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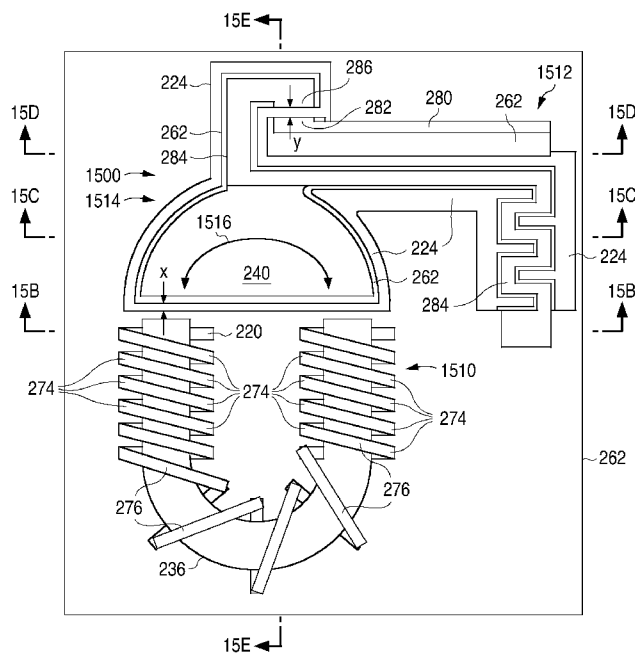


FIG. 15A

(57) Abstract: A micro-electromechanical (MEMS) relay (1500) decouples a flux path from an electrical path through a switch structure (1512) to eliminate signal degradations that result from fluctuations in the magnetic flux. The fluctuations in the magnetic flux are caused by fluctuations in a current through a coil (1510) around a core (236) that occur during magnetic actuation.

## MEMS RELAY

## TECHNICAL FIELD

5           The present invention relates to relays and, more particularly, to a MEMS relay that has a flux path from magnetic actuation that is decoupled from an electrical path through the switch, and a suspension structure that is independent of the core structure, and a method of forming the same.

## 10 BACKGROUND ART

A switch is a well-known device that connects, disconnects, or changes connections between devices. An electrical switch is a switch that provides a low-impedance electrical pathway when the switch is "closed," and a high-impedance electrical pathway when the switch is "opened." A mechanical-electrical switch is a type of switch where the low-impedance electrical pathway is formed by physically bringing two electrical contacts together, and the high-impedance electrical pathway is formed by physically separating the two electrical contacts from each other.

20           An actuator is a well-known mechanical device that moves or controls a mechanical member to move or control another device. Actuators are commonly used with mechanical-electrical switches to move or control a mechanical member that closes and opens the switch, thereby providing the low-impedance and high-impedance electrical pathways, respectively, in response to the actuator.

25           A relay is a combination of a switch and an actuator where the mechanical member in the actuator moves in response to electromagnetic changes in the conditions of an electrical circuit. For example, electromagnetic changes due to the presence or absence of a current in a coil can cause the mechanical member in the actuator to close and open the switch.

One approach to implementing actuators and relays is to use micro-electromechanical (MEMS) technology. MEMS devices are formed using the same

fabrication processes that are used to form conventional semiconductor structures, such as the interconnect structures that provide electrical connectivity to the transistors on a die.

One drawback of conventional MEMS relays is that the flux path that  
5 actuates the device also typically follows the electrical path through the switch. Traditionally, relays are used for power switching, and thus signal attenuation through the switch due to fluctuations in the current around the core and, thereby the flux, has not been a concern.

However, when MEMS relays are passing signals with very small  
10 amplitudes through the switch, fluctuations in the current around the core and, thereby the flux, can lead to an unacceptable degradation of the signal passing through the switch. Thus, there is a need for a MEMS relay that has a flux path that is decoupled from the electrical path through the switch.

Another drawback of conventional MEMS relays is that the suspension  
15 structure is typically formed as part of the core structure. The suspension and core structures, however, commonly have conflicting requirements. The ideal geometry of the core structure is a short flux path with a large cross-sectional area. However, the ideal geometry of the suspension structure is a long path with a small cross-sectional area because this reduces the spring stiffness of the  
20 beam, and thus the force required to close the switch. Thus, there is also a need for a MEMS relay that has a suspension structure that is independent of the core structure.

## DISCLOSURE OF THE INVENTION

25

A micro-electromechanical (MEMS) relay of the present invention decouples a flux path from an electrical path through a switch structure to eliminate signal degradations that result from fluctuations in the magnetic flux. The fluctuations in the magnetic flux are caused by fluctuations in a current through a coil around  
30 a core that occur during magnetic actuation.

The MEMS relay of the present invention includes a core that touches a dielectric structure, and a coil that touches the dielectric structure. The core has a magnetically conductive material. The coil is wrapped around the core. The MEMS relay also includes a switch member that touches the dielectric structure,  
5 and a suspension member that touches the dielectric structure. The suspension member has a magnetically conductive material. No portion of the suspension member touches the core when no current flows through the coil. The suspension member is movable towards the core in response to a current flowing through the coil.

10 A method of forming the MEMS relay of the present invention includes forming a number of spaced-apart lower coil members that form a number of lower horizontal sections of a coil, and forming a lower dielectric layer that touches the spaced-apart lower coil members. The method also includes forming a sacrificial structure that touches the lower dielectric layer, and forming a core, a  
15 switch member, and a suspension member that touch the lower dielectric layer. The suspension member touches the sacrificial layer. No portion of the switch member touches the core.

#### BRIEF DESCRIPTION OF DRAWINGS

20 FIG. 1 is a view illustrating an example of a method 100 of forming a MEMS relay in accordance with the present invention.

FIGS. 2A-15A, 2B-15B, 2C-15C, 2D-15D, and 2E-15E are a series of views that illustrate an example of method 100 in accordance with the present example.

25 FIGS. 2A-15A are plan views. FIGS. 2B-15B are cross-sectional views taken along lines 2B-2B of FIG. 2A through 15B-15B of FIG. 15A, respectively. FIGS. 2C-15C are cross-sectional views taken along lines 2C-2C of FIG. 2A through 15C-15C of FIG. 15A, respectively. FIGS. 2D-15D are cross-sectional views taken along lines 2D-2D of FIG. 2A through 15D-15D of FIG. 15A, respectively. FIGS. 2E-15E are  
30 cross-sectional views taken along lines 2E-2E of FIG. 2A through 15E-15E of FIG. 15A, respectively.

FIGS. 16A-18A, 16B-18B, 16C-18C, 16D-18D, and 16E-18E are a series of views illustrating a first example of an alternate way of implementing element 110 of method 100 in accordance with the present invention. FIGS. 16A-18A are plan views. FIGS. 16B-18B are cross-sectional views taken along lines 16B-16B of FIG. 16A through 18B-18B of FIG. 18A, respectively. FIGS. 16C-18C are cross-sectional views taken along lines 16C-16C of FIG. 16A through 18C-18C of FIG. 18A, respectively. FIGS. 16D-18D are cross-sectional views taken along lines 16D-16D of FIG. 16A through 18D-18D of FIG. 18A, respectively. FIGS. 16E-18E are cross-sectional views taken along lines 16E-16E of FIG. 16A through 18E-18E of FIG. 18A, respectively.

FIGS. 19A-21A, 19B-21B, 19C-21C, 19D-21D, and 19E-21E are a series of views illustrating a second example of an alternate way of implementing element 110 of method 100 in accordance with the present invention. FIGS. 19A-21A are plan views. FIGS. 19B-21B are cross-sectional views taken along lines 19B-19B of FIG. 19A through 21B-21B of FIG. 21A, respectively. FIGS. 19C-21C are cross-sectional views taken along lines 19C-19C of FIG. 19A through 21C-21C of FIG. 21A, respectively. FIGS. 19D-21D are cross-sectional views taken along lines 19D-19D of FIG. 19A through 21D-21D of FIG. 21A, respectively. FIGS. 19E-21E are cross-sectional views taken along lines 19E-19E of FIG. 19A through 21E-21E of FIG. 21A, respectively.

FIGS. 22A-26A, 22B-26B, 22C-26C, 22D-26D, and 22E-26E are a series of views illustrating an example of an alternate way of implementing element 118 of method 100 in accordance with the present invention. FIGS. 22A-26A are plan views. FIGS. 22B-26B are cross-sectional views taken along lines 22B-22B of FIG. 22A through 26B-26B of FIG. 26A, respectively. FIGS. 22C-26C are cross-sectional views taken along lines 22C-22C of FIG. 22A through 26C-26C of FIG. 26A, respectively. FIGS. 22D-26D are cross-sectional views taken along lines 22D-22D of FIG. 22A through 26D-26D of FIG. 26A, respectively. FIGS. 22E-26E are cross-sectional views taken along lines 22E-22E of FIG. 22A through 26E-26E of FIG. 26A, respectively.

FIGS. 27A-27E are a series of views illustrating an example of sacrificial structure 230 and spring member 254 with a different shape in accordance with the present invention.

FIGS. 28A-28E are a series of views illustrating an example of sacrificial structure 230, core 236, intermediate member 246, and spring member 254 with a different shape in accordance with the present invention.

### MODE(S) FOR CARRYING OUT THE INVENTION

As described in greater detail below, the present invention is a MEMS relay, and a method of forming the relay, that has a flux path from magnetic actuation which is decoupled from the electrical path through the switch. In addition, the MEMS relay has a suspension structure that is independent of the core structure.

FIG. 1 shows an example of a method 100 of forming the MEMS relay in accordance with the present invention. As shown in FIG. 1, method 100 begins in 110 by forming a number of spaced-apart lower coil members that form the lower horizontal sections of a to-be-formed coil. In addition, a pair of lower input/output members can optionally be formed at the same time that the lower coil members are formed.

FIGS. 2A-15A, 2B-15B, 2C-15C, 2D-15D, and 2E-15E show a series of views that illustrate an example of method 100 in accordance with the present example. FIGS. 2A-3A, 2B-3B, 2C-3C, 2D-3D, and 2E-3E show a series of views that illustrate an example of method 100 forming a number of spaced-apart lower coil members in accordance with the present invention.

As shown in FIGS. 2A-2E, method 100 utilizes a conventionally formed single-crystal silicon semiconductor wafer 210 that has an overlying base dielectric layer 212. Base dielectric layer 212 can represent a dielectric layer that includes no metal structures, or a dielectric layer that includes metal structures, such as the dielectric layer of a metal interconnect structure.

When formed as the dielectric layer of a metal interconnect structure, base dielectric layer 212 includes levels of metal traces, which are typically aluminum, a

large number of contacts that connect the bottom metal trace to electrically conductive regions on wafer 210, and a large number of inter-metal vias that connect the metal traces in adjacent layers together. Further, selected regions on the top surfaces of the metal traces in the top metal layer function as pads which provide external connection points.

In the present example, base dielectric layer 212 represents the dielectric layer of a metal interconnect structure that also includes pads P1-P4. Pads P1 and P2 are selected regions on the top surfaces of two of the metal traces in the top layer of metal traces that provide electrical connections for a to-be-formed coil, while pads P3 and P4 are selected regions on the top surfaces of the metal traces that provide electrical input/output connections for a to-be-formed switch. (Only pads P1-P4, and not the entire metal interconnect structure, are shown in cross-section for clarity.)

Referring again to FIGS. 2A-2E, method 100 begins by forming a metal layer 214 on the top surface of base dielectric layer 212. In the present example, since base dielectric layer 212 represents the dielectric layer of a metal interconnect structure, metal layer 214 is also formed on the top surfaces of the pads P1-P4.

Metal layer 214 can include, for example, a layer of titanium (e.g., 100Å thick), a layer of titanium nitride (e.g., 200Å thick), a layer of aluminum copper (e.g., 1.2µm thick), a layer of titanium (e.g., 44Å thick), and a layer of titanium nitride (e.g., 250Å thick). Once metal layer 214 has been formed, a lower mask 216 is formed and patterned on the top surface of metal layer 214.

As shown in FIGS. 3A-3E, following the formation and patterning of mask 216, metal layer 214 is etched to remove the exposed regions of metal layer 214 and form a number of spaced-apart lower coil members 220. The lower coil members 220, which have a horseshoe shape, form the lower sides of the to-be-formed coil. Since base dielectric layer 212 represents the dielectric layer of a metal interconnect structure in the present example, the ends of the lower coil members 220 that correspond with the opposite ends of the to-be-formed coil are physically and electrically connected to pads P1 and P2.

In addition, the etch can optionally form a pair of lower input/output members 222 that are physically and electrically connected to the input/output pads P3 and P4. After the lower coil members 220 and the pair of lower input/output members 222 have been formed, mask 216 is removed.

5       Returning to FIG. 1, once the lower coil members and the pair of lower input/output members have been formed, method 100 moves to 112 to form a lower dielectric layer that touches the lower coil members and the pair of input/output members. FIGS. 4A, 4B, 4C, 4D, and 4E show a series of views that illustrate an example of method 100 forming a lower dielectric layer in accordance  
10       with the present invention.

As shown in FIGS. 4A-4E, a lower dielectric layer 224, such as an oxide layer, is formed on base dielectric layer 212, the lower coil members 220, and the pair of lower input/output members 222. For example, lower dielectric layer can be formed by depositing an oxide, and then chemically-mechanically polishing the  
15       oxide to have, for example, a target thickness of, for example, 2000Å, over base dielectric layer 212.

Referring back to FIG. 1, after the lower dielectric layer has been formed, method 100 moves to 114 to form a sacrificial structure that touches the lower dielectric layer. FIGS. 5A-6A, 5B-6B, 5C-6C, 5D-6D, and 5E-6E show a series of  
20       views that illustrate an example of method 100 forming a sacrificial structure in accordance with the present invention.

As shown in FIGS. 5A-5E, once lower dielectric layer 224 has been formed, a sacrificial layer 226 is formed on the top surface of lower dielectric layer 224. For example, a layer of amorphous silicon that has a thickness of, for example,  
25       2000Å, can be formed on the top surface of lower dielectric layer 224. Once sacrificial layer 226 has been formed, a mask 228 is formed and patterned on the top surface of sacrificial layer 226.

As shown in FIGS. 6A-6E, following the formation and patterning of mask 228, sacrificial layer 226 is etched to remove the exposed regions of sacrificial  
30       layer 226 and form a sacrificial structure 230. After sacrificial layer 226 has been etched to form sacrificial structure 230, mask 228 is removed.

Referring again to FIG. 1, after the sacrificial structure has been formed, method 100 moves to 116 to form a core, a switch member, and a suspension member that touch the lower dielectric layer. No portion of the switch member touches the core. FIGS. 7A-9A, 7B-9B, 7C-9C, 7D-9D, and 7E-9E show a series of views that illustrate an example of method 100 forming a core, a switch member, and a suspension member in accordance with the present invention.

As shown in FIGS. 7A-7E, after the formation of sacrificial structure 230, a seed layer 232 is formed on the top surface of lower dielectric layer 224 and sacrificial structure 230. For example, seed layer can be formed by depositing 300Å of titanium, 3000Å of copper, and 300Å of titanium. After seed layer 232 has been formed, a plating mold 234 (shown cross-hatched) is formed and patterned on the top surface of seed layer 232.

Next, following the formation of plating mold 234, as illustrated in FIGS. 8A-8E, the top titanium layer is stripped and a magnetic material, such as an alloy of nickel and iron like permalloy, is deposited by electroplating to a thickness of, for example, 10µm, to form a core 236, a switch member 238, and a suspension member 240.

After this, plating mold 234 is removed, followed by the removal of the underlying regions of seed layer 232. As shown in FIGS. 9A-9E, core 236, which mirrors the shape of the to-be-formed coil, also has a horseshoe shape that lies over the lower coil members 220, while switch member 238 has a contact sidewall 244.

As further shown in FIGS. 9A-9E, suspension member 240 has an intermediate member 246. Intermediate member 246 lies between core 236 and switch member 238, and lies adjacent to the contact sidewall 244 of switch member 238. As a result, intermediate member 246 is separated from core 236 by an actuation gap 250, while intermediate member 246 is separated from the contact sidewall 244 of switch member 238 by a contact gap 252.

Actuation gap 250 can be made to be slightly larger than contact gap 252, thereby ensuring that an electrical connection will always be made when the relay is activated. The sizes of actuation gap 250 and contact gap 252 are defined by

the pattern in plating mold 234. Further, in the present example, intermediate member 246 is also formed to have a half-circle shape, and is oriented towards core 236 to form a racetrack shape. Suspension member 240 also includes a spring member 254. In the present example, as shown in FIGS. 9A-9E, spring member 254 is implemented with a base section 256, which provides the only point where suspension member 240 touches lower dielectric layer 224, and an extension section 260 that, along with intermediate member 246, are spaced apart from dielectric layer 224.

Referring again to FIG. 1, after the core, the switch member, and the suspension member have been formed, method 100 moves to 118 to form tops and sides that touch the lower coil members to form a coil, a conductive first switch trace that sits over the switch member, and a conductive second switch trace that sits over and rides on the suspension member. No portion of the coil is wrapped around the suspension member.

FIGS. 10A-14A, 10B-14B, 10C-14C, 10D-14D, and 10E-14E show a series of views that illustrate an example of method 100 forming tops and sides that touch the lower coil members to form a coil, a conductive first switch trace that sits over the switch member, and a conductive second switch trace that sits over and rides on the suspension member in accordance with the present invention.

As shown in FIGS. 10A-10E, after the formation of core 236, switch member 238, and suspension member 240 have been formed, and after the removal of plating mold 234 and the underlying regions of seed layer 232, an upper dielectric layer 262, such as an oxide layer, is formed on lower dielectric layer 224, core 236, switch member 238, and suspension member 240. For example, upper dielectric layer 262 can be formed by conformally depositing an oxide to a thickness of, for example, 1 $\mu$ m, over lower dielectric layer 224. After upper dielectric layer 262 has been formed, a mask 264, such as a layer of photoresist, is then formed and patterned on the top surface of upper dielectric layer 262.

Following the formation and patterning of mask 264, as shown in FIGS. 11A-11E, the exposed regions of the upper dielectric layer 262 and underlying

lower dielectric layer 224 are etched to form a number of vertical openings 266. The vertical openings 266 include via-type openings that expose the top surfaces of the ends of the lower coil members 220 that form the lower sides of the to-be-formed coil. The vertical openings 266 also expose the pair of lower input/output members 222. In addition, the vertical openings 266 also form a trench that extends from base section 256 around suspension member 240 and back again to base section 256.

In accordance with the present invention, the exposed regions of sacrificial structure 230 are not to be removed during this etch. As a result, vertical openings 266 are formed with an etchant that is highly selective to the material used to form sacrificial structure 230. In addition, sacrificial structure 230, which was formed to have the same thickness as lower dielectric layer 224, can also be formed to be thicker than lower dielectric layer 224 to ensure that a significant portion of the exposed regions of sacrificial structure 230 remain after the etch. Following the etch, mask 264 is then removed.

Once mask 264 has been removed, as shown in FIGS. 12A-12E, a seed layer 270 is formed on the exposed ends of the lower coil members 220, the exposed input/output members 222, lower dielectric layer 224, sacrificial structure 230, and the top surface of upper dielectric layer 262. For example, seed layer can be formed by depositing 300Å of titanium, 3000Å of copper, and 300Å of titanium. After seed layer 270 has been formed, a plating mold 272 (shown cross-hatched) is formed and patterned on the top surface of seed layer 270. The pattern in plating mold 272 is shown hatched in FIG. 12A.

Next, as shown in FIGS. 13A-13E, following the formation and patterning of plating mold 272, the top titanium layer is stripped and copper is deposited by electroplating to form a number of copper side sections 274 of the coil, and a number of copper upper sections 276 of the coil. In addition, the electroplating also forms a first switch trace 280 with a sidewall contact 282, and a second switch trace 284 with a sidewall contact 286. The first and second switch traces 280 and 284 also touch the input/output members 222 to make an electrical connection. As further shown in FIGS. 13A-13E, lower coil member 220-1, side

section 274-1, and upper section 276-1 form three sides of one coil loop. Following this, as shown in FIGS. 14A-14E, plating mold 272 and the underlying regions of seed layer 270 are removed.

Referring again to FIG. 1, after the coil, the conductive first switch trace, and the conductive second switch trace have been formed, method 100 moves to 120 to remove the sacrificial structure so that the suspension member moves in response to changes in a current flowing through the coil.

In other words, the conductive second switch trace makes and breaks electrical contact with the first conductive switch trace as the suspension member moves in response to changes in a current flowing through the coil. In addition, a magnetic flux passes through a portion of the suspension member and substantially no magnetic flux passes through the first and the second conductive switch traces when a current flows through the coil.

FIGS. 15A-15E show a series of views that illustrate an example of method 100 removing sacrificial structure 230 in accordance with the present invention. As shown in FIGS. 15A-15E, after the coil, first switch trace 280, and second switch trace 284 have been formed, sacrificial structure 230 is removed. The removal of sacrificial structure 230 leaves intermediate member 246 and extension section 260 of spring member 254 floating. For example, in the example shown in FIGS. 15A-15E, intermediate member 246 and extension section 260 each float, connected to lower dielectric layer 224 only via base section 256.

Floating extension section 260 was vertically spaced apart from lower dielectric layer 224 by underlying sacrificial structure 230, and thereby floats after underlying sacrificial structure 230 has been removed. As a result, the thickness of sacrificial structure 230 determines an offset gap 290, which is the vertical spacing that lies between lower dielectric layer 224 and floating extension section 260.

Thus, as shown in FIGS. 15A-15E, the method of the present invention forms a MEMS relay 1500 that includes core 236 and a coil 1510 that is wrapped around core 236. Coil 1510 can be implemented with the lower coil members

220, the copper side sections 274, and the copper upper sections 276. In addition, both core 236 and coil 1510 touch lower dielectric layer 224.

As further shown in FIGS. 15A-15E, MEMS relay 1500 also includes a switch structure 1512 and a suspension structure 1514. Switch structure 1512  
5 can be implemented with switch member 238, which touches lower dielectric layer 224, and upper dielectric layer 262. Suspension structure 1514 can be implemented with suspension member 240, which touches lower dielectric layer 224, and upper dielectric layer 262. Further, no portion of coil 1510 is wrapped around suspension structure 1514.

10 As additionally shown in FIGS. 15A-15E, MEMS relay 1500 includes first switch trace 280 that touches and extends along switch structure 1512, and second switch trace 284 that touches and extends along suspension structure 1514. Further, first switch trace 280 has a first sidewall contact 282, and second switch trace 284 has a second sidewall contact 286.

15 In operation, when no current is present in coil 1510, suspension structure 1514 lies in a rest position as shown in FIG. 15A. In addition, suspension structure 1514 and core 236 are spaced apart by a minimum distance  $X$  when no current is present in coil 1510, while first sidewall contact 282 and second sidewall contact 286 are spaced apart by a minimum distance  $Y$  when no current  
20 is present in coil 1510 that is equal to or less than the minimum distance  $X$ . The minimum distance  $Y$ , in turn, provides a high-impedance electrical pathway.

Thus, one of the advantages of MEMS relay 1500 is that suspension structure 1514 is independent of core 236 (i.e., no portion of suspension structure 1514 touches core 236 when no current flows through coil 1514). Thus, the  
25 suspension structure 1514 can be optimized to reduce the stiffness of the spring while core 236 can be optimized for a short flux path.

On the other hand, when a current flows through coil 1510 and generates an electromagnetic field that is stronger than the spring force of suspension structure 1514, suspension structure 1514 moves towards core 236 so that the  
30 first and second sidewall contacts 282 and 286 touch, thereby providing a low-impedance electrical pathway.

Thus, the second sidewall contact 286 of second switch trace 284 moves towards and touches the first sidewall contact 282 of first switch trace 280 when a current flows through coil 1510, and moves away from the first sidewall contact 282 of first switch trace 280 when no current flows through coil 1510. Thus, no  
5 portion of suspension structure 1514 touches core 236 when no current flows through coil 1510.

Further, as shown in FIG. 15A, in accordance with the present invention, a magnetic flux 1516 passes through a portion of suspension member 240 when a current flows through coil 1510, while and substantially no magnetic flux passes  
10 through the first and the second switch traces 280 and 284 when a current flows through coil 1510. Thus, one of the advantages of the present invention is that MEMS relay 1500 is insensitive to fluctuations in the current around the core and, thereby the flux. As a result, signals with very small amplitudes can pass through relay 1500 with no flux-based distortion.

15 Thus, a method of forming a MEMS relay in accordance with the present invention has been described. The elements shown in FIG. 1 can be implemented in a number of different ways. For example, the spaced-apart lower coil members that form the lower horizontal sections of the coil described in element 110 of FIG. 1 can be alternately formed.

20 FIGS. 16A-18A, 16B-18B, 16C-18C, 16D-18D, and 16E-18E show a series of views that illustrate a first example of an alternate way of implementing element 110 of method 100, which forms a number of spaced-apart lower coil members of the to-be-formed coil, in accordance with the present invention.

As with the example shown in FIGS. 2A-3E, the example shown in FIGS.  
25 16A-18E also utilizes single-crystal silicon semiconductor wafer 210 with overlying base dielectric layer 212. The FIGS. 16A-18E example begins by forming a seed layer 1610 on base dielectric layer 212 and the pads P1-P4 which are exposed via openings in base dielectric layer 212.

Once seed layer 1610 has been formed, a plating mold 1612 is formed on  
30 the top surface of seed layer 1610. As shown in FIGS. 17A-17E, following the formation of plating mold 1612, copper is deposited by electroplating to form the

number of spaced-apart lower coil members 220 and the pair of lower input/output members 222.

As shown in FIGS. 18A-18E, after the lower coil members 220 and the pair of lower input/output members 222 have been formed, plating mold 1612 is removed, followed by the removal of the underlying regions of seed layer 1610. As shown, the structure illustrated in FIGS. 18A-18E is similar to the structure shown in FIGS. 3A-3E.

FIGS. 19A-21A, 19B-21B, 19C-21C, 19D-21D, and 19E-21E show a series of views that illustrate a second example of an alternate way of implementing element 110 of method 100, which forms a number of spaced-apart lower coil members of the to-be-formed coil, in accordance with the present invention.

As with the example shown in FIGS. 2A-3E, the example shown in FIGS. 19A-21E also utilizes single-crystal silicon semiconductor wafer 210 with overlying base dielectric layer 212. The FIGS. 19A-21E example begins by forming a mask 1910 on the top surface of base dielectric layer 212. Following this, the exposed regions of base dielectric layer 212 are etched to form a number of spaced-apart trenches 1912, which will define the spaced-apart lower coil members of the to-be-formed coil, in the top surface of base dielectric layer 212. One of the trenches 1912 exposes pad P1, while another of the trenches 1912 exposes pad P2. In addition, the etch also forms a pair of openings 1914 in base dielectric layer 212 that expose the pair of pads P3 and P4.

Following the etch, as shown in FIGS. 20A-20E, with mask 1910 in place, a copper structure 1916 is formed in the trenches 1912 and the openings 1914 on the exposed regions of base dielectric layer 212, pads P1-P4, and mask 1910. Copper structure 1916 can be formed by, for example, evaporating, in sequence, 300Å of titanium, 1µm copper, and 300Å of titanium.

Next, as shown in FIGS. 21A-21E, after copper structure 1916 has been formed, mask 1910 is stripped which, in turn, lifts off the overlying layer of copper structure 1916. The removal of mask 1910 leaves the copper structure 1916 only on base dielectric layer 212, thereby forming the number of spaced-apart lower coil members 220 and the pair of lower input/output members 222.

As shown, other than being recessed, the structure illustrated in FIGS. 21A-21E is similar to the structure shown in FIGS. 3A-3E.

FIGS. 22A-26A, 22B-26B, 22C-26C, 22D-26D, and 22E-26E show a series of views that illustrate an example of an alternate way of implementing element 118 of method 100, which forms the tops and the sides of the to-be-formed coil and the traces for the switch, in accordance with the present invention.

The FIGS. 22A-26E example is the same as the FIGS. 2A-15E example up through the formation of seed layer 270, and differs by forming a plating mold 2210 on the top surface of seed layer 270 in lieu of plating mold 272. Plating mold 2210 differs from plating mold 272 in that plating mold 2210 prevents the first and second sidewall contacts 282 and 286 from being formed from the to-be-formed copper. The pattern in mold 2210 is shown hatched in FIG. 22A.

Next, following the formation of mold 2210, copper is deposited by electroplating to form the number of copper side sections 274 of the coil, and the number of copper upper sections 276 of the coil. In addition, the electroplating also forms a first switch trace 2212, which is the same as switch trace 280 except that there is no sidewall contact 282, and a second switch trace 2214, which is the same as switch trace 284 except that there is no sidewall contact 286. Following this, as shown in FIGS. 23A-23E, mold 2210 and the underlying regions of seed layer 270 are removed.

Following this, as shown in FIGS. 24A-24E, a mask 2216 is formed and patterned on upper dielectric layer 262, the copper upper sections 276, first switch trace 2212, and second switch trace 2214. Once mask 2216 has been formed and patterned, a conductive layer 2220, such as a layer of titanium, nickel, or chrome, and an overlying layer of gold, is deposited on the exposed regions of upper dielectric layer 262 that surround switch member 238, the exposed regions of upper dielectric layer 262 that surround suspension member 240, the exposed regions of sacrificial structure 230, and mask 2216. When sputtered, titanium, nickel, chrome, and gold provide good coverage on the high-aspect ratio (vertical) sidewalls of the switch member 238 and suspension

member 240 that face each other. Titanium, nickel, and chrome, in turn, improve the adhesion of gold.

As shown in FIGS. 25A-25E, after conductive layer 2220 has been formed, mask 2216 is stripped which, in turn, lifts off the overlying layer of conductive layer 2220. The removal of mask 2216 leaves the conductive layer 2220 on the sidewalls of upper dielectric layer 262 over switch member 238 and first switch trace 2212, and the sidewalls of upper dielectric layer 262 over suspension member 240 and second switch trace 2214, thereby forming a sidewall contact 2222 of first switch trace 2212 and a sidewall contact of 2224 of second switch trace 2214 that faces sidewall contact 2222.

Following this, as shown in FIGS. 26A-26E, sacrificial structure 230 is removed. The removal of sacrificial structure 230 leaves intermediate member 246 and extension section 260 of spring member 254 floating as before, but with gold contacts.

In addition to the above, the structures can be formed to have different shapes. For example, mask 228 can be formed to have different shapes so that sacrificial structure 230 has different shapes. In addition, plating mold 234 can be formed to have different shapes that correspond with the shapes of sacrificial structure 230 so that core 236, switch member 238, and suspension member 240 have different shapes.

For example, FIGS. 27A-27E show a series of views that illustrate an example of sacrificial structure 230 and spring member 254 with a different shape in accordance with the present invention. In the FIGS. 27A-27E example, spring member 254 is formed with a pair of facing structures that each include a base section 256 and a C-shaped extension section 260.

Further, FIGS. 28A-28E show a series of views that illustrate an example of sacrificial structure 230, core 236, intermediate member 246, and spring member 254 with a different shape in accordance with the present invention. In the FIGS. 28A-28E example, core 236 is formed as a nearly complete doughnut shape, while intermediate member 246 is formed with a wedge or pie shape that fits into the opening in the nearly complete doughnut shape. In addition, spring member 254

is also formed with a pair of facing structures that each include base section 256 and a C-shaped section 260.

As noted above, dielectric layer 212 can represent a dielectric layer that is free of metal structures. When free of metal structures, the electrical connections to coil 1510 can be made, for example, by wire bonding to points on the copper upper sections 276 that represent opposite ends of coil 1510. In addition, connections to the first and second switch traces 280 and 284 can be made, for example, by wire bonding. Another of the advantages of the present invention is that the present invention requires relatively low processing temperatures. As a result, the present invention is compatible with conventional backend CMOS processes.

It should be understood that the above descriptions are examples of the present invention, and that various alternatives of the invention described herein may be employed in practicing the invention. For example, the various seed layers can be implemented as copper seed layers, or as tungsten, chrome, or combination seed layers as need to provide the correct ohmic and mechanical (peel) characteristics. In addition, a double throw switch can be easily fabricated by using two MEMS relays 1500 which are positioned as mirror images of each other. Thus, it is intended that the following claims define the scope of the invention and that structures and methods within the scope of these claims and their equivalents be covered thereby.

