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(54) Title: MANUFACTURING STRUCTURE AND PROCESS FOR COMPLIANT MECHANISMS

(57) **Abstract**: The invention relates, in various aspects, to systems and methods for MEMS actuated displays that can be driven at high speeds and at low voltages for improved image quality and reduced power consumption.

Manufacturing Structure and Process for Compliant Mechanisms

Reference to Related Applications

This application claims the benefit of U.S. Provisional Patent Application Serial No. 61/108,783, filed on October 27, 2008, entitled "MEMS Anchors", which is incorporated by reference herein in its entirety. This application also claims the benefit of U.S. Provisional Patent Application Serial No. 61/109,045, filed on October 28, 2008, entitled "Manufacturing Structure and Process for Compliant Mechanisms", which is incorporated by reference herein in its entirety.

Field of the Invention

In general, the invention relates to the field of micro-electromechanical systems; in particular, the invention relates to actuation structures for mechanical light modulators.

Background of the Invention

Displays built from mechanical light modulators are an attractive alternative to displays based on liquid crystal technology. Mechanical light modulators are fast enough to display video content with good viewing angles and with a wide range of color and grey scale. Mechanical light modulators have been successful in projection display applications, and have recently been proposed for direct view applications. There is a need in the art for fast, bright, low-powered mechanically actuated displays. Specifically there is a need for mechanically actuated displays that can be driven at high speeds and at low voltages for improved image quality and reduced power consumption.

Summary of the Invention

Accordingly, in one aspect, the invention relates to a MEMS device comprising a first narrow beam wherein the first narrow beam completely enclose the boundary of a space. In some embodiments the first narrow beam forms a loop. In one aspect the MEMS device includes a mechanical light modulator supported over a substrate by the first narrow beam. In one aspect the MEMS device includes a mechanical light modulator in which the first narrow beam forms a portion of an actuator for moving the mechanical light modulator to modulate light. In certain embodiments, the first narrow beam is compliant beams. In one aspect the MEMS device includes an anchor connecting the first narrow beam to the substrate. In some embodiments, the MEMS device includes a second narrow beam, in which the first and second narrow beam enclose respective, non-intersecting spaces. In certain embodiments the second narrow beam encloses a space that is completely enclosed by the first narrow beam.

In another aspect, the invention relates to a method of manufacturing a MEMS device, comprising forming a first narrow beam coupled to a substrate such that the first narrow beam completely encloses the boundary of a space. In certain embodiments, forming the first narrow beam includes depositing a mold material onto a sacrificial layer, etching a shape into the mold material to form a mold having at least one sidewall and at least one lower horizontal surface, depositing material onto the etched mold such that the deposited material adheres to at least the side walls and the lower horizontal surface of the etched mold, etching away a portion of the deposited material to remove the deposited material from the lower horizontal surface while leaving substantially all of the material deposited on the sidewalls intact, and removing the mold such that material remaining on the sidewalls forms the first narrow beam. In one aspect, the sidewalls include walls of a mesa formed in the mold, and the first narrow beam encloses the mesa. In another aspect, the sidewalls comprises walls of a recess formed in the mold, and the first narrow beam encloses the recess. In some embodiments, the mold material is deposited on top of a layer of sacrificial material, and the method further includes removing the sacrificial material to release the first narrow beam.

In one aspect, the mold further comprises an upper horizontal surface, the material deposited on the mold adheres to the upper horizontal surface, and the method further comprises applying a mask to the upper horizontal surface prior to etching away the deposited material such that a portion of the material deposited on the upper horizontal surface remains on the upper horizontal surface after the etch to form a mechanical light modulator. In some embodiments, prior to etching the shape into the mold, etching anchor holes into the mold material, in which the material deposited onto the mold fills the anchor holes to form anchors. In one aspect, the formation of the anchors, first narrow beam, and the mechanical light modulator requires the utilization of no more than three photolithographic masks. In certain embodiments, the MEMS device includes a mechanical light modulator and an anchor, and the first narrow beam supports the mechanical light modulator over a substrate and connects the mechanical light to the substrate via the anchor, in which the method comprises utilizing no more than three photolithographic masks.

Brief Description of the Drawings

The foregoing discussion will be understood more readily from the following detailed description of the invention with reference to the following drawings:

Figure 1A is an isometric view of display apparatus, according to an illustrative embodiment of the invention;

Figure 1B is a block diagram of the display apparatus of Figure 1A, according to an illustrative embodiment of the invention;

Figure 2A is a perspective view of an illustrative shutter-based light modulator suitable for incorporation into the MEMS-based display of Figure 1A, according to an illustrative embodiment of the invention;

Figure 2B is a cross-sectional view of a roller-shade-based light modulator suitable for incorporation into the MEMS-based display of Figure 1A, according to an illustrative embodiment of the invention;

Figure 2C is a cross sectional view of a light-tap-based light modulator suitable for incorporation into an alternative embodiment of the MEMS-based display of Figure 1A, according to an illustrative embodiment of the invention;

Figure 3A is a schematic diagram of a control matrix suitable for controlling the light modulators incorporated into the MEMS-based display of Figure 1A, according to an illustrative embodiment of the invention;

Figure 3B is a perspective view of an array of shutter-based light modulators connected to the control matrix of Figure 3A, according to an illustrative embodiment of the invention;

Figures 4A and 4B are plan views of a dual-actuated shutter assembly in the open and closed states respectively, according to an illustrative embodiment of the invention.

Figure 5 is a cross-sectional view of a display apparatus, according to an illustrative embodiment of the invention;

Figures 6A-6E are cross sectional views of stages of construction of a composite shutter assembly similar to that shown in Figure 2A, according to an illustrative embodiment of the invention;

Figures 7A-7D are isometric views of stages of construction of an alternate shutter assembly with narrow sidewall beams, according to an illustrative embodiment of the invention;

Figure 8 is a plan view of a shutter assembly incorporating a looped drive beam, according to an illustrative embodiment of the invention;

Figure 9 is an isometric view of a shutter assembly built according to a 3-mask process, according to an illustrative embodiment of the invention;

Figure 10 is an isometric view of the 2d sacrificial material patterned into a mold at an interim point in the fabrication process leading to the shutter assembly of Figure 9, according to an illustrative embodiment of the invention;

Figure 11 is an isometric view of a shutter assembly built according to a 3-mask process, according to an illustrative embodiment of the invention;

Figure 12 is an isometric view of the 2d sacrificial material patterned into a mold at an interim point in the fabrication process leading to the shutter assembly of Figure 11, according to an illustrative embodiment of the invention;

Figure 13 is an isometric view of two connected shutter assemblies built according to a 3-mask process, according to an illustrative embodiment of the invention;

Figure 14 is an isometric view of a shutter assembly built according to a 3-mask process, according to an illustrative embodiment of the invention;

Figure 15 is an isometric view of a shutter assembly built according to a 3-mask process, according to an illustrative embodiment of the invention; and

Figure 16 is an isometric view of a shutter assembly built according to a 3-mask process, according to an illustrative embodiment of the invention.

Description of Certain Illustrative Embodiments

To provide an overall understanding of the invention, certain illustrative embodiments will now be described, including apparatus and methods for displaying images. However, it will be understood by one of ordinary skill in the art that the systems and methods described herein may be adapted and modified as is appropriate for the application being addressed and that the systems and methods described herein may be employed in other suitable applications, and that such other additions and modifications will not depart from the scope hereof.

Figure 1A is a schematic diagram of a direct-view MEMS-based display apparatus 100, according to an illustrative embodiment of the invention. The display apparatus 100 includes a plurality of light modulators 102a–102d (generally "light modulators 102") arranged in rows and columns. In the display apparatus 100, light modulators 102a and 102d are in the open state, allowing light to pass. Light modulators 102b and 102c are in the closed state, obstructing the passage of light. By selectively setting the states of the light modulators 102a–102d, the display apparatus 100 can be utilized to form an image 104 for a backlit display, if illuminated by a lamp or lamps 105. In another implementation, the apparatus 100 may form an image by modulating reflection of ambient light originating from the front of the apparatus. In another implementation, the apparatus 100 may form an image by reflection of light from a lamp or lamps positioned in the front of the display, i.e. by use of a front-light. In another implementation, the apparatus 100 may form an image by modulating both the transmission of light from a source behind the modulating array and simultaneously the reflection of light from a source (lamp or lamps) positioned in the front of the display, called transflective operation. In one of the closed or open states, the light modulators 102 interfere with light in an optical path by, for example, and without limitation, blocking, reflecting, absorbing, filtering, polarizing, diffracting, or otherwise altering a property or path of the light.

In the display apparatus 100, each light modulator 102 corresponds to a pixel 106 in the image 104. In other implementations, the display apparatus 100 may utilize a plurality of light modulators to form a pixel 106 in the image 104. For example, the display apparatus 100 may include three color-specific light modulators 102. By selectively opening one or more of the color-specific light modulators 102 corresponding to a particular pixel 106, the display apparatus 100 can generate a color pixel 106 in the image 104. In another example, the display apparatus 100 includes two or more light modulators 102 per pixel 106 to provide grayscale in an image 104. With respect to an image, a "pixel" corresponds to the smallest picture element defined by the resolution of the image. With respect to structural components of the display apparatus 100, the term "pixel" refers to the combined mechanical and electrical components utilized to modulate the light that forms a single pixel of the image.

Display apparatus 100 is a direct-view display in that it does not require imaging optics. The user sees an image by looking directly at the display apparatus 100. In alternate embodiments the display apparatus 100 is incorporated into a projection display. In such embodiments, the display forms an image by projecting light onto a screen or onto a wall. In projection applications the display apparatus 100 is substantially smaller than the projected image 104.

Direct-view displays may operate in either a transmissive or reflective mode or both simultaneously (defined as transflective). In a transmissive display, the light modulators filter or selectively block light which originates from a lamp or lamps positioned behind the display. The light from the lamps is optionally injected into a light guide or "backlight". Transmissive direct-view display embodiments are often built onto transparent or glass substrates to facilitate a sandwich assembly arrangement where one substrate, containing the light modulators, is positioned directly on top of the backlight. In some transmissive display embodiments, a color-specific light modulator is created by associating a color filter material with each modulator 102. In other transmissive display embodiments colors can be generated, as described below, using a field sequential color method by alternating illumination of lamps with different primary colors.

Each light modulator 102 includes a shutter 108 and an aperture 109. To illuminate a pixel 106 in the image 104, the shutter 108 is positioned such that it allows light to pass through the aperture 109 towards a viewer. To keep a pixel 106 unlit, the shutter 108 is positioned such that it obstructs the passage of light through the aperture 109. The aperture 109 is defined by an opening patterned through a reflective or light-absorbing material.

The display apparatus also includes a control matrix connected to the substrate and to the light modulators for controlling the movement of the shutters. The control matrix includes a series of electrical interconnects (e.g., interconnects 110, 112, and 114), including at least one write-enable interconnect 110 (also referred to as a "scan-line interconnect") per row of pixels, one data interconnect 112 for each column of pixels, and one common interconnect 114 providing a common voltage to all pixels, or at least to pixels from both multiple columns and multiples rows in the display apparatus 100. In response to the application of an appropriate voltage (the "write-enabling voltage, V_{we}"), the write-enable interconnect 110 for a given row of pixels prepares the pixels in the row to accept new shutter movement instructions. The data interconnects 112 communicate the new movement instructions in the form of data voltage pulses. The data voltage pulses applied to the data interconnects 112, in some implementations, directly contribute to an electrostatic movement of the shutters. In other implementations, the data voltage pulses control switches, e.g., transistors or other non-linear circuit elements that control the application of separate actuation voltages, which are typically higher in magnitude than the data voltages, to the light modulators 102. The application of these actuation voltages then results in the electrostatic driven movement of the shutters 108.

Figure 1B is a block diagram 150 of the display apparatus 100. Referring to Figures 1A and 1B, in addition to the elements of the display apparatus 100 described above, as depicted in the block diagram 150, the display apparatus 100 includes a plurality of scan drivers 152 (also referred to as “write enabling voltage sources”) and a plurality of data drivers 154 (also referred to as “data voltage sources”). The scan drivers 152 apply write enabling voltages to scan-line interconnects 110. The data drivers 154 apply data voltages to the data interconnects 112. In some embodiments of the display apparatus, the data drivers 154 are configured to provide analog data voltages to the light modulators, especially where the gray scale of the image 104 is to be derived in analog fashion. In analog operation the light modulators 102 are designed such that when a range of intermediate voltages is applied through the data interconnects 112 there results a range of intermediate open states in the shutters 108 and therefore a range of intermediate illumination states or gray scales in the image 104.

In other cases the data drivers 154 are configured to apply only a reduced set of 2, 3, or 4 digital voltage levels to the control matrix. These voltage levels are designed to set, in digital fashion, either an open state or a closed state to each of the shutters 108.

The scan drivers 152 and the data drivers 154 are connected to digital controller circuit 156 (also referred to as the “controller 156”). The controller 156 includes an input processing module 158, which processes an incoming image signal 157 into a digital image format appropriate to the spatial addressing and the gray scale capabilities of the display 100. The pixel location and gray scale data of each image is stored in a frame buffer 159 so that the data can be fed out as needed to the data drivers 154. The data is sent to the data drivers 154 in mostly serial fashion, organized in predetermined sequences grouped by rows and by image frames. The data drivers 154 can include series to parallel data converters, level shifting, and for some applications digital to analog voltage converters.

The display 100 apparatus optionally includes a set of common drivers 153, also referred to as common voltage sources. In some embodiments the common drivers 153 provide a DC common potential to all light modulators within the array of light modulators 103, for instance by supplying voltage to a series of common interconnects 114. In other embodiments the common drivers 153, following commands from the controller 156, issue voltage pulses or signals to the array of light modulators 103, for instance global actuation pulses which are capable of driving and/or initiating simultaneous actuation of all or some light modulators in multiple rows and columns of the array 103.

All of the drivers (e.g., scan drivers 152, data drivers 154, and common drivers 153) for different display functions are time-synchronized by a timing-control module 160 in the controller 156. Timing commands from the module 160 coordinate the illumination of red, green and blue and white lamps (162, 164, 166, and 167 respectively) via lamp drivers 168, the write-enabling and sequencing of specific rows within the array of pixels 103, the output of voltages from the data drivers 154, and the output of voltages that provide for light modulator actuation.

The controller 156 determines the sequencing or addressing scheme by which each of the shutters 108 in the array 103 can be re-set to the illumination levels appropriate to a new image 104. Details of suitable addressing, image formation, and gray scale techniques can be found in U.S. Patent Application Nos. 11/326,696 and 11/643,042, incorporated herein by reference. New images 104 can be set at periodic intervals. For instance, for video displays, the color images 104 or frames of video are refreshed at frequencies ranging from 10 to 300 Hertz. In some embodiments the setting of an image frame to the array 103 is synchronized with the illumination of the lamps 162, 164, and 166 such that alternate image frames are illuminated with an alternating series of colors, such as red, green, and blue. The image frames for each respective color is referred to as a color sub-frame. In this method, referred to as the field sequential color method, if the color sub-frames are alternated at frequencies in excess of 20 Hz, the human brain will average the alternating frame images into the perception of an image having a broad and continuous range of colors. In alternate implementations, four or more lamps with primary colors can be employed in display apparatus 100, employing primaries other than red, green, and blue.

In some implementations, where the display apparatus 100 is designed for the digital switching of shutters 108 between open and closed states, the controller 156 determines the addressing sequence and/or the time intervals between image frames to produce images 104 with appropriate gray scale. The process of generating varying levels of grayscale by controlling the amount of time a shutter 108 is open in a particular frame is referred to as time division gray scale. In one embodiment of time division gray scale, the controller 156 determines the time period or the fraction of time within each frame that a shutter 108 is allowed to remain in the open state, according to the illumination level or gray scale desired of that pixel. In other implementations, for each image frame, the controller 156 sets a plurality of sub-frame images in multiple rows and columns of the array 103, and the controller alters the duration over which each sub-frame image is illuminated in proportion to a gray scale value or significance value employed within a coded word for gray scale. For instance, the illumination times for a series of sub-frame images can be varied in proportion to the binary coding series 1,2,4,8 ... The shutters 108 for each pixel in the array 103 are then set to either the open or closed state within a sub-frame image according to the value at a corresponding position within the pixel's binary coded word for gray level. It is also possible to have more than two levels for example a 4 level state for the pixel might involve partially open and partially closed states for additional spatially varied grey levels.

In other implementations, the controller alters the intensity of light from the lamps 162, 164, and 166 in proportion to the gray scale value desired for a particular sub-frame image. A number of hybrid techniques are also available for forming colors and gray scale from an array of shutters 108. For instance, the time division techniques described above can be combined with the use of multiple shutters 108 per pixel, or the gray scale value for a particular sub-frame image can be established through a combination of both sub-frame timing and lamp intensity. Details of these and other embodiments can be found in U.S. Patent Application 11/643,042, referenced above.

In some implementations the data for an image state 104 is loaded by the controller 156 to the modulator array 103 by a sequential addressing of individual rows, also referred to as scan lines. For each row or scan line in the sequence, the scan driver 152 applies a write-enable voltage to the write enable interconnect 110 for that row of the array 103, and subsequently the data driver 154 supplies data voltages, corresponding to desired shutter states, for each column in the selected row. This process repeats until data has been loaded for all rows in the array. In some implementations the sequence of selected rows for data loading is linear, proceeding from top to bottom in the array. In other implementations the sequence of selected rows is pseudo-randomized, in order to minimize visual artifacts. And in other implementations the sequencing is organized by blocks, where, for a block, the data for only a certain fraction of the image state 104 is loaded to the array, for instance by addressing only every 5th row of the array in sequence.

In some implementations, the process for loading image data to the array 103 is separated in time from the process of actuating the shutters 108. In these implementations, the modulator array 103 may include data memory elements for each pixel in the array 103 and the control matrix may include a global actuation interconnect for carrying trigger signals, from common driver 153, to initiate simultaneous actuation of shutters 108 according to data stored in the memory elements. Various addressing sequences, many of which are described in U.S. Patent Application 11/643,042, can be coordinated by means of the timing control module 160.

In alternative embodiments, the array of pixels 103 and the control matrix that controls the pixels may be arranged in configurations other than rectangular rows and columns. For example, the pixels can be arranged in hexagonal arrays or curvilinear rows and columns. In general, as used herein, the term scan-line shall refer to any plurality of pixels that share a write-enabling interconnect.

The display 100 is comprised of a plurality of functional blocks including the timing control module 160, the frame buffer 159, scan drivers 152, data drivers 154, and drivers 153 and 168. Each block can be understood to represent either a distinguishable hardware circuit and/or a module of executable code. In some implementations the functional blocks are provided as distinct chips or circuits connected together by means of circuit boards and/or cables. Alternately, many of these circuits can be fabricated along with the pixel array 103 on the same substrate of glass or plastic. In other implementations, multiple circuits, drivers, processors, and/or control functions from block diagram 150 may be integrated together within a single silicon chip, which is then bonded directly to the transparent substrate holding pixel array 103.

The controller 156 includes a programming link 180 by which the addressing, color, and/or gray scale algorithms, which are implemented within controller 156, can be altered according to the needs of particular applications. In some embodiments, the programming link 180 conveys information from environmental sensors, such as ambient light or temperature sensors, so that the controller 156 can adjust imaging modes or backlight power in correspondence with environmental conditions. The controller 156 also comprises a power supply input 182 which provides the power needed for lamps as well as light modulator actuation. Where necessary, the drivers 152 153, 154, and/or 168 may include or be associated with DC-DC converters for transforming an input voltage at 182 into various voltages sufficient for the actuation of shutters 108 or illumination of the lamps, such as lamps 162, 164, 166, and 167.

MEMS Light Modulators

Figure 2A is a perspective view of an illustrative shutter-based light modulator 200 suitable for incorporation into the MEMS-based display apparatus 100 of Figure 1A, according to an illustrative embodiment of the invention. The shutter-based light modulator 200 (also referred to as shutter assembly 200) includes a shutter 202 coupled to an actuator 204. The actuator 204 is formed from two separate compliant electrode beam actuators 205 (the “actuators 205”), as described in U.S. Patent Application No. 11/251,035, filed on October 14, 2005. The shutter 202 couples on one side to the actuators 205. The actuators 205 move the shutter 202 transversely over a surface 203 in a plane of motion which is substantially parallel to the surface 203. The opposite side of the shutter 202 couples to a spring 207 which provides a restoring force opposing the forces exerted by the actuator 204. It is possible to replace the spring 207 by another actuator so that an actuation force rather than a elastic spring force can be used to move the shutter 202 transversely over a surface 203 in the opposite direction from that of actuator 204.

Each actuator 205 includes a compliant load beam 206 connecting the shutter 202 to a load anchor 208. The load anchors 208 along with the compliant load beams 206 serve as mechanical supports, keeping the shutter 202 suspended proximate to the surface 203. The load anchors 208 physically connect the compliant load beams 206 and the shutter 202 to the surface 203 and electrically connect the load beams 206 to a bias voltage, in some instances, ground.

Each actuator 205 also includes a compliant drive beam 216 positioned adjacent to each load beam 206. The drive beams 216 couple at one end to a drive beam anchor 218 shared between the drive beams 216. The other end of each drive beam 216 is free to move. However, there are implementations where the other end of the drive beam 216 is not completely free to move but partially restrained. Each drive beam 216 can be curved such that it is closest to the load beam 206 near the free end of the drive beam 216 and the anchored end of the load beam 206.

The surface 203 includes one or more apertures 211 for admitting the passage of light in the transmissive or transflective embodiments. If the shutter assembly 200 is formed on an opaque substrate, made for example from silicon, then the surface 203 is a surface of the substrate, and the apertures 211 are formed by etching an array of holes through the substrate. If the shutter assembly 200 is formed on a transparent substrate, made for example of glass or plastic, then the surface 203 is a surface of a light blocking layer deposited on the substrate, and the apertures are formed by etching the surface 203 into an array of holes 211. The apertures 211 can be generally circular, elliptical, polygonal, serpentine, or irregular in shape. In reflective or some transflective embodiments the regions 211 can represent areas of higher reflection or lower reflection than the surrounding substrate such that movement of the shutter assembly 200 modulates the total reflected light from the shutter based light modulator 200.

In operation, a display apparatus incorporating the light modulator 200 applies an electric potential to the drive beams 216 via the drive beam anchor 218. A second electric potential may be applied to the load beams 206. The resulting potential difference between the drive beams 216 and the load beams 206 pulls the free ends of the drive beams 216 towards the anchored ends of the load beams 206, and pulls the shutter ends of the load beams 206 toward the anchored ends of the drive beams 216, thereby driving the shutter 202 transversely towards the drive anchor 218. The compliant members 206 act as springs, such that when the voltage across the beams 206 and 216 is removed, the load beams 206 push the shutter 202 back into its initial position, releasing the stress stored in the load beams 206.

