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(54) Title: A MULTI-LAYER 3D DEVICE AND METHOD OF MANUFACTURING

(57) Abstract: An apparatus suitable for three-dimensional micro-electromechanical system (MEMS) apparatus wherein features of the 3D structure contribute to functionality, and a method for assembly thereof is disclosed. The apparatus includes one or more sidewalls supporting a plurality of stacked, parallel layers in precisely fixed relative positions. Both sidewalls and layers, which may be made from any of a variety of materials, may support active and inactive electronic, optical, and microelectromechanical elements. The invention may be applied to optical switching and provides accurate alignment of optical elements through relatively precise design and manufacturing of components of the apparatus rather than by accurate positioning of individual elements. Precisely manufactured positioning elements are provided on the sidewalls for positioning layers, which are fixed thereto. The apparatus is also suitable for containing fluids between layers that may be required for their optical properties.



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A MULTI-LAYER 3D DEVICE AND METHOD OF MANUFACTURING

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to three-dimensional (3D) assembling technologies and, more particularly, to the fabrication and assembly of multi-layer 3D Micro-Electro-Mechanical Systems (MEMS) devices.

There are several conventional methods for assembling 3D semiconductor devices. Those methods were invented for packaging semiconductor Multi-Chip Modules (MCM) to generate Very-Large-Scale Integrated (VLSI) semiconductor dice, which are usually housed in semiconductor packages.

Many patents, including US patents US 5 495 398, US 5 291 061, US 6 080 264, and US 6 049 975 describe those conventional methods for MCM packaging.

3D MCMs are used to reduce the footprint (or real estate) of a circuit, increase speed, reduce noise, *etc.* These packages are limited to only a few layers.

These conventional methods have limitations in assembling a multi-layer MEMS device wherein the 3D structure is required for the functionality of the device, such as in 3D optical switches.

The 3D structure of an optical switch is, itself, part of the device; light may pass *via* the top layer through all other layers to the bottom one, or may be switched by any layer of the device. Therefore there are several requirements of such a 3D structure, including but not limited to:

- The pitch between adjacent layers has to be precisely fixed;
- The layers have to be parallel to each other; and
- Free space is needed between layers.

There is thus a widely recognized need for, and it would be highly advantageous to have a method of 3D packaging that meets the needs of multi-layer MEMS devices such as 3D optical switches.

SUMMARY OF THE INVENTION

5 According to the present invention there is provided a three-dimensional micro-electro-mechanical system (MEMS) apparatus including: a plurality of stacked substantially planar layers including active and inactive elements of the micro-electromechanical system, each layer having at least one wing for supporting said layer; at least one supporting wall for supporting the plurality of planar layers in a fixed relation to one another and to at least one
10 supporting wall, each supporting wall having: a reference surface; and a plurality of positioning devices for supporting a respective wings, each positioning device: having at least one locating surface for positioning the wings to a specified precision relative to the reference surface; and a plurality of securing elements for holding the wings firmly in respective positioning devices.

15 According to further features of the invention described below there is provided a method of fabricating a three-dimensional micro-electromechanical system apparatus including the steps of: fabricating a plurality of stacked substantially planar layers comprising active and inactive elements of the micro-electromechanical system, each layer having at least one wing; fabricating at least one supporting wall for supporting the plurality of planar layers in a fixed
20 relation to one another and to at least one supporting wall, each supporting wall having: a reference surface; and a plurality of positioning devices for supporting a respective wing, each positioning device having at least one locating surface for positioning the wings to a specified precision relative to the reference surface; fabricating a plurality of securing elements for holding the wings firmly in respective positioning devices; assembling the three-dimensional
25 micro-electromechanical system apparatus; and securing the planar layers to the supporting walls.

According to still further features in the described exemplary embodiments there is provided a three-dimensional micro-electromechanical system (MEMS) apparatus having a plurality of

stacked substantially planar layers including active and inactive elements of the micro-electromechanical system, including: a first layer, having at least one activated-mirror optical switch and having at least one free optical path that is interruptable by the optical switch; at least one other layer having at least a first optical element connecting to a first optical fiber
5 operative to transfer light from the first optical fiber to the at least one free optical path on the first layer; and at least one other optical element connecting to a second optical fiber residing on any layer; wherein an optical beam coming from the first optical fiber *via* the first optical connecting element is directed to at least one free optical path, and wherein the optical beam, upon being interrupted by the optical switch, is switched to at least one other optical element
10 and, therethrough, to the second optical fiber.

The present invention discloses an innovative approach to design of 3D microelectromechanical devices, as applied to switching within optical circuits. By so doing, the present invention successfully addresses the shortcomings of presently known configurations in providing accurate alignment of optical elements by transferring accuracy provision from the
15 assembly process to the design and manufacturing stages of components of the apparatus.

More specifically, the present invention is of an apparatus and a method suitable for a 3D MEMS device wherein features of the 3D structure contribute to functionality, and a method for assembly thereof. Features like but not limited to: free space between layers, presence of gas or liquid between layers, accurate and constant pitch between layers, accurate distance
20 between a reference surface and corresponding surfaces of the layers, parallelism of layers.

Specifically, the present invention includes a plurality of Supporting Walls (SW) and a plurality of layers. The SWs include positioning devices to position the layers in relative to one another and to the SWs to a desired degree of precision. Active and inactive elements of the 3DD may be located on the SWs or the layers.

25 The positioning devices include: recesses, stairs, slots, holes, wells, stages (like rungs in a ladder), protrusions, *etc*, or any combination thereof for precisely locating each layer with respect to each SW.

The positioning devices contain locating surfaces, manufactured to a required degree of precision as regards location and parallelism to the reference surface, in order to position layers to a required degree of precision.

5 A feature of the present invention is the use of the SWs also for bearing interconnections among the various layers and between the 3DD and the external world. Interconnections may be like but not limited to electrical, fluidic, and optical.

Another feature of the present invention is use of the SWs and/or the layers for connecting optical devices on the various layers to external optical fibers by using integrated optics or hybrid optics.

10 A further feature of the present invention adds hybrid or integrated circuitry, in addition to conductive lines. The circuitry may control the operation of devices on the layers and act as an electronic interface between devices on the layers and the system controller, which can reside in a host computer. Devices on the layers can include: MEMS, electronic circuitry, optical devices, or any combination thereof. The advantage of this feature is that the 3DD
15 becomes a MEMS system-on-a-package.

Another aspect of the present invention is that the SWs afford physical protection to the 3DD.

The SWs of a exemplary embodiment of the present invention may be made from any of the range of materials used in MEMS, such as a single-crystal silicon wafer, silicon on insulator (SOI) wafer, GaAs wafer, quartz, crystalline Ge, GaP, InP, SiC, metal, polymer *etc.*

20 The present invention may use any of several securing devices for securing a layer in a fixed position relative to the apparatus by forcing and holding each layer against at least two locating surfaces of a respective positioning device, including use of urging elements like but not limited to: a spring, a shape memory alloy (SMA), slopes, or bonding methods like but not limited to a ball grid array (BGA), bumps, glue, *etc.*

25 Depending on the requirements of the device the present invention may choose among several methods for manufacturing SWs. For example, when accuracy of positioning and parallelism are critical for the operation of a 3DD, an embodiment of the present invention may use a

single-crystal silicon (SCS) wafer, anisotropic etching, and photolithography masks for manufacturing SWs.

If accuracy of positioning and parallelism are less critical the present invention may use other methods including: isotropic etching, dry etching, laser ablation, *etc.*

- 5 If the SWs are made of metal, the manufacturing process may employ electroplating. The manufacture of polymer SWs may include using material such as Su 8 and lithographic techniques.

The number of layers in each 3DD depends on the functionality of the device and is not limited in the present invention.

- 10 Moreover, the present invention is not limited to two SWs. A 3DD with a different number of SWs may be manufactured according to the present invention.

Other objects, features, and advantages of the present invention will become apparent in the following detailed description of different embodiments and in the claims. The present invention is not limited to the embodiments described hereunder; those skilled in the art will

- 15 see that many variants are possible.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

Figure 1 illustrates a typical staired supporting wall (SW);

- 20 Figure 2 is a plan view of a typical layer of a 3D device with staired supporting walls;

Figure 3 shows a front view (Figure 3a), a side view (Figure 3b), and top view (Figure 3c) of an exemplary embodiment of a three-dimensional device (3DD) with 5 layers, wherein the SWs have supporting stairs;

Figure 4 illustrates an exemplary embodiment of a 3DD with 5 layers, wherein the SWs have holes — front view (Figure 4a), side view (Figure 4b) and top view (Figure 4c);

Figure 5 illustrates several methods for bonding layers to the SWs;

5 Figure 6 shows another embodiment of a 3DD according to the present invention, using a single SW — front view (Figure 6a) and side view (Figure 6b);

Figure 7 illustrates another embodiment of the present invention having three SWs;

Figure 8 illustrates an application of the present invention in an optical switch; Figure 8a is a prior art optical switch, for comparison and Figure 8b is an
10 optical switch with the same functionality as the prior art but manufactured according to the present invention.

The purpose of the drawings is to describe embodiments of the present invention and not for production. Dimensions of components and features shown in the figures are therefore chosen for convenience and clarity of presentation and are not necessarily to scale. For
15 convenience, different drawings of a 3D device (3DD) may emphasize different aspects of the manufacturing process from other views of the same 3DD. For convenience, only some elements of the same type may be labeled with numerals.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

20 The present invention is of an apparatus suitable for a 3D MEMS device wherein features of the 3D structure contribute to functionality, and a method for assembly thereof.

The principles and operation of multi-layer MEMS 3D devices and the production thereof according to the present invention may be better understood with reference to the drawings and the accompanying description.

Referring now to the drawings, in which like numerals refer to like parts throughout the
25 several views, the embodiment of Figure 1 shows a SW 110F of a 3DD wherein the

positioning devices are stairs built thereinto. A second substantially identical SW **110B** is located substantially parallel to and in line with SW **110F**, as shown in Figure 3b. (Since SWs **110F** and **110B** are substantially identical, they will be referred to collectively as **110**.)

SW **110** has a base surface **112**, which serves as a reference surface for the 3DD, and two sets, left (**L**) and right (**R**), of four stairs, **114L**, **116L**, **118L**, and **120L** and **114R**, **116R**, **118R**, and **120R**. The performance of the 3DD requires that the respective heights, **H₁**, **H₂**, **H₃**, and **H₄**, above base-line **112** of each stair pair (**114L/114R**, *etc*) be accurate to a desired precision and that the upper surface of each stair be substantially parallel to base-line **112** and thus to the corresponding surfaces of other stairs. The upper surface of each stair (**114** to **120**) serves as the locating surface for positioning respective layers. In this embodiment, SW **110** is made of a Single Crystal Silicon (SCS) wafer with (110) orientation according to Miller indexes. This orientation is selected in order to define the surface of base-line **112** and steps **114** – **120**. The end walls of each stair, **113L**, **113R**, **115L**, **115R**, *etc*, are shown in the drawings as perpendicular to base-line **112** and thus to steps **114** – **120**, but are not necessarily so. If the functionality of the 3DD requires perpendicularity, additional processing may be needed.

The width of each level, **W₁** – **W₅**, and the width of each step, **114**, **116**, **118**, and **120** (**L** and **R**), depends on the number of layers (**200a**, **200b**, **200c**, **200d**, and **200e** in Figure 3a), the size of the device and the number of connecting elements, electronic **160**, optic **180**, or other (*e.g.* pipes for cooling liquid, *etc*), to and from each stair. Each level is successively wider than a preceding lower level: **W_m** > **W_{m-1}**.

