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(71) Applicant: FUTUREWEI TECHNOLOGIES, INC.

[US/US]; 5700 Tennyson Parkway, Suite 600, Plano, Texas 75024 (US).

(72) Inventors: **KIM, Tae Hong**; 2075 W. Ray Road, Suite 120, Chandler, Arizona 85226 (US). **HE, Jiangqi**; 3075 W. Ray Road, Suite 120, Chandler, Arizona 85226 (US). **WANG, Guotao**; 3075 W. Ray Road, Suite 120, Chandler, Arizona 85226 (US).

(74) Agent: **DIETRICH, William H.** et al.; CONLEY ROSE, P.C., 5601 Granite Parkway, Suite 500, Plano, Texas 75024 (US).

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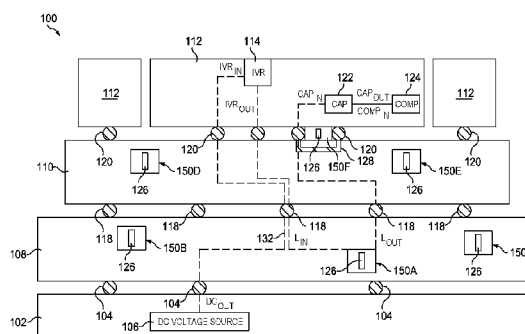


FIG. 1A

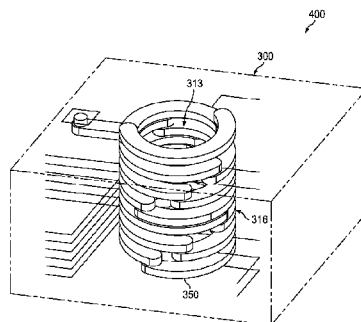


FIG. 4A

(57) Abstract: A method of forming a package, comprising drilling a blind hole into a non-magnetic core of an inductor, depositing magnetic material into the blind hole, and magnetically aligning the magnetic material within the blind hole.



High Density Embedded Inductor with Injected Magnetic Material

TECHNICAL FIELD

[0001] The present application relates to inductors and, in particular, to inductors for Integrated Voltage Regulator (IVR) applications.

BACKGROUND

[0002] New areas like artificial intelligence, autonomous cars, etc., have created a huge demand for high performance processing units (central processing units (CPUs), graphics processing units (GPUs), application-specific integrated circuits (ASICs), field-programmable gate arrays (FPGAs), etc.). To supply enough computational power to the processing units, the number of power components on a system has dramatically increased and dynamic power control has been a must-have for system efficiency. The integrated voltage regulator (IVR) has gained attention because the IVR is capable of faster dynamic power control relative to conventional voltage regulators. In addition, the IVR is able to reduce the number of power components needed within, for example, a printed circuit board (PCB).

SUMMARY

[0003] According to a first aspect of the present disclosure, there is provided a method of forming a package. The method comprises drilling a blind hole into a non-magnetic core of an inductor, depositing magnetic material into the blind hole, magnetically aligning the magnetic material within the blind hole.

[0004] In a first implementation of the method according to the first aspect, the blind hole is drilled to a bottom end of the non-magnetic core, and the inductor is embedded within a substrate of the package.

[0005] In a second implementation of the method according to the first aspect or any preceding implementation of the first aspect, a width of the blind hole is less than a width of the non-magnetic core of the inductor.

[0006] In a third implementation of the method according to the first aspect or any preceding implementation of the first aspect, the drilling is performed using a laser drill.

[0007] In a fourth implementation of the method according to the first aspect or any preceding implementation of the first aspect, the magnetic material is deposited into the blind hole until a consolidation of the magnetic material within the non-magnetic core reaches a pre-defined permeability.

[0008] In a fifth implementation of the method according to the first aspect or any preceding implementation of the first aspect, the method further comprises compressing the magnetic material into the blind hole after injecting the magnetic material into the blind hole.