The shutter assembly 200, also referred to as an elastic shutter assembly, incorporates a passive restoring force, such as a spring, for returning a shutter to its rest or relaxed position after voltages have been removed. A number of elastic restore mechanisms and various electrostatic couplings can be designed into or in conjunction with electrostatic actuators, the compliant beams illustrated in shutter assembly 200 being just one example. Other examples are described in U.S. Patent Applications 11/251,035 and 11/326,696, incorporated herein by reference. For instance, a highly non-linear voltage-displacement response can be provided which favors an abrupt transition between “open” vs. “closed” states of operation, and which, in many cases, provides a bi-stable or hysteretic operating characteristic for the shutter assembly. Other electrostatic actuators can be designed with more incremental voltage-displacement responses and with considerably reduced hysteresis, as may be preferred for analog gray scale operation.

The actuator 205 within the elastic shutter assembly is said to operate between a closed or actuated position and a relaxed position. The designer, however, can choose to place apertures 211 such that shutter assembly 200 is in either the "open" state, i.e. passing light, or in the "closed" state, i.e. blocking light, whenever actuator 205 is in its relaxed position. For illustrative purposes, it is assumed below that elastic shutter assemblies described herein are designed to be open in their relaxed state.

In many cases it is preferable to provide a dual set of "open" and "closed" actuators as part of a shutter assembly so that the control electronics are capable of electrostatically driving the shutters into each of the open and closed states.

Display apparatus 100, in alternative embodiments, includes light modulators other than transverse shutter-based light modulators, such as the shutter assembly 200 described above. For example, Figure 2B is a cross-sectional view of a rolling actuator shutter-based light modulator 220 suitable for incorporation into an alternative embodiment of the MEMS-based display apparatus 100 of Figure 1A, according to an illustrative embodiment of the invention. As described further in U.S. Patent No. 5,233,459, entitled "Electric Display Device," and U.S. Patent No. 5,784,189, entitled "Spatial Light Modulator," the entireties of which are incorporated herein by reference, a rolling actuator-based light modulator includes a moveable electrode disposed opposite a fixed electrode and biased to move in a preferred direction to produce a shutter upon application of an electric field. In one embodiment, the light modulator 220 includes a planar electrode 226 disposed between a substrate 228 and an insulating layer 224 and a moveable electrode 222 having a fixed end 230 attached to the insulating layer 224. In the absence of any applied voltage, a moveable end 232 of the moveable electrode 222 is free to roll towards the fixed end 230 to produce a rolled state. Application of a voltage between the electrodes 222 and 226 causes the moveable electrode 222 to unroll and lie flat against the insulating layer 224, whereby it acts as a shutter that blocks light traveling through the substrate 228. The moveable electrode 222 returns to the rolled state by means of an elastic restoring force after the voltage is removed. The bias towards a rolled state may be achieved by manufacturing the moveable electrode 222 to include an nonuniform initial stress or strain state.

Figure 2C is a cross-sectional view of an illustrative non shutter-based MEMS light modulator 250. The light tap modulator 250 is suitable for incorporation into an alternative embodiment of the MEMS-based display apparatus 100 of Figure 1A, according to an illustrative embodiment of the invention. As described further in U.S. Patent No.

5,771,321, entitled "Micromechanical Optical Switch and Flat Panel Display," the entirety of which is incorporated herein by reference, a light tap works according to a principle of frustrated total internal reflection. That is, light 252 is introduced into a light guide 254, in which, without interference, light 252 is for the most part unable to escape the light guide 254 through its front or rear surfaces due to total internal reflection. The light tap 250 includes a tap element 256 that has a sufficiently high index of refraction that, in response to the tap element 256 contacting the light guide 254, light 252 impinging on the surface of the light guide 254 adjacent the tap element 256 escapes the light guide 254 through the tap element 256 towards a viewer, thereby contributing to the formation of an image.

In one embodiment, the tap element 256 is formed as part of beam 258 of flexible, transparent material. Electrodes 260 coat portions of one side of the beam 258. Opposing electrodes 260 are disposed on the light guide 254. By applying a voltage across the electrodes 260, the position of the tap element 256 relative to the light guide 254 can be controlled to selectively extract light 252 from the light guide 254.

The roller-based light modulator 220 and light tap 250 are not the only examples of MEMS light modulators suitable for inclusion in various embodiments of the invention. It will be understood that other MEMS light modulators can exist and can be usefully incorporated into the invention.

U.S. Patent Applications Nos. 11/251,035 and 11/326,696 have described a variety of methods by which an array of shutters can be controlled via a control matrix to produce images, in many cases moving images, with appropriate gray scale. In some cases, control is accomplished by means of a passive matrix array of row and column interconnects connected to driver circuits on the periphery of the display. In other cases it is appropriate to include switching and/or data storage elements within each pixel of the array (the so-called active matrix) to improve either the speed, the gray scale and/or the power dissipation performance of the display.

Figure 3A is a schematic diagram of a control matrix 300 suitable for controlling the light modulators incorporated into the MEMS-based display apparatus 100 of Figure 1A, according to an illustrative embodiment of the invention. Figure 3B is a perspective view of an array 320 of shutter-based light modulators connected to the control matrix 300 of Figure 3A, according to an illustrative embodiment of the invention. The control matrix 300 may address an array of pixels 320 (the "array 320"). Each pixel 301 includes an elastic shutter assembly 302, such as the shutter assembly 200 of Figure 2A, controlled by an actuator 303.

Each pixel also includes an aperture layer 322 that includes apertures 324. Further electrical and mechanical descriptions of shutter assemblies such as shutter assembly 302, and variations thereon, can be found in U.S. Patent Applications Nos. 11/251,035 and 11/326,696. Descriptions of alternate control matrices can also be found in U.S. Patent Application No. 11/607,715.

The control matrix 300 is fabricated as a diffused or thin-film-deposited electrical circuit on the surface of a substrate 304 on which the shutter assemblies 302 are formed. The control matrix 300 includes a scan-line interconnect 306 for each row of pixels 301 in the control matrix 300 and a data-interconnect 308 for each column of pixels 301 in the control matrix 300. Each scan-line interconnect 306 electrically connects a write-enabling voltage source 307 to the pixels 301 in a corresponding row of pixels 301. Each data interconnect 308 electrically connects a data voltage source, ("V_d source") 309 to the pixels 301 in a corresponding column of pixels 301. In control matrix 300, the data voltage V_d provides the majority of the energy necessary for actuation of the shutter assemblies 302. Thus, the data voltage source 309 also serves as an actuation voltage source.

Referring to Figures 3A and 3B, for each pixel 301 or for each shutter assembly 302 in the array of pixels 320, the control matrix 300 includes a transistor 310 and a capacitor 312. The gate of each transistor 310 is electrically connected to the scan-line interconnect 306 of the row in the array 320 in which the pixel 301 is located. The source of each transistor 310 is electrically connected to its corresponding data interconnect 308. The actuators 303 of each shutter assembly 302 include two electrodes. The drain of each transistor 310 is electrically connected in parallel to one electrode of the corresponding capacitor 312 and to one of the electrodes of the corresponding actuator 303. The other electrode of the capacitor 312 and the other electrode of the actuator 303 in shutter assembly 302 are connected to a common or ground potential. In alternate implementations, the transistors 310 can be replaced with semiconductor diodes and or metal-insulator-metal sandwich type switching elements.

In operation, to form an image, the control matrix 300 write-enables each row in the array 320 in a sequence by applying V_{we} to each scan-line interconnect 306 in turn. For a write-enabled row, the application of V_{we} to the gates of the transistors 310 of the pixels 301 in the row allows the flow of current through the data interconnects 308 through the transistors 310 to apply a potential to the actuator 303 of the shutter assembly 302. While the row is write-enabled, data voltages V_d are selectively applied to the data interconnects

308. In implementations providing analog gray scale, the data voltage applied to each data interconnect 308 is varied in relation to the desired brightness of the pixel 301 located at the intersection of the write-enabled scan-line interconnect 306 and the data interconnect 308. In implementations providing digital control schemes, the data voltage is selected to be either a relatively low magnitude voltage (i.e., a voltage near ground) or to meet or exceed V_{at} (the actuation threshold voltage). In response to the application of V_{at} to a data interconnect 308, the actuator 303 in the corresponding shutter assembly 302 actuates, opening the shutter in that shutter assembly 302. The voltage applied to the data interconnect 308 remains stored in the capacitor 312 of the pixel 301 even after the control matrix 300 ceases to apply V_{we} to a row. It is not necessary, therefore, to wait and hold the voltage V_{we} on a row for times long enough for the shutter assembly 302 to actuate; such actuation can proceed after the write-enabling voltage has been removed from the row. The capacitors 312 also function as memory elements within the array 320, storing actuation instructions for periods as long as is necessary for the illumination of an image frame.

The pixels 301 as well as the control matrix 300 of the array 320 are formed on a substrate 304. The array includes an aperture layer 322, disposed on the substrate 304, which includes a set of apertures 324 for respective pixels 301 in the array 320. The apertures 324 are aligned with the shutter assemblies 302 in each pixel. In one implementation the substrate 304 is made of a transparent material, such as glass or plastic. In another implementation the substrate 304 is made of an opaque material, but in which holes are etched to form the apertures 324. In yet another implementation for reflective or transflective operation, the regions 324 can represent areas of higher or lower reflectivity than the surrounding substrate such that motion of the shutter assembly serves to modulate the reflected component of light from a source in front of the modulating plane.

Components of shutter assemblies 302 are processed either at the same time as the control matrix 300 or in subsequent processing steps on the same substrate. The electrical components in control matrix 300 are fabricated using many thin film techniques in common with the manufacture of thin film transistor arrays for liquid crystal displays. Available techniques are described in Den Boer, Active Matrix Liquid Crystal Displays (Elsevier, Amsterdam, 2005), incorporated herein by reference. The shutter assemblies are fabricated using techniques similar to the art of micromachining or from the manufacture of micromechanical (i.e., MEMS) devices. Many applicable thin film MEMS techniques are described in Rai-Choudhury, ed., Handbook of Microlithography, Micromachining &

Microfabrication (SPIE Optical Engineering Press, Bellingham, Wash. 1997), incorporated herein by reference. Fabrication techniques specific to MEMS light modulators formed on glass substrates can be found in U.S. Patent Application Nos. 11/361,785 and 11/731,628, incorporated herein by reference in their entireties. For instance, as described in those applications, the shutter assembly 302 can be formed from thin films of amorphous silicon, deposited by a chemical vapor deposition process.

The shutter assembly 302 together with the actuator 303 can be made bi-stable. That is, the shutters can exist in at least two equilibrium positions (e.g. open or closed) with little or no power required to hold them in either position. More particularly, the shutter assembly 302 can be mechanically bi-stable. Once the shutter of the shutter assembly 302 is set in position, no electrical energy or holding voltage is required to maintain that position. The mechanical stresses on the physical elements of the shutter assembly 302 can hold the shutter in place.

The shutter assembly 302 together with the actuator 303 can also be made electrically bi-stable. In an electrically bi-stable shutter assembly, there exists a range of voltages below the actuation voltage of the shutter assembly, which if applied to a closed actuator (with the shutter being either open or closed), holds the actuator closed and the shutter in position, even if an opposing force is exerted on the shutter. The opposing force may be exerted by a spring such as spring 207 in shutter-based light modulator 200, or the opposing force may be exerted by an opposing actuator, such as an “open” or “closed” actuator.

The light modulator array 320 is depicted as having a single MEMS light modulator per pixel. Other embodiments are possible in which multiple MEMS light modulators are provided in each pixel, thereby providing the possibility of more than just binary “on’ or “off” optical states in each pixel. Certain forms of coded area division gray scale are possible where multiple MEMS light modulators in the pixel are provided, and where apertures 324, which are associated with each of the light modulators, have unequal areas.

In other embodiments the roller-based light modulator 220 and the light tap 250, as well as other MEMS-based light modulators, can be substituted for the shutter assembly 302 within the light modulator array 320.

Figures 4A and 4B illustrate an alternative shutter-based light modulator (shutter assembly) 400 suitable for inclusion in various embodiments of the invention. The light modulator 400 is an example of a dual actuator shutter assembly, and is shown in Figure 4A in an open state. Figure 4B is a view of the dual actuator shutter assembly 400 in a closed state. Shutter assembly 400 is described in further detail in U.S. Patent Application 11/251,035, referenced above. In contrast to the shutter assembly 200, shutter assembly 400 includes actuators 402 and 404 on either side of a shutter 406. Each actuator 402 and 404 is independently controlled. A first actuator, a shutter-open actuator 402, serves to open the shutter 406. A second opposing actuator, the shutter-close actuator 404, serves to close the shutter 406. Both actuators 402 and 404 are compliant beam electrode actuators. The actuators 402 and 404 open and close the shutter 406 by driving the shutter 406 substantially in a plane parallel to an aperture layer 407 over which the shutter is suspended. The shutter 406 is suspended a short distance over the aperture layer 407 by anchors 408 attached to the actuators 402 and 404. The inclusion of supports attached to both ends of the shutter 406 along its axis of movement reduces out of plane motion of the shutter 406 and confines the motion substantially to a plane parallel to the substrate. By analogy to the control matrix 300 of Figure 3A, a control matrix suitable for use with shutter assembly 400 might include one transistor and one capacitor for each of the opposing shutter-open and shutter-close actuators 402 and 404.

The shutter 406 includes two shutter apertures 412 through which light can pass. The aperture layer 407 includes a set of three apertures 409. In Figure 4A, the shutter assembly 400 is in the open state and, as such, the shutter-open actuator 402 has been actuated, the shutter-close actuator 404 is in its relaxed position, and the centerlines of apertures 412 and 409 coincide. In Figure 4B the shutter assembly 400 has been moved to the closed state and, as such, the shutter-open actuator 402 is in its relaxed position, the shutter-close actuator 404 has been actuated, and the light blocking portions of shutter 406 are now in position to block transmission of light through the apertures 409 (shown as dotted lines).

Each aperture has at least one edge around its periphery. For example, the rectangular apertures 409 have four edges. In alternative implementations in which circular, elliptical, oval, or other curved apertures are formed in the aperture layer 407, each aperture may have only a single edge. In other implementations the apertures need not be separated or disjoint in the mathematical sense, but instead can be connected. That is to say, while portions or shaped sections of the aperture may maintain a correspondence to each shutter, several of these sections may be connected such that a single continuous perimeter of the aperture is shared by multiple shutters.

In order to allow light with a variety of exit angles to pass through apertures 412 and 409 in the open state, it is advantageous to provide a width or size for shutter apertures 412 which is larger than a corresponding width or size of apertures 409 in the aperture layer 407. In order to effectively block light from escaping in the closed state, it is preferable that the light blocking portions of the shutter 406 overlap the apertures 409. Figure 4B shows a predefined overlap 416 between the edge of light blocking portions in the shutter 406 and one edge of the aperture 409 formed in aperture layer 407.

The electrostatic actuators 402 and 404 are designed so that their voltage - displacement behavior provides a bi-stable characteristic to the shutter assembly 400. For each of the shutter-open and shutter-close actuators there exists a range of voltages below the actuation voltage, which if applied while that actuator is in the closed state (with the shutter being either open or closed), will hold the actuator closed and the shutter in position, even after an actuation voltage is applied to the opposing actuator. The minimum voltage needed to maintain a shutter's position against such an opposing force is referred to as a maintenance voltage V_m. A number of control matrices which take advantage of the bi-stable operation characteristic are described in U.S. Patent Application No. 11/607,715, referenced above.

Figure 5 is a cross sectional view of a display apparatus 500 incorporating shutter-based light modulators (shutter assemblies) 502, according to an illustrative embodiment of the invention. Each shutter assembly incorporates a shutter 503 and an anchor 505. Not shown are the compliant beam actuators which, when connected between the anchors 505 and the shutters 503, help to suspend the shutters a short distance above the surface. The shutter assemblies 502 are disposed on a transparent substrate 504, preferably made of plastic, quartz, or glass. A rear-facing reflective layer, reflective film 506, disposed on the substrate 504 defines a plurality of surface apertures 508 located beneath the closed positions of the shutters 503 of the shutter assemblies 502. The reflective film 506 reflects light not passing through the surface apertures 508 back towards the rear of the display apparatus 500. The reflective aperture layer 506 can be a fine-grained metal film without inclusions formed in thin film fashion by a number of vapor deposition techniques including sputtering, evaporation, ion plating, laser ablation, or chemical vapor deposition. In another implementation, the rear-facing reflective layer 506 can be formed from a mirror, such as a dielectric mirror. A dielectric mirror is fabricated as a stack of dielectric thin films which alternate between materials of high and low refractive index. The vertical gap which separates the shutters 503 from the reflective film 506, within which the shutter is free to move, is in the range of 0.5 to 10 microns. The magnitude of the vertical gap is preferably less than the lateral overlap between the edge of shutters 503 and the edge of apertures 508 in the closed state, such as the overlap 416 shown in Figure 4B.

The display apparatus 500 includes an optional diffuser 512 and/or an optional brightness enhancing film 514 of various potential orientations of which only one is shown here, which separate the substrate 504 from a planar light guide 516. The light guide is comprised of a transparent, i.e. glass or plastic material. The light guide 516 is illuminated by one or more light sources 518, forming a backlight. The light sources 518 can be, for example, and without limitation, incandescent lamps, fluorescent lamps, lasers, or light emitting diodes (LEDs). A reflector 519 helps direct light from lamp 518 towards the light guide 516. A front-facing reflective film 520 is disposed behind the backlight 516, reflecting light towards the shutter assemblies 502. Light rays such as ray 521 from the backlight that do not pass through one of the shutter assemblies 502 will be returned to the backlight and reflected again from the film 520. In this fashion light that fails to leave the display to form an image on the first pass can be recycled and made available for transmission through other open apertures in the array of shutter assemblies 502. Such light recycling has been shown to increase the illumination efficiency of the display.

The light guide 516 includes a set of geometric light redirectors or prisms 517 which re-direct light from the lamps 518 towards the apertures 508 and hence toward the front of the display. The light re-directors can be molded into the plastic body of light guide 516 with shapes that can be alternately triangular, trapezoidal, or curved in cross section. The density of the prisms 517 generally increases with distance from the lamp 518.

In alternate embodiments the aperture layer 506 can be made of a light absorbing material, and in alternate embodiments the surfaces of shutter 503 can be coated with either a light absorbing or a light reflecting material. In alternate embodiments the aperture layer 506 can be deposited directly on the surface of the light guide 516. In alternate embodiments the aperture layer 506 need not be disposed on the same substrate as the shutters 503 and anchors 505 (see the MEMS-down configuration described below). These and other embodiments for a display illumination system are described in detail in the U.S.

Patent Application Nos. 11/218,690 and 11/528,191, incorporated herein by reference in their entireties.

In one implementation the light sources 518 can include lamps of different colors, for instance, the colors red, green, and blue. A color image can be formed by sequentially illuminating images with lamps of different colors at a rate sufficient for the human brain to average the different colored images into a single multi-color image. The various color-specific images are formed using the array of shutter assemblies 502. In another implementation, the light source 518 includes lamps having more than three different colors. For example, the light source 518 may have red, green, blue and white lamps or red, green, blue, and yellow lamps.

A cover plate 522 forms the front of the display apparatus 500. The rear side of the cover plate 522 can be covered with a black matrix 524 to increase contrast. In alternate implementations the cover plate includes color filters, for instance distinct red, green, and blue filters corresponding to different ones of the shutter assemblies 502. The cover plate 522 is supported a predetermined distance away from the shutter assemblies 502 forming a gap 526. The gap 526 is maintained by mechanical supports or spacers 527 and/or by an adhesive seal 528 attaching the cover plate 522 to the substrate 504.

The adhesive seal 528 seals in a working fluid 530. The working fluid 530 is engineered with viscosities preferably below about 10 centipoise and with relative dielectric constant preferably above about 2.0, and dielectric breakdown strengths above about 10^4 V/cm. The working fluid 530 can also serve as a lubricant. In one implementation, the working fluid 530 is a hydrophobic liquid with a high surface wetting capability. In alternate implementations the working fluid 530 has a refractive index that is either greater than or less than that of the substrate 504.

The sealing material 528 can be formed from polymer adhesives such as epoxies, acrylates, or a silicone materials. The adhesive seal 528 should have a curing temperature preferably below about 200.degree. C., it should have a coefficient of thermal expansion preferably below about 50 ppm per degree C. and should be moisture resistant. An exemplary sealant 528 is EPO-TEK B9021-1, sold by Epoxy Technology, Inc. In an alternate embodiment the adhesive is formed from a heat reflowable material such as a solder metal or a glass frit compound.

The adhesive seal 528 seals in a working fluid 530. The working fluid 530 is engineered with viscosities preferably below about 10 centipoise and with relative dielectric constant preferably above about 2.0, and dielectric breakdown strengths above about 10.sup.4 V/cm. The working fluid 530 can also serve as a lubricant. In alternate implementations the working fluid 530 has a refractive index that is either greater than or less than that of the substrate 504. In one implementation the working fluid has a refractive index greater than 2.0. Suitable working fluids 530 include, without limitation, de-ionized water, methanol, ethanol, silicone oils, heptane, octane, fluorinated silicone oils, dimethylsiloxane, polydimethylsiloxane, hexamethyldisiloxane, and diethylbenzene.

In another implementation, the working fluid 530 is a hydrophobic liquid with a high surface wetting capability. Preferably, its wetting capabilities are sufficient to wet the front as well as the rear surfaces of the shutter assemblies 502. Hydrophobic fluids are capable of displacing water from the surfaces of shutter assemblies 502. In another implementation, the working fluid 530 contains a suspension of particles with diameters in the range of 0.2 to 20 microns. Such particles scatter light to increase the viewing angle of a display. In another implementation the working fluid 530 contains dye molecules in solution for absorbing some or all frequencies of visible light to increase the contrast of the display. In another implementation the fluid contains additives such as ethanol, ionic fluids, BHT or other additives to slightly conduct or in other ways prevent the buildup of static charge on the surfaces of the assemblies

A sheet metal or molded plastic assembly bracket 532 holds the cover plate 522, the substrate 504, the backlight 516 and the other component parts together around the edges. The assembly bracket 532 is fastened with screws or indent tabs to add rigidity to the combined display apparatus 500. In some implementations, the light source 518 is molded in place by an epoxy potting compound. Reflectors 536 help return light escaping from the edges of light guide 516 back into the light guide. Not shown in Figure 5 are electrical interconnects which provide control signals as well as power to the shutter assemblies 502 and the lamps 518.

Further details and alternate configurations for the display apparatus 500, including manufacturing methods therefore, can be found in U.S. Patent Application Nos. 11/361,785 and 11/731,628, incorporated herein by reference in their entireties.

Display apparatus 500 is referred to as the MEMS-up configuration, wherein the MEMS-based light modulators are formed on a front surface of substrate 504, i.e. the surface that faces toward the viewer. The shutter assemblies 502 are built directly on top of the reflective aperture layer 506. In an alternate embodiment of the invention, referred to as the MEMS-down configuration, the shutter assemblies are disposed on a substrate separate from the substrate on which the reflective aperture layer is formed. The substrate on which the reflective aperture layer is formed, defining a plurality of apertures, is referred to herein as the aperture plate. In the MEMS-down configuration, the substrate that carries the MEMS-based light modulators takes the place of the cover plate 522 in display apparatus 500 and is oriented such that the MEMS-based light modulators are positioned on the rear surface of the top substrate, i.e. the surface that faces away from the viewer and toward the back light 516. The MEMS-based light modulators are thereby positioned directly opposite to and across a gap from the reflective aperture layer. The gap can be maintained by a series of spacer posts connecting the aperture plate and the substrate on which the MEMS modulators are formed. In some implementations the spacers are disposed within or between each pixel in the array. The gap or distance that separates the MEMS light modulators from their corresponding apertures is preferably less than 10 microns, or a distance that is less than the overlap between shutters and apertures, such as overlap 416. Further details and alternate embodiments for the MEMS-down display configuration can be found in the U.S. Patent Applications 11/361,785, 11/528,191, and 11/731,628 referenced above.

