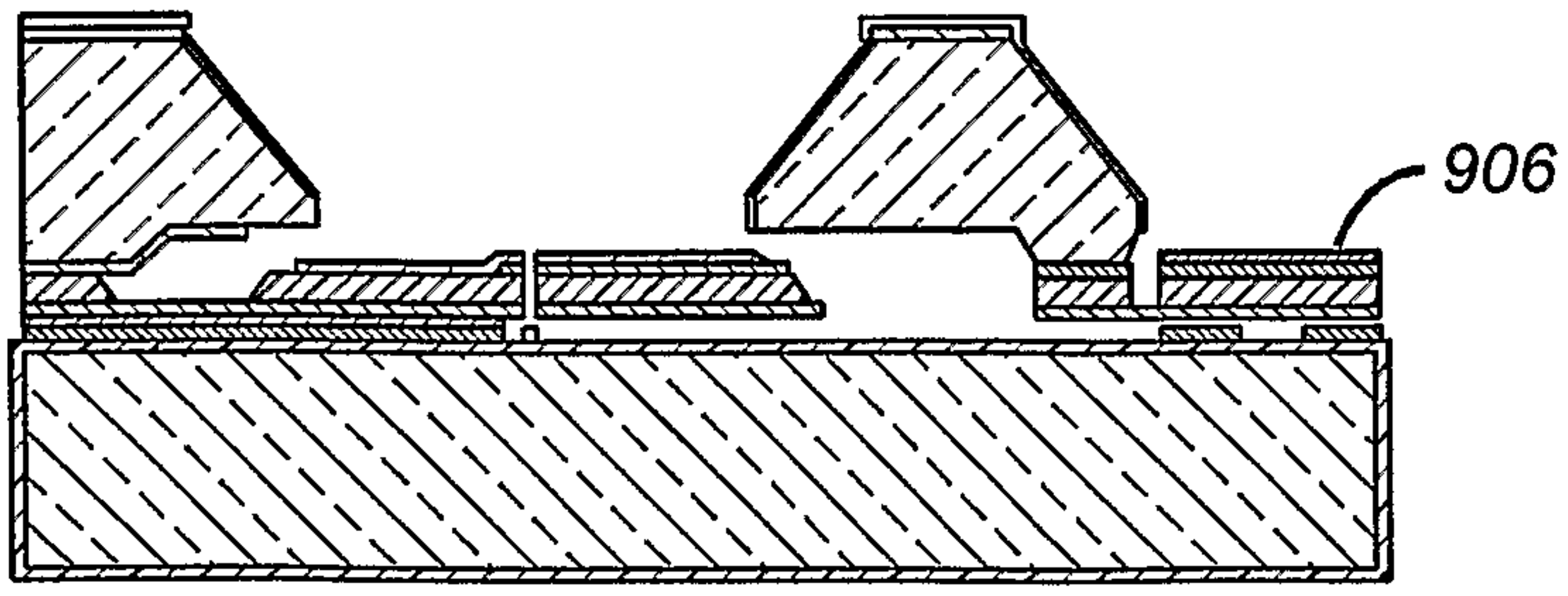

FIG. 9C

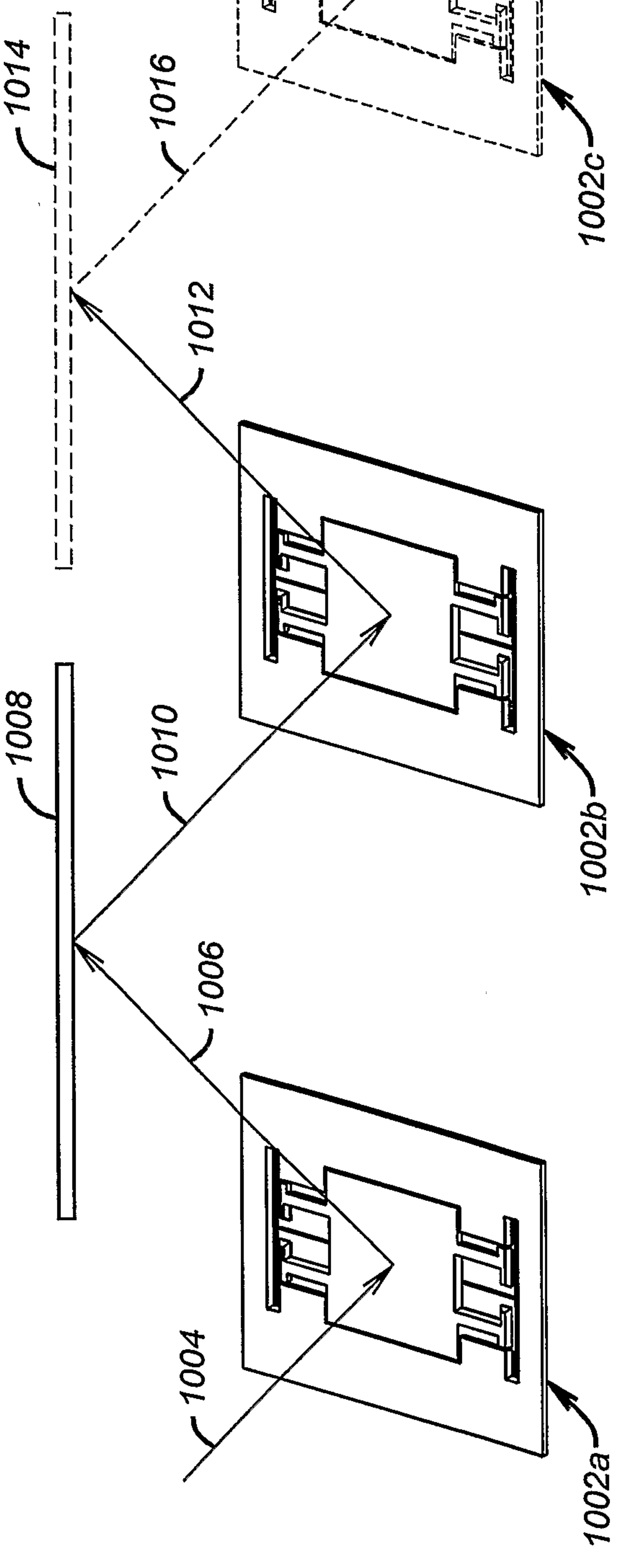