[0009] In a sixth implementation of the method according to the first aspect or any preceding implementation of the first aspect, the method further comprises applying heat to the magnetic material within the blind hole after depositing the magnetic material into the blind hole.

[0010] In a seventh implementation of the method according to the first aspect or any preceding implementation of the first aspect, the method further comprises adjusting a width of the blind hole to adjust an amount of the magnetic material within the blind hole of the inductor.

[0011] In a eighth implementation of the method according to the first aspect or any preceding implementation of the first aspect, magnetically aligning the magnetic material within the blind hole comprises adjusting the temperature of the magnetic material within the blind hole of the inductor over a period of time.

[0012] According to a second aspect of the present disclosure, there is provided a package. The package comprises a package substrate, an interposer electrically coupled to the package substrate, a die including an integrated voltage regulator and electrically coupled to the interposer, an inductor embedded within at least one of the package substrate or the interposer, the inductor comprising a non-magnetic core filled with magnetic material.

[0013] In a first implementation of the package according to the second aspect, the magnetic material comprises discrete magnetic particles, and wherein the magnetic material comprises soft magnetic material.

[0014] In a second implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a nickel iron (NiFe) alloy.

[0015] In a third implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises iron having a body-centered cubic (BCC) structure or iron having a face-centered cubic (FCC) structure.

[0016] In a fourth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises nickel having the BCC structure, nickel having the hexagonal closed packed (HCP) structure, or cobalt having the HCP structure.

[0017] In a fifth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises gadolinium having the HCP structure.

[0018] In a sixth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises gadolinium having the HCP structure.

[0019] In a seventh implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a manganese bismuthide (MnBi) having a hexagonal structure.

[0020] In an eighth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises an 81 nickel (Ni) - 19 iron (Fe) having the FCC structure, a 50Ni - 50Fe having the FCC structure, or a 3Ni - 97Fe having the BCC structure.

[0021] In a ninth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a nickel-iron-aluminum alloy.

[0022] In a tenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises an 80Ni - 17Fe - 3 cobalt (Co) having the FCC structure, a 57Ni - 13Fe - 30Co having the FCC structure, a 48.6Ni - 2.8Fe - 48.6Co having the FCC structure, or a 45Ni - 30Fe - 25Co having the FCC structure.

[0023] In a eleventh implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a nickel-iron-chromium having the FCC structure or a nickel-iron-copper.

[0024] In a twelfth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises nickel-iron-molybdenum having the FCC structure.

[0025] In a thirteenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises nickel-iron-phosphorus.

[0026] In a fourteenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises iron-aluminum with about 22% to about 25% aluminum having the BCC structure.

[0027] In a fifteenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises 50Fe-50Co having the BCC structure.

[0028] In a sixteenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises 5Fe-95Co.

[0029] In a seventeenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises nickel-copper having the FCC structure.

[0030] In an eighteenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises nickel-palladium having the FCC structure.

[0031] In a nineteenth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a nickel alloy.

[0032] In a twentieth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises cobalt-copper, cobalt-nickel, or cobalt-phosphorous.

[0033] In a twenty first implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises cobalt-nickel-phosphorous or cobalt-nickel-phosphorous with a mixture of the HCP structure and the FCC structure.

[0034] In a twenty second implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a ferrite (NiFe_2O_4) film having a cubic structure.

[0035] In a twenty third implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a garnet film ($\text{Y}_3\text{Fe}_5\text{O}_{12}$) having a cubic structure.

[0036] In a twenty fourth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a NiFe with a ratio of about 45%/55% and a permeability up to about 1300.

[0037] In a twenty fifth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises $\text{Ni}_{81}\text{Fe}_{17}\text{Cu}_{1.5}\text{Mo}_{0.5}$ spherical particles having a particle diameter in a range of 2 micrometers (μm) to about 20 μm in a polymer matrix.

[0038] In a twenty sixth implementation of the package according to the second aspect or any preceding implementation of the second aspect, the magnetic material comprises a polycrystalline or monocrystal-line layer of a ferromagnetic metal, alloy, or magnetic oxide about 0.01 μm to about 10 μm thick.