For illustrative purposes, only two electronic connections **160** and one optical connecting element **180** are shown. Those connections run between base-line **112** and external surfaces **130** and **131** respectively of SW **110**. Those skilled in the art will appreciate that other connections, starting from base-line **112** or from stair, **114**, **116**, **118**, or **120**, can be incorporated in the present invention.

Conductive lines **160** may be made from metal, polysilicon, *etc*. Each line may be terminated **162** by solder bumps, conductive pads, or the like. The technology for manufacturing conductive lines is well known in the art.

Optical path **180** includes two optical connectors, **184** and **188**, and an integrated optical wave-guide **182**. Optical connector **188** is connectible to an external fiber (not shown in the drawing) and may be an integrated connector manufactured as part of the manufacturing process of SW **110**, such as a V-groove or any other suitable groove, or a hybrid connector attached to SW **110**. Optical connector **184**, at another end of wave-guide **182**, transfers light from wave-guide **182** to an appropriate layer, or *vice versa*. Optical connector **184** may be an optical element such as a micro-lens, a diffractive optical element, a micro-prism, *etc.*

In another embodiment of the present invention, optical path **180** may be installed in the layers themselves and not in SW **110**. This approach improves efficiency by eliminating two optical connectors **184** and their mating connectors on the layer, as well as wave-guide **182** on SW **110**. In the case that optical path **180** is located on and/or within a layer, connector **184** may transfer light from wave-guide **182** to an appropriate optical device on the same layer or on another layer *via* free space between the layers, thereby forming a 3D spatial device.

Another embodiment of the present invention may have optical paths in both the layers and SW **110**. Having an optical path on layers and/or SW **110** simplifies the processes of assembling and aligning a 3DD. The accuracy is achieved mainly during the design and the fabrication of the product and not at the assembly stage, as described below in conjunction with Figure 8.

Yet another embodiment of the present invention includes hybrid or integrated circuitry (not shown in the drawings) in addition to conductive lines **160**. The circuitry may control the operation of devices on each layer and act as an electronic interface between devices and the system controller, which can reside in an external computer. The devices on each layer may be, but are not limited to: MEMS, electronic circuitry, optical, fluidic. The advantage thereby is that the 3DD becomes a MEMS system-on-a-package. Adding hybrid or integrated circuitry to SW **110** can be done prior to assembling the 3DD by using technology commonly known to those skilled in the art.

Figure 2 is a plan view of a typical layer **200** of a 3DD with SWs **110**. Layer **200**, which has at least one planar surface, is preferably manufactured from a silicon wafer, although other

suitable substrate materials having a generally planar surface can be used. By way of example, quartz, glass, metal, or polymeric materials may be used to form the substrate. To achieve the best performance from the present invention it is preferable to assemble each layer so that a surface bearing sensitive devices faces the steps. In applications wherein
 5 sensitive devices are located on both surfaces of a layer, both surfaces should be substantially parallel to each other.

Layer **200** has a main area **210** (shown as unshaded) and two protruding wings, **220F** and **220B** (shaded). Main area **210** may contain devices (not shown in the drawing), which may be MEMS, electronic circuitry, optical, inter-connections, *etc.* Main area **210** lies between
 10 two substantially parallel SWs **110** while wings **220F** and **220B** lie upon an appropriate stair pair thereof and hold layer **200** in position.

A length, ML_m , of main area **210** of a layer **m** ($1 \leq m \leq \text{number of layers}$) depends on the functionality of layer **m**; a width, MW_m , of main area **210** layer **m** is limited by a distance between two SWs **110**. A distance DW_m between the outer edges of wings **220F** and **220B** is
 15 designed to support layer **200** on SWs **110**. A wing length, WL_m , is less than distance W_m and greater than the distance between the members of preceding stair pair **m-1**, that is $W_{m-1} < WL_m < W_{m+1}$. Thus, for example, length WL_4 of the wing of fourth layer **m** is greater than W_3 but smaller than W_5 (Figure 1).

In general, the number and shapes of wings of a layer depend on the number and shapes of the
 20 SWs used in the 3DD. Some other examples are described in conjunction with Figures 3, 4, and 6.

Figure 3a is a front view, Figure 3b a side view, and Figure 3c a plan view of an embodiment of a 3DD **300** with five layers, **200a** – **200e**, wherein the SWs have supporting stairs. A number of layers **200** other than five can be stacked using the method of the present invention.
 25 In this embodiment, 3DD **300** includes two SWs **110F** and **110B**. SWs **110** may be made of a single-crystal silicon (SCS) wafer. In other embodiments the SWs **110** may be made of metal or polymer.

Figures 3a – 3c show layers **200a** – **200e** in place, hard against SW **110F** at a front of 3DD **300** and SW **110B** at a back 3DD **300**.

Since bottom surface **230** of each of layers **200** is substantially planar and all of layers **200** are forced against planar surfaces that are substantially parallel to each other (stairs **114** to **120** and base-line **112**), then layers **200a** to **200e** are substantially mutually parallel.

5 The lengths ML_m of main areas of layers **200a** to **200e** may be different from one other; they can be shorter than a length of the SWs, as shown for layers **200a** and **200e**, or longer, as for layers **200b**, **200c**, and **200d**.

10 Uppermost layer **200e** is illustrated as before bonding. A bottom surface **230e** of wings **220F** and **220B** of layer **200e** is forced against stairs **120L** and **120R** and an edge **220FS** of the wings is forced against right end wall **121R** of stair **120R**. Since a length of the wing is smaller than the distance between end walls **121L** and **121R**, a left edge **220FS'** of the wing does not reach left end wall **121L**. By this method, layer **220e** is forced to a correct position in the structure.

For simplicity, no electrical or other connection lines on the SWs are shown in Figures 3.

15 Figure 3b is a side view of 3DD **300**. It can be seen that bonding material **310** is placed on external faces of SWs **110F** and **110B** and below wings **220F** and **220B**. In other exemplary embodiments, bonding material may be placed on an internal side of SWs **110**, or in any other suitable place.

20 Figure 3c is a plan view of 3DD **300** showing two SWs **110**, wings **220B** and **220F**, and the main area **210e** of fifth layer **200e**, and the unobscured parts of fourth and third layers **210d** and **210c**.

25 SW **110** may be manufactured using photolithography and anisotropic wet etching. Anisotropic wet etching may be done using solutions such as KOH (potassium hydroxide) or TMAH (tetramethylammonium hydroxide), *etc.* This technology is known to those skilled in the art; more information about it can be found in *Fundamentals of MicroFabrication* (Marc Madou, CRC Press, 1997).

In wet anisotropic etching, etching speed varies according to crystal surface orientation. Therefore judicious selection of wafer orientation and mask alignment results in the fabrication of walls at a selected angle, with atomic spacing accuracy. For example, by using

(110) single-crystal silicon, one may fabricate a planar surface of each stair, **114**, **116**, **118**, and **120 (L and R)** and base-line **112** parallel to each other to within atomic accuracy. Thus, the accuracy of the photolithography mask influences the accuracy of the dimensions of SWs **110**.

- 5 If accuracy and parallelism are less critical, other methods may be used, such as: isotropic etching, dry etching, laser ablation, *etc.*

The hybrid optical elements of connectors **184** and **188** may be precisely located in wells that may be etched anisotropically. Using this method provides for precise alignment and assembly of the optical elements and thus minimizes losses due to misalignment.

- 10 A method of manufacturing the 3DD may use a Die-Bonder or a "Pick and Place" machine, such as manufactured by companies like KARL-SUSS in Germany.

SWs **110F** and **110B** are precisely held in required relative positions by, for example, a mechanical jig.

- 15 Then first layer **200a** is placed between SWs **110F** and **110B** by the Die-Bonder or "Pick and Place" machine, with wings **220F** and **220B** respectively lying on base-line **112** of each SW.

A bottom surface (usually the device-bearing surface) **230a** of layer **200a** is forced against base-line **112** and against a right end-wall **113R** of base-line **112**. While being held in position, layer **200a** is bonded to SWs **110F** and **110B**. Bonding can be done by any of several methods, for instance by using bumps **310a** and **320a** (Figures 3a & 3b).

- 20 In other embodiments, in which the devices are located on an upper surface of layer **200a** or on both surfaces thereof, additional treatment (for example polishing) may be needed to process both surfaces of layer of layer **200a** to be parallel to each other.

- 25 Another method uses UV adhesive material for securing layer **200a** in place instead of bumps **310a** and **320a**: UV glue is applied on a side of the SWs below the wings of the layer but not on the surface of the step. Therefore bonding of the layer to SWs **110F** and **110B** is made without affecting the parallelism of the layers. An appropriate UV light source (such as PC-3 or 3010-EC manufactured by Dymax Corporation, Torrington, CT, USA, illuminates glue

310a and **320a** (Figures 3a & 3b), and cures the UV glue, thereby bonding layer **200a** to SWs **110F** and **110B**.

Then second layer **200b** is placed between SWs **110F** and **110B** with wings **220B** and **220F** lying on the respective members of stair pair **114L** and **114R**. A bottom surface **230b** (Figure 3a) of layer **200b** is forced against stairs **114R** and **114L** and against a right end wall **115R** and the layer is similarly bonded to SWs **110F** and **110B**. The same process continues with layers **200c**, **200d**, and **200e**. Using this method provides free spaces, **330a – 330d**, between consecutive layers.

Figures 4a and 4b show another configuration, **400**, of a 3DD with five mutually parallel layers, **450**, **452**, **454**, **456**, and **458**, supported by the wings thereof, wherein the positioning devices are rectangular holes, instead of stairs. Five layers are shown by way of illustration; a number of layers other than five can be stacked using the method of the present invention.

The holes are manufactured using the same methods that have been described above, in conjunction with Figure 3, so that a bottom surface of each hole is substantially parallel to the bottom surface of every other hole.

The four wings of each layer are forced against the bottom edge of the appropriate holes, forcing all the layers to be parallel to each other. For example one of the pairs of wings (**464aF**, **464bF**) of layer **454** is supported by bottom edges **424ad** and **424bd** of holes **424a** and **424b** respectively.

3DD **400** has a pair of substantially identical and substantially parallel SWs **410**, **410F** at a front and **410B** at a back thereof (Figure 4b). In SW **410F**, hole pairs: **420aF/420bF**, **422aF/422bF**, **424aF/424bF**, **426aF/426bF**, and **428aF/428bF** support a front end of layers, **450**, **452**, **454**, **456**, and **458**, respectively. Each hole pair **420aF/420bF** *etc*, is arranged in a same plane that intersects SW **410F** at a right angle. The planes correspond to layers **450 – 458** and are mutually substantially parallel.

Each hole has a lower surface, **424ad** in hole **424aF** and **424bd** in hole **424bF**, *etc*, that is made planar to a required precision and that serves as a locating surface for positioning the layer. Each right-hand hole, **420bF**, **422bF**, **424bF**, **426bF**, **428bF**, has a right-hand end

surface such as **424br** in hole **424bF** that is made planar to a required precision. SW **410B** has substantially identical holes.

The two horizontal surfaces of all the holes (for example in hole **424bF**, an upper surface, **424bu** and bottom surface **424bd**) are substantially parallel to each other.

