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(54) **ELECTRICAL ASSEMBLIES INCLUDING
MAGNETIC DEVICES**

(52) **U.S. Cl.**

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(2013.01); **H01F 27/38** (2013.01); **H02M**
1/0064 (2021.05)

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Publication Classification

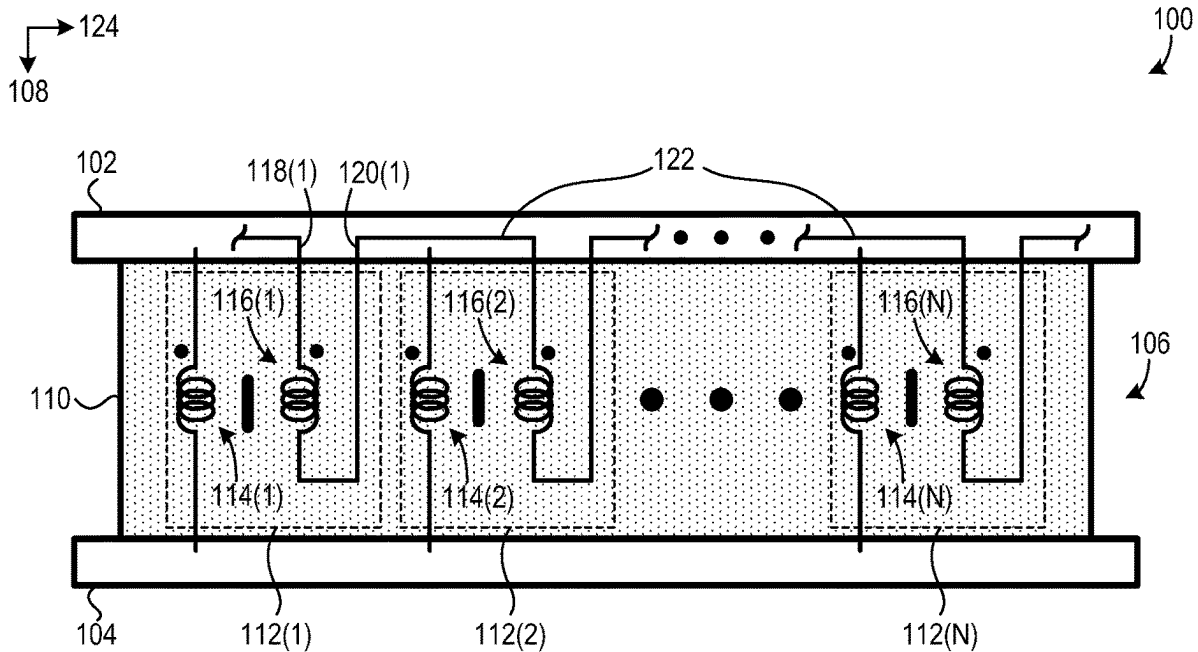
(51) **Int. Cl.**

H01F 27/30 (2006.01)
H01F 27/24 (2006.01)
H01F 27/38 (2006.01)
H02M 1/00 (2007.01)

(57)

ABSTRACT

An electrical assembly includes a first substrate, a second substrate, and a magnetic device disposed between the first substrate and the second substrate. The magnetic device includes (1) a magnetic core, (2) a first primary winding extending through the magnetic core and electrically coupling the first substrate to the second substrate, (3) a second primary winding extending through the magnetic core and electrically coupling the first substrate to the second substrate, (4) a first secondary winding wound around at least a portion of the magnetic core, and (5) a second secondary winding wound around at least a portion of the magnetic core. The electrical assembly further includes one or more electrical conductors on the first substrate electrically coupling the first secondary winding in series with the second secondary winding.



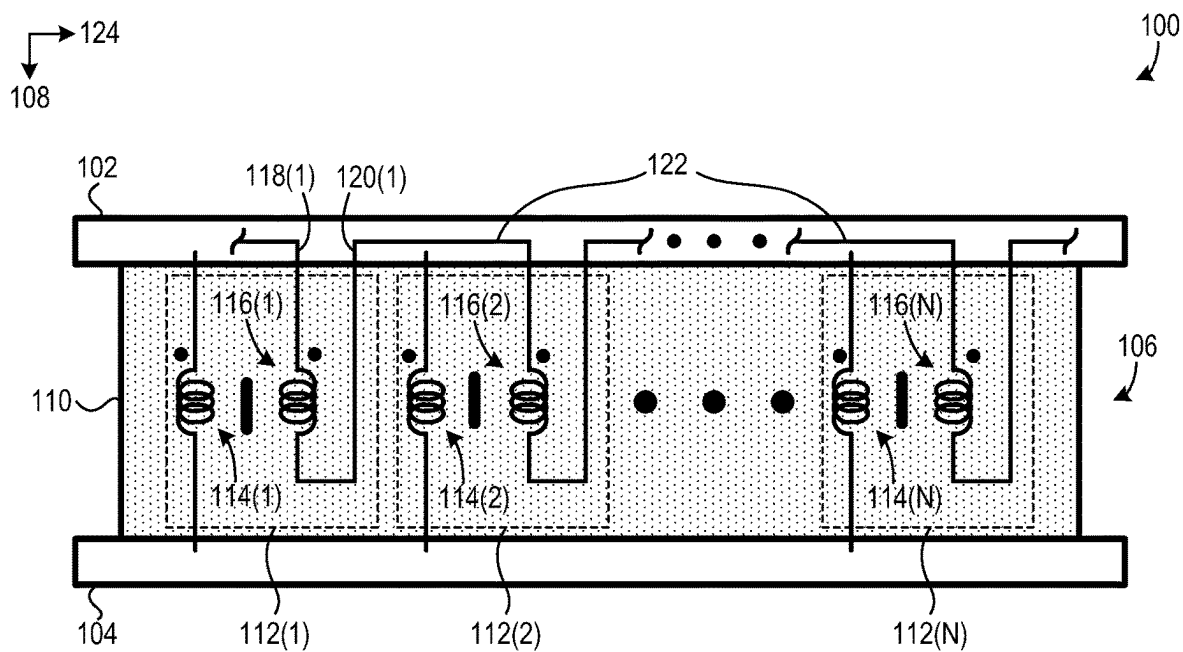


FIG. 1

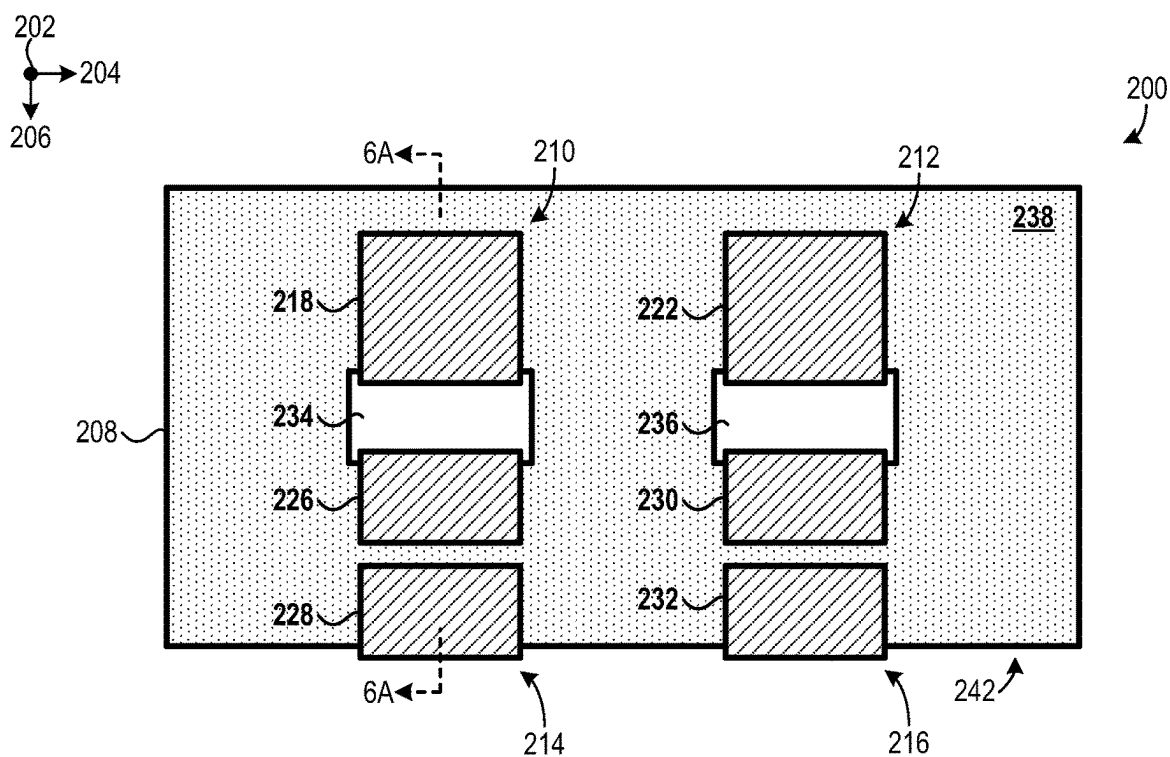


FIG. 2

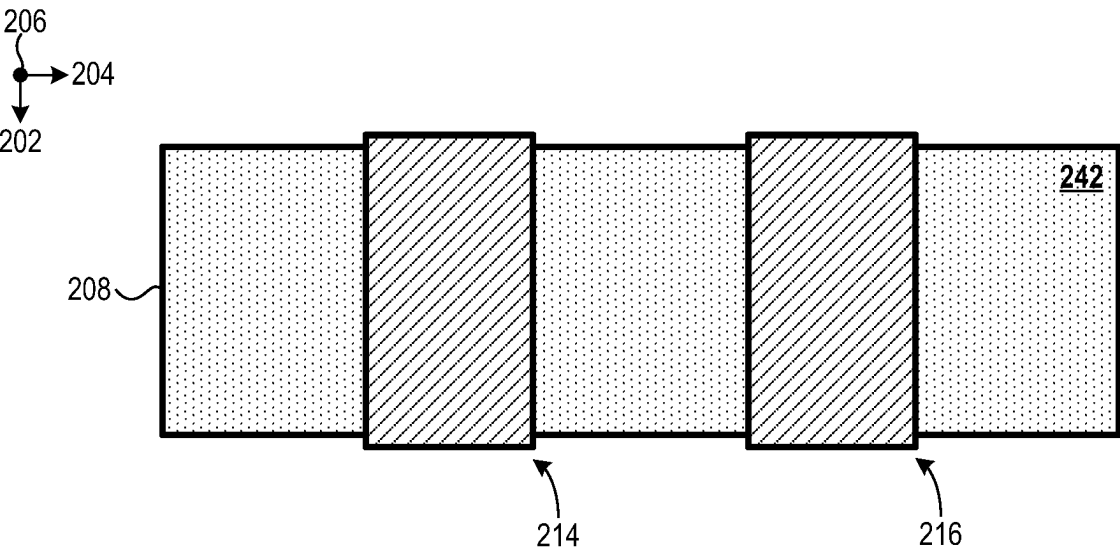


FIG. 3

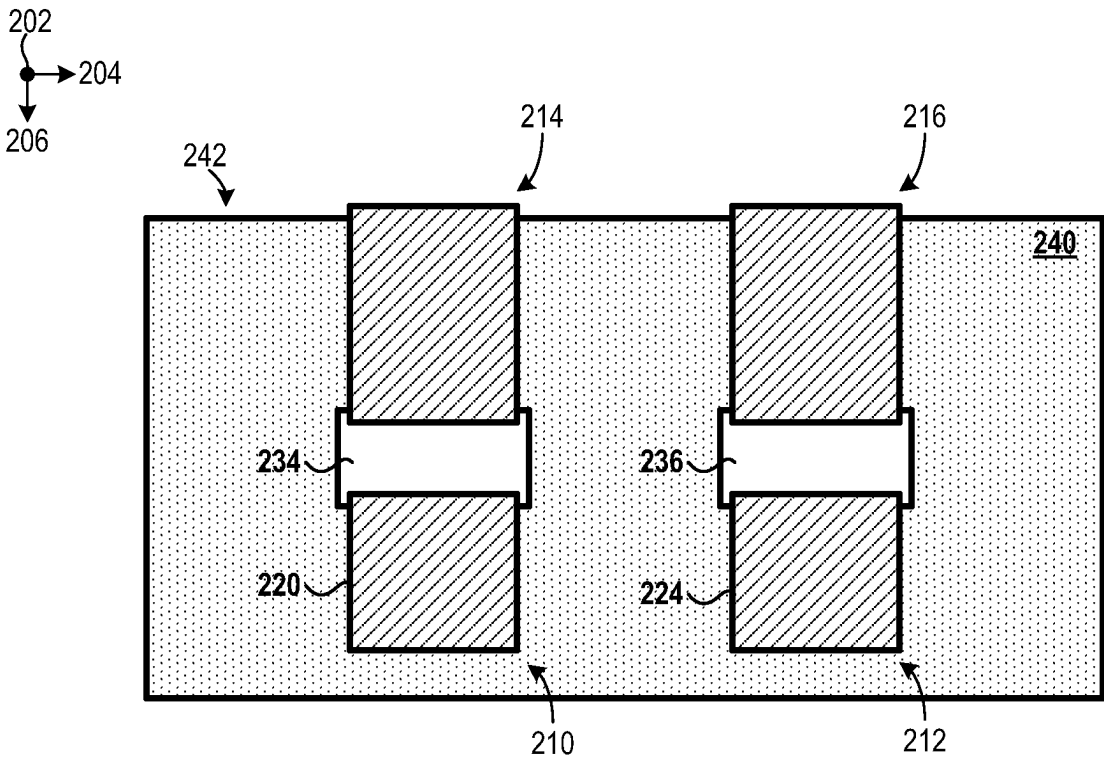


FIG. 4

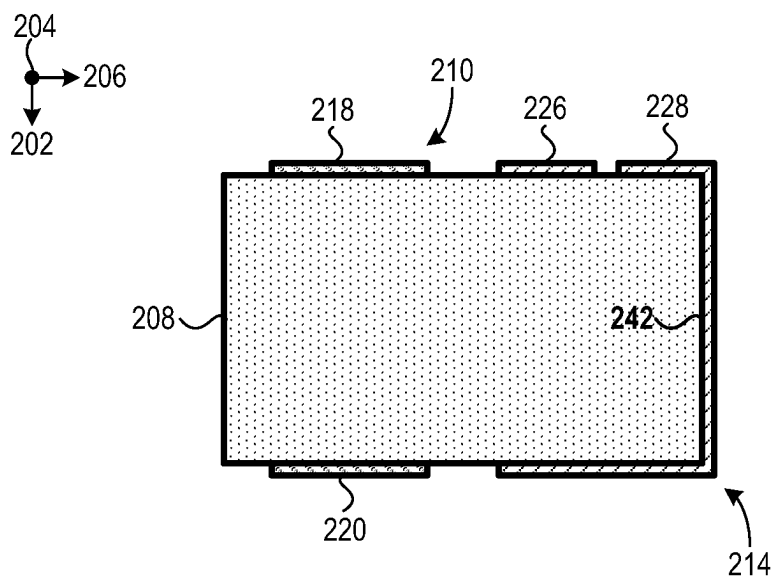


FIG. 5

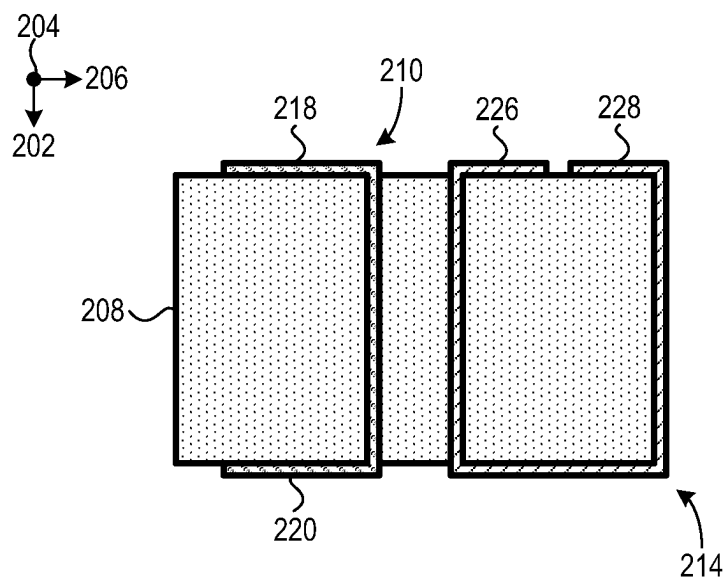


FIG. 6

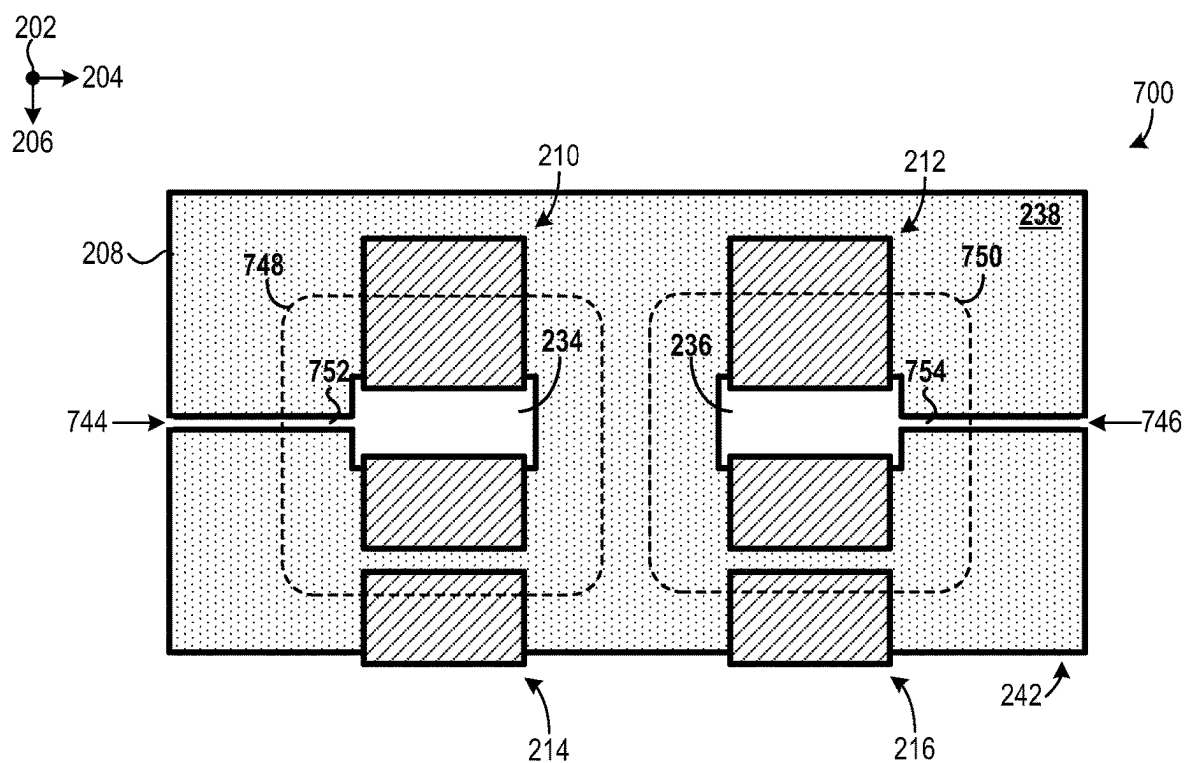


FIG. 7

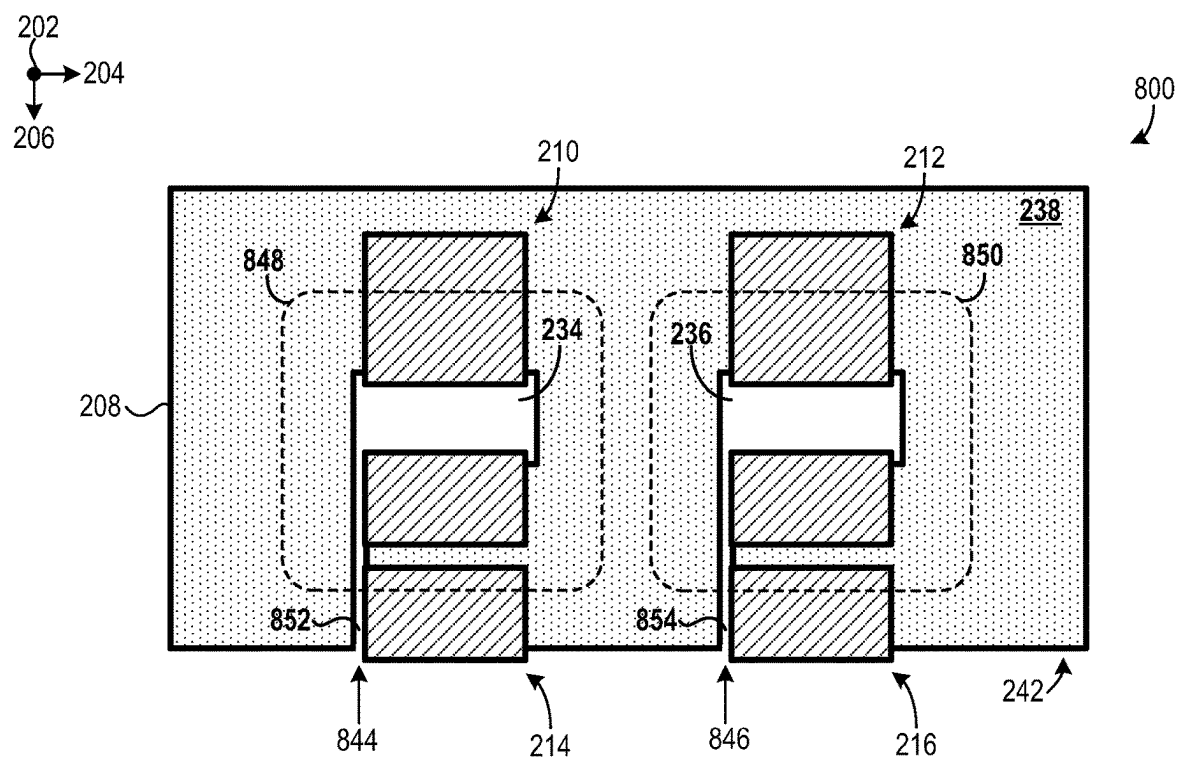


FIG. 8

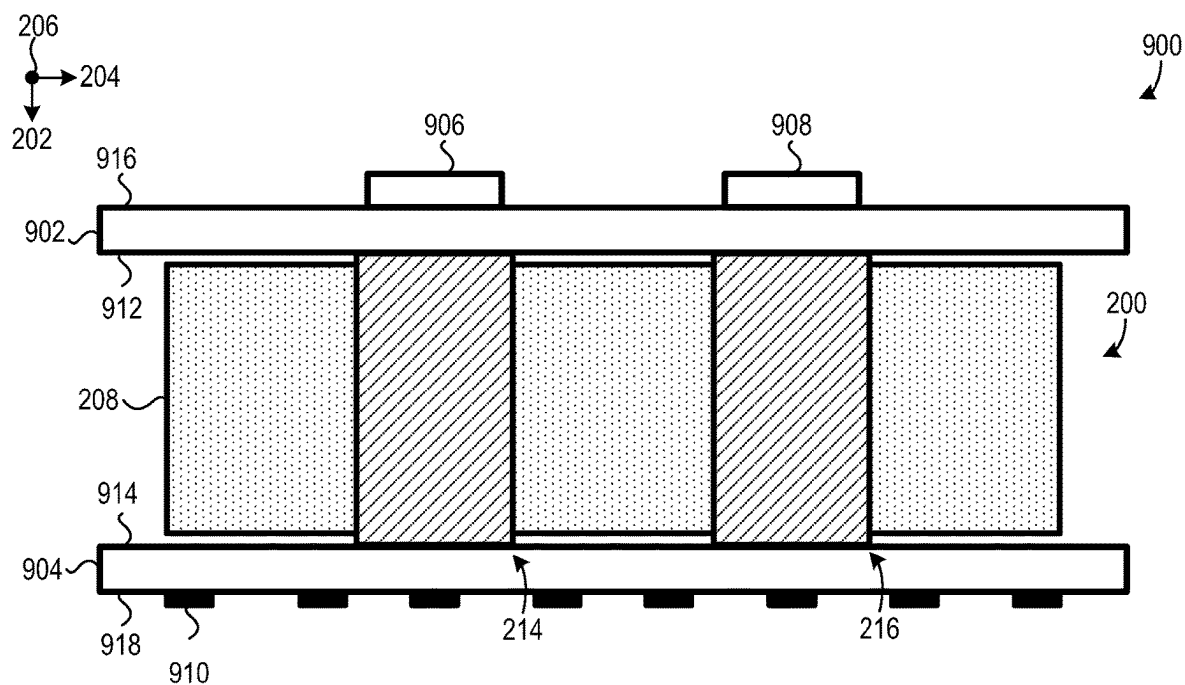


FIG. 9

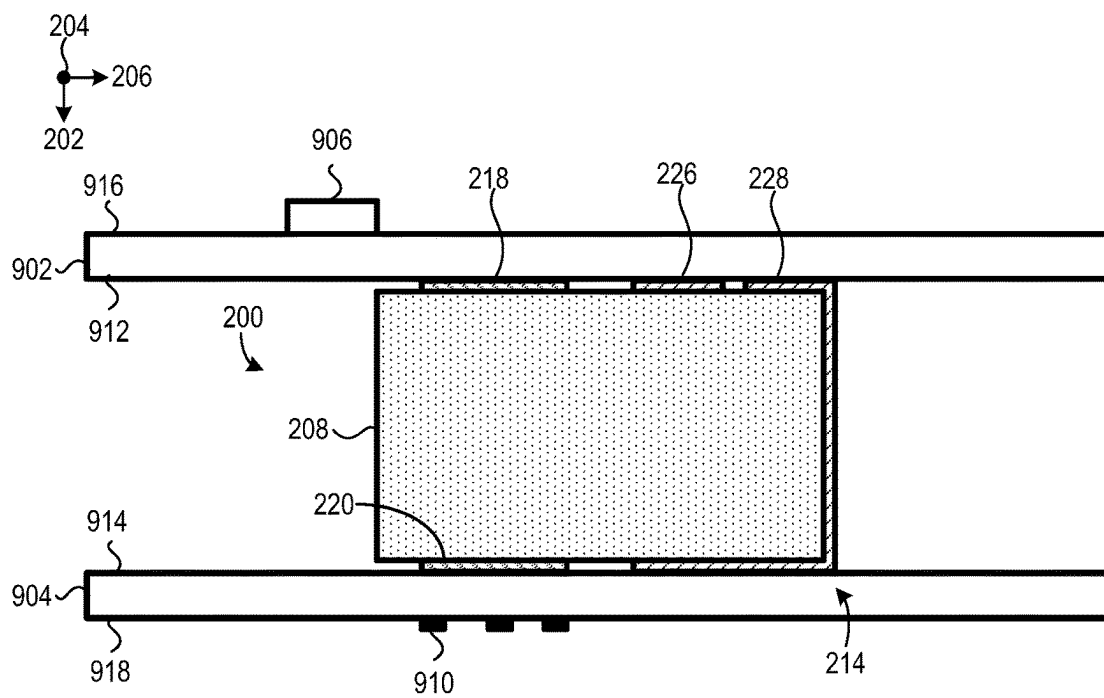


FIG. 10

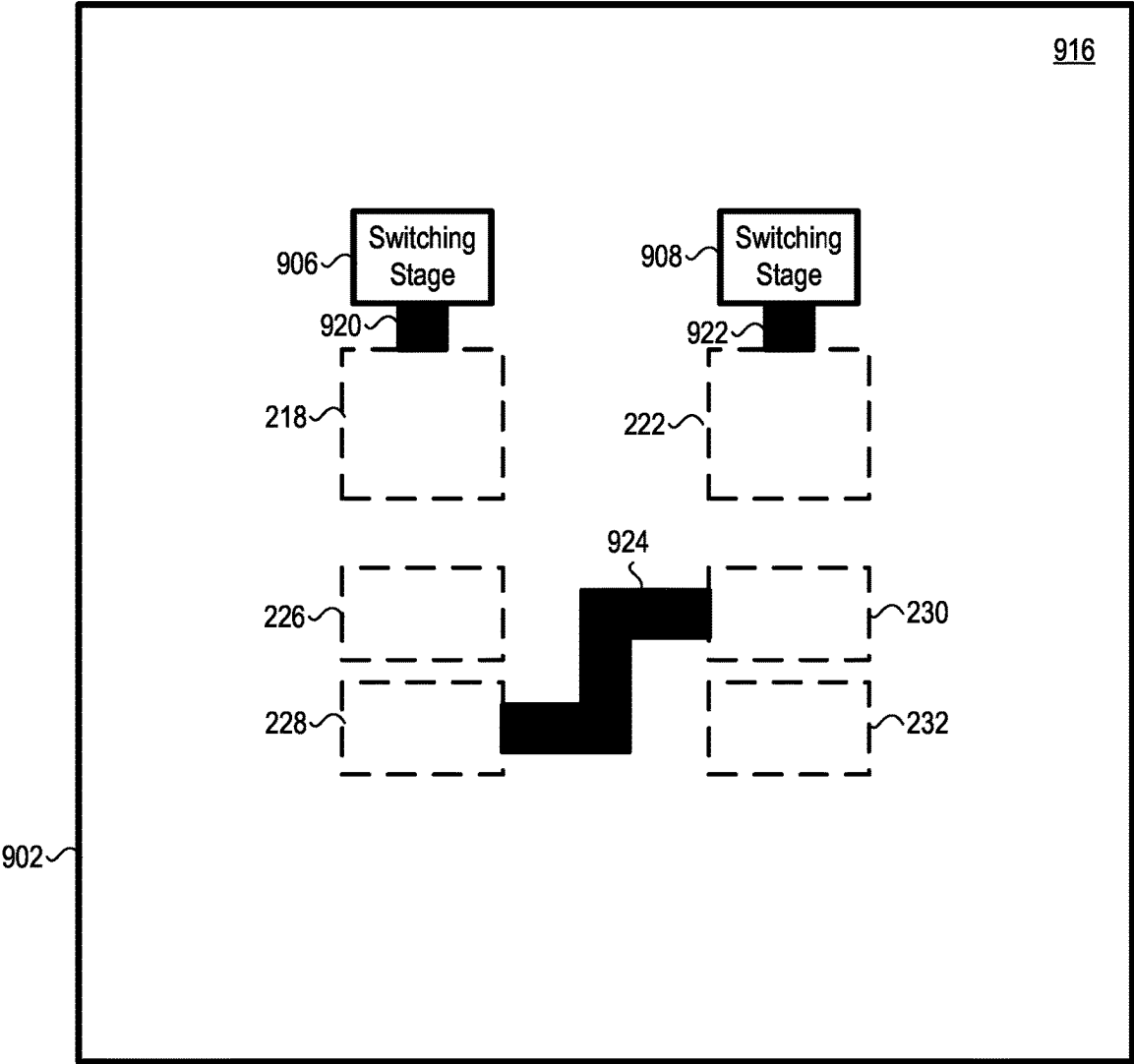
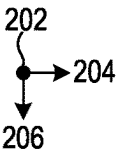