[0039] According to a third aspect of the present disclosure, there is provided a method of forming a package. The method comprises drilling a blind hole into a non-magnetic core of an inductor, and depositing magnetic material into the blind hole positioned within the non-magnetic core, the inductor being embedded within a substrate of the package, and the magnetic material comprising discrete magnetic particles.

[0040] According to a fourth aspect of the present disclosure, there is provided a package. The package comprises a die including an integrated voltage regulator, a package substrate electrically coupled to the die, an interposer electrically coupled to the package substrate and a

printed circuit board, and an inductor embedded within at least one of the package substrate or the interposer, the inductor comprising a non-magnetic core filled with magnetic material.

[0041] In a first implementation according to the fourth aspect, the magnetic materials are magnetically aligned.

[0042] Any of the preceding methods may be performed, or implementations executed, to overcome the scaling issues with air core inductors. The method or implementations disclosed herein increase a permeability of a non-magnetic core of the inductor, thereby increasing the inductance of the inductor. The preceding methods may also be performed, or implementations executed, to reduce the real estate or space occupied by the inductor in and/or on a package or integrated circuit. The preceding methods may also be performed, or implementations executed, to increase the inductance of the inductor in and/or on the package or integrated circuit.

[0043] For the purpose of clarity, any one of the foregoing embodiments may be combined with any one or more of the other foregoing embodiments to create a new embodiment within the scope of the present disclosure.

[0044] These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0045] For a more complete understanding of this disclosure, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, wherein like reference numerals represent like parts.

[0046] FIGS. 1A-B are diagrams illustrating different embodiments of a package containing an IVR and an inductor according to various embodiments of the disclosure.

[0047] FIG. 2 is a diagram illustrating another embodiment of a package containing the IVR and the inductor of FIGS. 1A-B according to various embodiments of the disclosure.

[0048] FIG. 3 is a diagram illustrating an embodiment of the inductor shown in FIGS. 1-2 according to various embodiments of the disclosure.

[0049] FIGS. 4A-C collectively illustrate an embodiment of a process flow used to form the inductor of FIG. 3 according to various embodiments of the disclosure.

[0050] FIG. 5 is an embodiment of a method of forming the inductor of FIG. 3 according to various embodiments of the disclosure.

DETAILED DESCRIPTION

[0051] It should be understood at the outset that although an illustrative implementation of one or more embodiments are provided below, the disclosed systems and/or methods may be implemented using any number of techniques, whether currently known or in existence. The disclosure should in no way be limited to the illustrative implementations, drawings, and techniques illustrated below, including the exemplary designs and implementations illustrated and described herein, but may be modified within the scope of the appended claims along with their full scope of equivalents.

[0052] New areas of technology have created a larger demand for smaller processing units with increased power capacity and dynamic power control. Recently, fully integrated voltage regulators have included air core inductors (ACIs) instead of magnetic core inductors. An ACI is an inductor that does not depend on magnetic material to achieve a specified inductance. The ACI, which is connected to an IVR, is used as an energy storage device. The IVR with the ACI reduces the number of power components on a PCB.

[0053] However, a conventional ACI has a low inductance and is relatively large or bulky in size compared to magnetic core inductors, thereby occupying a large footprint on the packages. Therefore, while a conventional ACI is lightweight and cost-efficient, the conventional ACI consumes a significant amount of space on the package without providing a high inductance. In this way, as the process technology continues to shrink to sizes of 14

nanometers (nm), 10 (nm), and or even smaller, conventional ACIs are no longer practical due to the size of the conventional ACI.

[0054] Disclosed herein is an inductor with a non-magnetic core, such as an ACI, in which magnetic material is injected into the non-magnetic core to increase an inductance of the inductor. When magnetic material is injected into the non-magnetic core of the inductor, the permeability or density of the non-magnetic core increases. By increasing the permeability of the non-magnetic core, the inductance of the inductor increases to significantly more than an inductance of a conventional ACI. In some embodiments, the inductor with the non-magnetic core is embedded in a substrate of a package.