## WHAT IS CLAIMED IS:

1. A micro-electromechanical (MEMS) relay comprising:  
a core that touches a dielectric structure, the core having a magnetically  
5 conductive material;  
a coil that touches the dielectric structure, the coil being wrapped around  
the core;  
a switch member that touches the dielectric structure; and  
a suspension member that touches the dielectric structure, the suspension  
10 member having a magnetically conductive material, no portion of the suspension  
member touching the core when no current flows through the coil, the suspension  
member being movable towards the core in response to a current flowing through  
the coil.
- 15 2. The MEMS relay of claim 1 and further comprising:  
a first conductive trace that touches the switch member; and  
a second conductive trace that touches the suspension member.
- 20 3. The MEMS relay of claim 2 wherein the second conductive trace  
makes and breaks electrical contact with the first conductive trace as the  
suspension member moves in response to changes in a current flowing through  
the coil.
- 25 4. The MEMS relay of claim 3 wherein a magnetic flux passes through  
a portion of the suspension member and substantially no magnetic flux passes  
through the first and the second conductive traces when a current flows through  
the coil.
- 30 5. The MEMS relay of claim 2 wherein the first conductive trace has a  
first contact surface and the second conductive trace has a second contact  
surface.

6. The MEMS relay of claim 5 wherein the second contact surface of the second conductive trace moves towards and touches the first contact surface of the first conductive trace when a current flows through the coil, and moves  
5 away from the first contact surface of the first conductive trace when no current flows through the coil.

7. The MEMS relay of claim 6 wherein a magnetic flux passes through a portion of the suspension member and substantially no magnetic flux passes  
10 through the first and the second conductive traces when a current flows through the coil.

8. The MEMS relay of claim 7 wherein the suspension member and the core have a first minimum separation distance when no current flows through the  
15 coil, and the first contact surface of the first conductive trace and the second contact surface of the second conductive trace have a second minimum separation distance when no current flows through the coil that is equal to or less than the first maximum separation distance.

20 9. The MEMS relay of claim 6 wherein the core has a U shape.

10. The MEMS relay of claim 6 wherein no portion of the coil is wrapped around the suspension member.

11. A method of forming a micro-electromechanical (MEMS) relay comprising:

forming a number of spaced-apart lower coil members that form a number of lower horizontal sections of a coil;

5 forming a lower dielectric layer that touches the spaced-apart lower coil members;

forming a sacrificial structure that touches the lower dielectric layer;

forming a core, a switch member, and a suspension member that touch the lower dielectric layer, the suspension member touching the sacrificial layer, no  
10 portion of the switch member touching the core.

12. The method of claim 11 and further comprising forming tops and sides that touch the lower coil members to form a coil, a first conductive trace that sits over the switch member, and a second conductive trace that sits over  
15 and rides on the suspension member, no portion of the coil being wrapped around the suspension member.

13. The method of claim 12 and further comprising removing the sacrificial structure after the coil, the first conductive trace, and the second  
20 conductive trace have been formed so that the suspension member moves in response to changes in a current flowing through the coil.

14. The method of claim 13 wherein the second conductive trace makes and breaks electrical contact with the first conductive trace as the suspension  
25 member moves in response to changes in a current flowing through the coil.

15. The method of claim 14 wherein a magnetic flux passes through a portion of the suspension member and substantially no magnetic flux passes through the first and the second conductive traces when a current flows through  
30 the coil.

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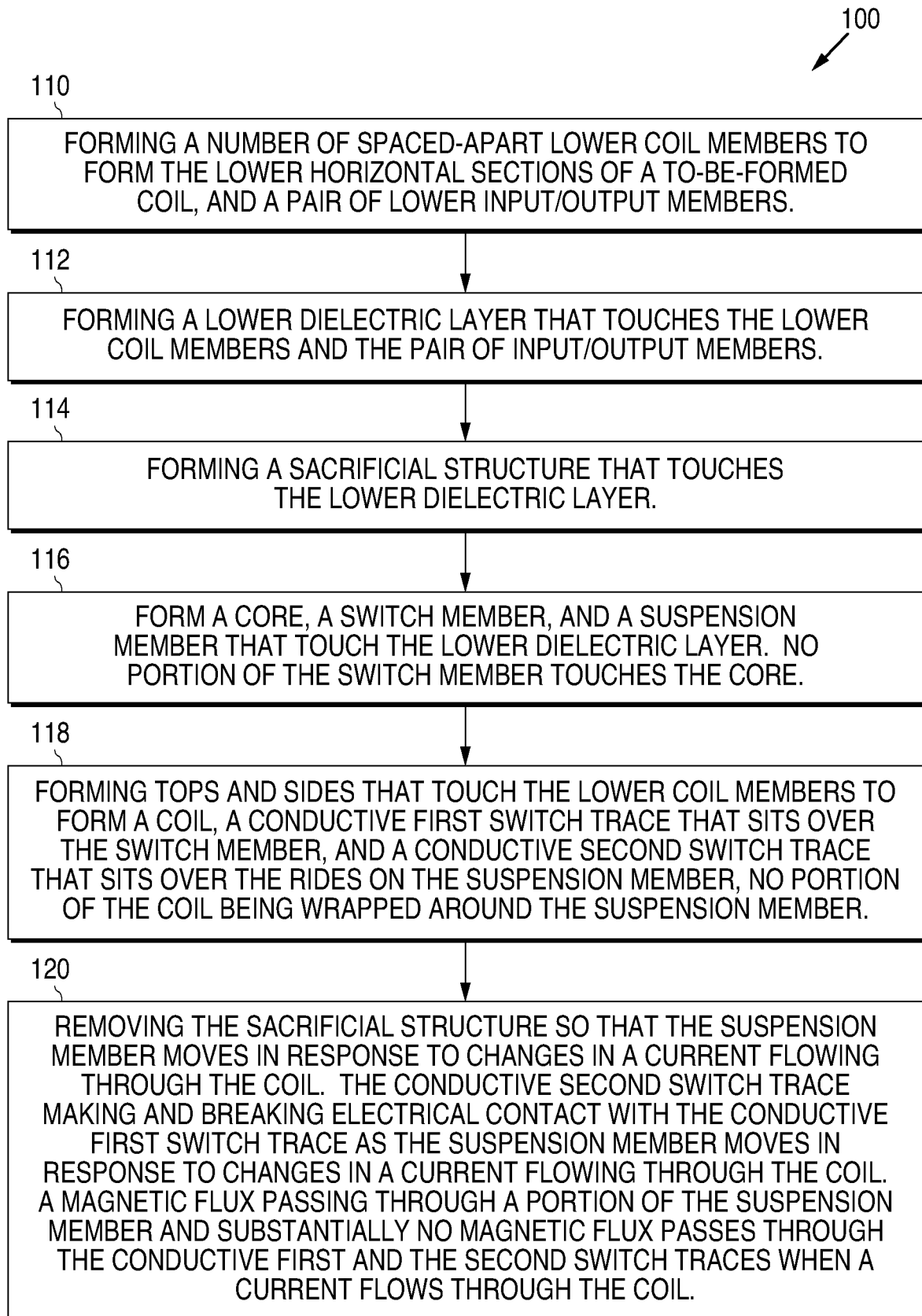


FIG. 1

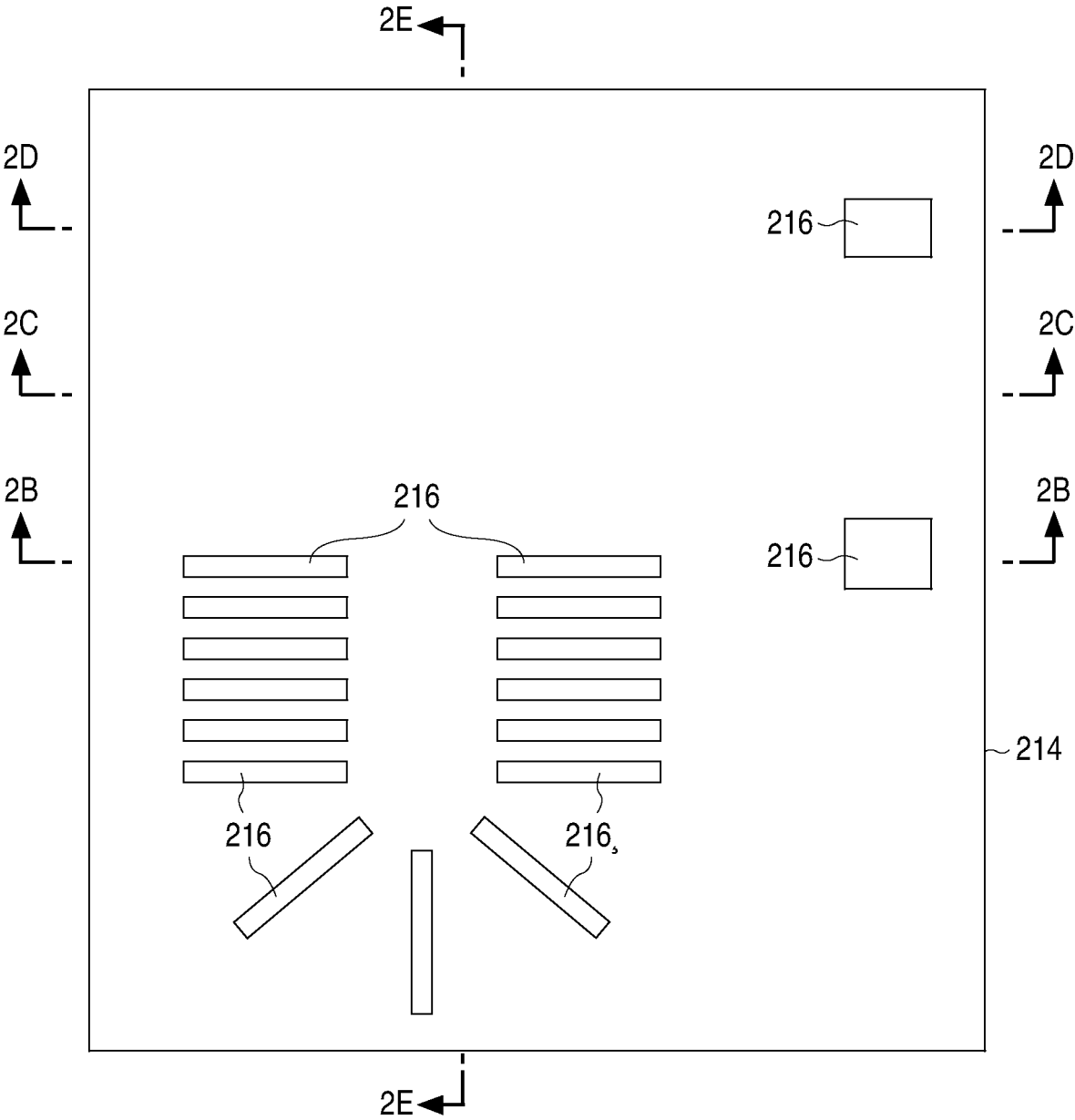


FIG. 2A

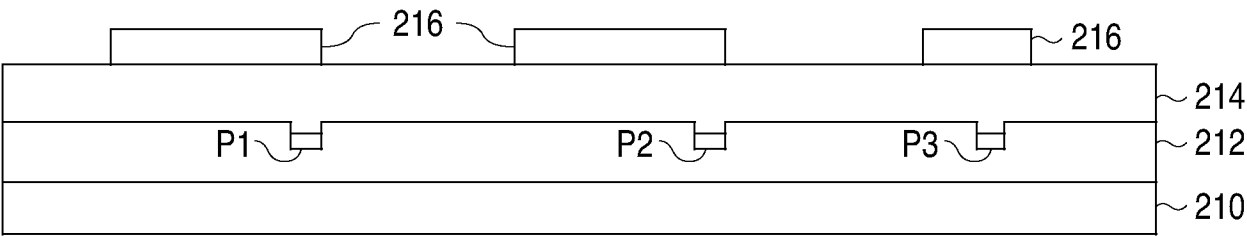


FIG. 2B

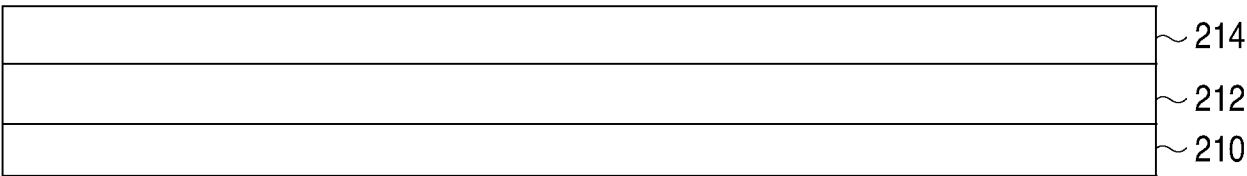


FIG. 2C

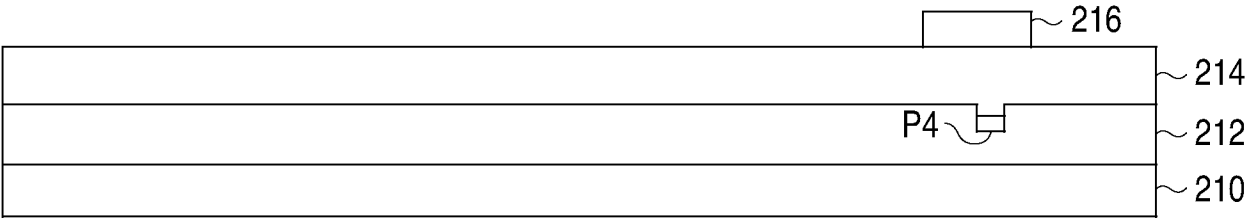
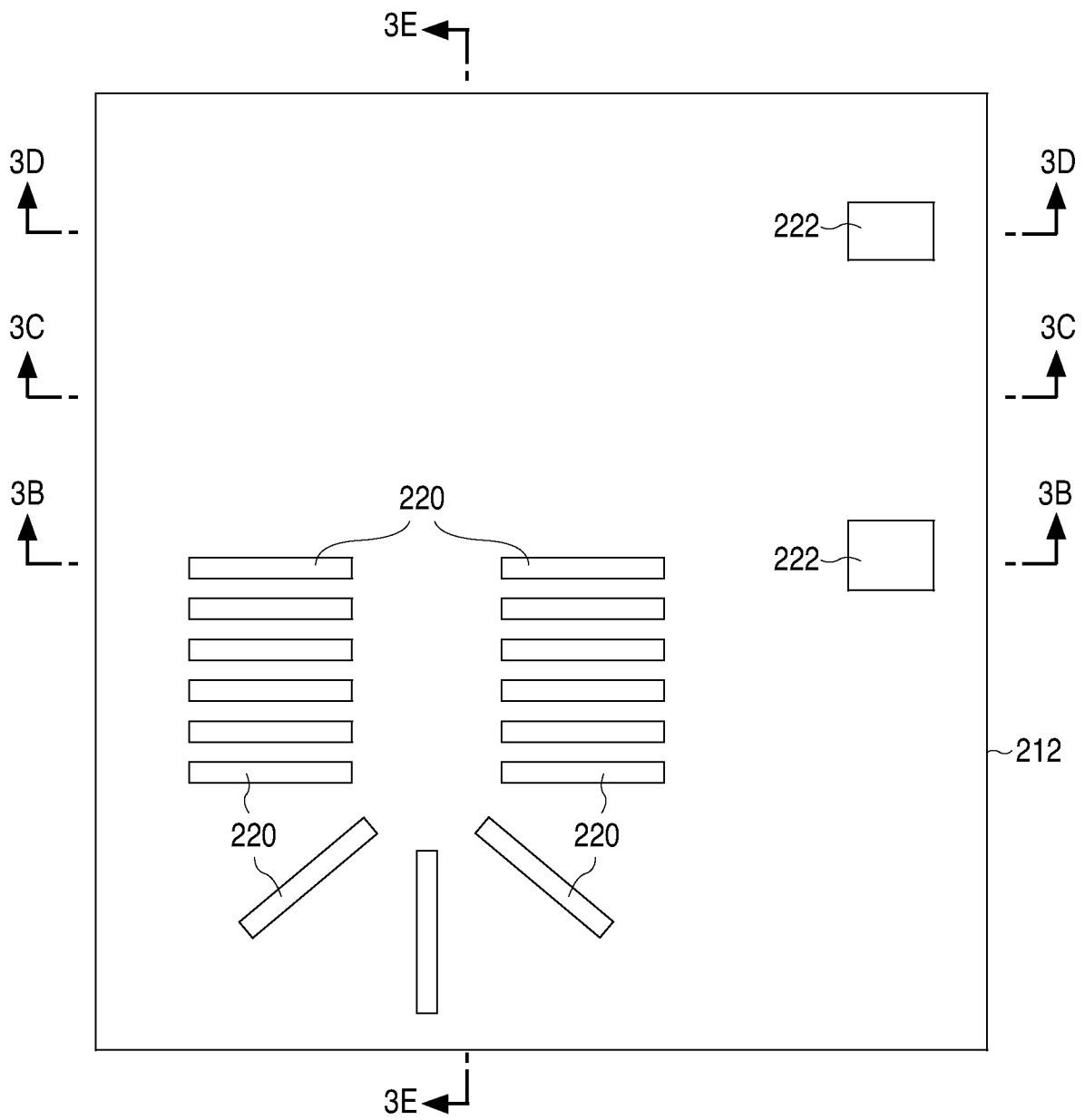


FIG. 2D



FIG. 2E



**FIG. 3A**

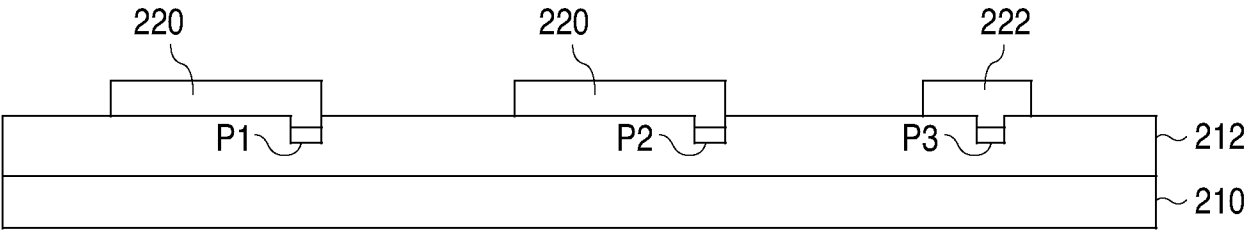


FIG. 3B

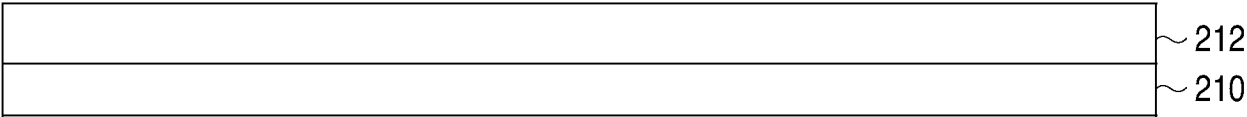


FIG. 3C

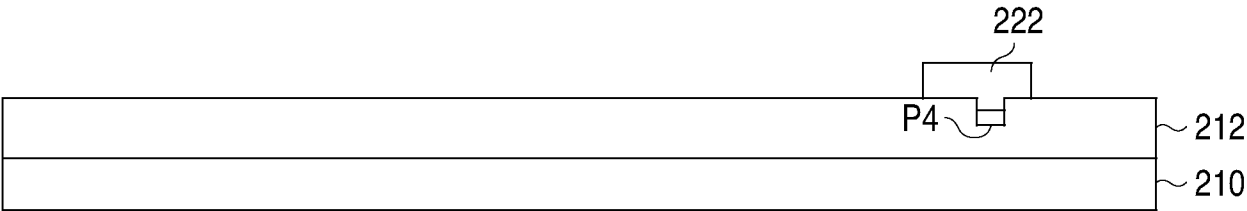


FIG. 3D

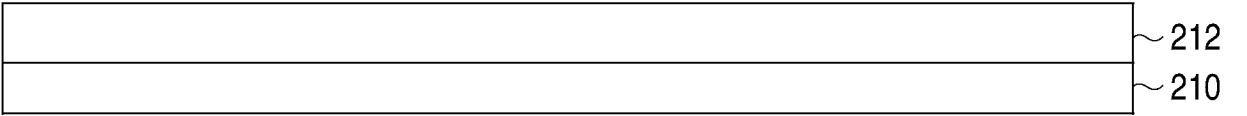
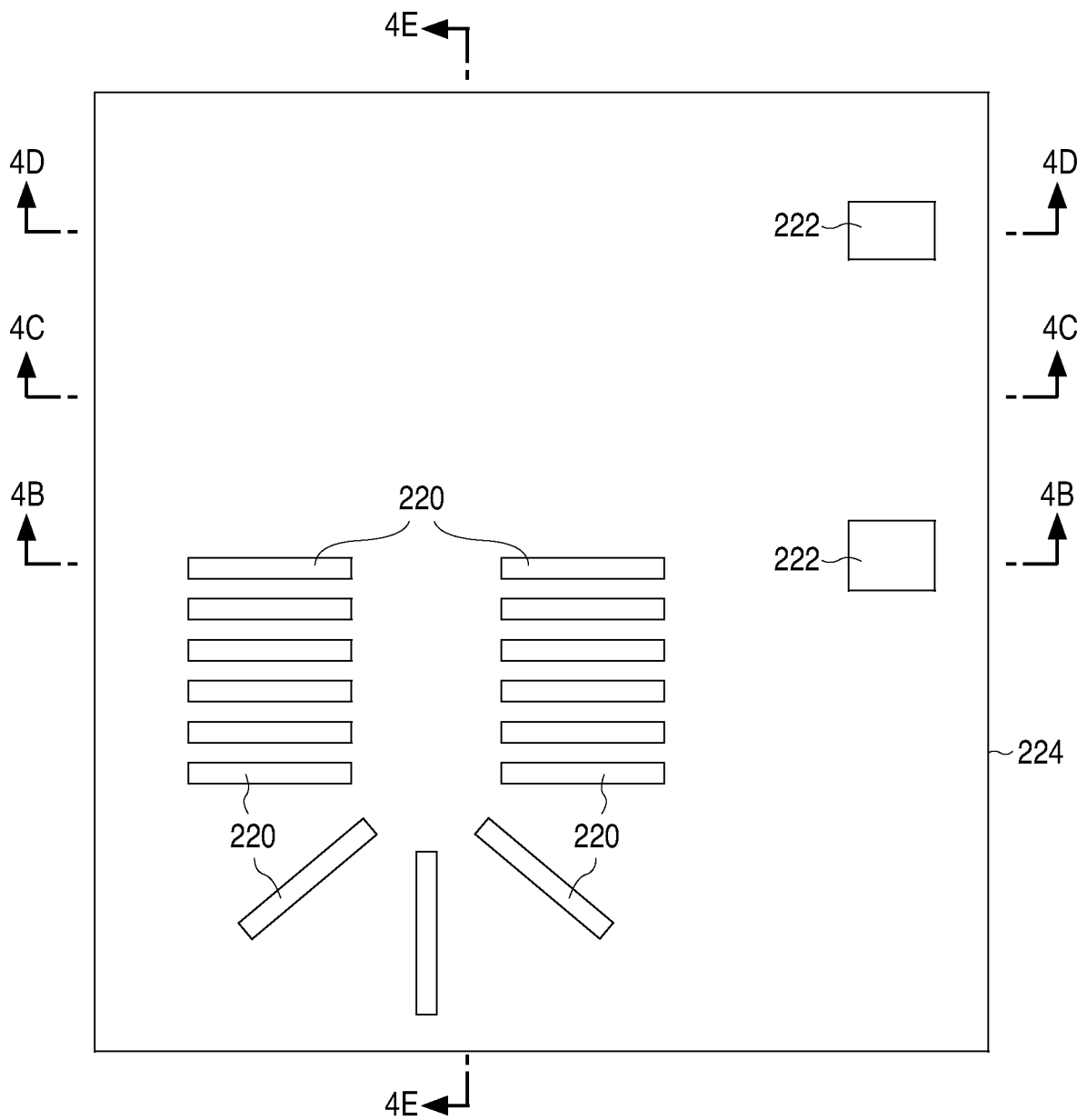


FIG. 3E

**FIG. 4A**

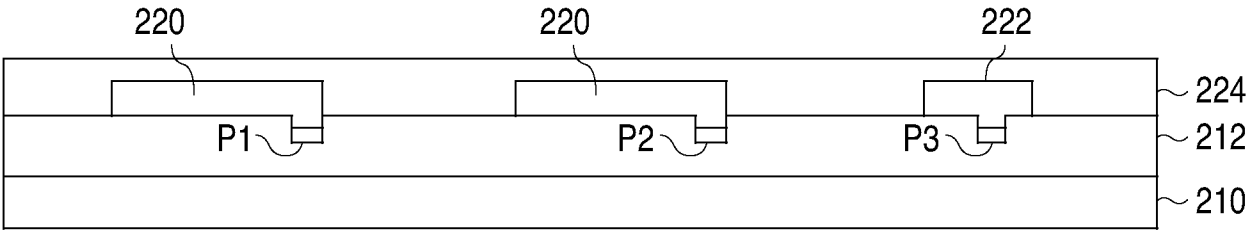


FIG. 4B

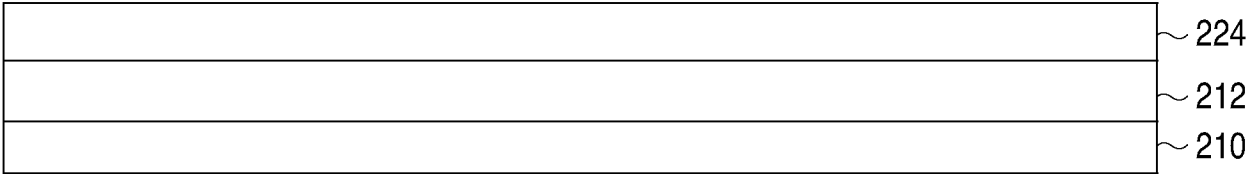


FIG. 4C

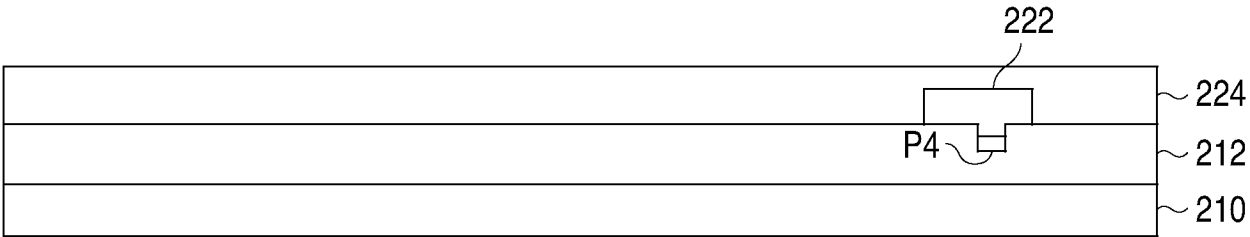
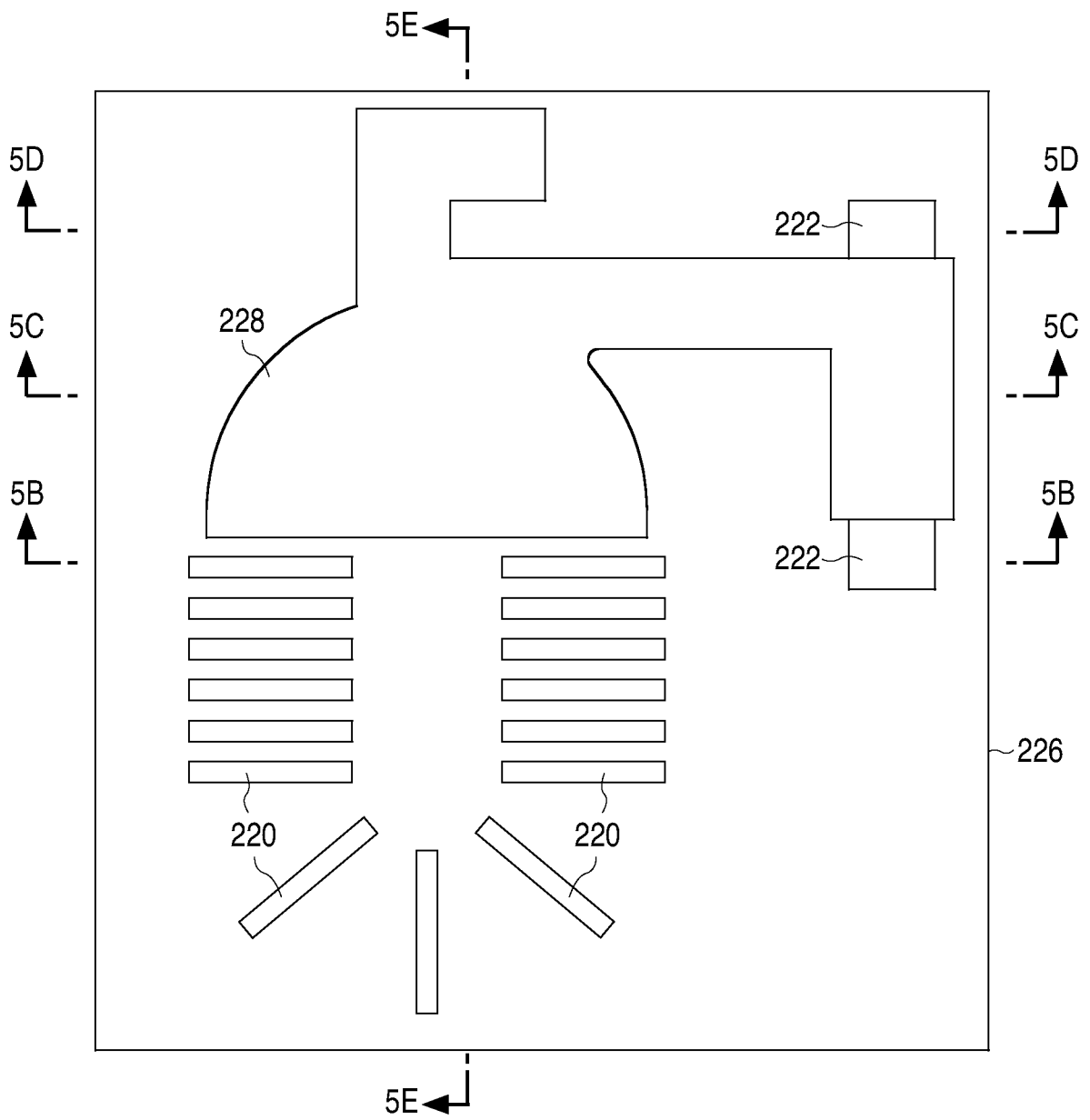