- 5 The end walls of each hole, *e.g.* **424br**, are not necessarily perpendicular to the two horizontal surfaces of the holes (*e.g.* upper surface **424bu** and bottom surface **424bd**) but, for convenience, are shown that way. If it is required by the functionality of the 3DD that an end wall be perpendicular to horizontal surfaces, additional processes may be needed during manufacture.
- 10 Layers **450 – 458** are like layer **200**, which has been described above in conjunction with Figure 2. The main difference is that each of layers **450 – 458** has at least two pairs of wings, **460aF** and **460aB**, and **460bF** and **460bB**, while layer **200** has only one pair. Each wing is smaller than a corresponding hole thereof. The wings may include connection lines to connect devices located on the layers to the external world or to another layer *via* connection
- 15 lines **160** on SWs **410F** and **410B**.

Connection between layers may be done by various methods that are known in the art (not shown in the drawing) such as flex circuit from each layer or wire bonding. The present invention may also use conductive lines such as **160** that run on and/or within SWs **410** and connect conductive lines on the wings of the layers to the external world, or conductive lines

20 such as **170** connecting wings of different layers **462aF** and **464aF**. As an example, bumps over pad **164** (Figures 4a and 4b) connect conductive line **160** to a connecting conductive line (not shown in the drawing) on layer **450**. Those skilled in the art will appreciate that other methods may be used for connecting the conductive lines on SWs **410** with conductive lines on layers **450 – 458**. Another end of line **160** terminates at connector pin **166** (Figure 4b) that

25 may connect to external circuitry (not shown in the drawing). Lines **160** can run on both sides of the SWs, on an external side **410E** and on an internal side **410I** (not shown in the drawing).

SWs **410** may be used for optically connecting optical devices on each layer to the external world *via* an optical path **180** including optical connectors such as **184** and **188** and a wave-

guide **182** (Figure 4b). The present invention may use a similar optical path on at least one of the layers to connect that layer directly to external fibers (not shown in the drawing).

In some embodiments, SWs **410F** and **410B** may carry a plurality of optical paths **180** to connect optical devices (not shown in the drawing) on a layer to external fibers (not shown in the drawing). Optical path **180** starts with an optical connector **184** that conveys light from a suitable connector on the layer to a wave-guide (WG) **182**. Another end of WG **182** can be connected to optical fiber lying in a V-groove, or other type of connection **188** that can be connected to an external fiber (not shown in the drawing). Optical paths **180** may run on both sides of the SWs, on external side **410E** (Figure 4) and on internal side **410I**. More information about optical paths that may run also on layers, **450 – 458**, has been given in conjunction with Figure 1.

Electrical connections and optical paths are described above in conjunction with Figure 1.

Another embodiment of the present invention includes hybrid or integrated circuitry (not shown in the drawings) on SWs **410F** and **410B** in addition to conductive lines. The circuitry may control the operation of devices on each layer and act as an electronic interface between devices on each layer and a system controller, which can reside in an external computer. Devices on each layer may be: MEMS, electronic circuitry, optical, fluidic, *etc.* The advantage thereby is that the 3D structure becomes a MEMS system-on-a-package. Hybrid or integrated circuitry can be added to SWs **410** prior to assembling the 3DD using technology known to those skilled in the art.

Figure 4c is a plan view of an exemplary embodiment of a 3DD with five layers, wherein SWs **410F** and **410B**, have holes and five layers, **450 – 458**, two pairs of wings each. For convenience only upper three layers, **458**, **456**, and **454** are shown.

The two wings of each layer are forced against a right end of the appropriate holes. For example, wing pair (**468bF**, **468bB**) of layer **458** is forced against right end **428br** of holes **428b** in SW **410F** and **410B**. Wings **468bF** and **468bB** do not contact left ends **428bl** of holes **428b**. The other pair of wings of each layer, *e.g.* **468aF** and **468aB**, do not contact any of the side edges of the holes wherein they reside, *e.g.* **428L** and **428R**, respectively.

SWs **410** may be made of materials like the materials of SW **110** and be manufactured using methods, like those described above in conjunction with Figure 1. An exemplary method of assembling 3DD **400** may use a Die-Bonder or “Pick and Place” machine, such as are manufactured by companies like KARL-SUSS.

- 5 The main difference in the manufacturing process is the mask needed for the photolithographic process.

SW **410F** is held in a required position using any of several methods, such as a mechanical jig that holds SW **410F** horizontally, with an outer surface facing downwards.

- 10 Left wings, *i.e.* **460aF** and **460bF**, of each of layers **450 – 458**, the layers being vertical, are placed in respective holes *i.e.* wing **460aF** in hole **420aF** and wing **460bF** in hole **420bF**, and so on.

Then SW **410B** is placed horizontally above layers **450 – 458** so that that the wings, in another end of the layers enter respective holes in SW **410B**, *i.e.* wing **460aB** in hole **420aB** and wing **460bB** in hole **420bB**, and so on.

- 15 The mechanical jig holds SWs **410F** and **410B** and five layers, **450 – 458**, in place while SWs **410F** and **410B** are forced towards each other as each layer is pushed down and right, so that wings **460bF – 468bF** and **460bB – 468bB** (not shown in the drawing), are pressed hard against bottom and the right edges of the holes, *e.g.* wing **464bF** is forced against edges **424bd** and **424br**. Since the bottom edges of all the holes are mutually parallel, all the layers
20 are forced to be parallel to one another.

Securing the layers to the SWs may be done by any of several methods. Some exemplary methods are described in conjunction with Figure 5 below.

Refer now to Figure 5, which illustrates several methods for securing a wing of a layer against a bottom edge of a hole located as shown by the encircled part of Figure 4a.

- 25 Figure 5a illustrates an embodiment that uses a Shape Memory Alloy (SMA) **530** to hold a layer against a bottom edge **520B** of a hole **520** in a SW **505**. The original thickness of SMA **530** is greater than a distance *d* between an upper surface of wing **510** and an upper edge

520U of hole **520**, while a thickness of a deformed state of SMA **530** is smaller than distance *d*.

During securing of the 3DD, SMA **530** is in a deformed state and placed between the upper surface of wing **510** and the upper edge **520U** of hole **520**. Then the temperature is raised,
5 causing SMA **530** to expand to an original size thereof and forcing wing **510** against bottom edge **520B** of hole **520**.

In another embodiment **520** represents a wedge used to hold a layer securely in place.

Figure 5b is a cross-section through a hole in SW **505** of an embodiment that uses solder pads **540** and **547** and a solder bump **545** to hold a layer wing **510** to SW **505**. Those skilled in the
10 art will appreciate that solder is not mandatory and other methods may be used according to the present invention *e.g.* an electro-plated connection may replace the solder.

In the securing stage of the assembly of the 3DD, the temperature is elevated, while urging layers against a bottom surface of respective holes, so that bonding solder **545** melts and bonds wing **510** against bottom edge **520B** of hole **520**.

15 Pads **540** and **547** can be on either surface, **505E** or **505I**, of SW **505**, or on both sides thereof.

Figure 5c illustrates a hole in SW **505** of another embodiment using a curable glue, such as UV curable glue, to hold the layers to SWs **505**. Those familiar with the art will appreciate that UV glue is not mandatory and another type of glue may be used according to the present invention *e.g.* epoxy, thermal curing, *etc.*

20 During the bonding stage of assembly of the 3DD, layer **510** is forced against bottom edge **520B** of hole **520** and UV curable glue **550**, such as manufactured by companies such as AI Technology Inc., NORLAND, ABLESTIK, EPO-TEK, DYMAX, Torrington, CT, USA *etc.*, is applied within some of the corners between a bottom surface of wing **510** and external surface **505E** or internal surface **505I** of SW **505**, or on both surfaces.

25 Then at least one appropriate UV light source, such as manufactured by Dymax Engineering Adhesives Products, Torrington, CT, USA, EFOS, *etc.*, provides UV light, which illuminates

surfaces of glue **550** so that the light penetrates and cures UV glue **550** thereby holding a bottom surface of wing **510** firmly against bottom edge **520B** of hole **520**.

Figures 5d and 5e respectively illustrate side and front views of SW **505** in an embodiment that uses springs **562** to hold the layers to SWs **505**.

- 5 At least one comb **560** of springs **562** is fixed to external surface **505E** of SW **505** overlapping hole **520** in such a way that an overlap of **562** exceeds a distance between an upper surface **510U** of wing **510** and an upper edge **520U** of hole **520**.

Wing **510** penetrates the hole from the side of internal surface **505I** and pushes springs **562** outwards. Spring **562** reacts by forcing wing **510** against bottom edge **520B** of hole **520**.

- 10 Upper surface **510U** of wing **510** may have grooves (not shown in the drawings) perpendicular to external surfaces **505I** and **505E** of side wall **505**, each having a V cross-section to engage a respective tooth **562** of comb **560** to impede left-right motion $L \leftrightarrow R$ in figure 5e.

- 15 Springs **562** may be made from any of various materials, such as metal, epoxy, *etc.* *e.g.* SU 8, a polymer which is preferably impervious to the etching solutions (*e.g.* KOH or TMAH).

An exemplary manufacturing process of SW **505** includes, among other stages, applying a layer of a polymer onto the silicon wafer. Using photolithographic techniques and an appropriate etching process, the shapes of comb **560** are generated at the appropriate locations on the wafer.

- 20 Next, holes **520** are etched by using a mask with the shapes of holes **520**, and appropriate anisotropic wet etching. The etchant etches the silicon below and around comb **560** but does not etch comb **560** itself. The process results in hole **520** and associated spring **562** protruding thereover.

- 25 A further embodiment may use a hybrid comb of springs. This comb is fabricated in a separate process and later bonded to SW **505**.

Yet another embodiment may use a metal comb and further utilize the metal springs to connect conductive lines on SW **505** with conductive lines on the layers.

Still another embodiment may use a shape other than a comb. For example, the spring may be a stiff, flexible plate.

Figure 5f illustrates another embodiment using a slope **572** in a transition area between the main area of **510** and wing **570** thereof. Upon pushing layer **510** against side wall **505**, slope **572** acts as a wedge and generates a vertical force that secures wing **570** against bottom surface **520B** of the **520**.

Another configuration, **600**, of the present invention, which uses a single SW **610** is shown in Figure 6. Figure 6a is a front view and Figure 6b is a side view of a single SW 3DD that, for purposes of illustration, has three layers **650**.

10 SW **610** has three holes **620** and is manufactured as described above for SW **110** or SW **410**. In order to provide the required stability to 3DD **600**, SW **610** may be thicker than SWs **110** or **410**. SW **610** can be made from a thick wafer, for example from a 2 mm wafer, or from several wafers bonded together to generate a wide SW.

15 Each layer **650** may be a different size from the others. Layers **650** are manufactured in the same way as the layers of the previous embodiments. The main difference between layers **650** and the previously described layers is that layer **650** has a single wing that may be at one of the ends thereof, like wing **662**, or within the main area of the layer, like wings **664** and **666**.

Figure 7 illustrates another embodiment **700** of the present invention with three SWs **710**.
20 Layers **750** of 3DD **700** have a hexagonal shape with three wings **760**, which fit holes **720** in SWs **710**.

Other embodiments may use other numbers of supporting walls.

Figures 8 illustrate an application of the present invention, an Optical Switch (OS). Figure 8a shows a prior art OS **800a** and Figure 8b shows an OS **800b** having a same functionality as
25 OS **800a**, but manufactured according to the present invention.