In other embodiments, the roller-based light modulator 220 or the light tap 250, as well as other MEMS-based light modulators, can be substituted for the shutter assemblies 502 within the display assembly 500.

Shutter Manufacturing

A shutter must satisfy mechanical, optical and electrical properties. Mechanically, the shutter film support the load and stress of device under operation. Electrically, the material must be at least minimally conductive to allow electrostatic actuation. Optically, the shutter film must be opaque enough to block light. It is possible to have a single film satisfy all the mechanical, electrical and optical requirements. However, using multiple films in a composite stack offers more design and process latitude.

Figures 6A-6E are cross-sectional views of stages of construction of an exemplary composite shutter assembly 600, similar to that shown in Figure 2A, according to an illustrative embodiment of the invention. Figure 6A shows a cross sectional detail of a composite shutter assembly 600, according to an illustrative embodiment of the invention. The shutter assembly 600 includes shutter 601, a compliant beam 602, and anchor structure 604 built-up on substrate 603 and aperture layer 606. The elements of the composite shutter assembly include a first mechanical layer 605, a conductor layer 607, a second mechanical layer 609, and an encapsulating dielectric 611. At least one of the mechanical layers 605 or 609 will be deposited to thicknesses in excess of 0.05 microns, as one or both of the mechanical layers will comprise the principle load bearing and mechanical actuation member for the shutter assembly. Candidate materials for the mechanical layers 605 and 609 include, without limitation, metals such as Al, Cu, Ni, Cr, Mo, Ti, Ta, Nb, Nd, or alloys thereof; dielectric materials such as Al_2O_3, SiO_2, Ta_2O_5, or Si_xN_y; or semiconducting materials such as diamond-like carbon, Si, Ge, GaAs, CdTe or alloys thereof. At least one of the layers, such as conductor layer 607, should be electrically conducting so as to carry charge on to and off of the actuation elements. Candidate materials include, without limitation, Al, Cu, Ni, Cr, Mo, Ti, Ta, Nb, Nd, or alloys thereof or semiconducting materials such as diamond-like carbon, Si, Ge, GaAs, CdTe or alloys thereof, especially when the semiconductors are doped with impurities such as phosphorus, arsenic, boron, or aluminum. Figure 6A shows a 3 layer sandwich configuration for the composite in which the mechanical layers 605 and 609 with similar thicknesses and mechanical properties are deposited on either side of the conductor layer 607. In some embodiments the sandwich structure helps to ensure that stresses remaining after deposition and/or stresses that are imposed by temperature variations will not cause bending or warping of the shutter assembly 600. For some applications a 2 layer sandwich or 1 layer shutter assembly could be sufficient to meet required performance specifications.

In some implementations, the order of the layers in composite shutter assembly 600 can be inverted, such that the outside of the sandwich is comprised of a conducting layer while the inside of the sandwich is comprised of a mechanical layer.

Further description of materials for use in shutter 601, including the incorporation of materials selected for the absorption or reflection of incident light can be found in U.S. Patent Application No. 11/361,785, entitled “Display Apparatus and Methods For Manufacture Thereof,” filed February 23, 2006 incorporated herein by reference in its entirety.

Shutter assembly 600 includes a dielectric layer 611 which can encapsulate or partially cover the shutter assembly. Dielectric coatings can be applied in conformal fashion, such that all bottom, tops, and side surfaces of the shutters and beams are uniformly coated or applied such that the surfaces that are to make contact are coated only. Such thin films can be grown by thermal oxidation and/or by conformal chemical vapor deposition of an insulator such as Al_2O_3, Cr_2O_3, TiO_2, HfO_2, V_2O_5, Nb_2O_5, Ta_2O_5, SiO_2, or Si_3N_4, or by depositing similar materials by means of atomic layer deposition. The dielectric coating layer can be applied with thicknesses in the range of 10 nm to 1 micron. Completely conformal dielectric coatings are not always needed. In some cases, sputtering and evaporation can be used to deposit the dielectric coating onto sidewalls, without covering the underside of the devices.

Figures 6B-6E show an exemplary process for building shutter assembly 600, according to an illustrative embodiment of the invention. In many implementations, the shutter assembly is built on top of a pre-existing control matrix, for instance an active matrix array of thin film transistors. The processes used for constructing the control matrix on top of or in conjunction with an aperture layer 606 is described in U.S. Patent Application No. 11/361,785, referred to and incorporated above.

Figure 6B is a cross sectional view of a first step in the process of forming the shutter assembly 600, according to an illustrative embodiment of the invention. As shown in Figure 6B, a sacrificial layer 613 is deposited and patterned. Novolac resin, or any of the thermoplastic phenol-formaldehyde resins made with an excess of phenol in the reaction, is a preferred sacrificial material. Other candidate sacrificial materials include polymer materials such as polyimide, polyamide, fluoropolymer, benzocyclobutene, polyphenylquinoxylene, parylene, or polynorbornene. These materials are chosen for their ability to planarize rough surfaces, maintain mechanical integrity at processing temperatures in excess of 250 °C, and their ease of etch and/or thermal decomposition during removal. Alternate sacrificial layers can be found among the photoresists: polyvinyl acetate, polyvinyl ethylene, polyimides and phenolic or novolac resins, although their use will typically be limited to temperatures below 350 °C. An alternate sacrificial layer is SiO_2, which can be removed preferentially as long as other electronic or structural layers are resistant to the hydrofluoric acid solutions used for its removal (e.g., Si_3N_4 is so resistant). Another alternate sacrificial layer is silicon, which can be removed preferentially as long as other electronic and structural layers are resistant to the fluorine plasmas or XeF_2 used for its removal (e.g., most metals and/or Si_3N_4 are so resistant). Yet another alternate sacrificial layer is aluminum, which can be removed preferentially as long as other electronic or structural layers are resistant to strong base solutions, such as concentrated NaOH (e.g., Cr, Ni, Mo, Ta, and Si are so resistant). Still another alternate sacrificial layer is copper, which can be removed preferentially as long as other electronic or structural layers are resistant to nitric or sulfuric acid solutions (e.g., Cr, Ni, and Si are so resistant).

Next the sacrificial layer 613 is patterned to expose holes or vias at the anchor regions 604. The preferred novolac resin material and other polymer resins can be formulated to include photoactive agents – enabling regions exposed through a UV photomask to be preferentially removed in a developer solution. Other sacrificial layers 613 can be patterned by coating the sacrificial layer in an additional layer of photoresist, photo-patterning the photoresist, and finally using the photoresist as an etching mask. Other sacrificial layers can be patterned by coating the sacrificial layer with a hard mask, which can be a thin layer of SiO_2 or metal such as chromium. A photo-pattern is then transferred to the hard mask by means of photoresist and wet chemical etching. The pattern developed in the hard mask can be very resistant to dry chemical, anisotropic, or plasma etching – techniques which can be used to impart very deep and narrow anchor holes into the sacrificial layer.

After the anchor 604 or via regions have been opened in the sacrificial layer, the exposed and underlying conducting surface 614 can be etched, either chemically or via the sputtering effects of a plasma, to remove any surface oxide layers. Such a contact etching step can improve the ohmic contact between the underlying conductor and the shutter material.

After patterning of the sacrificial layer, any photoresist layers or hard masks can be removed through use of either solvent cleans or acid etching.

Next, in the process for building shutter assembly 600, as shown in Figure 6C, the shutter materials are deposited. The shutter assembly 600 is composed of multiple thin films 605, 607, and 609. In a preferred embodiment, the first mechanical layer 605 is an amorphous silicon layer, deposited first by PECVD or other low temperature method, followed by a conductor layer 607 comprised of aluminum, followed by a second layer 609 of amorphous silicon. The deposition temperature used for the shutter materials 605, 607, and 609 is below that at which physical degradation occurs for the sacrificial layer. For instance, novalac resin is known to decompose at temperatures above 300 °C. The shutter materials 605, 607 and 609 can be deposited at temperatures below 300 °C, thus allowing usage of novalac resin as a sacrificial material. Hydrogenated amorphous silicon is a useful mechanical material for layers 605 and 609 since it can be grown to thicknesses in the range of 0.05 to 3 microns, in a relatively stress-free state, by means of plasma-assisted chemical vapor deposition (PECVD) from silane gas at temperatures in the range of 150 to 350 °C. Phosphene gas (PH3) is used as a dopant so that the amorphous silicon can be grown with resistivities below 10 Megohm-cm. In alternate embodiments, a similar PECVD technique can be used for the deposition of Si_3N_4, silicon-rich Si_3N_4, or SiO_2 materials as the mechanical layer 605 or for the deposition of diamond-like carbon, Ge, SiGe, CdTe, or other semiconducting materials for mechanical layer 605. An advantage of the PECVD deposition technique is that the deposition can be quite conformal, that is, it can coat a variety of inclined surfaces or the inside surfaces of narrow via holes. Even if the anchor or via holes which are cut into the sacrificial material present nearly vertical sidewalls, the PECVD technique can provide a continuous coating between the bottom and top horizontal surfaces of the anchor.

In addition to the PECVD technique, alternate techniques available for the growth of shutter layers 605 or 609 include RF or DC sputtering, metal-organic chemical vapor deposition, evaporation, electroplating or electroless plating.

For the conducting layer 607, a metal thin film such as Al is preferred, although alternates such as Cu, Ni, Mo, Ta, Ti, W Cr, or alloys of the preceding can be chosen. The inclusion of such a conducting material serves two purposes. It reduces the overall sheet resistance of the shutter material and it helps to block the passage of visible light through the shutter material. (Amorphous silicon, if grown to thicknesses of less than 2 microns can transmit visible light to some degree.) The conducting material can be deposited either by sputtering or, in a more conformal fashion, by chemical vapor deposition techniques, electroplating, or electroless plating.

The process for building the shutter assembly 600 continues in Figure 6D. The shutter layers 605, 607, and 609 are photomasked and etched while the sacrificial layer 613 is still on the wafer. First a photoresist material is applied, then exposed through a photomask, and then developed to form an etch mask. Amorphous silicon, silicon nitride, and silicon oxide can then be etched in fluorine-based plasma chemistries. SiO_2 mechanical layers can be etched using HF wet chemicals; and any metals in the conductor layers can be etched with either wet chemicals or chlorine-based plasma chemistries.

The pattern shapes applied through the photomask at Figure 6D influence the mechanical properties, such as stiffness, compliance, and the voltage response in the actuators and shutters of the shutter assembly 600. The shutter assembly 600 includes a compliant beam 602, shown in cross section. Compliant beam 602 is shaped such that the width is less than the total height or thickness of the shutter material. It is preferable to maintain a beam dimensional ratio of at least >1:1, with the beams 602 being taller or thicker in the out of plane direction than they are wide so that the desired direction of motion is more flexible than the undesired directions.

The process for building the shutter assembly 600 continues as depicted in Figure 6E. The sacrificial layer 613 is removed, which frees-up all moving parts from the substrate 603, except at the anchor points. Novalac sacrificial materials are preferably removed in an oxygen plasma. Other polymer materials used for sacrificial layer 613 can also be removed in an oxygen plasma, or in some cases by thermal pyrolysis. Some sacrificial layers 613 (such as SiO_2) can be removed by wet chemical etching or by vapor phase etching.

In a final process, not shown in Figure 6E but shown in Figure 6A, a dielectric coating 611 is deposited on some of the exposed surfaces of the shutter. Dielectric coatings 611 can be applied in conformal fashion, such that all bottom, tops, and side surfaces of the shutters 601 and beams 602 are uniformly coated using chemical vapor deposition or nonuniformly. The required conformality and film thickness are determined by the application; the dielectric film on the drive beams need only be thick enough to stand off the actuation voltage when the actuation surfaces make contact during operation. Al_2O_3 and SiNx are a preferred dielectric coating for layer 611, which are deposited by atomic layer deposition or PECVD respectively to thicknesses in the range of 10 to 100 nanometers.

Finally, anti-stiction coatings can be applied to some of the surfaces of shutters 601 and beams 602. These coatings prevent the unwanted stickiness or adhesion between two independent beams of an actuator, for instance. Applicable coatings include carbon films (both graphite and diamond-like) as well as fluoropolymers, and/or low vapor pressure lubricants. These coatings can be applied by either exposure to a molecular vapor or by decomposition of a precursor compound by means of chemical vapor deposition. Anti-stiction coatings can also be created by the chemical alteration of shutter surfaces, as in the fluoridation, silanization, siloxidation, or hydrogenation of insulating surfaces.

The Sidewall Beams Process

US Patent Application No. 11/251,035 describes a number of useful designs for shutter assemblies and actuators. One class of suitable actuators for use in MEMS-based shutter displays includes compliant actuator beams for controlling shutter motion that is transverse to or in-the-plane of the display substrate. The voltage necessary for the actuation of such shutter assemblies decreases as the actuator beams become more compliant. The control of actuated motion also improves if the beams are shaped such that in-plane motion is preferred or promoted with respect to out-of-plane motion. In a preferred design, the compliant actuator beams have a rectangular cross section, such as beam 602 of Figure 6A, such that the beams are taller or thicker than they are wide.

The stiffness of a long rectangular beam with respect to bending within a particular plane scales with the thinnest dimension of that beam in that plane to the third power. It is of interest, therefore, to reduce the width of the compliant beams as far as possible to reduce the actuation voltages for in-plane motion. When using conventional photolithography equipment to define and fabricate the shutter and actuator structures, however, the minimum width of the beams is usually limited to the resolution of the optics. And although photolithography equipment has been developed for defining patterns in photoresist with features as narrow as 15 nanometers, such equipment is expensive and the areas over which can be patterning can be accomplished in a single exposure are limited. For economical photolithography over large panels of glass, the patterning resolution or minimum feature size is typically limited to 1 micron or 2 microns or greater.

Figures 7A-7D are isometric views of stages of construction of an exemplary shutter assembly 700 with narrow sidewall beams, according to an illustrative embodiment of the invention. In particular, Figures 7A–7D depict a technique whereby a shutter assembly 700 with compliant actuator beams 718 and 720 can be fabricated at dimensions well below the conventional lithography limits on large substrate panels. The technique of Figures 7A–7B is described further in U.S. Patent Application No. 11/361,785, referred to above. In the process of Figures 7A–7D, the compliant beams of shutter assembly 700 are formed as sidewall features on a mold made from a sacrificial material. The process is referred to as a sidewall beams process.

The process of forming a shutter assembly 700 with sidewall beams begins, as shown in Figure 7A, with the deposition and patterning of a first sacrificial material 701 on top an aperture layer 725 and substrate 726. The pattern defined in the first sacrificial material creates openings or vias 702 within which anchors for the shutter will eventually be formed. The deposition and patterning of the first sacrificial material 701 is similar in concept, and uses similar materials, as those described for the deposition and patterning described in relation to Figures 6A-6E. It is also possible to form the shutter assembly on top of control circuitry and metal interconnects, In such embodiments, the vias 702 can be to the substrate surface or to an element of an electrical circuit so as to control the potential of a portion of the shutter assembly 700 which is in electrical contact to the circuit through the via 702.

The process of forming sidewall beams continues with the deposition and patterning of a second sacrificial material 705. Figure 7B shows the shape of a mold 703 that is created after patterning of the second sacrificial material 705. The mold 703 also includes the first sacrificial material 701 with its previously defined vias 702. The mold 703 in Figure 7B includes two distinct horizontal levels: The bottom horizontal level 708 of mold 703 is established by the top surface of the first sacrificial layer 701 and is accessible in those areas where the second sacrificial layer 705 has been etched away. The top horizontal level 710 of the mold 703 is established by the top surface of the second sacrificial layer 705. The mold 703 illustrated in Figure 7B also includes substantially vertical sidewalls 709.

Materials for use as sacrificial materials 701 and 705 are described above with respect to sacrificial material 613.

The process of forming sidewall beams continues with the deposition and patterning of the shutter materials onto all of the exposed surfaces of the sacrificial mold 703, as depicted in Figure 7C. The preferred materials for use in shutter 712 are described above with respect to the shutter materials 605, 607, and 609. Alternate shutter materials and/or shutter coatings are described in U.S. Patent Application 11/361,785, referred to above. The shutter materials are deposited to a thickness of less than about 2 microns. In some implementations, the shutter materials are deposited to have a thickness of less than about 1.5 microns. In other implementations, the shutter materials are deposited to have a thickness of less than about 1.0 microns, and as thin as about 0.10 microns. After deposition, the shutter material (which may be a composite shutter as described above) is patterned, as shown in Figure 7C. The pattern developed into the photoresist is designed such that shutter material remains in the region of shutter 712 as well as at the anchors 714 and 715.

Particular equipment and chemistries are also chosen for the etching process used at the step shown in Figure 7C, known in the art as an anisotropic etch. The anisotropic etch of the shutter material is carried out in a plasma atmosphere with a voltage bias applied to the substrate 726, or to an electrode in proximity to the substrate 726. The biased substrate 726 (with electric field perpendicular to the surface of the substrate 726) leads to acceleration of ions toward the substrate 726 at an angle nearly perpendicular to the substrate 726. Such accelerated ions, coupled with the etching chemicals, lead to etch rates that are much faster in a direction that is normal to the plane of the substrate 726 as compared to directions parallel to the substrate 726. Undercut-etching of shutter material in the regions protected by photoresist is thereby substantially eliminated. Along sidewall surfaces 709 of mold 703, which are substantially parallel to the track of the accelerated ions, the shutter material is also substantially protected from the anisotropic etch. Such protected sidewall shutter material will later form compliant beams 716, 718, and 720 for supporting the shutter 712. The anisotropic etch used to form sidewall beams 716, 718, and 720 can be achieved in either RF or DC plasma etching equipment, commonly used in IC or LCD manufacturing. Along other (non-photoresist-protected) horizontal surfaces of the mold, such as top horizontal surface 710 or bottom horizontal surface 708, the shutter material has been completely removed by the etch.

The process of forming sidewall beams is completed with the removal of the remainder of the second sacrificial layer 705 and the first sacrificial layer 701, the result being shown in Figure 7D. The process of removing sacrificial material is similar to that described with respect to Figure 6E. The material deposited on the sidewalls 709 of the mold 703 remain as the compliant beams 716, 718, and 720. The compliant load beams 716 mechanically connect the anchors 714 to the shutter 712. The anchors 714 connect to an aperture layer 725. The compliant beams 716, 718, and 720 are tall and narrow. The width of the sidewall beams 716, 718, and 720, as formed from the surface of the mold 703, is similar to the thickness of the shutter material as deposited. In some cases, the beam width at 716 will be the same as the thickness of the horizontal shutter material at 712; in other cases, the beam width will be only about ½ the thickness of the shutter material. The height of the sidewall beams 716, 718, and 720 is determined by the thickness of the second sacrificial material 705, or in other words, by the depth of the mold 703 as created during the patterning step described in relation to Figure 7B. As long as the thickness of the deposited shutter material is chosen to be less than 2 microns (for many applications the thickness range of 0.1 to 2.0 micron is suitable), the method illustrated in Figures 7A-7D is well suited for the production of very narrow beams. Conventional photolithography would limit the patterned features shown in Figures 7A, 7B, and 7C to much larger dimensions, for instance allowing minimum resolved features no smaller than 2 microns or 5 microns.

Figure 7D depicts an isometric view of a shutter assembly 700, formed after the release step in the above-described process, yielding compliant beams with cross sections of high aspect ratio. As long as the thickness of the second sacrificial layer is, for example, greater than 4 times larger than the thickness of the shutter material, the resulting ratio of beam height to beam width will be produced to a similar ratio, i.e. to a ratio greater than 4.

An optional step, not illustrated above but included as part of the process leading to Figure 7C, involves isotropic etching of the sidewall beam material to separate or decouple the compliant load beams 720 from the compliant drive beams 718. For instance, the shutter material at point 724 has been removed from the sidewall through use of an in isotropic etch. An isotropic etch is one whose etch rate is the same in all directions, so that sidewall material in regions such as point 724 is no longer protected. The isotropic etch can be accomplished in the typical plasma etch equipment as long as a bias voltage is not applied to the substrate. Isotropic etch can also be achieved using wet chemical or vapor phase etching techniques. Prior to this optional 4th masking and etch step, the sidewall beam material existed essentially continuously around the perimeter of the recessed features in mold 703. The 4th mask and etch step is used to separate and divide the sidewall material, forming the distinct beams 718 and 720. The separation of beams at point 724 is achieved through a 4th process of photoresist dispense, and exposure through a mask. The photoresist pattern in this case is designed to protect the sidewall beam material against isotropic etching at all points except at the separation point 724.

As a final step in the sidewall process, an encapsulating dielectric, such as dielectric 611, Figure 6A, is deposited around the outside surfaces of the sidewall beams, or, at a minimum, on the surfaces of the beams that might touch during operation.

In order to protect the shutter material deposited on sidewalls 709 of the mold 703 and to produce sidewall beams 716 of substantially uniform cross section, some particular process guidelines can be followed. For instance, in Figure 7B, the sidewalls 709 can be made as vertical as possible. Slopes at the sidewalls 709 and/or exposed surfaces become susceptible to the anisotropic etch. Vertical sidewalls 709 can be produced if the patterning step at Figure 7B, the patterning of the second sacrificial material 705, is also carried out in anisotropic fashion. The use of an additional photoresist coating or a hard mask in conjunction with patterning of the second sacrificial layer 705 (see the discussion with respect to Figure 12) makes it possible to employ aggressive plasmas and/or high substrate bias in the anisotropic etch of the second sacrificial material 705, without fear of excessive wear of the photoresist. Vertical sidewalls 709 can also be produced in photo-imageable sacrificial materials, as long as care is taken to control the depth of focus during the UV exposure and excessive shrinkage is avoided during final cure of the resist.

Another process specification that helps during sidewall beam processing regards the conformality of the shutter material deposition. The surfaces of the mold 703 are preferably covered with similar thicknesses of shutter material, regardless or the orientation of those surfaces, either vertical or horizontal. Such conformality can be achieved when depositing with a chemical vapor deposition technique (CVD). In particular, the following conformal techniques can be employed: plasma enhanced chemical vapor deposition (PECVD), low pressure chemical vapor deposition (LPCVD), and atomic or self-limited layer deposition (ALD). In the above CVD techniques, the growth rate of the thin film can be limited by reaction rates on a surface as opposed to exposing the surface to a directional flux of source atoms. In such conformal deposition techniques, the thickness of material grown on vertical surfaces is preferably at least 50% of the thickness of material grown on horizontal surfaces. Alternatively, shutter materials can be conformally deposited from solution by electroless plating or electroplated, as long as a metal seed layer is provided that coats all surfaces before plating.