FIG. 11

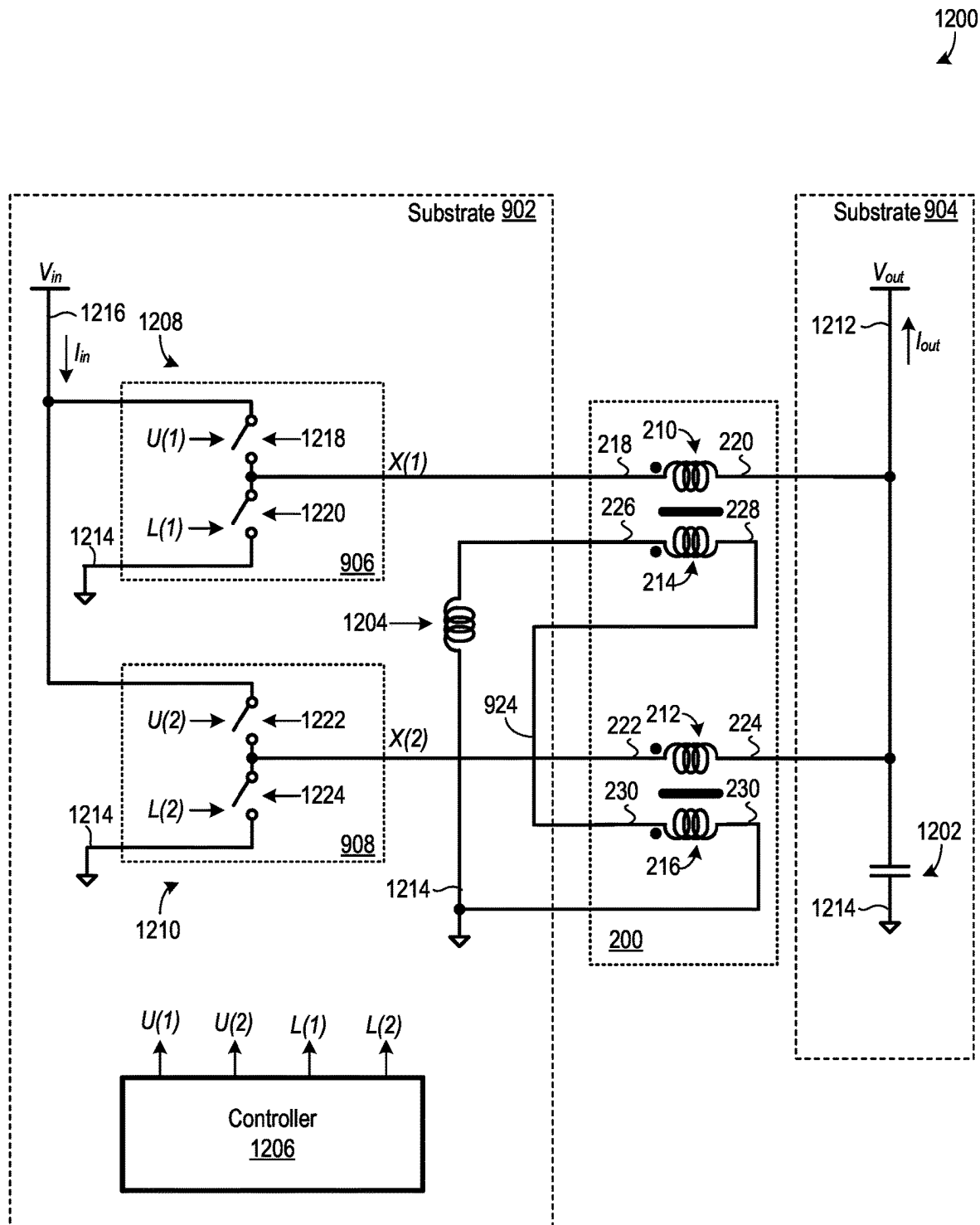


FIG. 12

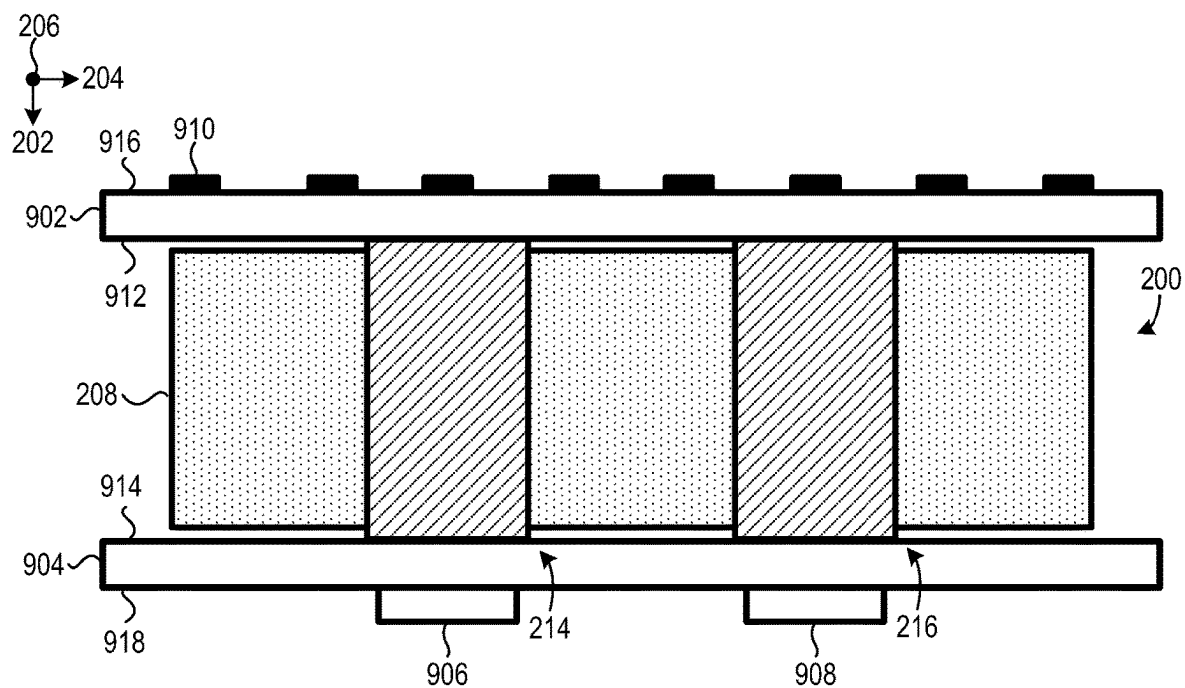


FIG. 13

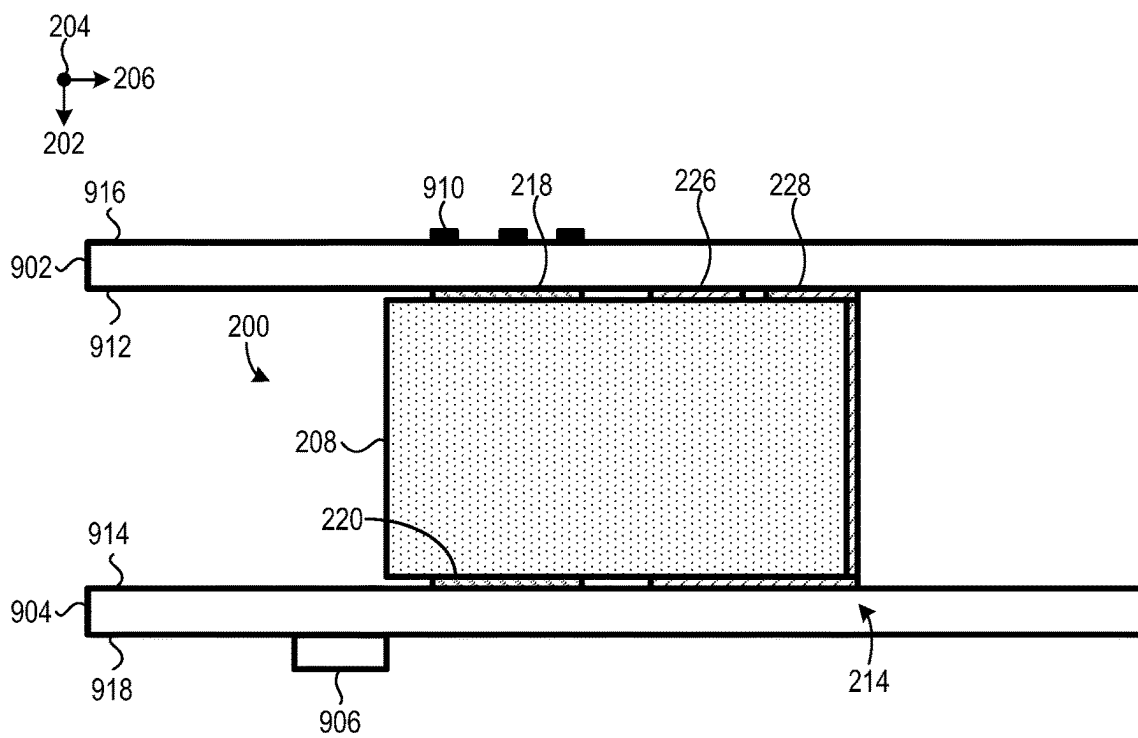


FIG. 14

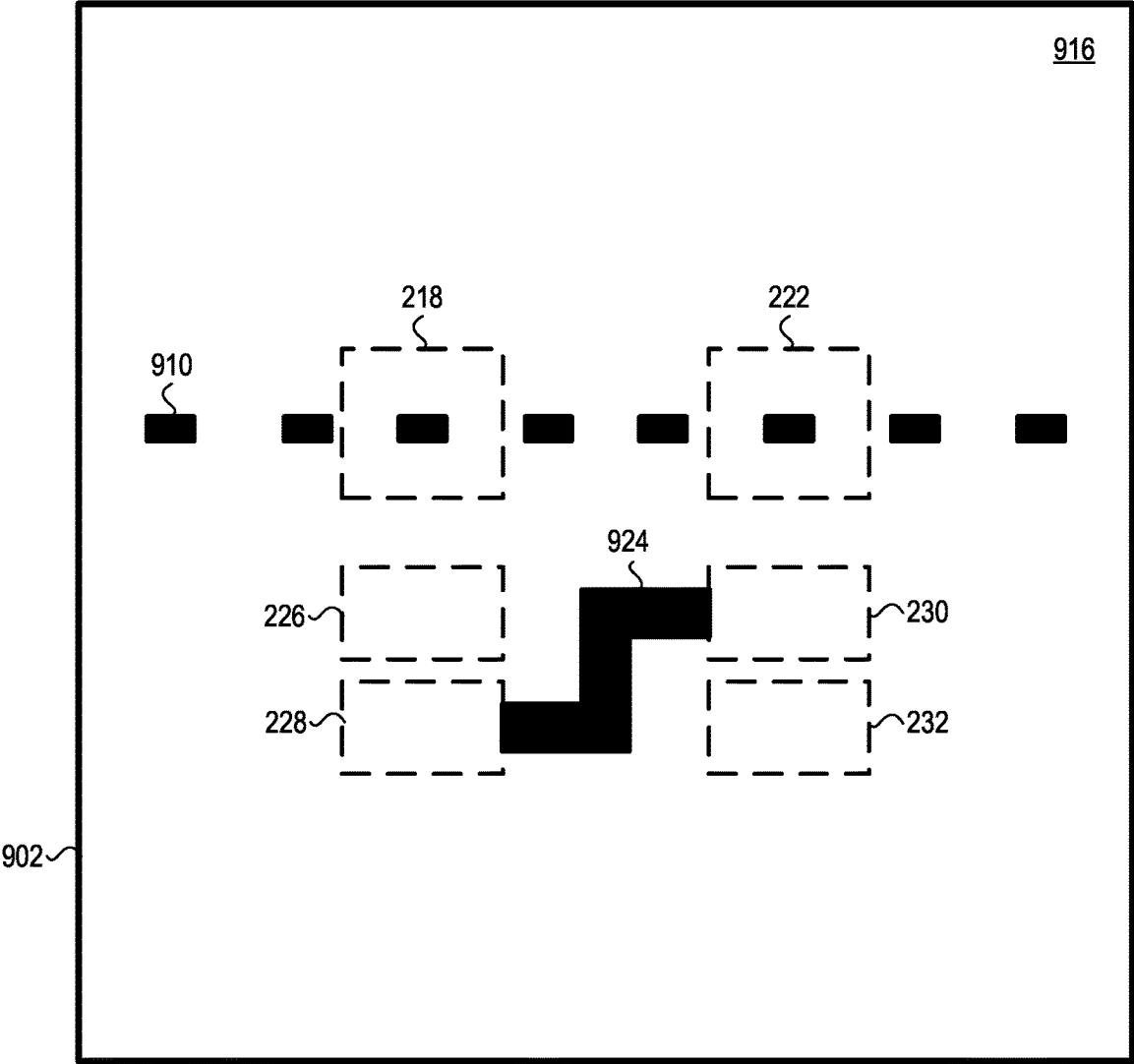
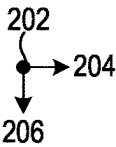