[0055] FIG. 1A is a diagram of an embodiment of a package 100, which may also be referred to as a semiconductor package, integrated circuit package, and so on, according to various embodiments of the disclosure. As shown, the package 100 can be mounted on a printed circuit board (PCB) 102. In an embodiment, the package 100 is electrically coupled to the PCB 102 through one or more solder features 104 such as, for example, a ball grid array (BGA). However, the package 100 and the PCB 102 may be otherwise electrically coupled. For example, the package 100 and the PCB 102 may also be electrically coupled together by way of pins and a corresponding socket. In an embodiment, the PCB 102 and/or the solder features 104 are included within the package 100.

[0056] The package 100 is supplied with direct current (DC) voltage by way of a DC voltage source 106 on the PCB 102. In an embodiment, the DC voltage source 106 is a DC-to-DC converter. While the DC voltage source 106 is the only component, device, element, or feature illustrated on the PCB 102 in FIG. 1A, it should be understood that other components, devices, elements, or features may be included on or in the PCB 102 in practical applications. While the DC voltage source 106 is shown as being embedded within the PCB 102 in FIG. 1A,

it should be appreciated that the DC voltage source 106 may also be positioned on the PCB 102 (e.g., not embedded within the PCB 102).

[0057] As shown, the package 100 includes a package substrate 108, an interposer 110, at least one die 112, an IVR 114, and one or more inductors 150A-F. Each of these elements of the package 100 will be more fully described below.

[0058] The package substrate 108 is provided to support, and convey electrical signals from, the die 112 and/or the interposer 110. In an embodiment, the package substrate 108 includes numerous horizontal traces coupled together by vertical vias (not shown). The traces and vias may terminate in one or more contact pads (not shown) proximate the upper or bottom surface of the package substrate 108. The traces, vias, and/or contact pads are formed from a conductive material such as, for example, copper, gold, or other conductive metal to conduct an electrical signal through the package substrate 108.

[0059] The package substrate 108 is electrically coupled to the interposer 110. In an embodiment, the package substrate 108 and the interposer 110 are electrically coupled together using one or more solder features 118, such as controlled collapse chip connection (C4) bumps, as shown in FIG. 1A. In such embodiments, the structure including the interposer 110 and die 112 may be “flipped” onto the package substrate 108 using what is known as a flip chip method. Despite this example, the package substrate 108 and the interposer 110 may be otherwise electrically coupled in other embodiments.

[0060] In an embodiment, the interposer 110 is formed from silicon (Si) or other suitable substrate material. In an embodiment, the interposer 110 includes metallization such as horizontal traces coupled together by vertical vias (not shown). The traces and vias may terminate in one or more contact pads (not shown) proximate the upper or bottom surface of the interposer 110. The traces, vias, and/or contact pads are formed from a conductive material

such as, for example, copper, gold, or other conductive metal to conduct an electrical signal through the interposer 110.

[0061] In an embodiment, the interposer 110 is a passive wafer, which means that the interposer 110 contains only passive components. Passive components are those that cannot provide any power gain to a circuit. Indeed, passive components are incapable of controlling the current (or energy) flow in the circuit and need the help of active components to operate. Some examples of passive components are resistors, inductors, and capacitors.

[0062] In an embodiment, the interposer 110 is an active wafer, which means that the interposer 110 contains active components. An active component is any component that is capable of providing a power gain. Active components inject power to the circuit, and can control the current (or energy) flow within the circuit. Some examples of active components are transistors, silicon controller rectifiers (SCRs), thyristors, batteries, and so on.

[0063] The interposer 110 is electrically coupled to the one or more die 112. In an embodiment, the interposer 110 and the one or more die 112 are electrically coupled together through one or more solder features 120 such as, for example, microbumps (μ bumps) as shown in FIG. 1A. However, other types of electrical connection may be utilized in other embodiments. For example, in an embodiment the die 112 may be coupled to the interposer 110 by pins, leads, wire bonding, surface mounting, and so on.