OS **800a** is a switching device that receives a plurality of input signals from sets of input fibers **812a** – **814a** and provides a plurality of output signals to two sets of output fibers:

OUTPUT 1, containing fibers **812b** and **814b**, and OUTPUT 2, containing fibers **812c** and **814c**. For simplicity of presentation, OS **800a** is shown having only two fibers, **812** and **814**, in each port, and only two output ports OUTPUT 1 and OUTPUT 2, by way of example only. That is to say, OS **800a** can have more than two fibers at each port and more than two output ports and, moreover, need not necessarily have equal numbers of fibers at each port.

OS **800a** has switches, **872**, **874a**, **874b**, and **876**, arranged in a two- or three-dimensional array configuration. At least two of switches, **872** – **876**, which are preferably microelectro-mechanical (MEMS) switches, reside on respective, distinct substrate layers, **852**, **854**, and **856**.

In one embodiment, switches **872** – **876** are planar and move parallel to layers **852** – **876**. In an OFF position of the switch, a light signal (represented by a beaded line) travels *via* a transparent zone, **862**, **864a**, **864b**, and **866**, of at least one layer. In an ON position, switches **872** to **876**, which are mirrors, cover an appropriate transparent zone and reflect the light into another direction.

For example, in case that OS **800a** has to transfer a light signal from fiber **814a** to fiber **814b** and from fiber **812a** to **814c**, OS **800a** is set with switch **876** in an OFF position and light travels *via* transparent zone **866** to switch **874b** which is set to an ON position and reflects light to fiber **814b**. Switches **874a** and **872** are set to OFF and let a second beam traverse both transparent zones **864a** and **862** to reach fiber **814c**.

More information about an exemplary OS **800a** can be found in PCT International Publication Number WO 01/43450 A2, 14 June 2001.

Figures 8a and 8b represent a logical layer of switches in a 3D OS while the die represents a physical layer. Each logical layer has optical input/output ports (**810a**, **810b**, and **810c**). Each optical port is a one-dimensional array per logical-layer. The number of logical layers can be expanded (for example, at least one additional logical layer may be placed in a direction out of the plane of the figure). The plurality of logical layers transforms the one-dimensional array of fibers into a two-dimensional array of input and output fibers.

In general, the numbers of layers, switches, and input/output fibers of optical switches in a single device may be in the hundreds. This necessitates accurate assembly and complicated adjusting methods with spatial operating equipment to adjust the fibers in their Fiber Lens Array Plate (FLAP) and to align the FLAP within the 3DD to achieve a required optical alignment.

Figure 8b illustrates a cross-section of 3DD **800b**, which is an OS manufactured according to the present invention having integrated optical connection to the fibers. OS **800b** has the same functionality as OS **800a**. Other optical switches with different types of mirror activation (*e.g.* gimbals, analog beam steering mirror, pop-up mirror, *etc*) may be implemented according to the present invention.

The dies thereof may be supported and positioned by a front SW and a back SW that are, however, not shown for ease of demonstrating the optical paths. The SWs may have stairs or holes as described above in conjunction with figures 3 and 4.

OS **800b** connects to external fibers — a set of input fibers (**812a** and **814a**) and two sets of output fibers (**812b** and **814b**) and (**812c** and **814c**) — by using direct optical connections on the layers thereof. The optical connections include optical connectors, **188** to the fiber, an integrated wave-guide **182**, and an optical connector **184** at another end of wave-guide **182**. This optical path has been described above in conjunction with Figure 1. Optical connector **184** can be an optical element, such as: a micro lens, a diffractive optic element, a micro prism, *etc*.

To generate the same optical paths (beaded lines) as in OS **800a** in this exemplary embodiment, an additional two layers, **858** and **850**, have been added with optical connections to fibers **814a**, **812b**, and **814c** and two layers **856** and **852** have been extended to include optical connections to fibers **812a**, **814b**, and **812c**.

Optical switches **872** – **876** are set the same as in OS **800a**.

The present invention solves the problem of aligning a plurality of layers in 3D space by dividing the problem into two independent processes. A first process is a 2D placement of fibers and free-space optical connectors **184** (lens, prism, *etc*) on a die. A second process is

the relative placement of dies. In both processes, accuracy is achieved mainly during design and fabrication of the product and not during assembly of the 3DD. Using this method eliminates the need for spatial alignment of the FLAPs. The accuracy of the position of optical path **182**, **184**, and **188** is determined during the design and the fabrication of the layer in the wafer and/or the die stage. The accuracy in the positioning of integrated optic elements is achieved by the accuracy of the photolithographic technique and, in case of hybrid optics, alignment is done on the wafer/die by using accurate, generally available equipment or methods, *e.g.* a common pick and place machine.

Another method may use V-grooves or recesses, in which the hybrid elements are placed. Those recesses or V-grooves are made by a lithographic method, with high accuracy.

The design and the fabrication process of holding the layers in their position using the supporting walls, as described above, determine positional accuracy in a direction perpendicular to the dice, including distances therebetween.

Other embodiments, which use integrated optical connection to the fibers, according to the present invention may use methods other than supporting walls to hold the layers (dice) in position *e.g.* strut poles, adhesive material, anodic bonding, *etc.*

This method of connecting fibers to OS **800b** reduces the complicated alignment process and improves the accuracy in comparison to the FLAPs **810a**, **810b**, and **810c**, of OS **800a**.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made including some or all of the features of the disclosed invention as required for specific applications.

In the description and claims of the present application, each of the verbs, “comprise” “include”, and “have”, and conjugates thereof, are used to indicate that the object or objects of the verb are not necessarily a complete listing of members, components, elements, or parts of the subject or subjects of the verb.

WHAT IS CLAIMED IS:

1. A three-dimensional micro-electromechanical system (MEMS) apparatus comprising:
 - a) a plurality of stacked substantially planar layers including active and inactive elements of the micro-electromechanical system, each layer having at least one wing for supporting said layer;
 - b) at least one supporting wall for supporting said plurality of planar layers in a fixed relation to one another and to said at least one supporting wall, each said supporting wall having:
 - i) a reference surface; and
 - ii) a plurality of positioning devices for supporting a respective said wing, each said positioning device:
 - A) having at least one locating surface for positioning said wings to a specified precision relative to said reference surface; and
 - c) a plurality of securing elements for holding said wings firmly in respective said positioning devices.
2. The apparatus of claim 1 wherein said positioning devices are selected from the group consisting of: stairs, slots, holes, wells, stages, protrusions, or any combination thereof.
3. The apparatus of claim 1 wherein said locating surfaces are substantially parallel to said reference surface.
4. The apparatus of claim 1 wherein said securing elements are selected from the group consisting of: shape memory alloy, solder bump, UV curable glue, epoxy glue, spring, electroplated connection, wedge, and slope.

5. The apparatus of claim 1 wherein said supporting wall is manufactured from material selected from the group consisting of: single-crystal silicon wafer, silicon wafer, silicon on insulator wafer, GaAs wafer, quartz, and crystalline Ge, GaP, InP, SiC, metal, and polymeric materials.
6. The apparatus of claim 1 wherein said planar layer is manufactured from material selected from the group consisting of: silicon, quartz, glass, metal and polymeric materials.
7. The apparatus of claim 1 wherein said supporting wall bears at least one connecting element selected from the group consisting of: integrated optical path, hybrid optical path, optical connector, conductive line, integrated circuit, hybrid circuit, gas pipe, and fluid pipe.
8. The apparatus of claim 1 wherein said layers carry at least one connecting element selected from the group consisting of: integrated optical path, hybrid optical path, optical connector, conductive line, integrated circuit, hybrid circuit, gas pipe, and fluid pipe.
9. The apparatus of claim 1 wherein gas is contained between a pair of adjacent layers.
10. The apparatus of claim 1 wherein liquid is contained between a pair of adjacent layers.
11. The apparatus of claim 1 wherein a said layer includes at least one activated-mirror optical switch.
12. The apparatus of claim 11 further including an optical path connecting said at least one said activated-mirror optical switch to an external optical fiber.

13. The apparatus of claim 12 further including a free optical path between said at least one activated-mirror optical switch of a said layer and another said at least one activated-mirror optical switch of another said layer.
14. The apparatus of claim 13 wherein said free optical path is switchable by said optical switches to another said layer.
15. The apparatus of claim 14 wherein an alignment of said free optical path is determined by a mutual positioning of said layers.
16. The apparatus of claim 14 wherein said mutual positioning of said layers includes:
 - a) a specified distance therebetween;
 - b) an angle of relative orientation; and
 - c) a relative lateral displacement.
17. A method of fabricating a three-dimensional micro-electromechanical system apparatus comprising the steps of:
 - a) fabricating a plurality of stacked substantially planar layers comprising active and inactive elements of the micro-electromechanical system, each layer having at least one wing;
 - b) fabricating at least one supporting wall for supporting said plurality of planar layers in a fixed relation to one another and to said at least one supporting wall, each said supporting wall having:
 - i) a reference surface; and
 - ii) a plurality of positioning devices for supporting a respective said wing, each said positioning device having at least one locating surface for positioning said wings to a specified precision relative to said reference surface;

- c) fabricating a plurality of securing elements for holding said wings firmly in respective said positioning devices;
 - d) assembling the three-dimensional micro-electromechanical system apparatus; and
 - e) securing said planar layers to said supporting walls.
18. The method of claim 17 wherein said fabricating of said layers includes steps chosen from the group consisting of: photolithography, anisotropic wet etching, isotropic etching, dry etching, electroplating, and laser ablation.
19. The method of claim 17 wherein said fabricating of said supporting walls includes steps chosen from the group consisting of: photolithography, anisotropic wet etching, isotropic etching, dry etching, and laser ablation.
20. The method of claim 18 wherein said positioning devices are selected from the group consisting of: stairs, slots, holes, wells, stages, protrusions, or any combination thereof.
21. The method of claim 20 wherein said fabricating of said positioning devices includes the steps of photolithography and etching.
22. The method of claim 17 wherein said assembling include the steps of:
- a) supporting a first said supporting wall in a fixed position;
 - b) successively urging a wing of a said planar layer against a said locating surface of a respective said positioning device to a required precision of relative orientation, for all said planar layers;
 - c) securing said planar layers to said supporting wall;
 - d) successively urging respective said locating surfaces of other said supporting walls against other said wings; and
 - e) securing said planar layers to other said supporting walls.

23. The method of claim 17 wherein said securing includes the step of applying a securing element.
24. The method of claim 23 wherein said securing elements are selected from the group including bonding elements and urging elements.
25. The method of claim 24 wherein said bonding elements are selected from the group including solder bump, UV curable glue, epoxy glue, and electroplated connection.
26. The method of claim 25 wherein said bonding elements are applied between a said supporting wall adjacent to a positioning device and a said respective wing.
27. The method of claim 24 wherein:
- a) said urging elements are selected from the group consisting of shape memory alloy, wedge, spring, and slope; and
 - b) said positioning device includes a hole.
28. A three-dimensional micro-electromechanical system (MEMS) apparatus having a plurality of stacked substantially planar layers comprising active and inactive elements of the micro-electromechanical system, comprising:
- a) a first layer, having at least one activated-mirror optical switch and having at least one free optical path that is interruptable by said optical switch;
 - b) at least one other layer having at least a first optical element connecting to a first optical fiber operative to transfer light from said first optical fiber to said at least one free optical path on said first layer; and
 - c) at least one other optical element connecting to a second optical fiber residing on any said layer;

wherein an optical beam coming from said first optical fiber *via* said first optical connecting element is directed to said at least one free optical path, and wherein said optical beam, upon being interrupted by said optical switch, is switched to said at least one other optical element and, therethrough, to said second optical fiber.