FIG. 15

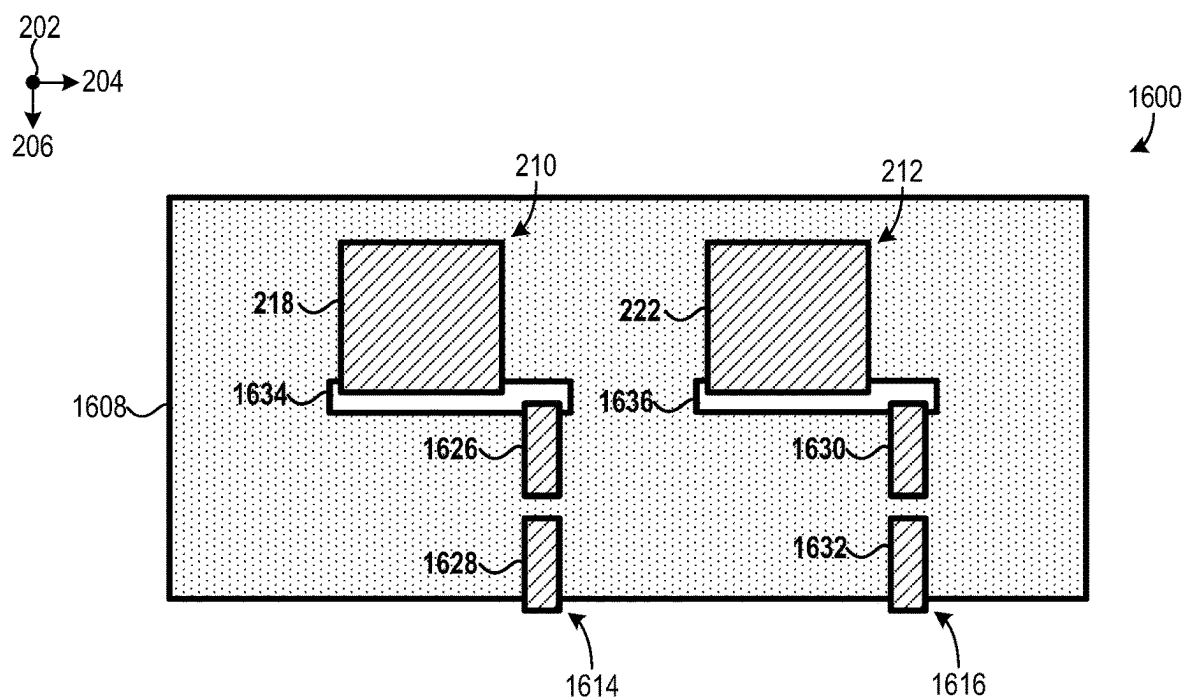


FIG. 16

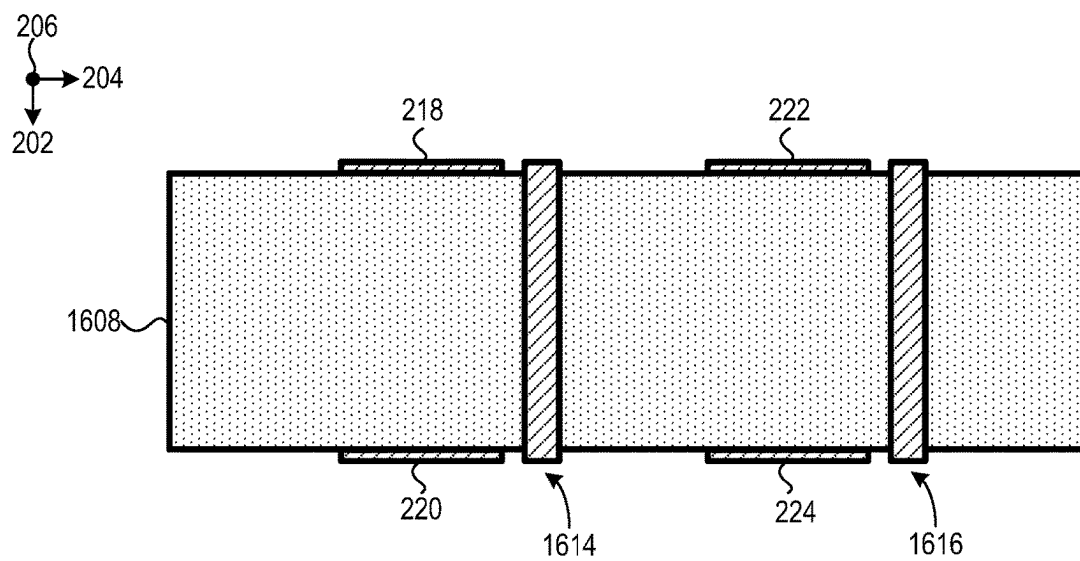


FIG. 17

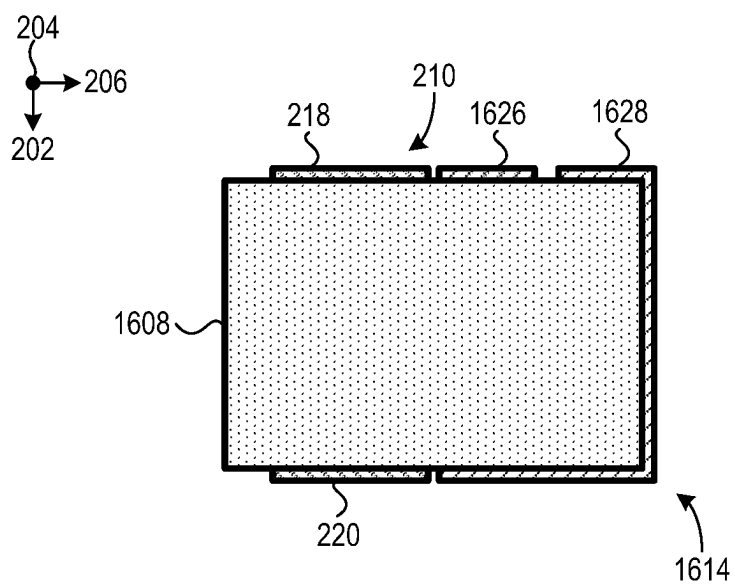


FIG. 18

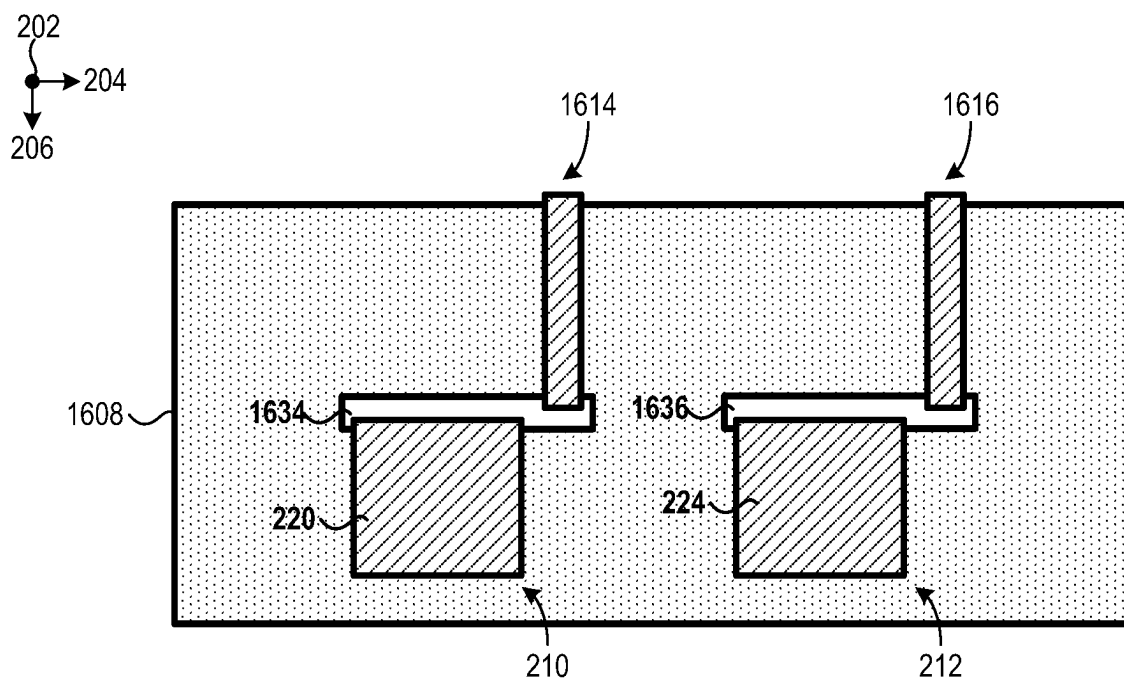


FIG. 19

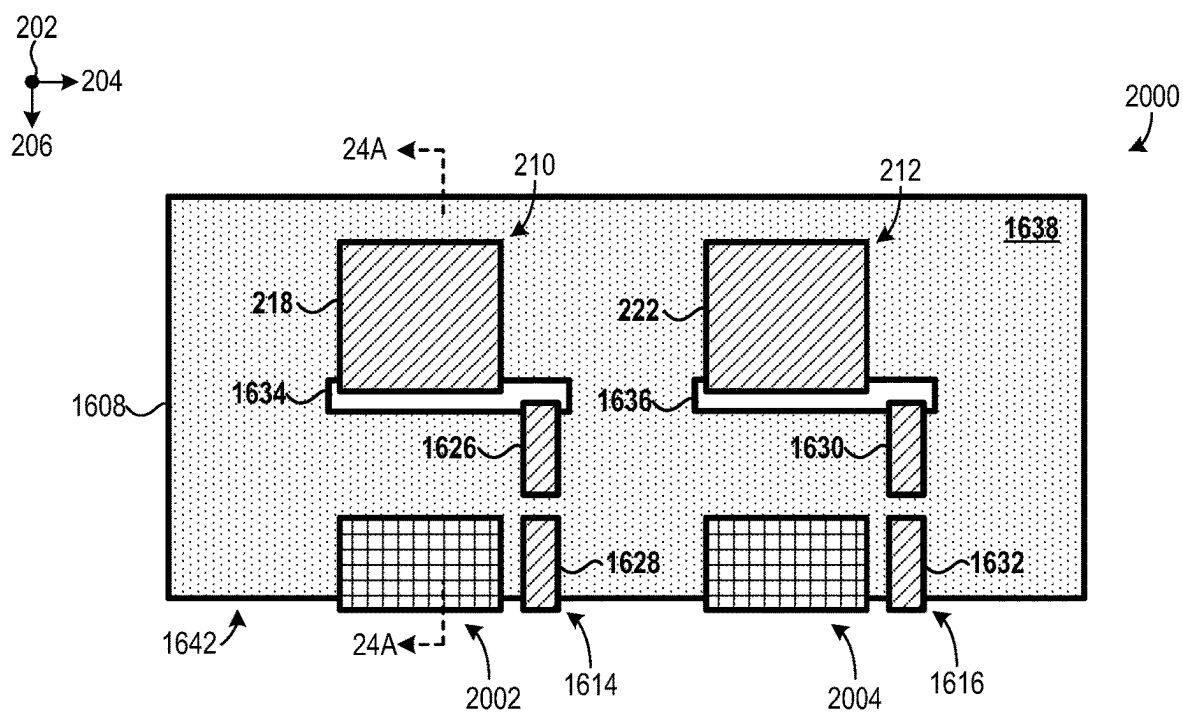


FIG. 20

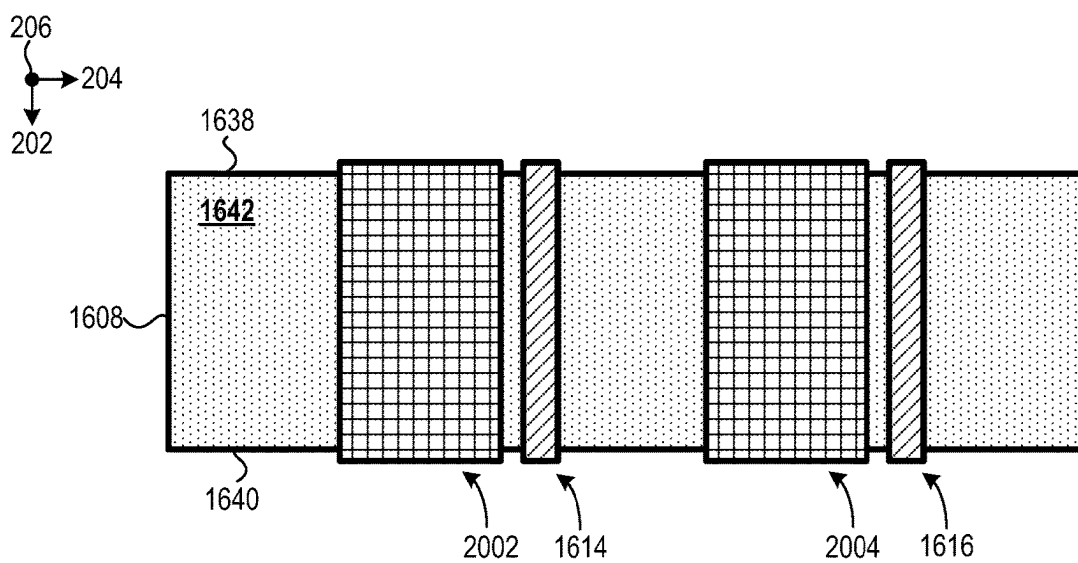


FIG. 21

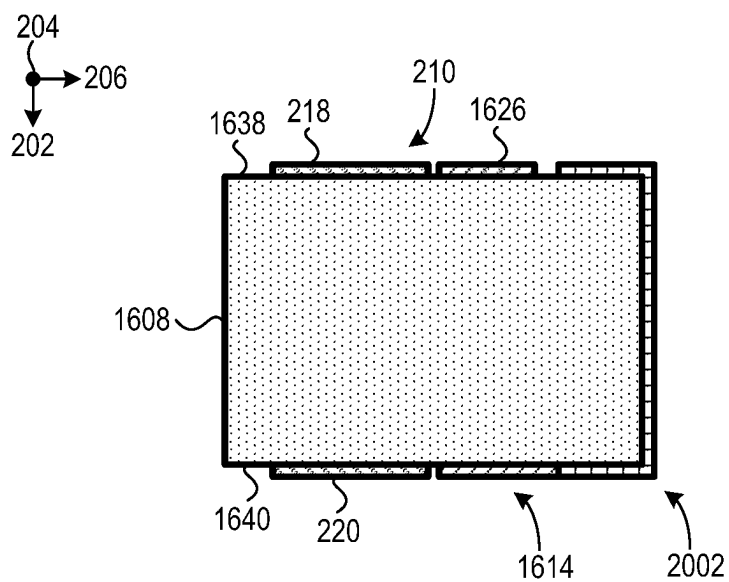


FIG. 22

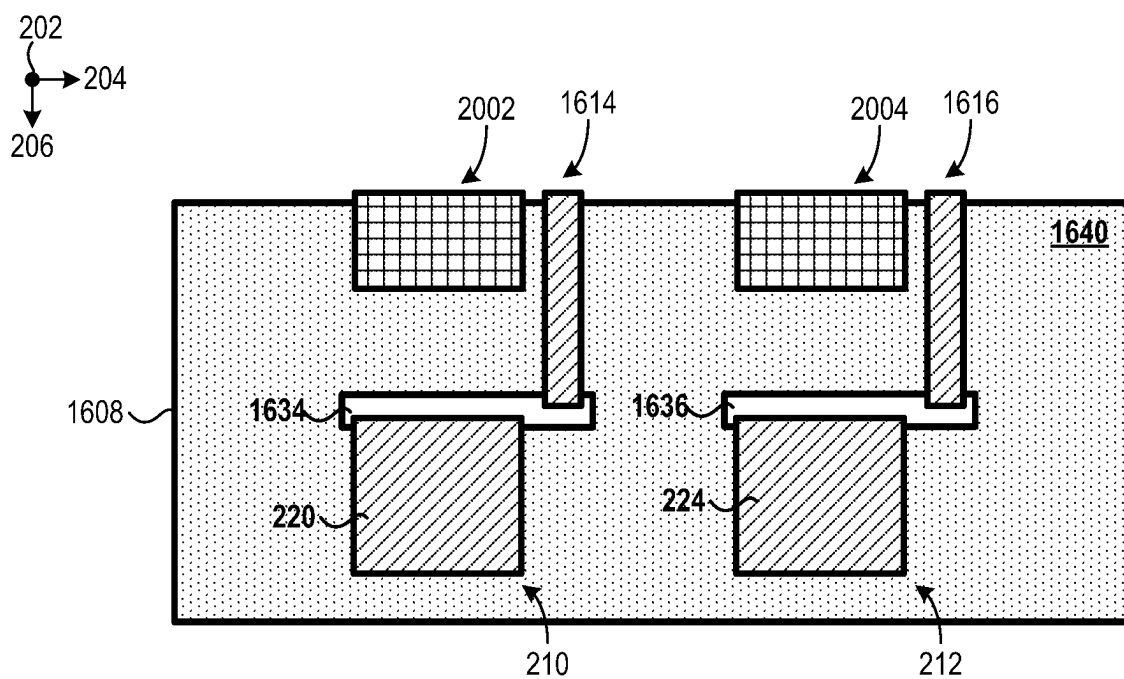


FIG. 23

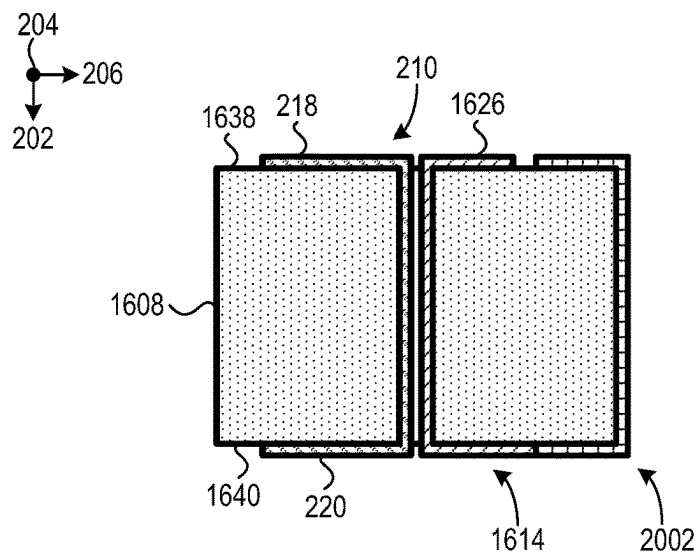


FIG. 24

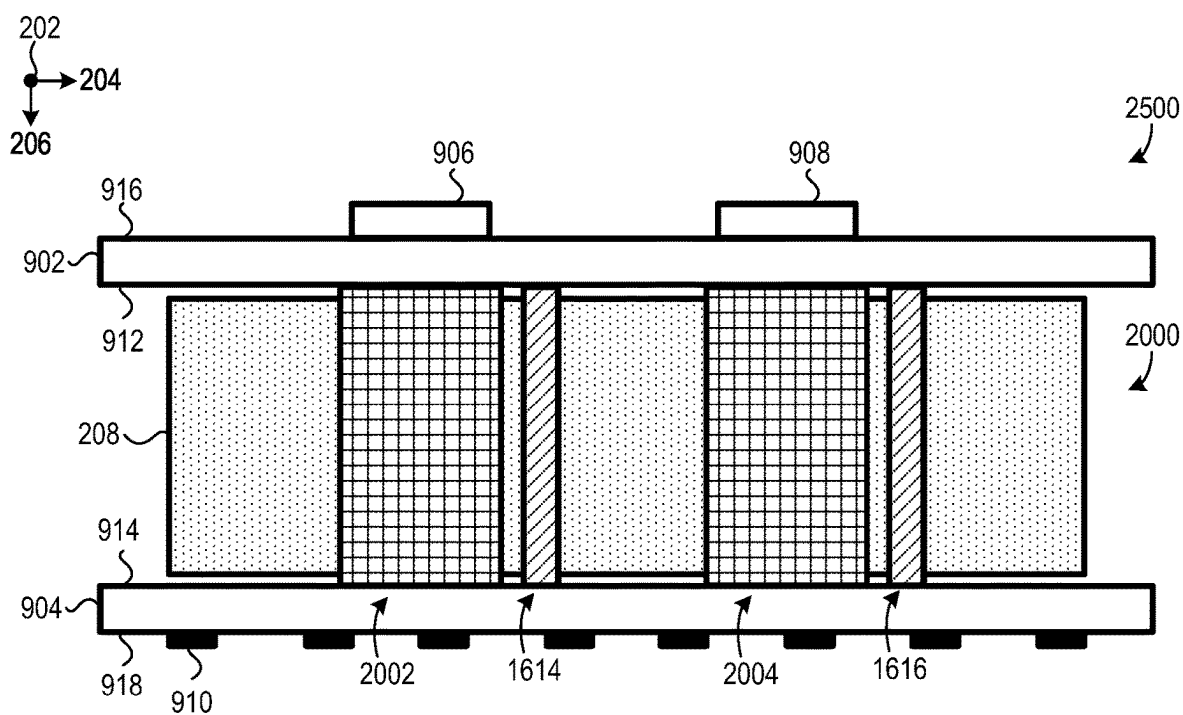


FIG. 25

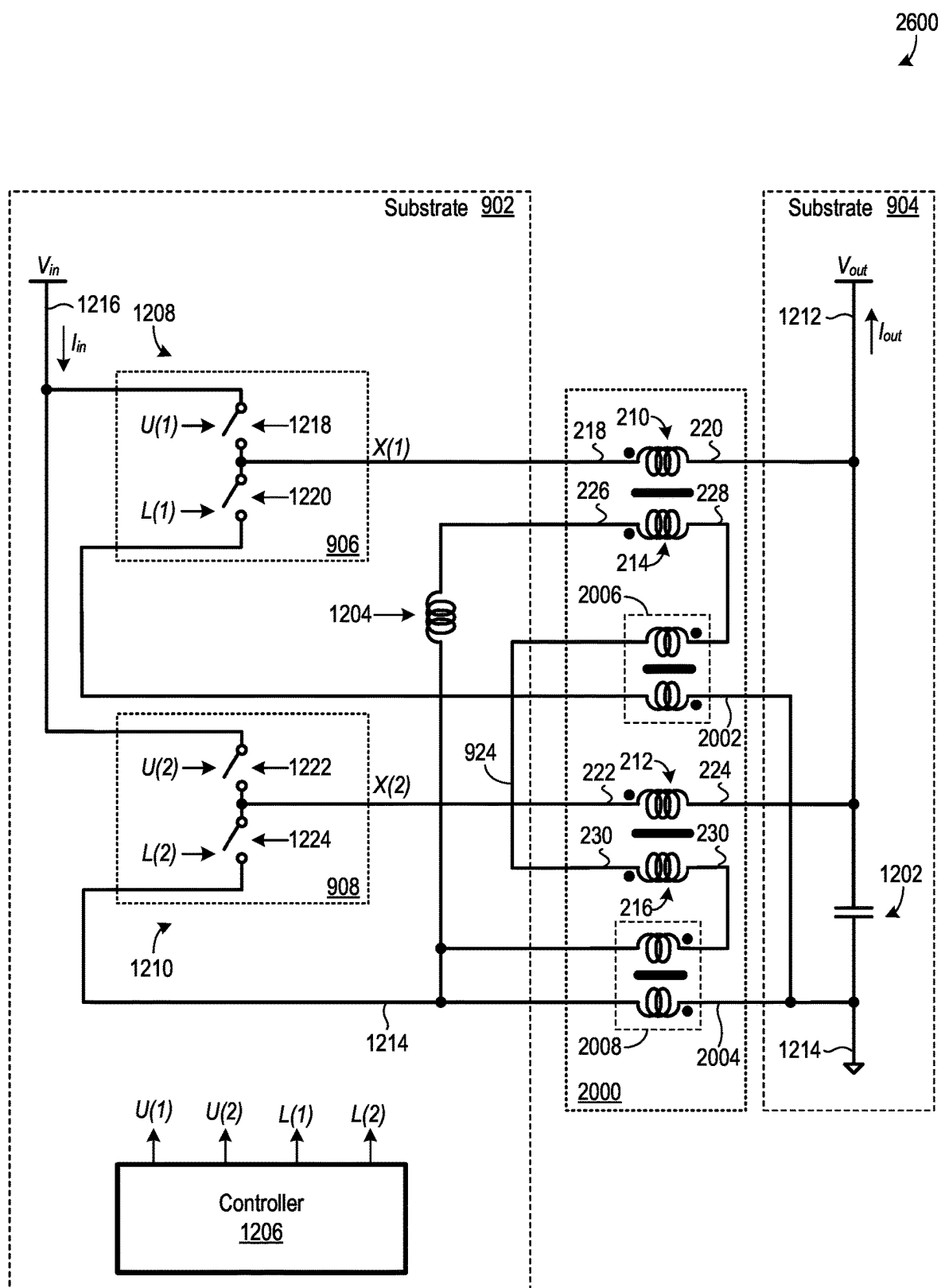


FIG. 26

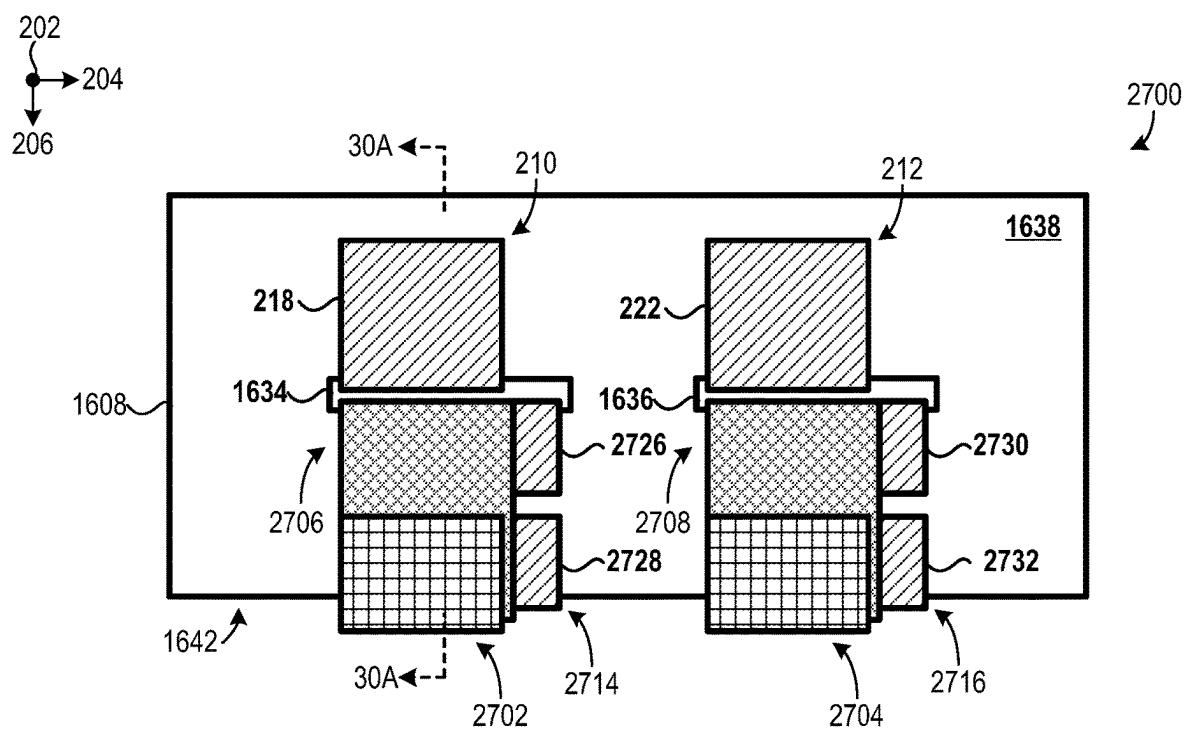


FIG. 27

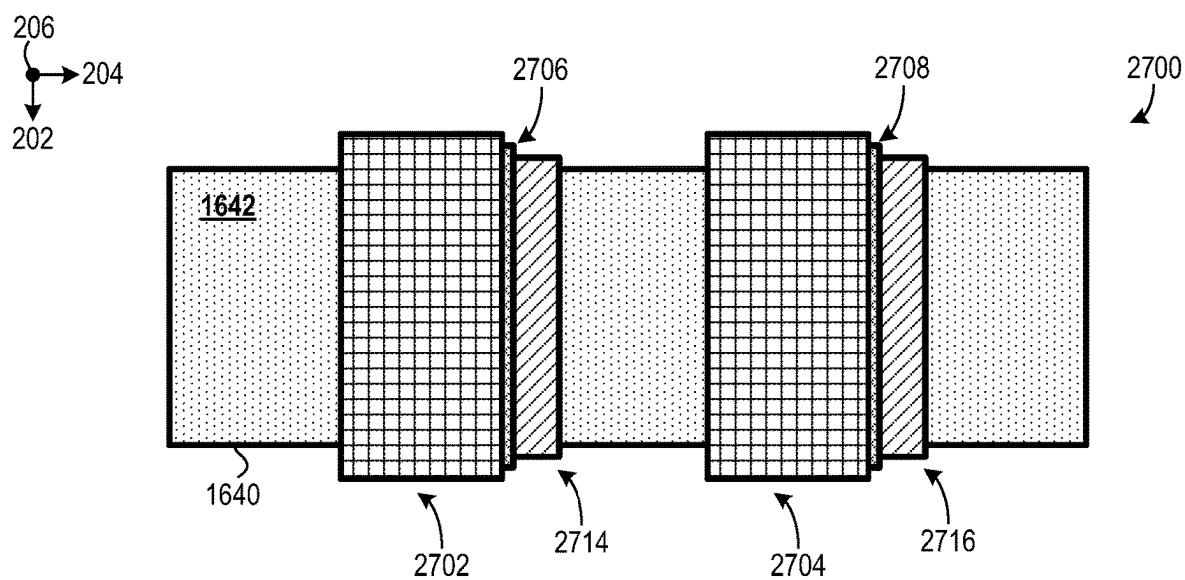


FIG. 28

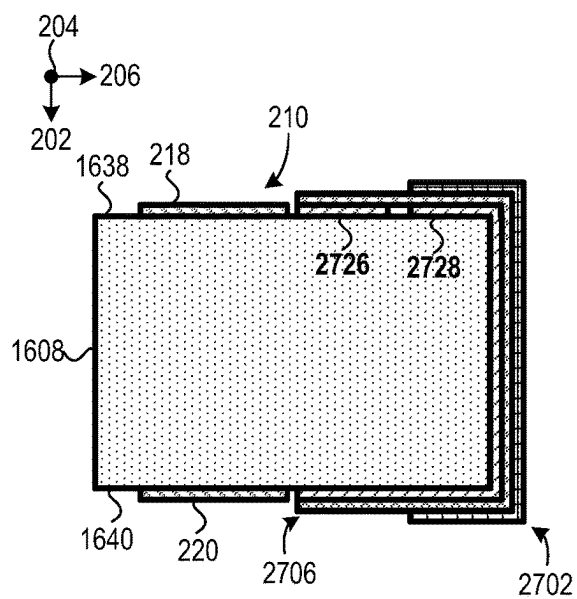


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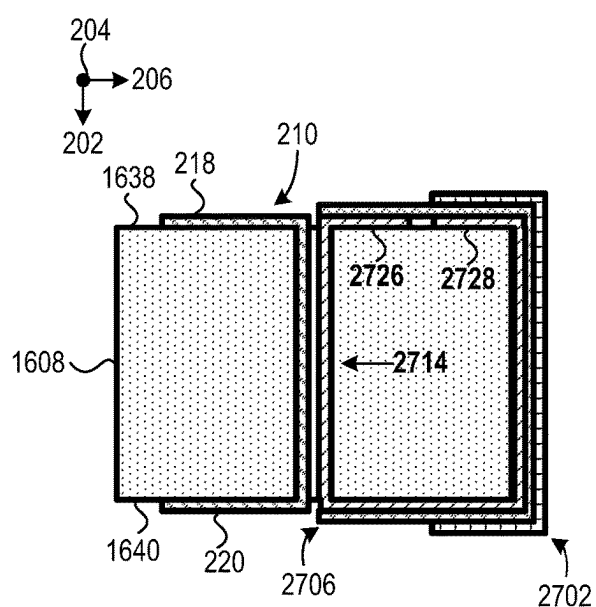


FIG. 30

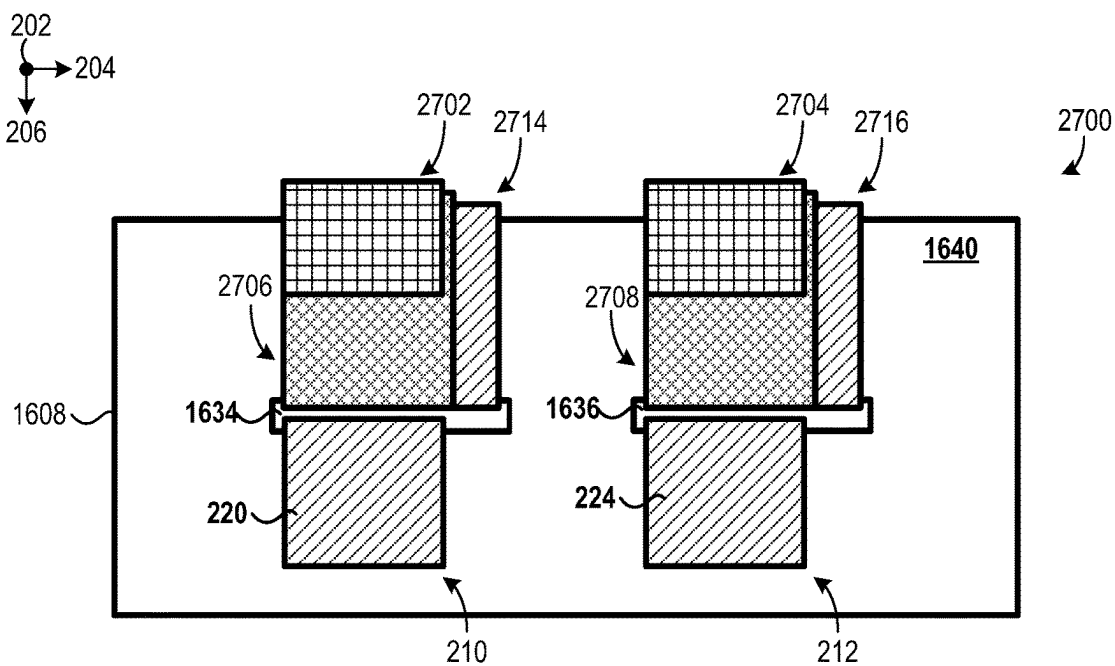


FIG. 31

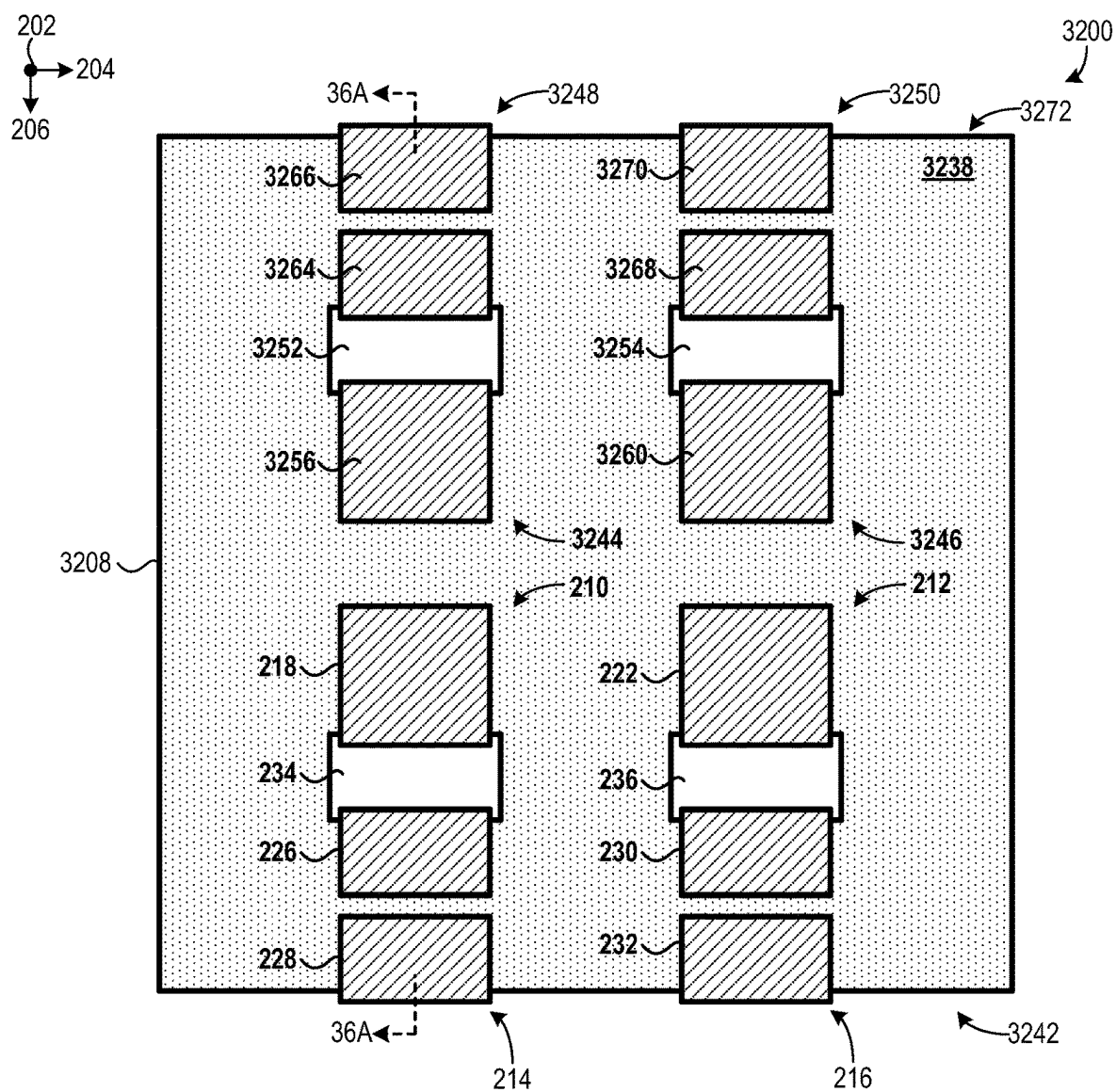


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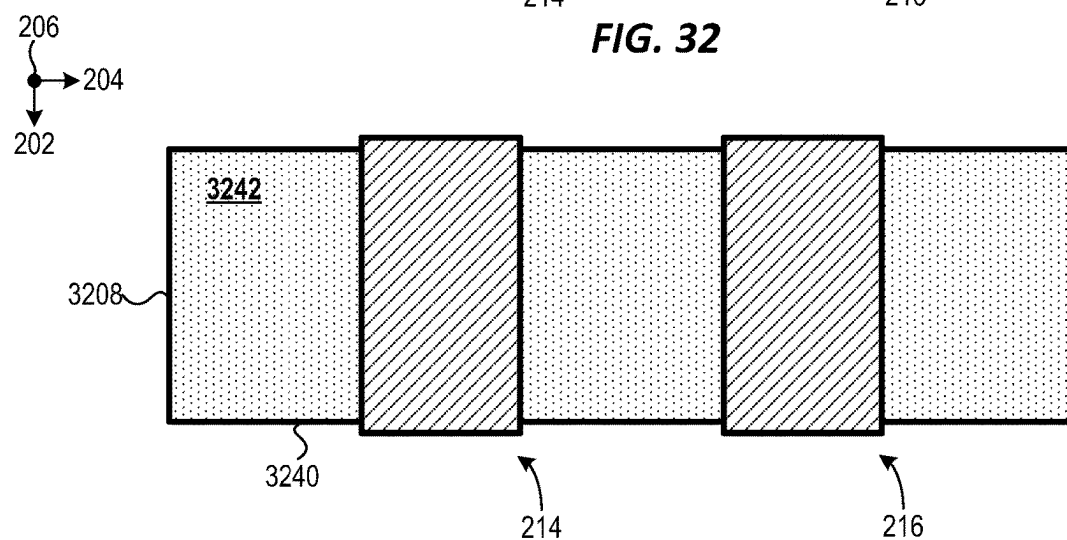


FIG. 33

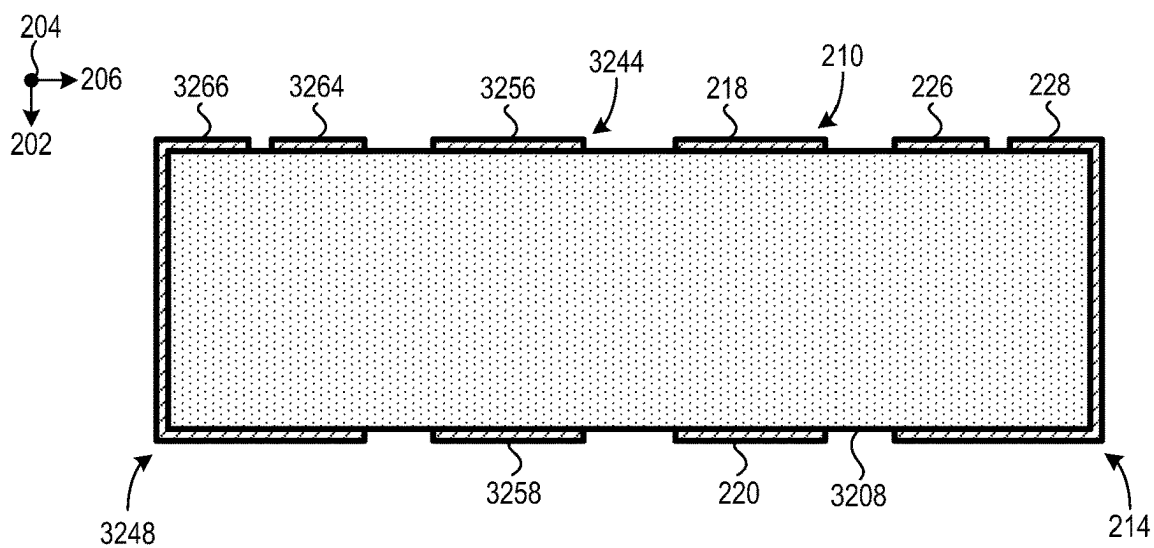


FIG. 34

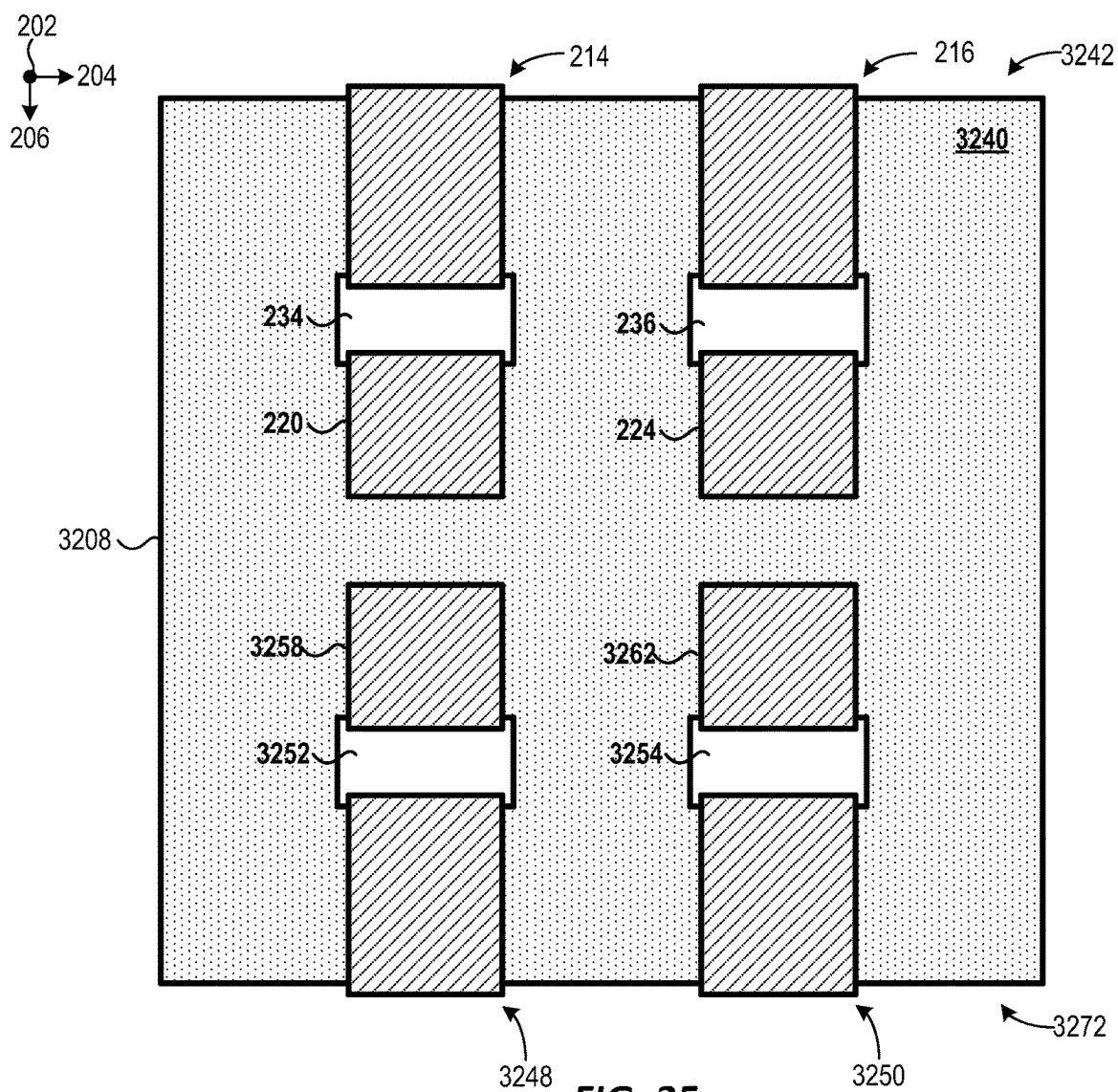


FIG. 35

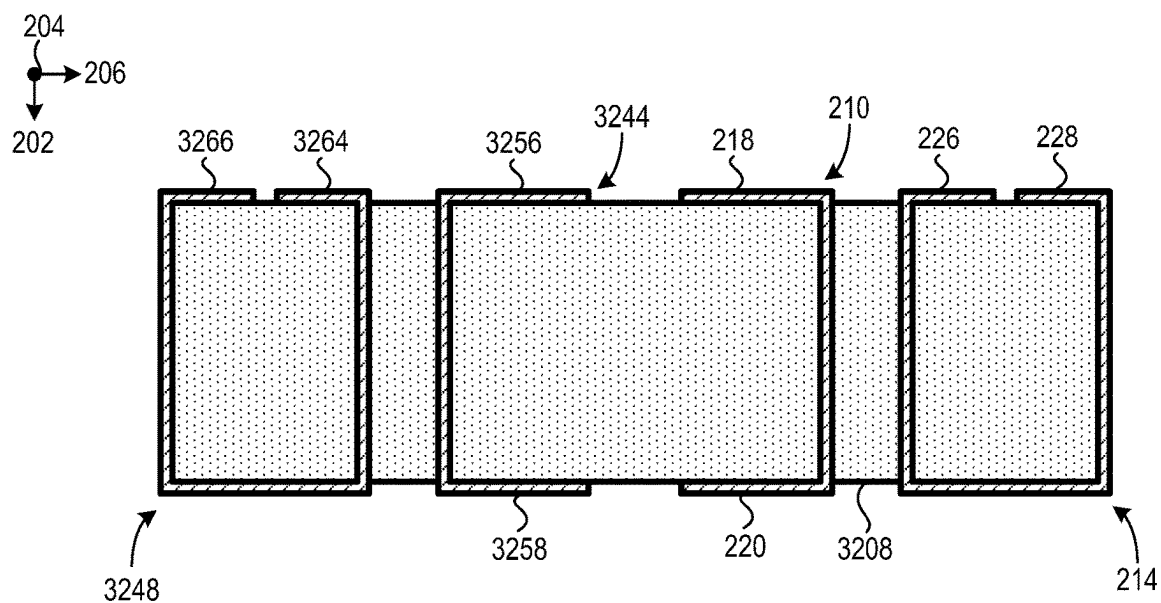


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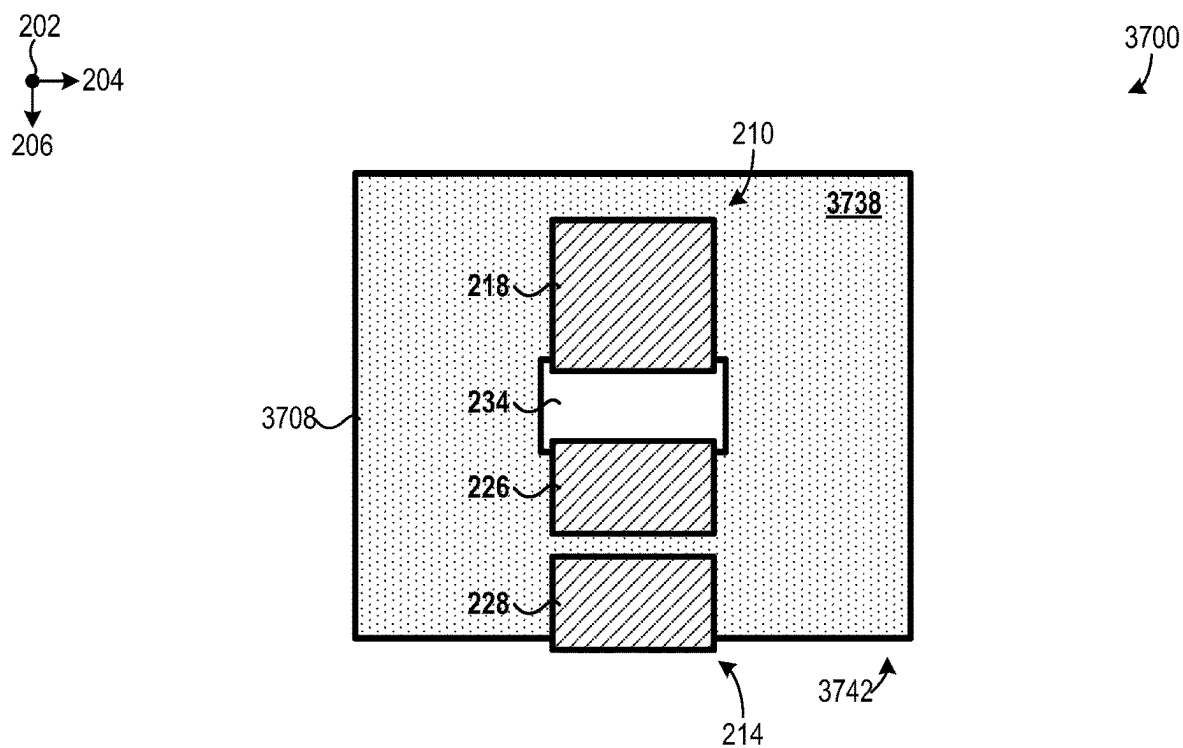


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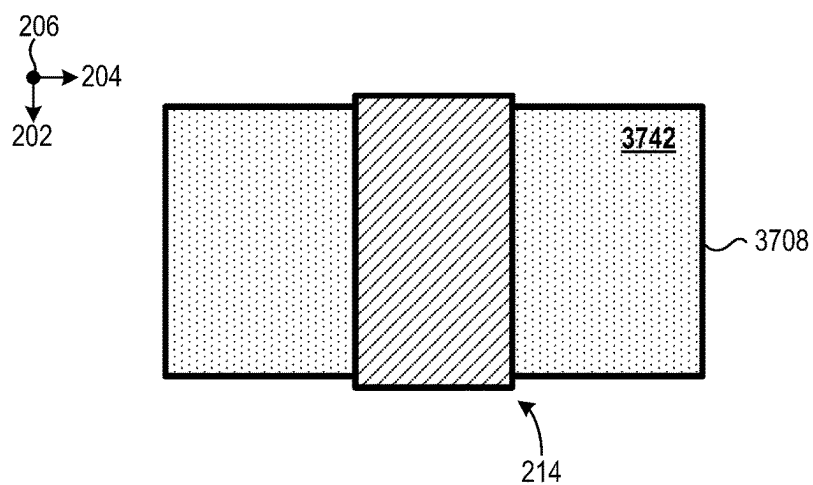