FIG. 4D



FIG. 4E



**FIG. 5A**

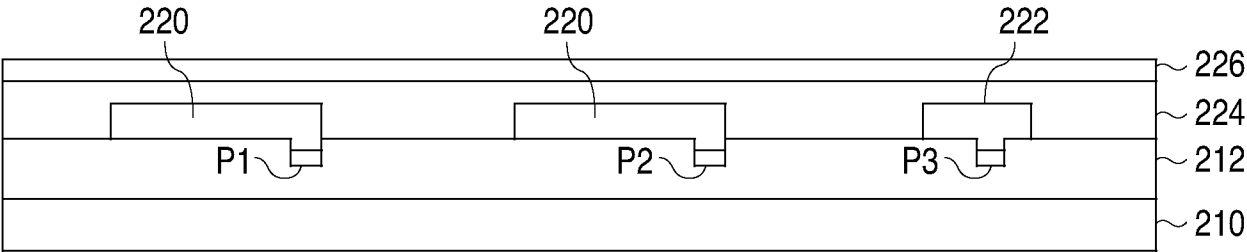


FIG. 5B

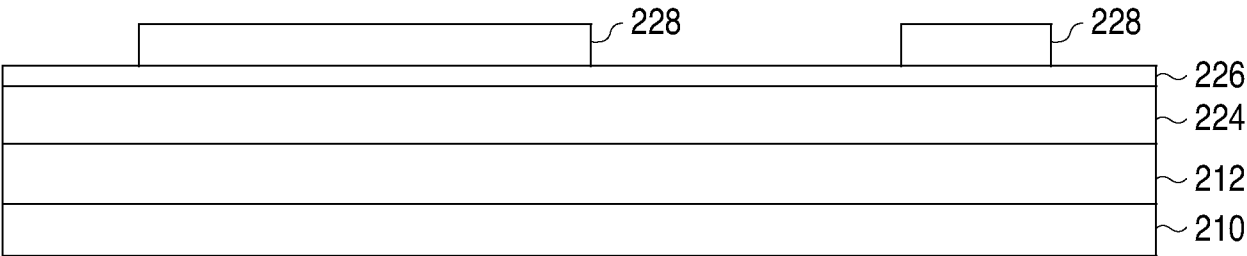


FIG. 5C

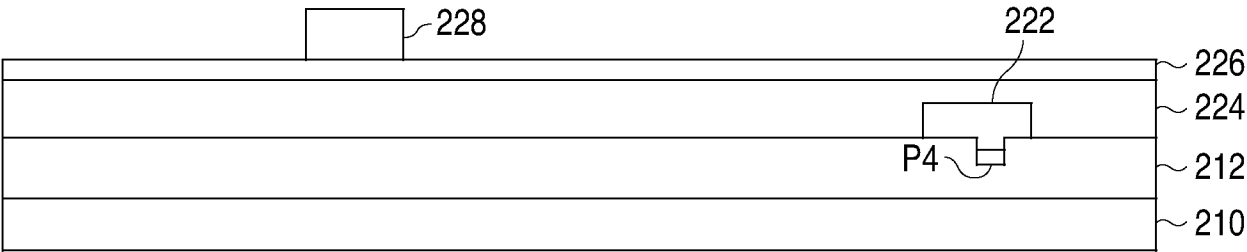


FIG. 5D

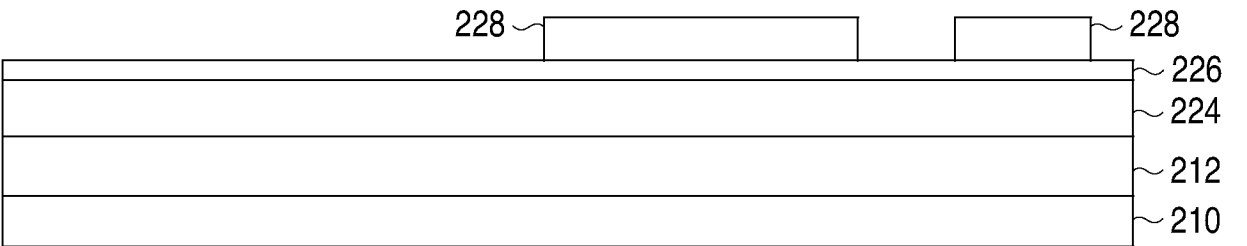
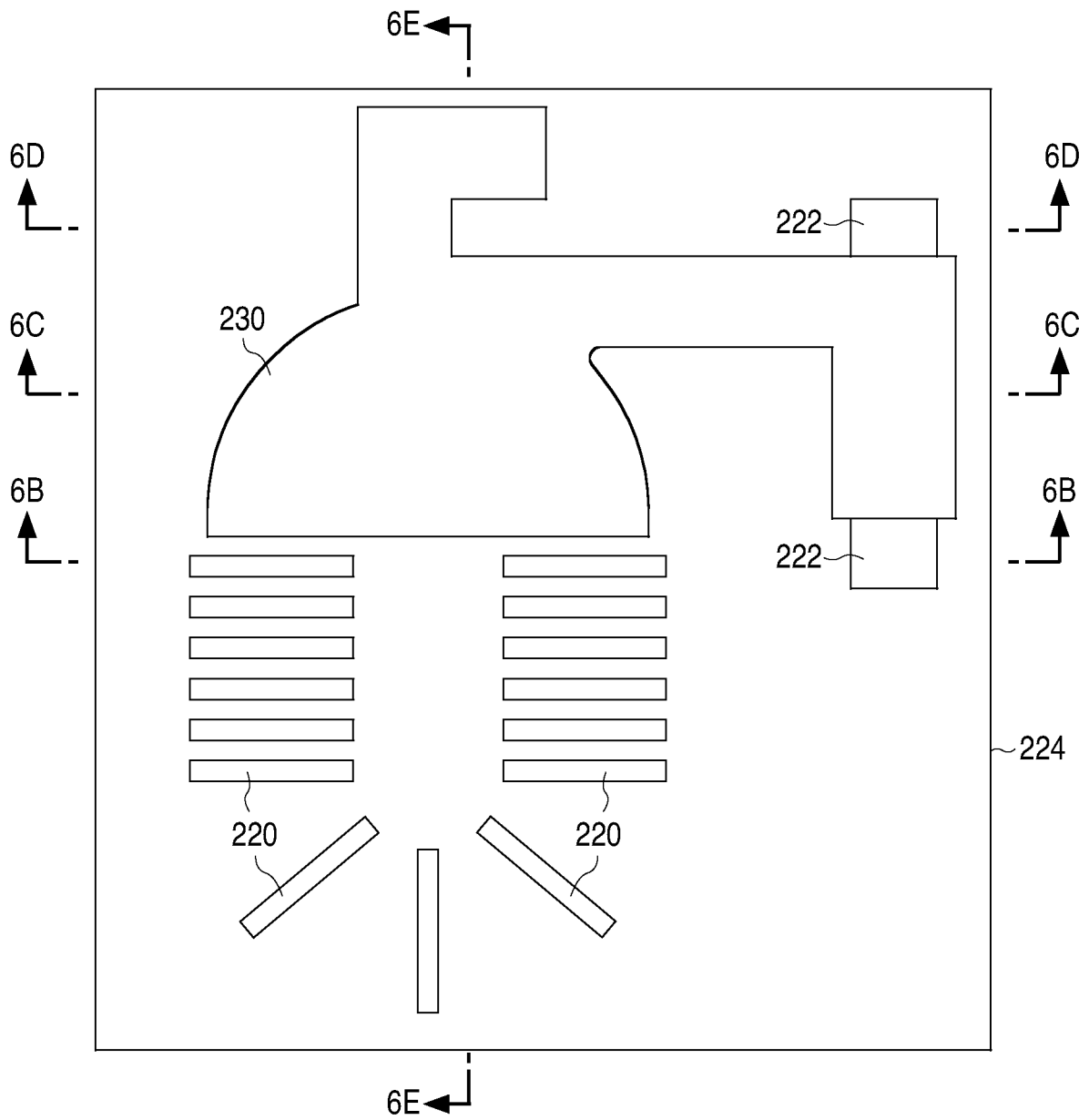
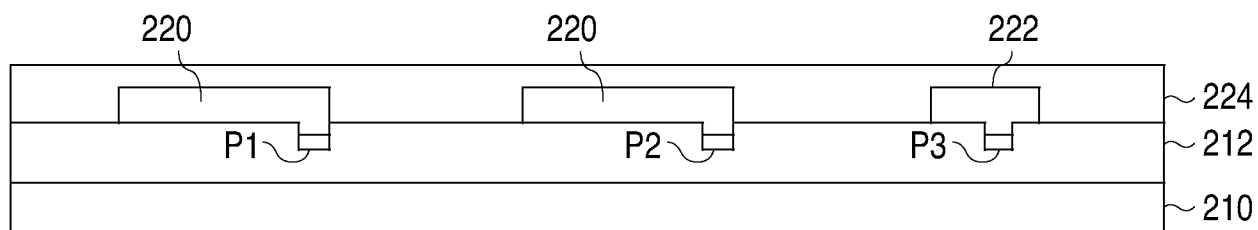


FIG. 5E

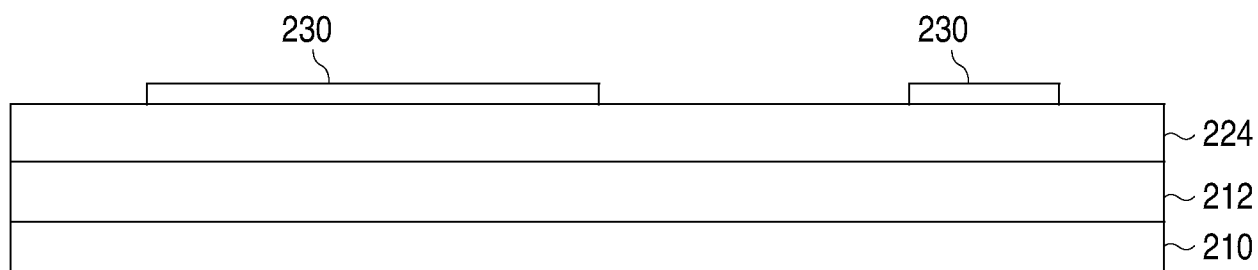


**FIG. 6A**

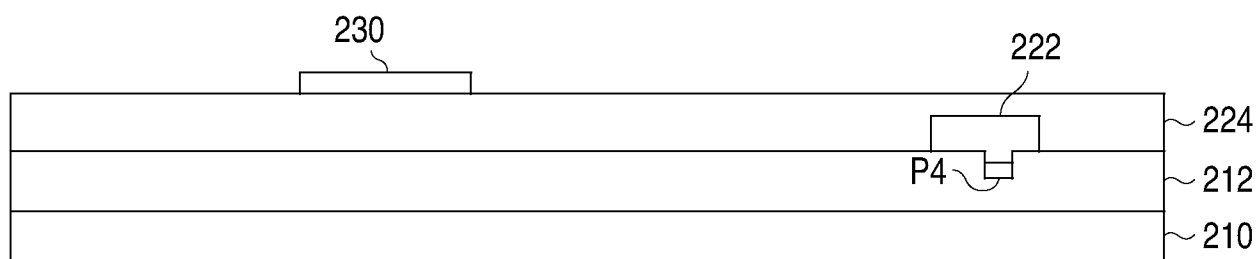
11/55



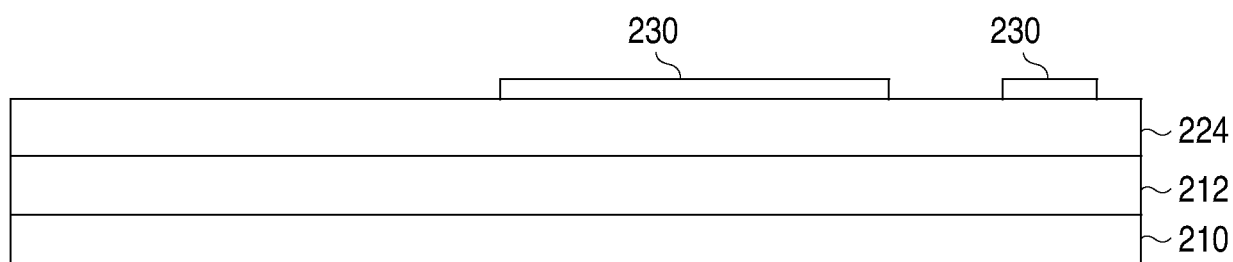
**FIG. 6B**



**FIG. 6C**



**FIG. 6D**



**FIG. 6E**

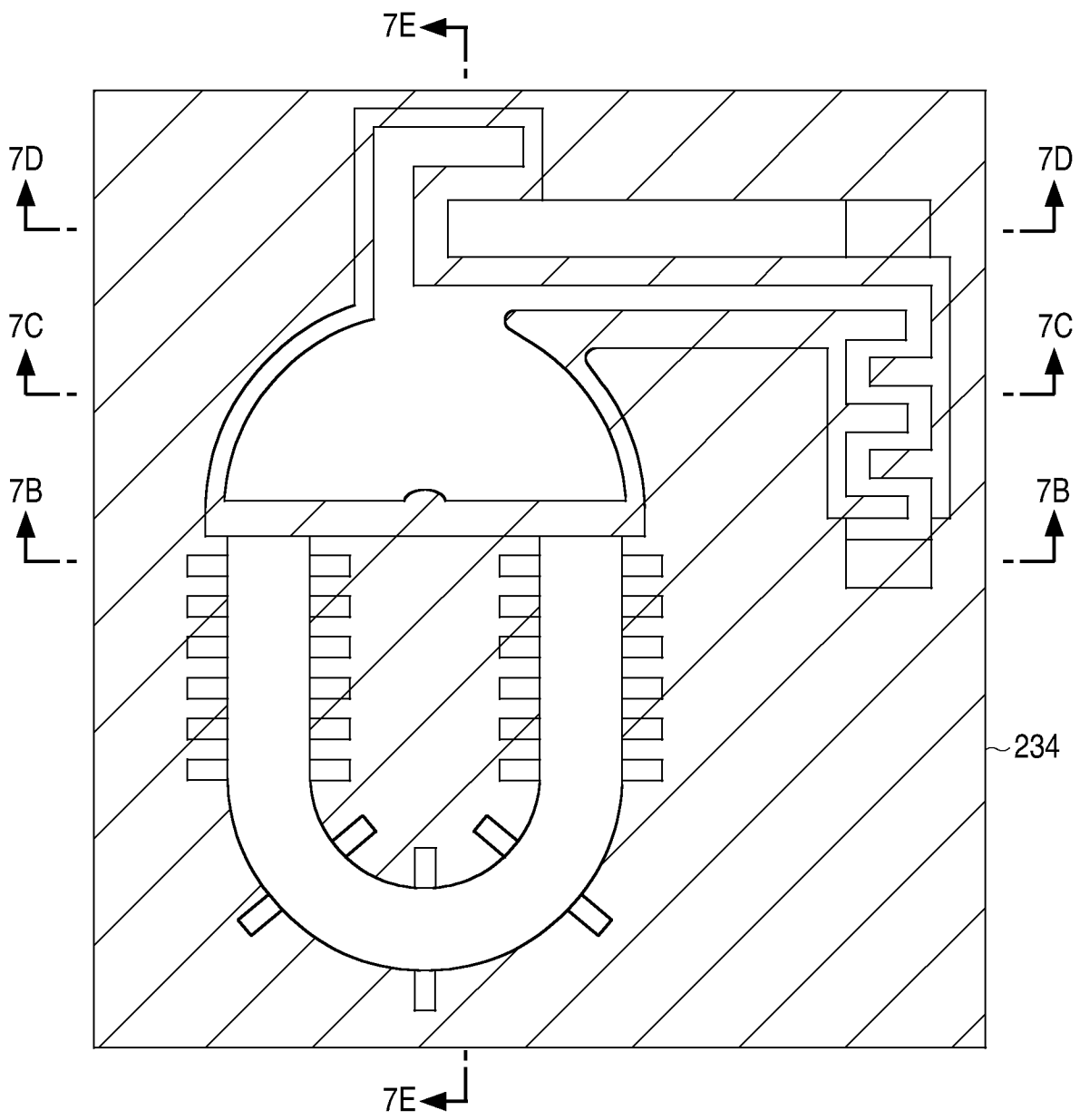


FIG. 7A

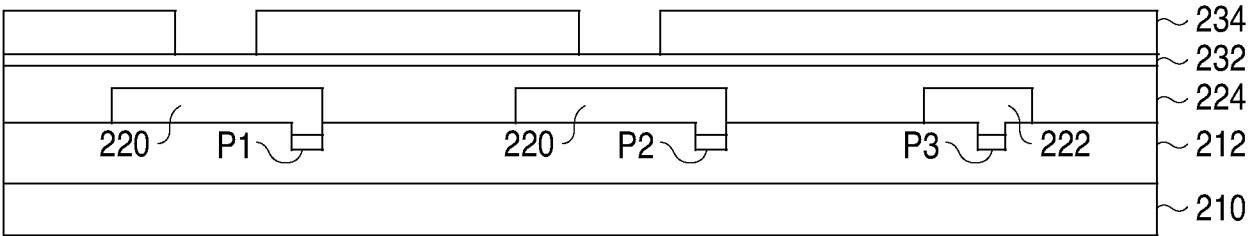


FIG. 7B

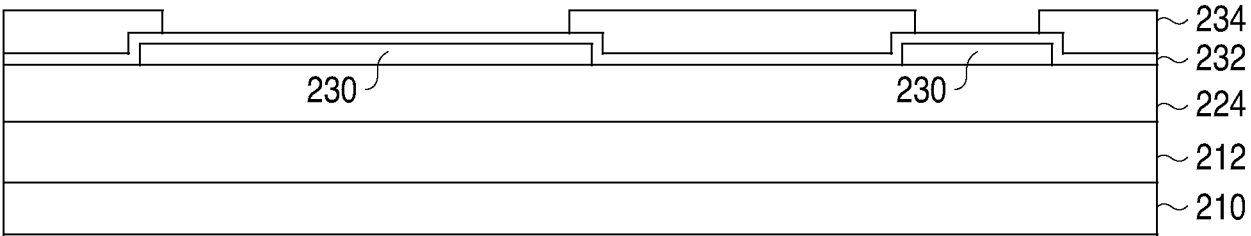


FIG. 7C

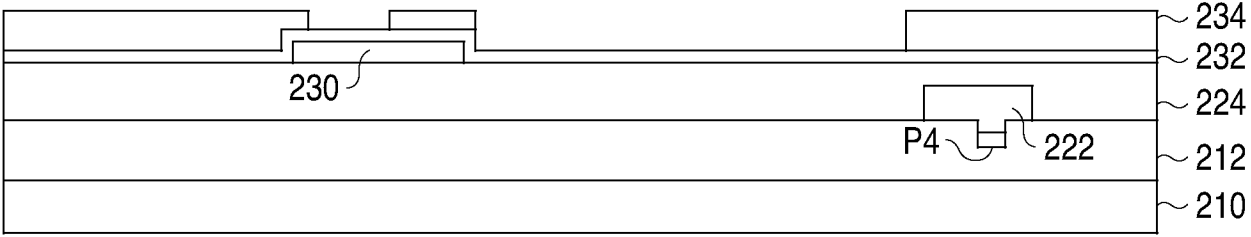


FIG. 7D

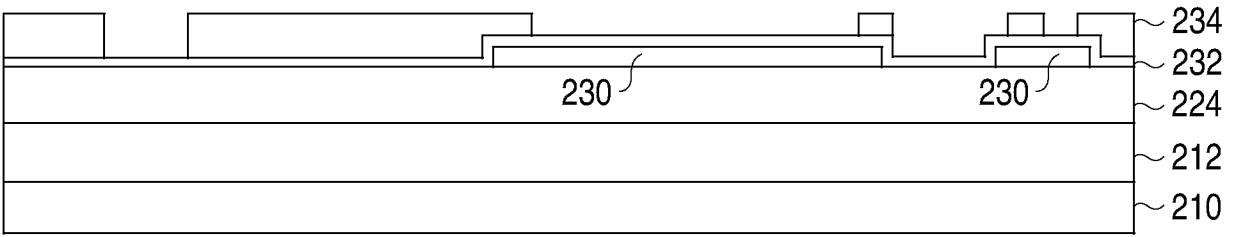
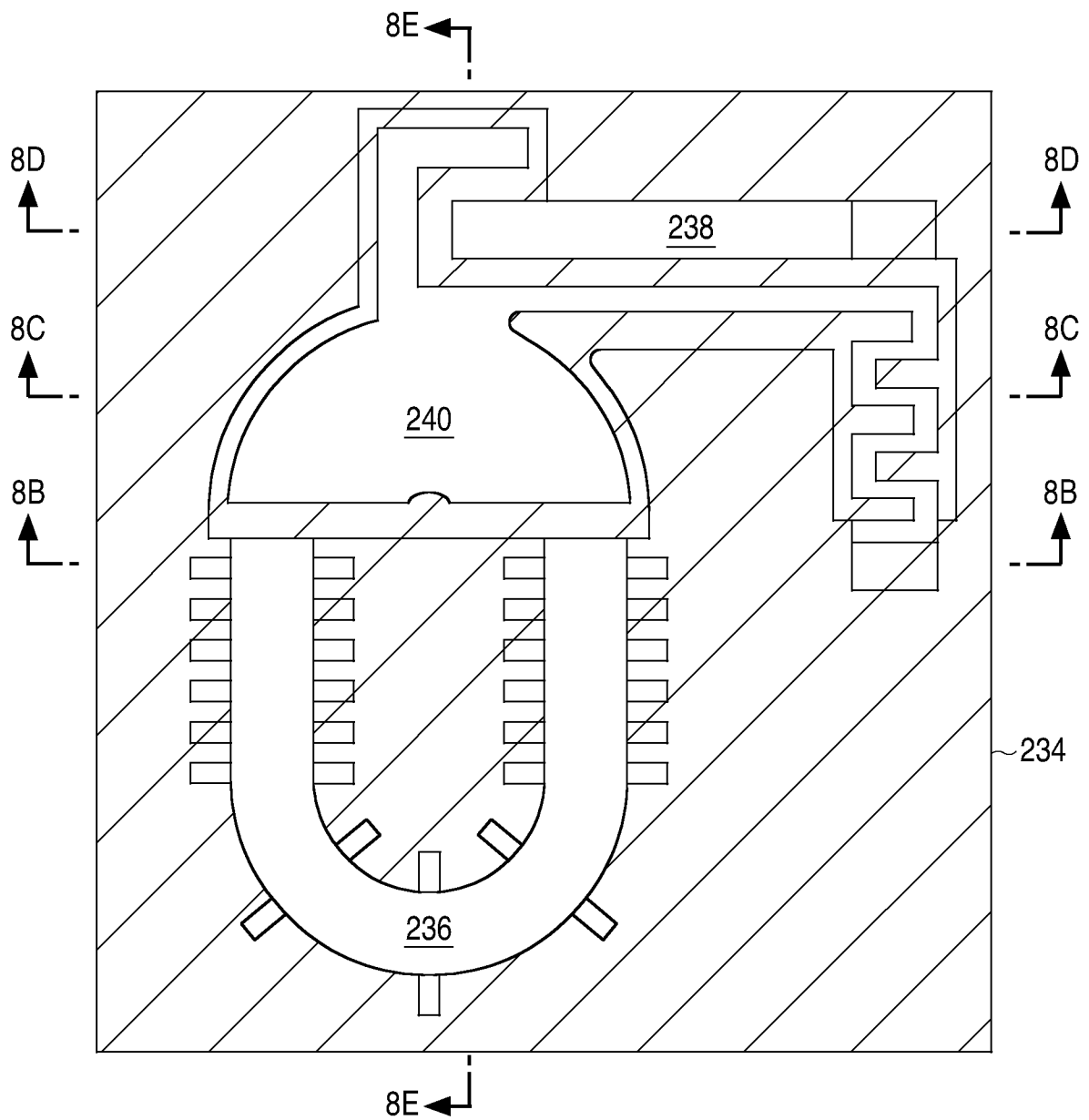
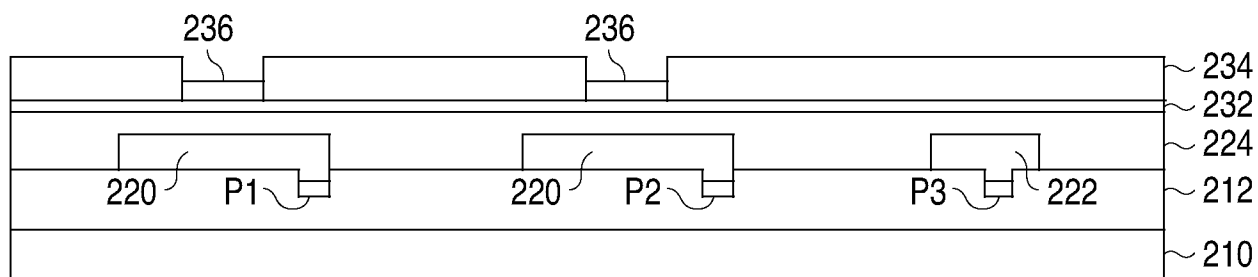
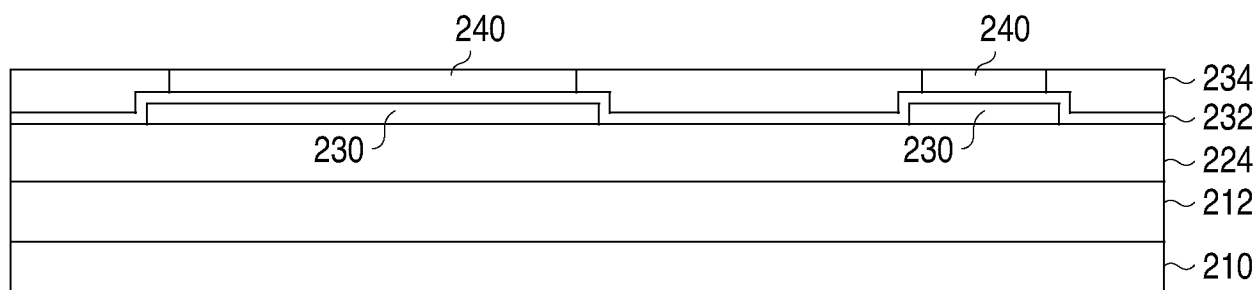
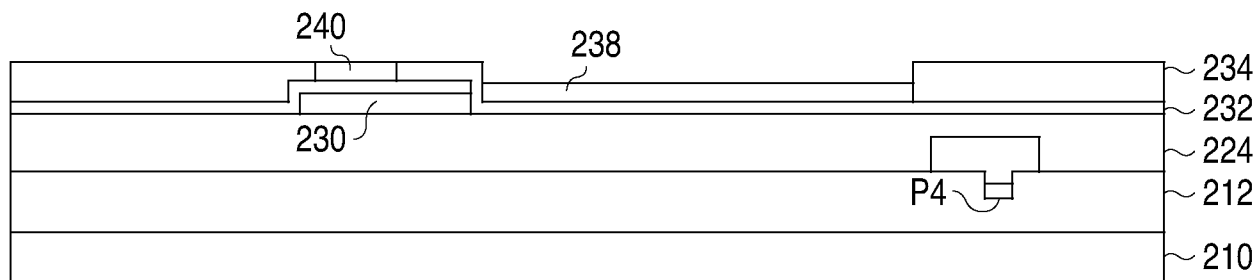
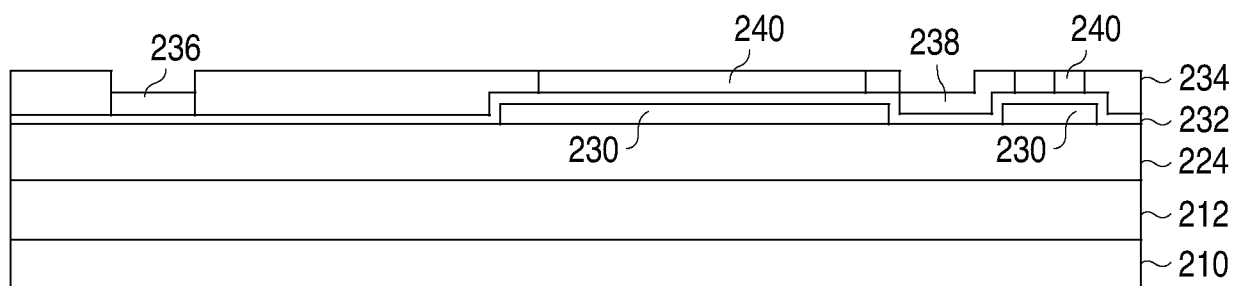


FIG. 7E



**FIG. 8A**

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**FIG. 8B****FIG. 8C****FIG. 8D****FIG. 8E**