29. The apparatus of claim 28 wherein said optical connecting element includes:

- i) an optical connection to said fiber;
- ii) an optical deflection element; and
- iii) a wave guide connecting said optical connection to a fiber to said optical deflection element.

30. The apparatus of claim 29 wherein said optical deflection element is an optical element selected from the group consisting of micro-lens, diffractive optical element, and micro-prism.

31. The apparatus of claim 29 wherein said optical connection to said fiber is an optical element selected from the group consisting of groove, V-groove, and hybrid connector attached to said layer.

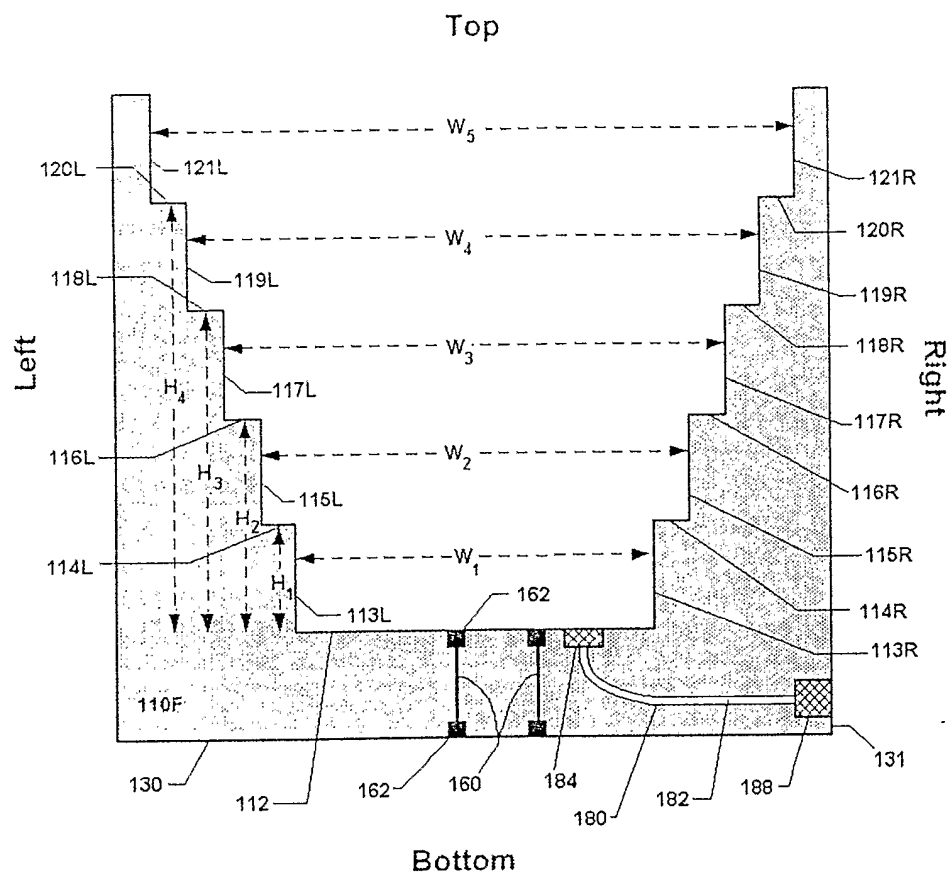


Figure 1 — Steaired supporting wall

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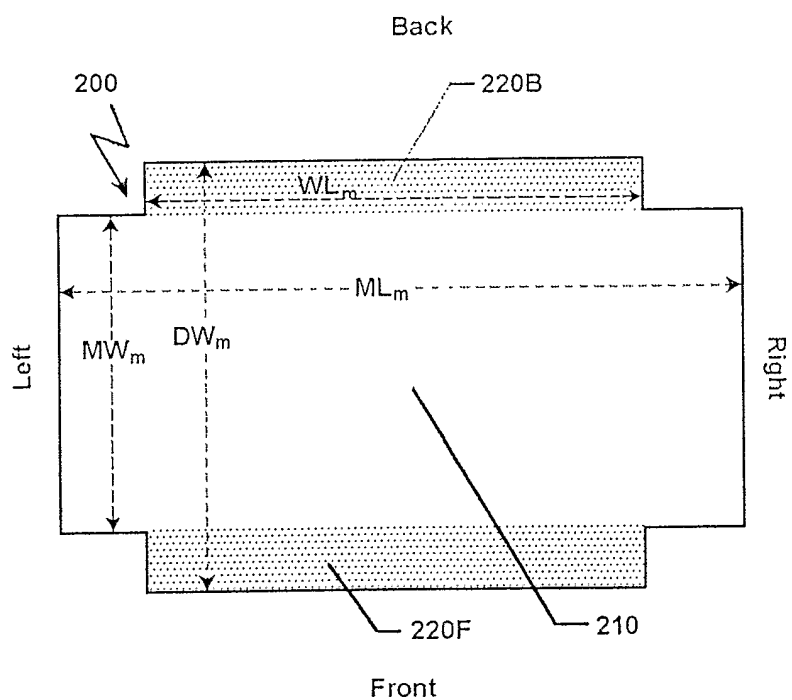


Figure 2 — Plan view of a typical layer of a 3D device with staired supporting walls

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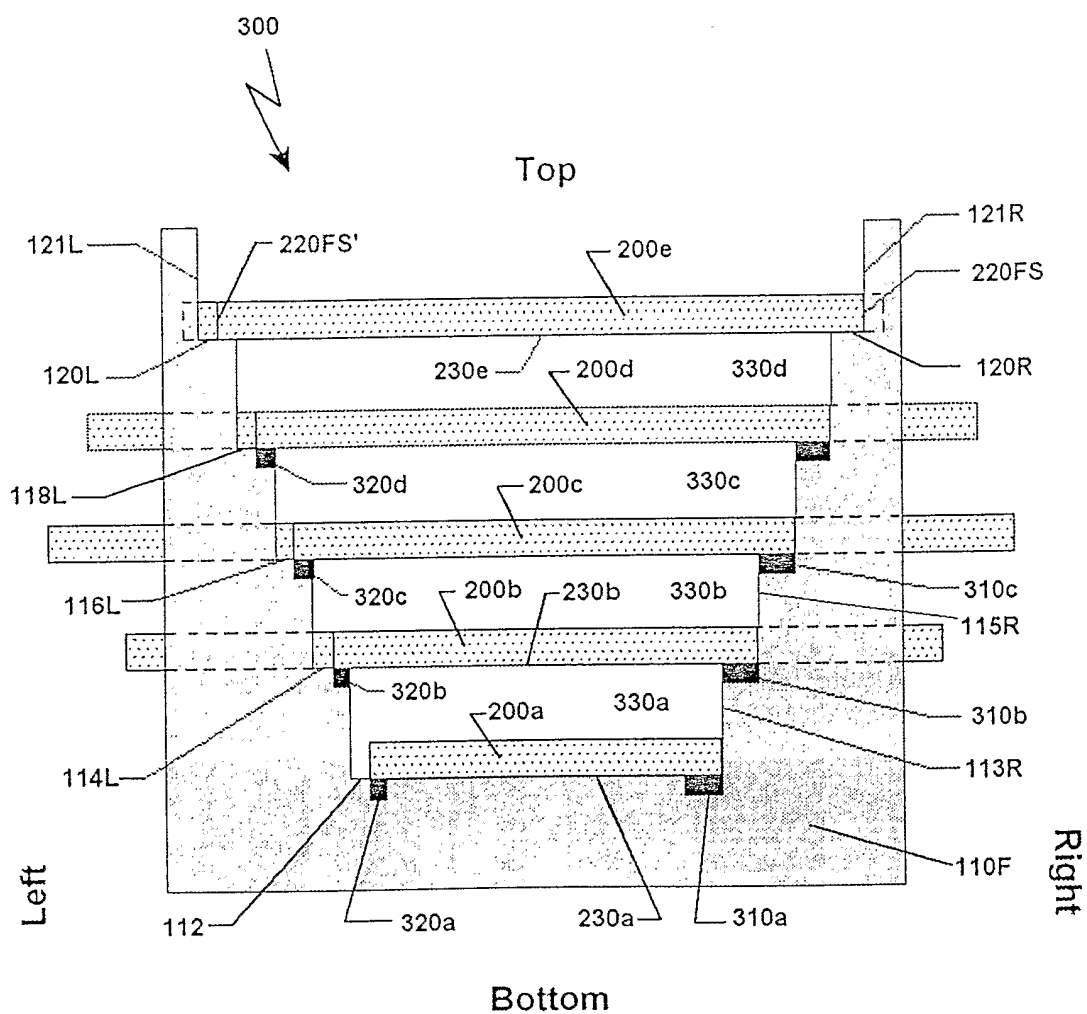