FIG. 38

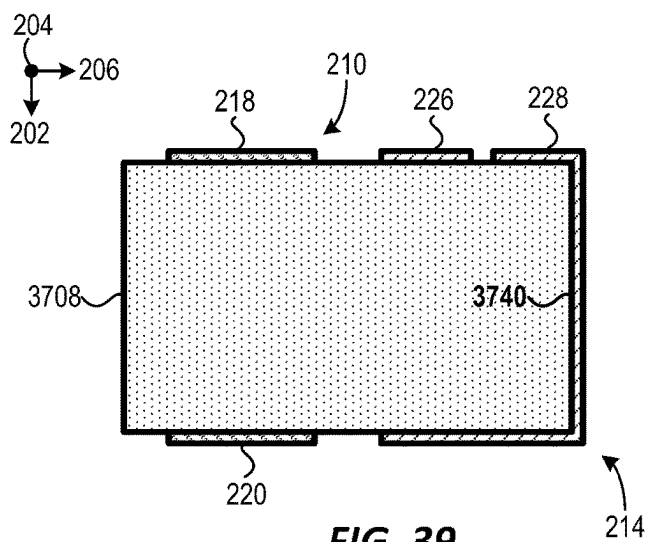


FIG. 39

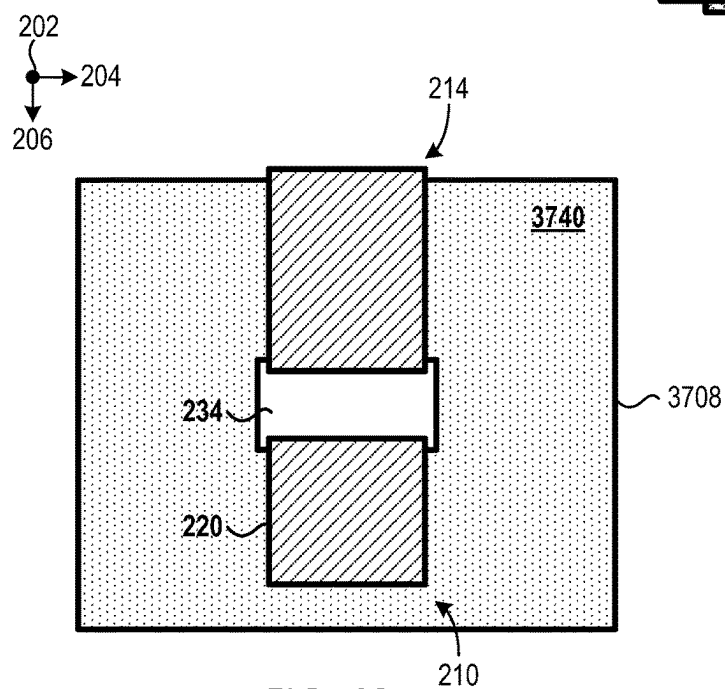


FIG. 40

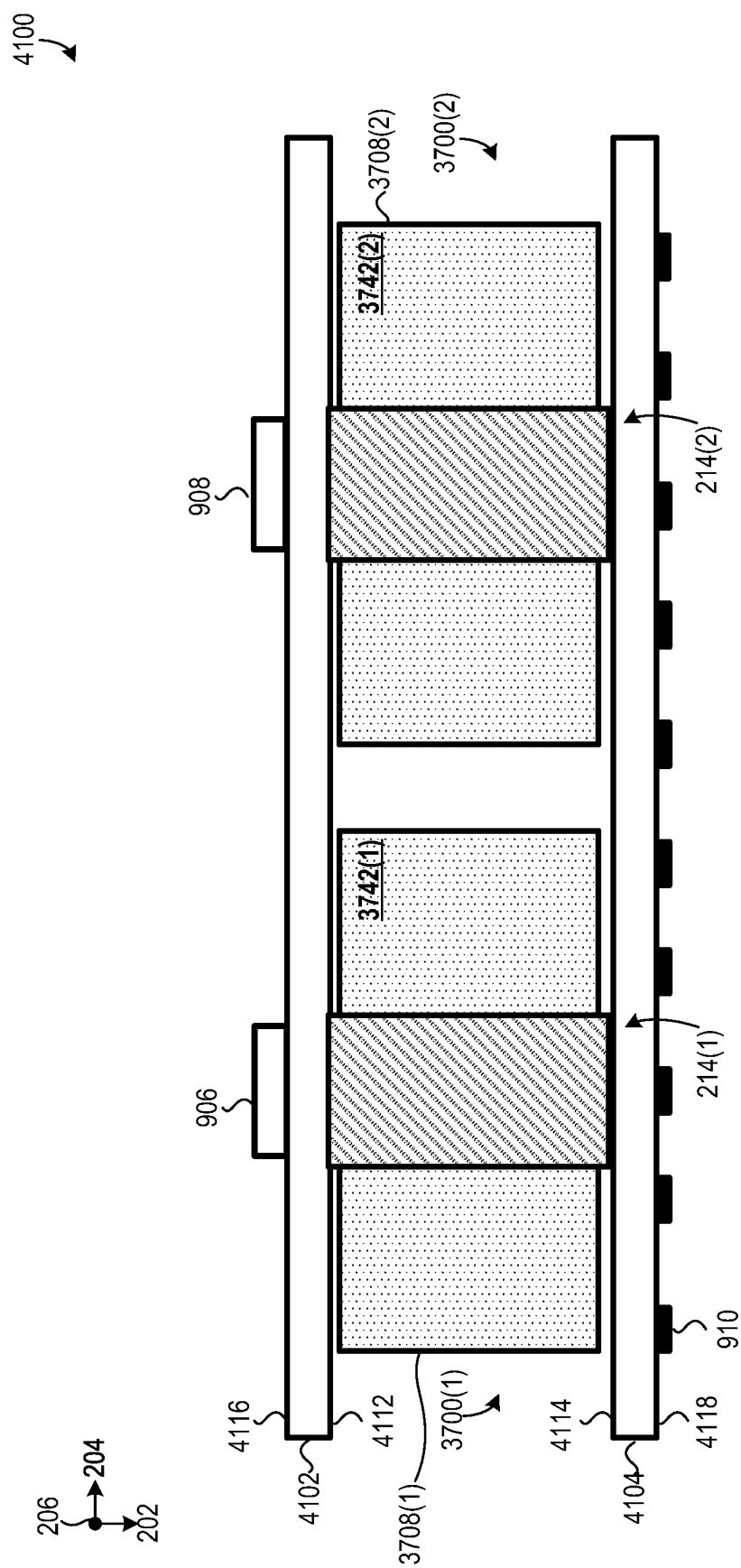


FIG. 41

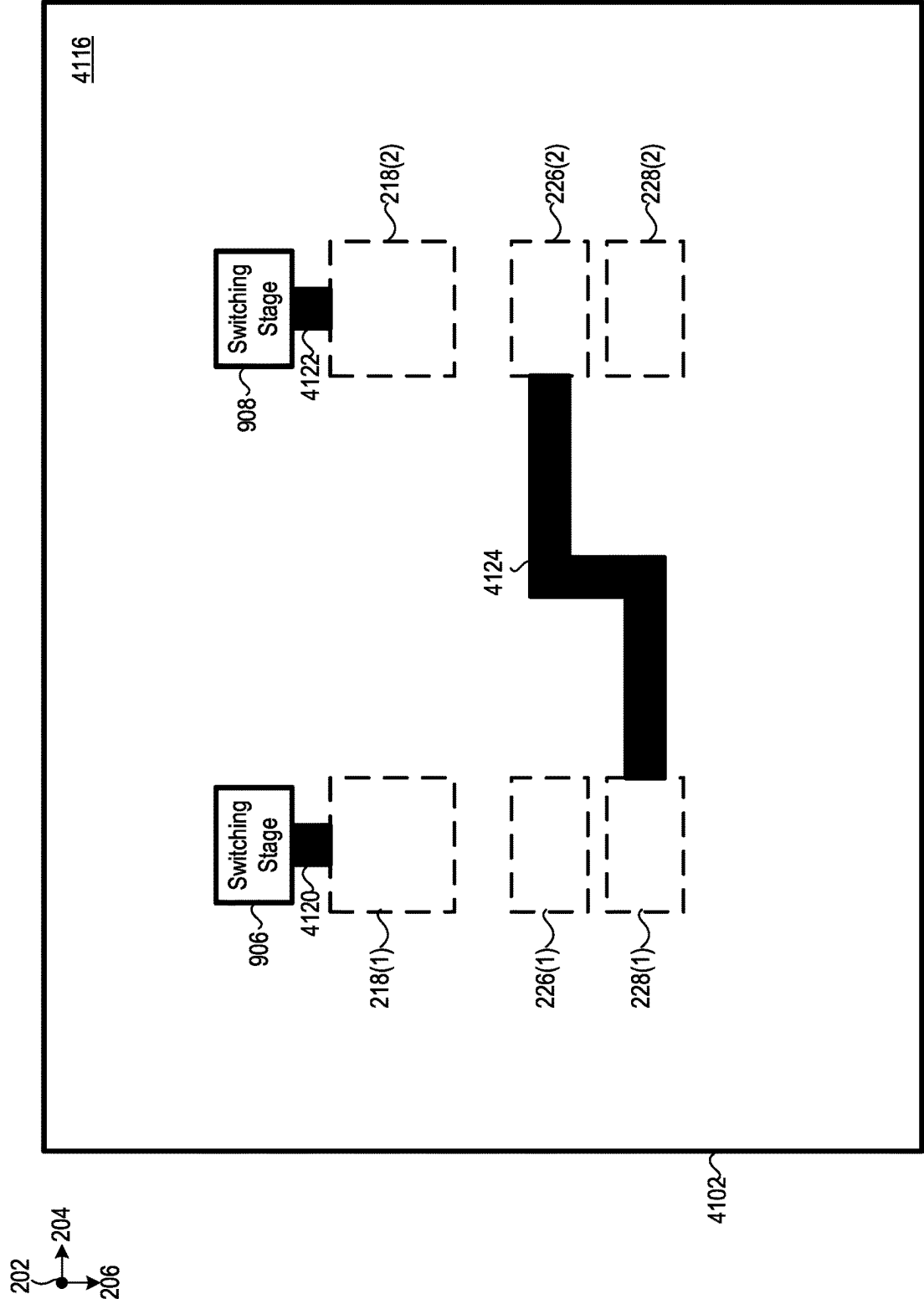


FIG. 42

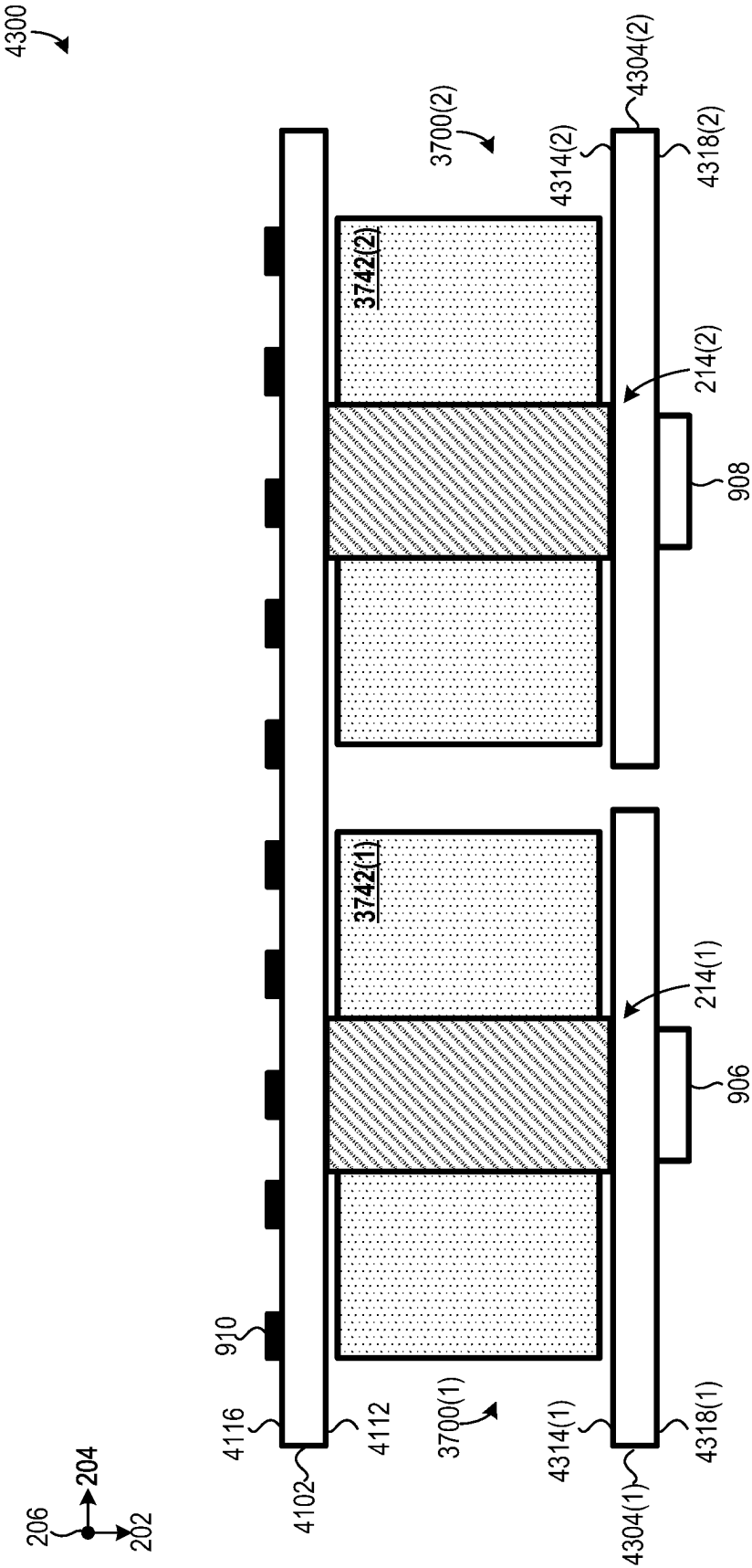


FIG. 43

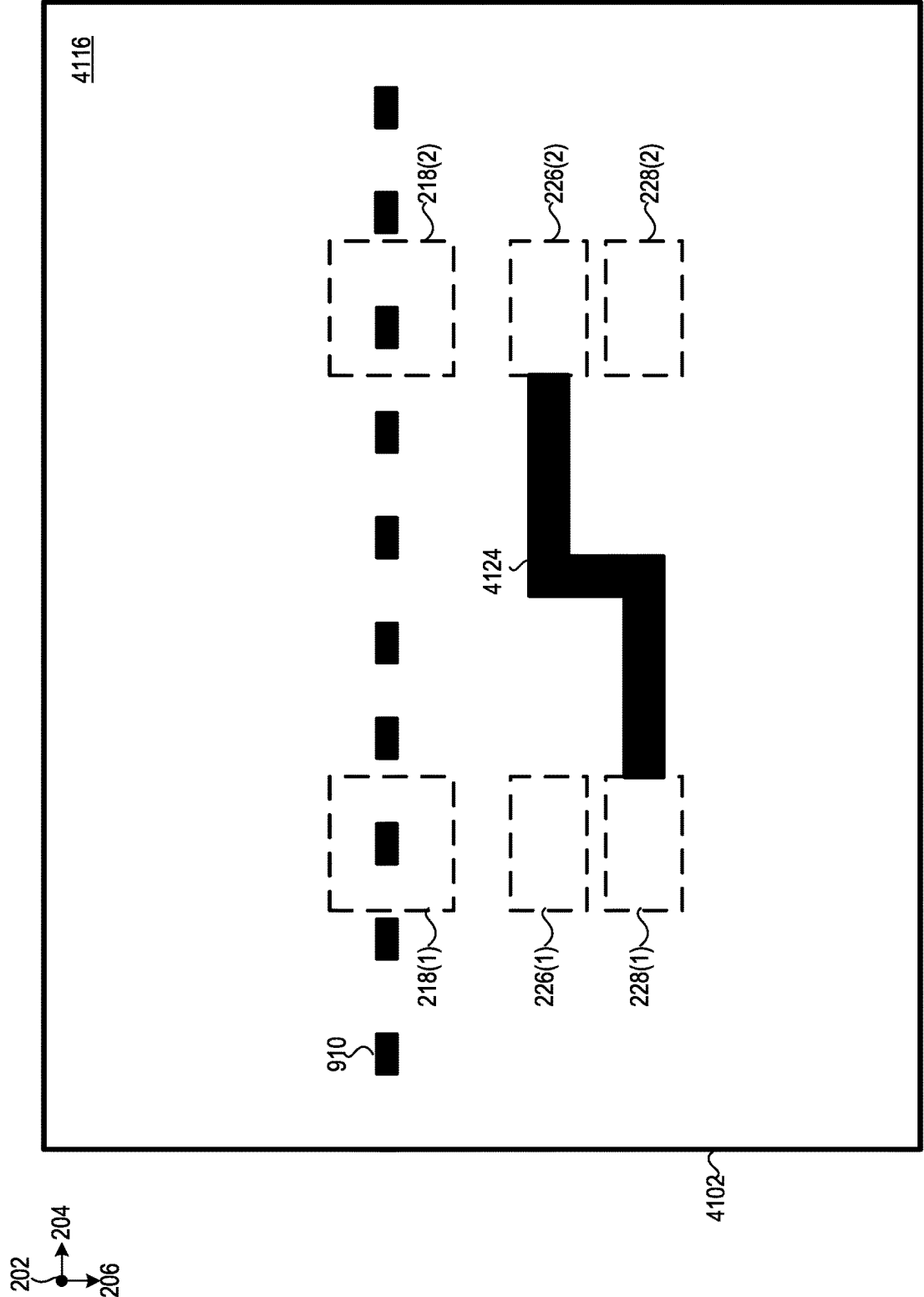


FIG. 44

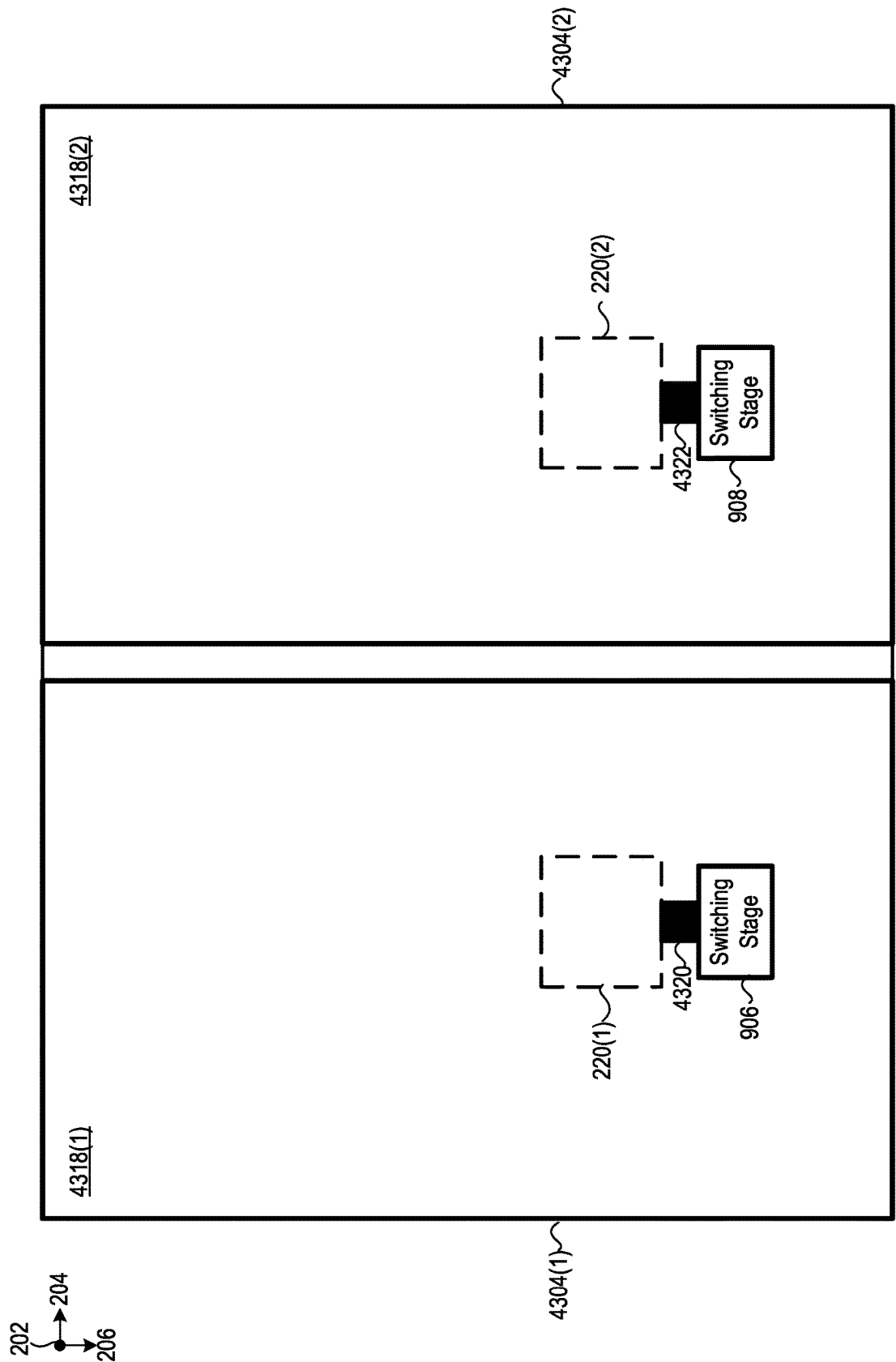


FIG. 45

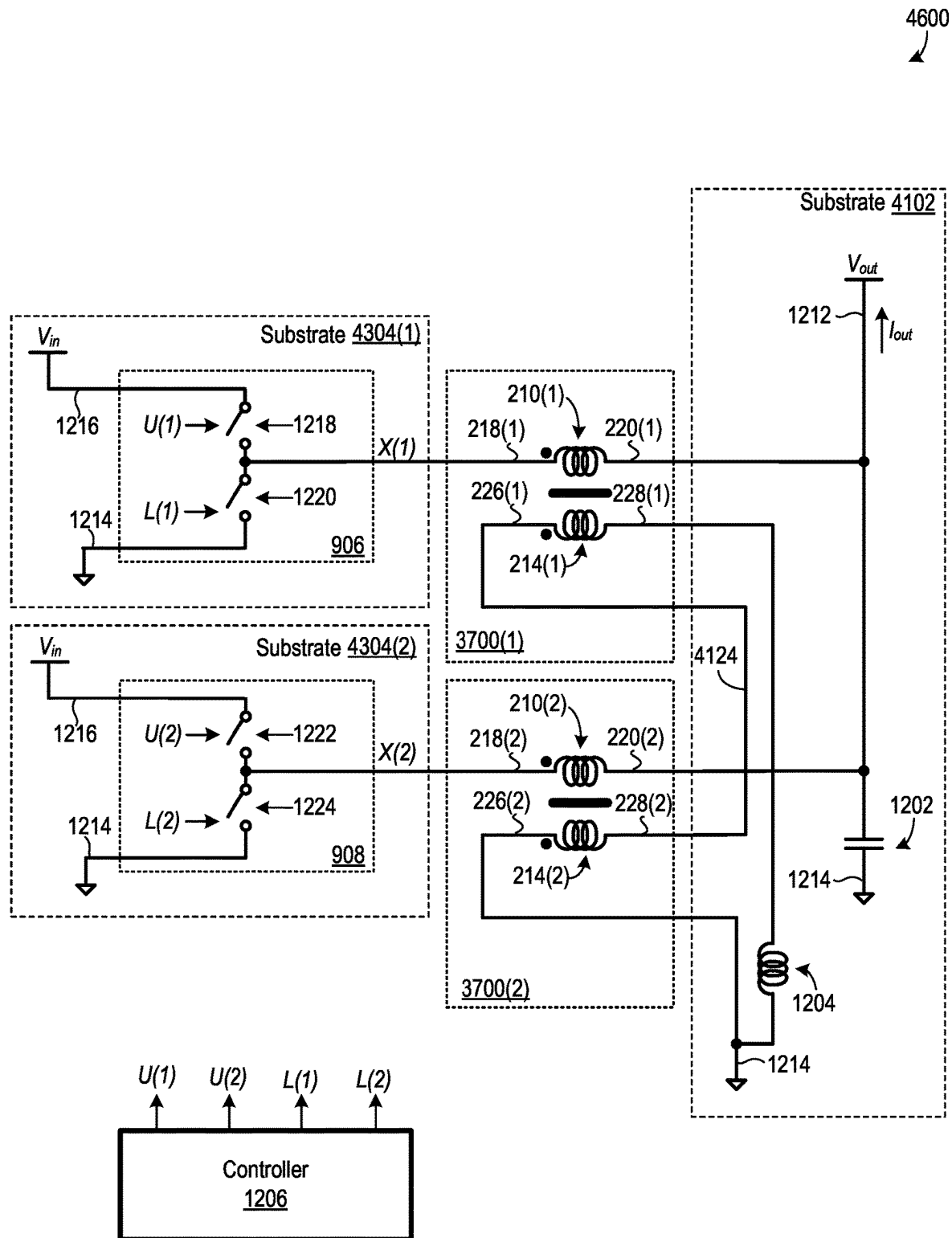


FIG. 46

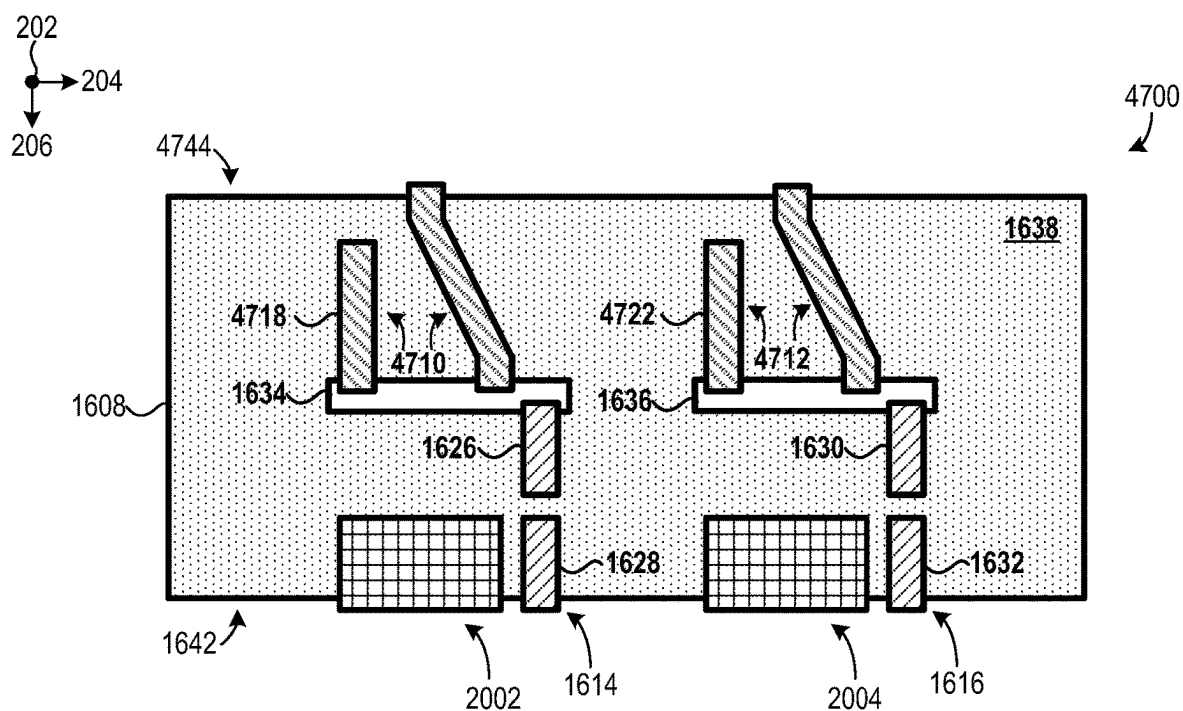


FIG. 47

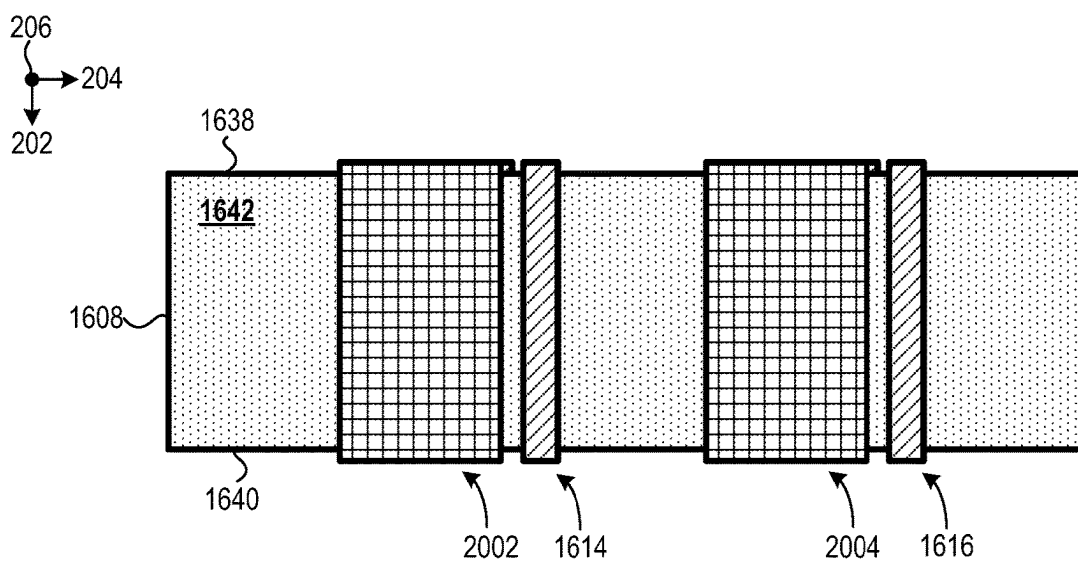


FIG. 48

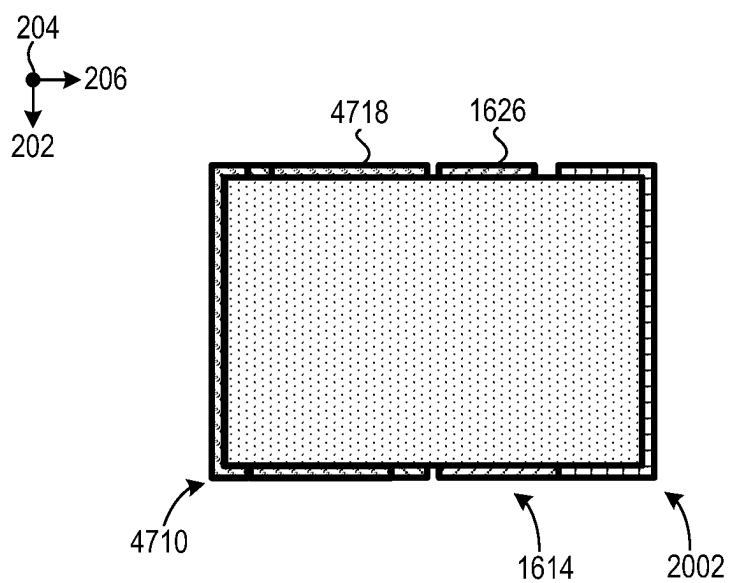


FIG. 49

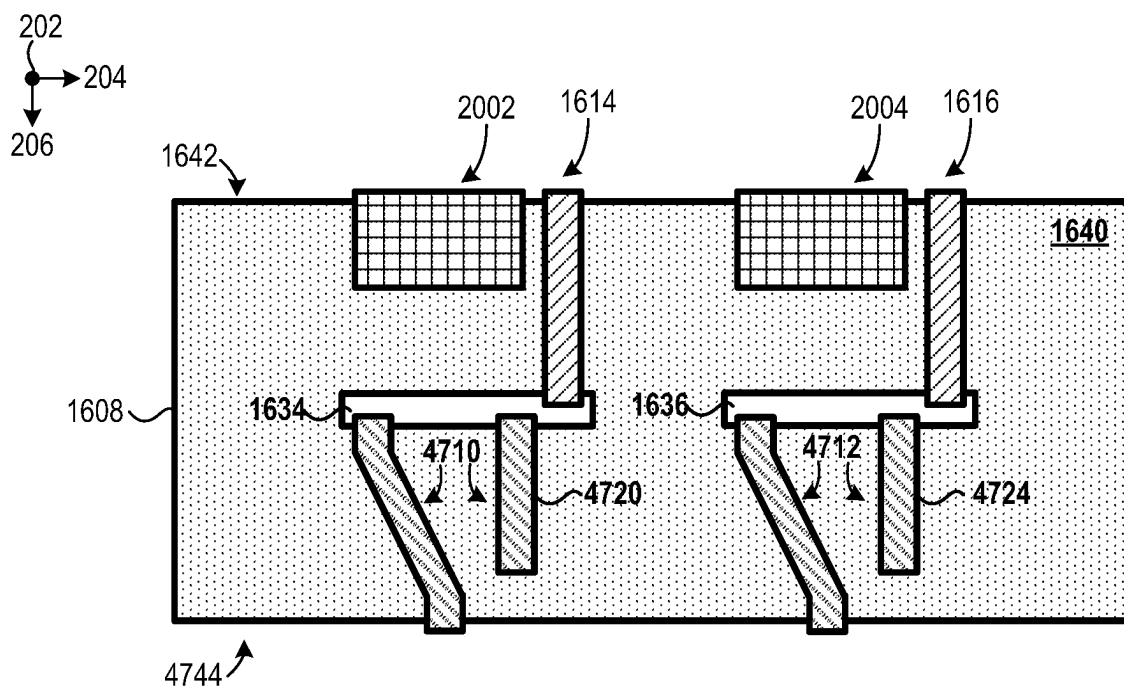


FIG. 50

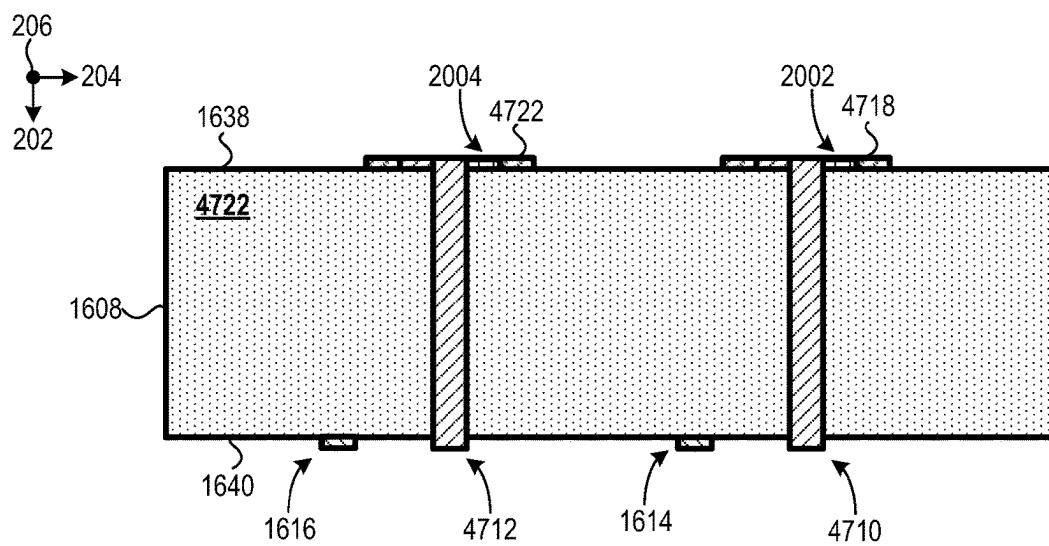


FIG. 51

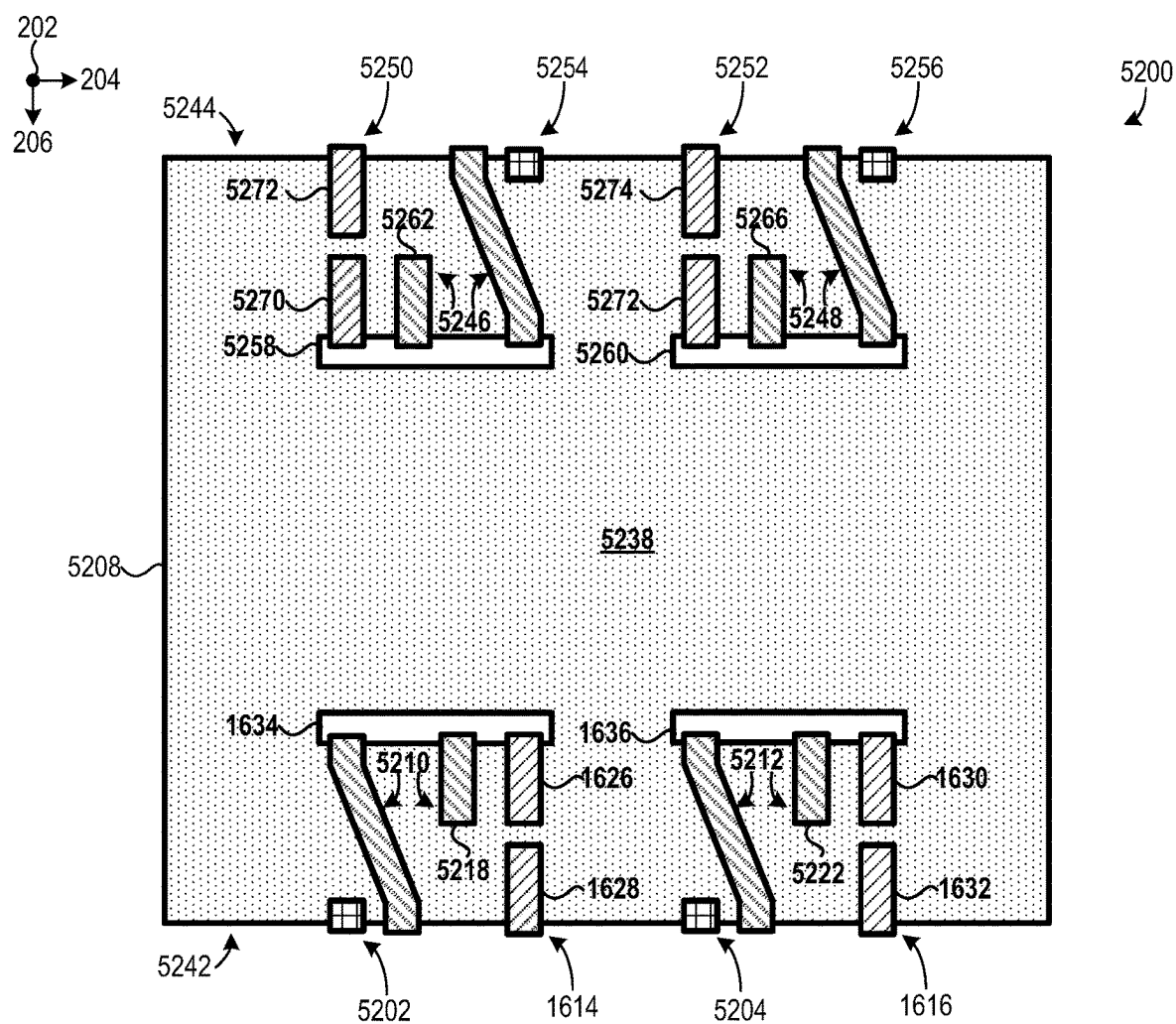


FIG. 52

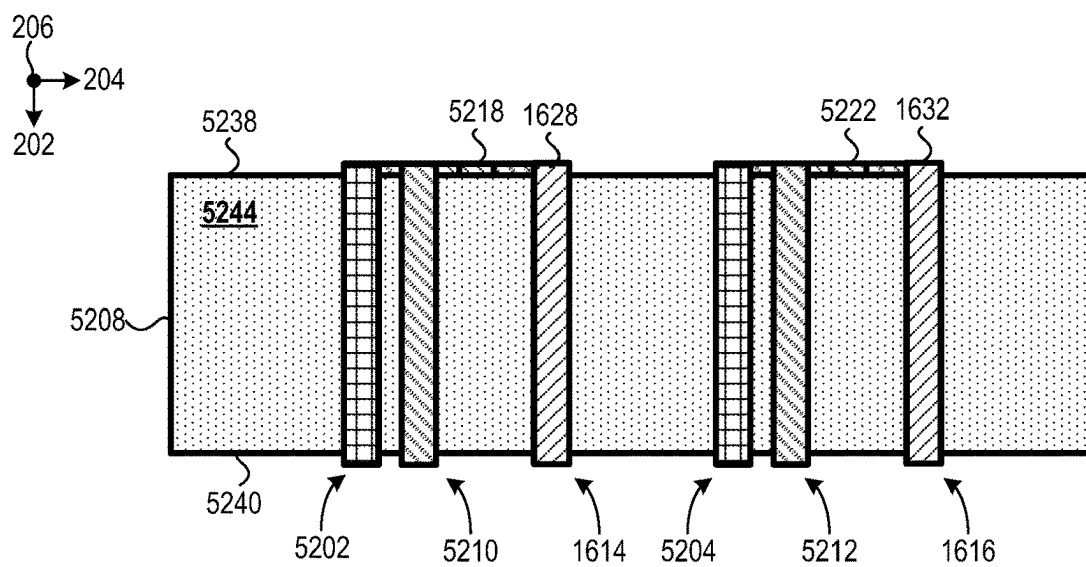


FIG. 53

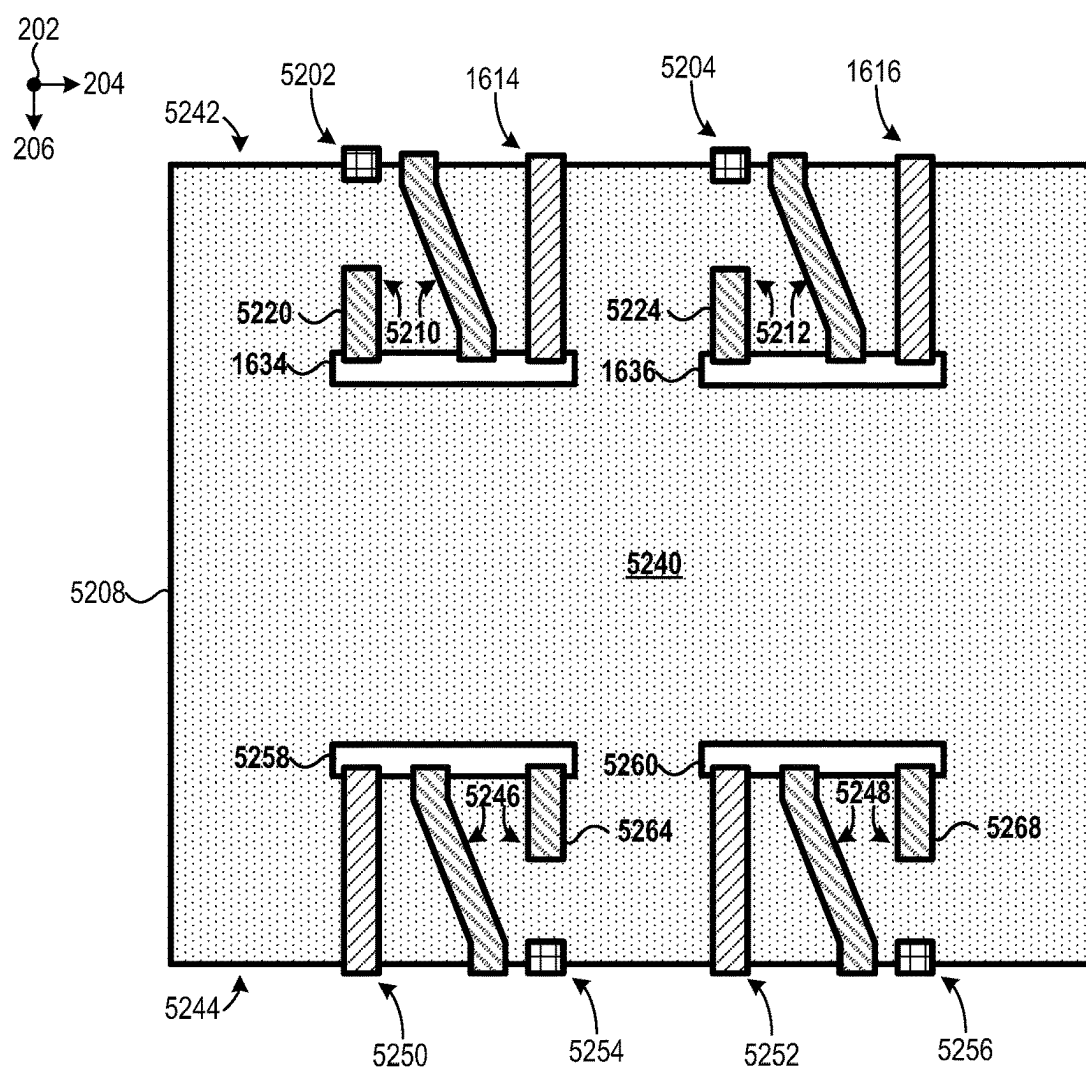


FIG. 54

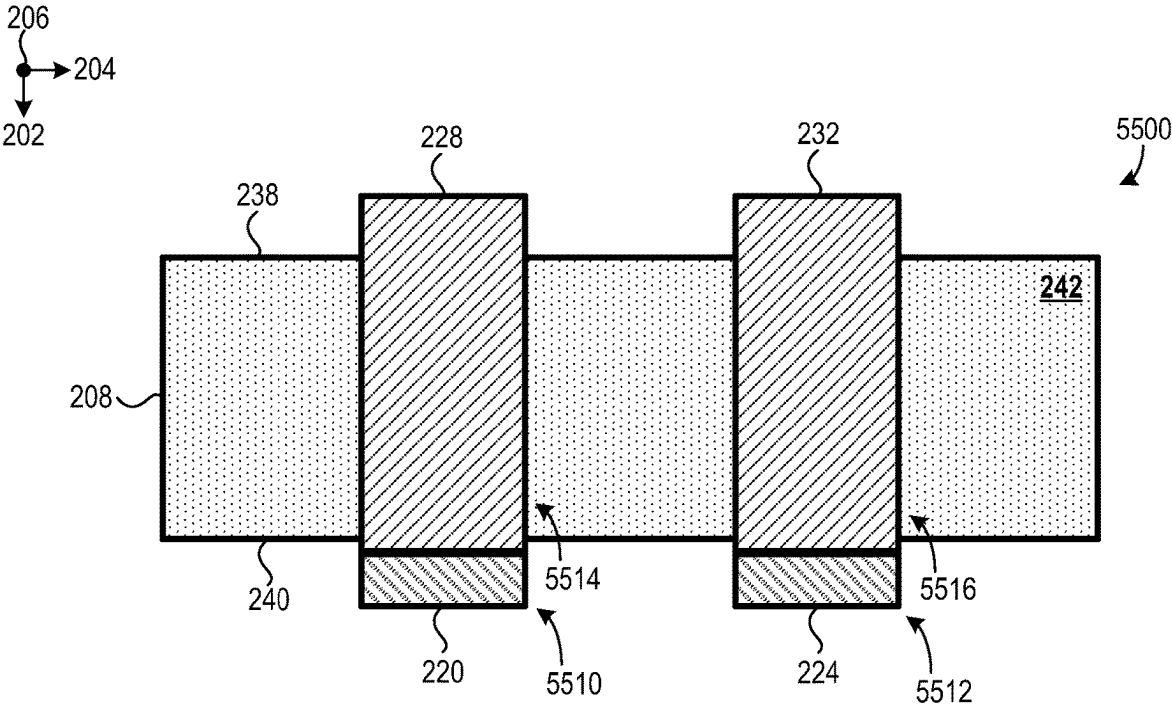


FIG. 55

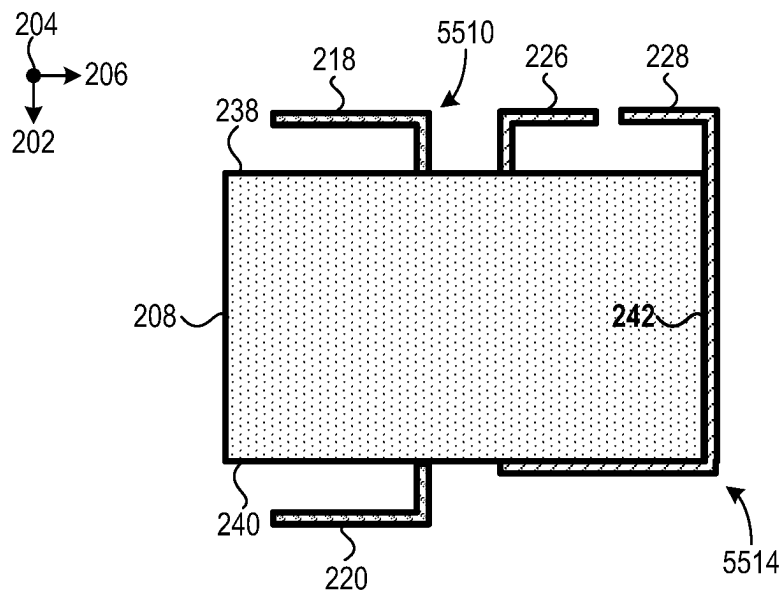


FIG. 56

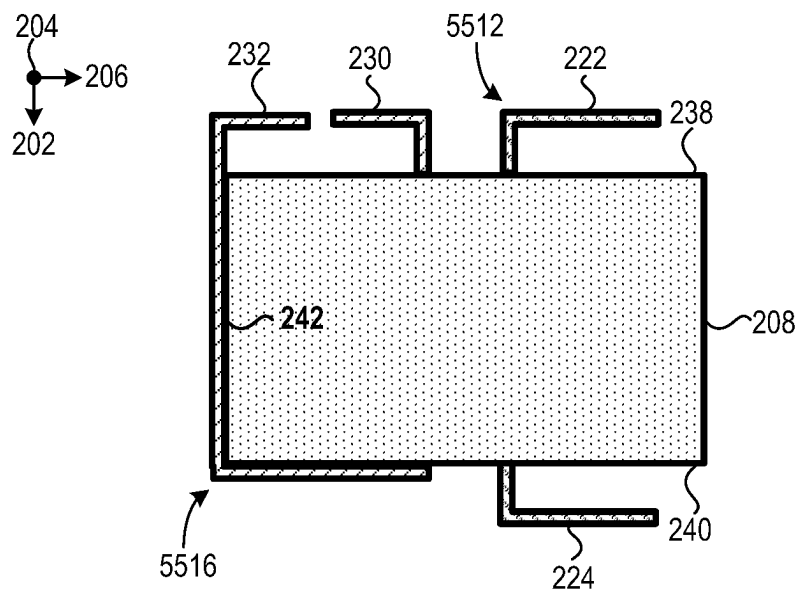


FIG. 57

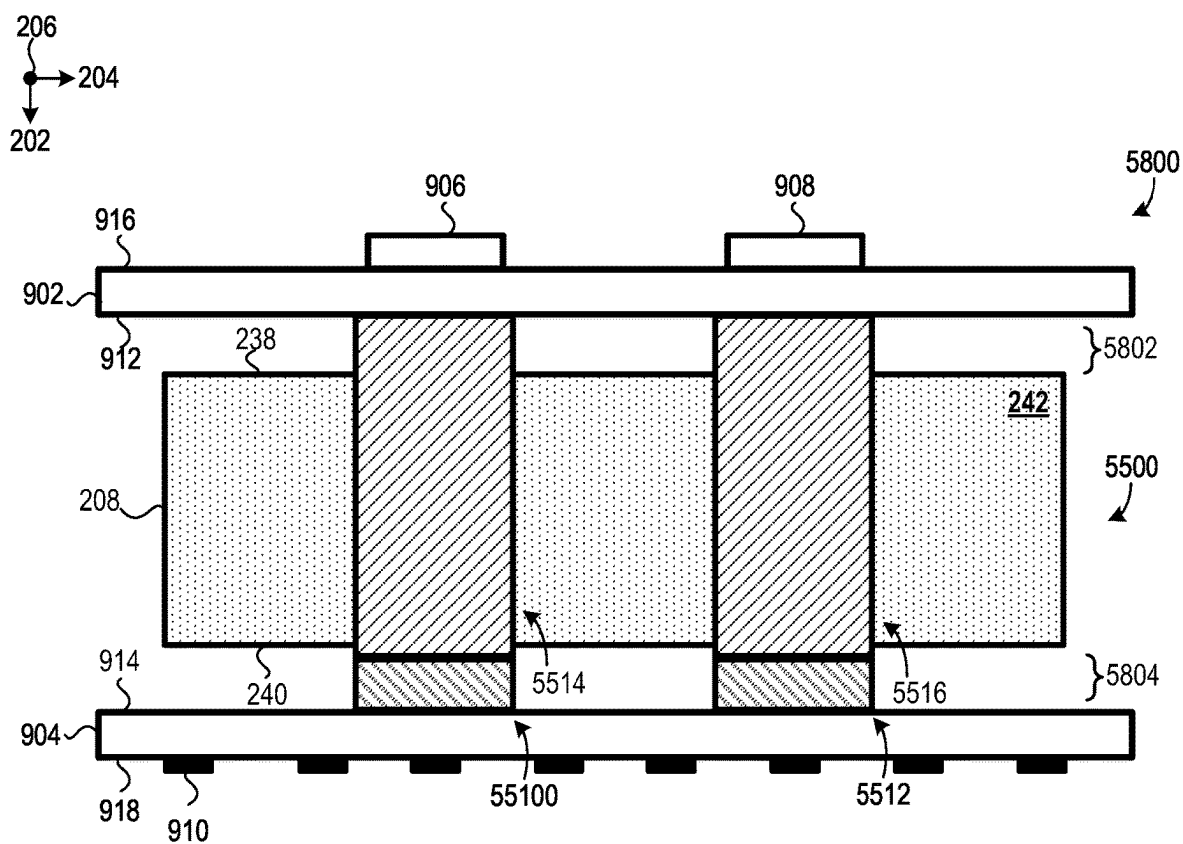


FIG. 58

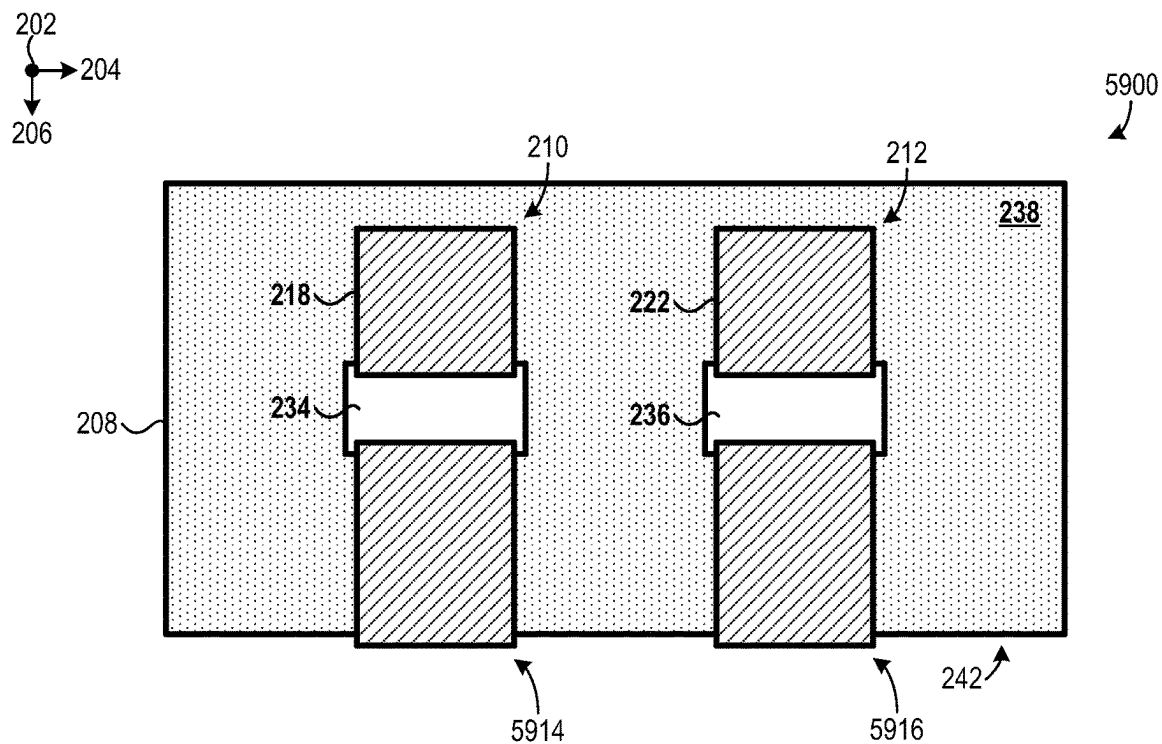


FIG. 59

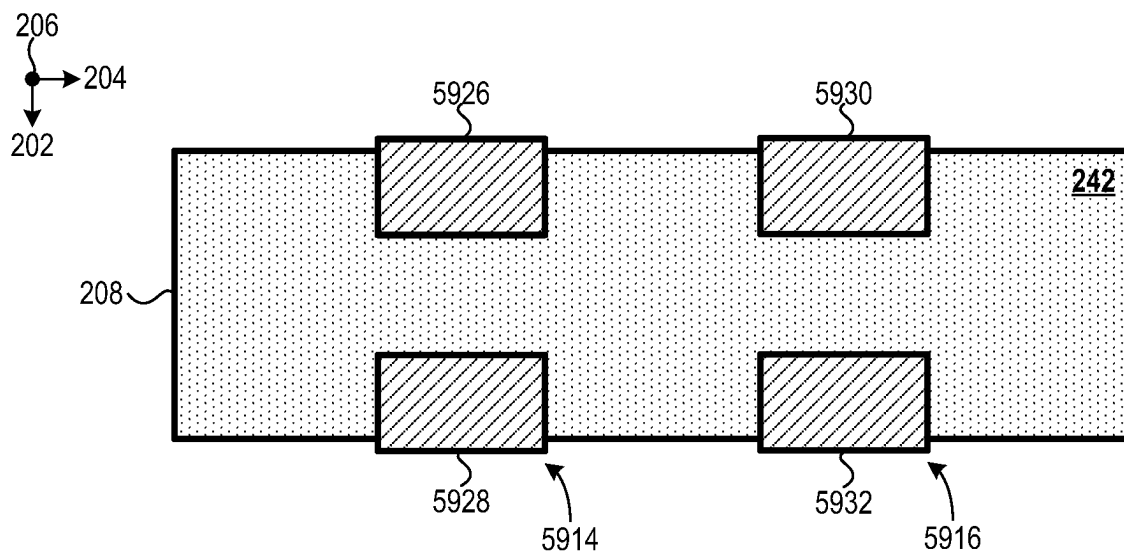


FIG. 60

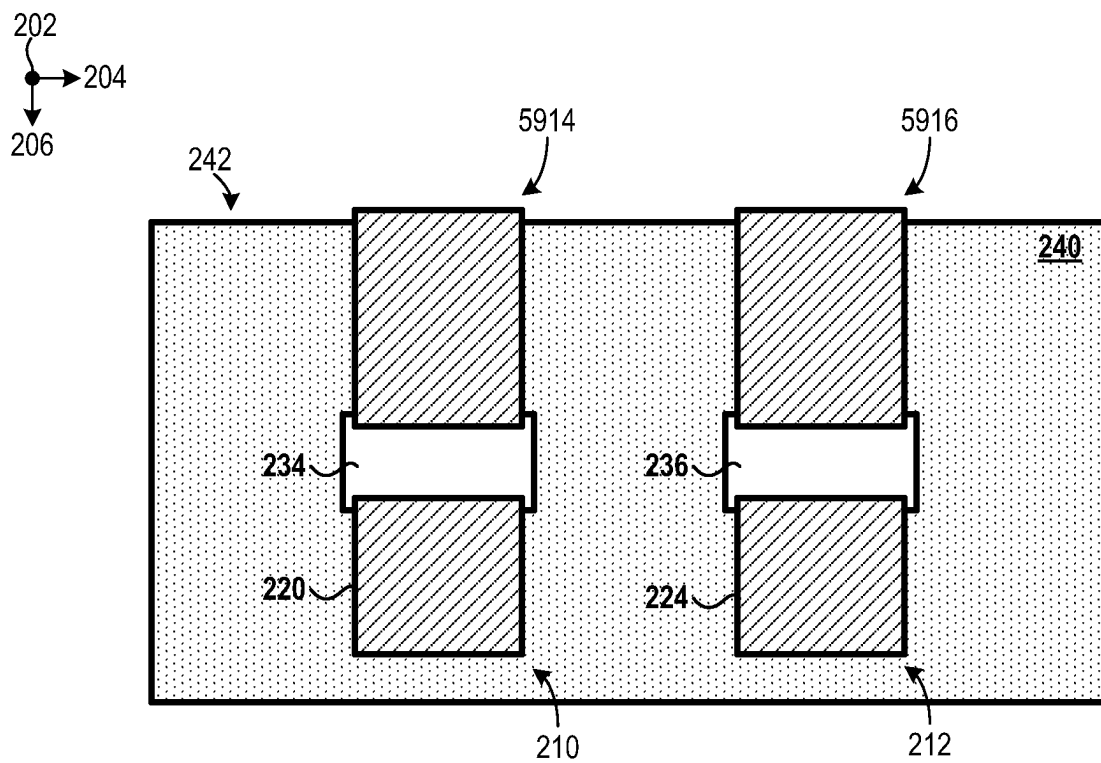


FIG. 61

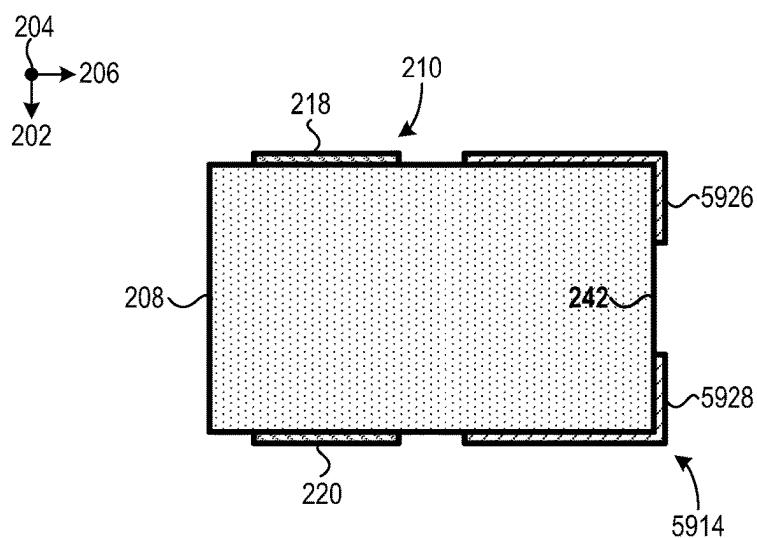


FIG. 62

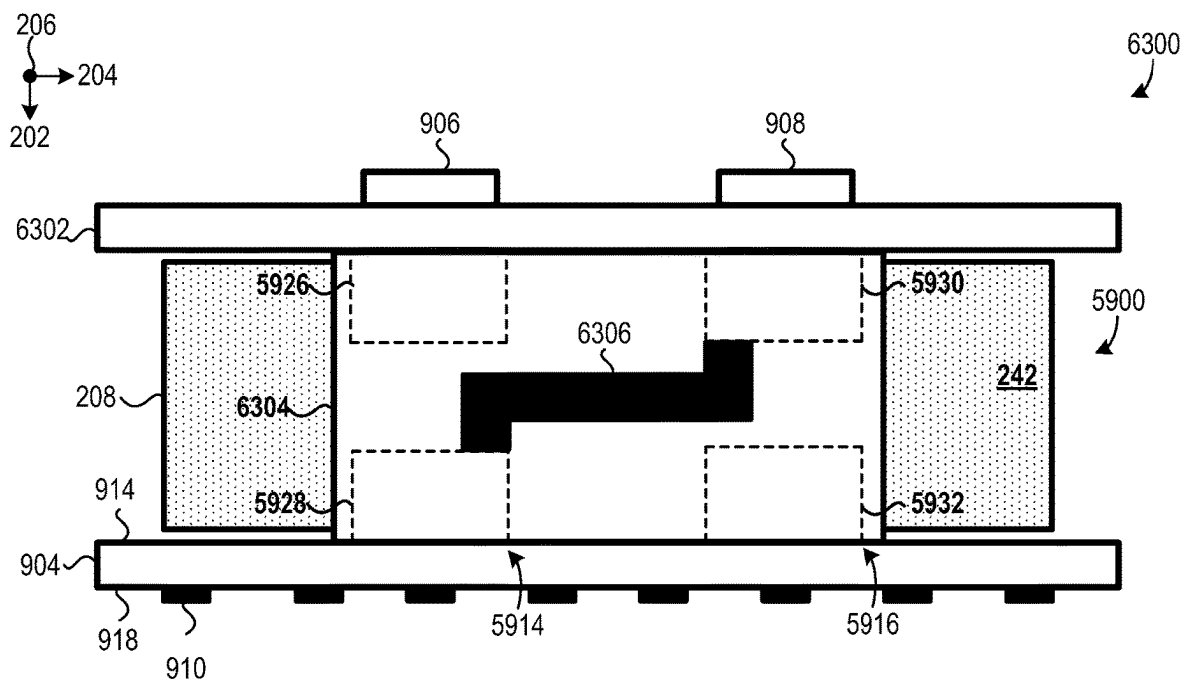


FIG. 63

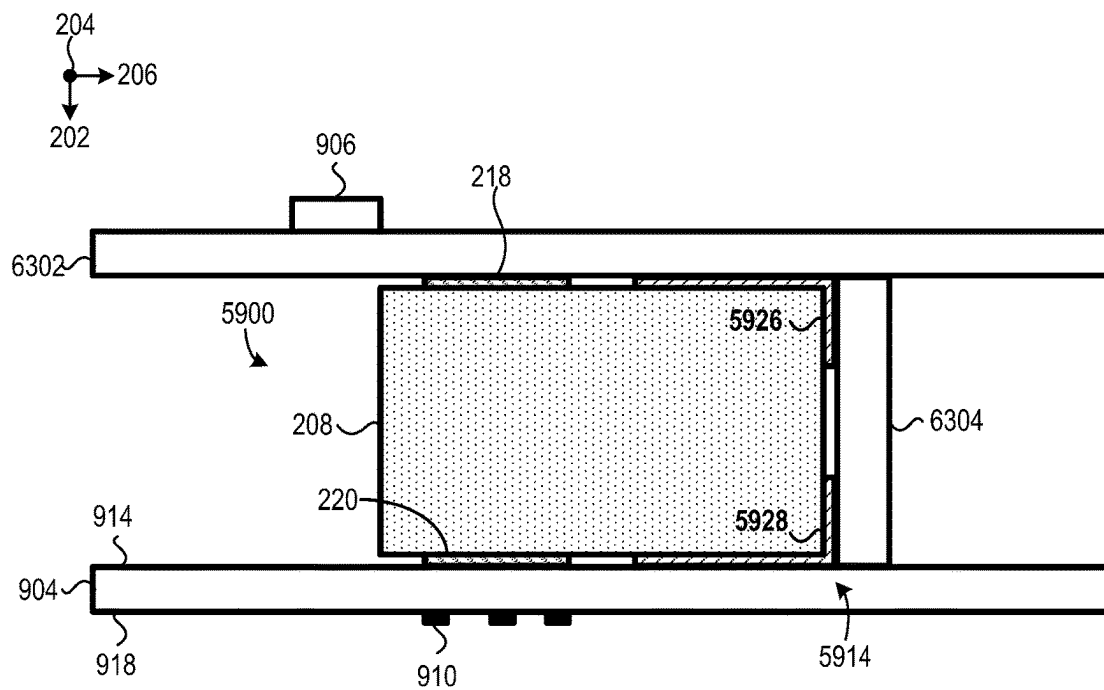


FIG. 64

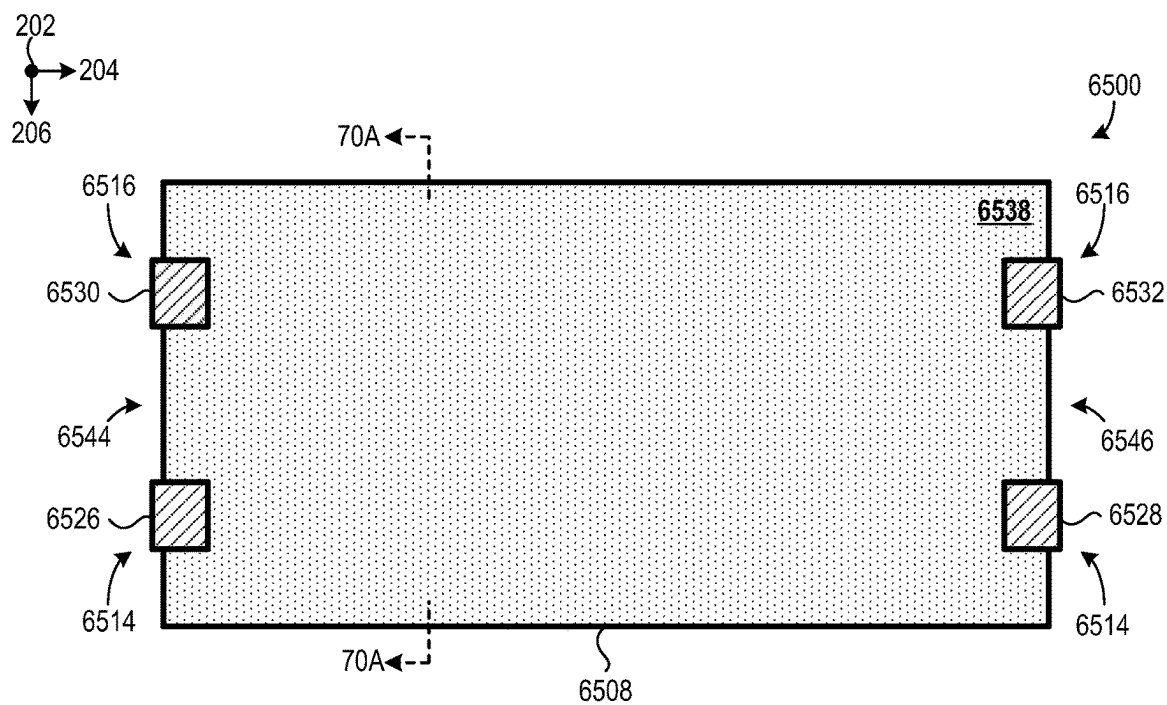


FIG. 65

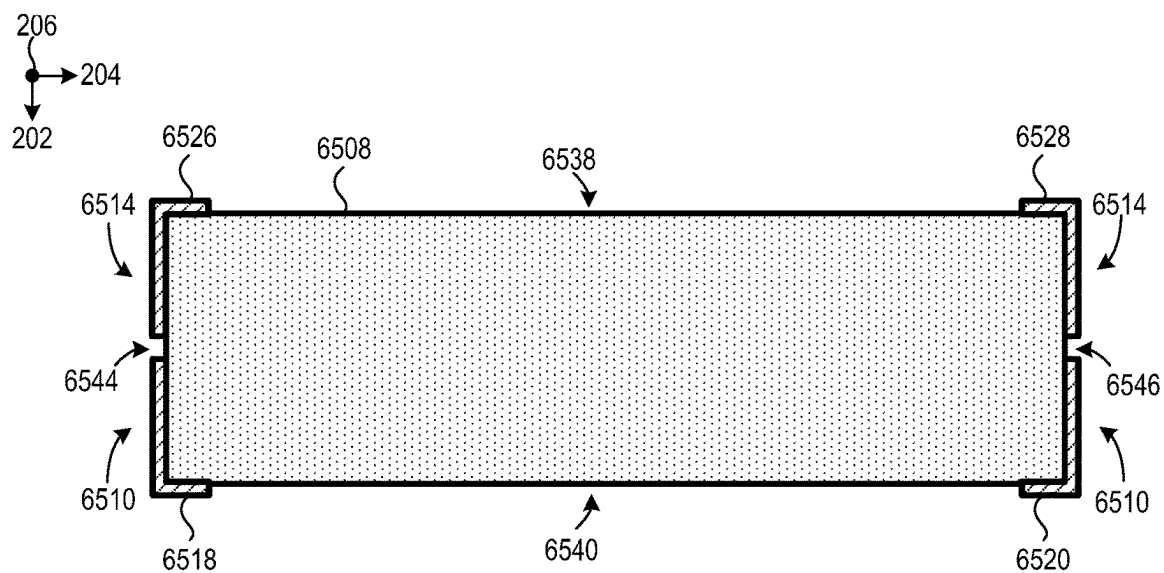


FIG. 66

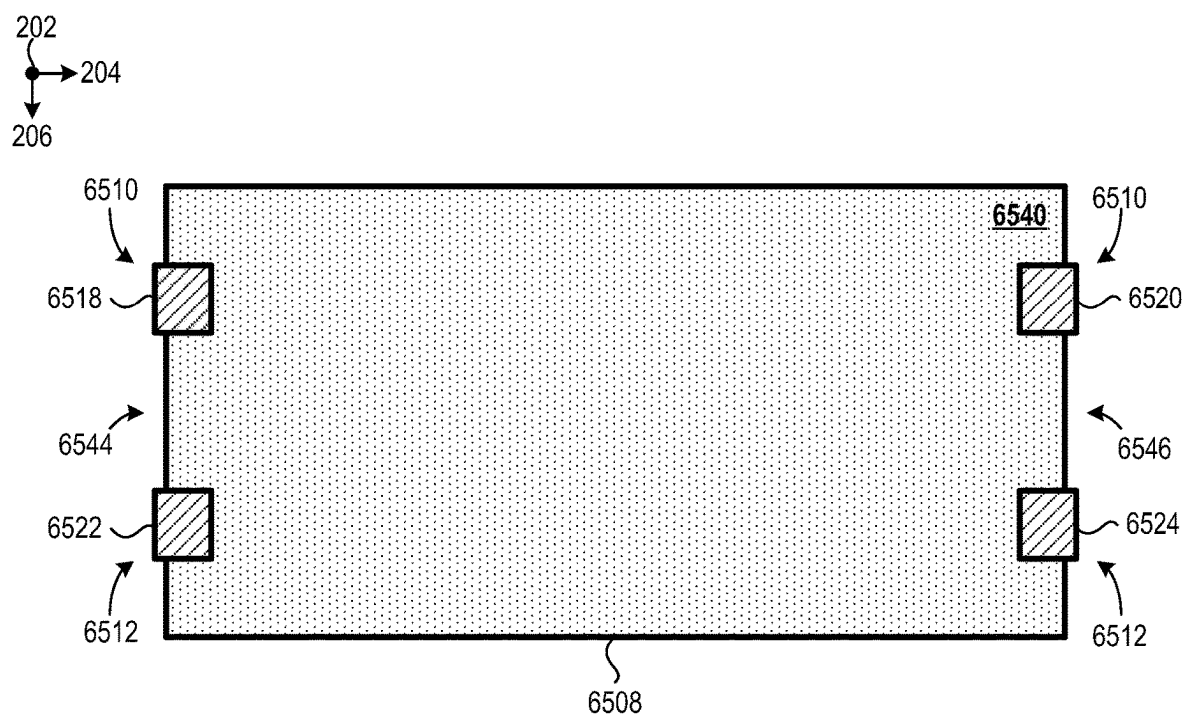


FIG. 67

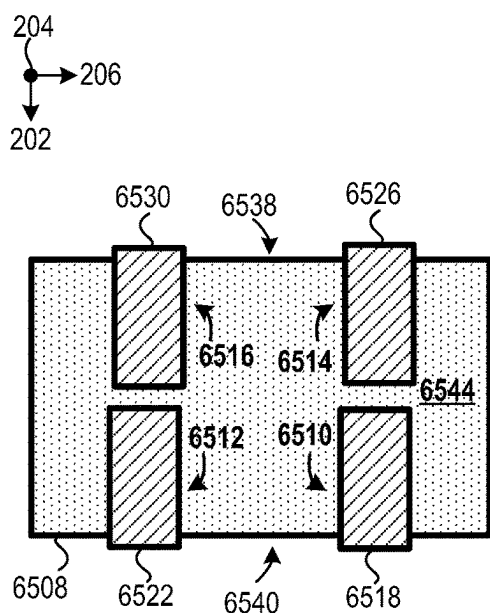


FIG. 68

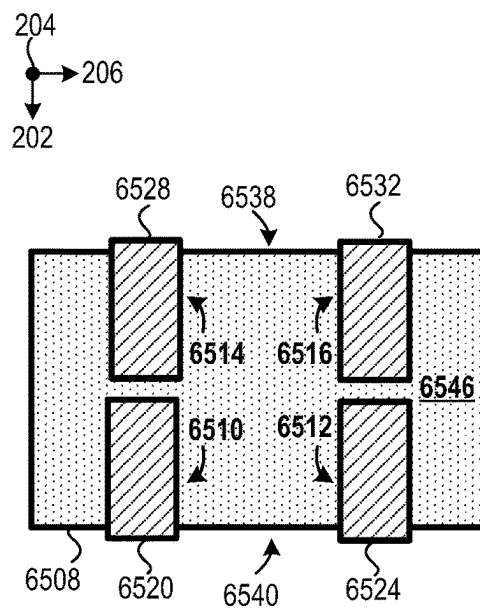


FIG. 69

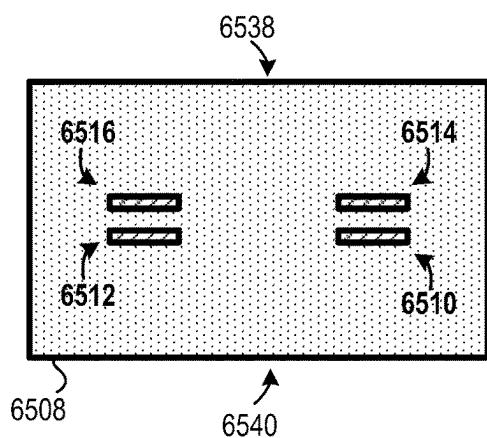


FIG. 70

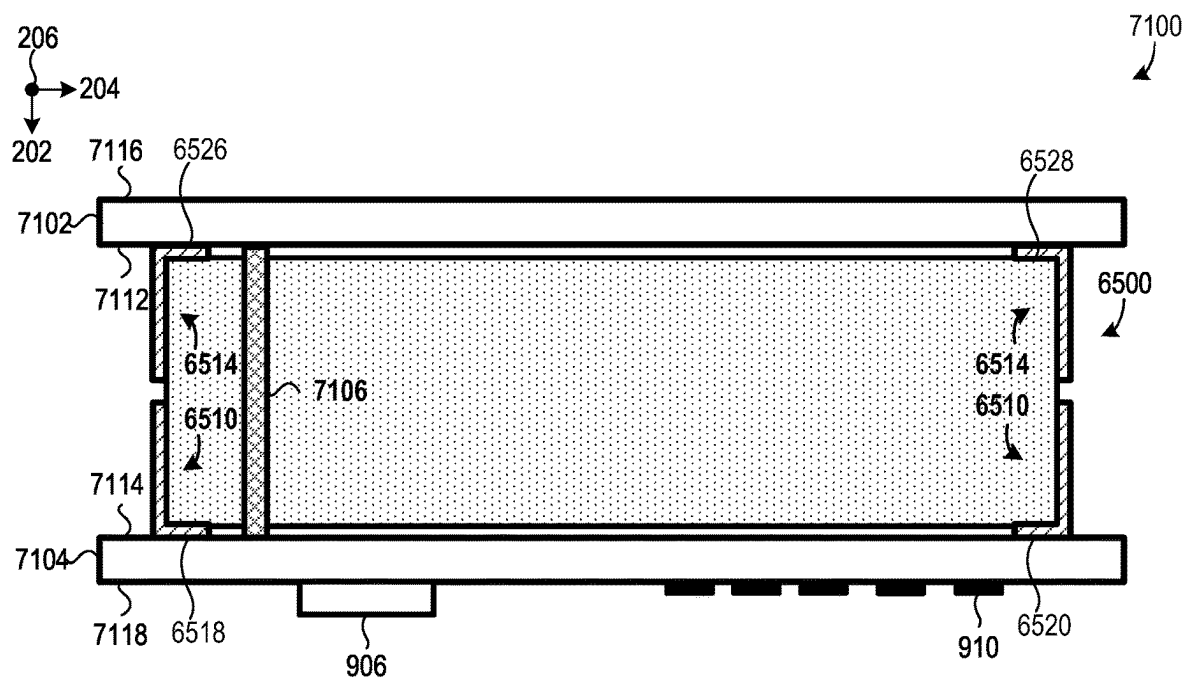


FIG. 71

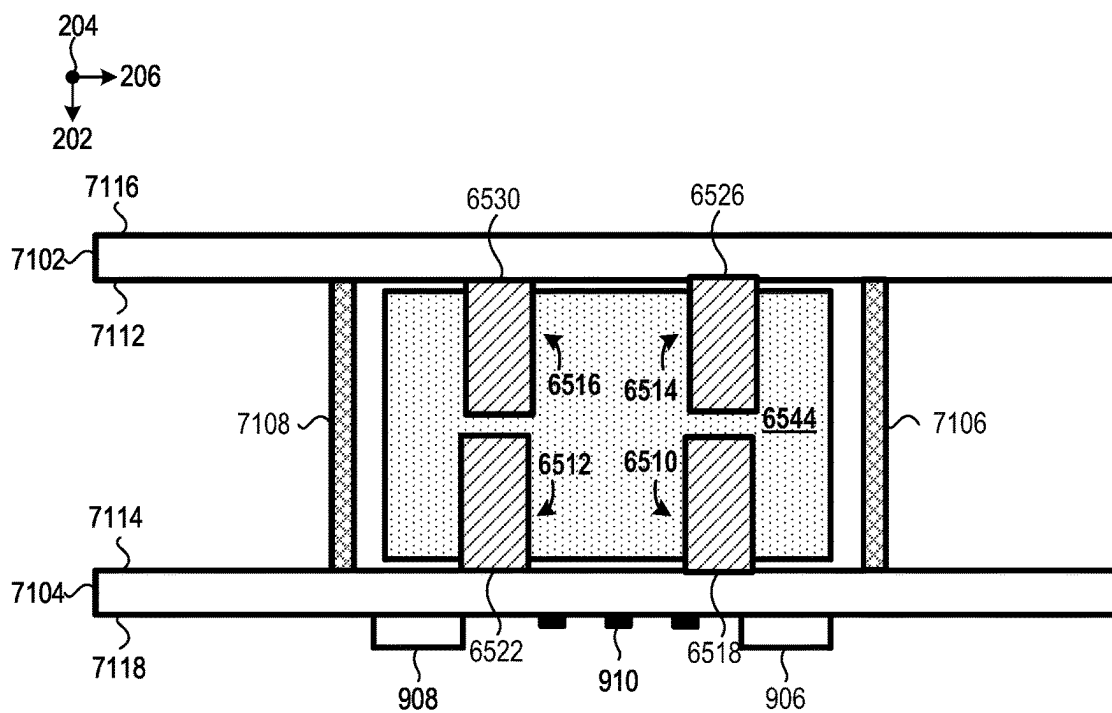


FIG. 72

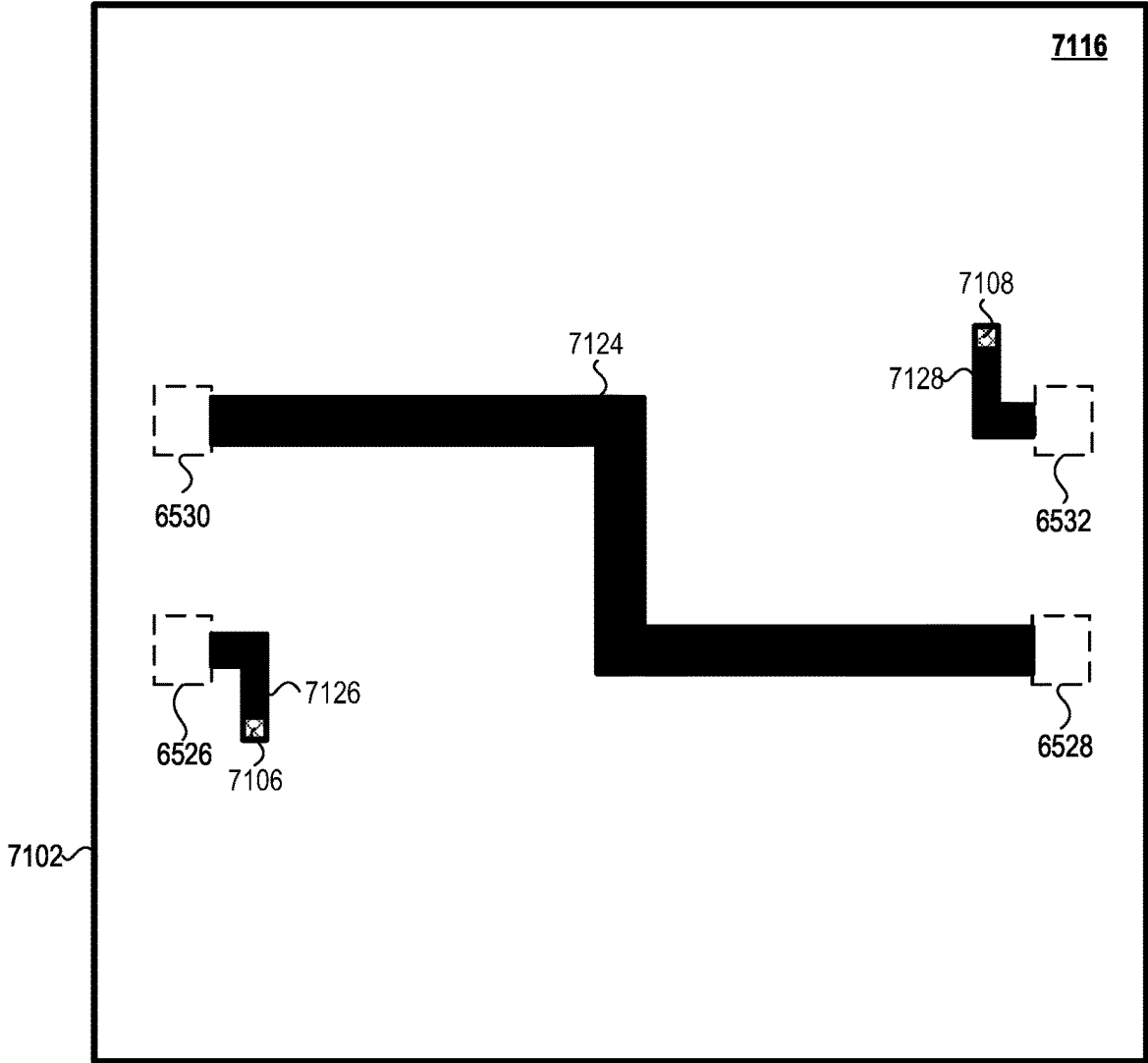
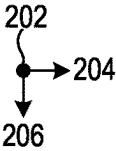


FIG. 73

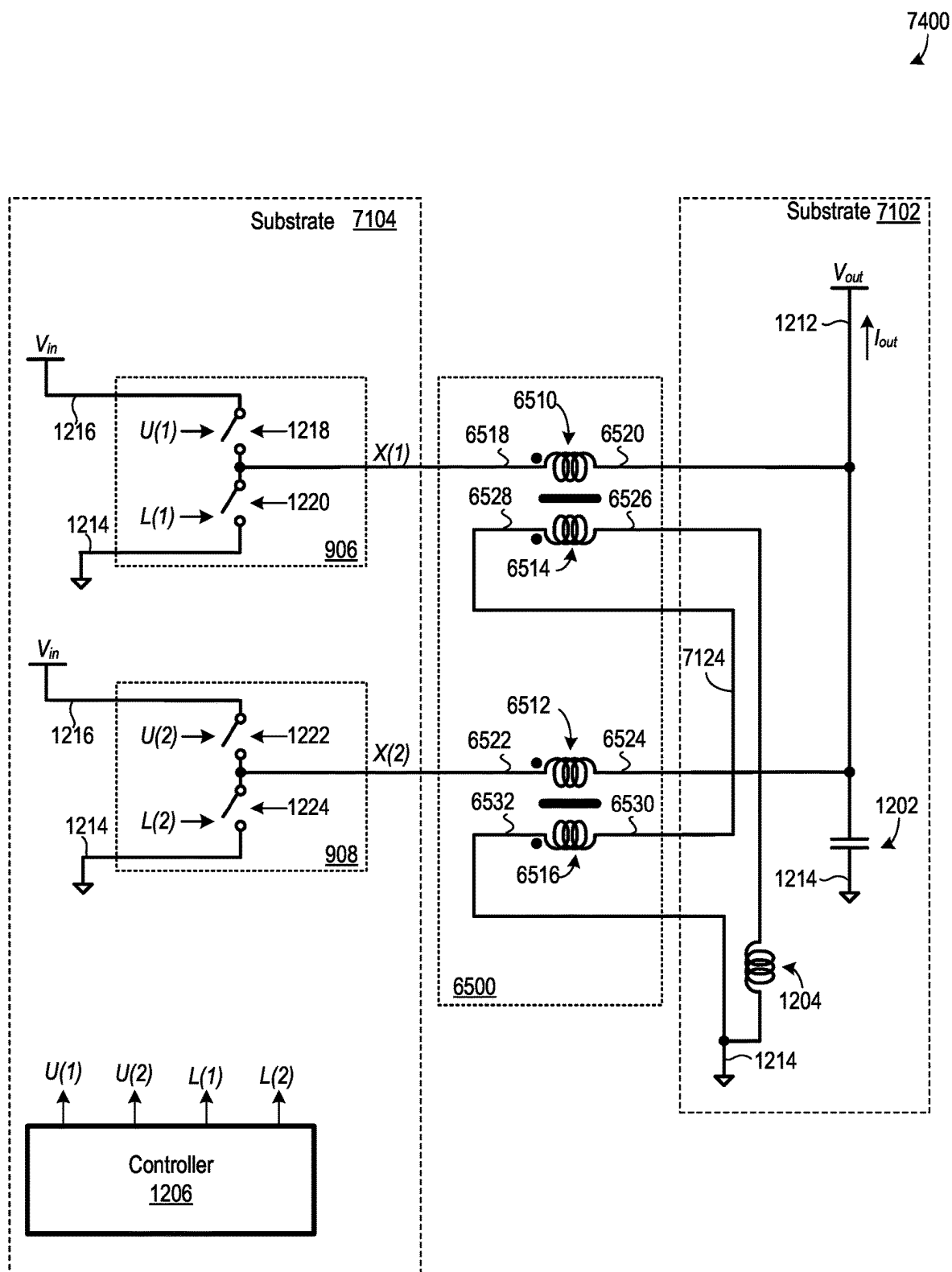


FIG. 74

ELECTRICAL ASSEMBLIES INCLUDING MAGNETIC DEVICES

BACKGROUND

[0001] Switching power converters are widely used in electronic devices, such as to provide a regulated electric power source. A switching power converter is configured such that its solid-state power switching devices do not continuously operate in their active states; instead, the power switching devices repeatedly switch between their on-states and off-states. Switching power converters commonly include one or more inductors for energy storage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] FIG. 1 is a schematic diagram of an electrical assembly including a magnetic device, according to an embodiment.

[0003] FIG. 2 is a top plan view of a magnetic device, according to an embodiment.

[0004] FIG. 3 is a front elevational view of the FIG. 2 magnetic device.

[0005] FIG. 4 is a bottom plan view of the FIG. 2 magnetic device.

[0006] FIG. 5 is a side elevational view of the FIG. 2 magnetic device.

[0007] FIG. 6 is a cross-sectional view of the FIG. 2 magnetic device taken along line 6A-6A of FIG. 2.

[0008] FIG. 7 is a top plan view of an embodiment of the FIG. 2 magnetic device where a magnetic core forms two gaps.

[0009] FIG. 8 is a top plan view of another embodiment of the FIG. 2 magnetic device where a magnetic core forms two gaps.

[0010] FIG. 9 is a front elevational view of an electrical assembly including an instance of the FIG. 2 magnetic device, according to an embodiment.

[0011] FIG. 10 is a side elevational view of the FIG. 9 electrical assembly.

[0012] FIG. 11 is top plan view of the FIG. 9 electrical assembly.

[0013] FIG. 12 is an electrical schematic diagram of a multi-phase switching power converter at least partially formed by elements of the FIG. 9 electrical assembly.

[0014] FIG. 13 is a front elevational view of an alternate embodiment of the FIG. 9 electrical assembly.

[0015] FIG. 14 is a side elevational view of the FIG. 13 electrical assembly.

[0016] FIG. 15 is top plan view of the FIG. 13 electrical assembly.

[0017] FIG. 16 is a top plan view of an alternate embodiment of the FIG. 2 magnetic device.

[0018] FIG. 17 is a front elevational view of the FIG. 16 magnetic device.

[0019] FIG. 18 is a side elevational view of the FIG. 16 magnetic device.

[0020] FIG. 19 is a bottom plan view of the FIG. 16 magnetic device.

[0021] FIG. 20 is a top plan view of an alternate embodiment of the FIG. 16 magnetic device further including ground conductors.

[0022] FIG. 21 is a front elevational view of the FIG. 20 magnetic device.

[0023] FIG. 22 is a side elevational view of the FIG. 20 magnetic device.

[0024] FIG. 23 is a bottom elevational view of the FIG. 20 magnetic device.

[0025] FIG. 24 is a cross-sectional view of the FIG. 20 magnetic device taken along line 24A-24A of FIG. 20.

[0026] FIG. 25 is a front elevational view of an alternate embodiment of the FIG. 9 electrical assembly including the FIG. 20 magnetic device in place of the FIG. 2 magnetic device.

[0027] FIG. 26 is schematic diagram of an alternate embodiment of the FIG. 12 multi-phase switching power converter including the FIG. 20 magnetic device in place of the FIG. 2 magnetic device.

[0028] FIG. 27 is a top plan view of another alternate embodiment of the FIG. 16 magnetic device further including ground conductors.

[0029] FIG. 28 is a front elevational view of the FIG. 27 magnetic device.

[0030] FIG. 29 is a side elevational view of the FIG. 27 magnetic device.

[0031] FIG. 30 is a cross-sectional view of the FIG. 27 magnetic device taken along line 30A-30A of FIG. 27.

[0032] FIG. 31 is a bottom plan view of the FIG. 27 magnetic device.

[0033] FIG. 32 is a top plan view of an alternate embodiment of the FIG. 2 magnetic device including two additional winding sets.

[0034] FIG. 33 is a front elevational view of the FIG. 32 magnetic device.

[0035] FIG. 34 is a side elevational view of the FIG. 32 magnetic device.

[0036] FIG. 35 is a bottom plan view of the FIG. 32 magnetic device.

[0037] FIG. 36 is a cross-sectional view of the FIG. 32 magnetic device taken along line 36A-36A of FIG. 32.

[0038] FIG. 37 is a top plan view of an alternate embodiment of the FIG. 2 magnetic device including only a single winding set.

[0039] FIG. 38 is a front elevational view of the FIG. 37 magnetic device.

[0040] FIG. 39 is a side elevational view of the FIG. 37 magnetic device.

[0041] FIG. 40 is a bottom plan view of the FIG. 37 magnetic device.

[0042] FIG. 41 is a front elevational view of an alternate embodiment of the FIG. 9 electrical assembly including two instances of the FIG. 37 magnetic device in place of the FIG. 2 magnetic device.

[0043] FIG. 42 is a top plan view of the FIG. 41 electrical assembly.

[0044] FIG. 43 is a front elevational view of an alternate embodiment of the FIG. 41 electrical assembly including two substrates in place of a single common substrate.

[0045] FIG. 44 is a top plan view of the FIG. 43 electrical assembly.

[0046] FIG. 45 is a bottom plan view of the FIG. 43 electrical assembly.

[0047] FIG. 46 is an electrical schematic diagram of a multi-phase switching power converter at least partially formed by elements of the FIG. 43 electrical assembly.

[0048] FIG. 47 is a top plan view of an alternate embodiment of the FIG. 20 magnetic device with primary windings forming two turns each.

[0049] FIG. 48 is a front elevational view of the FIG. 47 magnetic device.

[0050] FIG. 49 is a side elevational view of the FIG. 47 magnetic device.

[0051] FIG. 50 is a bottom plan view of the FIG. 47 magnetic device.

[0052] FIG. 51 is a back elevational view of the FIG. 47 magnetic device.

[0053] FIG. 52 is a top plan view of an alternate embodiment of the FIG. 47 magnetic device that is scalable in two directions.

[0054] FIG. 53 is a front elevational view of the FIG. 52 magnetic device.

[0055] FIG. 54 is a bottom plan view of the FIG. 52 magnetic device.

[0056] FIG. 55 is a front elevational view of an alternate embodiment of the FIG. 2 magnetic device where winding ends are offset from magnetic core outer surfaces.

[0057] FIG. 56 is a side elevational view of the FIG. 55 magnetic device.

[0058] FIG. 57 is a side elevational view of the FIG. 55 magnetic device opposite of the side elevational view of FIG. 56.

[0059] FIG. 58 is a front elevational view of an alternate embodiment of the FIG. 9 electrical assembly including the FIG. 55 magnetic device in place of the FIG. 2 magnetic device.

[0060] FIG. 59 is a top plan view of an alternate embodiment of the FIG. 2 magnetic device where secondary winding ends terminate on a front outer surface of a magnetic core instead of a top outer surface of the magnetic core.

[0061] FIG. 60 is a front elevational view of the FIG. 59 magnetic device.

[0062] FIG. 61 is a bottom plan view of the FIG. 59 magnetic device.

[0063] FIG. 62 is a side elevational view of the FIG. 59 magnetic device.

[0064] FIG. 63 is a front elevational view of an alternate embodiment of the FIG. 9 electrical assembly including the FIG. 59 magnetic device in place of the FIG. 2 magnetic device.

[0065] FIG. 64 is a side elevational view of the FIG. 63 electrical assembly.

[0066] FIG. 65 is a top plan view of a magnetic device where primary windings terminate on a different surface than secondary windings, according to an embodiment.

[0067] FIG. 66 is a front elevational view of the FIG. 65 magnetic device.

[0068] FIG. 67 is a bottom plan view of the FIG. 65 magnetic device.

[0069] FIG. 68 is a side elevational view of the FIG. 65 magnetic device

[0070] FIG. 69 is a side elevational view of the FIG. 65 magnetic device opposite of the FIG. 68 side elevational view.

[0071] FIG. 70 is a cross-sectional view of the FIG. 65 magnetic device taken along line 70A-70A of FIG. 65.

[0072] FIG. 71 is a front elevational view of an electrical assembly including the FIG. 65 magnetic device, according to an embodiment.

[0073] FIG. 72 is a side elevational view of the FIG. 71 electrical assembly.