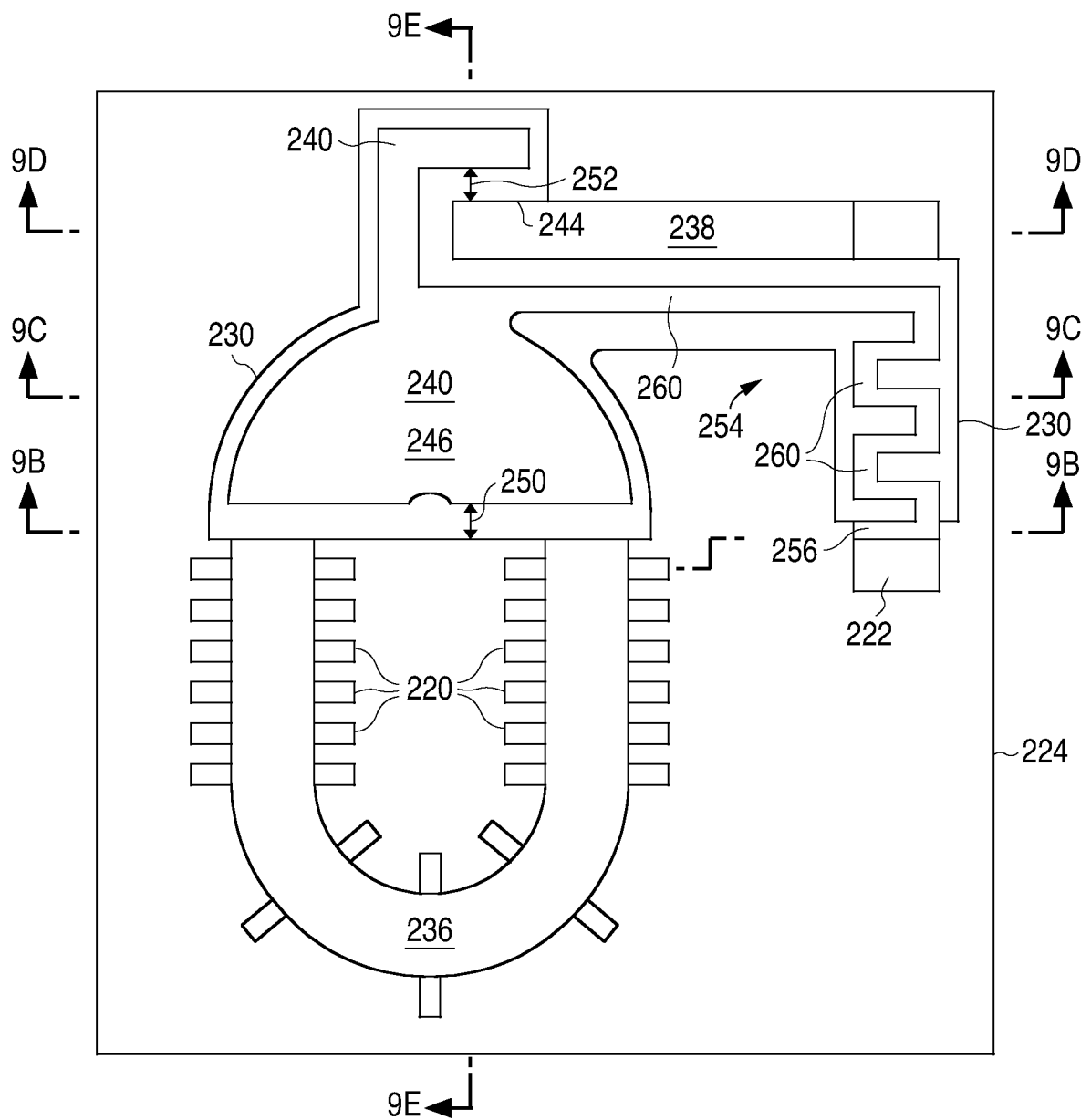
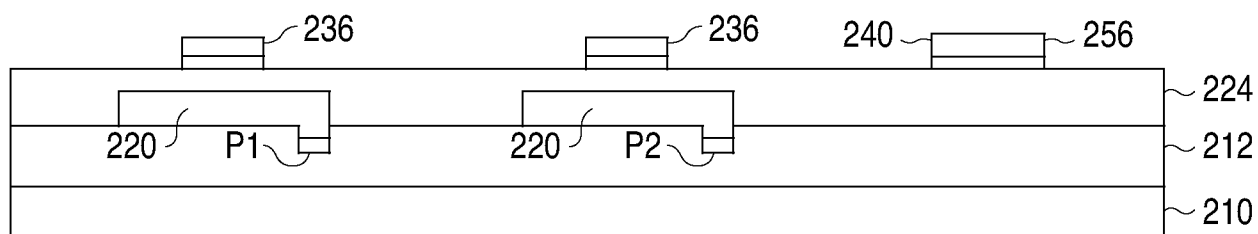
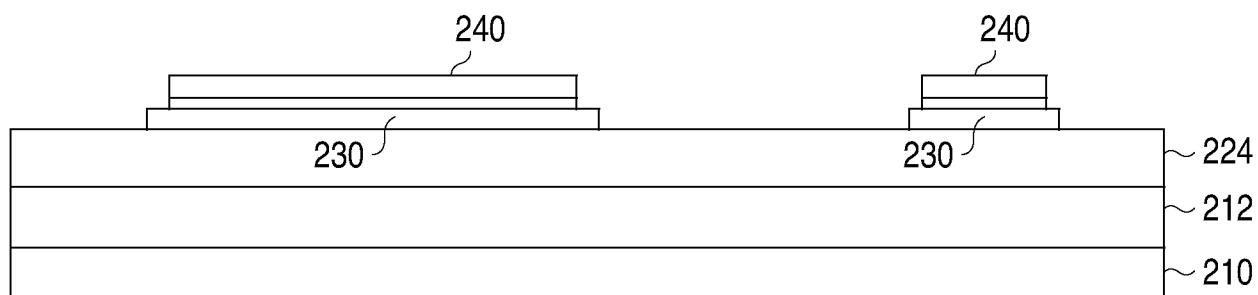
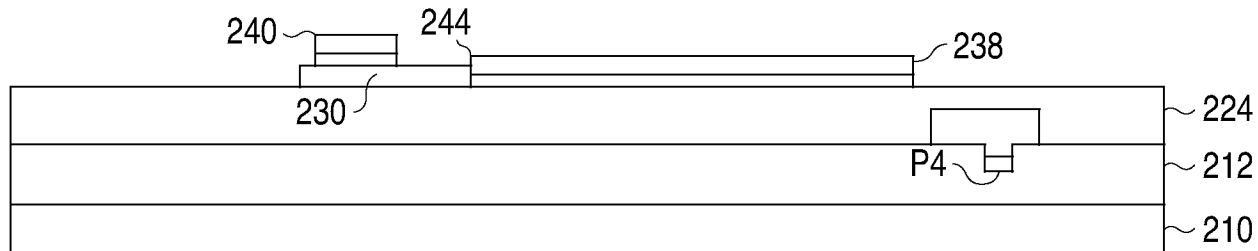
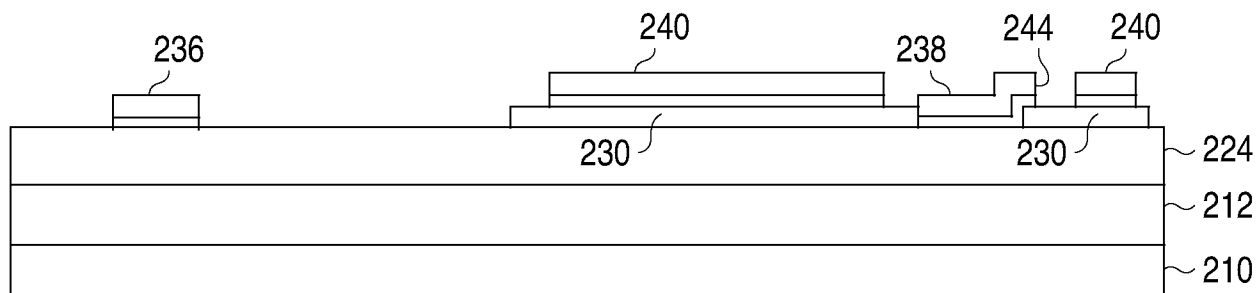
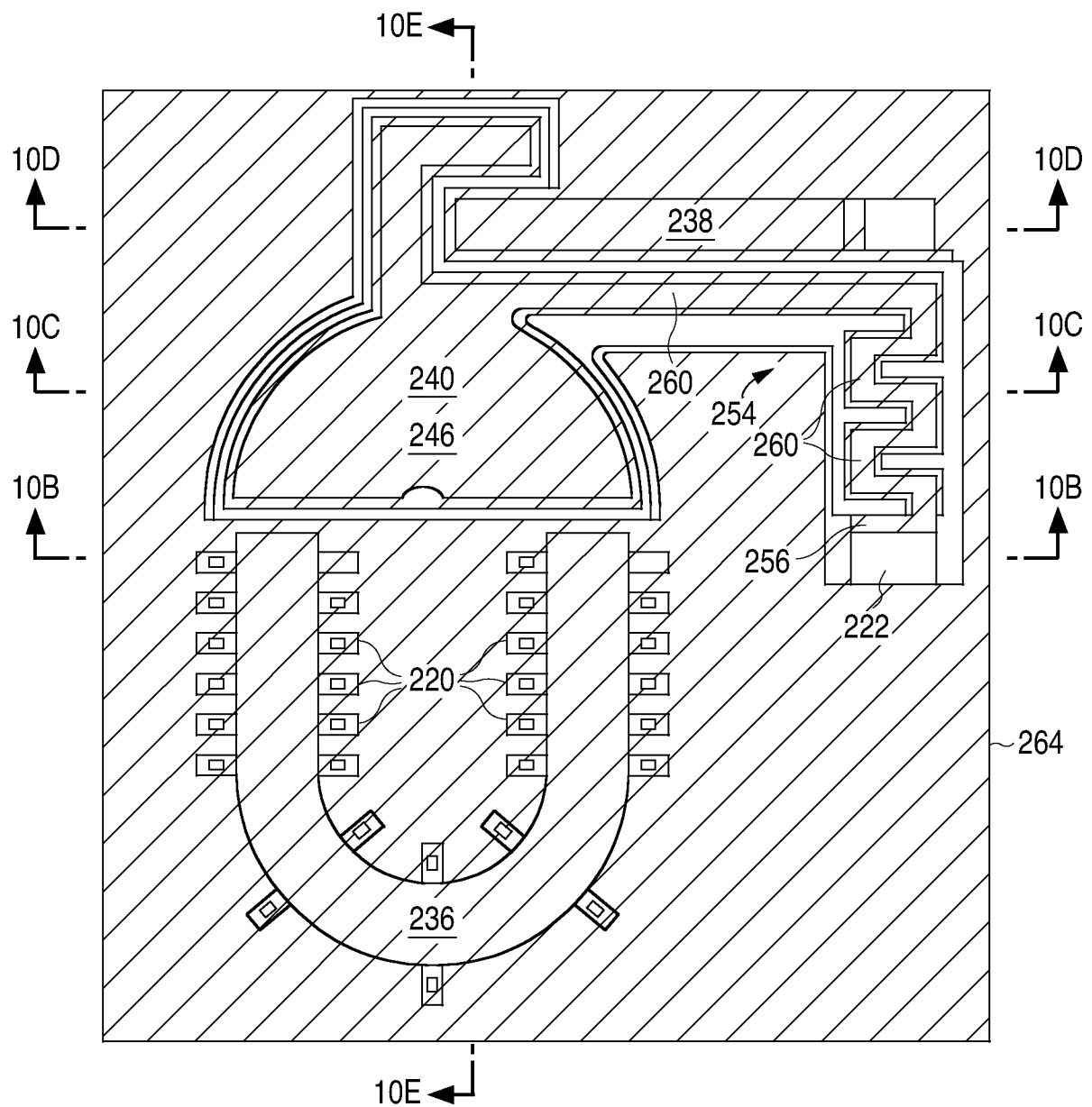


FIG. 9A

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**FIG. 9B****FIG. 9C****FIG. 9D****FIG. 9E**



**FIG. 10A**

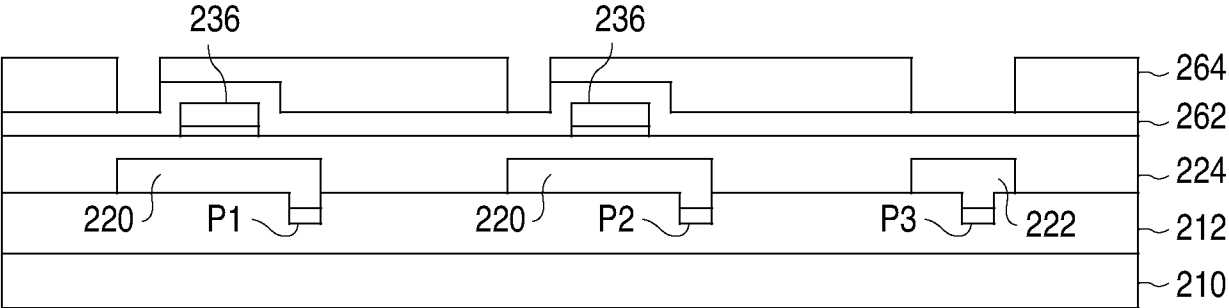


FIG. 10B

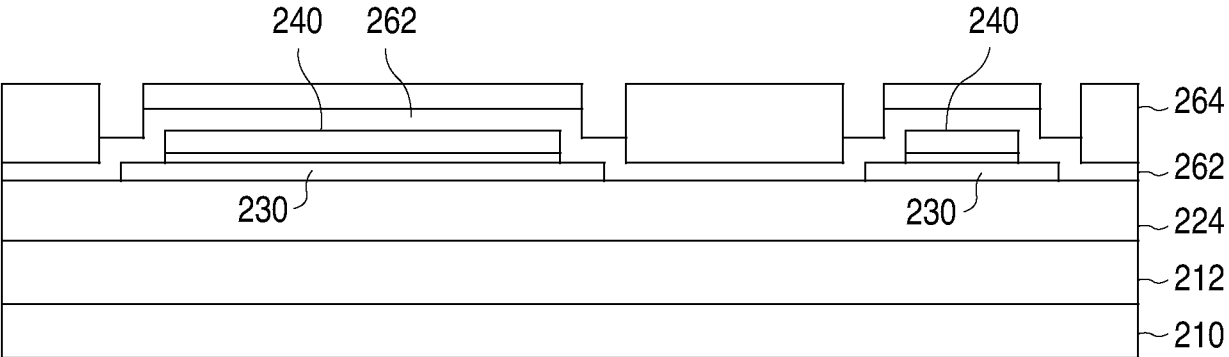


FIG. 10C

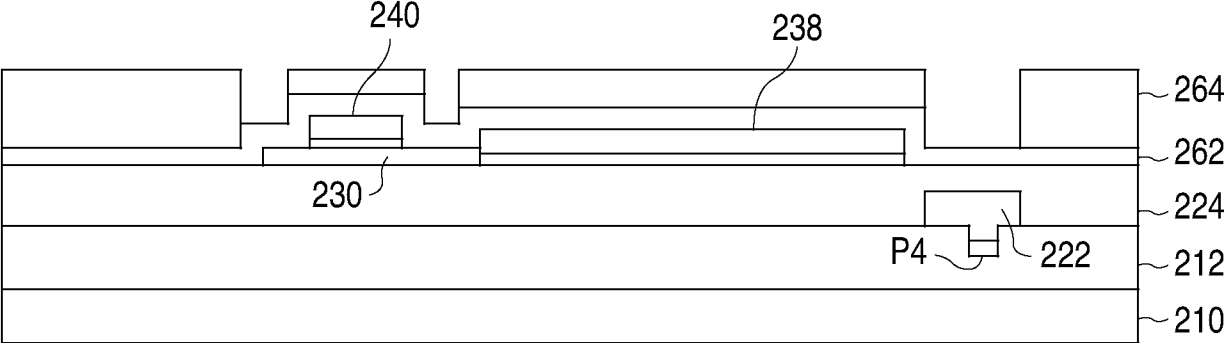


FIG. 10D

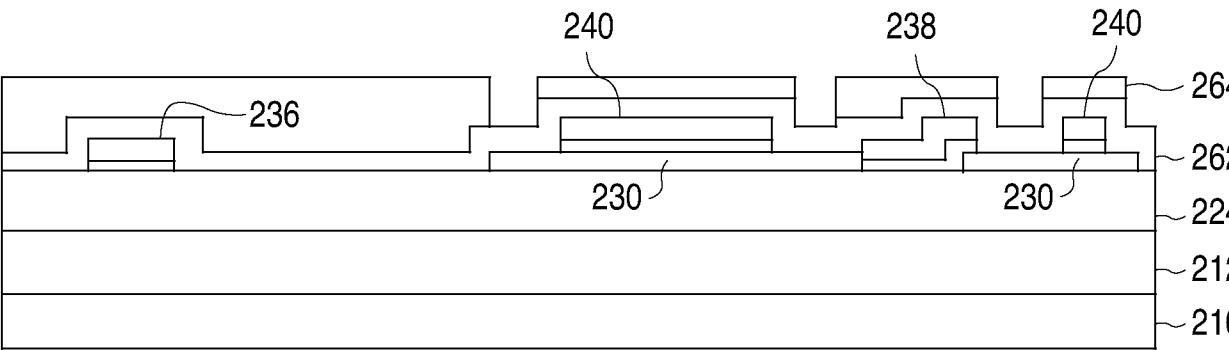


FIG. 10E

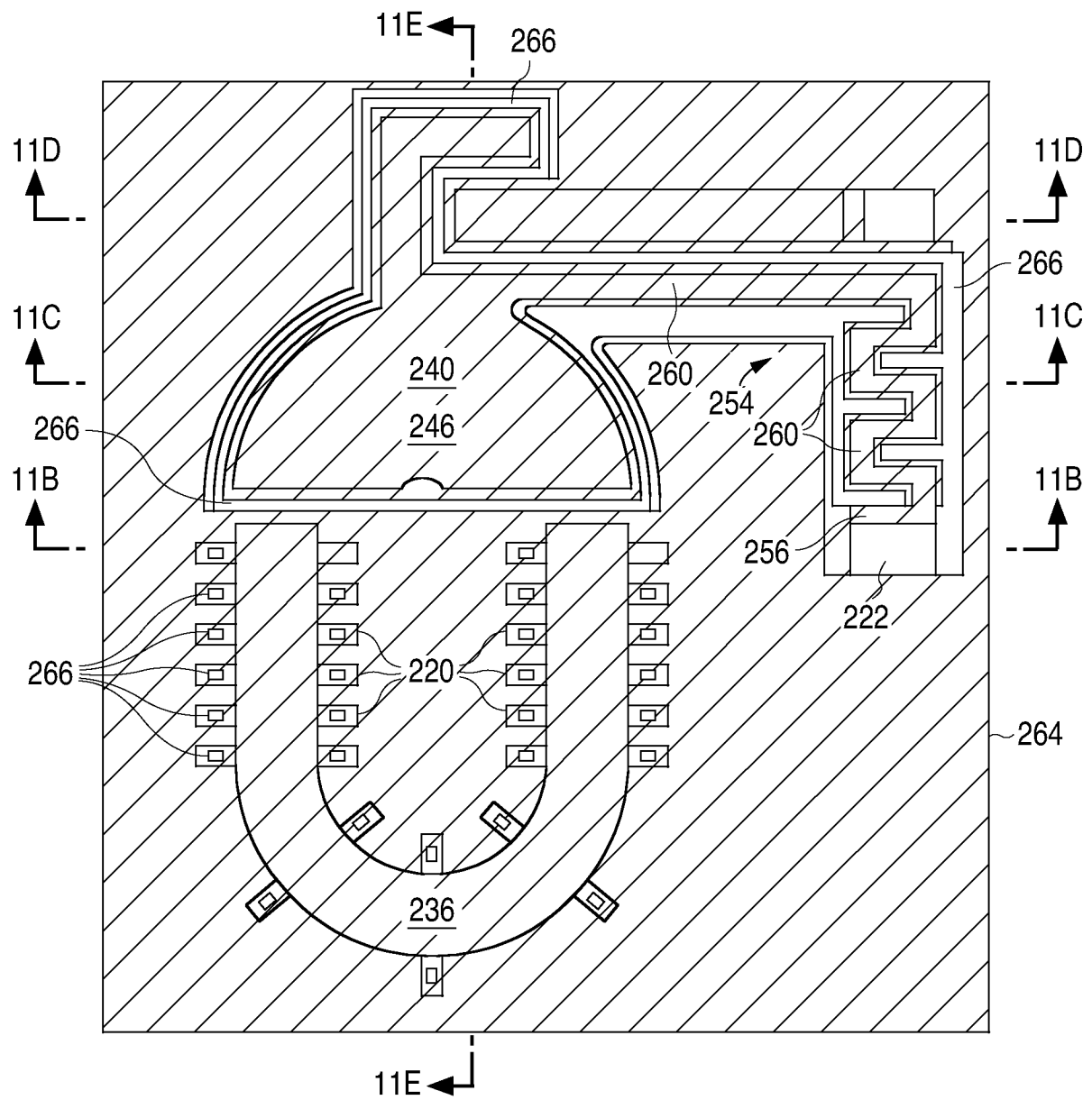
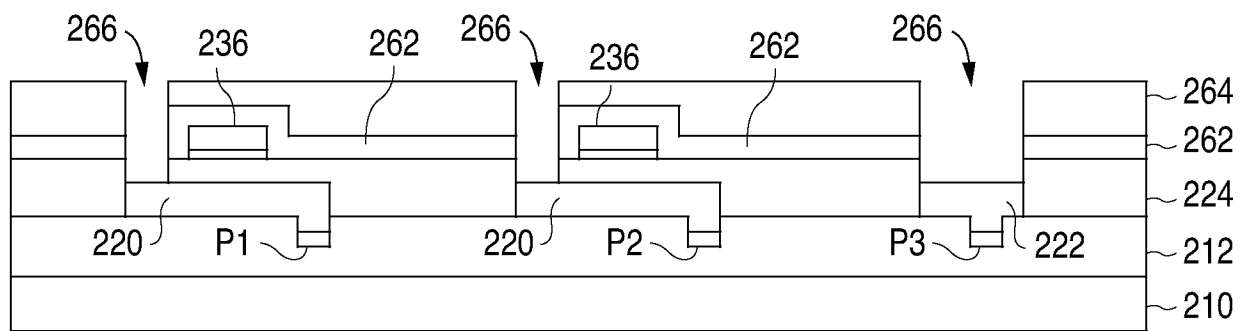
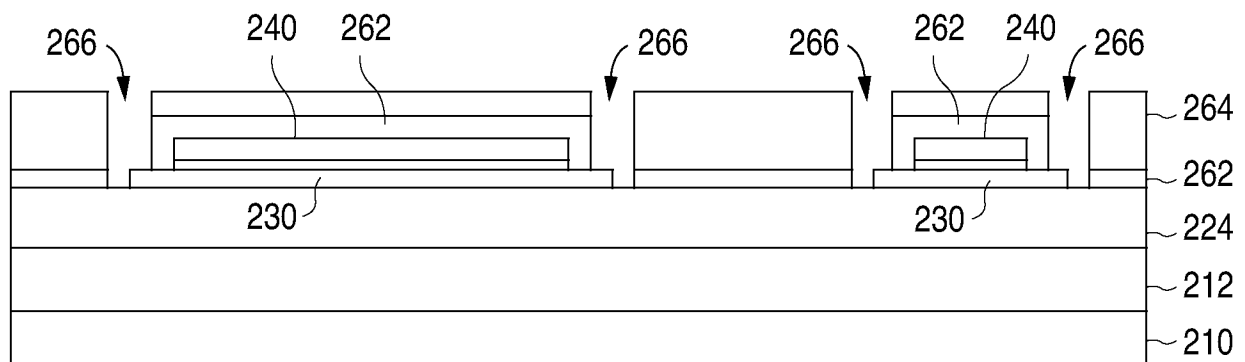
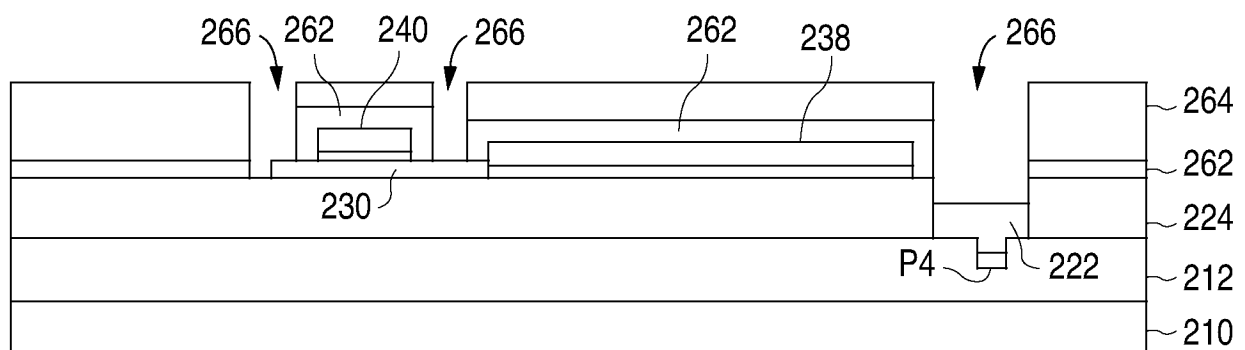
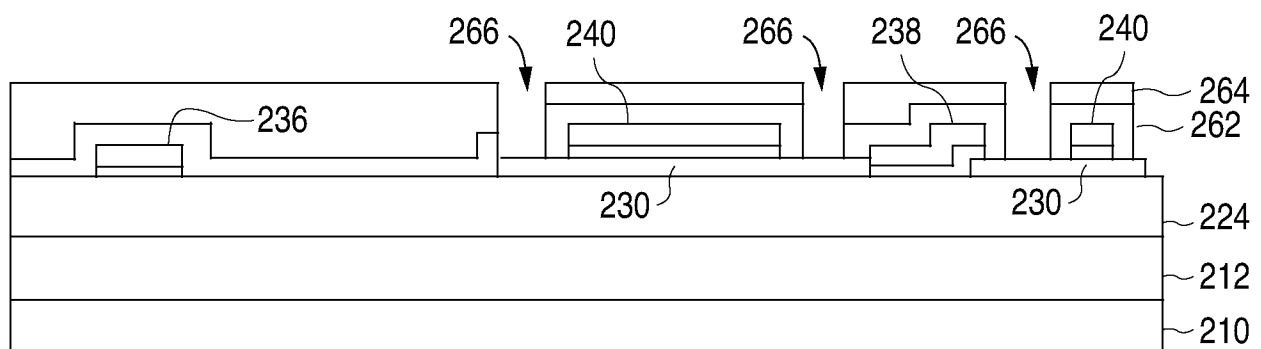
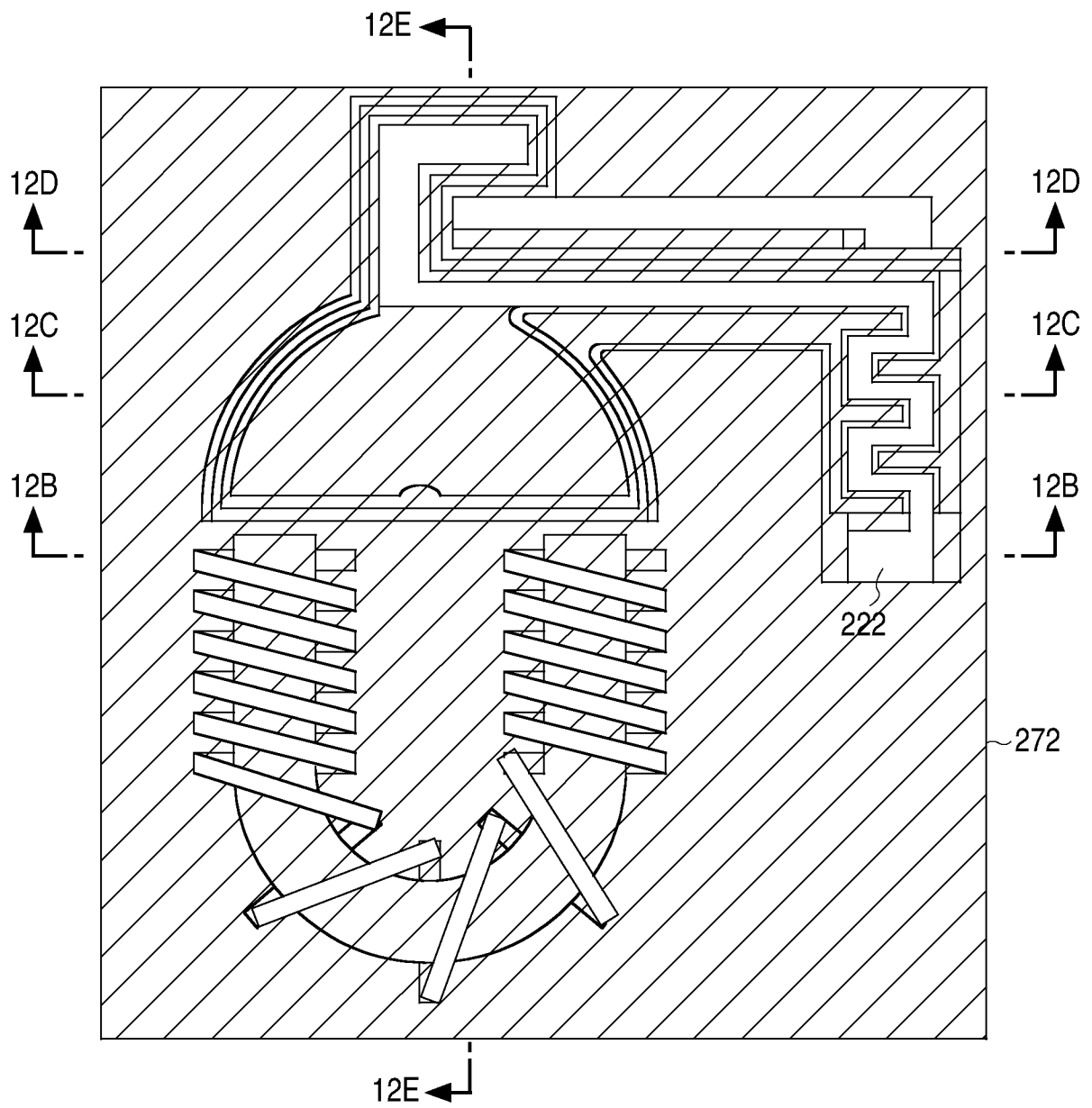


FIG. 11A

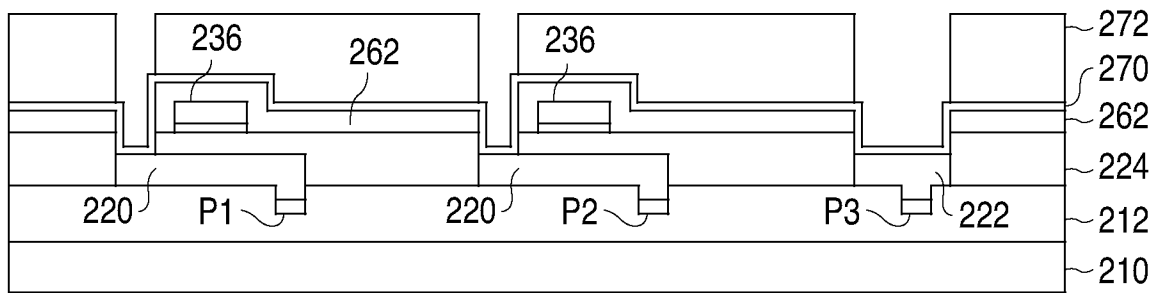
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**FIG. 11B****FIG. 11C****FIG. 11D****FIG. 11E**

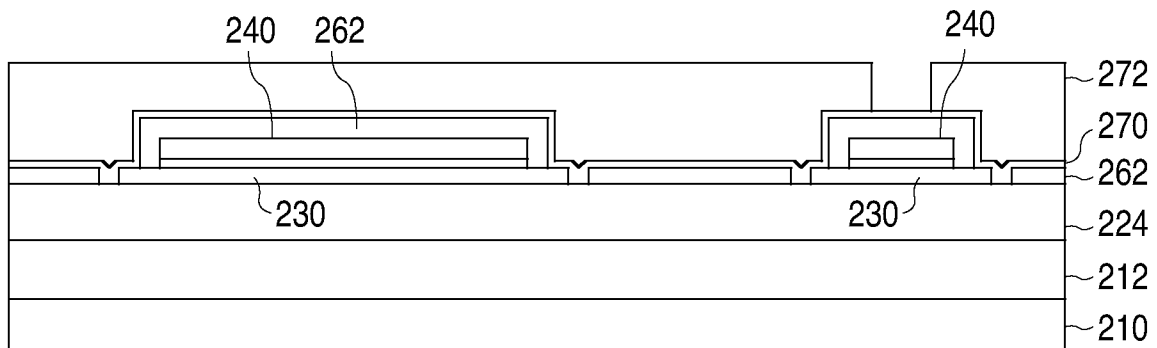


**FIG. 12A**

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**FIG. 12B**



**FIG. 12C**

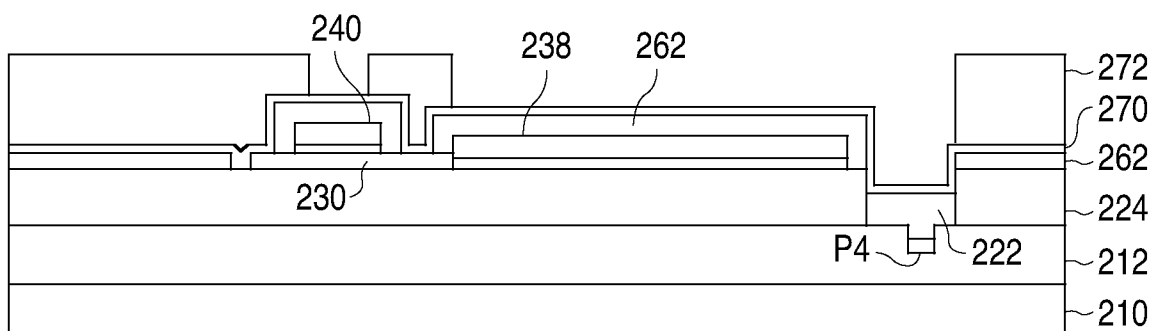
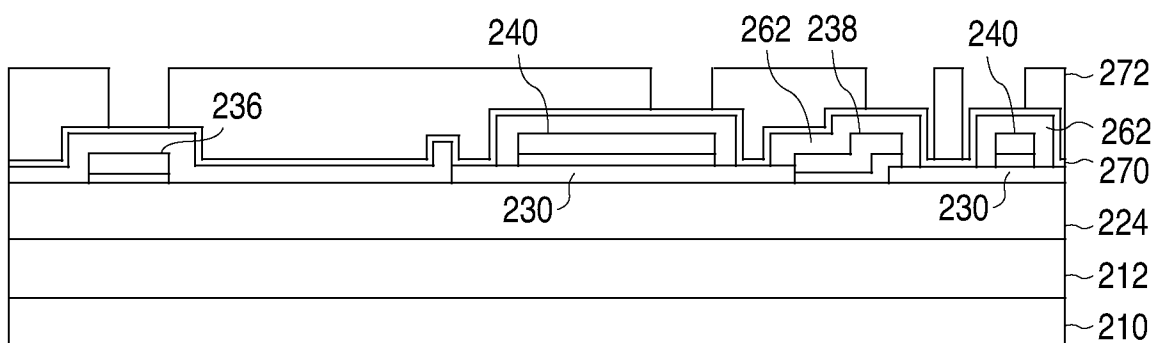