A 3-Mask Process

The process leading to the shutter assembly 700 in Figure 7D was a 4-mask process: meaning the process incorporated 4 distinct photolithography steps wherein a photo-sensitive polymer is exposed by illuminating a desired pattern through a photomask. The photolithography steps, also known as masking steps, are amongst the most expensive in the manufacture of MEMS devices, and so it is desirable to create a manufacturing process with a reduced number of masking steps.

In order to enable a 3-mask shutter assembly process, it is helpful to consider variations to the structure of the shutter assembly. The useful structural changes will be illustrated by 4 alternate shutter assemblies 900,1100, 1400 and 1500 in Figures 9,11, 14 and 15 respectively.

In Figure 7, the load beam 720 of shutter assembly 700 attaches to the shutter 712 at one end and to the load beam anchor 714 at the other end. The drive beam 718 attaches to the drive beam anchor 715 at one end while the other end is left unattached or free to move. It can be stated that the purpose of the 4th mask in the process leading to shutter assembly 700 in Figure 7C is to terminate or create the freely moving end for the drive beam 718. It is useful to create this freely moving end for drive beam 718, since the compliant shape of this beam helps to reduce the voltage needed for shutter actuation.

In various embodiments of this invention, however, the compliant drive beams need not have a photo-lithographically terminated freely moving end. In the shutter assembly 852 illustrated in Figure 8, for example, the drive beams 856 and 857 are patterned in the shape of loops.

Figure 8 is a plan view of exemplary shutter assembly 852 incorporating a looped drive beam, according to an illustrative embodiment of the invention. The shutter assembly 852 includes dual compliant actuator assembly 854, which is functionally similar to the actuator 404 designed for the shutter assembly 400, described above with respect to Figures 4A and 4B. The actuator assembly 854 includes compliant drive beams 856 and 857 along with compliant load beams 858 and 859. The load beams 858 and 859 support the shutter 860 on one end and are attached to load beam anchors 862 and 863, respectively, at the other end. The drive beams 856 and 857 are each formed into a loop wherein each end of the drive beam is attached to a common anchor 864. For each loop, there is a section of outgoing beam which is substantially parallel to a returning section of the same beam. The lengths of these two loop sections are substantially equal. When formed in a sidewall beam process, the stresses which would tend to deform the outgoing section of the looped drive beam 856 or 857 will mirror or oppose the stresses along the returning section of the beam.

The compliant beams that make up the loops 856 and 857 can be completely defined using only the first 3 mask steps described above with respect to shutter assembly 700. The 4th photo-lithography step, wherein the drive beam is separated from the load beam, is not required to manufacture the looped beams 856 and 857. The loops completely enclose or form the periphery around the boundary of a space. Since there is no termination in the loops, as is expected for the boundary around an enclosed space, the 4th photo-lithography step is not required.

In order to eliminate the 4th mask completely, a method is sought whereby other compliant beams in the structure are also made to incorporate shapes analogous to loops. In particular, a termination of a sidewall beam is not necessary as long as the beam forms a boundary which completely encloses a space. For example, load beam 858 in shutter assembly 852 is terminated at the load beam anchor 862. So, in this embodiment, a 4th masking step would be required to terminate the beam 858 at the anchor 862. Designs are therefore sought where the load beam 858 becomes part of a continuous boundary around an enclosed space.

Figure 9 is an isometric view of exemplary shutter assembly 900 built according to a 3-mask process, according to an illustrative embodiment of the invention. The shutter assembly 900 can be manufactured with only 3 photo-lithography steps. Those 3 masking steps are referred to as an anchor definition step, a mold definition step, and a shutter definition step, which are used to develop patterns into the first sacrificial layer, the second sacrificial layer, and the shutter material, respectively. As described with respect to shutter assembly 700, the compliant beams are formed at the sidewalls of the mold, also referred to as the second sacrificial layer. The shutter assembly 900 can be fabricated within a 3-mask process because the beams are designed as closed boundaries that enclose the periphery of features in the mold.

The shutter assembly 900 comprises a shutter 902, stiffening ribs 903, load beams 904, load beam anchors 906, drive beams 908, and drive beam anchors 910. The shutter assembly additionally includes peripheral beams 912 as well as peripheral anchors 914. The load beams 904 and the drive beams 908 together form a set of compliant actuator beams. When a voltage is imposed between these two beams 904 and 908, the shutter 902 is caused to move towards an open or closed position.

The drive beams 908 are each formed into a loop, which is attached to the substrate at anchor 910. The drive beams 908 enclose the space within the loop.

The load beams 904 extend from the shutter 902 to the load beam anchors 906. The peripheral beams 912 extend from the load beam anchors 906 to the peripheral anchors 914. The peripheral beams also connect together the peripheral anchors 914. The peripheral beams 912 play neither an active mechanical function nor an optical function within shutter assembly 900. The peripheral beams 912 serve to extend the geometry of the load beams 904 so that these compliant beams 904 and 912 can become connected. Together, the load beams 904 and peripheral beams 912 form a boundary which completely encloses a space.

Figure 10 is an isometric view of an exemplary mold 1000, designed to enable the manufacture of shutter assembly 900 of Figure 9, according to an illustrative embodiment of the invention. The mold 1000 is formed from the second sacrificial material, and is patterned as part of the second photo-lithography step in the fabrication of shutter assembly 900. Figure 10 shows the outline of the sacrificial mold before the shutter material has been deposited. The outlines of the shutter 902 are therefore not present in Figure 10. The mold 1000 does, however, comprise rib indentations 1003 that will be used to shape the stiffening ribs 903 of shutter assembly 900.

The mold shape is generally comprised of three kinds of surfaces. The mold includes sidewalls, upon which the compliant beams will be formed, as well as upper and lower surfaces. The lower surfaces of the mold are the horizontal surfaces formed by the interface between the first and second sacrificial materials. The upper surfaces of the mold are horizontal surfaces in a plane most distant from the substrate.

A mold generally defines two kinds of shapes, both of which are enclosed or bounded by sidewalls upon which the compliant beams can be formed. A “mesa,” as used herein, is a space defined by a presence of mold material enclosed by mold sidewalls. A “recess,” as used herein, is defined by a space of mold material absence, enclosed by mold sidewalls.

The mold 1000 comprises mesa shapes 1008. The sidewalls which enclose the mesas 1008 will be used to form the drive beams 908. The drive beams 908 will thereby have the shape of loops without termination.

The mold 1000 also comprises a recess shape 1004. The sidewalls which enclose this recess 1004 are used to form the load beams 904.

The mold 1000 also comprises load beam anchor holes 1006. The anchor holes 1006 were formed in a previous step as part of the first sacrificial layer. The mold also comprises drive beam anchor holes 1010.

Both the load beams 904 and the drive beams 908 in shutter assembly 900 are therefore formed as boundaries that completely enclose a space. The spaces are formed from one of either a mesa shape or a recess shape in the mold 1000. In particular, load beams 904 and drive beams 908 are formed as boundaries enclosing spaces 1004 and 1008, respectively. The boundaries of the shapes that form the load beams 904 and the drive beams 908 do not intersect. The loop for the drive beam 908 is completely enclosed within the loop that forms the load beam 904 (which is a combination of beams 904 and 912).

Figure 11 is an isometric view of exemplary shutter assembly 1100, built according to a 3-mask process, according to an illustrative embodiment of the invention. The shutter assembly 1100 can be manufactured with only 3 photo-lithography steps, similar to those described with respect to shutter assemblies 700 and 900 of Figure 7 and 9, respectively. As described above with respect to shutter assembly 700, compliant beams are formed at the sidewalls of the mold, also referred to as the second sacrificial layer. The shutter assembly 1100 can be fabricated within a 3-mask process because the beams are designed as closed boundaries that enclose the periphery of features in the mold.

The shutter assembly 1100 comprises a shutter 1102, load beams 1104, load beam anchors 1106, drive beams 1108, and drive beam anchors 1110. The load beams 1104 and the drive beams 1108 together form a set of compliant actuator beams. The shutter assembly additionally comprises a set of peripheral beams 1112.

The drive beams 1108 are formed into a loop, which is attached to the substrate at anchor 1110. The drive beams 1108 enclose the space within the loop.

The load beams 1104 extend from the shutter to the load beam anchors 1106. The peripheral beams 1112 extend between the load beam anchors 1106. The peripheral beams 1112 play neither an active mechanical function nor an optical function within shutter assembly 1100. The peripheral beams 1112 serve to extend the geometry of the load beams 1104 so that these compliant beams 1104 and 1112 can become connected. Together, the load beams 1104 and peripheral beams 1112 form a boundary which completely encloses a space.

Figure 12 is an isometric view of exemplary mold 1200, designed to enable the manufacture of shutter assembly 1100 of Figure 11, according to an illustrative embodiment of the invention. The mold 1200 is formed from the second sacrificial material, and is patterned as part of the second photo-lithography step in the fabrication of shutter assembly 1100. Figure 12 shows the outline of the sacrificial mold before the shutter material has been deposited. The outlines of the shutter 1102 are therefore not present in Figure 10. The mold 1200 does, however, comprise rib indentations 1203 that will be used to shape the stiffening ribs 1103 shown in shutter assembly 1100.

The mold 1200 includes recesses 1208. The recess shape 1208 is the inverse of the mesa shape 1008 employed for drive beams in mold 1000. The sidewalls which enclose the recesses 1208 will be used to form the drive beams 1108. The drive beams 1108 will thereby have the shape of loops without termination.

The mold 1200 also includes a recess 1204. The sidewalls of this recess are used to form the load beams 1104.

The mold 1200 also includes load beam anchor holes 1206. The anchor holes were formed in a previous step as part of the first sacrificial layer. The mold 1200 also comprises drive beam anchor holes 1210.

In this particular embodiment, the load beam recess 1204 used to form the load beams 1104 is connected or merged with the recesses 1203 used to form the ribs 1103.

The boundaries of the shapes that form the load beams 1104 and the drive beams 1108 do not intersect. The loop for the drive beam 1108 encloses a shape that lies outside of the shape that forms the load beam 1104 (which is a combination of beams 1104 and 1112).

For a 3-mask process, two different types of enclosed areas need to be defined: load beams 904 and drive beams 908. These enclosed boundaries can either define an isolated area of mold polymer (a mesa), or they can define an area where the resist is removed (a recess). Depending on the choice, the drive beams and load beams will be fabricated either on side of a recess or the side of a mesa. Figure 14 shows an embodiment 1400 where the load beams 1404 and drive beams 1408 are formed on the side of a hole. Figure 15 shows an embodiment 1500 where the load beams 1504 and drive beams 1508 are formed on the side of a mesa. While either embodiment is effective, the choice of polymer and fab equipment may make it easier to pattern recesses rather than mesa or mesa rather than recesses. Similarly the area outside the display active area can either have resist present or be cleared of resist. Often it is easier to do the third masking step on substrates in which in which the field area is co-planar with the active area of the display, in which case a third closed boundary may be needed around the shutter assembly perimeter. Two possible embodiments of this third closed boundary are illustrated in Figures 14 and 15 as elements 1412 and 1512, respectively. Certain polymers may have high stress or high shrinkage or swelling upon processing and cause problems if left as large continuous sheets in the perimeter area of the display. In this case, the mold mask can be used to pattern dummy features in perimeter area to break up continuous areas of resist and lower the film stress. Figure 16 illustrates one possible embodiment 1600 of stress relief features 1616.

An additional consideration when defining the enclosed mold boundaries is whether the shutter should be fabricated on the top of the mold polymer (on a mesa) on in an area where the mold resist is cleared away (in the bottom of a recess). Figures 14 and 15 show shutters 1402 and 1502 fabricated on the bottom of as recess; as compared to figures 9 and 11,where shutters 902 and 1102 are fabricated on the top of a mesa. Again, both options are acceptable, but final device specifications may make one embodiment preferable over the other.

Figure 13 is an isometric view of two connected exemplary shutter assemblies 1300 built according to a 3-mask process, according to an illustrative embodiment of the invention. The shutter assembly 1300 can be manufactured with only 3 photo-lithography steps, similar to those described with respect to shutter assemblies 700 and 900 of Figures 7 and 9, respectively. As described above with respect to shutter assembly 700, compliant beams are formed at the sidewalls of the mold, also referred to as the second sacrificial layer. The shutter assembly 1300 can be fabricated within a 3-mask process because the beams are designed as closed boundaries that enclose the periphery of features in the mold.

The shutter assembly 1300 comprises a shutter 1302, load beams 1304, load beam anchors 1306, drive beams 1308, and drive beam anchors 1310. The load beams 1304 and the drive beams 1308 together form a set of compliant actuator beams. The shutter assembly additionally comprises a set of peripheral beams 1312.

The drive beams 1308 are each formed into a loop, which is attached to the substrate at anchor 1310. The drive beams 1308 enclose the space within the loop.

The load beams 1304 extend from the shutter 1302 to the load beam anchors 1306. The peripheral beams extend between the load beam anchors 1306. The peripheral beams 1312 play neither an active mechanical function nor an optical function within shutter assembly 1300. The peripheral beams 1312 serve to extend the geometry of the load beams 1304 so that these compliant beams can become connected. Together, the load beams 1304 and peripheral beams 1312 form a boundary which completely encloses a space.

In shutter assembly 1300, the peripheral beams 1312 in many cases are used to connect between load beam anchors 1306 that correspond to two different or neighboring shutter assemblies. The load beams 1304 along with peripheral beams 1312 together form a continuous boundary that encloses a space. The space which is enclosed by the beams 1304 and 1312 comprises two shutter assemblies. In alternate embodiments, a large number of shutter assemblies (> 100) can be enclosed by a single continuous compliant beam. The compliant beam will be attached to the substrate at multiple points, preferably with at least one attachment point or anchor corresponding to each of the shutter assemblies in the group. The load beams 1304 for each of the corresponding shutter assemblies can be formed from the same loop that encloses multiple shutter assemblies.

The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments are therefore to be considered in all respects illustrative, rather than limiting of the invention.

What is claimed is:

1. A MEMS device comprising:

a first narrow beam wherein the first narrow beam completely enclose the boundary of a space.

2. The MEMS device of claim 1, wherein the first narrow beam forms a loop.

3. The MEMS device of claim 1, comprising a mechanical light modulator supported over a substrate by the first narrow beam.

4. The MEMS device of claim 1, comprising a mechanical light modulator, wherein the first narrow beam forms a portion of an actuator for moving the mechanical light modulator to modulate light.

5. The MEMS device of claim 4, wherein the first narrow beam is compliant beams.

6. The MEMS device of claim 1, comprising an anchor connecting the first narrow beam to the substrate.

7. The MEMS device of claim 1, comprising a second narrow beam, wherein the first and second narrow beam enclose respective, non-intersecting spaces.

8. The MEMS device of claim 7, wherein the second narrow beam encloses a space that is completely enclosed by the first narrow beam.

9. A method of manufacturing a MEMS device, comprising:

forming a first narrow beam coupled to a substrate such that the first narrow beam completely encloses the boundary of a space.

10. The method of claim 9, wherein forming the first narrow beam comprises:

depositing a mold material onto a sacrificial layer;

etching a shape into the mold material to form a mold having at least one sidewall and at least one lower horizontal surface;

depositing material onto the etched mold such that the deposited material adheres to at least the side walls and the lower horizontal surface of the etched mold;

etching away a portion of the deposited material to remove the deposited material from the lower horizontal surface while leaving substantially all of the material deposited on the sidewalls intact; and

removing the mold such that material remaining on the sidewalls forms the first narrow beam.

11. The method of claim 10, wherein the sidewalls comprises walls of a mesa formed in the mold, and the first narrow beam encloses the mesa.

12. The method of claim 10, wherein the sidewalls comprises walls of a recess formed in the mold, and the first narrow beam encloses the recess.

13. The method of claim 10, wherein the mold material is deposited on top of a layer of sacrificial material, the method further comprising removing the sacrificial material to release the first narrow beam.

14. The method of claim 10, wherein the mold further comprises an upper horizontal surface, and the material deposited on the mold adheres to the upper horizontal surface, the method further comprising:

applying a mask to the upper horizontal surface prior to etching away the deposited material such that a portion of the material deposited on the upper horizontal surface remains on the upper horizontal surface after the etch to form a mechanical light modulator.

15. The method of claim 14, further comprising, prior to etching the shape into the mold, etching anchor holes into the mold material, and wherein the material deposited onto the mold fills the anchor holes to form anchors.

16. The method of claim 15, wherein formation of the anchors, first narrow beam, and the mechanical light modulator requires the utilization of no more than three photolithographic masks.

17. The method of claim 10, wherein the MEMS device comprises a mechanical light modulator and an anchor, and the first narrow beam supports the mechanical light modulator over a substrate and connects the mechanical light to the substrate via the anchor, the method comprising utilizing no more than three photolithographic masks.

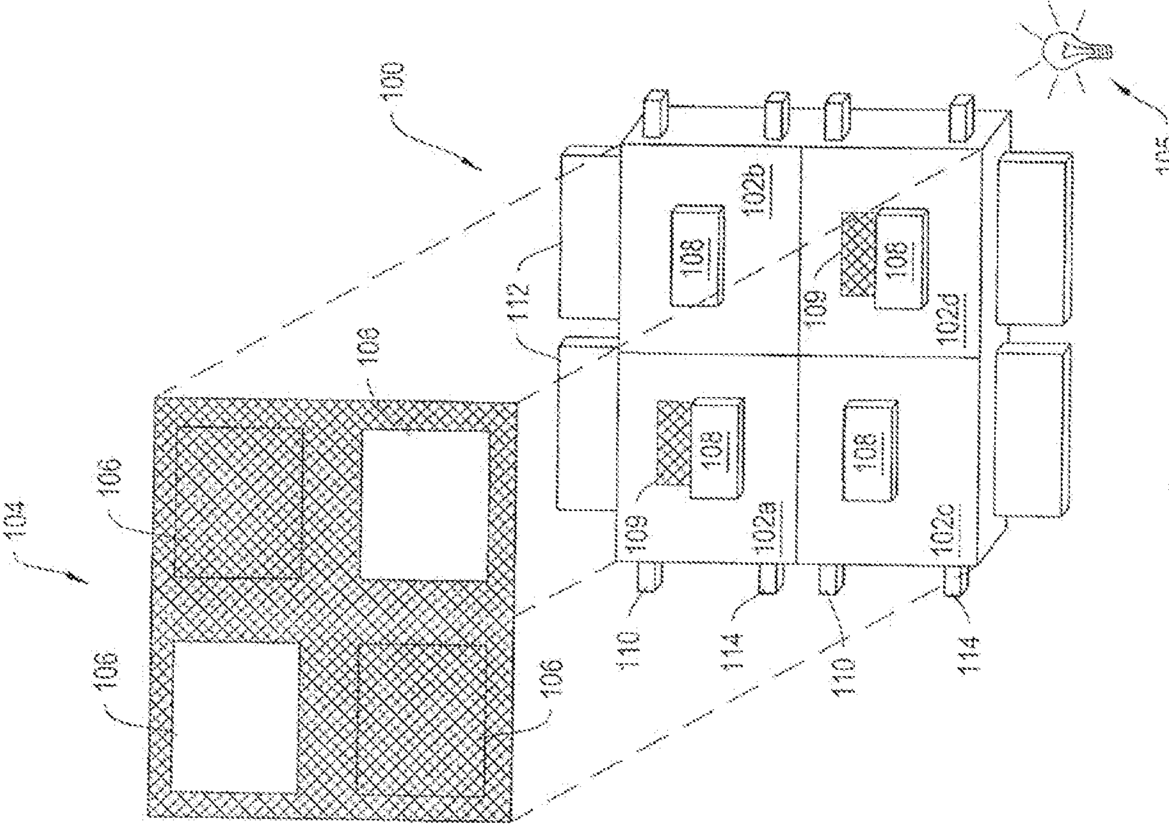
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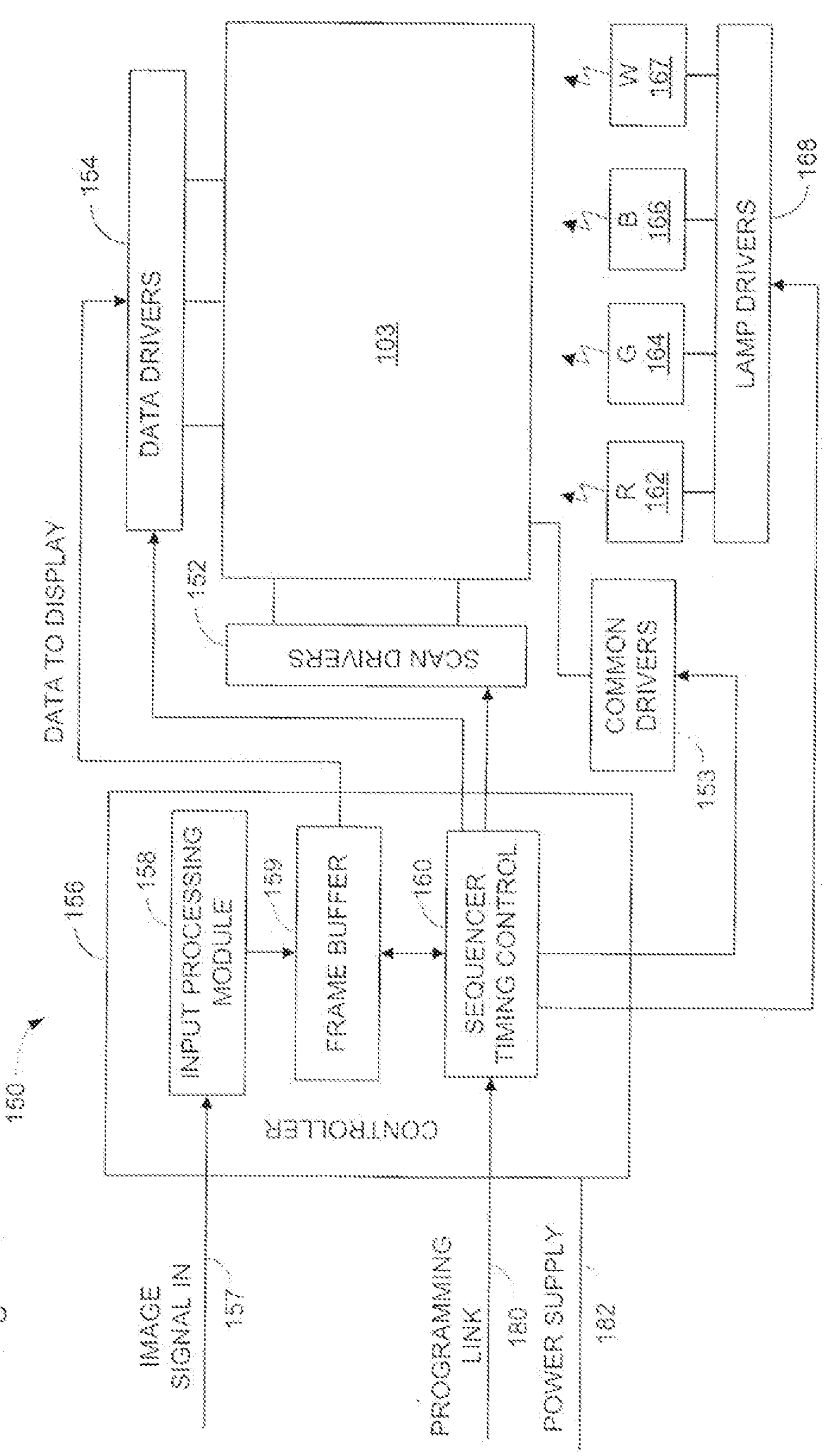
Figure 1A