**Figure 3a — Five-layered, staired, 3-D device
– Front view**

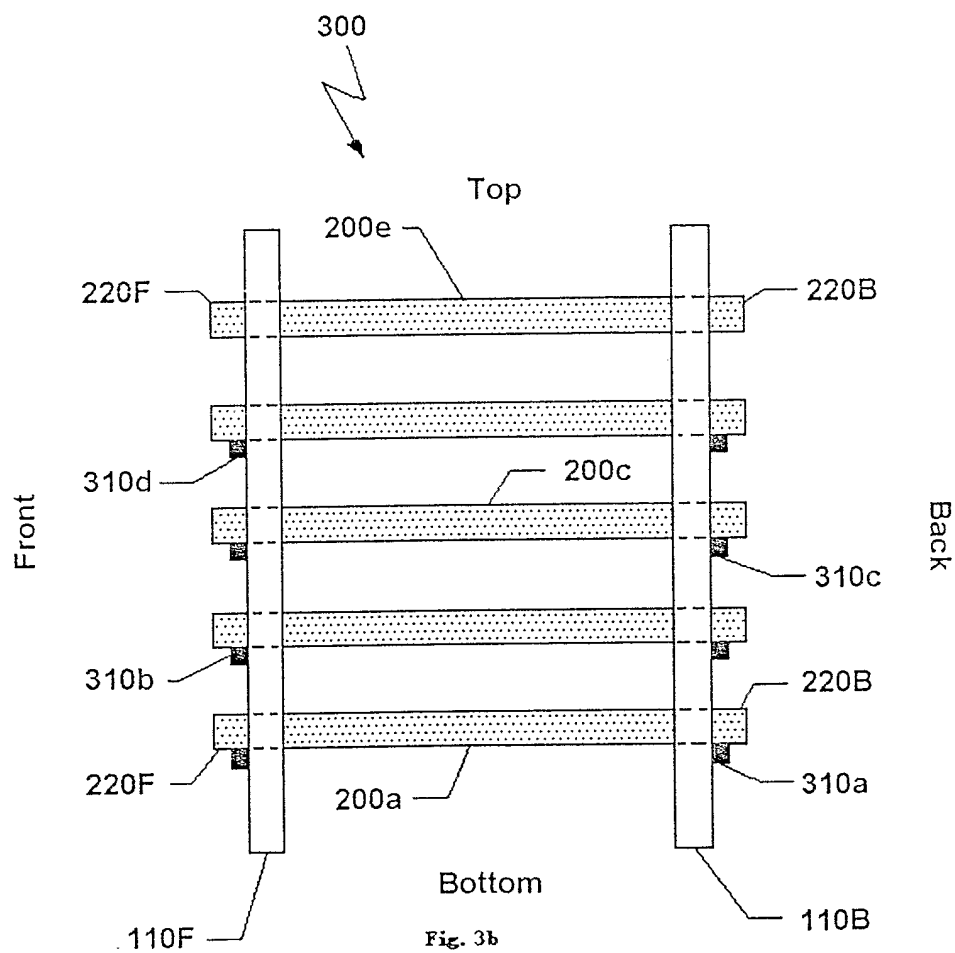


**Figure 3b — Five-layered, staired, 3-D device
– Side view**

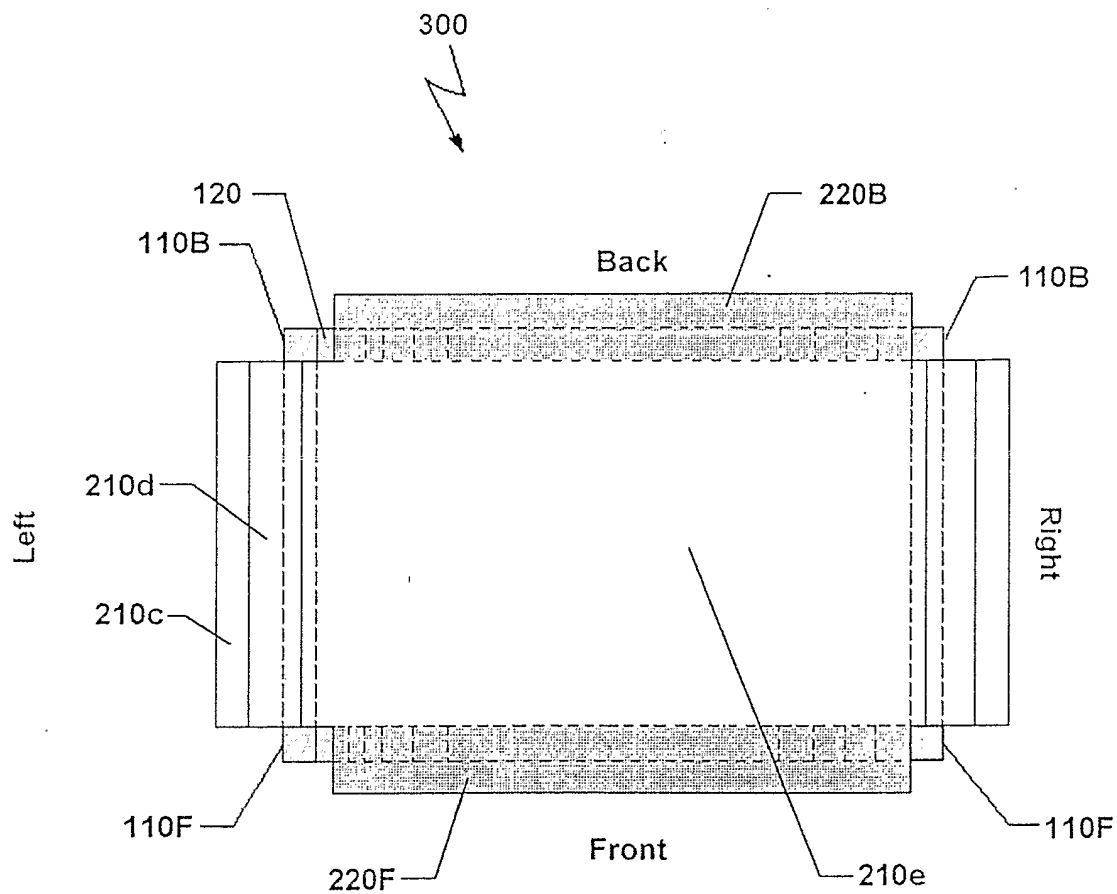


**Figure 3c — Five-layered, staired, 3-D device
— Plan view**

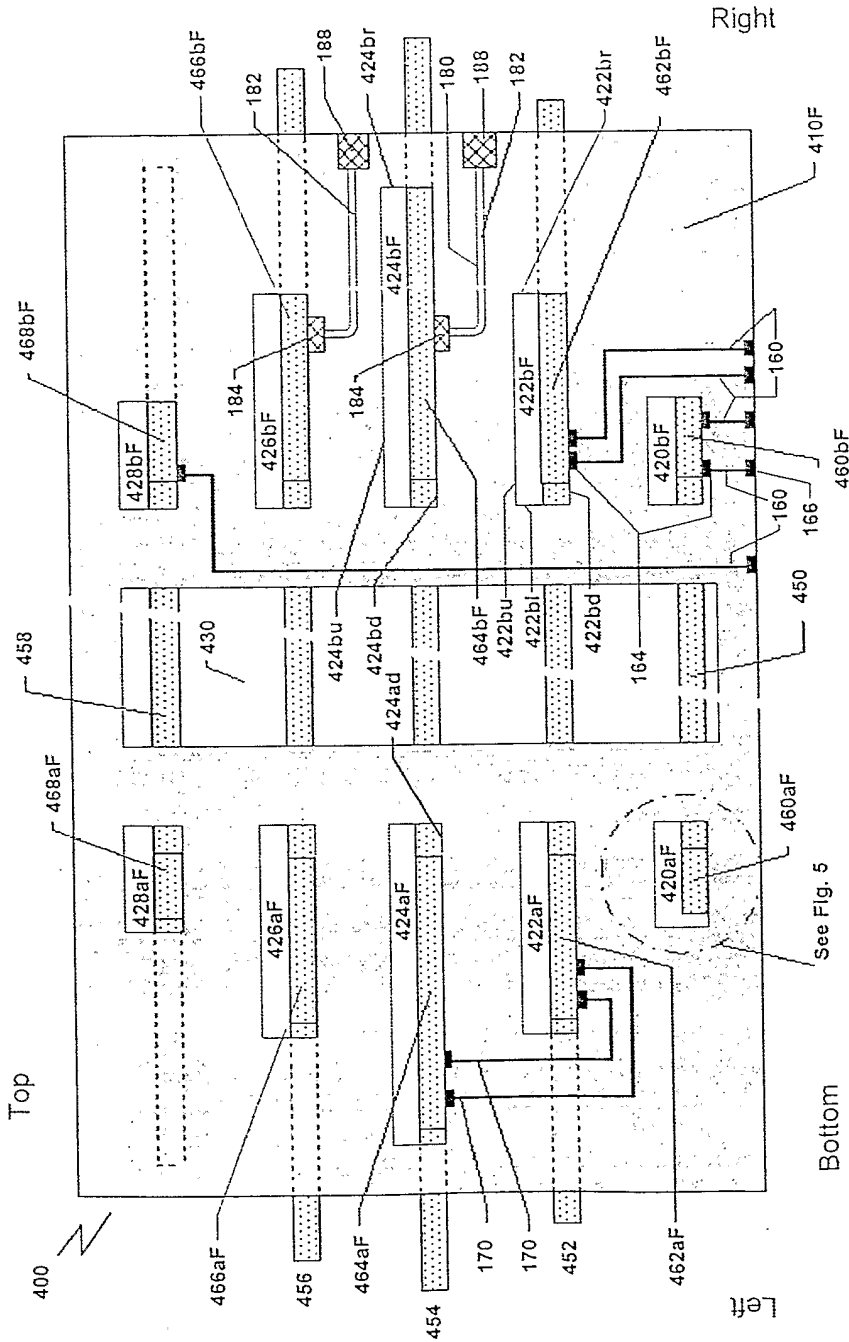


Figure 4a

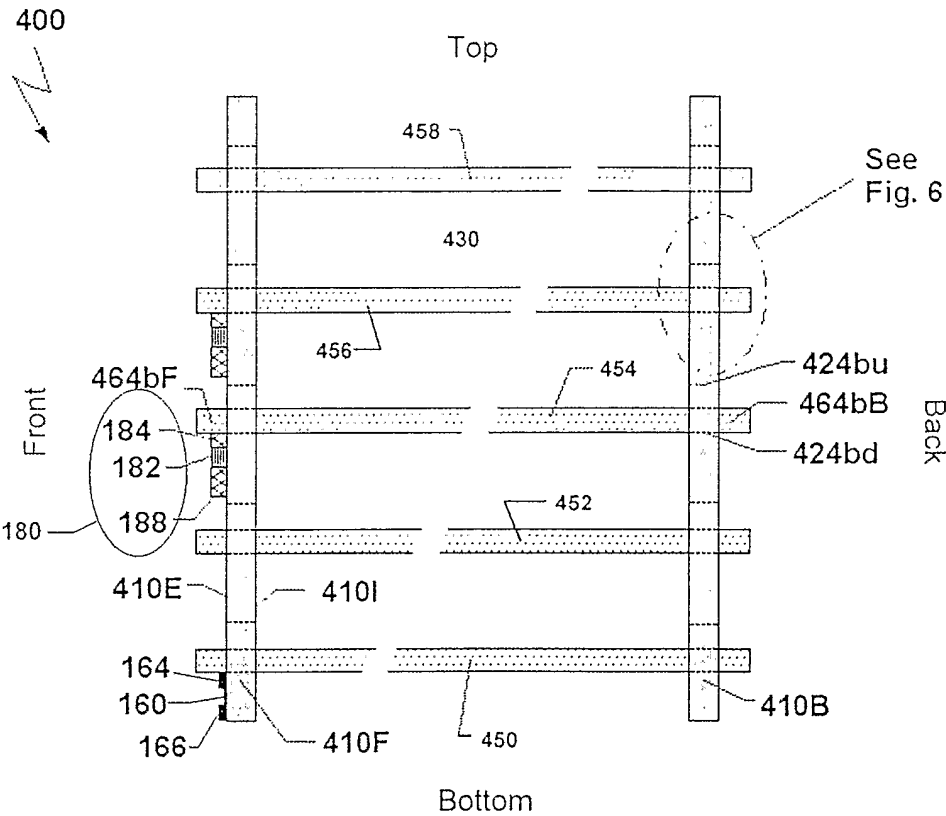
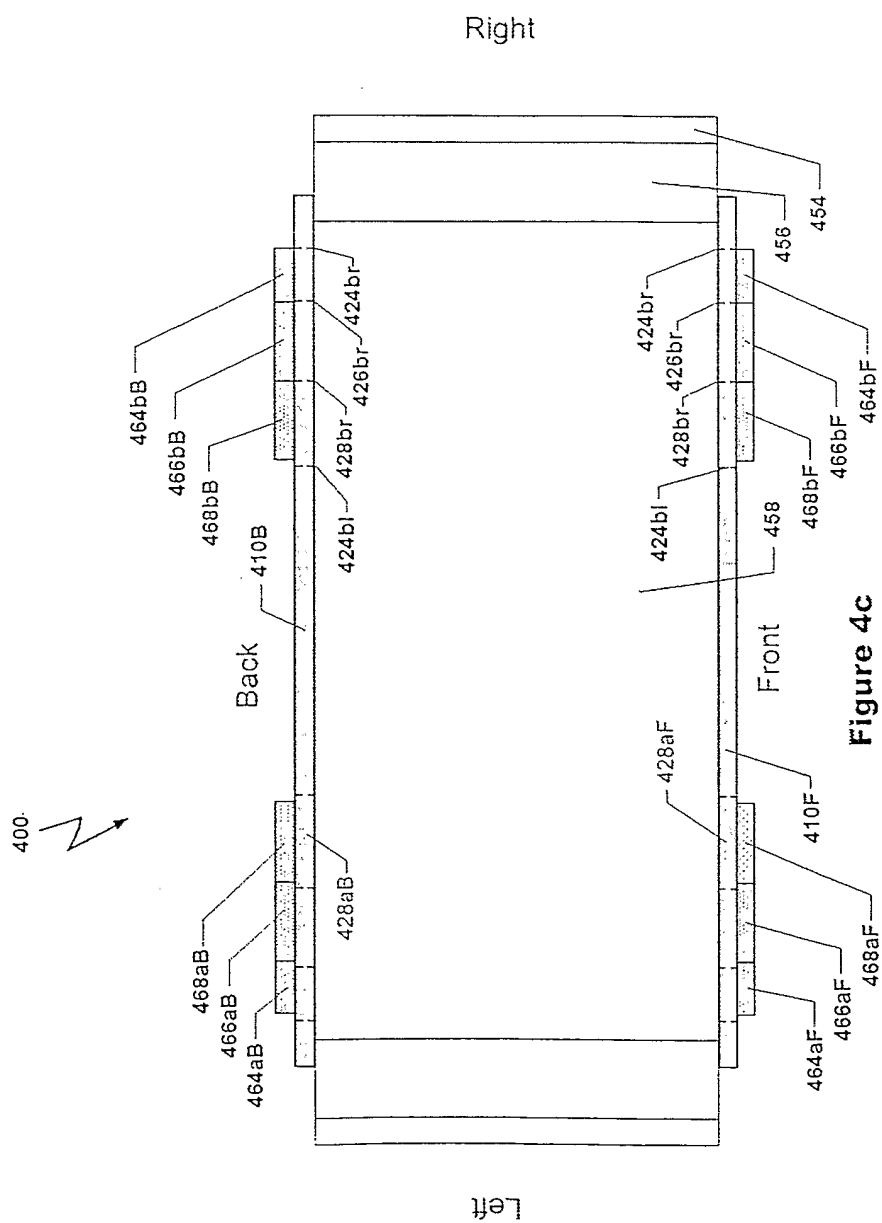