FIG. 12D



**FIG. 12E**

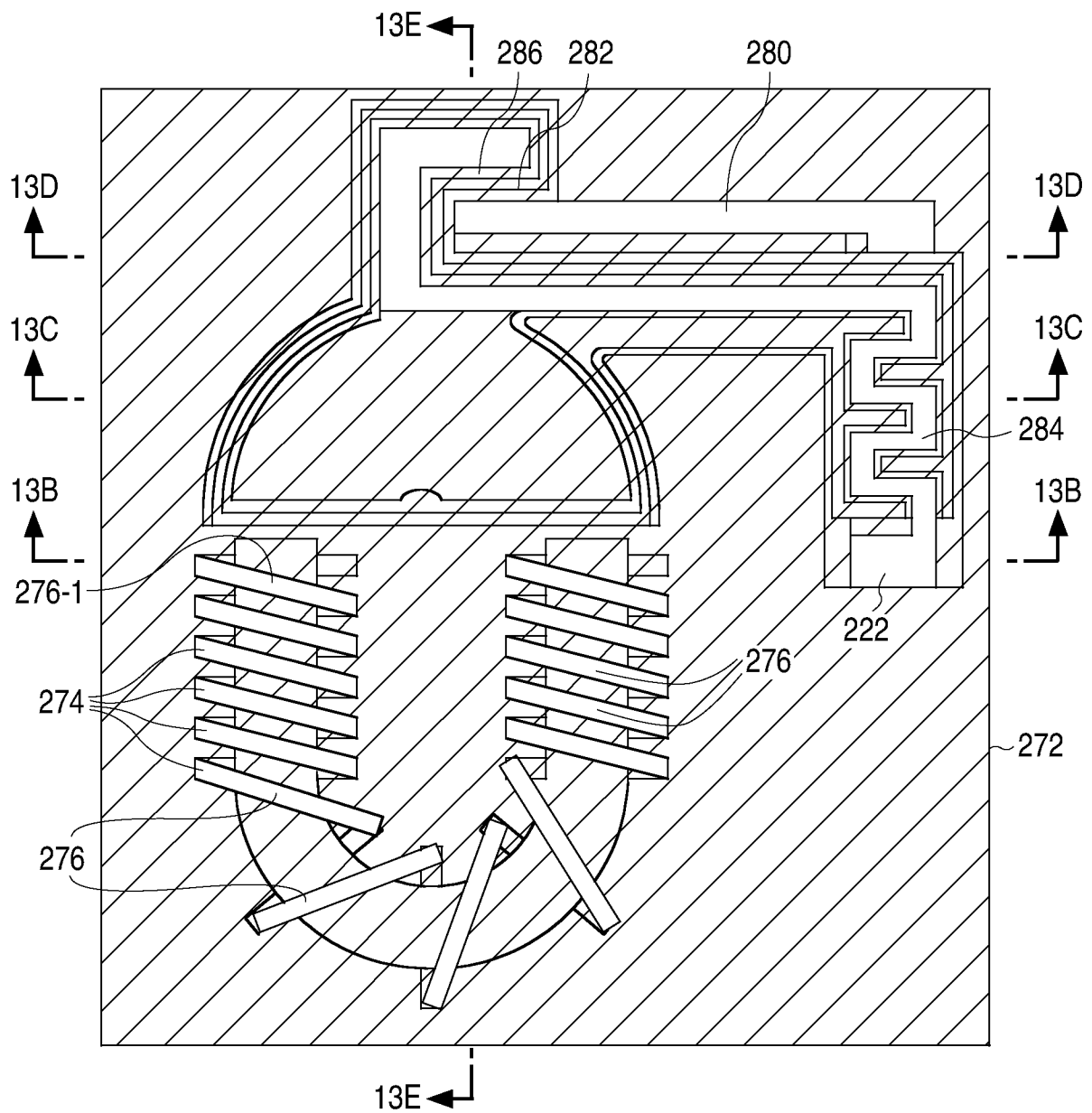
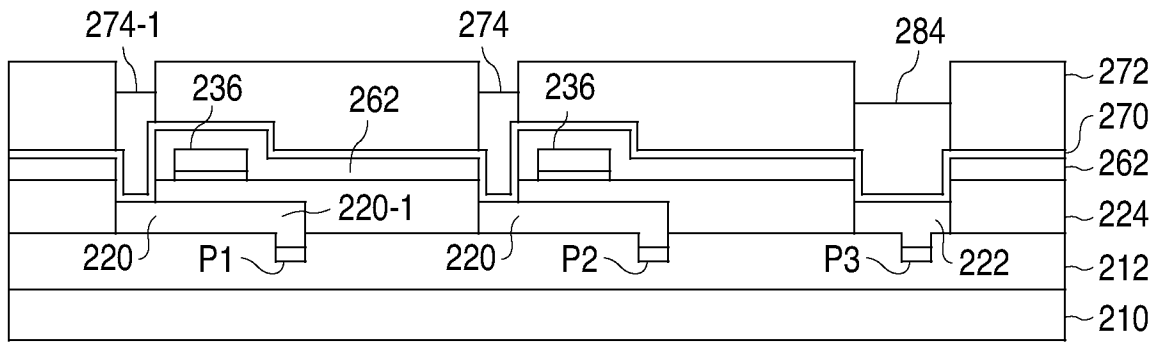
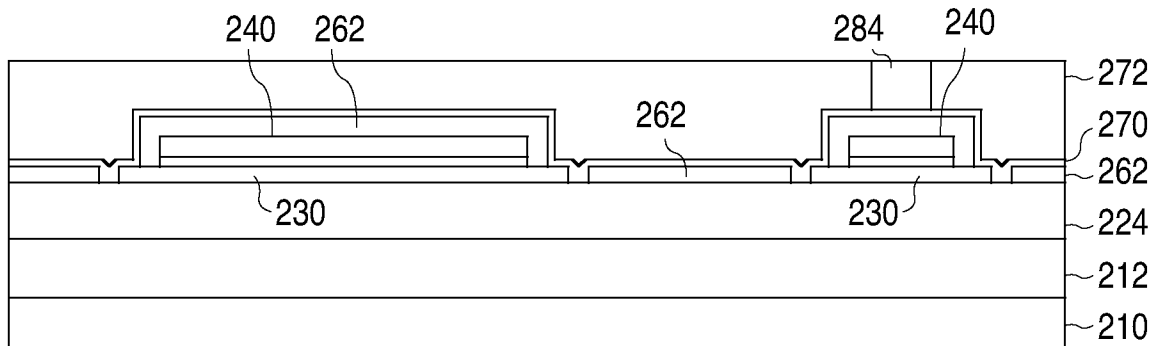


FIG. 13A

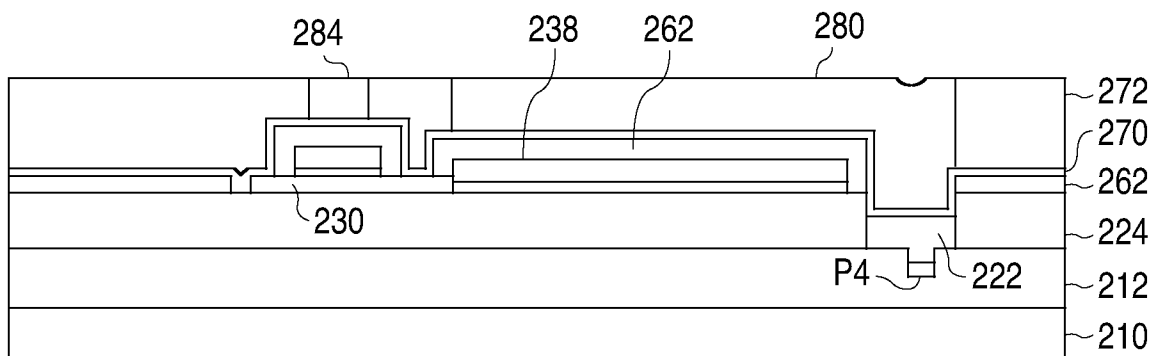
25/55



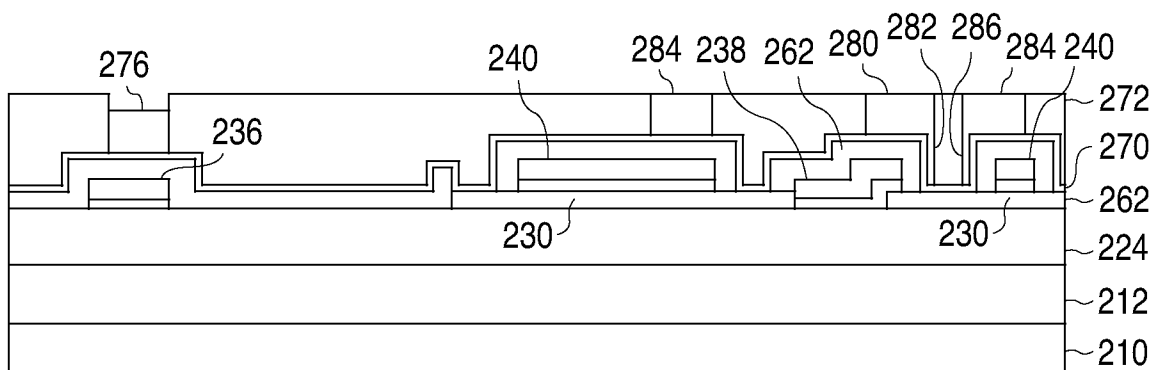
**FIG. 13B**



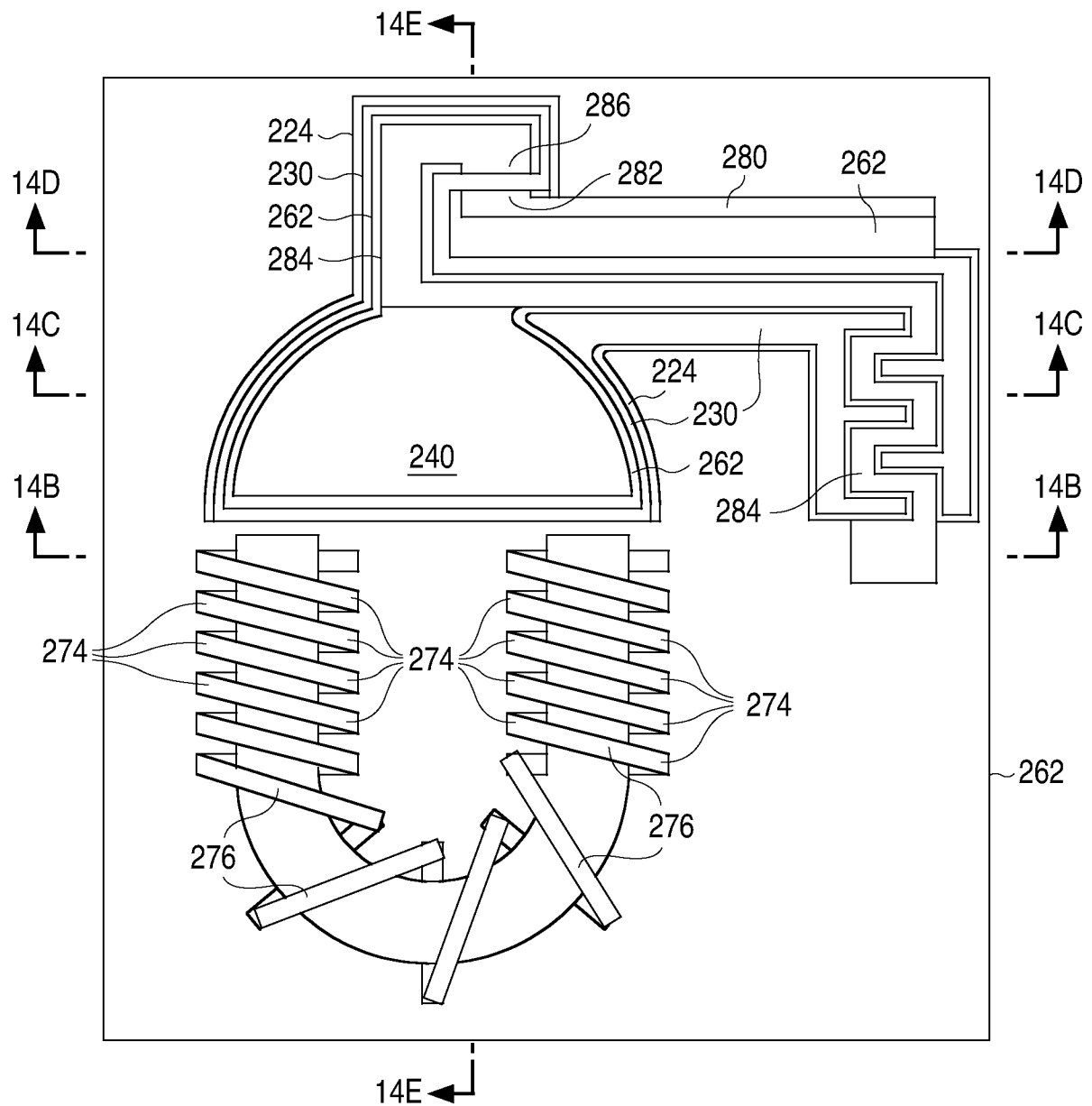
**FIG. 13C**



**FIG. 13D**

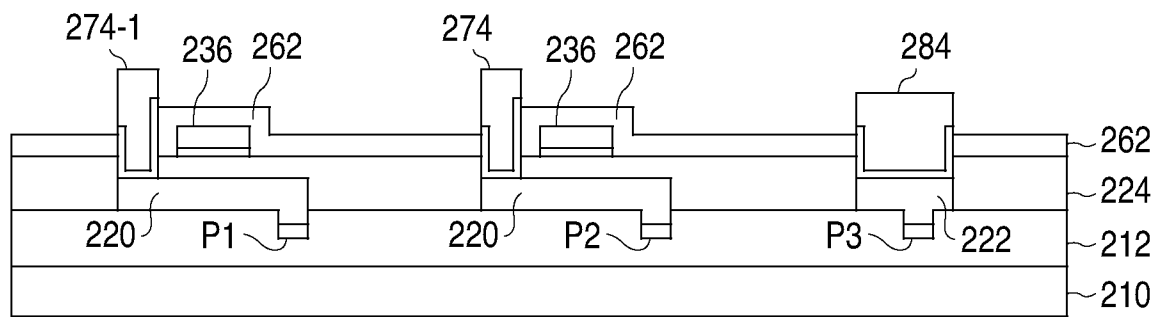
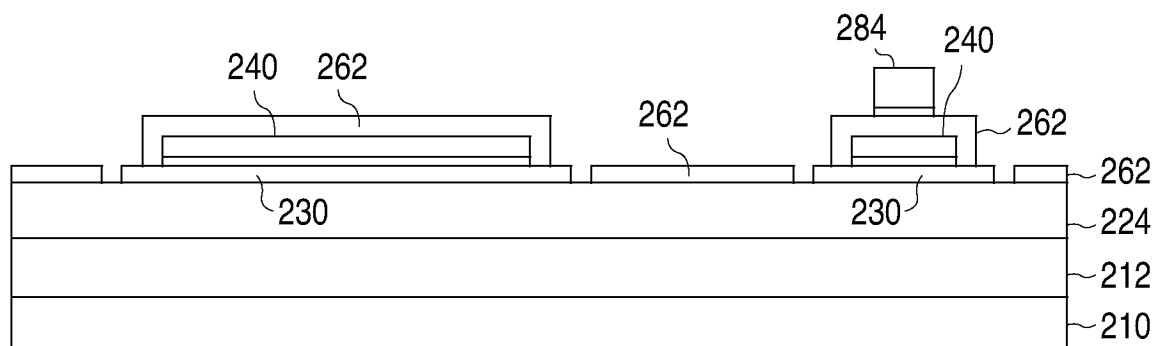
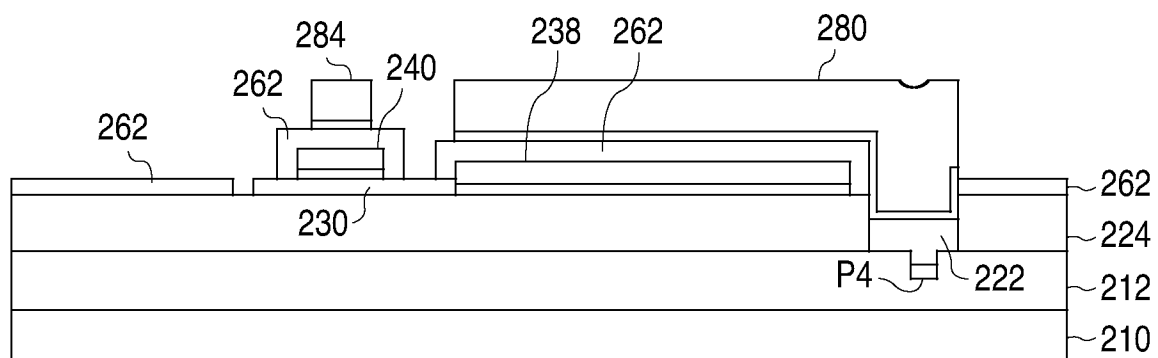
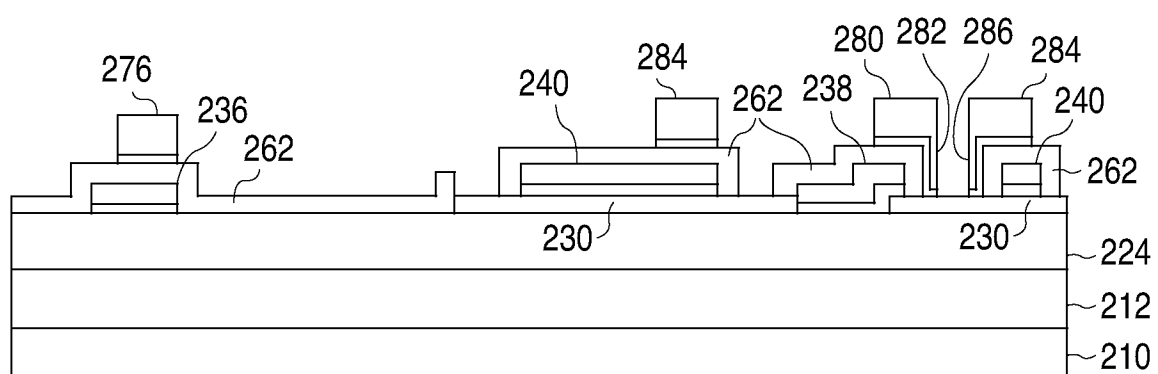


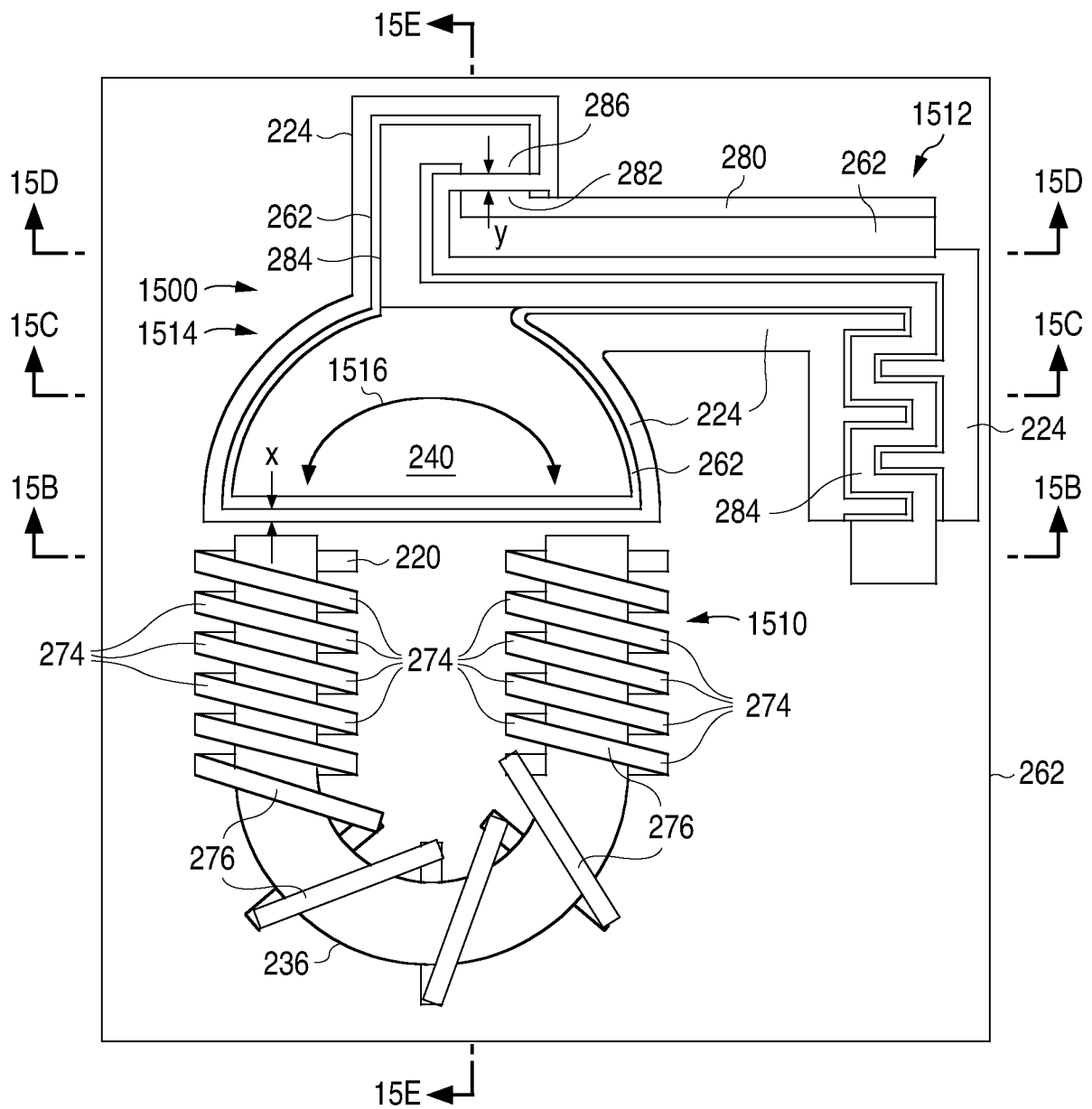
**FIG. 13E**



**FIG. 14A**

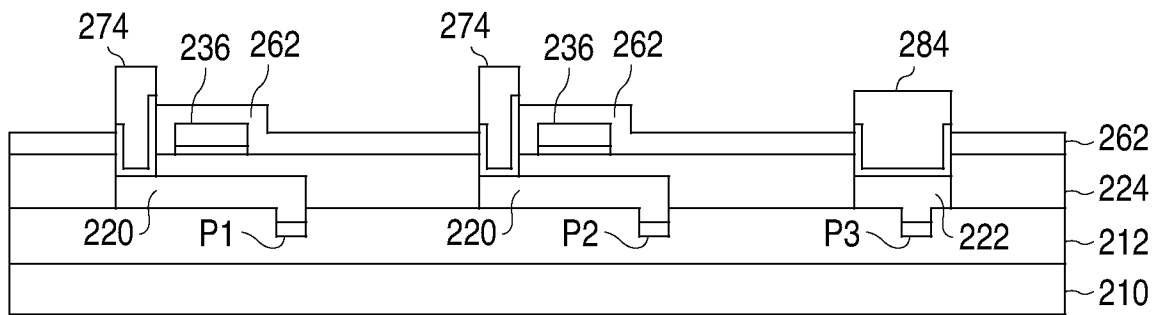
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**FIG. 14B****FIG. 14C****FIG. 14D****FIG. 14E**

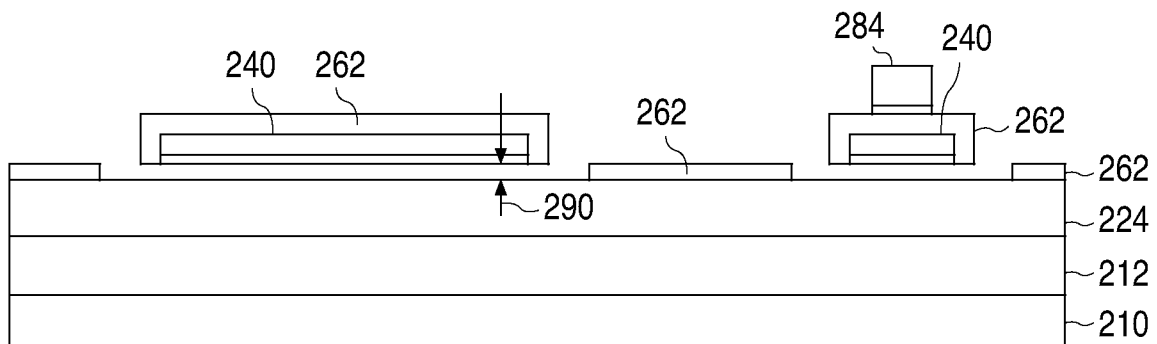


**FIG. 15A**

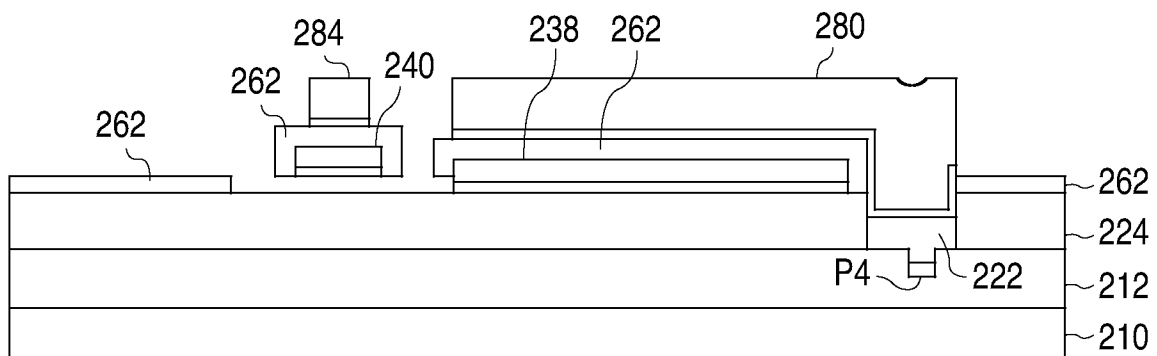
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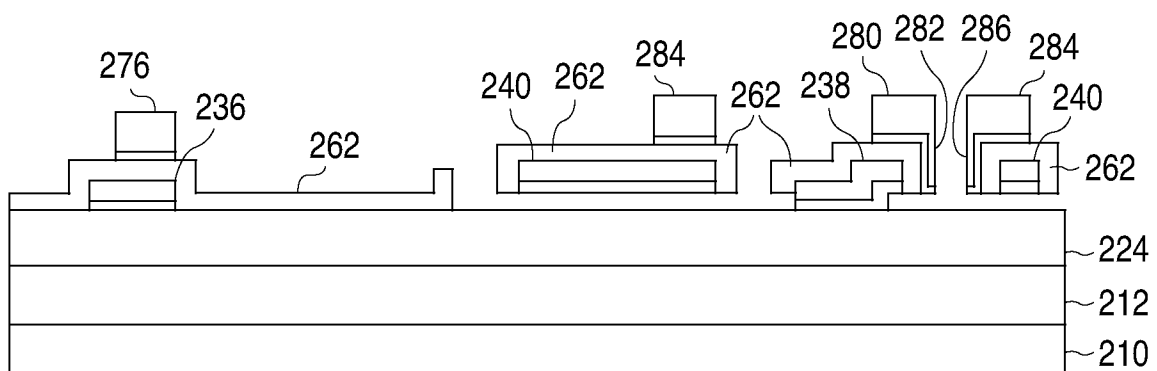
**FIG. 15B**



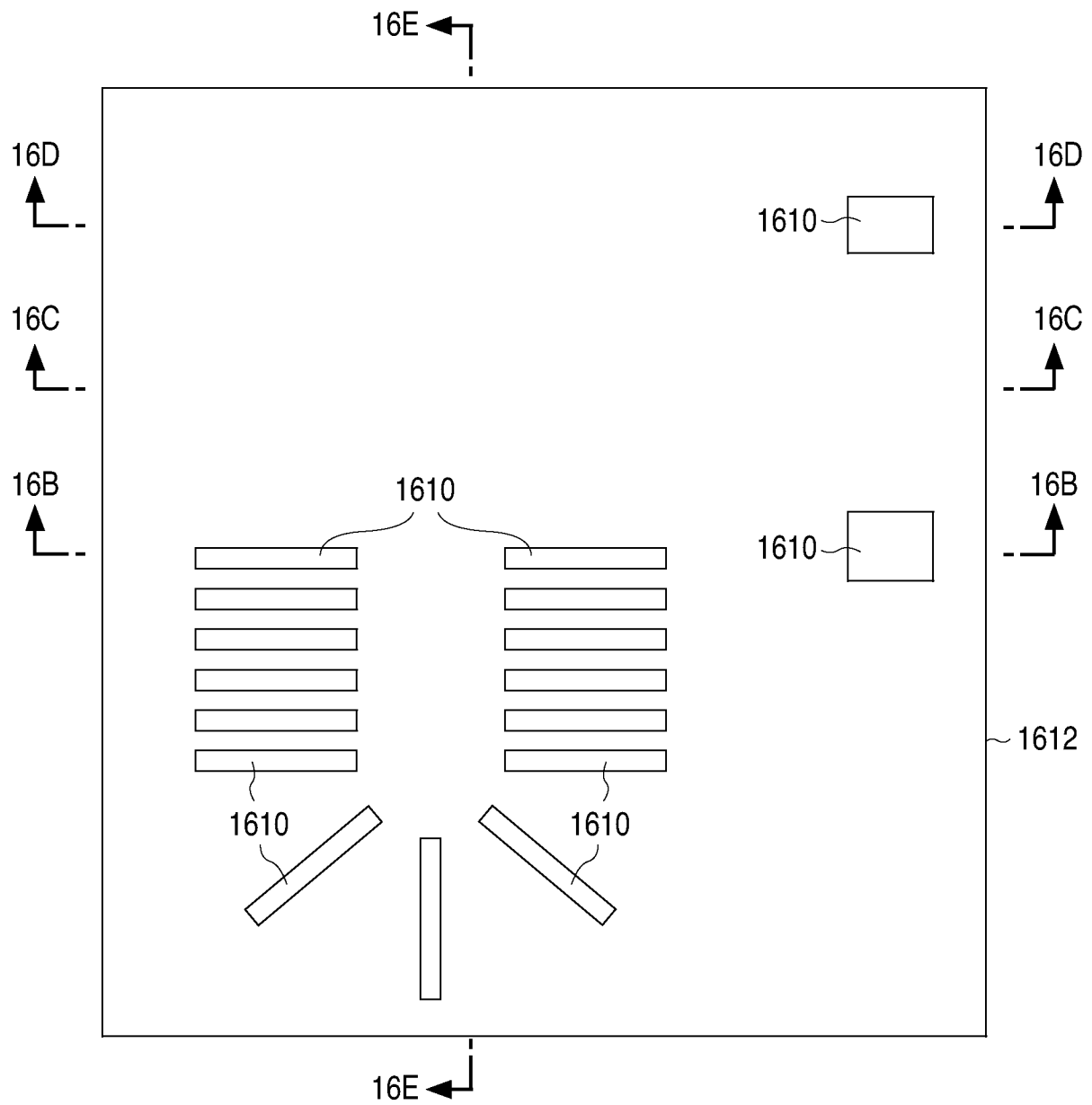
**FIG. 15C**



**FIG. 15D**



**FIG. 15E**



**FIG. 16A**

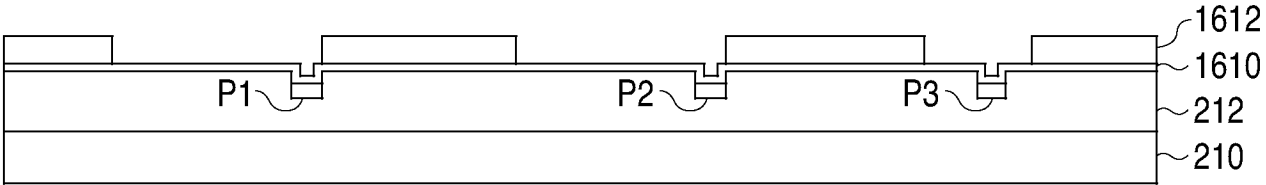


FIG. 16B

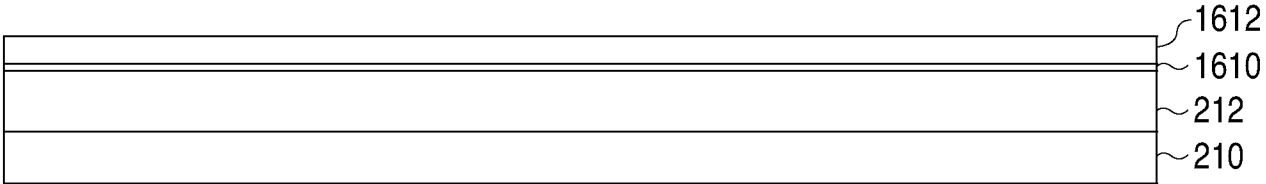


FIG. 16C

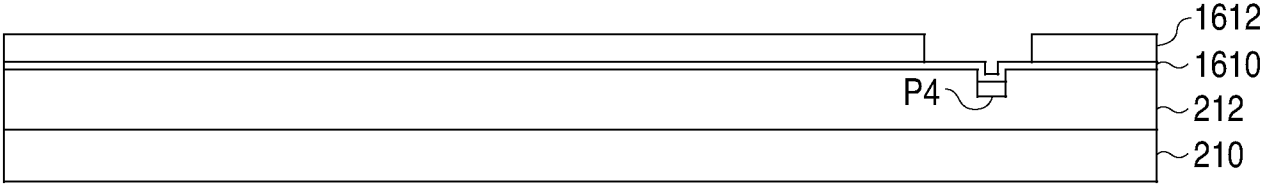


FIG. 16D

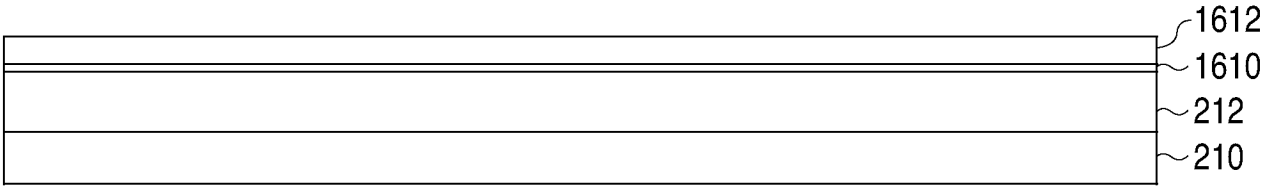


FIG. 16E

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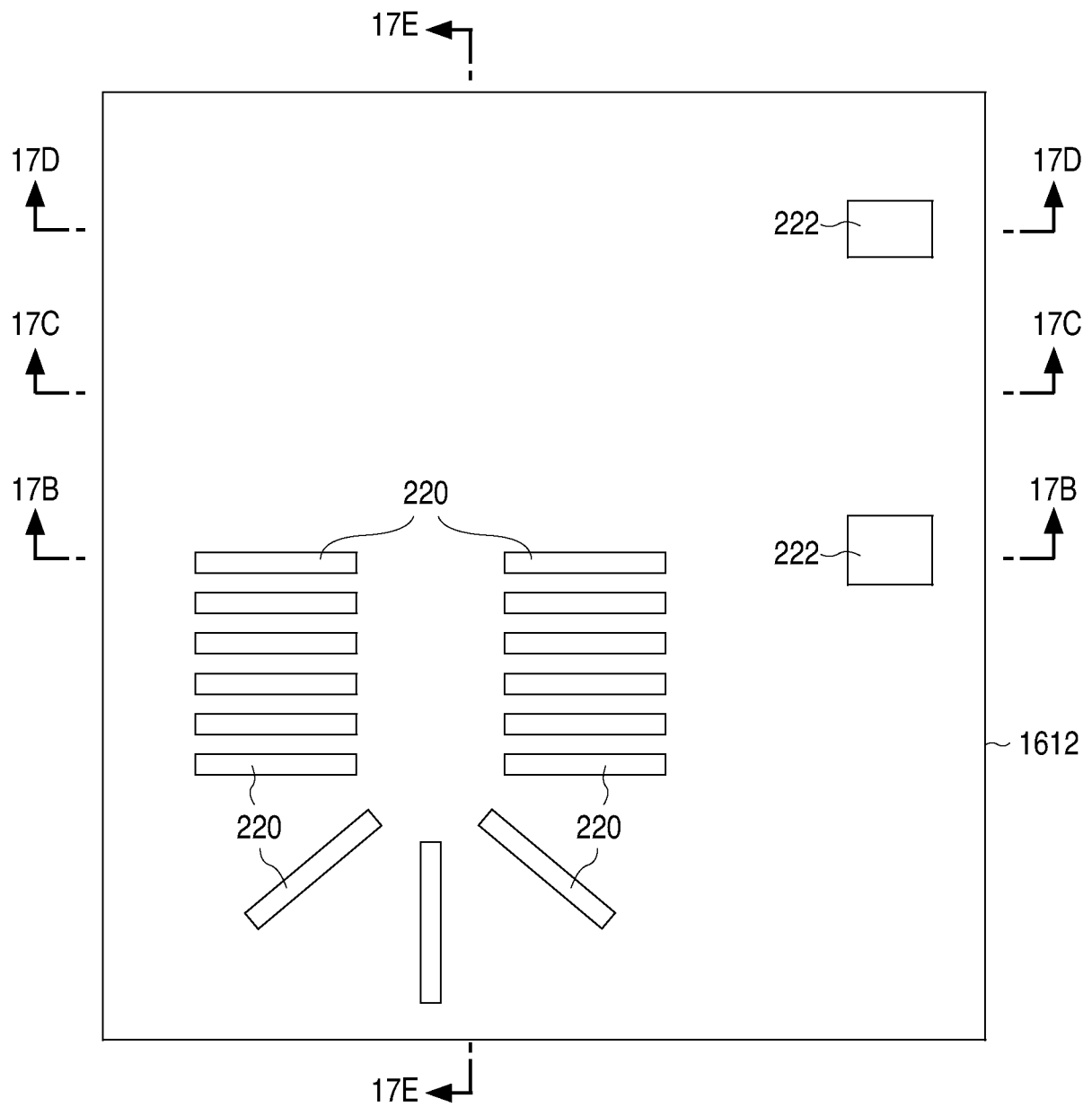