Fig. 1B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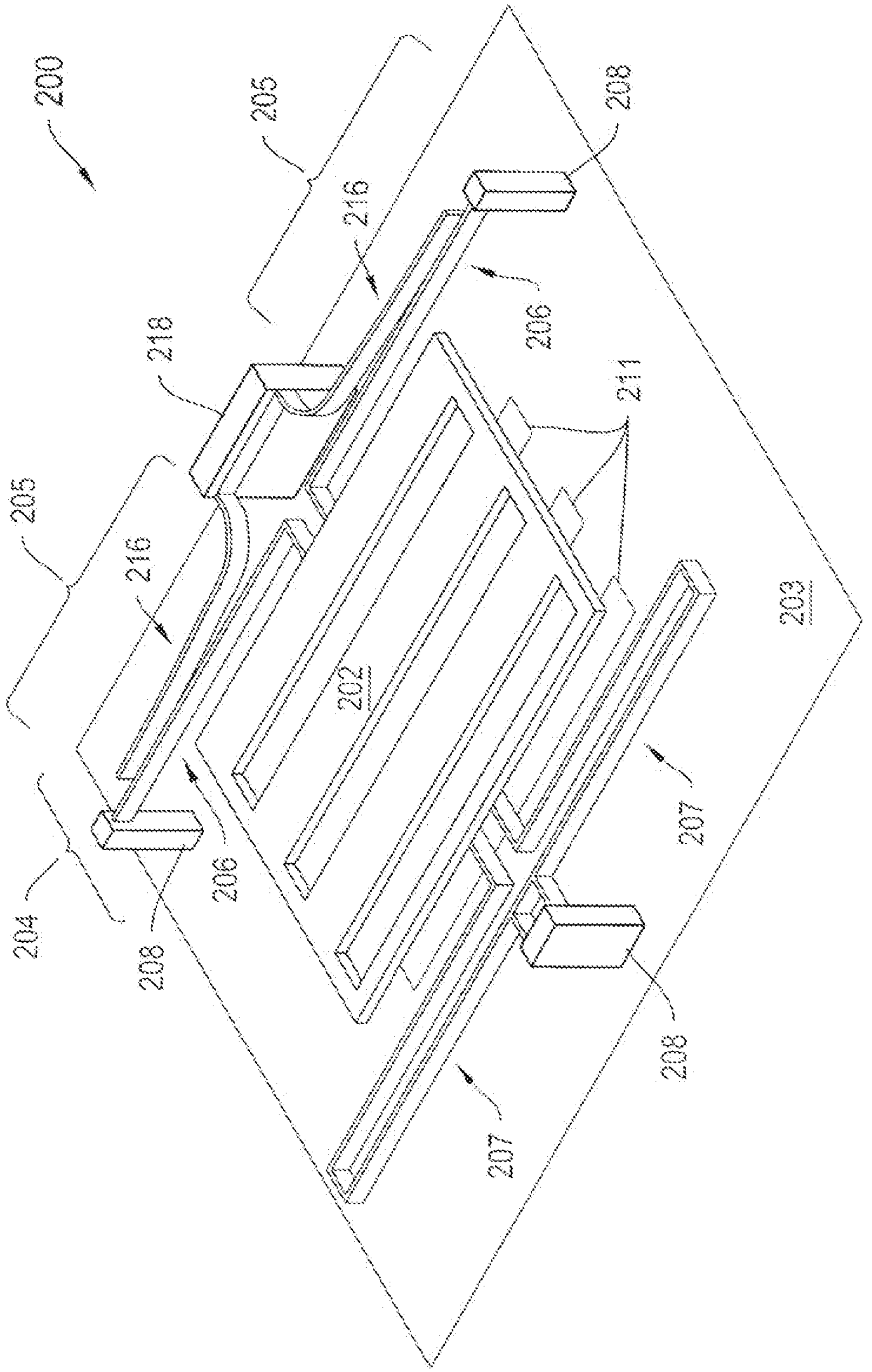
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Figure 2A

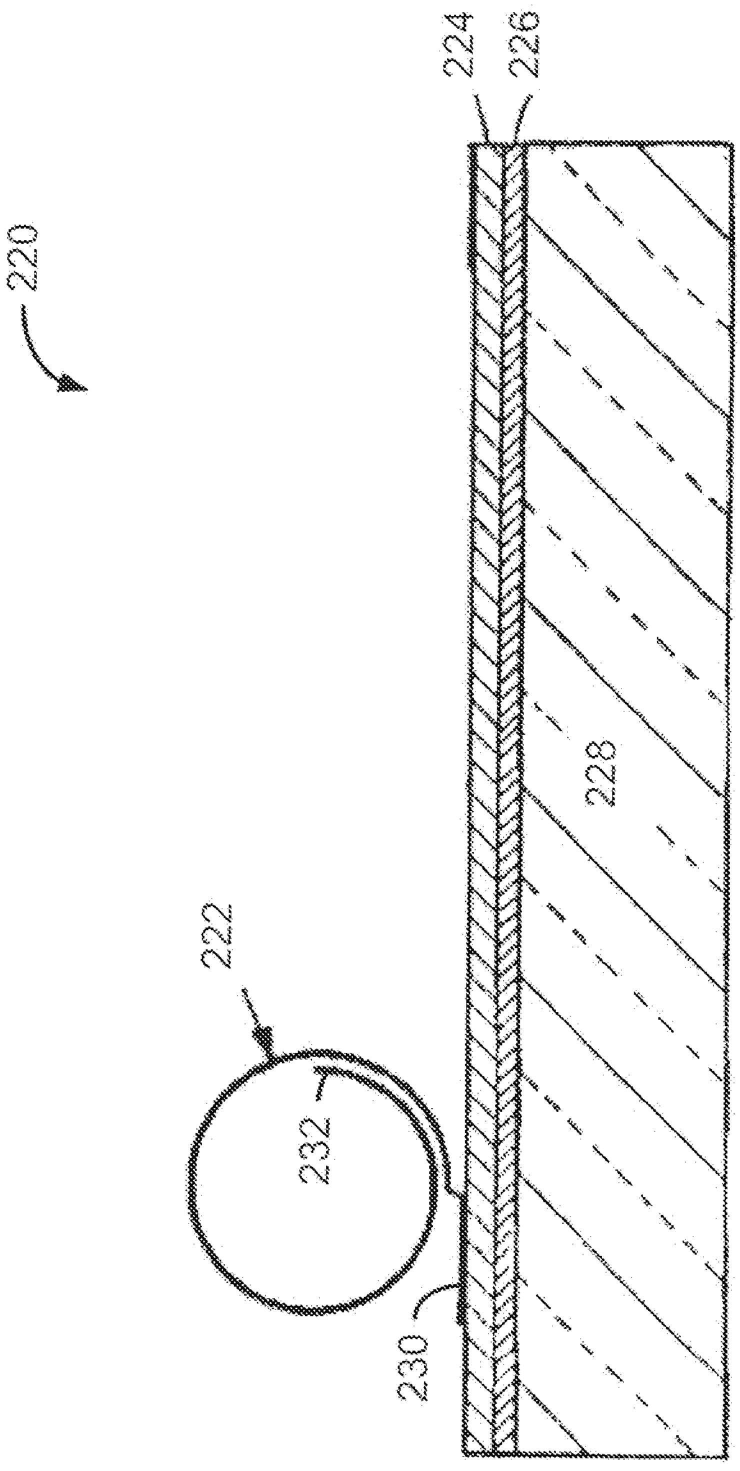

Figure 2B

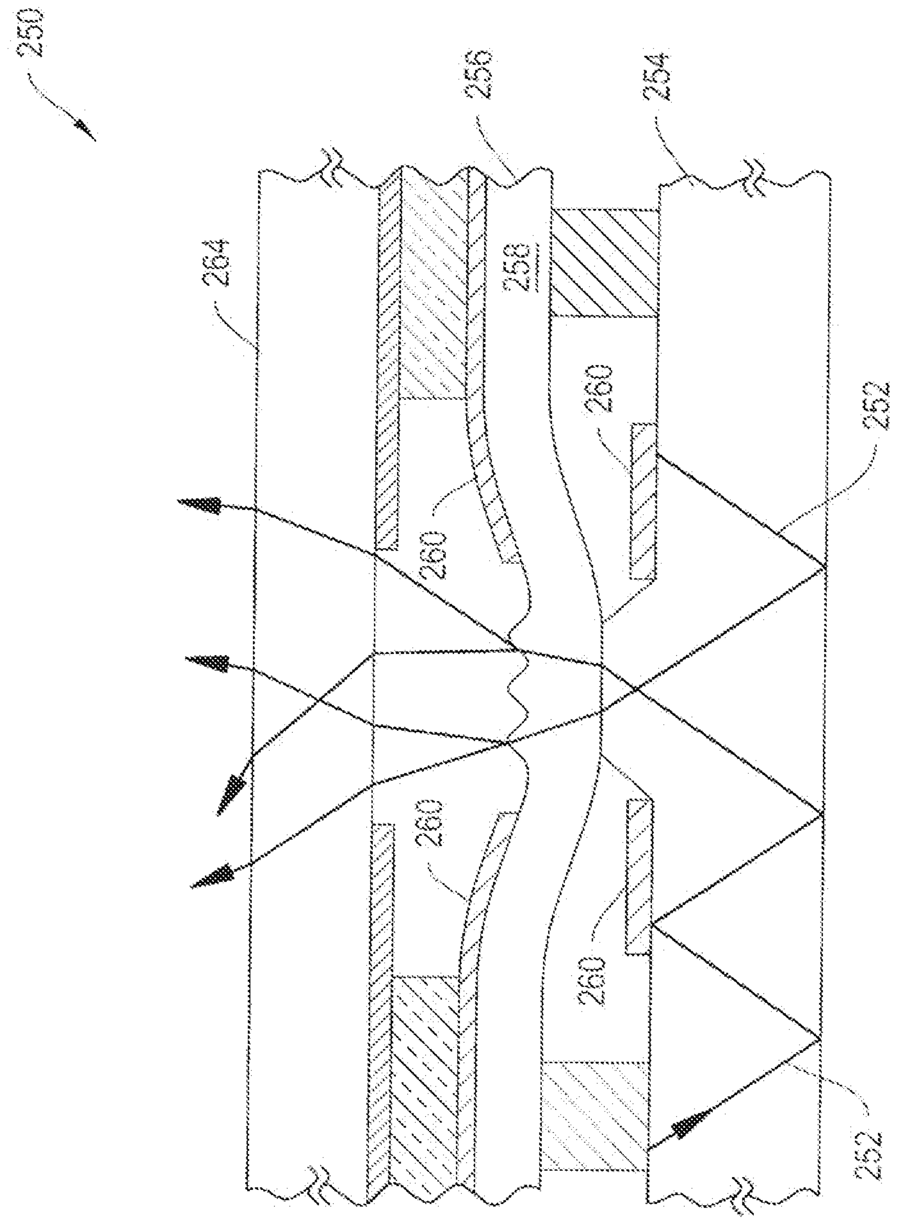

Fig. 2C

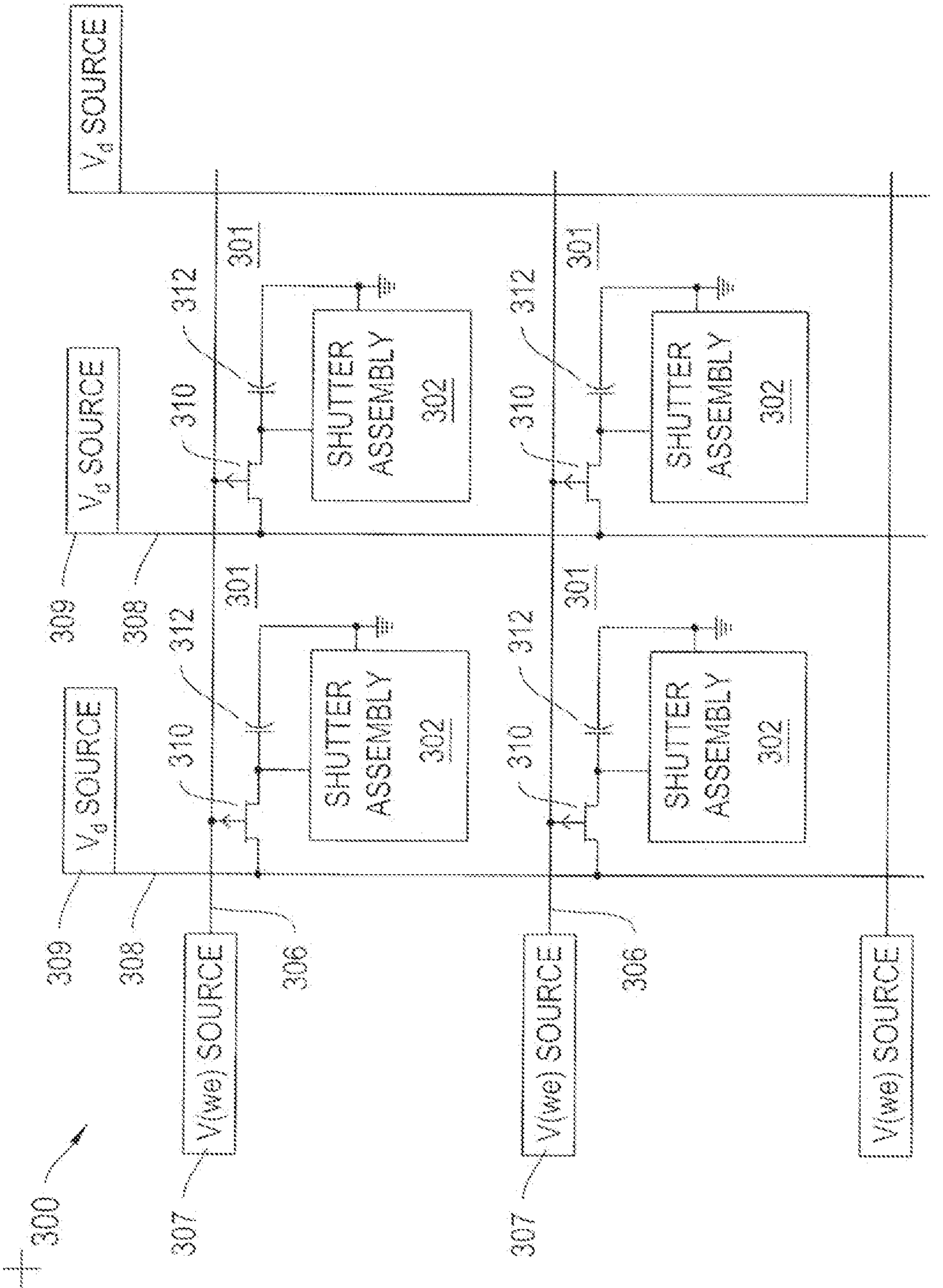
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Figure 3A

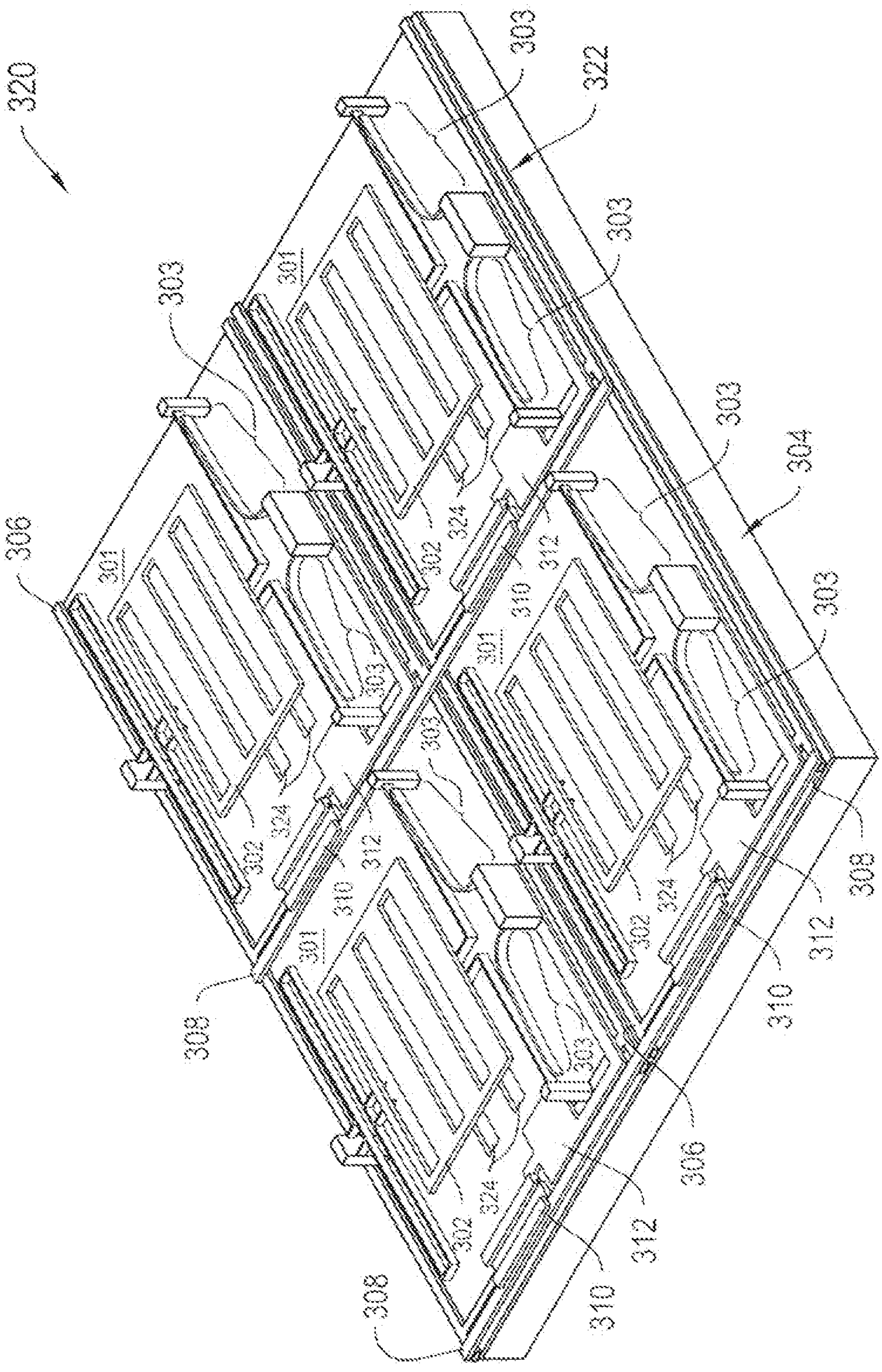
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Figure 3B

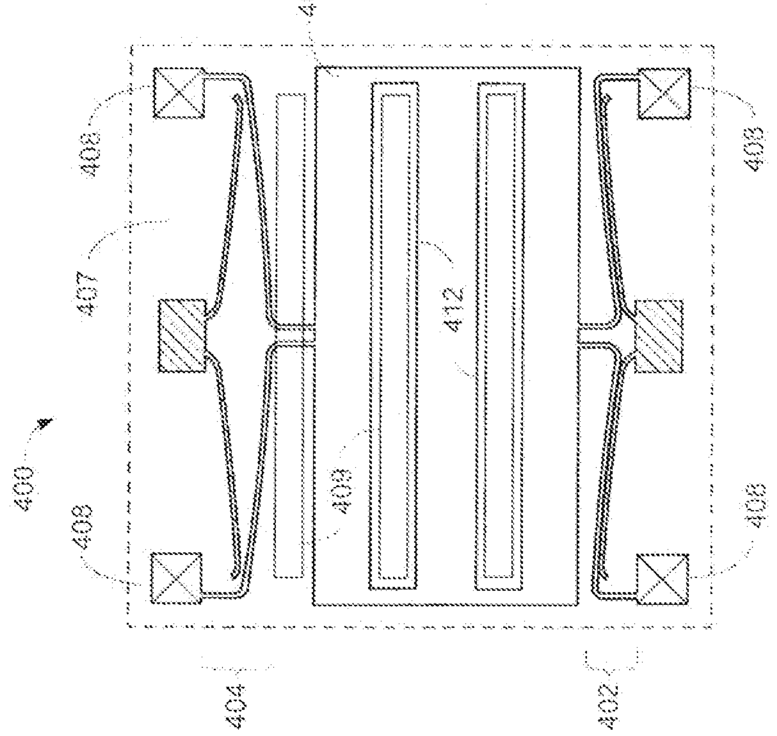

Fig. 4A

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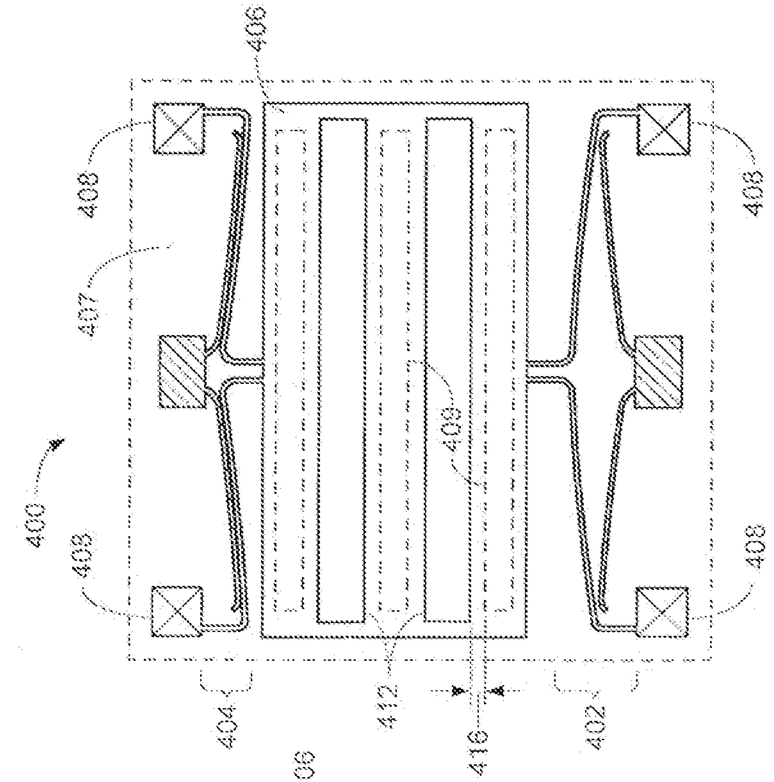