[0074] FIG. 73 is a top plan view of the FIG. 71 electrical assembly.

[0075] FIG. 74 is an electrical schematic diagram of a multi-phase switching power converter at least partially formed by elements of the FIG. 71 electrical assembly.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0076] Some switching power converters include a plurality of phases, where each phase includes a respective switching stage and a respective inductor. Such switching power converters may be referred to as multi-phase switching power converters. While not required, the respective switching stage of each phase typically switches out-of-phase with respect to the respective switching stage of each other phase. The inductors of a multi-phase switching power converter may be magnetically coupled to realize significant benefits, such as lower ripple current magnitude and/or faster transient response, than an otherwise similar multi-phase switching power converter without magnetic coupling of its inductors. Alternately, phases of a multi-phase switching power converter may be electrically coupled by replacing each inductor with a primary winding, magnetically coupled a respective secondary winding with each primary winding, and electrically coupling the secondary windings in series. Such electrical coupling of phases may also lower ripple current magnitude and/or improve transient response, albeit not to the degree that is possible with magnetic coupling of phases. The magnetic coupling of phases can also be combined with electrical coupling of phases; for example, two of four phase magnetically coupled inductors can be electrically coupled to each other.

[0077] Electrical assemblies including switching power converters may include more than one substrate, such as more than one printed circuit board (PCB). For example, switching stages of a switching power converter may be located on one substrate, and output capacitors of the switching power converter may be located on a second substrate. The first and second substrates are electrically connected, for example, by metallic pins joining the substrates.

[0078] Disclosed herein are electrical assemblies including magnetic devices which significantly advance the state of the art of multi-phase switching power converters with electrical coupling of phases. Particular embodiments include a magnetic device sandwiched between a first substrate and a second substrate, such as between a first and a second PCB. The magnetic device includes a plurality primary windings extending through a magnetic core of the magnetic device, and each primary winding electrically couples the first substrate to the second substrate, such that one end of each primary winding is electrically coupled to the first substrate and an opposing end of the primary winding is electrically coupled to the second substrate. Additionally, the magnetic device includes a respective secondary winding magnetically coupled to each primary winding, and opposing ends of each secondary winding are electrically coupled to the first substrate. The secondary windings are electrically coupled in series by one or more electrical conductors on the first substrate.

[0079] Furthermore, some embodiments include a plurality of magnetic devices, where each magnetic device is disposed between a first substrate and a second substrate. Each magnetic device includes a primary winding extending through a magnetic core of the magnetic device and electrically coupling the first substrate to the second substrate.

Each magnetic device further includes a secondary winding magnetically coupled to the primary winding of the magnetic device, and opposing ends of the secondary winding are electrically coupled to the first substrate. The secondary windings of the magnetic devices are electrically coupled in series by one or more electrical conductors on the first substrate.

[0080] Additionally, certain embodiments include a plurality of magnetic devices, where each magnetic device is disposed between a common substrate and a respective additional substrate. Each magnetic device includes a primary winding extending through a magnetic core of the magnetic device and electrically coupling the first substrate to the respective additional substrate of the magnetic device. Each magnetic device further includes a secondary winding magnetically coupled to the primary winding of the magnetic device, and opposing ends of the secondary winding are electrically coupled to the first substrate. The secondary windings of the magnetic devices are electrically coupled in series by one or more electrical conductors on the first substrate.

[0081] The new electrical assemblies may achieve significant advantages that may not be realized by conventional approaches. For example, in particular embodiments, the primary windings form electrical connections between substrates, thereby reducing, or even eliminating, the need for additional electrical conductors to electrically couple the primary windings to each substrate or additional conductors to pass the current between the substrates, which promotes low electrical resistance in primary winding connections. Low electrical resistance in primary winding connections, in turn, promotes low power loss, low resistive heating, and high efficiency. Additionally, in particular embodiments, the secondary windings terminate on a common plane, e.g., on the surface of a common substrate, which promotes ease of electrical connections to the secondary windings and promotes planarity of the magnetic device on a side of the magnetic device opposite of a side where the secondary windings terminate. Furthermore, some embodiments include standard geometry magnetic core elements that do not need to be redesigned to accommodate the secondary windings, such as two E-cores or an E-core and I-core, which promotes ease of manufacturing, low cost, and ease of sourcing the magnetic core elements. Moreover, particular embodiments are scalable, i.e., they can be configured to support any number of phases. Additionally, particular embodiments have a low profile, and some embodiments have small air gaps, or even no air gaps, which helps minimize potential for radiated electromagnetic interference (EMI) with other circuitry. Furthermore, particular embodiments implement electrical coupling of phases, which promotes fast transient response and/or low ripple current magnitude.

[0082] FIG. 1 is schematic diagram of an electrical assembly 100, which is one embodiment of the new electrical assemblies disclosed herein. Electrical assembly 100 includes a first substrate 102, a second substrate 104, and a magnetic device 106. In some embodiments, each of first substrate 102 and second substrate 104 is a respective PCB. First substrate 102 is separated from second substrate 104 in a direction 108, and magnetic device 106 is disposed between first substrate 102 and second substrate 104 in direction 108. Accordingly, magnetic device 106 is sandwiched between first substrate 102 and second substrate 104.

[0083] Magnetic device 106 includes a magnetic core 110 and N winding sets 112, where N is an integer greater than or equal to one. In this document, specific instances of an item may be referred to by use of a numeral in parentheses (e.g. winding set 112(1)) while numerals without parentheses refer to any such item (e.g. winding sets 112). While FIG. 1 illustrates N being equal to at least three, it is understood that N could alternately be equal to two or equal to one. Each winding set 112 includes a respective primary winding 114 and a respective secondary winding 116. The primary winding 114 and the secondary winding 116 of each winding set 112 are magnetically coupled. For example, primary winding 114(1) is magnetically coupled with secondary winding 116(1), and primary winding 114(2) is magnetically coupled with secondary winding 116(2). The windings of each winding set 112 are ideally not magnetically coupled with windings of each other winding set 112. For example, the windings of winding set 112(1) are ideally not magnetically coupled with the windings of winding set 112(2). However, there usually will be at least some magnetic coupling between windings of two or more winding sets 112 due to the winding sets 112 sharing a common magnetic core 110.

[0084] Each primary winding 114 extends through magnetic core 110 in first direction 108, and each primary winding 114 electrically couples first substrate 102 to second substrate 104. Each secondary winding 116 is wound around at least a portion of magnetic core 110, and opposing ends 118 and 120 of each secondary winding 116 are electrically coupled to first substrate 102. Only one instance of secondary winding 116 ends 118 and 120 are labeled in FIG. 1 for illustrative clarity. Secondary windings 116 are electrically coupled in series by one or more electrical conductors 122 on first substrate 102. While not required, electrical assembly 100 will commonly include additional elements, such as switching stages and capacitors, which cooperate with magnetic device 110 to collectively form a multi-phase switching power converter. While FIG. 1 illustrates winding sets 112 being separated from each other in a direction 124 that is orthogonal to direction 108, winding sets 112 could alternately and/or additionally be separated from each in a third direction that is orthogonal to each of directions 108 and 124, i.e., in a direction that is normal to the page of FIG. 1.

[0085] Discussed below are several example of embodiments of magnetic device 106 as well as several example embodiments of electrical assembly 100. It is understood, though, that magnetic device 106 and electrical assembly 100 are not limited to the example embodiments discussed below.