FIG. 17A

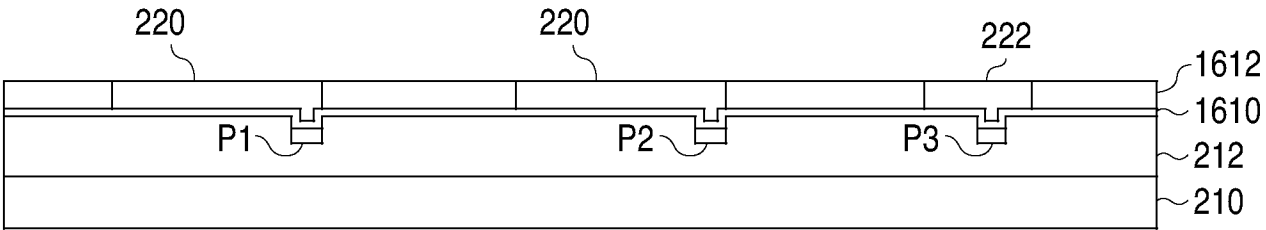


FIG. 17B

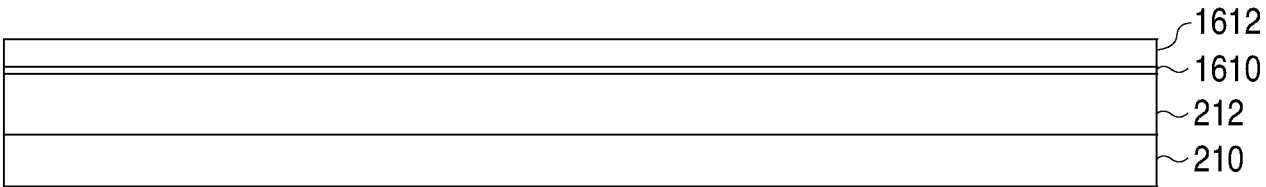


FIG. 17C

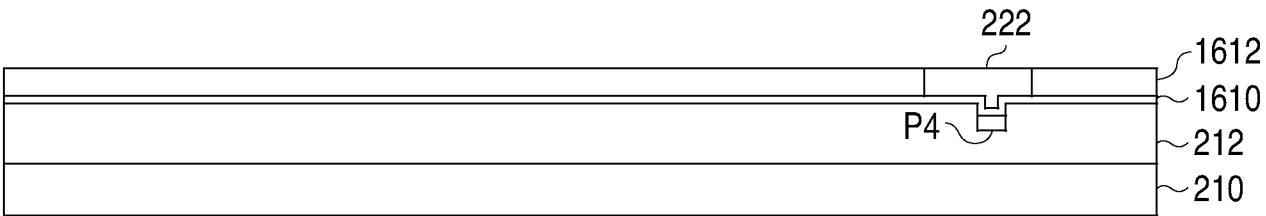


FIG. 17D

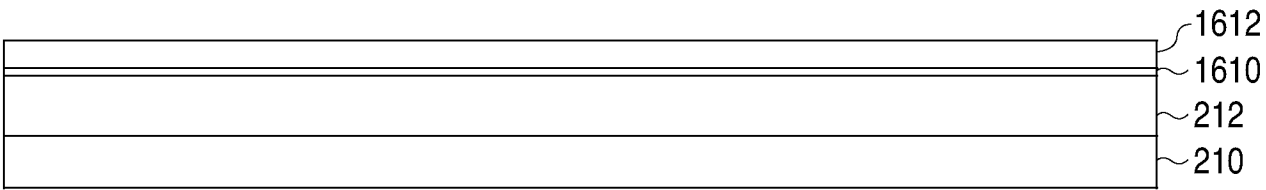
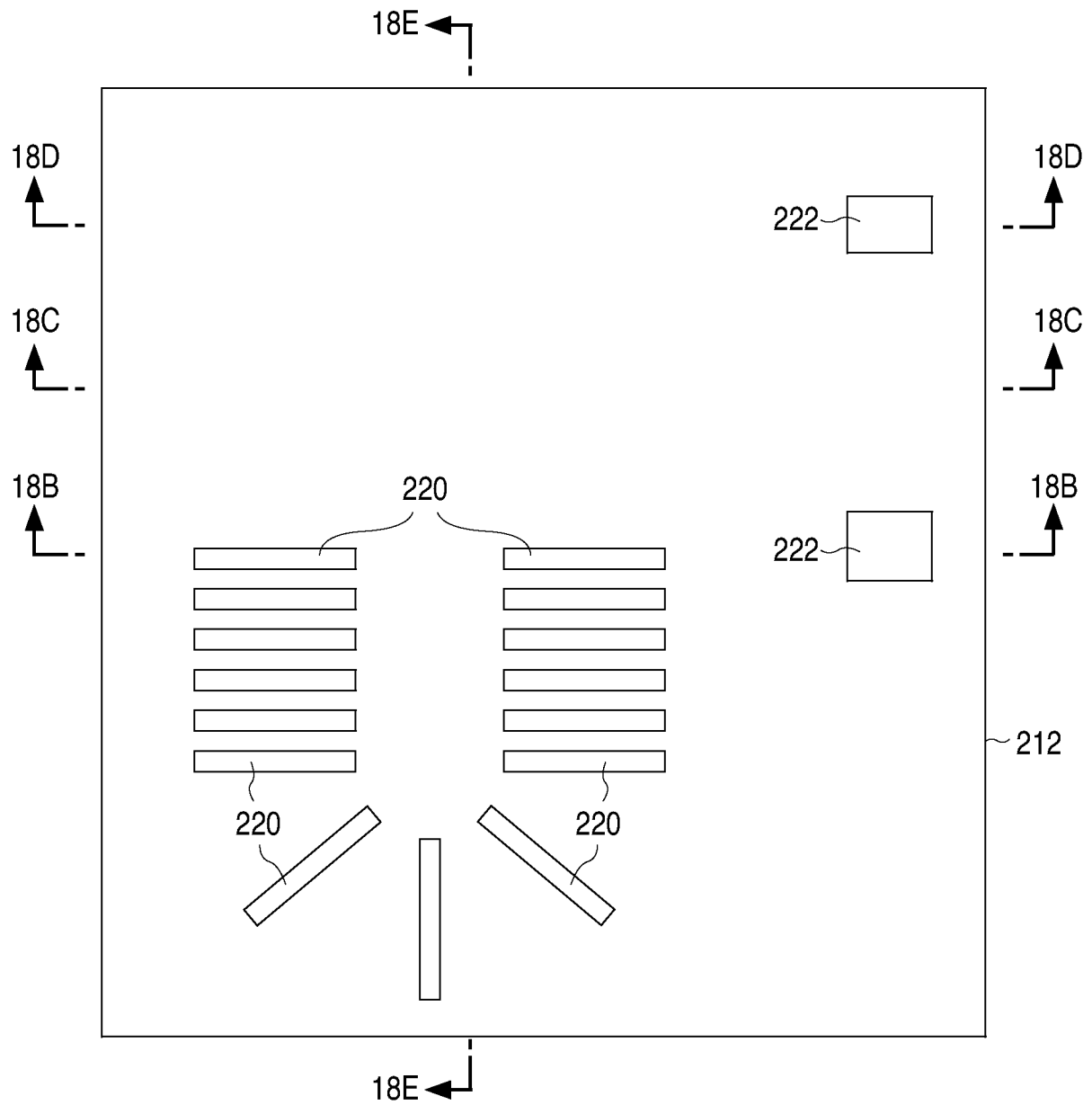


FIG. 17E

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**FIG. 18A**

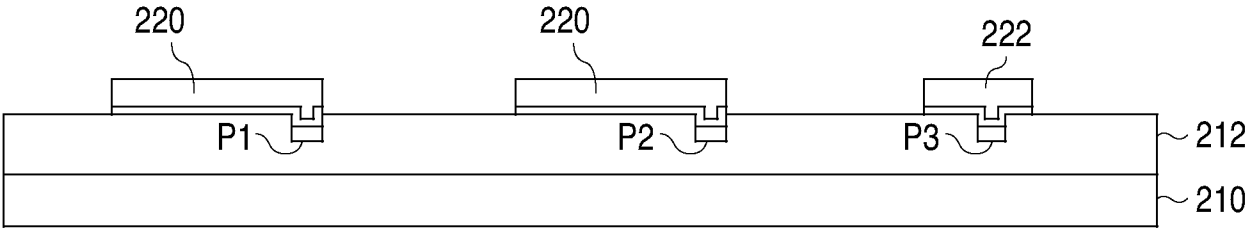


FIG. 18B



FIG. 18C

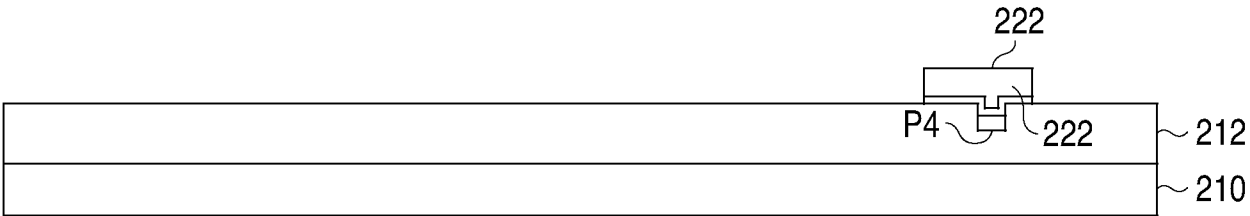


FIG. 18D

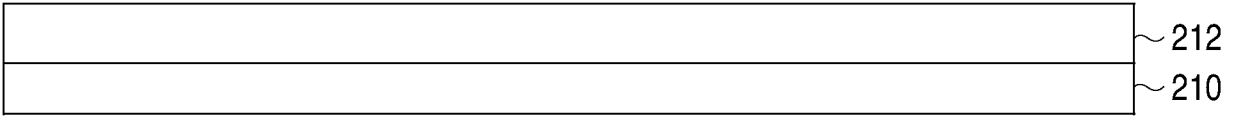
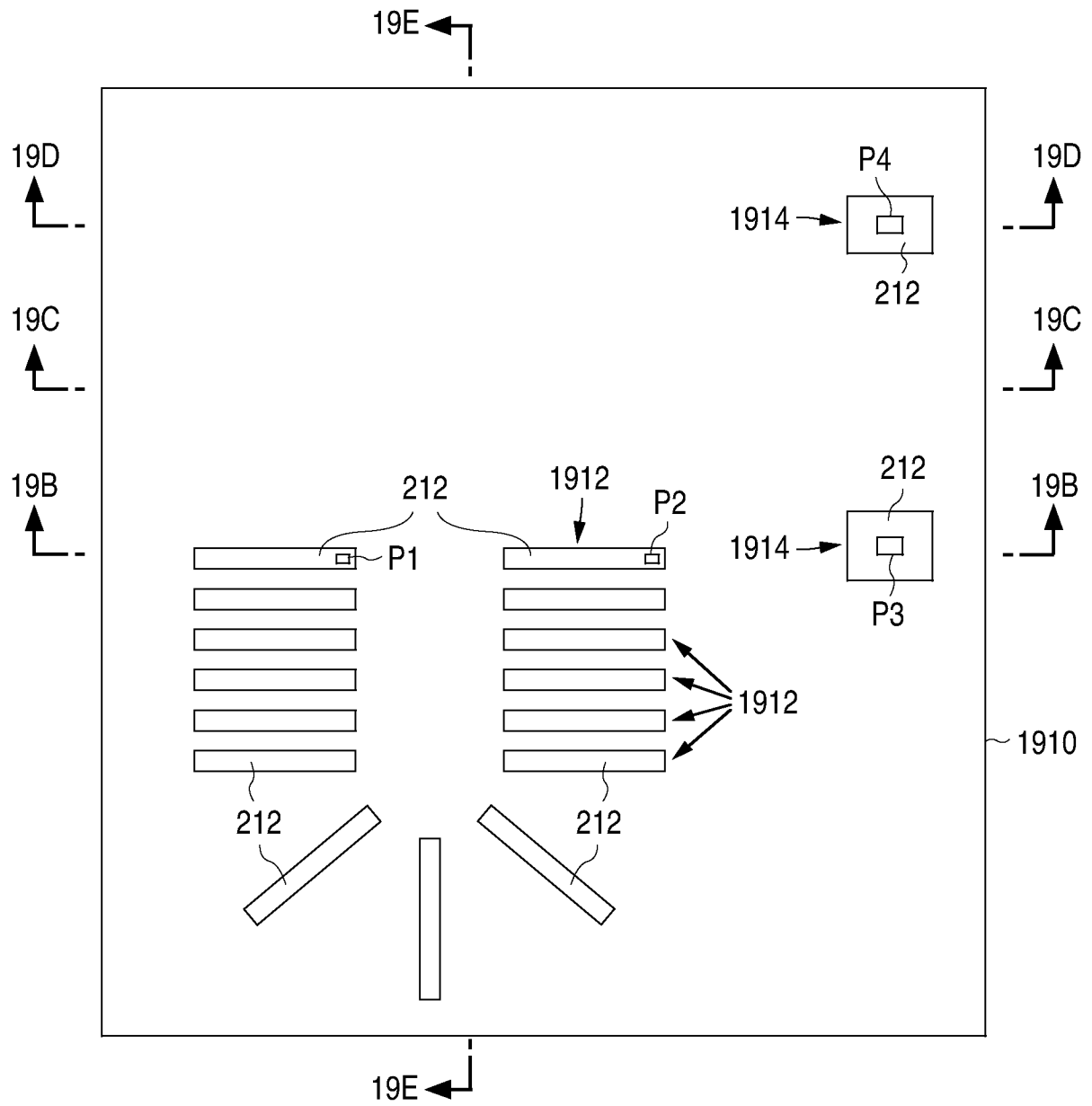


FIG. 18E



**FIG. 19A**

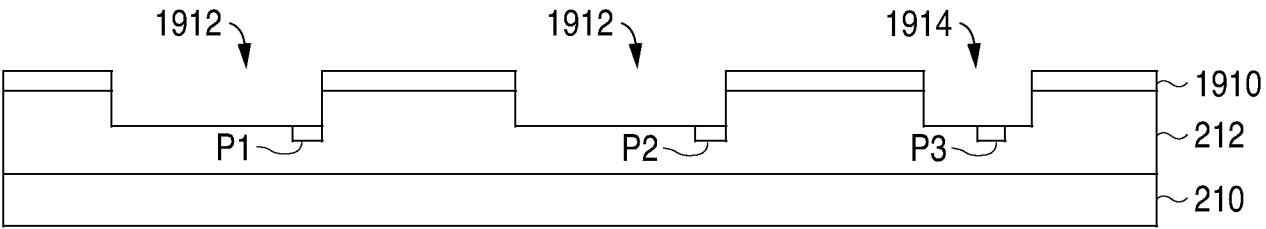


FIG. 19B

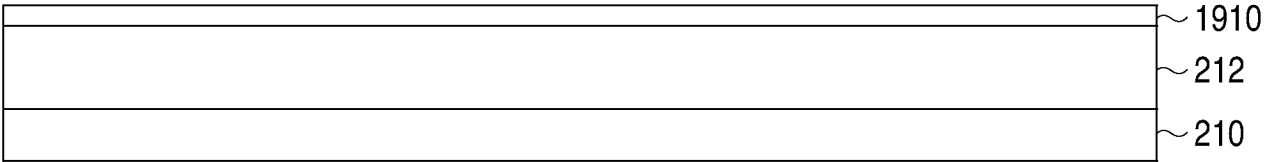


FIG. 19C

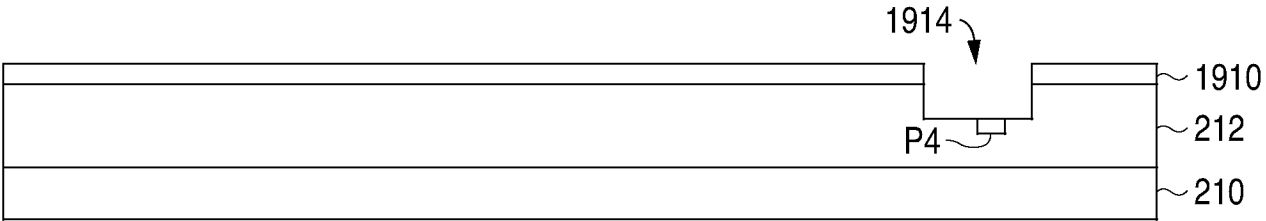


FIG. 19D

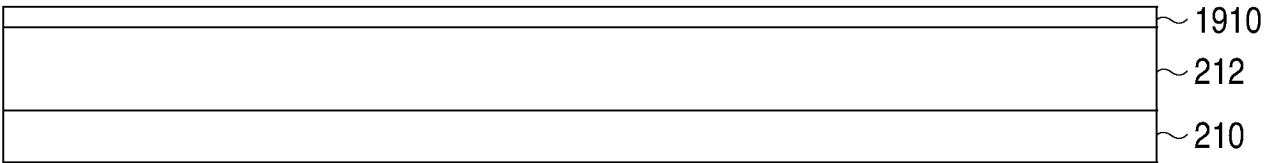


FIG. 19E

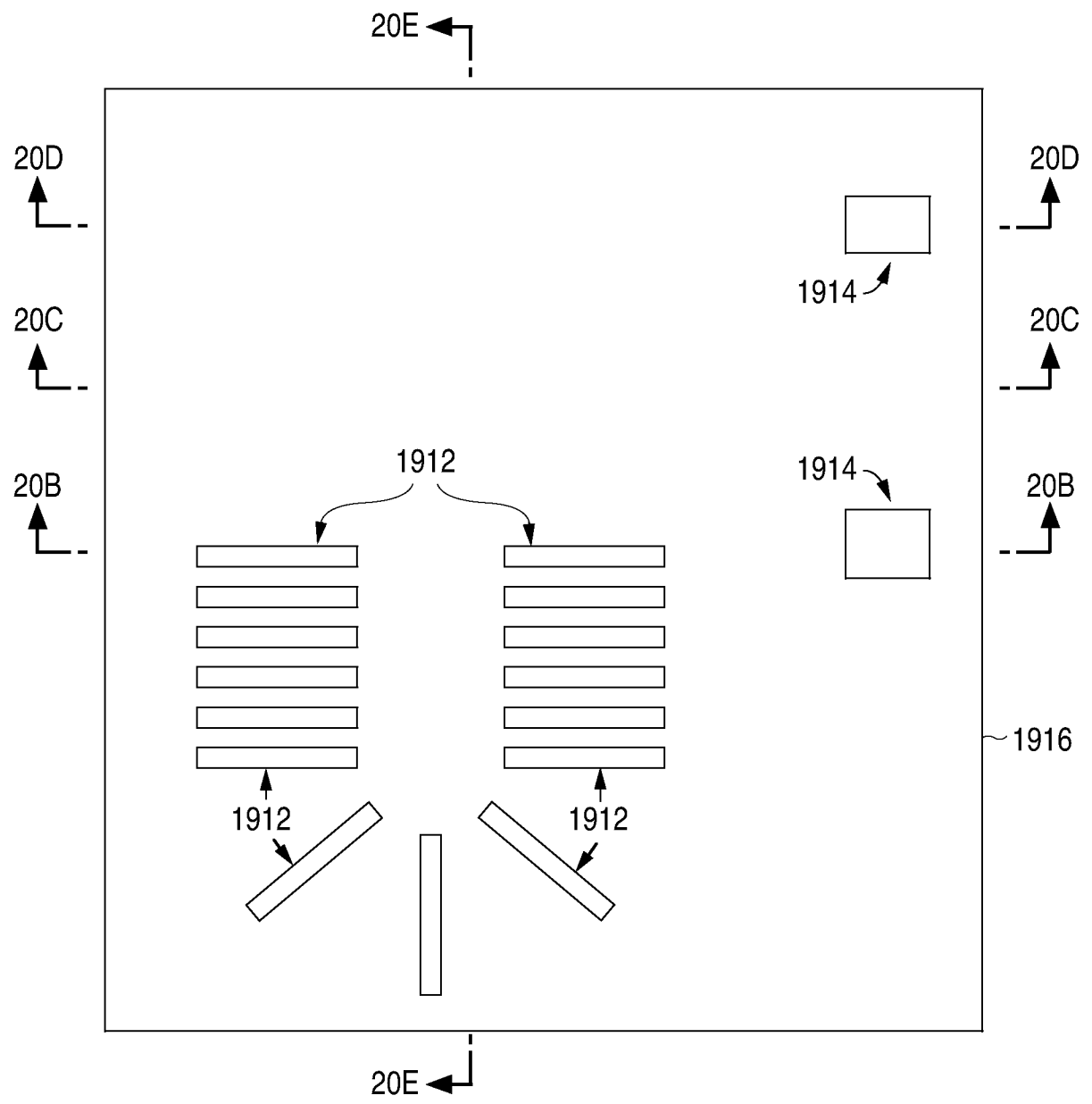


FIG. 20A

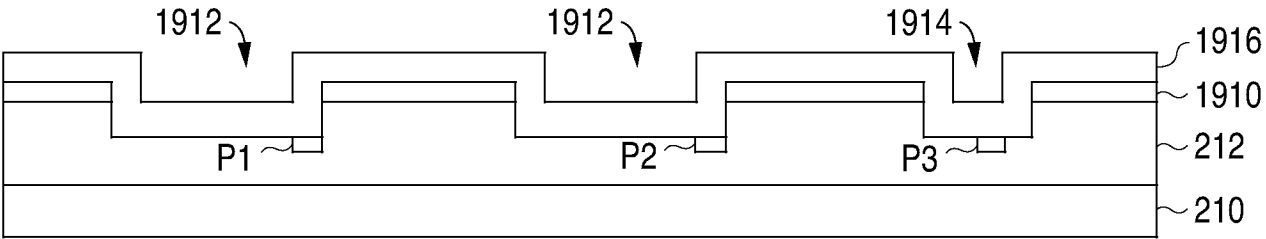


FIG. 20B

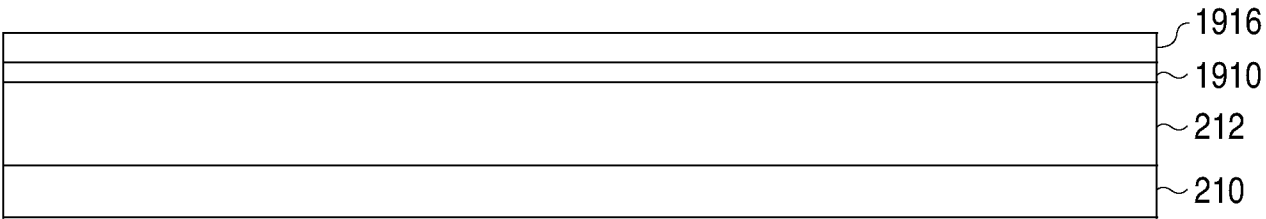


FIG. 20C

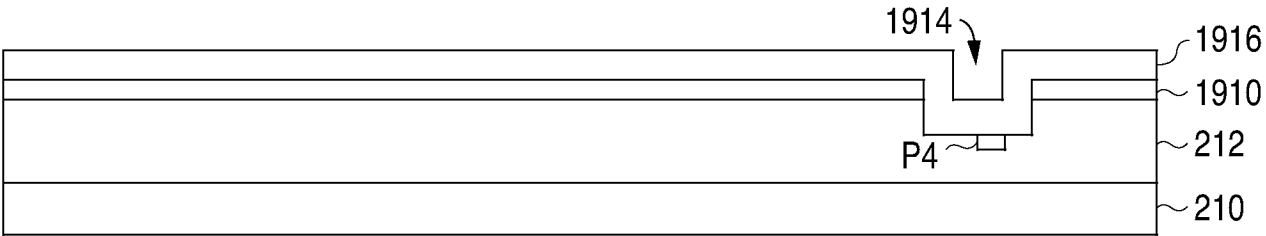


FIG. 20D

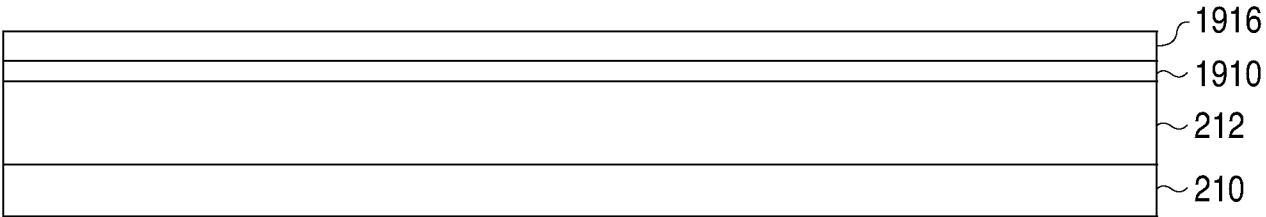
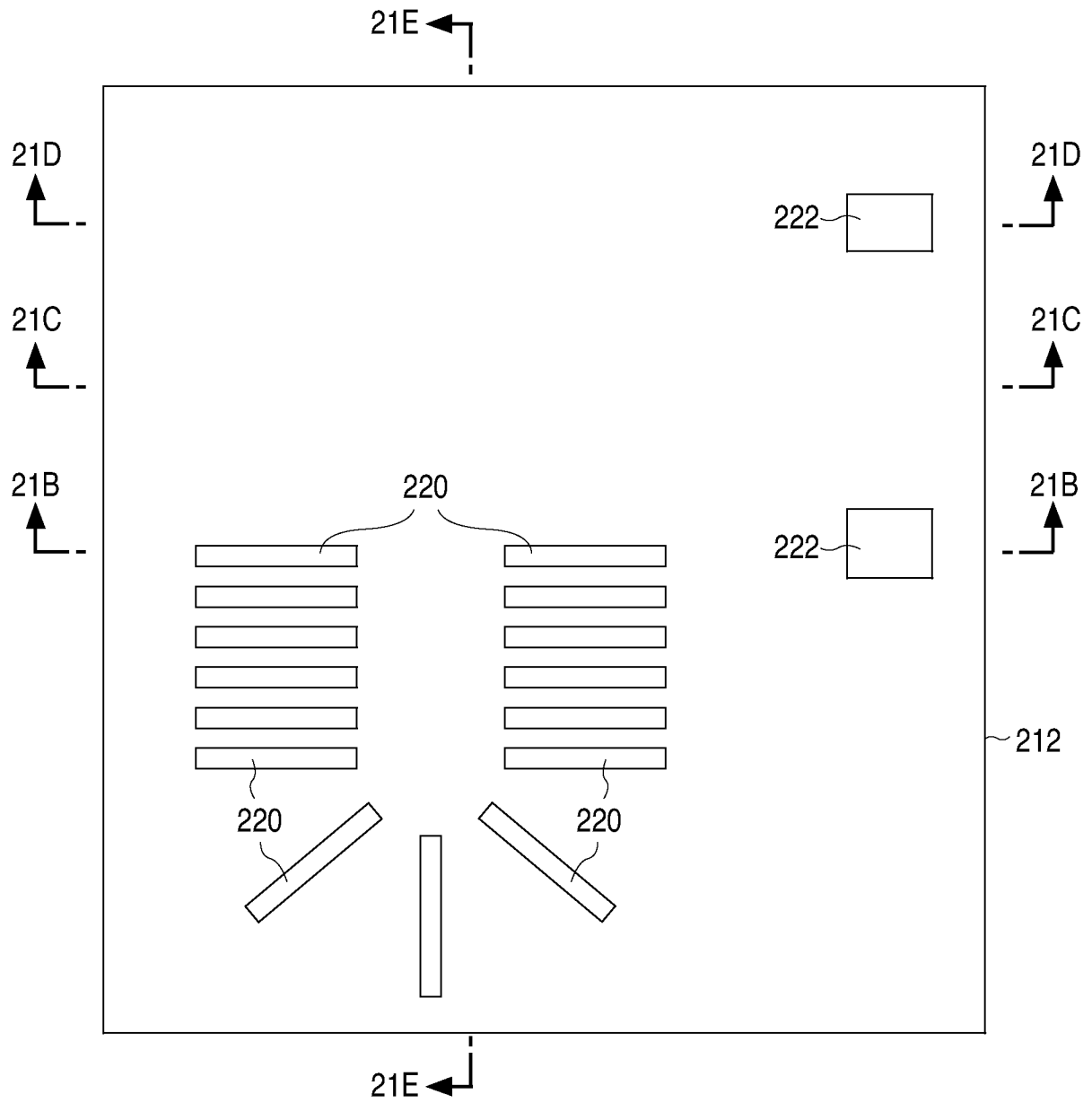