Figure 4b



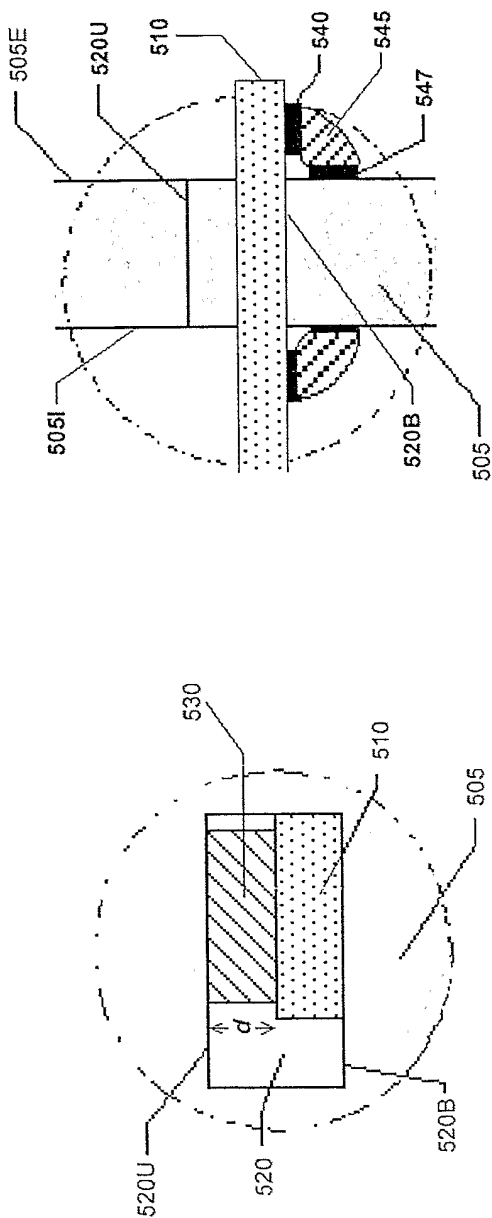


Figure 5b

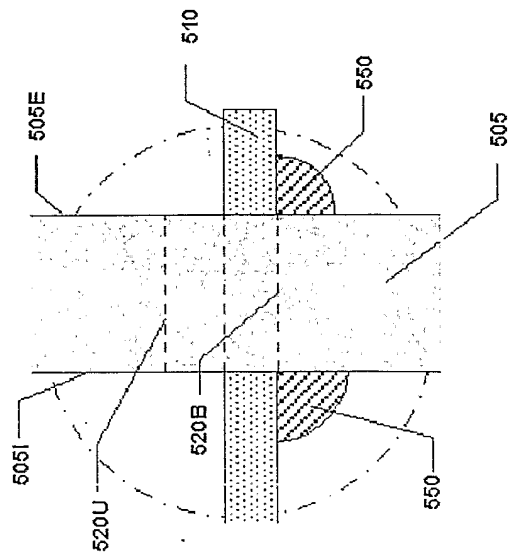
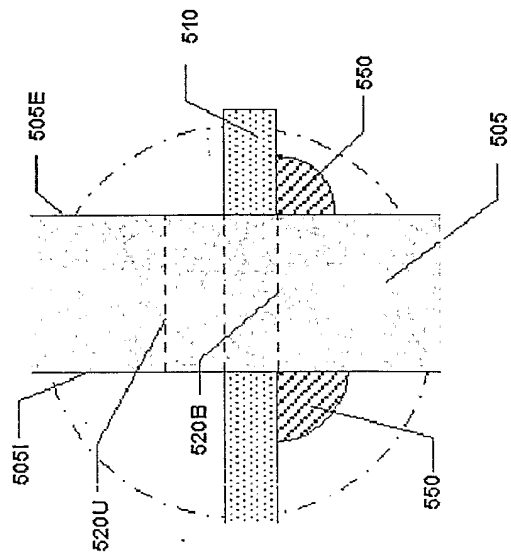


Figure 5a

Figure 5c



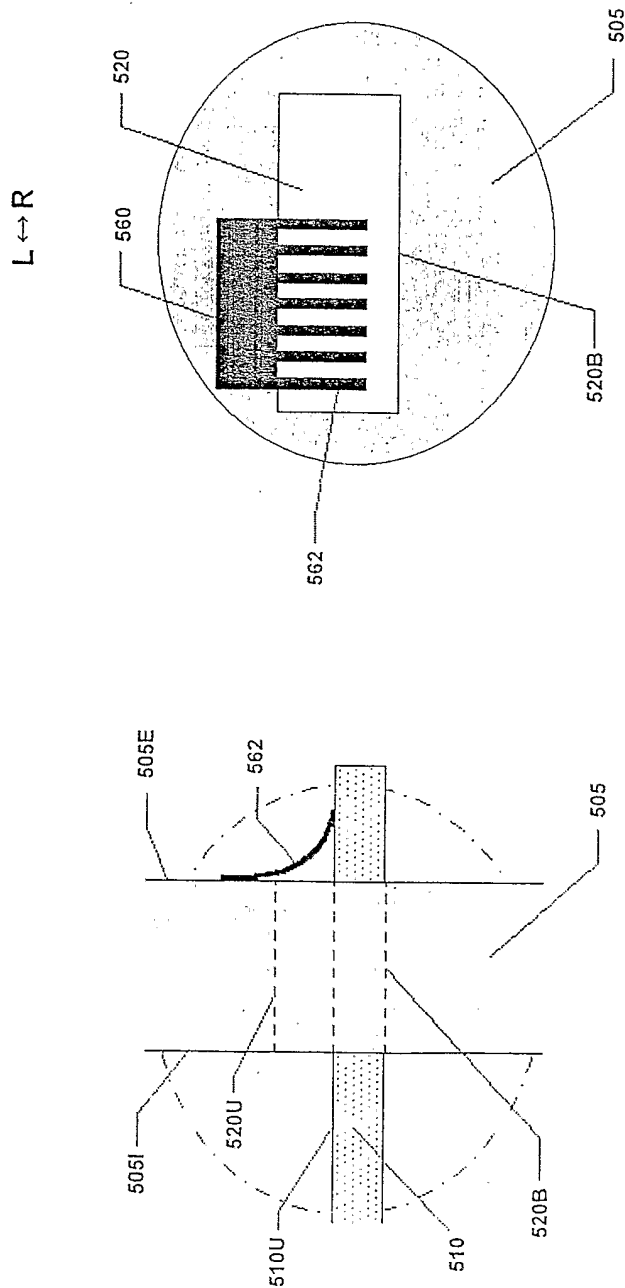


Figure 5e

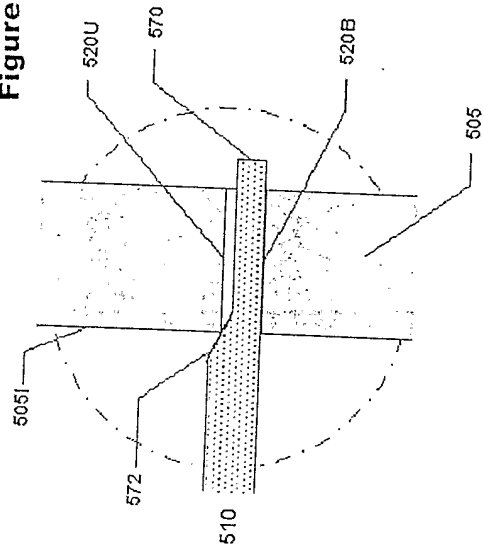
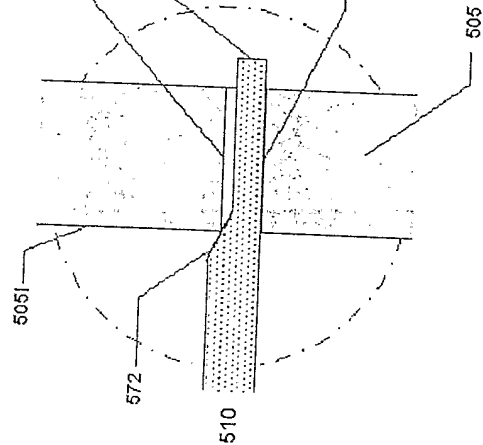