Fig. 4B

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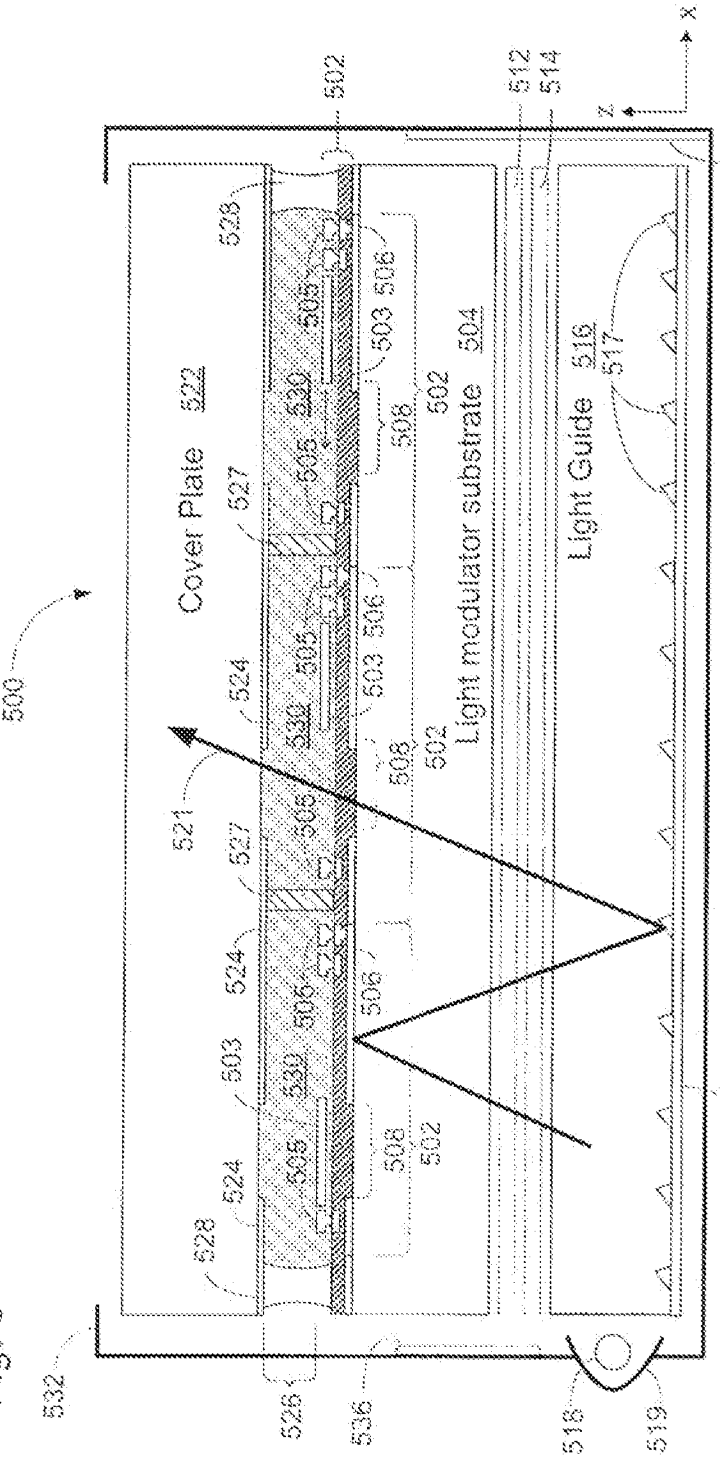
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Light modulator substrate 504
Light Guide 516
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x
z

Fig. 5

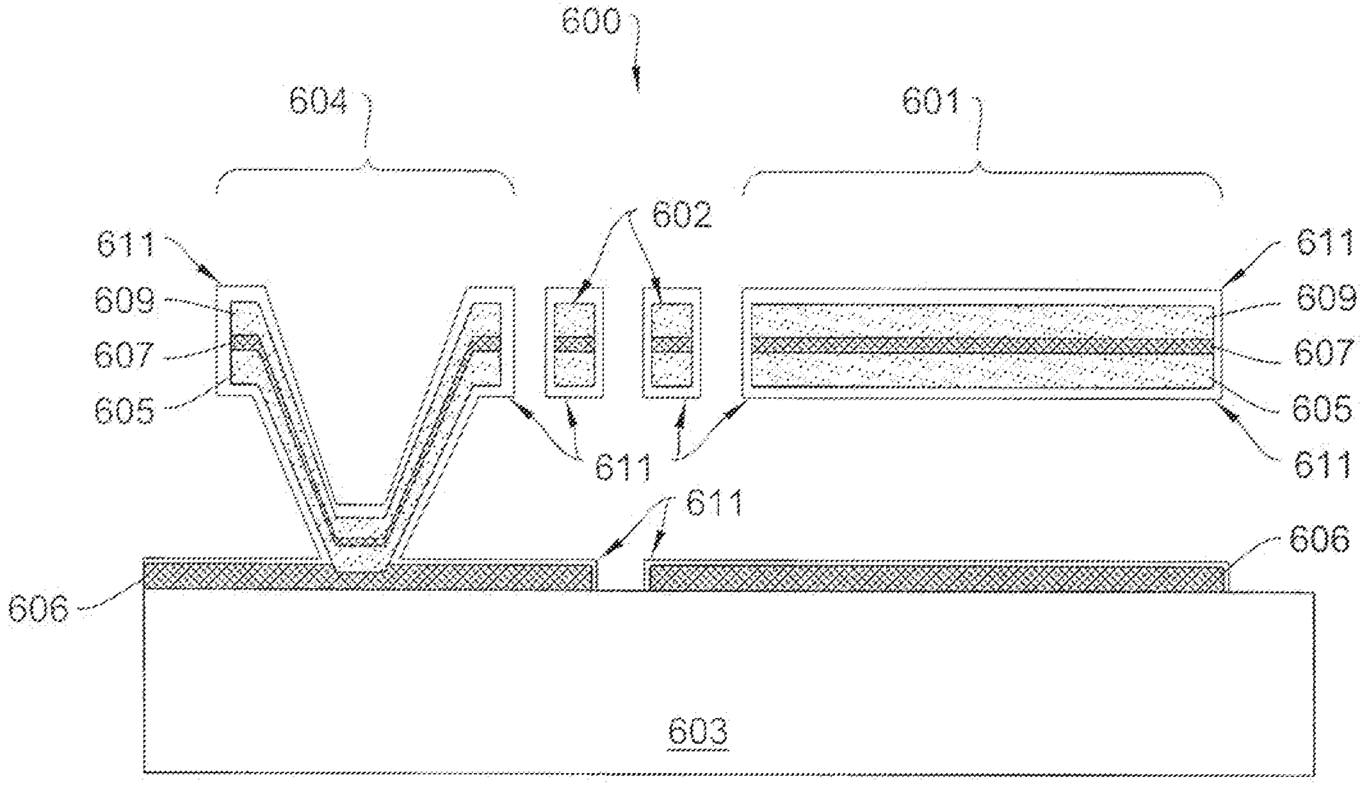
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Figure 6A