FIG. 20E



**FIG. 21A**

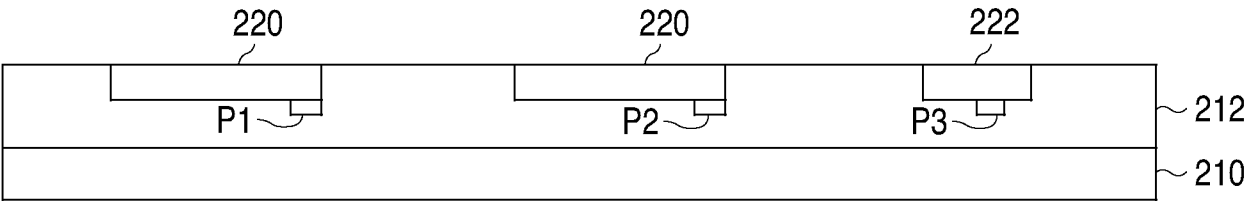


FIG. 21B



FIG. 21C

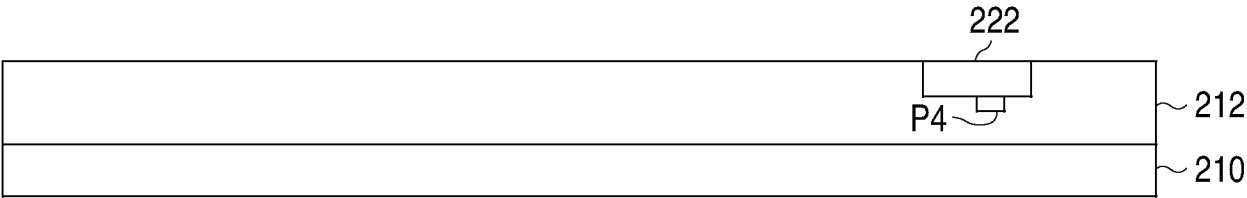


FIG. 21D

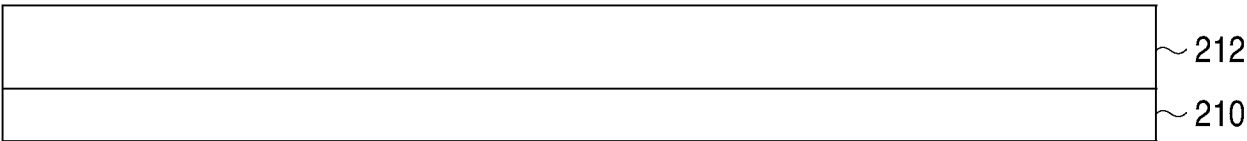


FIG. 21E

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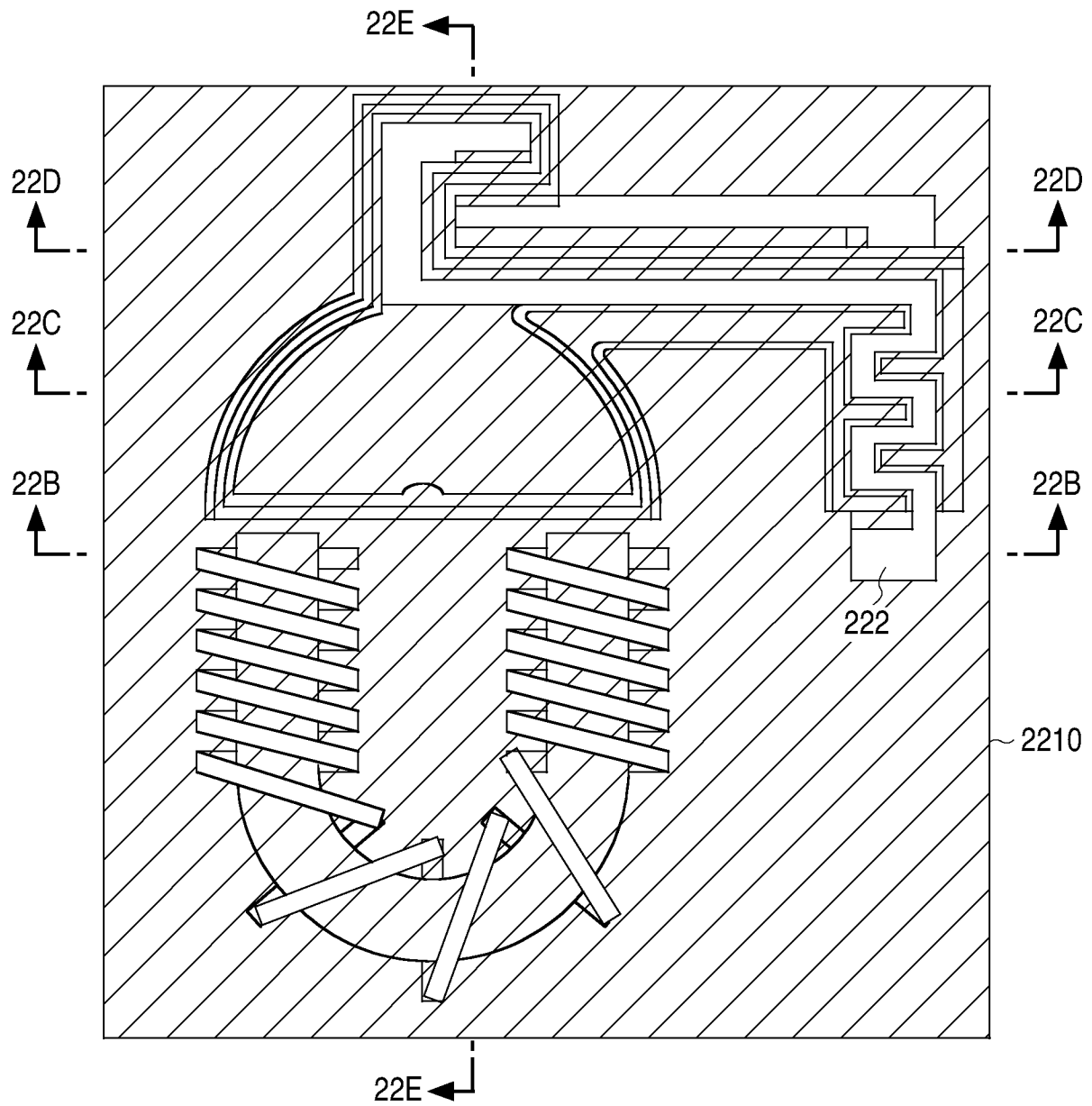
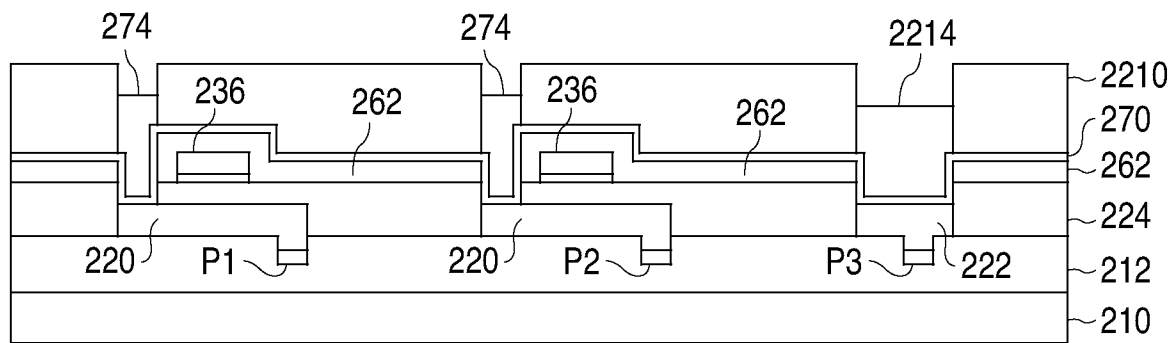
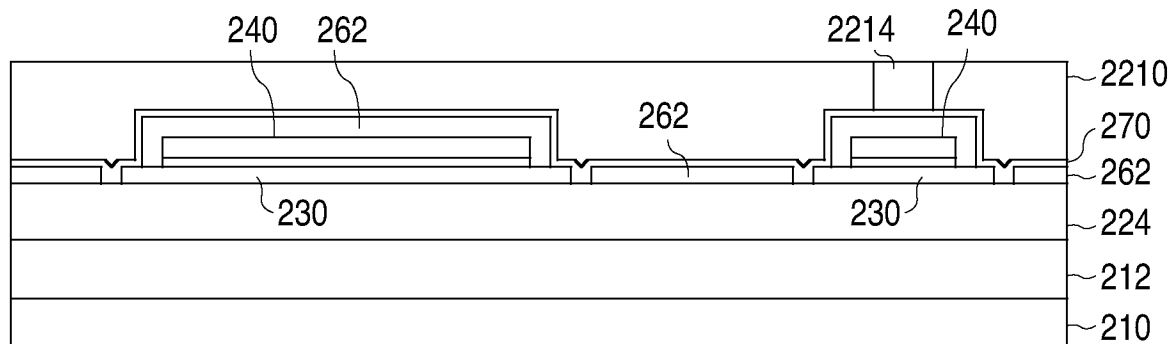


FIG. 22A

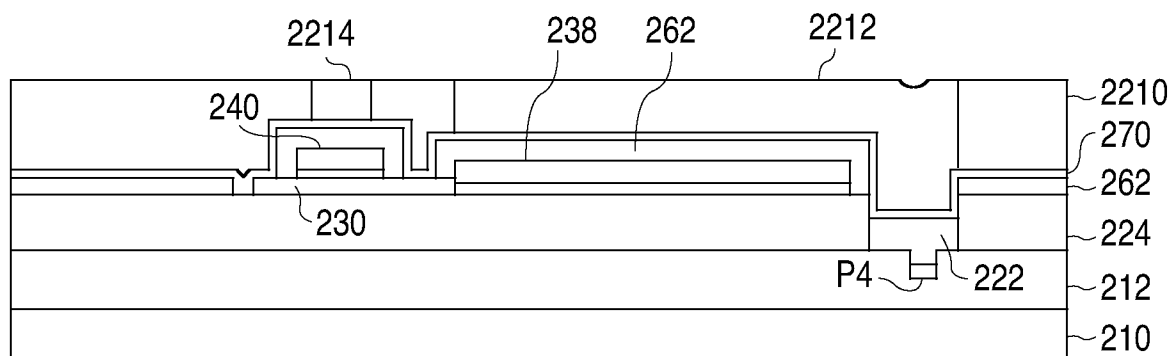
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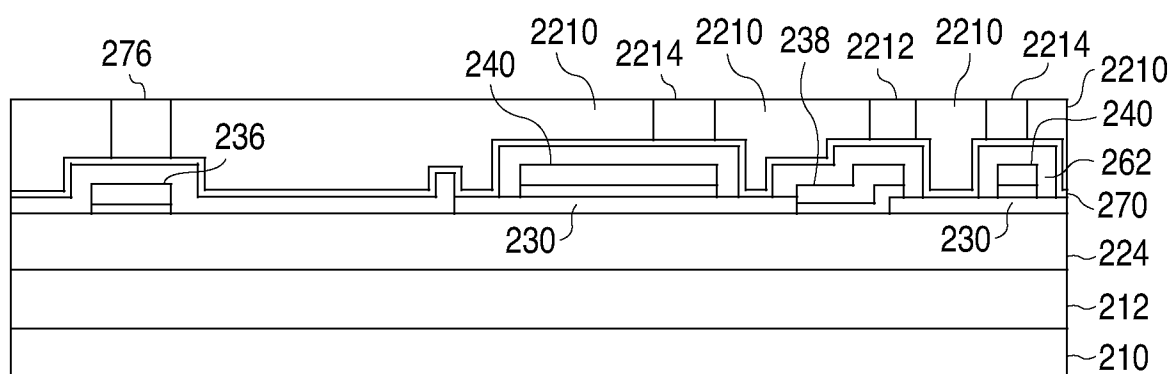
**FIG. 22B**



**FIG. 22C**

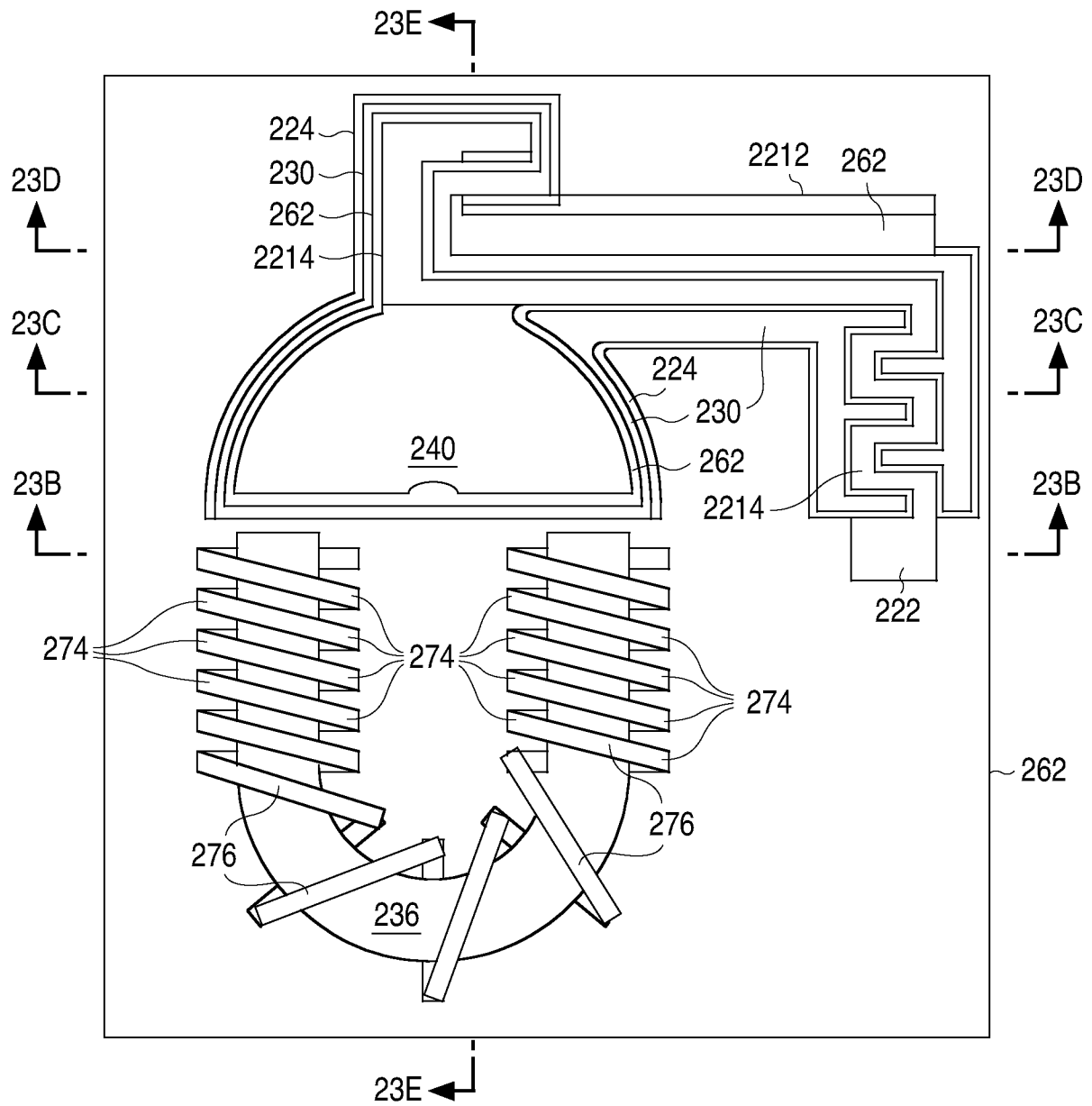


**FIG. 22D**

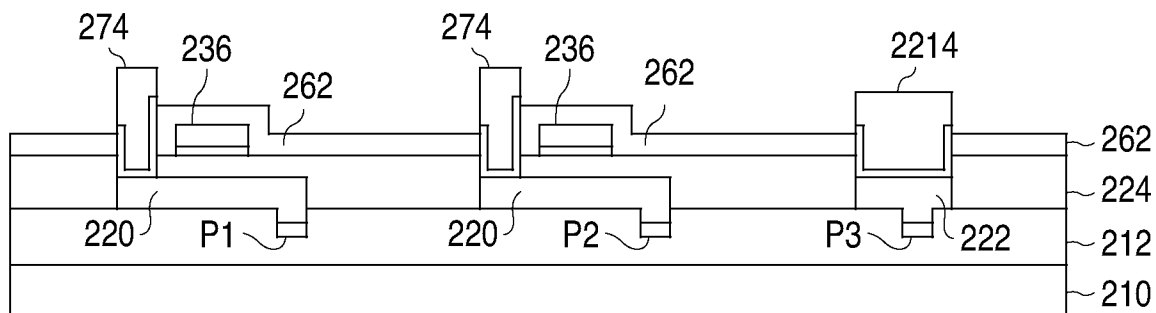
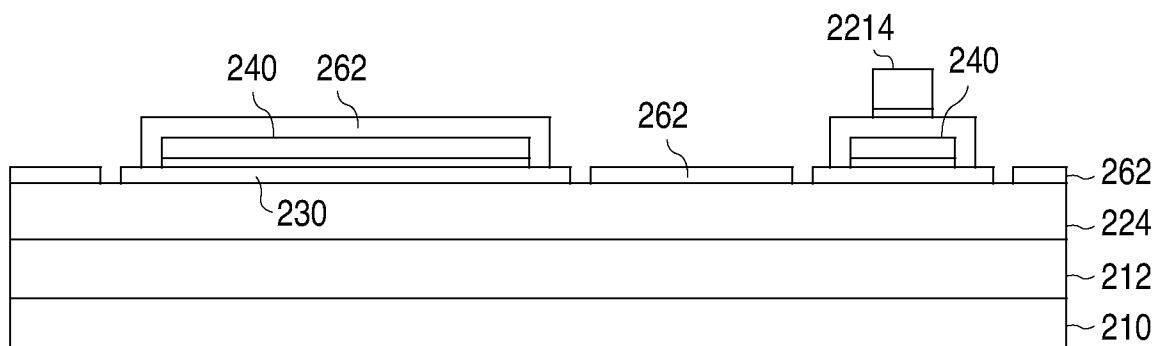
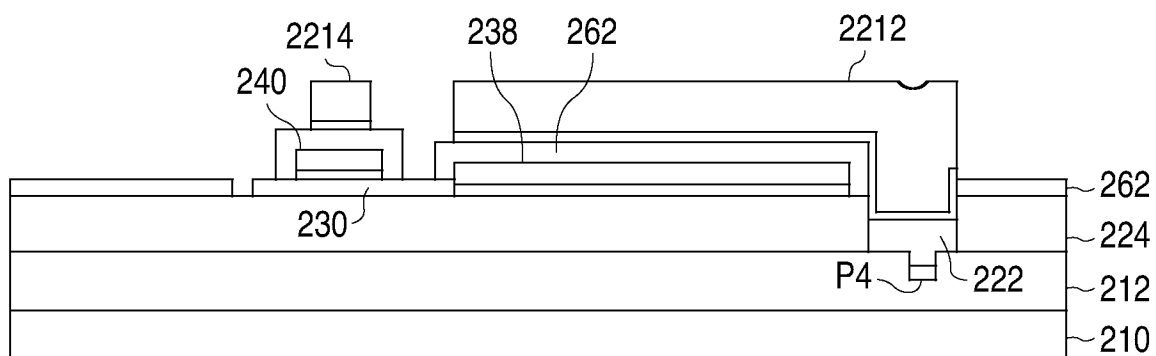
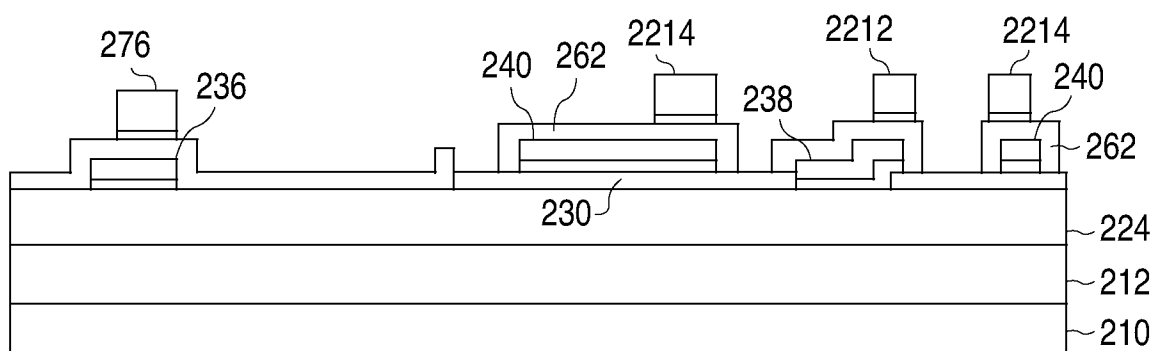


**FIG. 22E**

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**FIG. 23A**

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**FIG. 23B****FIG. 23C****FIG. 23D****FIG. 23E**

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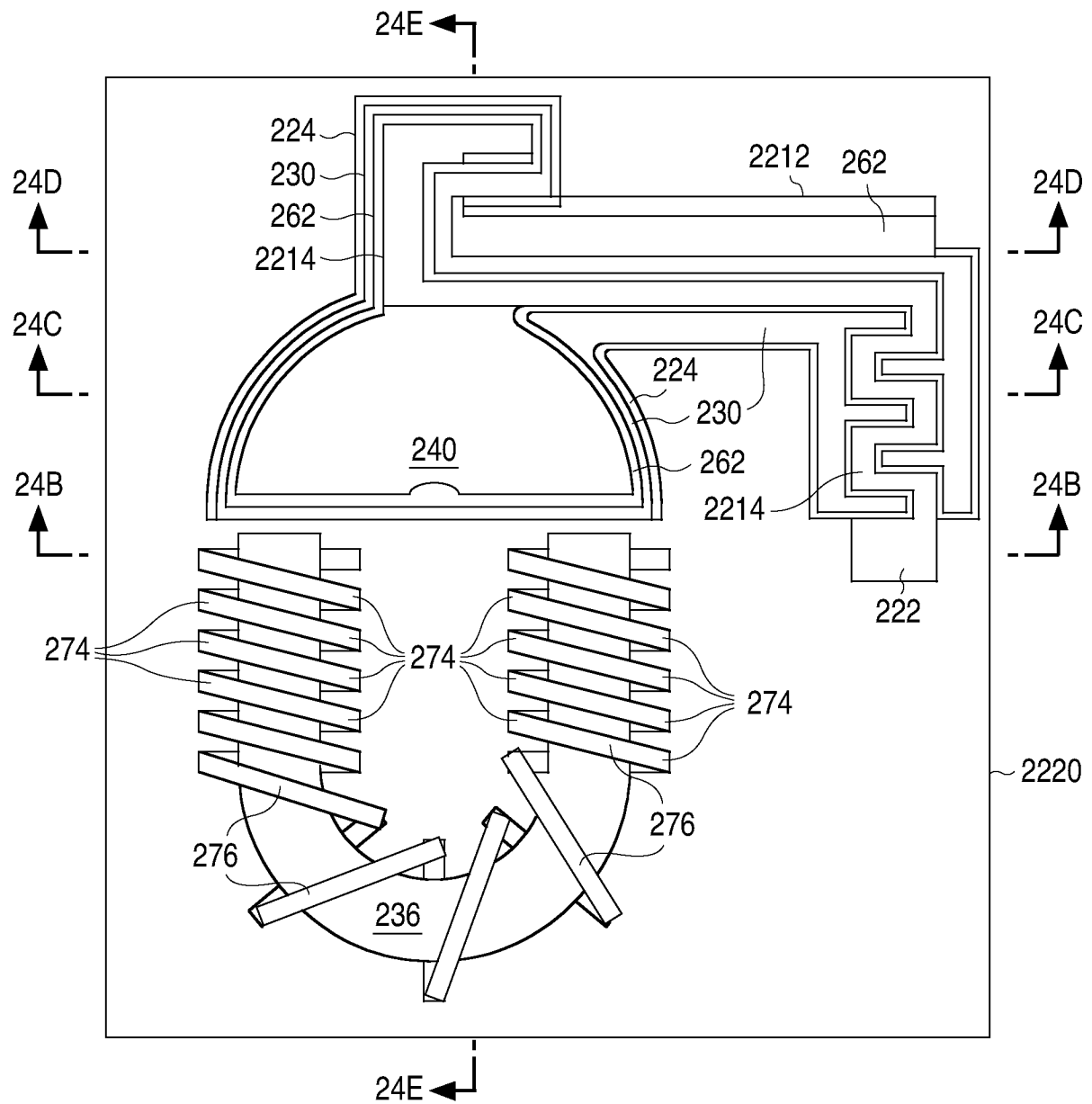


FIG. 24A

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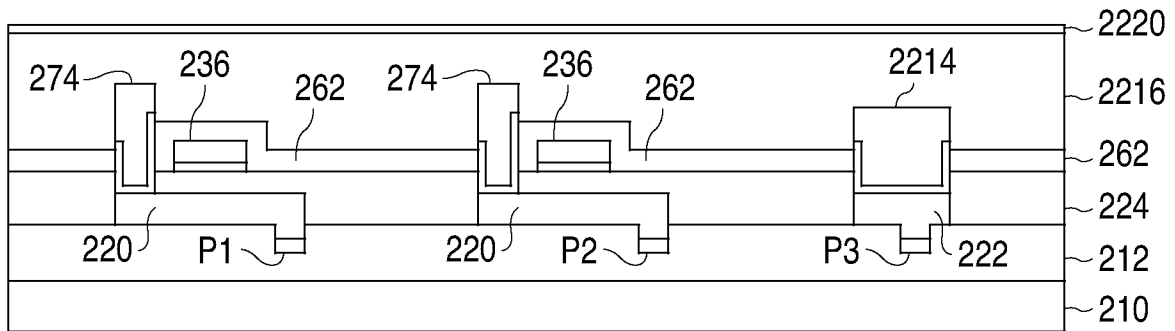