[0086] FIGS. 2-6 collectively illustrate a magnetic device 200, where magnetic device 200 is one possible embodiment of magnetic device 106 of FIG. 1 where N is equal to two. FIG. 2 is a top plan view of magnetic device 200, FIG. 3 is a front elevational view of magnetic device 200, FIG. 4 is a bottom plan view of magnetic device 200, FIG. 5 is a side elevational view of magnetic device 200, and FIG. 6 is a cross-sectional view of magnetic device 200 taken along line 6A-6A of FIG. 2. The terms “top,” “bottom,” “front,” and “side” in this document are used for convenience and do not require any particular orientation of their associated elements. For example, the top of magnetic device 200 illustrated in FIG. 2 may be considered a side of magnetic device 200 in applications where magnetic device 200 is rotated by 90 degrees relative to its orientation in FIGS. 2-6. FIGS. 2-6

collectively illustrate coordinate axes including a first direction **202**, a second direction **204**, and a third direction **206**, where the second direction **204** is orthogonal to the first direction **202**, and the third direction **206** is orthogonal to each of the first direction **202** and the second direction **204**.

[0087] Magnetic device **200** includes a magnetic core **208**, a first primary winding **210**, a second primary winding **212**, a first secondary winding **214**, and a second secondary winding **216**. Magnetic core **208** is an embodiment of magnetic core **110** (FIG. 1), each of first primary winding **210** and second primary winding **212** is an embodiment of a primary winding **114** instance (FIG. 1), and each of first secondary winding **214** and second secondary winding **216** is an embodiment of a secondary winding **116** instance (FIG. 1). First primary winding **210** has opposing ends **218** and **220**, and second primary winding **212** has opposing ends **222** and **224**. First secondary winding **214** has opposing ends **226** and **228**, and second secondary winding **216** has opposing ends **230** and **232**.

[0088] Magnetic core **208** forms a first winding window **234** and a second winding window **236** extending through magnetic core **208** in first direction **202**. First winding window **234** and second winding window **236** are separated from each other in second direction **204**. First primary winding **210** is wound through first winding window **234** such that first primary winding **210** extends through magnetic core **208** in first direction **202**. Additionally, first primary winding **210** is wound through first winding window **234** and around a portion of magnetic core **208** such that (i) end **218** of first primary winding **210** is on a top outer surface **238** of magnetic core **208** and (ii) end **220** of first primary winding **210** is on a bottom outer surface **240** of magnetic core **208**, where bottom outer surface **240** is opposite of top outer surface **238**. Similarly, second primary winding **212** is wound through second winding window **236** and around a portion of magnetic core **208** that (i) end **222** of second primary winding **212** is on top outer surface **238** of magnetic core **208** and (ii) end **224** of second primary winding **212** is on bottom outer surface **240** of magnetic core **208**.

[0089] First secondary winding **214** is wound through first winding window **234**, along bottom outer surface **240** of magnetic core **208**, and along a front outer surface **242** of magnetic core **208** such that of end **226** and end **228** of first secondary winding **214** are each on top outer surface **238** of magnetic core **208**. Front outer surface **242** of magnetic core **208** joins top outer surface **238** of magnetic core **208** and bottom outer surface **240** of magnetic core **208** in first direction **202**. Additionally, second secondary winding **216** is wound through second winding window **236**, along bottom outer surface **240** of magnetic core **208**, and along front outer surface **242** of magnetic core **208** such that of end **230** and end **232** of second secondary winding **216** are each on top outer surface **238** of magnetic core **208**. First secondary winding **214** is separated from first primary winding **210** in third direction **206** within first winding window **234**, and second secondary winding **216** is separated from second primary winding **212** in third direction **206** within second winding window **236**.

[0090] Magnetic core **208** is formed, for example, of a ferrite magnetic material. Particular embodiments of magnetic core **208** include (i) a first gap in series with a magnetic flux path in magnetic core **208** magnetically coupling first primary winding **210** and first secondary winding **214** and

(ii) a second gap in series with a magnetic flux path in magnetic core **208** magnetically coupling second primary winding **212** and second secondary winding **216**. For example, FIG. 7 is a top plan view of a magnetic device **700**, where magnetic device **700** is an embodiment of magnetic device **200** (FIGS. 2-6) where magnetic core **208** forms a first gap **744** and a second gap **746**. First gap **744** is in series with a magnetic flux path **748** in magnetic core **208** magnetically coupling first primary winding **210** and first secondary winding **214**, and second gap **746** is in series with a magnetic flux path **750** magnetically coupling second primary winding **212** and second secondary winding **216**. First gap **744** is filled with a first gap material **752**, and second gap **746** is filled with a second gap material **754**, where each of first gap material **752** and second gap material **754** have a lower magnetic permeability than a magnetic material forming magnetic core **208**. For example, in certain embodiments, first gap material **752** and second gap material **754** each include one or more of air, paper, plastic, glue, and low permeability magnetic material.

[0091] Respective locations of first gap **744** and second gap **746** may vary, although it is generally desirable that the gaps not be located in a portion of magnetic core that is within magnetic flux paths of both first primary winding **210** and second primary winding **212**, to help minimize magnetic coupling of first primary winding **210** and second primary winding **212**. Accordingly, it is generally desirable that gaps in magnetic core **208** not be located in a portion of magnetic core **208** between first winding window **234** and second winding window **236**.

[0092] FIG. 8 illustrates another possible location of gaps in magnetic core **208**. Specifically, FIG. 8 is a top plan view of a magnetic device **800**, where magnetic device **800** is an embodiment of magnetic device **200** (FIGS. 2-6) where magnetic core **208** forms a first gap **844** and a second gap **846**. First gap **844** is in series with a magnetic flux path **848** in magnetic core **208** magnetically coupling first primary winding **210** and first secondary winding **214**, and second gap **846** is in series with a magnetic flux path **850** magnetically coupling second primary winding **212** and second secondary winding **216**. First gap **844** is filled with a first gap material **852** analogous to first gap material **752** of FIG. 7, and second gap **846** is filled with a second gap material **854** analogous to second gap material **754** of FIG. 7.

[0093] Returning to FIGS. 2-6, magnetic core **208** could alternately be formed of magnetic material having a distributed gap instead of being formed of ferrite material or other high permeability magnetic material. For example, magnetic core **208** could be formed of material including powdered iron and a binder instead of being formed of a ferrite material. In certain of these embodiments where magnetic core **208** is formed of a magnetic material having a distributed gap, magnetic core **208** does not necessarily form explicit gaps.

[0094] FIGS. 9-11 illustrate an electrical assembly **900**, where electrical assembly **900** is one embodiment of an electrical assembly **100** (FIG. 1) where magnetic device **106** is embodied by magnetic device **200** (FIGS. 2-6). FIG. 9 is a front elevational view of electrical assembly **900**, FIG. 10 is a side elevational view of electrical assembly **900**, and FIG. 11 is a top plan view of electrical assembly **900**. FIGS. 9-11 include the same coordinate axes as FIGS. 2-6. Electrical assembly **900** includes a first substrate **902**, a second substrate **904**, an instance of magnetic device **200**, a first

switching stage 906, a second switching stage 908, and a plurality of capacitors 910, only one of which is labeled in FIGS. 9 and 10. Electrical assembly 900 may include additional elements, such as discussed below with respect to FIG. 12, without departing from the scope hereof. First substrate 902 is an embodiment of first substrate 102 (FIG. 1), and second substrate 904 is an embodiment of second substrate 104 (FIG. 1). First substrate 902 and second substrate 904 are separated from each other in first direction 202, and magnetic device 200 is disposed between first substrate 902 and second substrate 904 in first direction 202. End 218 of first primary winding 210, end 222 of second primary winding 212, ends 226 and 228 of first secondary winding 214, and ends 230 and 232 of second secondary winding 216 are connected to a bottom surface 912 of first substrate 902 by surface mount soldering. End 220 of first primary winding 210 and end 224 of second primary winding 212 are connected to a top surface 914 of second substrate 904 by surface mount soldering. In some alternate embodiments, the winding ends are connected to first substrate 902 and/or second substrate 904 by a method other than surface mount soldering, such as by through-hole pins soldered into plated through-holes in the substrates.