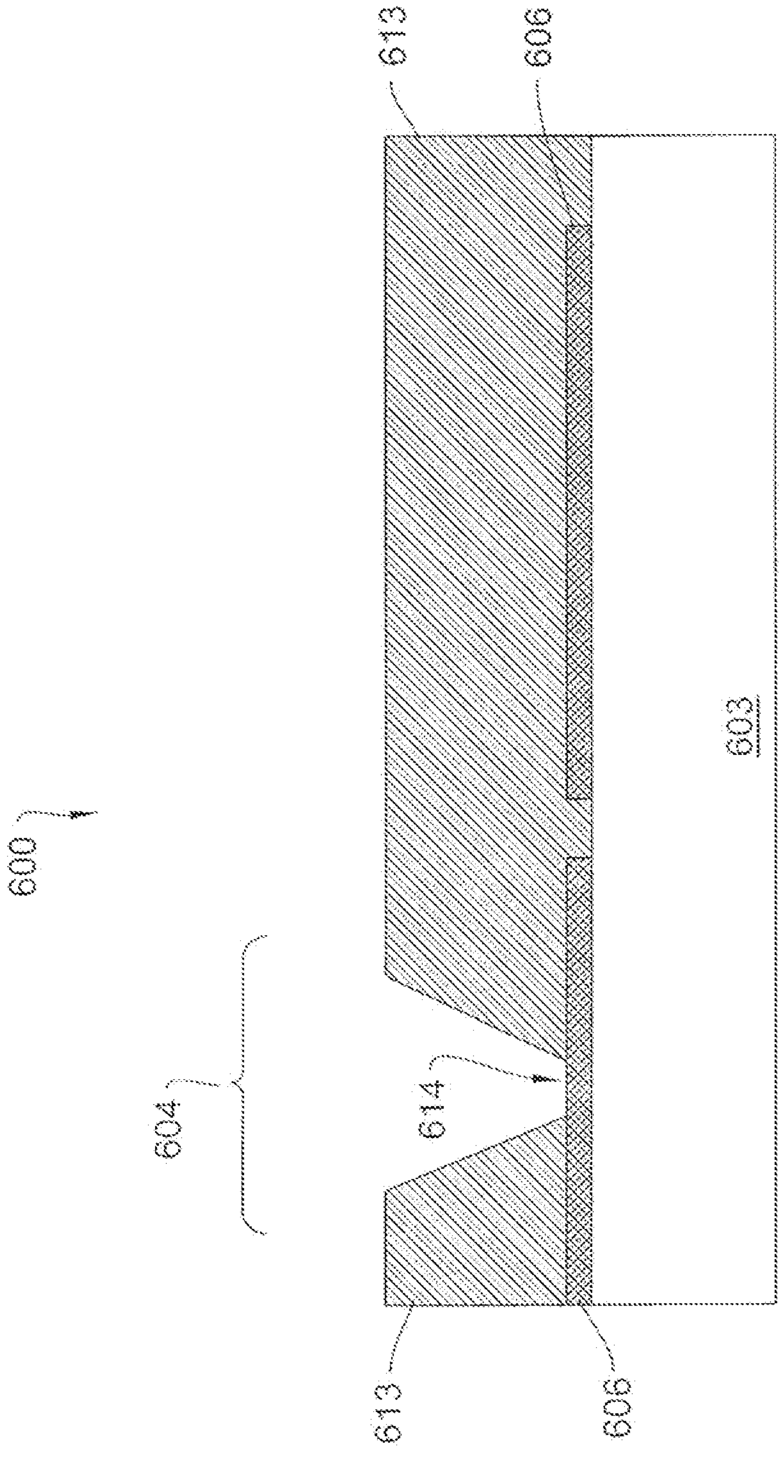


Figure 6B

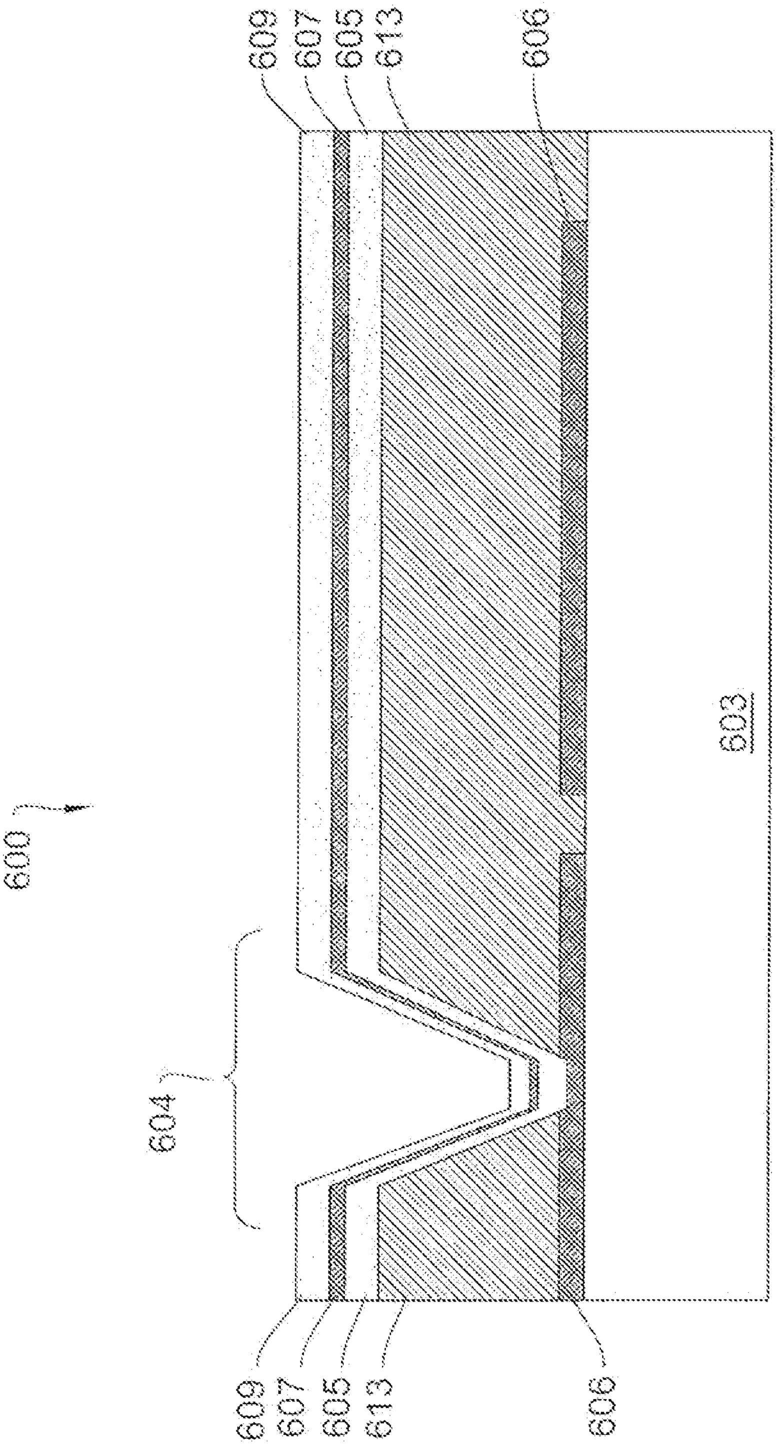


Figure 6C

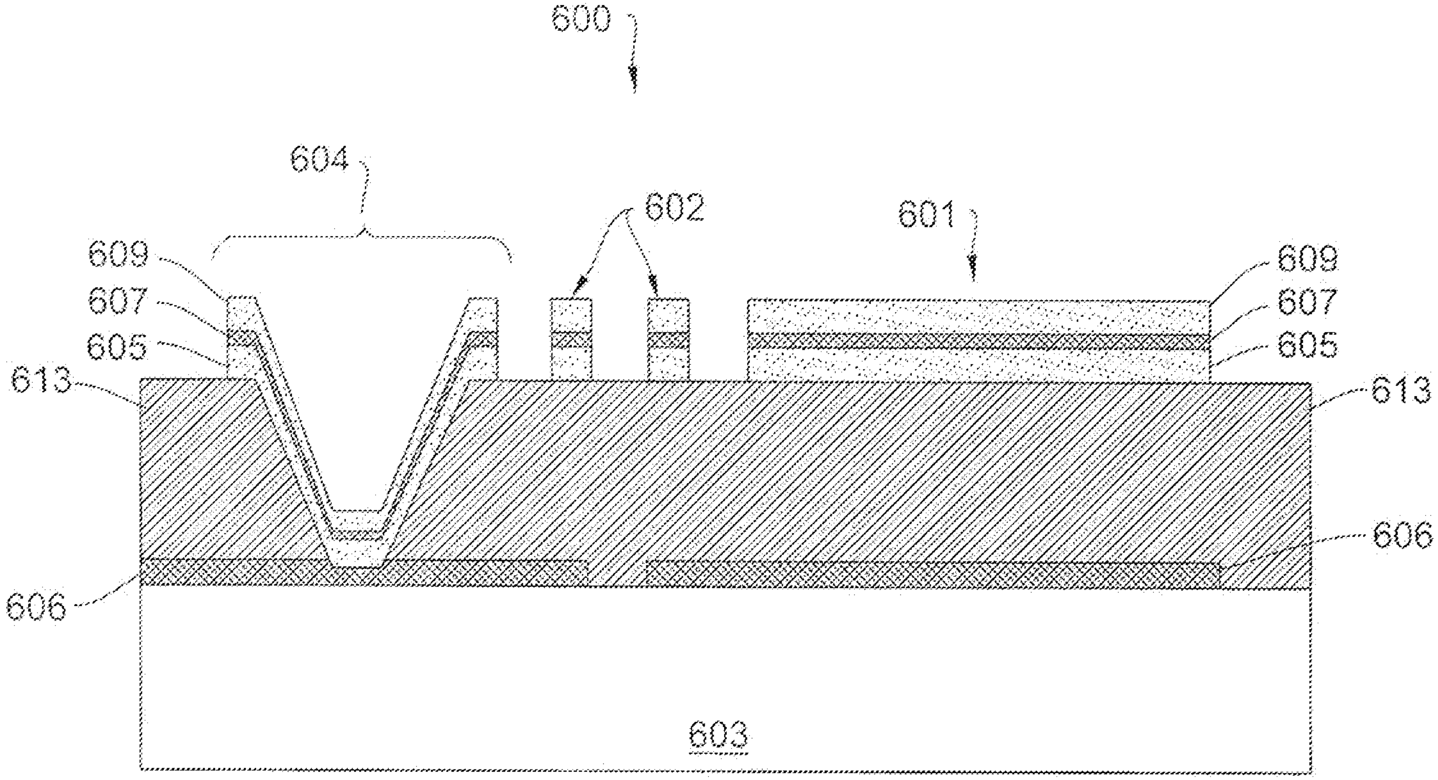


Figure 6D

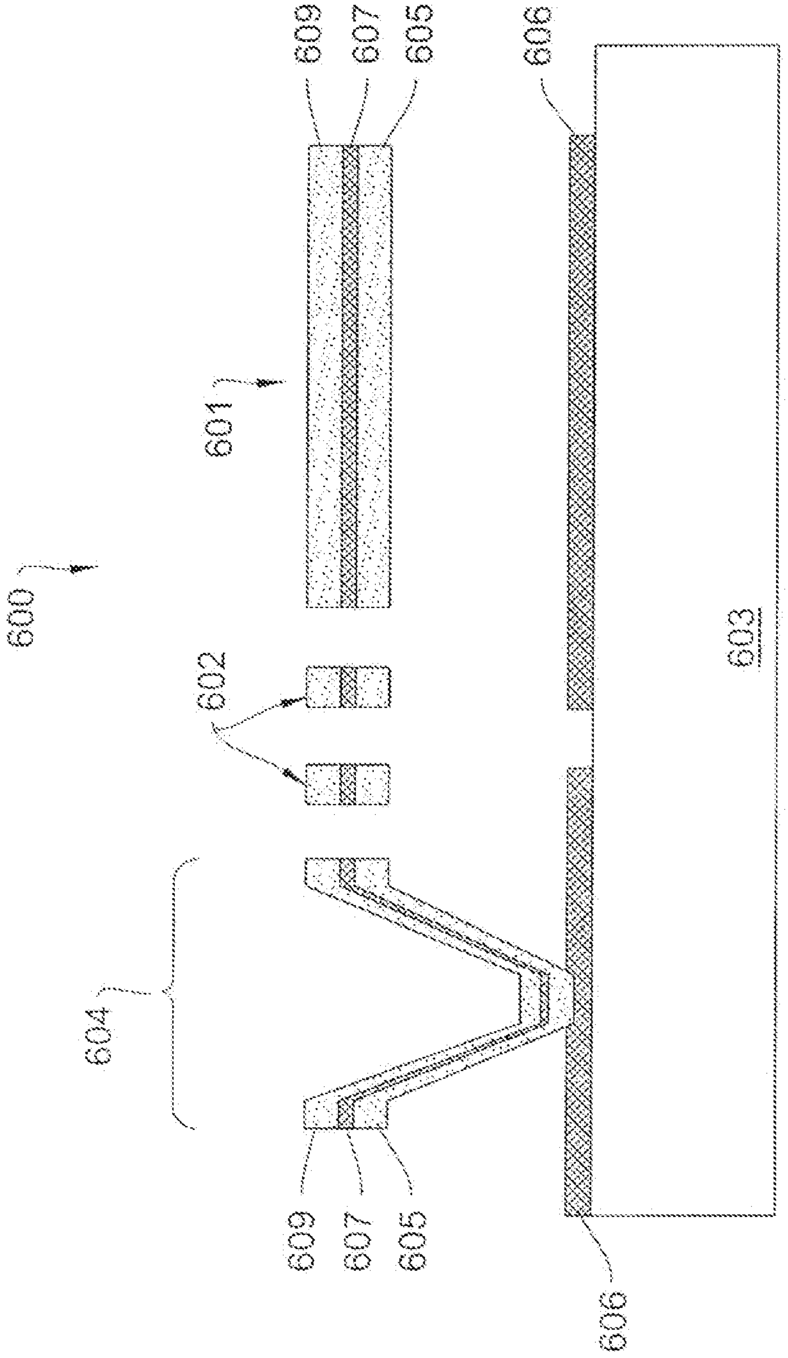


Figure 6E

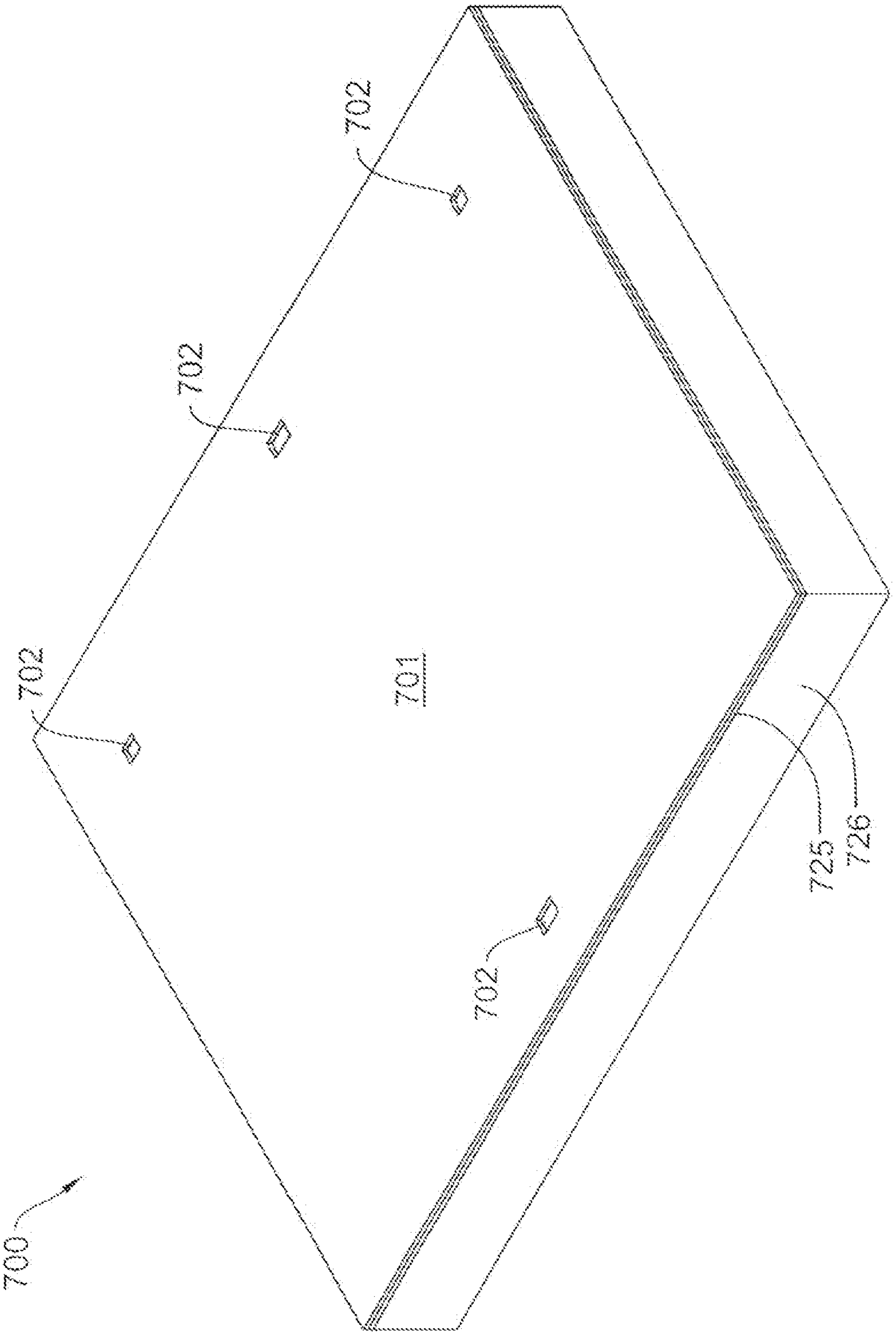
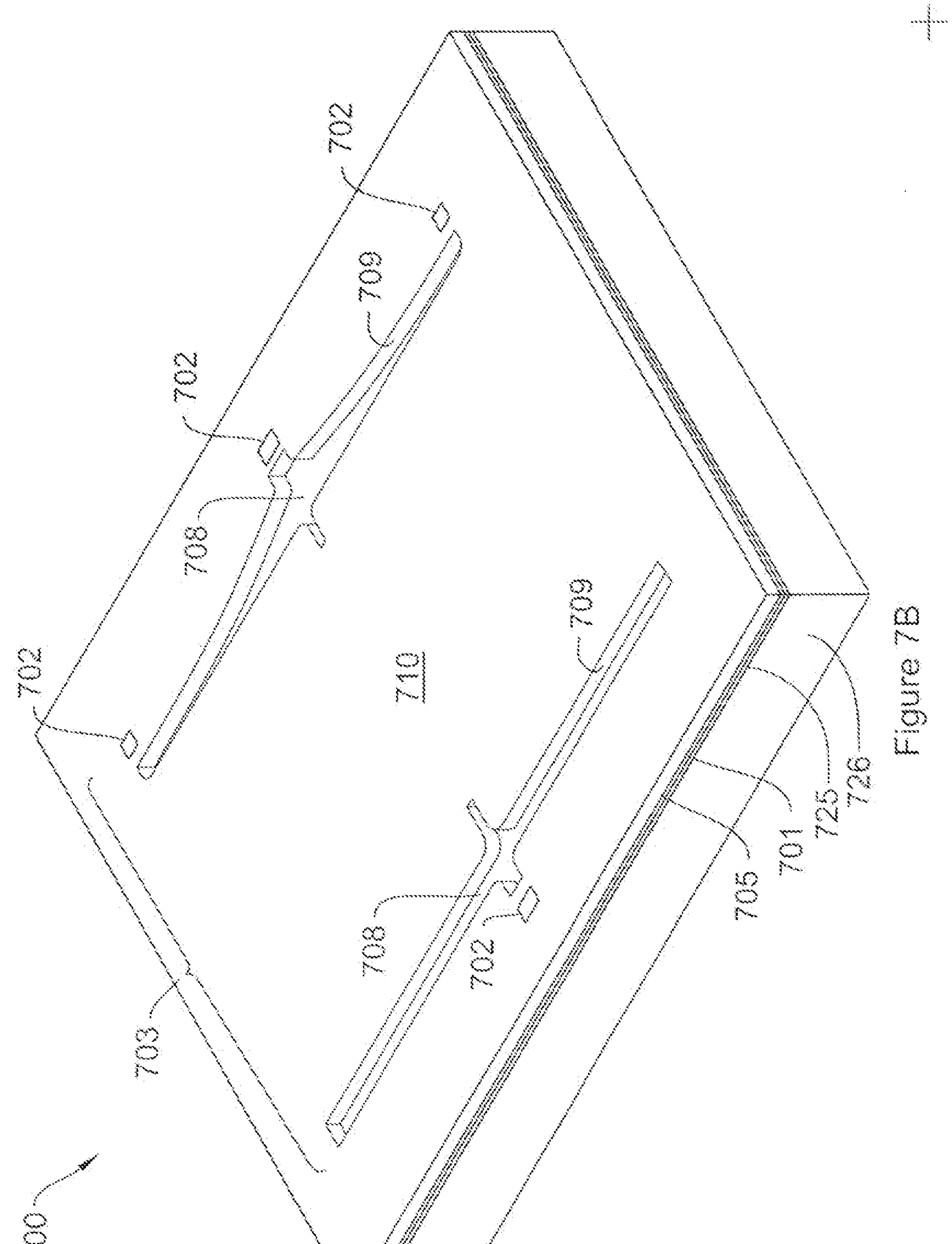


Figure 7A



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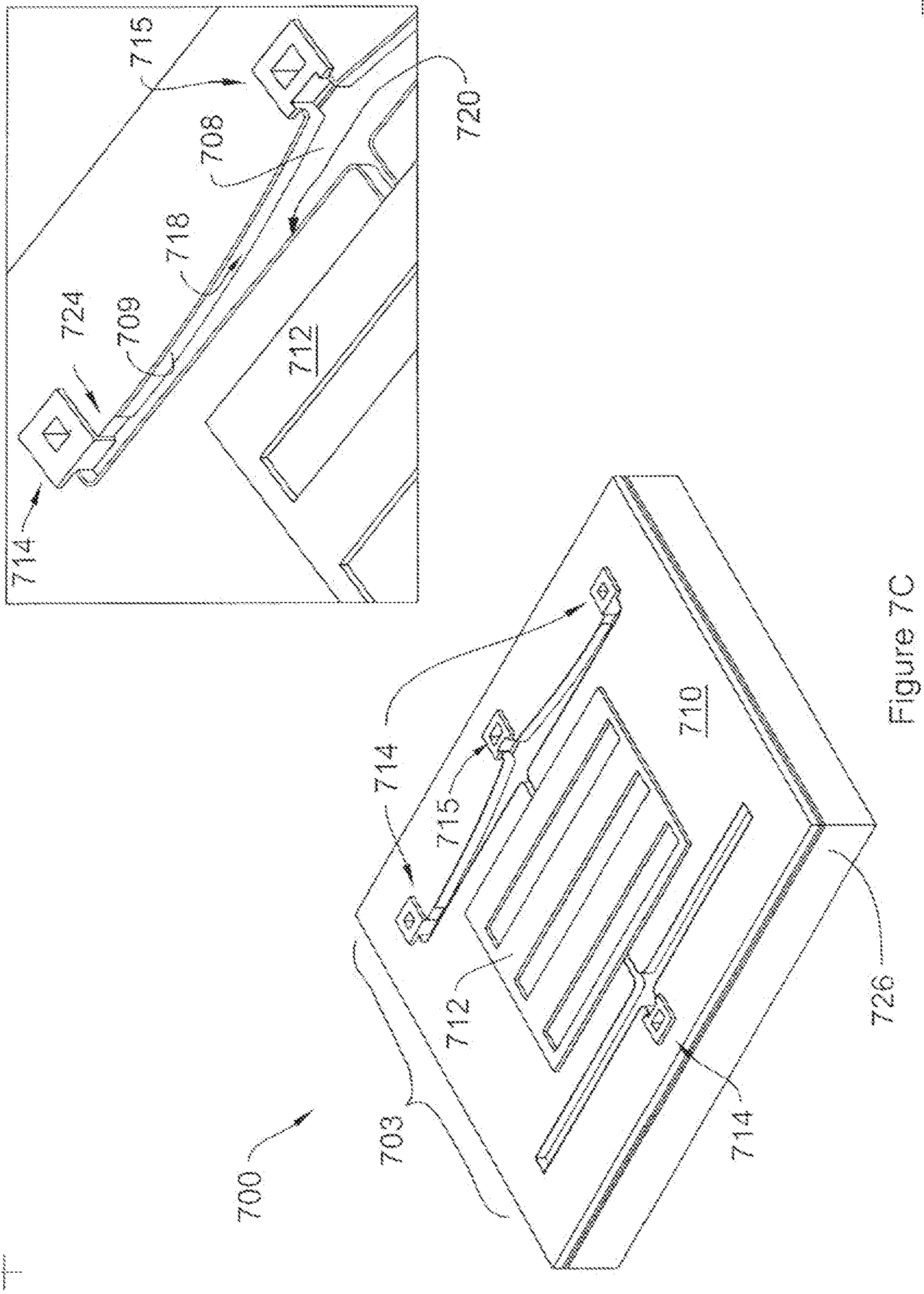
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Figure 7C

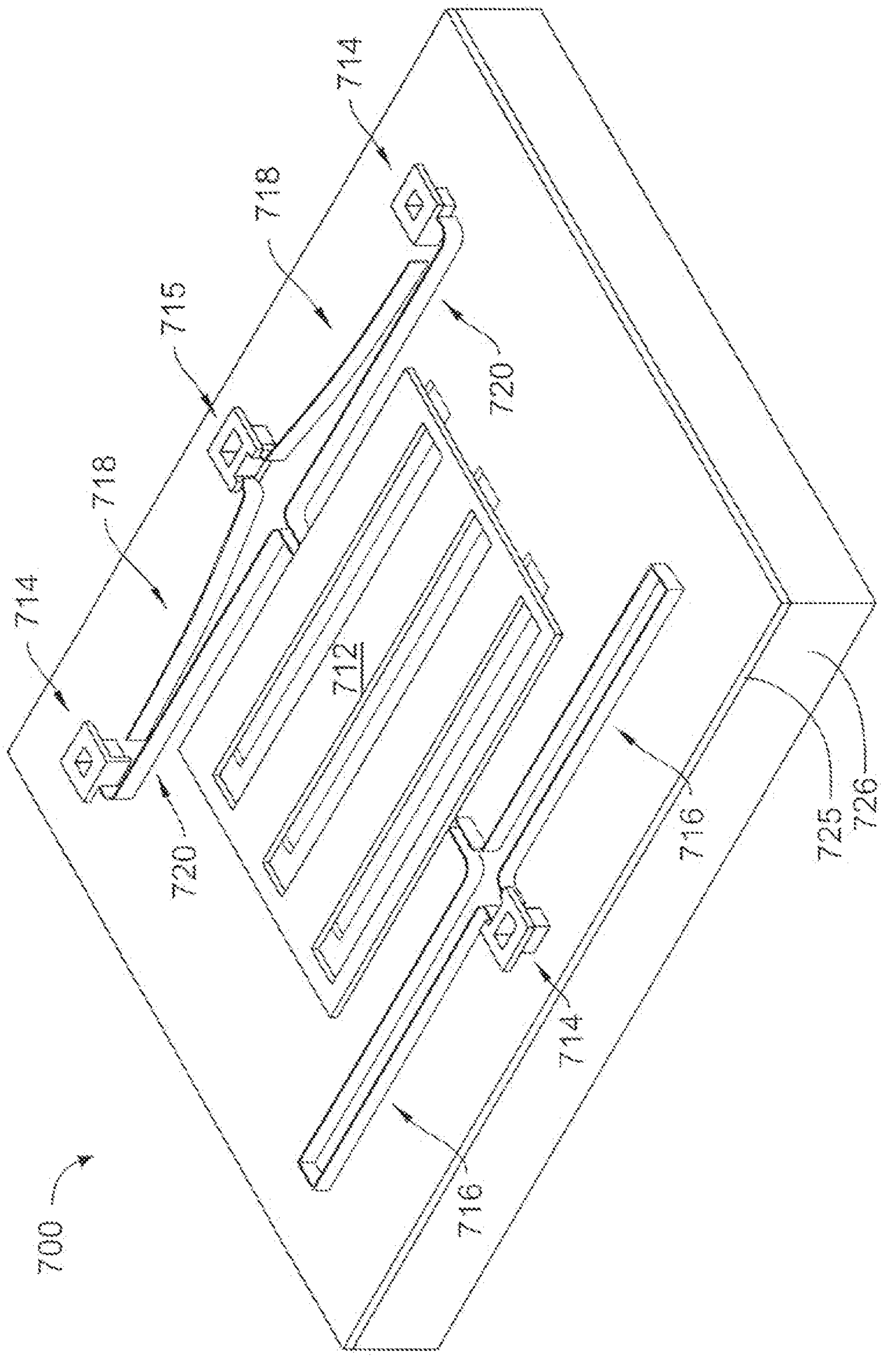


Figure 7D

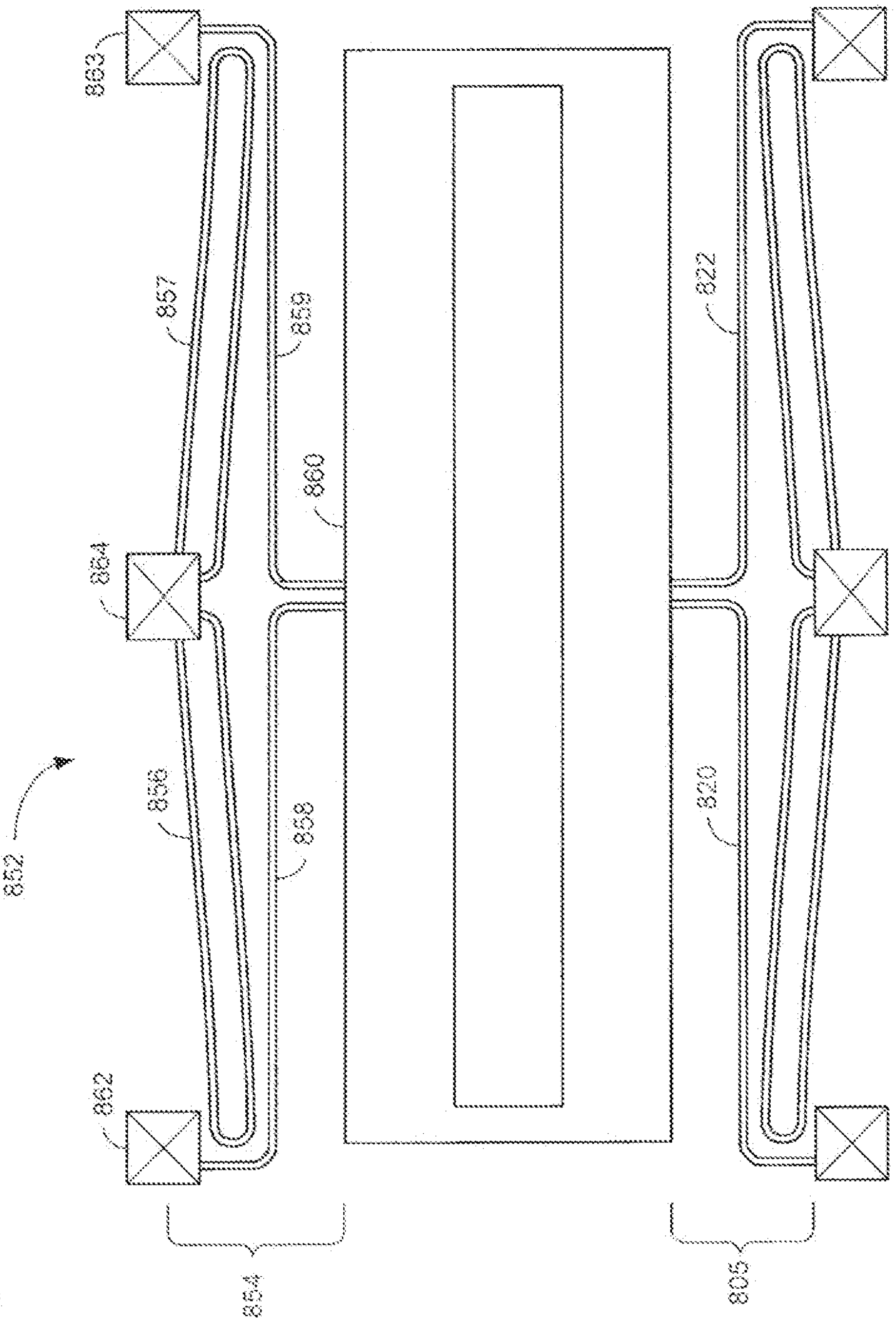
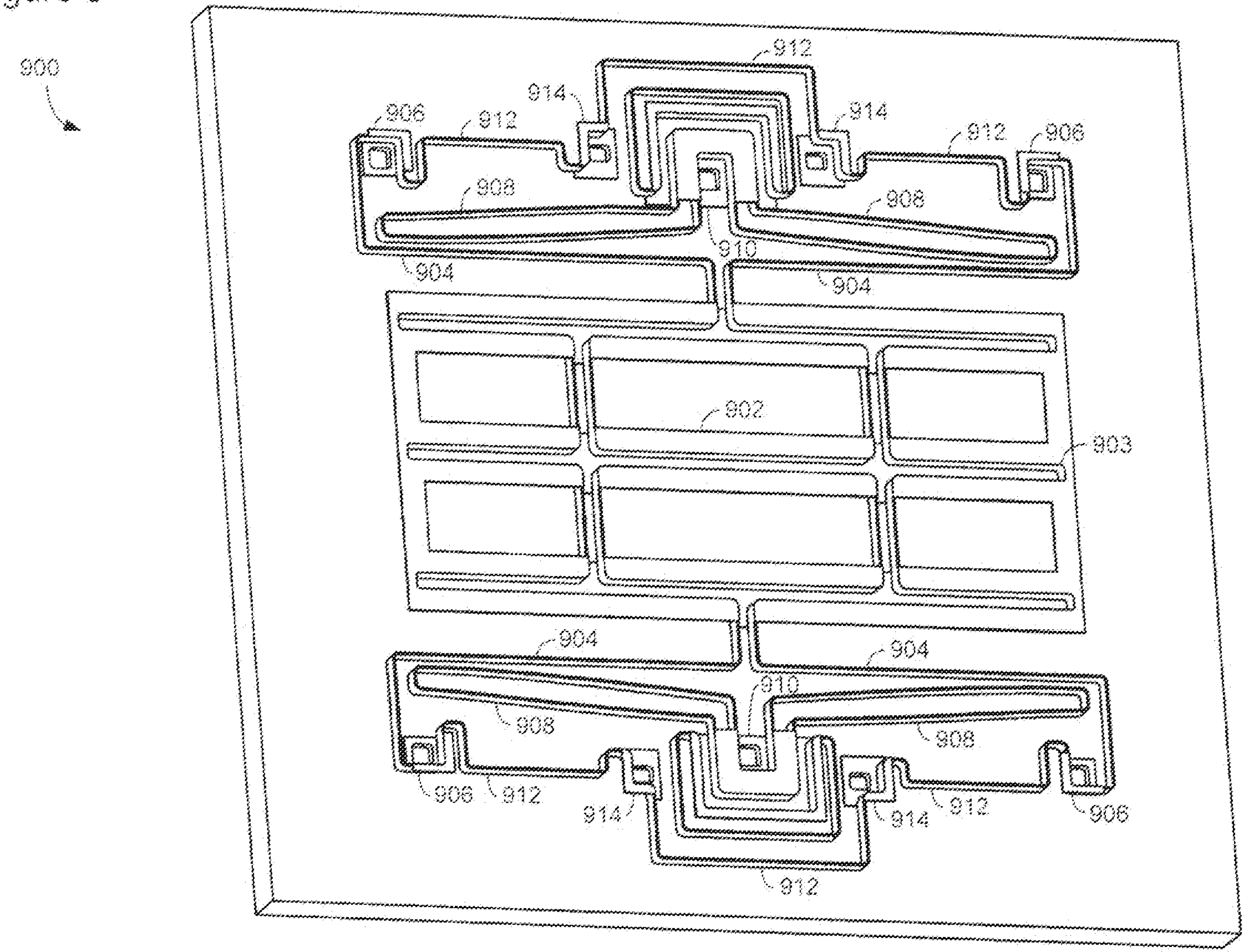