FIG. 10A

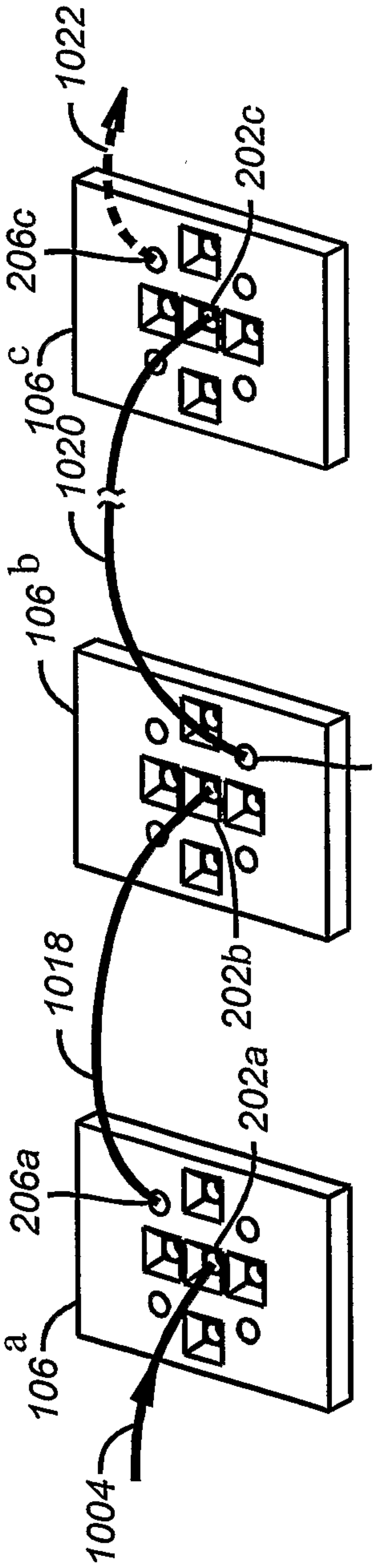

FIG. 10B