[0095] FIG. 11 illustrates in dashed lines outlines of winding ends that are connected to bottom surface 912 of first substrate 902, where bottom surface 912 is opposite of a top surface 914 of first substrate. Each of first switching stage 906 and second switching stage 908 is on first substrate 902. First switching stage 906 is electrically coupled 920 to end 218 of first primary winding 210, and second switching stage 908 is electrically coupled 922 to end 222 of second primary winding 212. An electrical conductor 924 of first substrate 902 electrically couples end 228 of first secondary winding 214 to end 230 of second secondary winding 216, thereby coupling first secondary winding 214 and second secondary winding 216 in series. Electrical conductor 924 includes, for example, a PCB trace or a PCB conductive polygon. Capacitors 910 are located on a bottom surface 918 of second substrate 904. In certain embodiments, capacitors 910 are electrically coupled to each of end 220 of first primary winding 210 and end 224 of second primary winding 212.

[0096] In particular embodiments, magnetic device 200, first switching stage 906, second switching stage 908, and capacitors 910 form part of a multi-phase switching power converter. For example, FIG. 12 is an electrical schematic diagram of a multi-phase switching power converter 1200 at least partially formed by elements of electrical assembly 900. It is understood, though, that electrical assembly 900 is not limited to forming the FIG. 12 multi-phase switching power converter. Multi-phase switching power converter 1200 includes an instance of magnetic device 200, first switching stage 906, second switching stage 908, output capacitance 1202, a tuning inductor 1204, and a controller 1206. Tuning inductor 1204 and controller 1206, which are not shown in FIGS. 9-11, are illustrated in FIG. 12 as being on first substrate 204. However, tuning inductor 1204 and/or controller 1206 could be located elsewhere without departing from the scope hereof. For example, tuning inductor 1204 and/or controller 1206 could be located on second substrate 904 instead of on first substrate 902. As another example, tuning inductor 1204 and/or controller 1206 could be located external to both of first substrate 902 and second substrate 904.

[0097] First switching stage 906, first primary winding 210, and first secondary winding 214 collectively form a first phase 1208 of multi-phase switching power converter 1200, and second switching stage 908, second primary winding 212, and second secondary winding 216 collectively form a second phase 1210 of multi-phase switching power converter 1200. First primary winding 210 is electrically coupled between a first switching node X(1) and an output power node 1212, and second primary winding 212 is electrically coupled between a second switching node X(2) and output power node 1212. Output power node 1212 has a voltage V_{out} relative to a ground node 1214, and an output current I_{out} flows to a load (not shown) electrically coupled to output power node 1212. Output current I_{out} could have a negative polarity without departing from the scope hereof. Output capacitance 1202, which represents collective capacitance of all capacitors 910 of electrical assembly 900, is electrically coupled between output power node 1212 and ground node 1214. Ground node 1214 need not be an earth ground node, and ground node 1214 accordingly could be at a different electrical potential than an earth ground. For example, ground node 1214 could be reference node that is floating with respect to an earth ground.

[0098] First switching stage 906 is configured to repeatedly switch first switching node X(1) between an input power node 1216 and ground node 1214 in response to control signals U(1) and L(1) generated by controller 1206, and second switching stage 908 is configured to repeatedly switch second switching node X(2) between input power node 1216 and ground node 1214 in response to control signals U(2) and L(2) generated by controller 1206. Connections between controller 1206 and first switching stage 906 and second switching stage 908 are not shown for illustrative clarity, although it is understood that one or more communication buses may communicatively couple control signals U and L from controller 1206 to first switching stage 906 and second switching stage 908. Input power node 1216 is at a voltage V_{in} relative to ground node 1214. Accordingly, first switching stage 906 repeatedly switches first switching node X(1) between voltage V_{in} and zero volts relative to ground node 1214, and second switching stage 908 repeatedly switches second switching node X(2) between voltage V_{in} and zero volts relative to ground node 1214. An input current I_{in} flows from an electrical power source (not shown) to multi-phase switching power converter 1200 via input power node 1216. Input current I_{in} could have a negative polarity without departing from the scope hereof. One or more input capacitors (not shown) are optionally electrically coupled between input power node 1216 and ground node 1214.

[0099] First switching stage 906 includes an upper switching device 1218 and a lower switching device 1220. Upper switching device 1218 is electrically coupled between input power node 1216 and first switching node X(1), and lower switching device 1220 is electrically coupled between first switching node X(1) and ground node 1214. Second switching stage 908 includes an upper switching device 1222 and a lower switching device 1224. Upper switching device 1222 is electrically coupled between input power node 1216 and second switching node X(2), and lower switching device 1224 is electrically coupled between second switching node X(2) and ground node 1214. Upper switching devices 1218 and 1222 switch in response to a respective control signals U(1) and U(2) from controller 1206, and

lower switching devices **1220** and **1224** switch in response to a respective control signals **L(1)** and **L(2)** from controller **1206**. Each of upper switching device **1218**, lower switching device **1220**, upper switching device **1222**, and lower switching device **1224** includes, for example, one or more transistors.

[0100] First secondary winding **214**, second secondary winding **216**, and tuning inductor **1204** are electrically coupled in series. While FIG. **12** illustrates the series connection including first secondary winding **214**, second secondary winding **216**, and tuning inductor **1204** being reference to ground node **1214**, in some alternate embodiments, these elements are electrically coupled in series without being referenced to ground node **1214**. Tuning inductor **1204** could be omitted without departing from the scope hereof, such as in embodiments where there is significant stray inductance in magnetic device **200**.

[0101] Controller **1206** is implemented, for example, by analog and/or electronic circuitry. In some embodiments, controller **1206** is at least partially implemented by a processor (not shown) executing instructions in the form of software and/or firmware stored in a memory (not shown). Although controller **1206** is depicted as a discrete element for illustrative simplicity, controller **1206** could be partially or fully integrated with one or more other elements of multi-phase switching power converter **1200**. For example, some subsystems of controller **1206** could be incorporated in one or more of first switching stage **906** and second switching stage **908**. Additionally, FIG. **12** should not be construed to require that there be a separate communication bus for each control signal. For example, controller **1206** could be implemented by a combination of a central integrated circuit and local control logic integrated in each of first switching stage **906** and second switching stage **908**, with a single communication bus running from the central integrated circuit to each of first switching stage **906** and second switching stage **908**. Furthermore, controller **1206** may include multiple constituent elements that need not be co-packaged or even disposed at a common location.

[0102] Controller **1206** is configured to generate control signals **U** and **L** to control duty cycle (**D**) of each of first phase **1208** and **2120**, where duty cycle of phase **1208** or **1210** is a portion of a switching cycle of the phase that the respective primary winding **210** or **212** of the phase is driven high, i.e., when the switching node **X(1)** or **X(2)** of the phase is connected to input power node **1216**, to regulate at least one parameter of multi-phase switching power converter **1200**. In some embodiments, controller **1206** is configured to control duty cycle of first phase **1208** and second phase **1210** using pulse width modulation (**PWM**) and/or pulse frequency modulation (**PFM**). Examples of possible regulated parameters include, but are not limited, magnitude of input voltage V_{in} , magnitude of input current I_{in} , magnitude of output voltage V_{out} , and magnitude of output current I_{out} . For example, in some embodiments, controller **1206** is configured to generate control signals **U** and **L** to regulate magnitude of output voltage V_{out} , and controller **1206** accordingly generates control signals **U** and **L** during continuous conduction operation of multi-phase switching power converter **1200** such that duty cycle of each of first phase **1208** and second phase **1210** is equal to a ratio of output voltage magnitude V_{out} over input voltage magnitude V_{in} . For example, if output voltage V_{out} is to be regulated to two volts and input voltage V_{in} is eight volts, controller **1206**

would generate control signals **U** and **L** such that duty cycle of each of first phase **1208** and second phase **1210** is 0.25. Controller **1206** is optionally configured to generate control signals **U** and **L** such that first phase **1208** and second phase **1210** switch out-of-phase with each other.

[0103] It should be appreciated that first phase **1208** and second phase **1210** are electrically coupled by the series connection of first secondary winding **214** and second secondary winding **216** via electrical conductor **924** of first substrate **902** (FIG. **11**). The electrical coupling of first phase **1208** and second phase **1210** advantageously promotes fast transient response and/or low ripple current magnitude relative to an otherwise similar multi-phase switching power converter without electrical coupling of phases.

[0104] Multi-phase switching power converter **1200** could be modified to include additional phases by adding a respective switching stage for each additional phase, as well as by modifying magnetic device **200** to include an additional primary winding and an additional secondary winding for each additional phase. One example of an alternate embodiment of magnetic device **200** including additional primary and second winding pairs is discussed below with respect to FIGS. **32-36**. Additionally, while each of first phase **1208** and second phase **1210** powers common output power node **1212** in multi-phase switching power converter **1200**, multi-phase switching power converter **1200** could be modified so that two or more phases power different output power nodes. Furthermore, although each of first phase **1208** and second phase **1210** is powered by a common input power node **1216** in multi-phase switching power converter **1200**, multi-phase switching power converter **1200** could be modified so that two or more phases are powered by different respective input power nodes. Moreover, while multi-phase switching power converter **1200** has a buck topology, multi-phase switching power converter **1200** could be modified to have a different topology, e.g., a boost topology or a buck-boost topology. Additionally, while a single tuning inductor **1204** electrically couples two phases of multi-phase switching power converter **1200** in FIG. **12**, tuning inductor **1204** could similarly couple more phases. For example, tuning inductor **1204** could be electrically coupled in series with each secondary winding in a four-phase switching power converter incorporating a magnetic device with four winding sets, such as a magnetic device **3200** discussed below with respect FIG. **32**. Furthermore, a single tuning inductor **1204** could be electrically coupled in series with secondary windings of several magnetic devices having different respective quantities of winding sets. For example, a single instance of tuning inductor **1204** could be electrically coupled in series with each of (i) secondary windings of one instance of magnetic device **3200** of FIG. **32**, (ii) the respective secondary windings of two instances of magnetic device **200**, (iii) the respective secondary windings of three instances of a magnetic device with a single winding set, such as magnetic device **3700** discussed below with respect to FIG. **37**.

[0105] FIGS. **13-15** illustrate an electrical assembly **1300**, which is an alternate embodiment of electrical assembly **900** (FIGS. **9-11**) where (i) each of first switching stage **906** and second switching stage **908** are located on second substrate **904** instead of on first substrate **902** and (ii) capacitors **910** are located first substrate **902** instead of on second substrate **904**. FIG. **13** is a front elevational view of electrical assembly **1300**, FIG. **14** is a side elevational view of electrical

assembly 1300, and FIG. 15 is a top plan view of electrical assembly 1300. Only one instance of a capacitor 910 is labeled in each FIGS. 13-15. Electrical assembly 1300 optionally forms at least part of a multi-phase switching power converter similar to multi-phase switching power converter 1200 of FIG. 12, but with opposing ends of each winding swapped. For example, end 218 of first primary winding 210 is connected to output power node 1212 instead of to first switching node X(1), and end 220 of first primary winding 210 is electrically coupled to first switching node X(1) instead of to output power node 1212, in embodiments of electrical assembly 1300 forming a multi-phase switching power converter similar to multi-phase switching power converter 1200.

[0106] Referring again to FIG. 2, it is anticipated first secondary winding 214 and second secondary winding 216 will frequently conduct zero, or essentially zero, direct current (DC) in multi-phase switching power converter applications of magnetic device 200. Consequently, in particular embodiments, first secondary winding 214 and second secondary winding 216 need not be capable of carrying as much current as first primary winding 210 and second primary winding 212. While it may be desirable for all windings of magnetic device 200 to have a common thickness to promote planarity, in some applications, first secondary winding 214 and second secondary winding 216 may be modified to have smaller widths than first primary winding 210 and second primary winding 212 due to the secondary windings carrying current of smaller magnitude than the primary windings.

[0107] For example, FIGS. 16-19 collectively illustrate a magnetic device 1600, which is an alternate embodiment of magnetic device 200 (FIGS. 2-6) having a different secondary winding configuration, as well as a different winding window configuration. FIG. 16 is a top plan view of magnetic device 1600, FIG. 17 is a front elevational view of magnetic device 1600, FIG. 18 is a side elevational view of magnetic device 1600, and FIG. 19 is a bottom plan view of magnetic device 1600. Magnetic device 1600 differs from magnetic device 200 in that (i) magnetic core 208 is replaced with a magnetic core 1608, (ii) first secondary winding 214 is replaced with a first secondary winding 1614, and (iii) second secondary winding 216 is replaced with a second secondary winding 1616. Magnetic core 1608 differs from magnetic core 208 in its dimensions and that first winding window 234 and second winding window 236 are replaced with a first winding window 1634 and a second winding window 1636, respectively. First winding window 1634 and second winding window 1636 are longer in second direction 204 than corresponding winding windows in magnetic core 208, but first winding window 1634 and second winding window 1636 are narrower in third direction 206 than corresponding winding windows in magnetic core 208. Consequently, magnetic core 1608 is longer in second direction 204, but narrower in third direction 206, than magnetic core 208.

[0108] First secondary winding 1614 and second secondary winding 1616 are narrower than first secondary winding 214 and second secondary winding 216, respectively. First secondary winding 1614 has opposing ends 1626 and 1628 in place of opposing ends 226 and 228, respectively. Additionally, second secondary winding 1616 has opposing ends 1630 and 1632 in place of opposing ends 230 and 232, respectively. First primary winding 210 is separated from

first secondary winding 1614 in first winding window 1634 in second direction 204, and second primary winding 212 is separated from second secondary winding 1616 in second winding window 1636 in second direction 204.

[0109] Referring again to FIG. 1, stray inductance between the primary winding 114 and the secondary winding 116 in a given winding set 112 can be helpful in some applications. For example, if such inductance is sufficiently large, it may eliminate the need for a tuning inductor, e.g., tuning inductor 1204 of FIG. 12, in embodiments where electrical assembly 100 forms part of a multi-phase switching power converter. However, excessive inductance between the primary winding 114 and the secondary winding 116 in a given winding set 112 may be detrimental because it impairs transient response of a multi-phase switching power converter including electrical assembly 100. Stray inductance between the primary winding 114 and the secondary winding 116 in a given winding set 112 can be reduced by reducing size of a current loop incorporating the primary winding 114 and the secondary winding 116 of a given winding set 112. Accordingly, any of the magnetic devices disclosed herein may include a respective ground conductor near each secondary winding, to help cause ground current flowing between opposing substrates to flow near the secondary windings, thereby helping reduce stray inductance between the primary winding 114 and the secondary winding 116 of each winding set 112. The ground conductors electrically couple a ground node of first substrate 102 to a ground node of second substrate 104.

[0110] For example, FIGS. 20-24 illustrate a magnetic device 2000, where magnetic device 2000 is an alternate embodiment of magnetic device 1600 (FIGS. 16-19) further including a respective ground conductor for each secondary winding. FIG. 20 is a top plan view of magnetic device 2000, FIG. 21 is a front elevational view of magnetic device 2000, FIG. 22 is a side elevational view of magnetic device 2000, FIG. 23 is a bottom elevational view of magnetic device 2000, and FIG. 24 is a cross-sectional view of magnetic device 2000 taken along line 24A-24A of FIG. 20. Magnetic device 2000 differs from magnetic device 1600 in that magnetic device 2000 further includes (i) a first ground conductor 2002 disposed adjacent to first secondary winding 1614 and (ii) a second ground conductor 2004 disposed adjacent to second secondary winding 1616. Each of first ground conductor 2002 and second ground conductor 2004 extend along a side outer surface 1642 of magnetic core 1608, and each of first ground conductor 2002 and second ground conductor 2004 wraps around magnetic core 1608 to extend over each of a top outer surface 1638 of magnetic core 1608 and a bottom outer surface 1640 of magnetic core 1608. Neither first ground conductor 2002 nor second ground conductor 2004, however, forms a complete loop around any portion of magnetic core 1608, to help minimize inductance associated with first ground conductor 2002 and second ground conductor 2004.

[0111] FIG. 25 is a front elevational view of an electrical assembly 2500, which is an alternate embodiment of electrical assembly 900 (FIGS. 9-11) with magnetic device 200 replaced with magnetic device 2000. Opposing ends of each of first ground conductor 2002 and second ground conductor 2004 are surface mount soldered to first substrate 902 and second substrate 904, respectively, although first ground conductor 2002 and second ground conductor 2004 could be connected to first substrate 902 and/or second substrate 904

in an alternative manner, e.g., by through-hole pins. Each of first ground conductor **2002** and second ground conductor **2004** electrically couple a ground node of first substrate **902** and a ground node of second substrate **904**. For example, FIG. **26** is an electrical schematic diagram of a multi-phase switching power converter **2600** at least partially formed by elements of the FIG. **25** electrical assembly. Multi-phase switching power converter **2600** is the same as multi-phase switching power converter **1200** of FIG. **12** except that multi-phase switching power converter **2600** includes magnetic device **2000** in place of magnetic device **200**. First ground conductor **2002** and second ground conductor **2004** electrically couple respective ground nodes **1214** of each of first substrate **902** and second substrate **904**, as shown in FIG. **26**. Additionally, FIG. **26** illustrates (i) magnetic coupling **2006** of first secondary winding **214** and first ground conductor **2002** and (ii) magnetic coupling **2008** of second secondary winding **216** and second ground conductor **2004**.

[0112] The magnetic devices disclosed herein could also include a respective ground conductor wound around each secondary winding, to help minimize separation between the ground conductors and the secondary windings. For example, FIGS. **27-31** illustrate a magnetic device **2700**, which is an alternate embodiment of magnetic device **1600** (FIGS. **16-19**) including a respective ground conductor wound around each secondary winding. FIG. **27** is top plan view of magnetic device **2700**, FIG. **28** is a front elevational view of magnetic device **2700**, FIG. **29** is a side elevational view of magnetic device **2700**, FIG. **30** is a cross-sectional view of magnetic device **2700** taken along line **30A-30A** of FIG. **27**, and FIG. **31** is a bottom plan view of magnetic device **2700**. Magnetic device **2700** differs from magnetic device **1600** in that (i) first secondary winding **1614** and second secondary winding **1616** are replaced with a first secondary winding **2714** and a second secondary winding **2716**, respectively, (ii) magnetic device **2700** further includes a first insulating layer **2706** and a second insulating layer **2708**, and (iii) magnetic device **2700** further includes a first ground conductor **2702** and a second ground conductor **2704**.

[0113] First secondary winding **2714** is wound through first winding window **1634**, along bottom outer surface **1640** of magnetic core **1608**, and along side outer surface **1642** of magnetic core **1608** such that an end **2726** and an end **2728** of first secondary winding **2714** are each on top outer surface **1638** of magnetic core **1608**. Additionally, second secondary winding **2716** is wound through second winding window **1636**, along bottom outer surface **1640** of magnetic core **1608**, and along side outer surface **1642** of magnetic core **1608** such that an end **2730** and an end **2732** of second secondary winding **2716** are each on top outer surface **1638** of magnetic core **1608**. First secondary winding **2714** is separated from first primary winding **210** in third direction **206** within winding window **1634**, and second secondary winding **2716** is separated from second primary winding **212** in third direction **206** within winding window **1636**.

[0114] First insulating layer **2706** is wrapped over first secondary winding **2714**, and first ground conductor **2702** is wrapped over first insulating layer **2706**. Additionally, second insulating layer **2708** is wrapped over second secondary winding **2716**, and second ground conductor **2704** is wrapped over second insulating layer **2708**. As such, first ground conductor **2702** is wound around first secondary winding **2714**, but first ground conductor **2702** is separated

from first secondary winding **2714** by first insulating layer **2706** to prevent electrical shorting of first secondary winding **2714** and first ground conductor **2702**. Additionally, second ground conductor **2704** is wound around second secondary winding **2716**, but second ground conductor **2704** is separated from second secondary winding **2716** by second insulating layer **2708** to prevent electrical shorting of second secondary winding **2716** and second ground conductor **2704**. Accordingly, each of first ground conductor **2702** and second ground conductor **2704** extend along side outer surface **1642** of magnetic core **1608**, and each of first ground conductor **2702** and second ground conductor **2704** wraps around magnetic core **1608** to extend over each of top outer surface **1638** of magnetic core **1608** and bottom outer surface **1640** of magnetic core **1608**. Neither first ground conductor **2702** nor second ground conductor **2704**, however, forms a complete loop around any portion of magnetic core **1608**, to help minimize inductance associated with first ground conductor **2702** and second ground conductor **2704**.

[0115] The magnetic devices discussed above with respect to FIGS. **2-31** include two winding sets, where each winding set includes a respective primary winding and a respective secondary winding. However, any of the above-discussed magnetic devices could be modified to include one or more additional winding sets, such as to support additional phases in a multi-phase switching power converter. For example, magnetic device **200** of FIGS. **2-6** could be extended in second direction **204** and/or in third direction **206** to include one or more winding windows and an associated winding set for each additional window. For instance, FIGS. **32-36** illustrate a magnetic device **3200**, which is an alternate embodiment of magnetic device **200** extended in third direction **206** to include additional winding windows and associated winding sets. FIG. **32** is a top plan view of magnetic device **3200**, FIG. **33** is a front elevational view of magnetic device **3200**, FIG. **34** is a side elevational view of magnetic device **3200**, FIG. **35** is a bottom plan view of magnetic device **3200**, and FIG. **36** is a cross-sectional view of magnetic device **3200** taken along line **36A-36A** of FIG. **32**.

[0116] Magnetic device **3200** differs from magnetic device **200** in that (i) magnetic device **3200** includes a magnetic core **3208** in place of magnetic core **208**, (ii) magnetic device **3200** further includes a third primary winding **3244** and a fourth primary winding **3246**, and (iii) magnetic device **3200** further includes a third secondary winding **3248** and a fourth secondary winding **3250**. Magnetic core **3208** differs from magnetic core **208** in that magnetic core **3208** is wider in third direction **206** and magnetic core **3208** forms two additional winding windows, i.e., a third winding window **3252** and a fourth winding window **3254**. Each of third winding window **3252** and fourth winding window **3254** extends through magnetic core **3208** in first direction **202**. Magnetic core **3208** includes a top outer surface **3238**, a bottom outer surface **3240**, and a front outer surface **3242** in place of top outer surface **238**, bottom outer surface **240**, and front outer surface **242**, respectively. Each of third primary winding **3244** and fourth primary winding **3246** is an embodiment of a primary winding **114** of FIG. **1**, and each of third secondary winding **3248** and fourth secondary winding **3250** is an embodiment of a secondary winding **116** of FIG. **1**. Third primary winding **3244** has opposing ends **3256** and **3258**, and fourth primary winding **3246** has opposing ends **3260** and **3262**. Third secondary winding

3248 has opposing ends **3264** and **3266**, and fourth secondary winding **3250** has opposing ends **3268** and **3270**.

[0117] Third primary winding **3244** is wound through third winding window **3252** and around a portion of magnetic core **3208** such that (i) end **3256** of third primary winding **3244** is on top outer surface **3238** of magnetic core **3208** and (ii) end **3258** of third primary winding **3244** is on bottom outer surface **3240** of magnetic core **3208**. Similarly, fourth primary winding **3246** is wound through fourth winding window **3254** and around a portion of magnetic core **3208** such that (i) end **3260** of fourth primary winding **3246** is on top outer surface **3238** of magnetic core **3208** and (ii) end **3262** of fourth primary winding **3246** is on bottom outer surface **3240** of magnetic core **3208**. Third secondary winding **3248** is wound through third winding window **3252**, along bottom outer surface **3240** of magnetic core **3208**, and along a back outer surface **3272** of magnetic core **3208** such that end **3264** and end **3266** of third secondary winding **3248** are each on top outer surface **3238** of magnetic core **3208**. Additionally, fourth secondary winding **3250** is wound through fourth winding window **3254**, along bottom outer surface **3240** of magnetic core **3208**, and along back outer surface **3272** of magnetic core **3208** such that end **3268** and end **3270** of fourth secondary winding **3250** are each on top outer surface **3238** of magnetic core **3208**.

[0118] Any of the above-discussed magnetic devices could also be modified to include only a single winding set. For example, FIGS. 37-40 illustrate a magnetic device **3700**, which is an alternate embodiment of magnetic device **200** (FIGS. 2-6) modified to include only a single winding set. FIG. 37 is a top plan view of magnetic device **3700**, FIG. 38 is a front elevational view of magnetic device **3700**, FIG. 39 is a side elevational view of magnetic device **3700**, and FIG. 40 is a bottom plan view of magnetic device **3700**. Magnetic device **3700** differs from magnetic device **200** in that (i) magnetic core **208** is replaced with a magnetic core **3708**, (ii) second primary winding **212** is omitted, and (iii) secondary winding **216** is omitted. Magnetic core **3708** includes a top outer surface **3738**, a bottom outer surface **3740**, and front outer surface **3742** in place of top outer surface **238**, bottom outer surface **240**, and front outer surface **242**, respectively. First primary winding **210** is henceforth referred to as “primary winding **210**” instead of “first primary winding **210**” in the context of magnetic device **3700** because magnetic device **3700** includes only one primary winding. Similarly, first secondary winding **214** is henceforth referred to as “secondary winding **214**” instead of “first secondary winding **214**” in the context of magnetic device **3700** because magnetic device **3700** includes only one secondary winding.

[0119] An electrical assembly may include multiple instances of magnetic device **3700** to support multiple phases, such as a respective instance of magnetic device **3700** for each phase of a multi-phase switching power converter. For example, FIGS. 41 and 42 illustrate an electrical assembly **4100**, where electrical assembly **4100** is an alternate embodiment of electrical assembly **900** (FIGS. 9-11) including two instances of magnetic device **3700** in place of magnetic device **200** (FIGS. 2-6). FIG. 41 is a front elevational view of electrical assembly **4100**, and FIG. 42 is a top plan view of electrical assembly **4100**. Only one instance of capacitors **910** is labeled in FIG. 41. Electrical assembly **4100** differs from electrical assembly **900** in that (i) magnetic device **200** is replaced with two instance of

magnetic device **3700**, i.e., magnetic devices **3700(1)** and **3700(2)**, (ii) first substrate **902** is replaced with a first substrate **4102**, and (iii) second substrate **904** is replaced with a second substrate **4104**. First substrate **4102** is similar to, but larger than, first substrate **902**, and second substrate **4104** is similar to, but larger than, second substrate **904**. First substrate **4102** includes a bottom surface **4112** and top surface **4116**, and second substrate **4104** includes a bottom surface **4118** and a top surface **4114**.

[0120] First substrate **4102** and second substrate **4104** are separated from each other in first direction **202**, and each magnetic device **3700** is disposed between first substrate **4102** and second substrate **4104** in first direction **202**. Magnetic devices **3700** are separated from each other in second direction **204**, and in some alternate embodiments, magnetic devices **3700** are separated from each other in third direction **206**, in place of, or in addition to, being separated from each other in second direction **204**. Ends **218** of primary windings **210**, ends **226** of secondary windings **214**, and ends **228** of secondary windings **214** are connected to bottom surface **4112** of first substrate **4102** by surface mount soldering. Ends **220** of primary windings **210** are connected to top surface **4114** of second substrate **4104**. In some alternate embodiments, the winding ends are connected to first substrate **4102** and/or second substrate **4104** by a method other than surface mount soldering, such as by through-hole pins soldered into plated through-holes in the substrates.

[0121] FIG. 42 illustrates in dashed lines outlines of winding ends that connect to bottom surface **4112** of first substrate **4102**. Each of first switching stage **906** and second switching stage **908** is on first substrate **4102**. First switching stage **906** is electrically coupled **4120** to end **218(1)** of primary winding **210(1)** of magnetic device **3700(1)**, and second switching stage **908** is electrically coupled **4122** to end **218(2)** of primary winding **210(2)** of magnetic device **3700(2)**. An electrical conductor **4124** of first substrate **4102** electrically couples end **228(1)** of secondary winding **214(1)** of magnetic device **3700(1)** to end **226(2)** of secondary winding **214(2)** of magnetic device **3700(2)**, thereby coupling secondary winding **214(1)** and secondary winding **214(2)** in series. Electrical conductor **4124** includes, for example, a PCB trace or a PCB conductive polygon.

[0122] In particular embodiments, magnetic device **3700(1)**, magnetic device **3700(2)**, first switching stage **906**, second switching stage **908**, and capacitors **910** of electrical assembly **4100** form part of a multi-phase switching power converter. For example, in some embodiments, the aforementioned elements of electrical assembly **4100** form a multi-phase switching power converter similar to multi-phase switching power converter **1200** of FIG. 12 where (i) primary winding **210(1)** of magnetic device **3700(1)** is electrically coupled between switching node **X(1)** and output power node **1212**, (ii) primary winding **210(2)** of magnetic device **3700(2)** is electrically coupled between switching node **X(2)** and output power node **1212**, and (iii) secondary winding **214(1)** of magnetic device **3700(1)** and secondary winding **214(2)** of magnetic device **3700(2)** are electrically coupled in series with tuning inductor **1204**.

[0123] FIGS. 43-45 illustrate an electrical assembly **4300**, which is an alternate embodiment of electrical assembly **4100** (FIGS. 41 and 42) where second substrate **4104** is replaced with a respective additional substrate **4304** for each magnetic device **3700**, and where each additional substrate

4304 includes a top surface **4314** and a bottom surface **4318**. First substrate **4102** remains as a common substrate for each magnetic device **3700** in electrical assembly **4300**. FIG. **43** is a front elevational view of electrical assembly **4300**, FIG. **44** is a top plan view of electrical assembly **4300**, and FIG. **45** is a bottom plan view of electrical assembly **4300**. Electrical assembly **4300** additionally differs from electrical assembly **4100** in that (i) first switching stage **906** is located on first additional substrate **4304(1)** instead of on first substrate **4102**, (ii) second switching stage **908** is located on second additional substrate **4304(2)** instead of on first substrate **4102**, and (iii) capacitors **910** are located on substrate **902** instead of on second substrate **4104**. Only one instance of capacitors **910** is labeled in each of FIGS. **43** and **44**. First switching stage **906** is electrically coupled **4320** to end **220(1)** of primary winding **210(1)** of magnetic device **3700(1)** on additional substrate **4304(1)**, as illustrated in FIG. **45**. Additionally, second switching stage **908** is electrically coupled **4322** to end **220(2)** of primary winding **210(2)** of magnetic device **3700(2)** on additional substrate **4304(2)**, as also illustrated in FIG. **45**.

[0124] FIG. **46** is an electrical schematic diagram of a multi-phase switching power converter **4600** at least partially formed by elements of electrical assembly **4300** (FIGS. **43-45**). It is understood, though, that electrical assembly **4300** is not limited to forming the FIG. **46** multi-phase switching power converter. Multi-phase switching power converter **4600** is similar to multi-phase switching power converter **1200** of FIG. **12** except that multi-phase switching power **4400** includes two instances of magnetic device **3700**, i.e., magnetic device **3700(1)** and **3700(2)**, in place of magnetic device **200**. Additionally, the arrangement of elements among substrates differs between multi-phase switching power converter **4400** and multi-phase switching power converter **1200**. For example, first switching stage **906** and second switching stage **908** are located on respective additional substrates **4304(1)** and **4304(1)**, instead of on common substrate **902**, in multi-phase switching power converter **4600**. As another example, tuning inductor **1204** (not shown in FIGS. **43-45**) is located on first substrate **4102** in multi-phase switching power converter **4600**.

[0125] The primary winding and the secondary winding of a given winding set form a common number of turns, such that a turns ratio is 1:1, in the example magnetic devices discussed above. However, any of the magnetic device disclosed herein could be modified so that the primary winding and the secondary winding of a given winding set form different respective numbers of turns, to obtain a turns ratio other than 1:1. For example, FIGS. **47-51** illustrate a magnetic device **4700**, which is an alternate embodiment of magnetic device **2000** (FIGS. **20-24**) with primary windings forming two turns each. FIG. **47** is a top plan view of magnetic device **4700**, FIG. **48** is a front elevational view of magnetic device **4700**, FIG. **49** is a side elevational view of magnetic device **4700**, FIG. **50** is a bottom plan view of magnetic device **4700**, and FIG. **51** is a back elevational view of magnetic device **4700**.

[0126] Magnetic device **4700** differs from magnetic device **2000** in that (i) first primary winding **210** is replaced with a first primary winding **4710** and (i) second primary winding **212** is replaced with a second primary winding **4712**. First primary winding **4710** is wound along a back outer surface **4744** of magnetic core **1608** and through first winding window **1634** to form two turns, and first primary

winding **4710** has opposing ends **4718** and **4720**. End **4718** is analogous to end **218** of first primary winding **210**, and end **4718** is accordingly on top outer surface **1638** of magnetic core **1608**. End **4720** is analogous to end **220** of first primary winding **210**, and end **4720** is accordingly on bottom outer surface **1640** of magnetic core **1608**. Similarly, second primary winding **4712** is wound along back outer surface **4744** of magnetic core **1608** and through second winding window **1636** to form two turns, and second primary winding **4712** has opposing ends **4722** and **4724**. End **4722** is analogous to end **222** of second primary winding **212**, and end **4722** is accordingly on top outer surface **1638** of magnetic core **1608**. End **4724** is analogous to end **224** of second primary winding **210**, and end **4724** is accordingly on bottom outer surface **1640** of magnetic core **1608**.

[0127] Magnetic device **4700** is scalable in second direction **204**, or stated differently, magnetic device **4700** could be modified by extending magnetic core **1608** in second direction **204** and adding one or more winding windows and associated winding sets that are separated from each other in second direction **204**. However, magnetic device **4700** is not scalable in third direction **206** due to windings being wound around both front outer surface **1642** of magnetic core **1608** and back outer surface **4744** of magnetic core **1608**. FIGS. **52-54** illustrate a magnetic device **5200** which is an alternate embodiment of magnetic device **4700** (FIGS. **47-51**) that is scalable in third direction **206** as well as in second direction **204**. FIG. **52** is a top plan view of magnetic device **5200**, FIG. **53** is a front elevational view of magnetic device **5200**, and FIG. **54** is a bottom plan view of magnetic device **5200**.