Figure 5d

Figure 5f



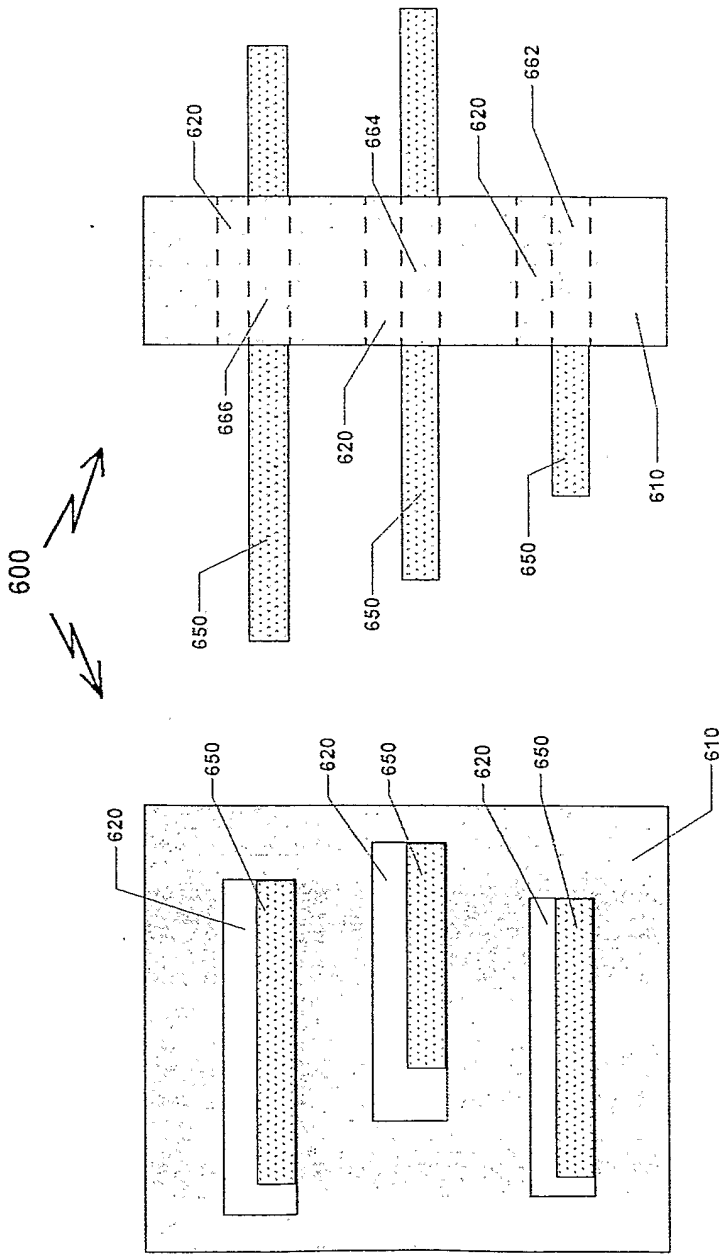
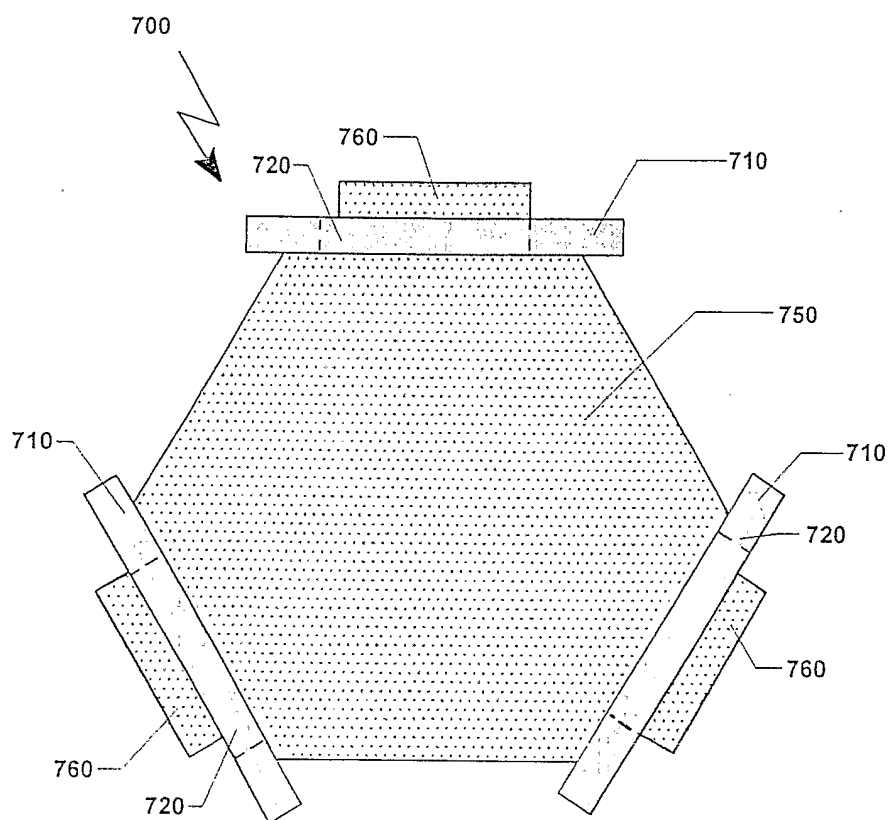


Figure 6b

Figure 6a

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**Figure 7**

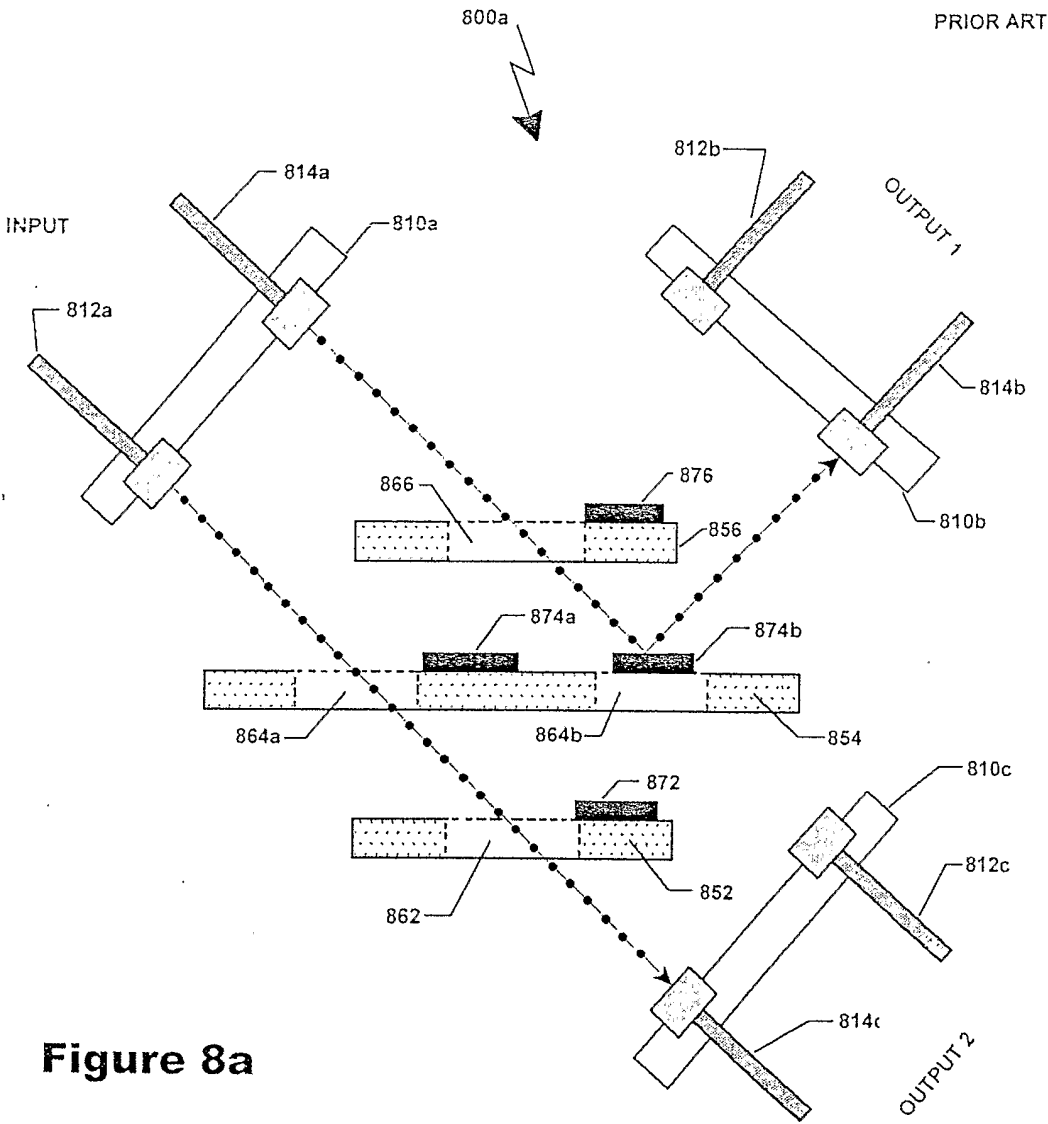


Figure 8a

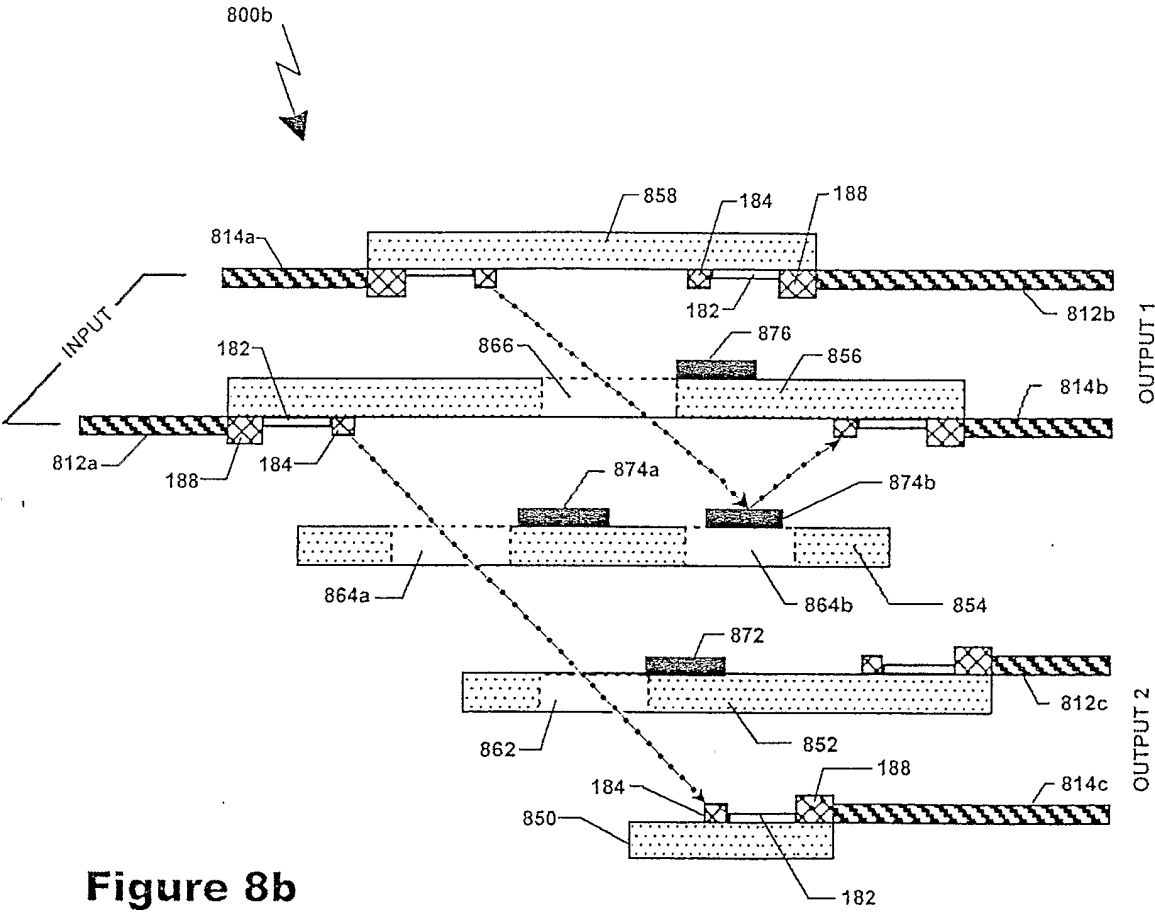


Figure 8b