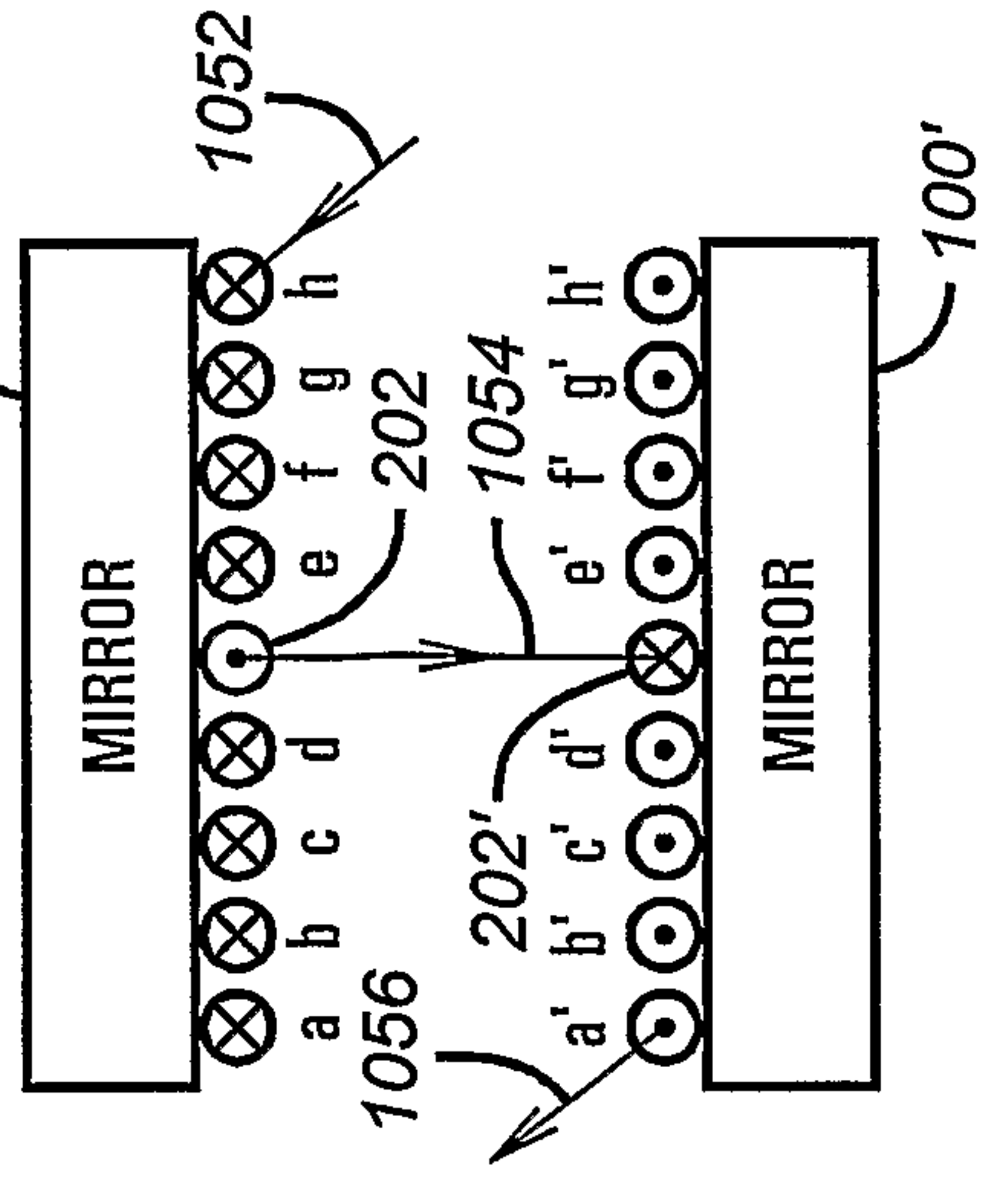

FIG. 10C

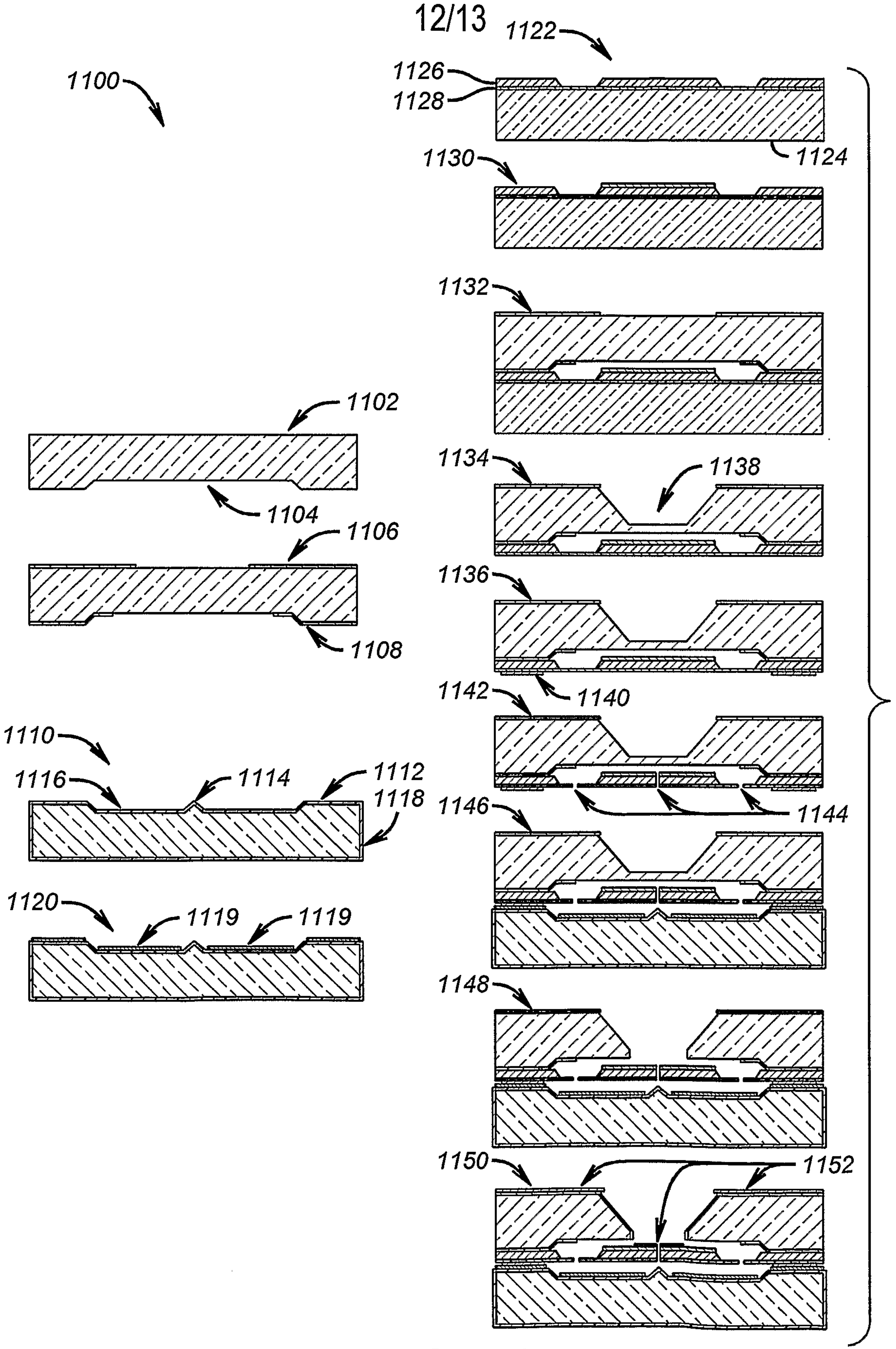