[0128] Magnetic device **5200** differs from magnetic device **4700** in that (i) magnetic core **1608** is replaced with a magnetic core **5208**, (ii) first primary winding **4710** and second primary winding **4712** are replaced with a first primary winding **5210** and a second primary winding **5212**, respectively, (iii) magnetic device **5200** further includes a third primary winding **5246** and a fourth primary winding **5248**, (iv) magnetic device **5200** further includes a third secondary winding **5250** and a fourth secondary winding **5252**, and (v) magnetic device **5200** further include a third ground conductor **5254** and a fourth ground conductor **5256**. Magnetic core **5208** includes a top outer surface **5238**, a bottom outer surface **5240**, a front outer surface **5242**, and a back outer surface **5244** in place of top outer surface **1638**, bottom outer surface **1640**, front outer surface **1642**, and back outer surface **4744**, respectively.

[0129] Magnetic core **5208** forms a third winding window **5258** and a fourth winding window **5260** each extending through first magnetic core **5208** in first direction **202**, in addition to first winding window **1634** and second winding window **1636**. Each of first ground conductor **5202** and second ground conductor **5204** extends along front outer surface **5242** of magnetic core **5208**, and each of first ground conductor **5202** and second ground conductor **5204** wraps around magnetic core **5208** to extend over each of top outer surface **5238** of magnetic core **5208** and bottom outer surface **5240** of magnetic core **5208**. Each of third ground conductor **5254** and fourth ground conductor **5256** extends along back outer surface **5244** of magnetic core **5208**, and each of third ground conductor **5254** and fourth ground conductor **5256** wraps around magnetic core **5208** to extend over each of top outer surface **5238** of magnetic core **5208** and bottom outer surface **5240** of magnetic core **5208**.

[0130] First primary winding 5210 is wound along front outer surface 5242 of magnetic core 5208 and through first winding window 1634 to form two turns, and first primary winding 5210 has opposing ends 5218 and 5220. End 5218 is analogous to end 218 of first primary winding 210, and end 5218 is accordingly on top outer surface 5238 of magnetic core 5208. End 5220 is analogous to end 220 of first primary winding 210, and end 5220 is accordingly on bottom outer surface 5240 of magnetic core 5208. Similarly, second primary winding 5212 is wound along front outer surface 5242 of magnetic core 5208 and through second winding window 1636 to form two turns, and second primary winding 5212 has opposing ends 5222 and 5224. End 5222 is analogous to end 222 of second primary winding 212, and end 5222 is accordingly on top outer surface 5238 of magnetic core 5208. End 5224 is analogous to end 224 of second primary winding 210, and end 5224 is accordingly on bottom outer surface 5240 of magnetic core 5208. Third primary winding 5246 has opposing ends 5262 and 5264. Third primary winding 5246 is analogous to first primary winding 5210, but (i) third primary winding 5246 is wound through third winding window 5258 instead of through first winding window 1634, and (ii) third primary winding 5246 is wound along back outer surface 5244 instead of along front outer surface 5242. Fourth primary winding 5248 has opposing ends 5266 and 5268. Fourth primary winding 5248 is analogous to second primary winding 5212, but (i) fourth primary winding 5248 is wound through fourth winding window 5260 instead of through second winding window 1636, and (ii) fourth primary winding 5248 is wound along back outer surface 5244 instead of along front outer surface 5242.

[0131] Third secondary winding 5250 has opposing ends 5270 and 5272 on top outer surface 5238 of magnetic core 5208. Third secondary winding 5250 is analogous to first secondary winding 1614 but (i) third second winding 5250 is wound through third winding window 5258 instead of through first winding window 1634, and (ii) third secondary winding 5250 is wound along back outer surface 5244 instead of along front outer surface 5242. Fourth secondary winding 5252 has opposing ends 5272 and 5274 on top outer surface 5238 of magnetic core 5208. Fourth secondary winding 5252 is analogous to second secondary winding 1616, but (i) fourth secondary winding 5252 is wound through fourth winding window 5260 instead of through second winding window 1636, and (ii) fourth secondary winding 5252 is wound along back outer surface 5244 instead of along front outer surface 5242.

[0132] Winding ends are disposed on magnetic core outer surfaces in the above-discussed examples, such as to promote low profile of the magnetic devices. However, any of the magnetic devices disclosed herein could be modified so that one or more winding ends are offset from an adjacent magnetic core outer surface, such as to provide room for components between the magnetic device and adjacent substrates. For example, FIGS. 55-57 illustrate a magnetic device 5500, which is an alternate embodiment of magnetic device 200 (FIGS. 2-6) where winding ends are offset from magnetic core outer surfaces. FIG. 55 is a front elevational view of magnetic device 5500, FIG. 56 is a side elevational view of magnetic device 5500, and FIG. 57 is a side elevational view of magnetic device 5500 that is opposite the side elevational view of FIG. 56.

[0133] Magnetic device 5500 differs from magnetic device 200 in that (i) first primary winding 210 is replaced with a first primary winding 5510, (ii) second primary winding 212 is replaced with a second primary winding 5512, (iii) first secondary winding 214 is replaced with a first secondary winding 5514, and (iv) second secondary winding 216 is replaced with a second secondary winding 5516. First primary winding 5510 differs from first primary winding 210 in that ends 218 and 220 are offset from magnetic core outer surfaces 238 and 240, respectively, in first direction 202. Similarly, second primary winding 5512 differs from second primary winding 212 in that ends 222 and 224 are offset from magnetic core outer surfaces 238 and 240, respectively, in first direction 202. First secondary winding 5514 differs from first secondary winding 214 in that ends 226 and 228 are offset from magnetic core outer surface 238 in first direction 202, and second secondary winding 5516 differs from second secondary winding 216 in that ends 230 and 232 are offset from magnetic core outer surface 238 in first direction 202.

[0134] FIG. 58 is a front elevational view of an electrical assembly 5800, which is an alternate embodiment of electrical assembly 900 (FIGS. 9-11) where magnetic device 200 (FIGS. 2-6) is replaced with magnetic device 5500 (FIGS. 55-57). It should be noted that the fact that winding ends are offset from magnetic core outer surfaces leaves space 5802 between magnetic core 208 and first substrate 902, as well as space 5804 between magnetic core 208 and second substrate 904, for locating additional components (not shown) of electrical assembly 5800.

[0135] The secondary windings in the above discussed magnetic devices could be modified so that the secondary winding ends terminate on a magnetic core outer surface other than a top outer surface or a bottom outer surface. For example, FIGS. 59-62 illustrate a magnetic device 5900 which is an alternate embodiment of magnetic device 200 (FIGS. 2-6) where secondary windings terminate on front outer surface 242 of magnetic core 208 instead of on top outer surface 238 of magnetic core 208. FIG. 59 is a top plan view of magnetic device 5900, FIG. 60 is a front elevational view of magnetic device 5900, FIG. 61 is a bottom plan view of magnetic device 5900, and FIG. 62 is a side elevational view of magnetic device 5900. Magnetic device 5900 differs from magnetic device 200 in that first secondary winding 214 and second secondary winding 216 are replaced with a first secondary winding 5914 and a second secondary winding 5916, respectively. First secondary winding 5914 has opposing ends 5926 and 5928 that are analogous to ends 226 and 228 of first secondary winding 214, respectively, and second secondary winding 5916 has opposing ends 5930 and 5932 that are analogous to ends 230 and 232 of second secondary winding 216, respectively. Each of ends 5926, 5928, 5930, and 5932 is on outer surface 242 of magnetic core 208.

[0136] FIG. 63 is a front elevational view of an electrical assembly 6300, which is an alternate embodiment of electrical assembly 900 (FIGS. 9-11) where (i) magnetic device 200 is replaced with magnetic device 5900, (ii) first substrate 902 is replaced with a first substrate 6302, and (iii) electrical assembly 6300 further includes a third substrate 6304. FIG. 64 is a side elevational view of electrical assembly 6300. Third substrate 6304 is placed over winding ends 5926, 5928, 5930, and 5932 in third direction 206. FIG. 63 illustrates in dashed lines outlines of winding ends 5926,

5928, 5930, and 5932 that are covered by third substrate 6304 in the FIG. 63 elevational view. First substrate 6302 is similar to first substrate 902 of electrical assembly 900, but first substrate 6302 does not electrically couple secondary windings in series. Instead, third substrate 6304 includes an electrical conductor 6306 electrically coupling end 5928 of first secondary winding 5914 to end 5930 of second secondary winding 5916, such that first secondary winding 5914 and second secondary winding 5916 are electrically coupled in series. Third substrate 6304 optionally also includes one or more additional electrical conductors (not shown), such as to route one or more signals between first substrate 6302 and second substrate 904.

[0137] Additionally, the magnetic devices discussed above could be modified so that primary winding ends terminate on a common outer surface of a magnetic core. For example, FIGS. 65-70 illustrate a magnetic device 6500 where primary windings terminate on one magnetic core outer surface and secondary windings terminate on an opposing magnetic core outer surface. FIG. 65 is a top plan view of a magnetic device 6500, FIG. 66 is a front elevational view of magnetic device 6500, FIG. 67 is a bottom plan view of magnetic device 6500, FIG. 68 is a side elevational view of magnetic device 6500, FIG. 69 is a side elevational view of magnetic device 6500 of opposite of the side elevational view of magnetic device 6500 of FIG. 68, and FIG. 70 is a cross-sectional view of magnetic device 6500 taken along line 70A-70A of FIG. 65. Magnetic device 6500 includes a magnetic core 6508, a first primary winding 6510, a second primary winding 6512, a first secondary winding 6514, and second secondary winding 6516. First primary winding 6510 is magnetically coupled with first secondary winding 6514, and second primary winding 6512 is magnetically coupled with second secondary winding 6516. First primary winding 6510 is ideally not magnetically coupled with second primary winding 6512, but there will typically be some magnetic coupling of first primary winding 6510 and second primary winding 6512 due to the two windings sharing common magnetic core 6508.

[0138] It is understood that the quantity of windings in magnetic device 6500 may vary, though, as long as magnetic device 6500 includes at least one primary winding and associated secondary winding. For example, magnetic device 6500 could be modified by omitting second primary winding 6512 and second secondary winding 6516. As another example, magnetic device 6500 could be modified to include one or more winding sets, where each winding set includes a respective primary winding and a respective secondary winding that are magnetically coupled with each other.

[0139] First primary winding 6510 has opposing ends 6518 and 6520. First primary winding 6510 extends through magnetic core 6508 in second direction 204. First primary winding 6510 wraps around a side outer surface 6544 of magnetic core 6508 and onto a bottom outer surface 6540 of magnetic core 6508 such that end 6518 is bottom outer surface 6540. Additionally, first primary winding 6510 wraps around a side outer surface 6546 of magnetic core 6508, where side outer surface 6546 is opposite of side outer surface 6544, and onto bottom outer surface 6540 of magnetic core 6508 such that end 6520 is on bottom outer surface 6540. Second primary winding has opposing ends 6522 and 6524. Second primary winding 6512 is configured similarly to first primary winding 6510, but second primary

winding 6512 is displaced from first primary winding 6510 in third direction 206. Accordingly, each of end 6522 and end 6524 of second primary winding 6512 is on second outer surface 6540 of magnetic core 6508.

[0140] First secondary winding 6514 has opposing ends 6526 and 6528. First secondary winding 6514 extends through magnetic core 6508 in second direction 204. First secondary winding 6514 wraps around side outer surface 6544 of magnetic core 6508 and onto a top outer surface 6538 of magnetic core 6508 such that end 6526 is on top outer surface 6538. Additionally, first secondary winding 6514 wraps around side outer surface 6546 of magnetic core 6508 and onto top outer surface 6538 of magnetic core 6508 such that end 6528 is on top outer surface 6538. Second secondary winding 6516 has opposing ends 6530 and 6532. Second secondary winding 6516 is configured similarly to first secondary winding 6514, but second secondary winding 6516 is displaced from first secondary winding 6514 in third direction 206. Accordingly, each of end 6530 and end 6532 of second secondary winding 6516 is on top outer surface 6538 of magnetic core 6508. First secondary winding 6514 is disposed over first primary winding 6510 in first direction 202, and second secondary winding 6516 is disposed over second primary winding 6512 in first direction 202. Although FIGS. 65-70 illustrate magnetic device 6500 as being a monolithic element, magnetic device 6500 could be formed by joining two or more elements. For example, in some embodiment, magnetic device 6500 is formed by stacking two elements in first direction 202, where each element includes a magnetic core and two windings.

[0141] FIGS. 71-73 illustrate an electrical assembly 7100, where electrical assembly 7100 is one embodiment of an electrical assembly including an instance of magnetic device 6500 (FIGS. 65-70). FIG. 71 is a front elevational view of electrical assembly 7100, FIG. 72 is a side elevational view of electrical assembly 7100, and FIG. 73 is a top plan view of electrical assembly 7100. Electrical assembly 7100 includes a first substrate 7102, a second substrate 7104, an instance of magnetic device 6500, an instance of first switching stage 906 (discussed above with respect to FIGS. 9-12), an instance of second switching stage 908 (discussed above with respect to FIGS. 9-12, a plurality of capacitors 910, a first pin 7106, and a second pin 7108. Only one capacitor 910 instance is labeled in FIGS. 71 and 72. Electrical assembly 7100 may include additional elements, such as discussed below with respect to FIG. 74, without departing from the scope hereof.

[0142] First substrate 7102 and second substrate 7104 are separated from each other in first direction 202, and magnetic device 6500 is disposed between first substrate 7102 and second substrate 7104 in first direction 202. In some embodiments, each of first substrate 7102 and second substrate 7104 is a respective PCB. End 6518 of first primary winding 6510, end 6520 of first primary winding 6510, end 6522 of second primary winding 6512, and end 6524 of second primary winding 6512 are connected to a top surface 7114 of second substrate 7104 by surface mount soldering. End 6526 of first secondary winding 6514, end 6528 of first secondary winding 6514, end 6530 of second secondary winding 6516, and end 6532 of second secondary winding 6516 are connected to a bottom surface 7112 of first substrate 7102 by surface mount soldering. In some alternate embodiments, the winding ends are connected to first substrate 7102 and/or second substrate 7104 by a method other

than surface mount soldering, such as by through-hole pins soldered into plated through-holes in the substrates.

[0143] Each of first pin **7106** and second pin **7108** is disposed between first substrate **7102** and second substrate **7104** in first direction **202**. Each of first pin **7106** and second pin **7108** is formed, for example, of an electrically conductive material such as a metal, and each of first pin **7106** and second pin **7108** electrically couple first substrate **7102** and second substrate **7104**.

[0144] FIG. **73** illustrates in dashed lines outlines of winding ends that are connected to bottom surface **7112** of first substrate **7102**, where bottom surface **7112** is opposite of a top surface **7116** of first substrate. An electrical conductor **7124** of first substrate **7102** electrically couples end **6528** of first secondary winding **6514** to end **6530** of second secondary winding **6516**, thereby coupling first secondary winding **6514** and second secondary winding **6516** in series. An electrical conductor electrically **7126** couples end **6526** of first secondary winding **6514** to first pin **7106**, and an electrical conductor **7128** electrically couples end **6532** of second secondary winding **6516** to second pin **7108**. Each of electrical conductor **7124**, **7126**, and **7128** includes, for example, a PCB trace or a PCB conductive polygon.

[0145] Each of first switching stage **906** and second switching stage **908** is on a bottom outer surface **7118** of second substrate **7104**. First switching stage **906** is electrically coupled to end **6518** of first primary winding **6110**, and second switching stage **908** is electrically coupled to end **6522** of second primary winding **6512**. Capacitors **910** are located on bottom surface **7118** of second substrate **904**. In certain embodiments, capacitors **910** are electrically coupled to each of end **6520** of first primary winding **6510** and end **6524** of second primary winding **6512**.

[0146] In particular embodiments, magnetic device **6500**, first switching stage **906**, second switching stage **908**, and capacitors **910** of electrical assembly **7100** form part of a multi-phase switching power converter. For example, FIG. **74** is an electrical schematic diagram of a multi-phase switching power converter **7400** at least partially formed by elements of electrical assembly **7100**. It is understood, though, that electrical assembly **7100** is not limited to forming the FIG. **74** multi-phase switching power converter. Multi-phase switching power converter **7400** is similar to multi-phase switching power converter **1200** of FIG. **12** except that multi-phase switching power **7400** includes magnetic device **6500** in place of magnetic device **200**. FIG. **74** illustrates tuning inductor **1204** (not shown in FIGS. **71-73**) being on first substrate **7102** and controller **1206** (not shown in FIGS. **71-73**) being on second substrate **7104**. However, the respective locations of tuning inductor **1204** and controller **1206** in multi-phase switching power converter **7400** could vary without departing from the scope hereof.

Combinations of Features

[0147] Features described above may be combined in various ways without departing from the scope hereof. The following examples illustrate some possible combinations.

[0148] (A1) An electrical assembly includes a first substrate, a second substrate, a magnetic device disposed between the first substrate and the second substrate, and one or more electrical conductors on the first substrate. The magnetic device includes (1) a magnetic core, (2) a first primary winding extending through the magnetic core and

electrically coupling the first substrate to the second substrate, (3) a second primary winding extending through the magnetic core and electrically coupling the first substrate to the second substrate, (4) a first secondary winding wound around at least a portion of the magnetic core, opposing ends of the first secondary winding being electrically coupled to the first substrate, and (5) a second secondary winding wound around at least a portion of the magnetic core, opposing ends of the second secondary winding being electrically coupled to the first substrate. The one or more electrical conductors on the first substrate electrically couple the first secondary winding in series with the second secondary winding.

[0149] (A2) The electrical assembly denoted as (A1) may further include (1) a first switching stage on the first substrate, where the first switching stage is electrically coupled to the first primary winding, and (2) a second switching stage on the first substrate, where the second switching stage is electrically coupled to the second primary winding.

[0150] (A3) In the electrical assembly denoted as (A2), the first switching stage, the second switching stage, and the magnetic device may collectively form at least part of a multi-phase switching power converter.

[0151] (A4) The electrical assembly denoted as (A1) may further include (1) a first switching stage on the second substrate, where the first switching stage is electrically coupled to the first primary winding, and (2) a second switching stage on the second substrate, where the second switching stage is electrically coupled to the second primary winding.

[0152] (A5) In the electrical assembly denoted as (A4), the first switching stage, the second switching stage, and the magnetic device may form at least part of a multi-phase switching power converter.

[0153] (A6) In any one of the electrical assemblies denoted as (A1) through (A5), the magnetic core may form a first winding window and a second winding window, each of the first primary winding and the first secondary winding may be wound through the first winding window, and each of the second primary winding and the second secondary winding may be wound through the second winding window.

[0154] (A7) In the electrical assembly denoted as (A6), the magnetic device may be disposed between the first substrate and the second substrate in a first direction, and each of the first winding window and the second winding window may extend through the magnetic core in the first direction.

[0155] (A8) In either one of the electrical assemblies denoted as (A6) or (A7), the first winding window may be separated from the second winding window in a second direction that is orthogonal to the first direction, the first primary winding may be separated from the first secondary winding in the first winding window in the second direction, and the second primary winding may be separated from the second secondary winding in the second winding window in the second direction.

[0156] (A9) In any one of the electrical assemblies denoted as (A1) through (A8), (1) the magnetic core may form a first gap in series with a magnetic flux path in the magnetic core magnetically coupling the first primary winding and the first secondary winding, the first gap being at least partially filled with a material having a lower magnetic permeability than a magnetic material forming the magnetic core, and (2) the magnetic core may form a second gap in

series with a magnetic flux path in the magnetic core magnetically coupling the second primary winding and the second secondary winding, the second gap being at least partially filled with a material having a lower magnetic permeability than the magnetic material forming the magnetic core.

[0157] (A10) In any one of the electrical assemblies denoted as (A1) through (A9), the magnetic device may further include (1) a first ground conductor electrically coupling a ground node of the first substrate to a ground node of the second substrate and (2) a second ground conductor electrically coupling the ground node of the first substrate to the ground node of the second substrate.

[0158] (A11) In the electrical assembly denoted as (A10), the first ground conductor may be wound around the first secondary winding, and the second ground conductor may be wound around the second secondary winding.

[0159] (B1) An electrical assembly includes a first substrate, a second substrate, a first magnetic device disposed between the first substrate and the second substrate, a second magnetic device disposed between the first substrate and the second substrate, and one or more electrical conductors on the first substrate. The first magnetic device includes (1) a first magnetic core, (2) a first primary winding extending through the first magnetic core and electrically coupling the first substrate to the second substrate, and (3) a first secondary winding wound around at least a portion of the first magnetic core, where opposing ends of the first secondary winding are electrically coupled to the first substrate. The second magnetic device includes (1) a second magnetic core, (2) a second primary winding extending through the second magnetic core and electrically coupling the first substrate to the second substrate, and (3) a second secondary winding wound around at least a portion of the second magnetic core, where opposing ends of the second secondary winding are electrically coupled to the first substrate. The one or more electrical conductors on the first substrate electrically couple the first secondary winding in series with the second secondary winding.

[0160] (B2) The electrical assembly denoted as (B1) may further include (1) a first switching stage electrically coupled to the first primary winding and (2) a second switching stage electrically coupled to the second primary winding, where the first switching stage, the second switching stage, the first magnetic device, and the second magnetic device collectively form at least part of a multi-phase switching power converter.

[0161] (B3) In either one of the electrical assemblies denoted as (B1) or (B2), (1) the first magnetic core may form a first winding window, (2) each of the first primary winding and the first secondary winding may be wound through the first winding window, (3) the second magnetic core may form a second winding window, and (4) each of the second primary winding and the second secondary winding may be wound through the second winding window.

[0162] (B4) In the electrical assembly denoted as (B3), (1) each of the first magnetic device and the second magnetic device may be disposed between the first substrate and the second substrate in a first direction, (2) the first winding window may extend through the first magnetic core in the first direction, (3) the second winding window may extend through the second magnetic core in the first direction, and (4) the second magnetic device may be separated from the first magnetic device in at least one of a second direction and

a third direction, the second direction being orthogonal to the first direction, and the third direction being orthogonal to each of the first direction and the second direction.

[0163] (B5) In any one of the electrical assemblies denoted as (B1) through (B4), the first magnetic device may further include a first ground conductor electrically coupling a ground node of the first substrate to a ground node of the second substrate, and the second magnetic device may further include a second ground conductor electrically coupling the ground node of the first substrate to the ground node of the second substrate.

[0164] (C1) An electrical assembly includes a common substrate, a first additional substrate, a second additional substrate, a first magnetic device disposed between the common substrate and the first additional substrate, a second magnetic device disposed between the common substrate and the second additional substrate, and one or more electrical conductors on the common substrate. The first magnetic device includes a first magnetic core, a first primary winding extending through the first magnetic core and electrically coupling the common substrate to the first additional substrate, and a first secondary winding wound around at least a portion of the first magnetic core, where opposing ends of the first secondary winding are electrically coupled to the common substrate. The second magnetic device includes a second magnetic core, a second primary winding extending through the second magnetic core and electrically coupling the common substrate to the second additional substrate, and a second secondary winding wound around at least a portion of the second magnetic core, where opposing ends of the second secondary winding are electrically coupled to the common substrate. The one or more electrical conductors on the common substrate electrically couple the first secondary winding in series with the second secondary winding.

[0165] (C2) The electrical assembly denoted as (C1) may further include (1) a first switching stage electrically coupled to the first primary winding and (2) a second switching stage electrically coupled to the second primary winding, where the first switching stage, the second switching stage, the first magnetic device, and the second magnetic device collectively form at least part of a multi-phase switching power converter.

[0166] (C3) In either one of the electrical assemblies denoted as (C1) or (C2), (1) the first magnetic core may form a first winding window, (2) each of the first primary winding and the first secondary winding may be wound through the first winding window, (3) the second magnetic core may form a second winding window, and (4) each of the second primary winding and the second secondary winding may be wound through the second winding window.

[0167] (C4) In the electrical assembly denoted as (C3), (1) the first magnetic device may be disposed between the common substrate and the first additional substrate in a first direction, (2) the second magnetic device may be disposed between the common substrate and the second additional substrate in the first direction, (3) the first winding window may extend through the first magnetic core in the first direction, (4) the second winding window may extend through the second magnetic core in the first direction, and (5) the second magnetic device may be separated from the first magnetic device in at least one of a second direction and a third direction, the second direction being orthogonal to

the first direction, and the third direction being orthogonal to each of the first direction and the second direction.

[0168] (D1) An electrical assembly includes a first substrate, a second substrate, a third substrate, a magnetic device disposed between the first substrate and the second substrate in a first direction, and one or more electrical conductors on the third substrate. The magnetic device includes (1) a first primary winding extending through the magnetic core and electrically coupling the first substrate to the second substrate, (2) a second primary winding extending through the magnetic core and electrically coupling the first substrate to the second substrate, (3) a first secondary winding wound around at least a portion of the magnetic core, opposing ends of the first secondary winding being electrically coupled to the third substrate, and (4) a second secondary winding wound around at least a portion of the magnetic core, opposing ends of the second secondary winding being electrically coupled to the third substrate. The one or more electrical conductors on the third substrate electrically couple the first secondary winding in series with the second secondary winding.

[0169] (D2) In the electrical assembly denoted as (D1), the third substrate may be over each of (i) the opposing ends of the first secondary winding and (ii) the opposing ends of the second secondary winding, in a direction orthogonal to the first direction.

[0170] (D3) In either one of the electrical assemblies denoted as (D1) or (D2), (1) a first end of the first primary winding may terminate on a first outer surface of the magnetic core, (2) a first end of the second primary winding may terminate on the first outer surface of the magnetic core, (3) a second end of the first primary winding may terminate on a second outer surface of the magnetic core, the second outer surface of the magnetic core being opposite of the first outer surface of the magnetic core, (4) the opposing ends of the first secondary winding may terminate on a third outer surface of the magnetic core, the third outer surface joining the first outer surface and the second outer surface in the first direction, and (5) the opposing ends of the of the second secondary winding may terminate on the third outer surface of the magnetic core.

[0171] (D4) Any one of the electrical assemblies denoted as (D1) through (D3) may further include (1) a first switching stage electrically coupled to the first primary winding and (2) a second switching stage electrically coupled to the second primary winding, where the first switching stage, the second switching stage, and the magnetic device collectively form at least part of a multi-phase switching power converter.

[0172] (D5) In any one of the electrical assemblies denoted as (D1) through (D4), (1) the magnetic core may form a first winding window extending through the magnetic core in the first direction, (2) each of the first primary winding and the first secondary winding may be wound through the first winding window, (3) the magnetic core may form a second winding window extending through the magnetic core in the second direction, and (4) each of the second primary winding and the second secondary winding may be wound through the second winding window.

[0173] (E1) An electrical assembly includes a first substrate, a second substrate, a magnetic device disposed between the first substrate and the second substrate in a first direction, and one or more electrical conductors on the first substrate. The magnetic device includes (1) a magnetic core,

(2) a first primary winding extending through the magnetic core in a second direction that is orthogonal to the first direction, where opposing ends of the first primary winding are connected to the second substrate, (3) a second primary winding extending through the magnetic core in the second direction, where opposing ends of the second primary winding are connected to the second substrate, (4) a first secondary winding extending through the magnetic core in the second direction, where opposing ends of the first secondary winding are connected to the first substrate, and (5) a second secondary winding extending through the magnetic core in the second direction, where opposing ends of the second secondary winding are connected to the first substrate. The one or more electrical conductors on the first substrate electrically couple the first secondary winding in series with the second secondary winding.

[0174] (E2) In the electrical assembly denoted as (E1), (1) the opposing ends of the first secondary winding and the opposing ends of the second secondary winding may terminate on a first outer surface of the magnetic core, and (2) the opposing ends of the first primary winding and the opposing ends of the second primary winding may terminate on a second outer surface of the magnetic core, where the second outer surface is opposite of the first outer surface.

[0175] (E3) Either one of the electrical assemblies denoted as (E1) or (E2) may further include (1) a first switching stage electrically coupled to the first primary winding and (2) a second switching stage electrically coupled to the second primary winding, where the first switching stage, the second switching stage, and the magnetic device collectively form at least part of a multi-phase switching power converter.

[0176] (E4) Any one of the electrical assemblies denoted as (E1) through (E3) may further include one or more pins disposed between the first substrate and the second substrate, where the one or more pins electrically couple the first substrate and the second substrate.

[0177] Changes may be made in the above methods, devices, and systems without departing from the scope hereof. It should thus be noted that the matter contained in the above description and shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover generic and specific features described herein, as well as all statements of the scope of the present method and system, which as a matter of language, might be said to fall therebetween.

What is claimed is:

1. An electrical assembly, comprising:

a first substrate;

a second substrate;

a magnetic device disposed between the first substrate and the second substrate, the magnetic device including:

a magnetic core,

a first primary winding extending through the magnetic core and electrically coupling the first substrate to the second substrate,

a second primary winding extending through the magnetic core and electrically coupling the first substrate to the second substrate,

a first secondary winding wound around at least a portion of the magnetic core, opposing ends of the first secondary winding being electrically coupled to the first substrate, and

a second secondary winding wound around at least a portion of the magnetic core, opposing ends of the second secondary winding being electrically coupled to the first substrate; and

one or more electrical conductors on the first substrate electrically coupling the first secondary winding in series with the second secondary winding.

2. The electrical assembly of claim 1, further comprising:

a first switching stage on the first substrate, the first switching stage being electrically coupled to the first primary winding; and

a second switching stage on the first substrate, the second switching stage being electrically coupled to the second primary winding.

3. The electrical assembly of claim 2, wherein the first switching stage, the second switching stage, and the magnetic device collectively form at least part of a multi-phase switching power converter.

4. The electrical assembly of claim 1, further comprising:

a first switching stage on the second substrate, the first switching stage being electrically coupled to the first primary winding; and

a second switching stage on the second substrate, the second switching stage being electrically coupled to the second primary winding.

5. The electrical assembly of claim 4, wherein the first switching stage, the second switching stage, and the magnetic device form at least part of a multi-phase switching power converter.

6. The electrical assembly of claim 1, wherein:

the magnetic core forms a first winding window and a second winding window;

each of the first primary winding and the first secondary winding are wound through the first winding window; and

each of the second primary winding and the second secondary winding are wound through the second winding window.

7. The electrical assembly of claim 6, wherein:

the magnetic device is disposed between the first substrate and the second substrate in a first direction; and

each of the first winding window and the second winding window extends through the magnetic core in the first direction.

8. The electrical assembly of claim 7, wherein

the first winding window is separated from the second winding window in a second direction that is orthogonal to the first direction;

the first primary winding is separated from the first secondary winding in the first winding window in the second direction; and

the second primary winding is separated from the second secondary winding in the second winding window in the second direction.

9. The electrical assembly of claim 1, wherein:

the magnetic core forms a first gap in series with a magnetic flux path in the magnetic core magnetically coupling the first primary winding and the first secondary winding, the first gap being at least partially filled with a material having a lower magnetic permeability than a magnetic material forming the magnetic core; and

the magnetic core forms a second gap in series with a magnetic flux path in the magnetic core magnetically

coupling the second primary winding and the second secondary winding, the second gap being at least partially filled with a material having a lower magnetic permeability than the magnetic material forming the magnetic core.

10. The electrical assembly of claim 1, wherein the magnetic device further includes:

a first ground conductor electrically coupling a ground node of the first substrate to a ground node of the second substrate; and

a second ground conductor electrically coupling the ground node of the first substrate to the ground node of the second substrate.

11. The electrical assembly of claim 10, wherein:

the first ground conductor is wound around the first secondary winding; and

the second ground conductor is wound around the second secondary winding.

12. An electrical assembly, comprising:

a first substrate;

a second substrate;

a first magnetic device disposed between the first substrate and the second substrate, the first magnetic device including:

a first magnetic core,

a first primary winding extending through the first magnetic core and electrically coupling the first substrate to the second substrate, and

a first secondary winding wound around at least a portion of the first magnetic core, opposing ends of the first secondary winding being electrically coupled to the first substrate;

a second magnetic device disposed between the first substrate and the second substrate, the second magnetic device including:

a second magnetic core,

a second primary winding extending through the second magnetic core and electrically coupling the first substrate to the second substrate, and

a second secondary winding wound around at least a portion of the second magnetic core, opposing ends of the second secondary winding being electrically coupled to the first substrate; and

one or more electrical conductors on the first substrate electrically coupling the first secondary winding in series with the second secondary winding.

13. The electrical assembly of claim 12, further comprising:

a first switching stage electrically coupled to the first primary winding; and

a second switching stage electrically coupled to the second primary winding,

wherein the first switching stage, the second switching stage, the first magnetic device, and the second magnetic device collectively form at least part of a multi-phase switching power converter.

14. The electrical assembly of claim 12, wherein:

the first magnetic core forms a first winding window;

each of the first primary winding and the first secondary winding are wound through the first winding window;

the second magnetic core forms a second winding window; and

each of the second primary winding and the second secondary winding are wound through the second winding window.

15. The electrical assembly of claim **14**, wherein:

each of the first magnetic device and the second magnetic device is disposed between the first substrate and the second substrate in a first direction;

the first winding window extends through the first magnetic core in the first direction;

the second winding window extends through the second magnetic core in the first direction; and

the second magnetic device is separated from the first magnetic device in at least one of a second direction and a third direction, the second direction being orthogonal to the first direction, and the third direction being orthogonal to each of the first direction and the second direction.

16. The electrical assembly of claim **12**, wherein:

the first magnetic device further includes a first ground conductor electrically coupling a ground node of the first substrate to a ground node of the second substrate; and

the second magnetic device further includes a second ground conductor electrically coupling the ground node of the first substrate to the ground node of the second substrate.

17. An electrical assembly, comprising:

a common substrate;

a first additional substrate;

a second additional substrate;

a first magnetic device disposed between the common substrate and the first additional substrate, the first magnetic device including:

a first magnetic core,

a first primary winding extending through the first magnetic core and electrically coupling the common substrate to the first additional substrate, and

a first secondary winding wound around at least a portion of the first magnetic core, opposing ends of the first secondary winding being electrically coupled to the common substrate;

a second magnetic device disposed between the common substrate and the second additional substrate, the second magnetic device including:

a second magnetic core,

a second primary winding extending through the second magnetic core and electrically coupling the common substrate to the second additional substrate, and

a second secondary winding wound around at least a portion of the second magnetic core, opposing ends of the second secondary winding being electrically coupled to the common substrate; and

one or more electrical conductors on the common substrate electrically coupling the first secondary winding in series with the second secondary winding.

18. The electrical assembly of claim **17**, further comprising:

a first switching stage electrically coupled to the first primary winding; and

a second switching stage electrically coupled to the second primary winding,

wherein the first switching stage, the second switching stage, the first magnetic device, and the second magnetic device collectively form at least part of a multi-phase switching power converter.

19. The electrical assembly of claim **17**, wherein:

the first magnetic core forms a first winding window;

each of the first primary winding and the first secondary winding are wound through the first winding window; the second magnetic core forms a second winding window; and

each of the second primary winding and the second secondary winding are wound through the second winding window.

20. The electrical assembly of claim **19**, wherein:

the first magnetic device is disposed between the common substrate and the first additional substrate in a first direction;

the second magnetic device is disposed between the common substrate and the second additional substrate in the first direction;

the first winding window extends through the first magnetic core in the first direction;

the second winding window extends through the second magnetic core in the first direction; and

the second magnetic device is separated from the first magnetic device in at least one of a second direction and a third direction, the second direction being orthogonal to the first direction, and the third direction being orthogonal to each of the first direction and the second direction.

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