Figure 8

Figure 9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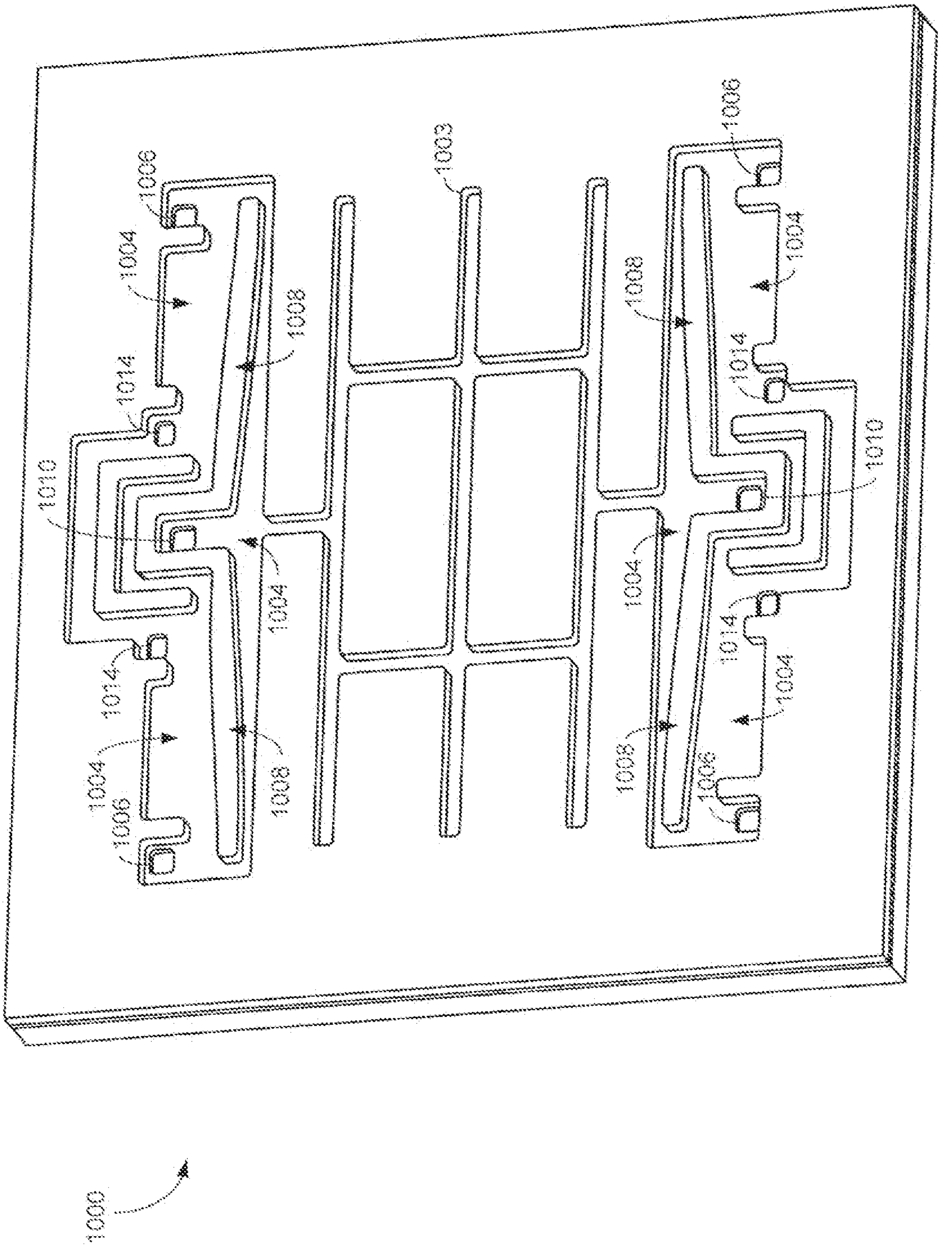
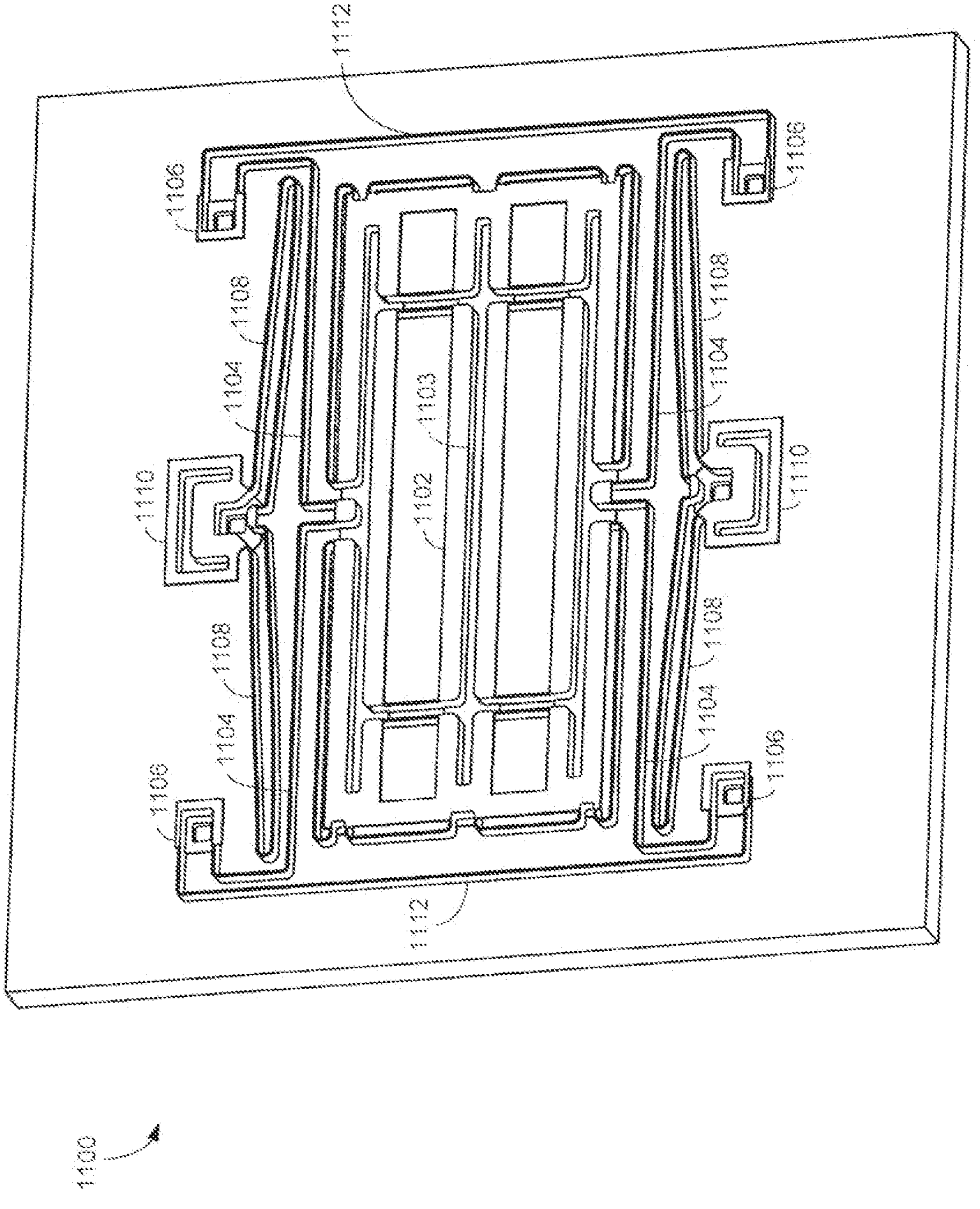


Figure 10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1112
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Figure 11

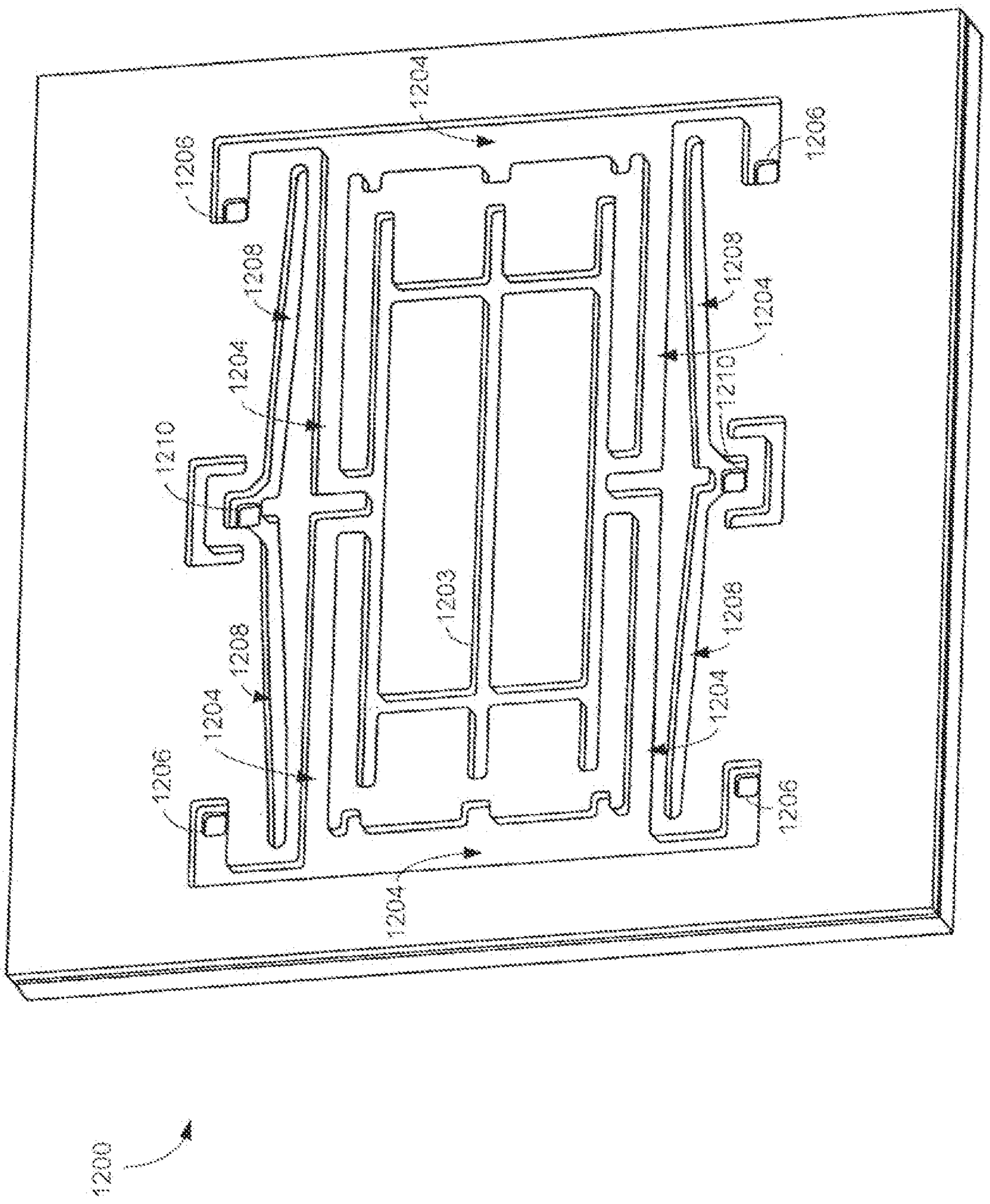
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Figure 12

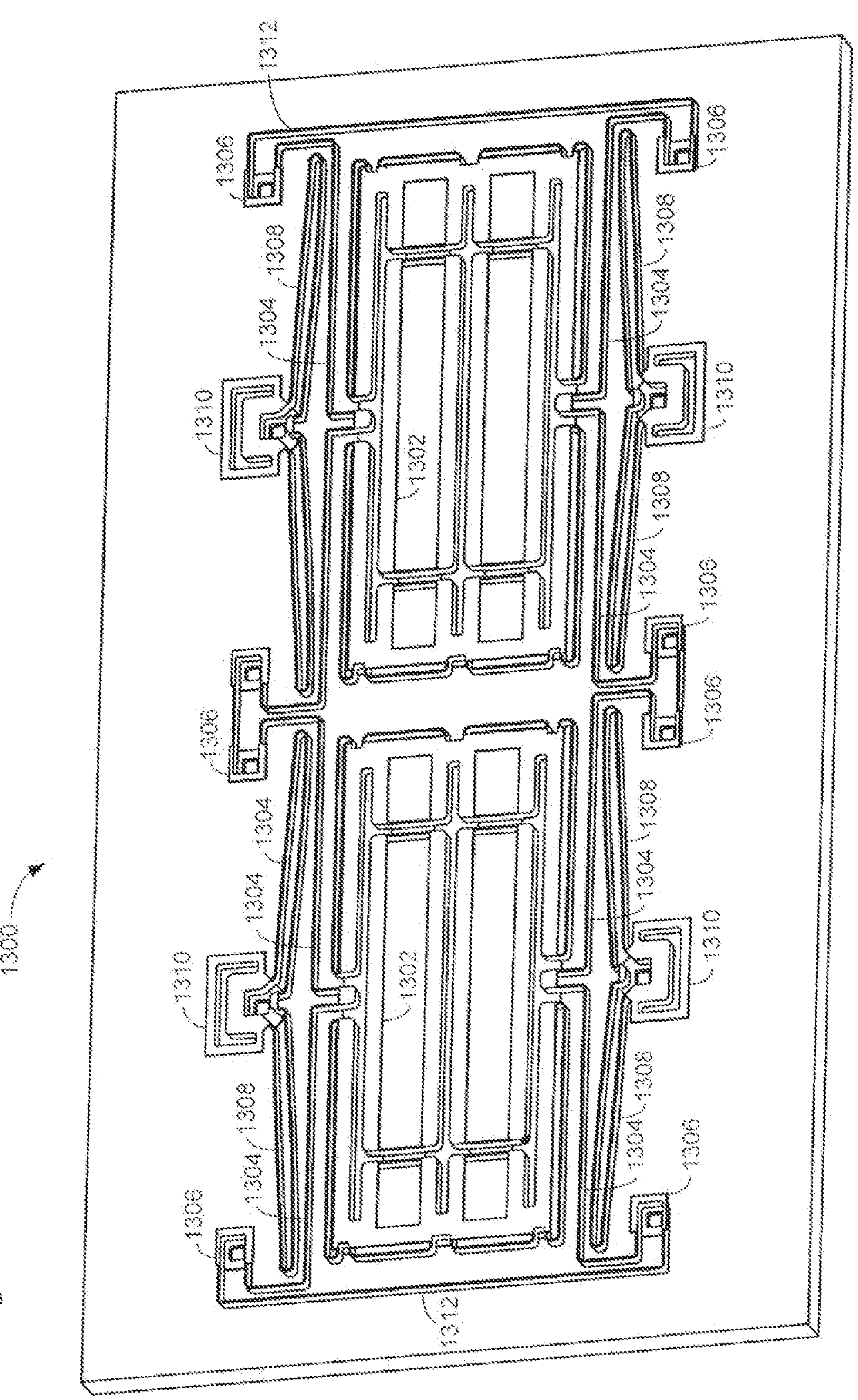
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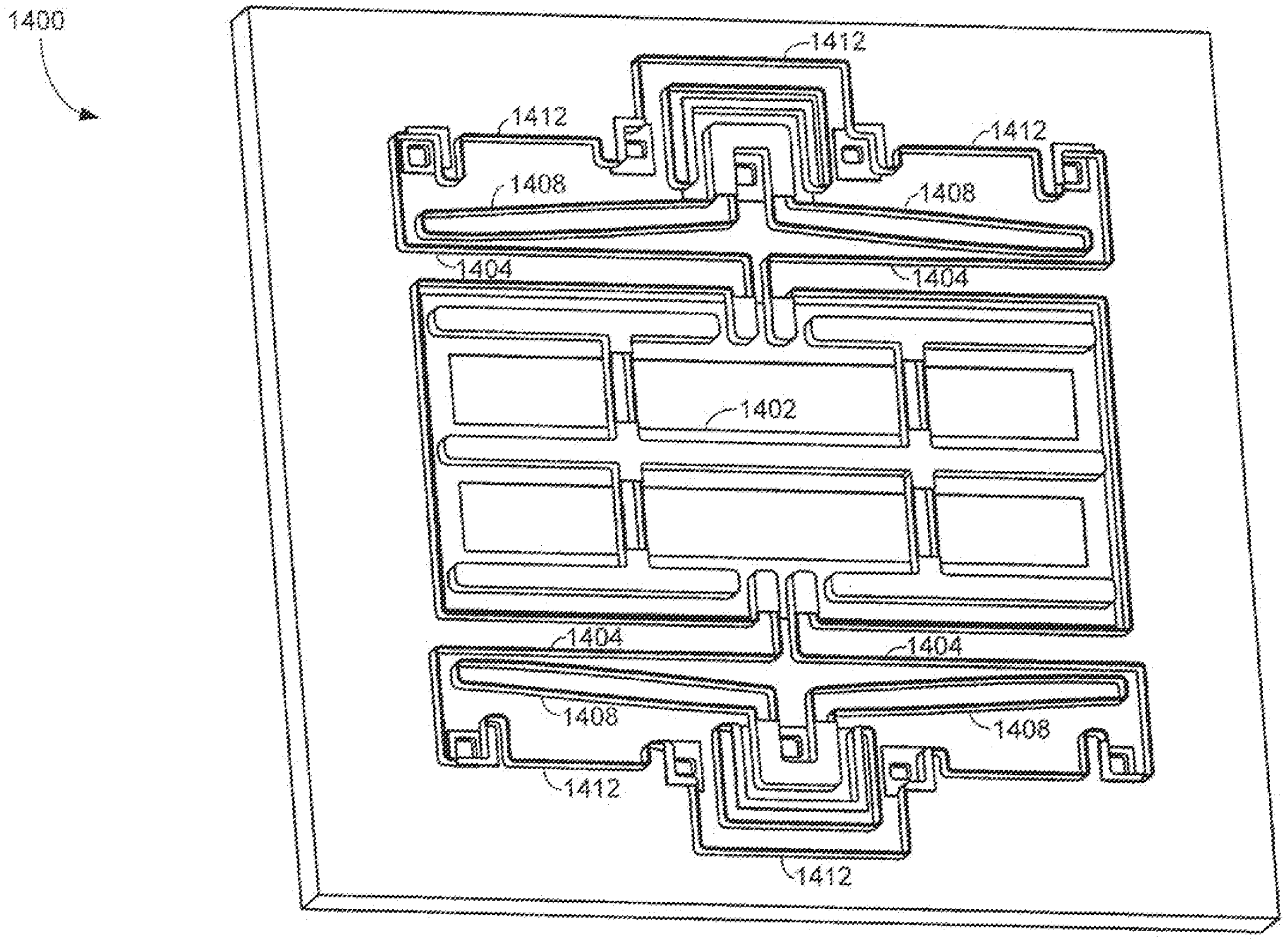
Figure 13

Figure 14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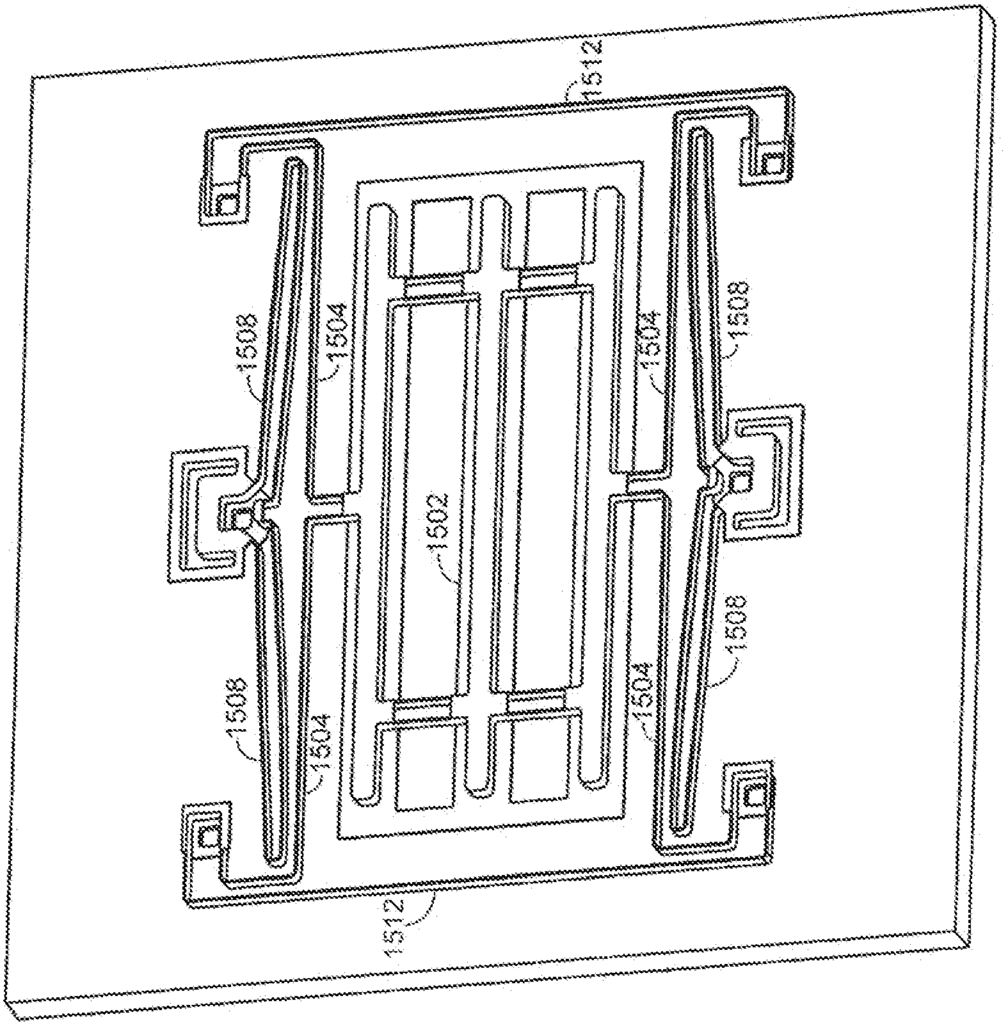

Figure 15

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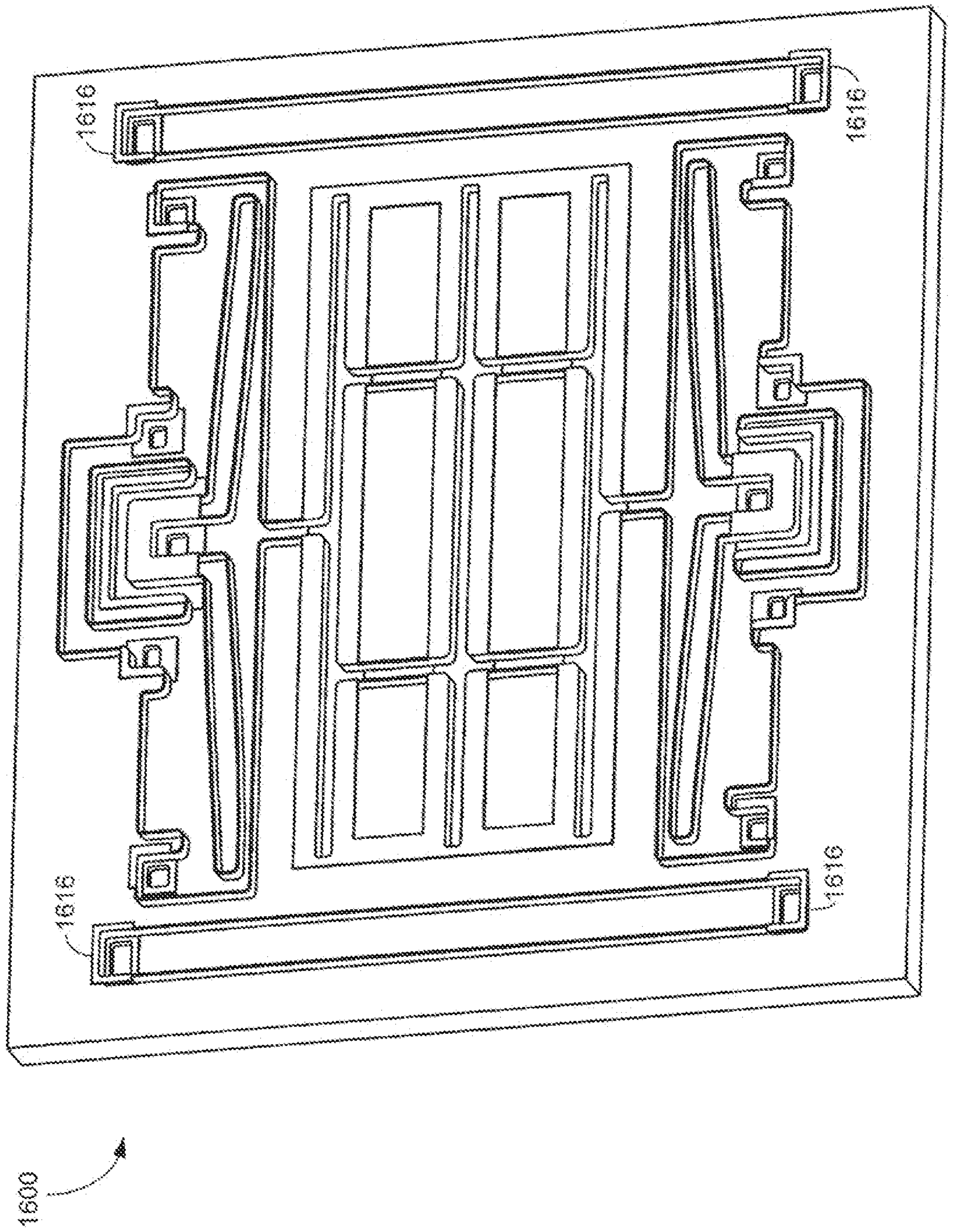

Figure 16