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FIG. 11

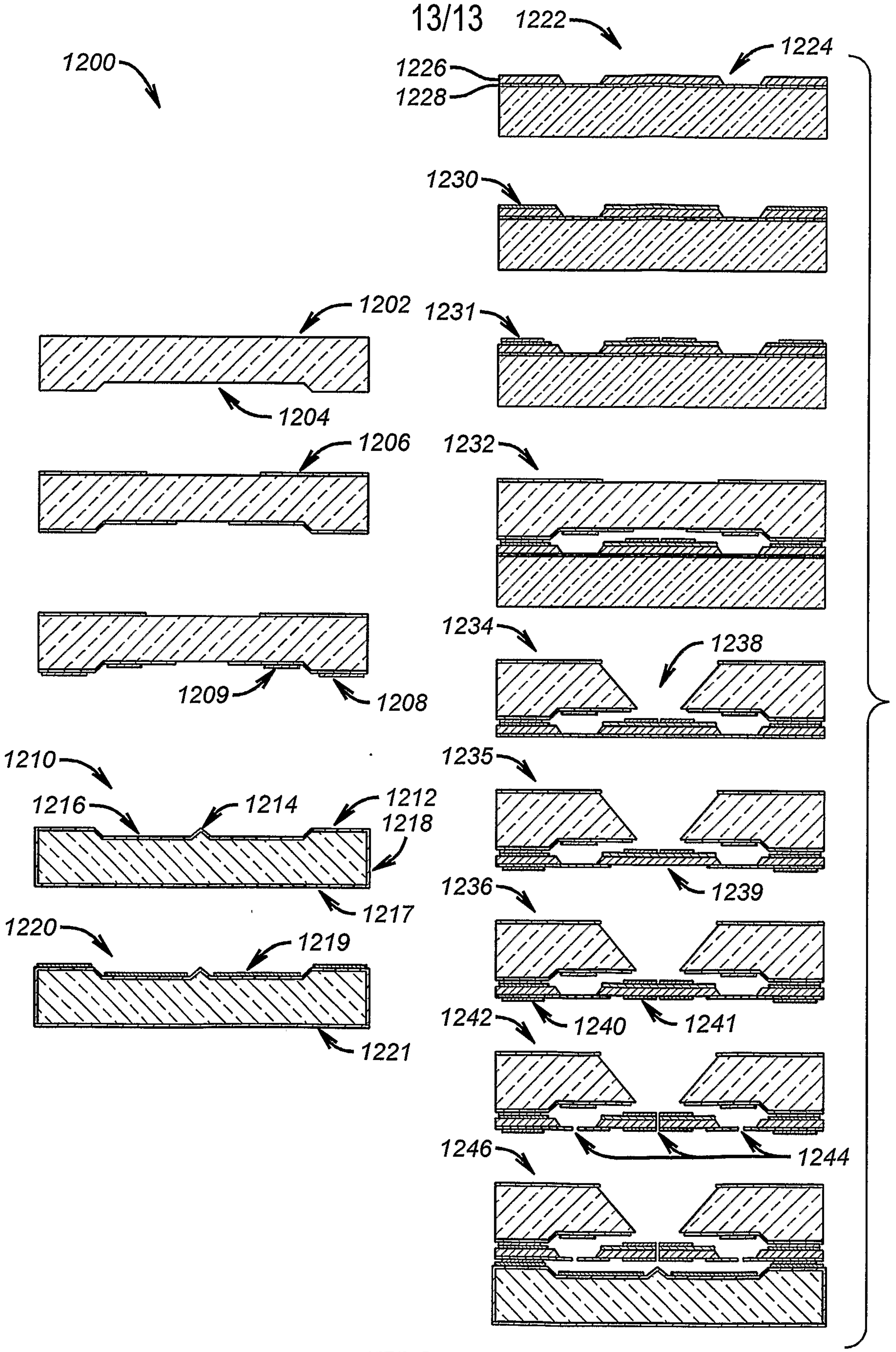