FIG. 24B

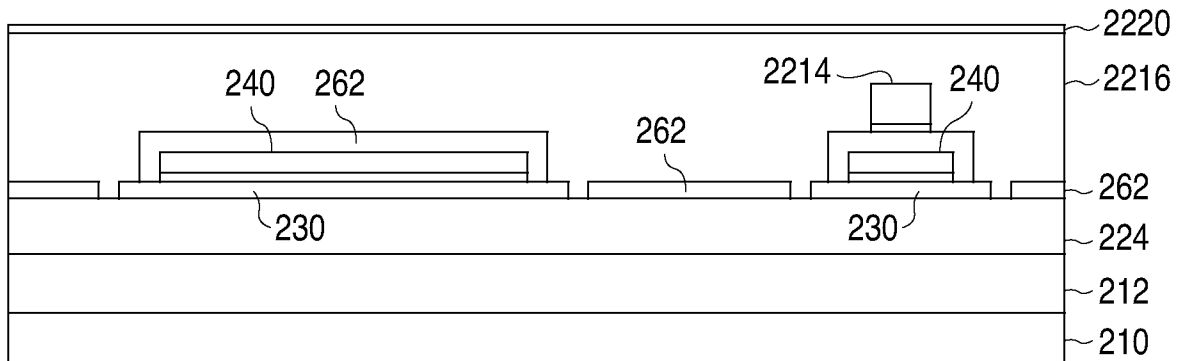


FIG. 24C

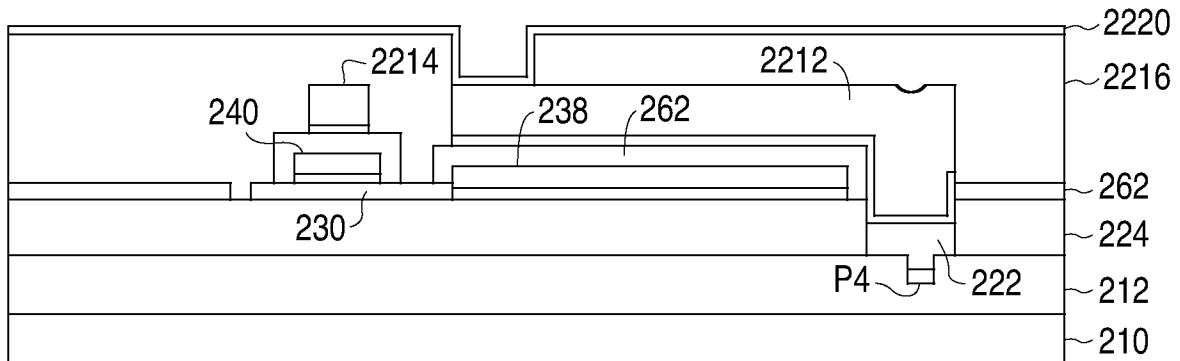


FIG. 24D

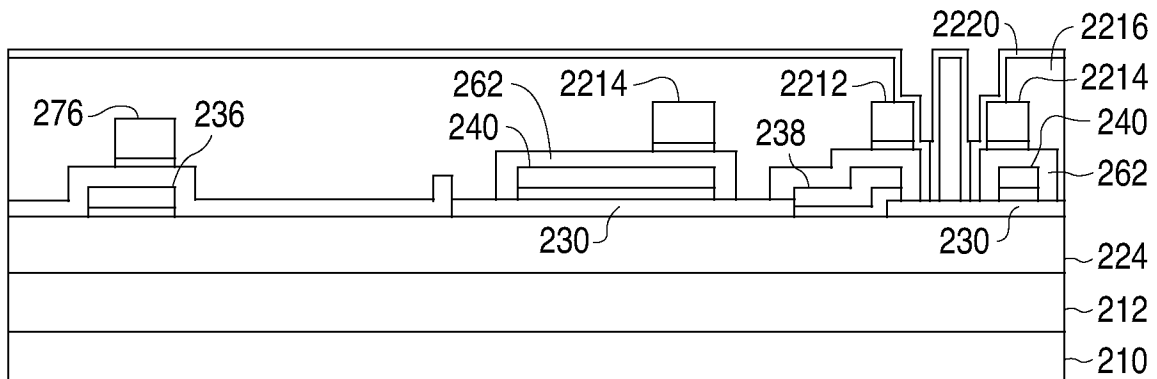


FIG. 24E

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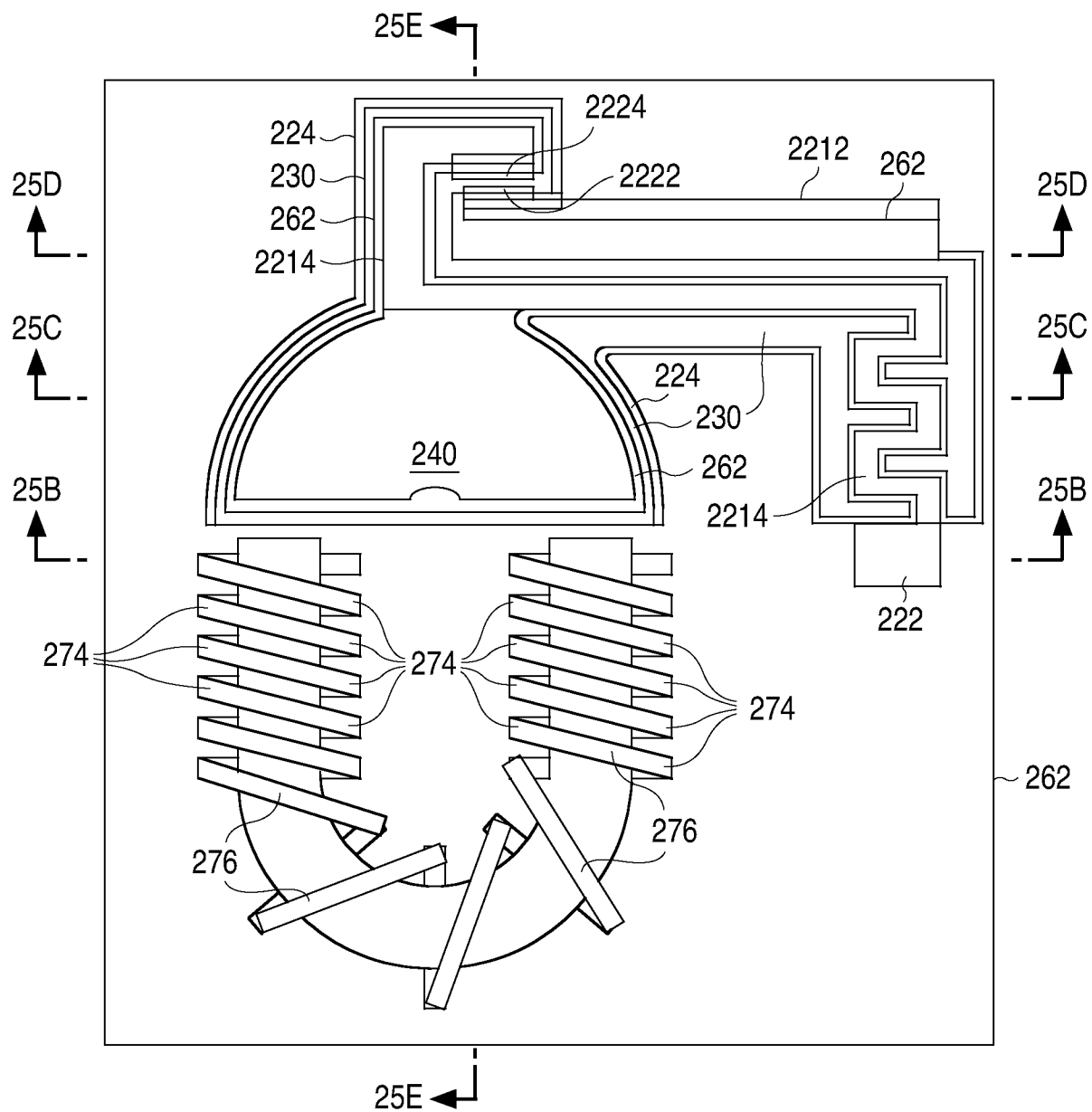
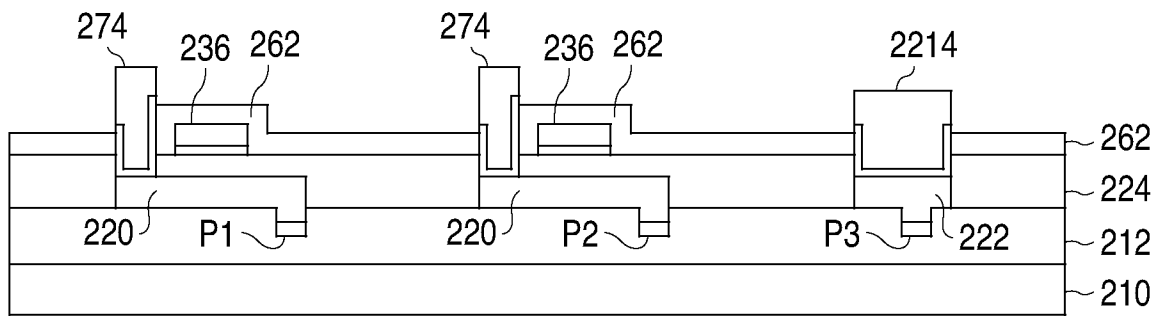
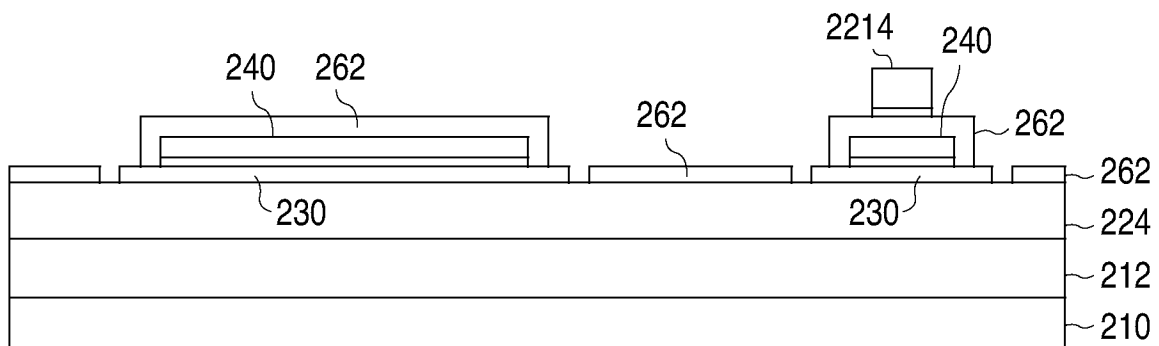
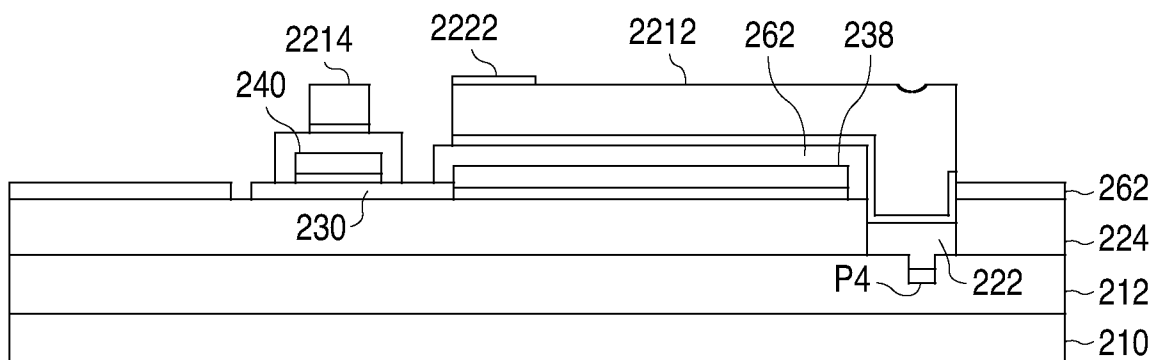
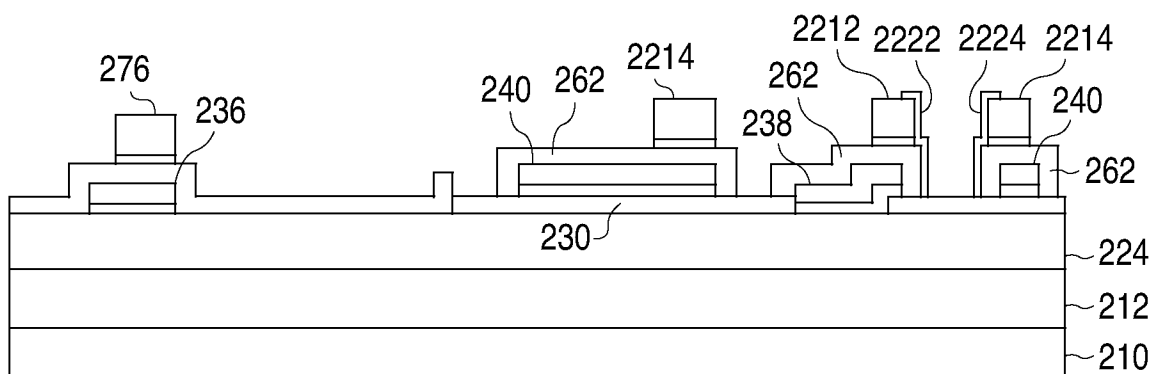


FIG. 25A

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**FIG. 25B****FIG. 25C****FIG. 25D****FIG. 25E**

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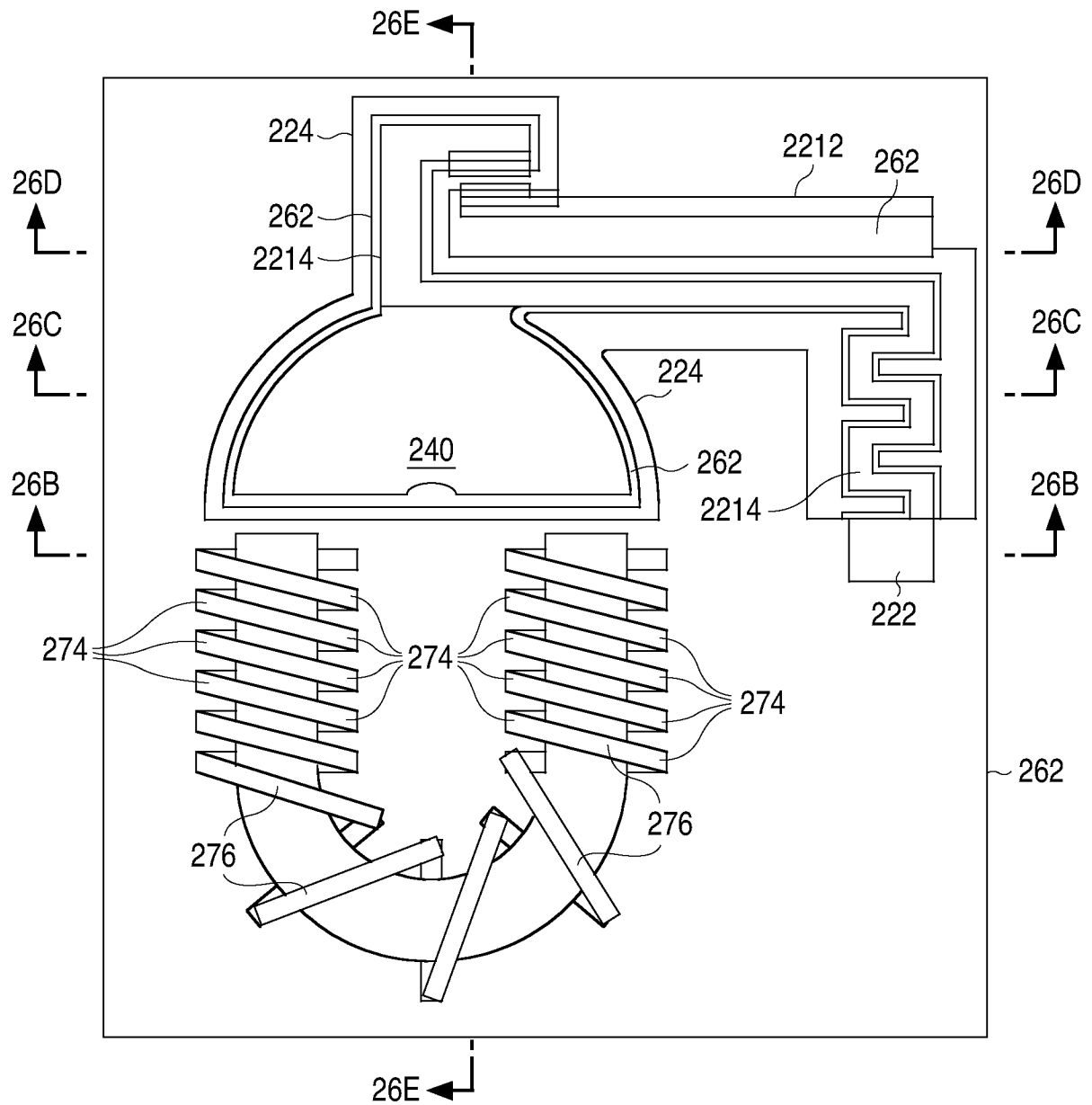
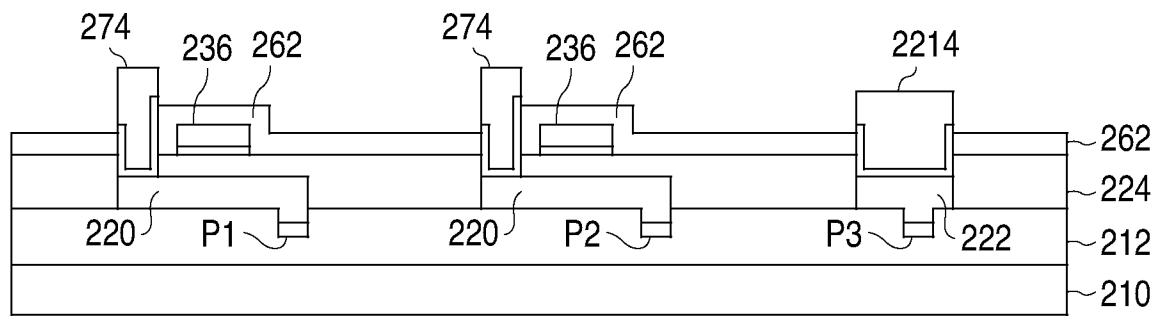
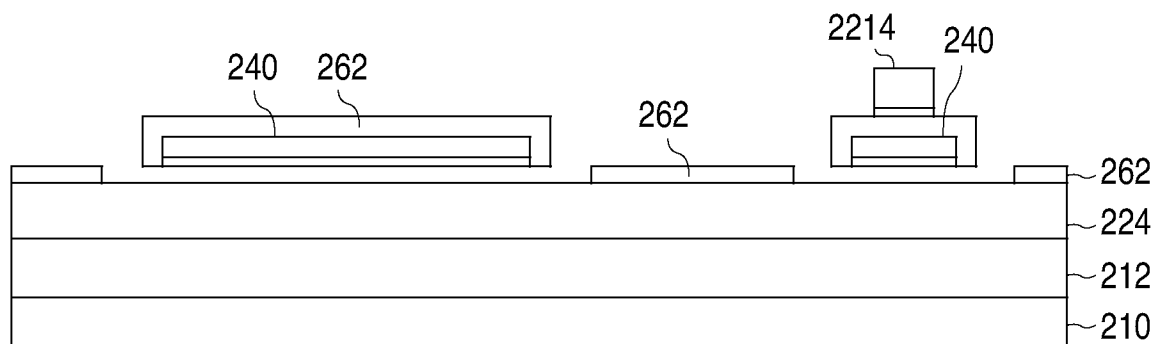
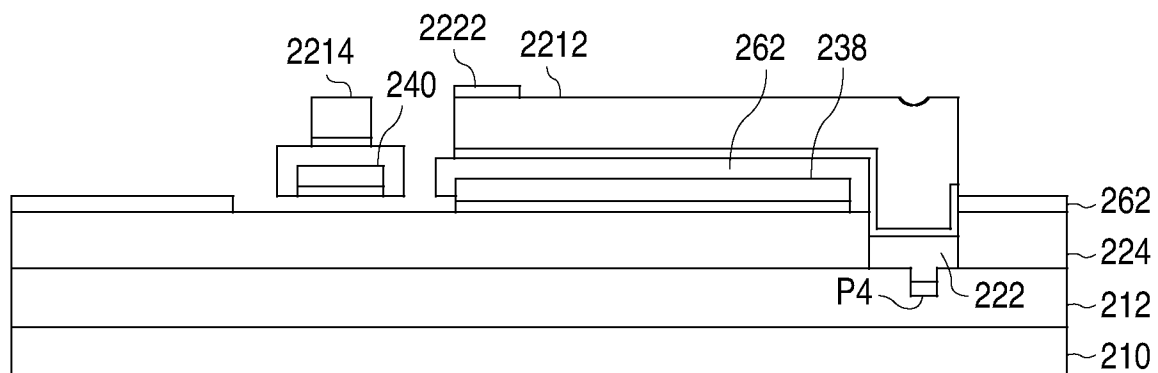
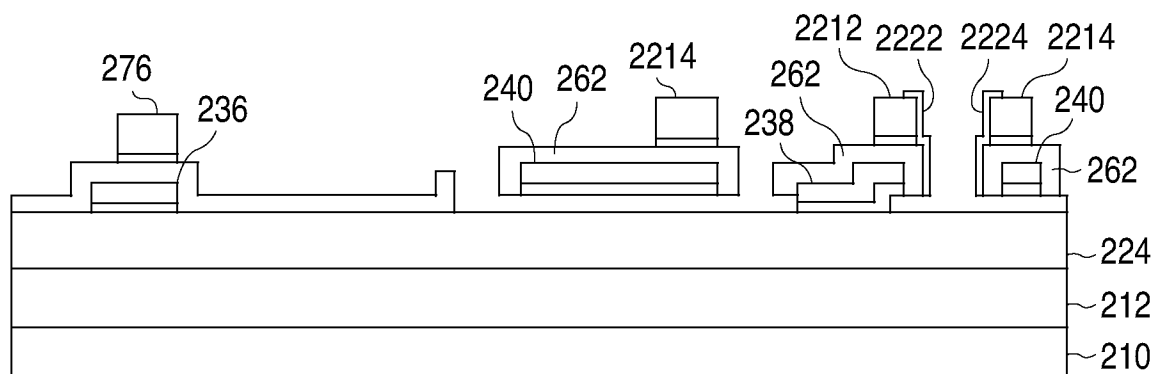


FIG. 26A

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**FIG. 26B****FIG. 26C****FIG. 26D****FIG. 26E**

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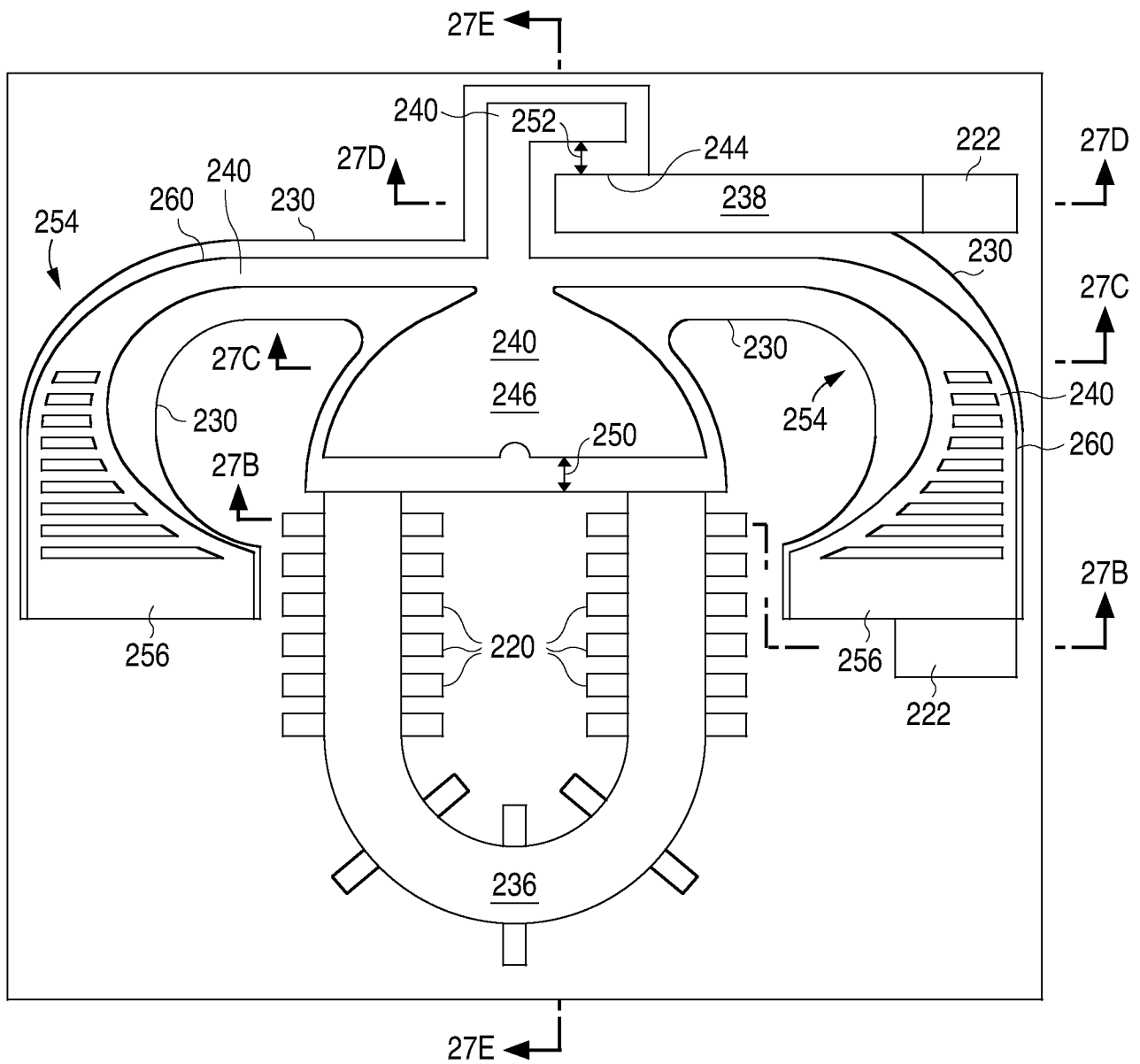
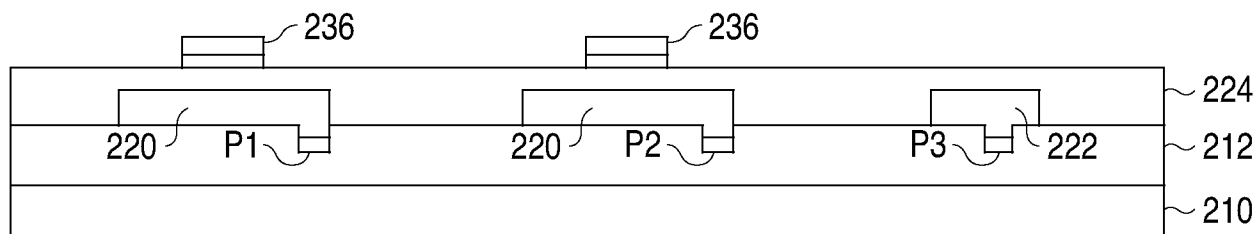
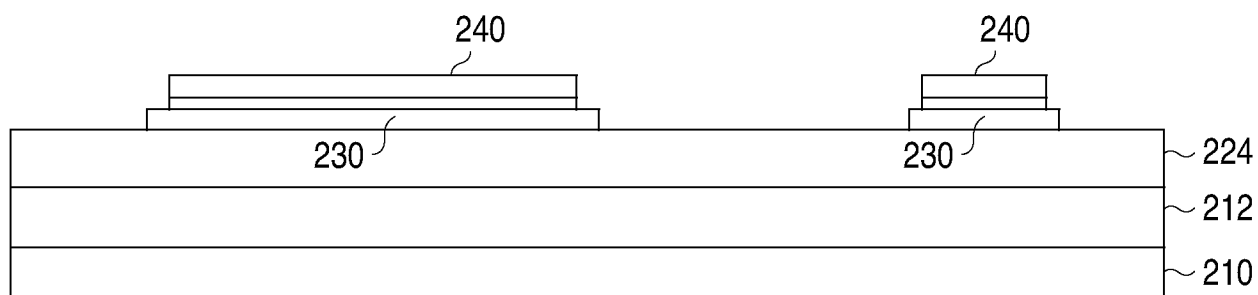
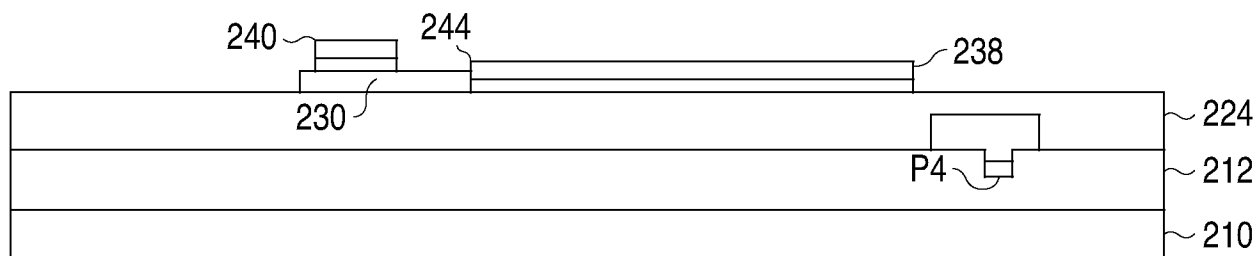
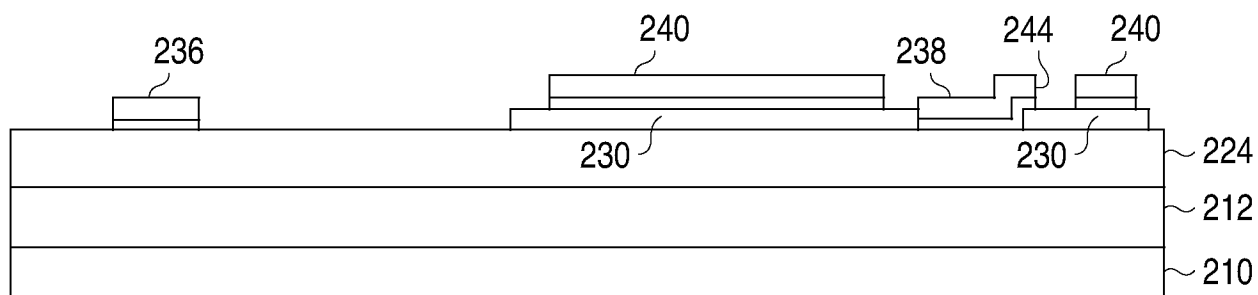
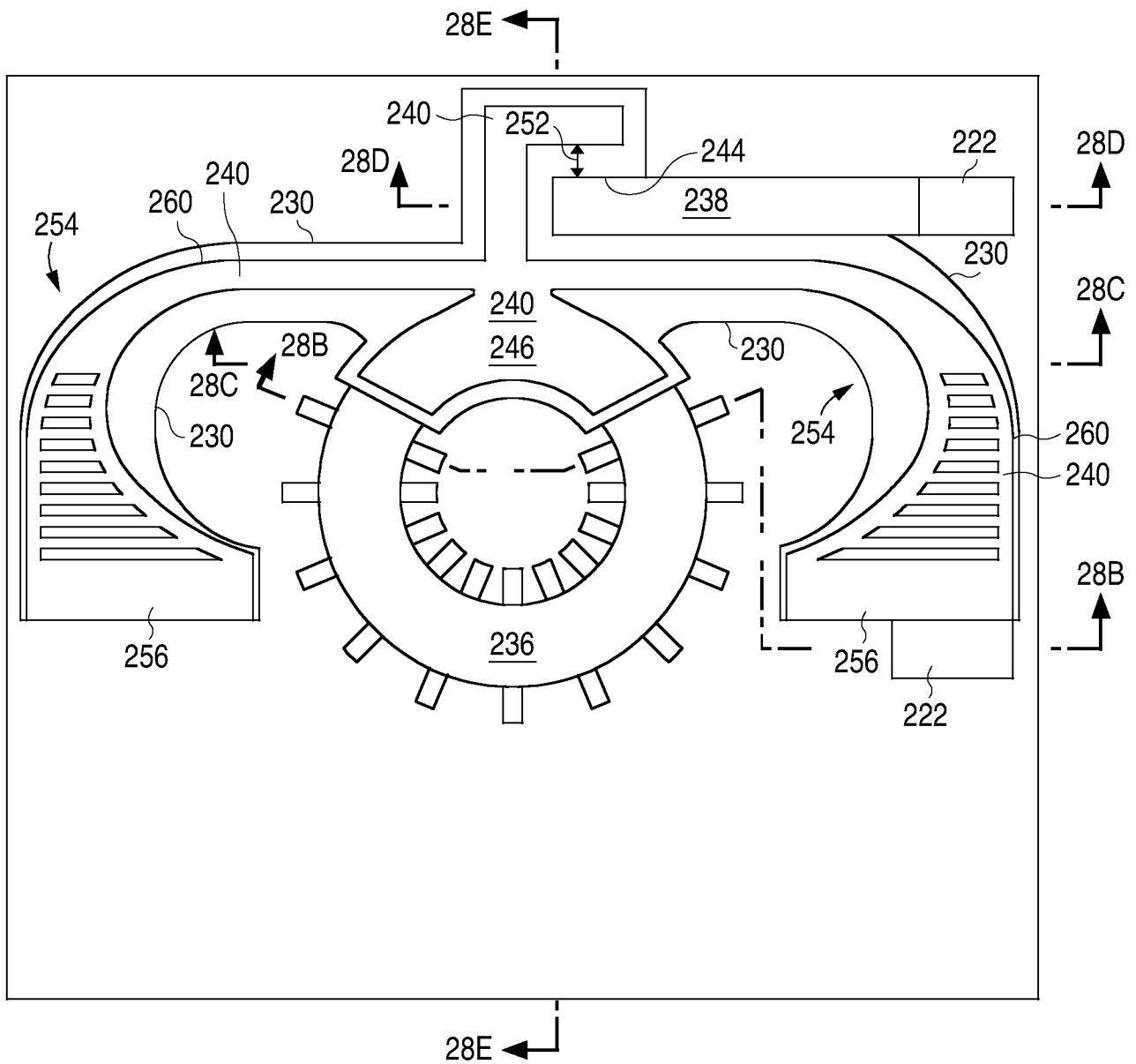


FIG. 27A

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**FIG. 27B****FIG. 27C****FIG. 27D****FIG. 27E**



**FIG. 28A**

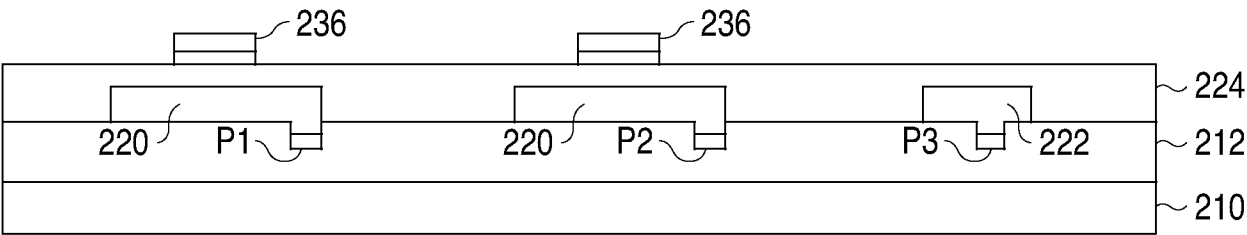


FIG. 28B

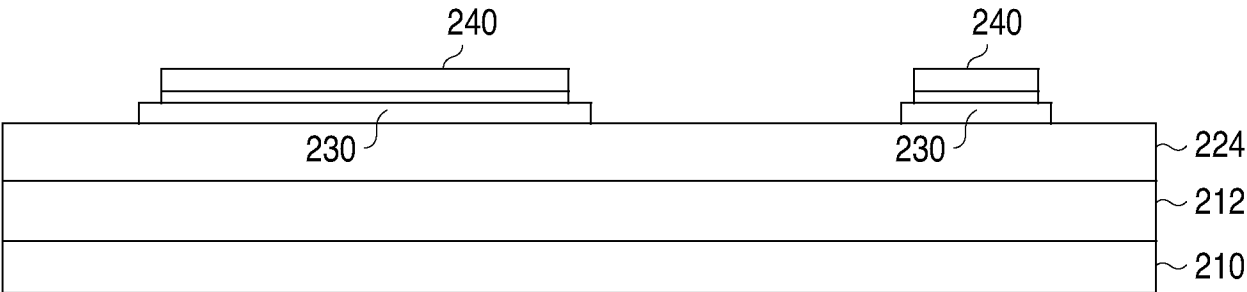


FIG. 28C

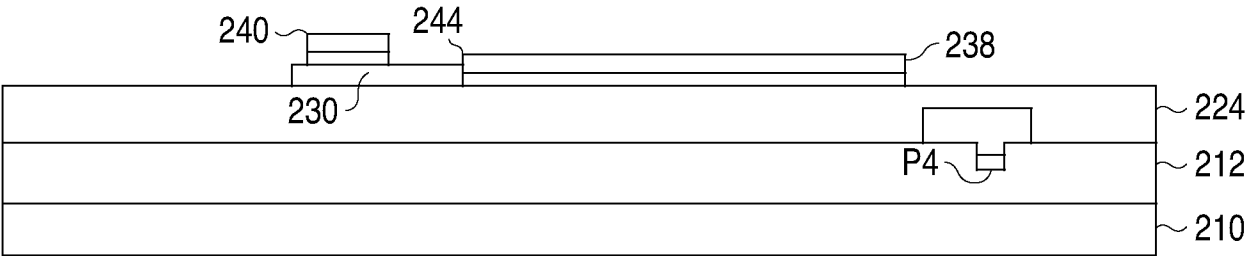


FIG. 28D

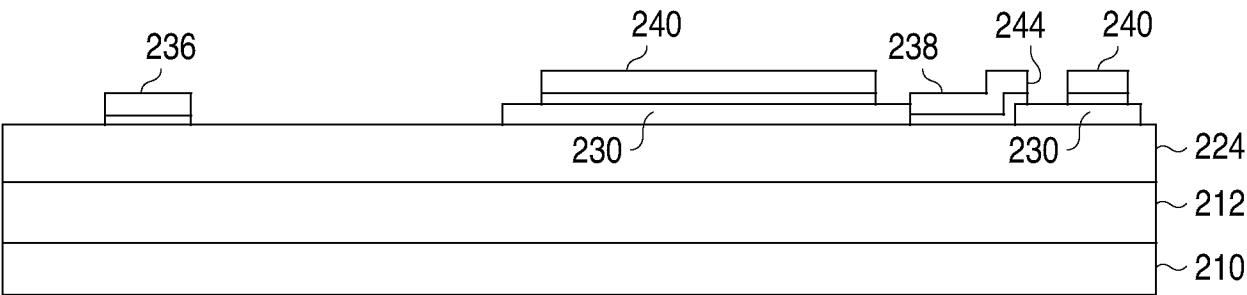


FIG. 28E