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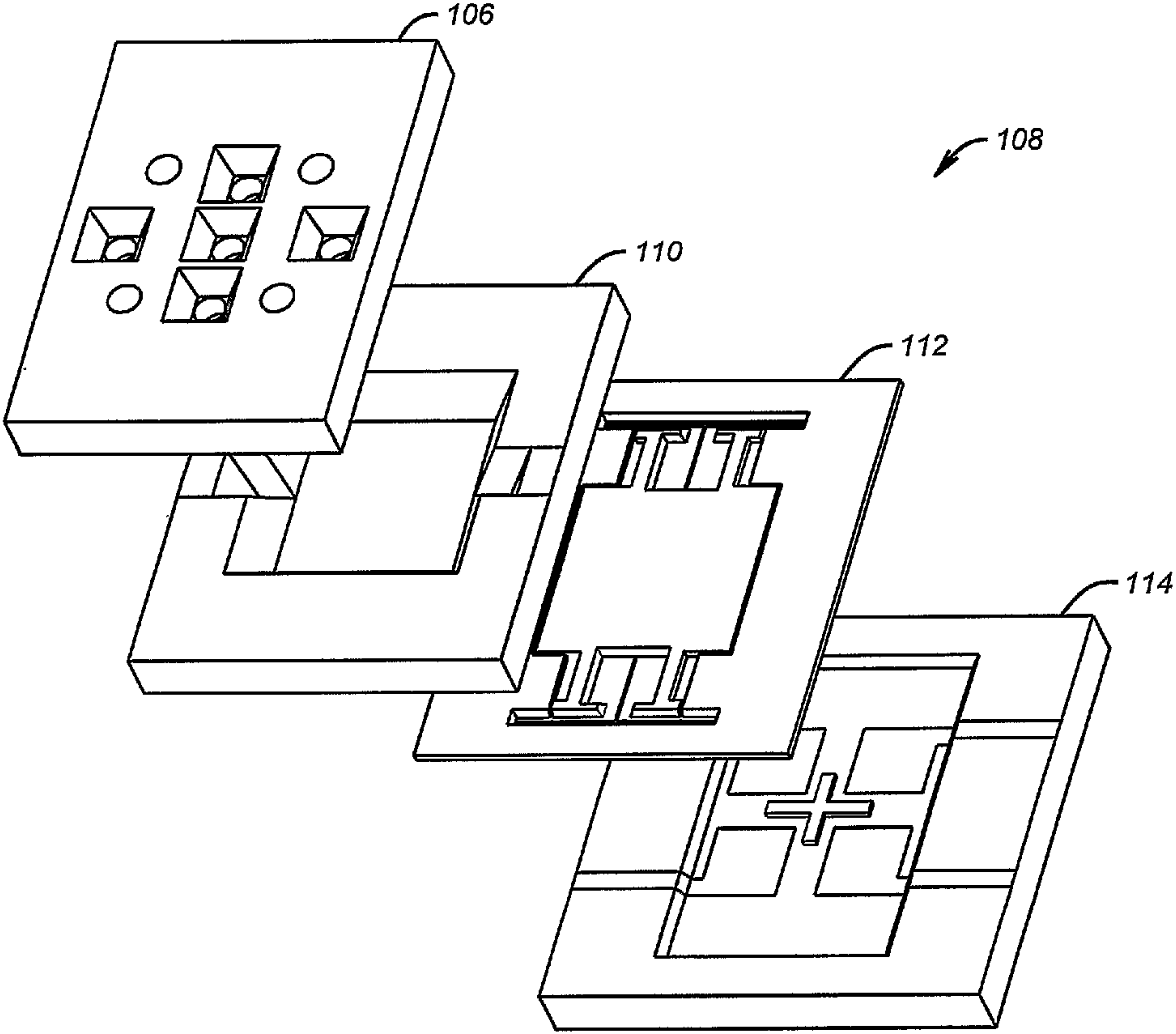
FIG. 12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