[0064] The die 112, in the context of integrated circuits, is a small block of semiconducting material on which a functional integrated circuit is fabricated. Typically, the integrated circuits are produced in large batches on a single wafer of electronic-grade silicon (EGS) or other semiconductor material (e.g., gallium arsenide (GaAs), etc.) through processes such as photolithography. The wafer is then cut (“diced”) into many pieces, each containing one copy of the integrated circuit. Each of these pieces is referred to as a die.

[0065] As shown by FIG. 1A, the die 112 contains at least one capacitor 122. The capacitor 122 is, for example, a passive two-terminal electrical component that stores potential energy in an electric field. The effect of capacitor 122 is known as capacitance, which is measured in farads. While some capacitance exists between any two electrical conductors in proximity in a circuit, a capacitor such as capacitor 122 is a component or embedded capacitor designed to add capacitance to a circuit of the die 112. In an embodiment, the capacitor 122 in FIG. 1A is optional.

[0066] The die 112 also supports or contains one or more electrical components 124 that form a portion of the functional circuit of the die 112. The electrical components 124 may be, for example, an integrated circuit, electronic device, or component thereof that uses or relies upon a supply of DC voltage to function or operate as intended.

[0067] In the embodiment illustrated in FIG. 1A, the die 112 supports the IVR 114. The IVR 114 is a device or system designed to maintain a relatively constant voltage level. In doing so, the IVR 114 is able to stabilize the DC voltage supplied to the one or more electrical components 124 (e.g., core IPs, memory controller IPs, I/O IPs, etc.) on the die 112. In an embodiment, the IVR 114 is configured to receive a voltage of about 1.8 volts (V) and output a voltage of about 0.8 V. However, the IVR 114 is able to input and output different voltages in other embodiments. In an embodiment, the IVR 114 is embedded within the die 112.

[0068] In the embodiment shown in FIG. 1A, the package 100 includes one or more inductors 150A-F. The inductors 150A-F are each inductors with a non-magnetic core that does not include magnetic material and does not depend on magnetic material to achieve a specified inductance. For example, the inductor 150A-F shown in FIG. 1A may be an ACL, ceramic core inductor, or any other inductor with a core that does not include ferromagnetic material (also referred to herein as simply “magnetic material”).

[0069] The effect of the inductors 150A-F is known as inductance, which is measured in Henries (H). Inductance refers to the ability of an inductor 150A-F to store energy using a magnetic field created by the flow of electrical current through the inductor 150A-F. As a result of the magnetic field created by the flow of current through the inductor 150A-F, the inductor 150A-F generates an opposing voltage proportional to the rate of change in current.

[0070] The inductors 150A-F may be structured or shaped in any manner fitting to include a non-magnetic core. For example, the inductor 150A-F may be a coil inductor, a wave inductor, a snake inductor, a spiral inductor, a solenoid inductor, a toroidal inductor, a bobbin-based inductor, a multilayer inductor, etc.

[0071] As shown by FIG. 1A, the inductors 150A-F may be embedded anywhere within the substrates (e.g., PCB 102, package substrate 108, interposer 110, and die 112) of the package 100 or between the substrates of the package 100. In an embodiment, the inductors 150A-F may be embedded anywhere within the PCB 102, package substrate 108, and/or the interposer 110. For example, as shown by FIG. 1A, the inductors 150A-C are embedded within the package substrate 108, and the inductors 150D-E are embedded within the interposer 110.

[0072] In some cases, the inductors 150A-F may be embedded within different layers of the substrates (e.g., PCB 102, package substrate 108, interposer 110, and die 112). As shown by FIG. 1A, the inductor 150A is embedded within layers of the package substrate 108 proximate to the PCB 102, while the inductor 150B is embedded within layers of the package substrate 108 proximate to the interposer 110. Similarly, the inductor 150E is embedded within layers of the interposer 110 farther away from the die 112 than the inductor 150D.

[0073] In an embodiment, one or more of the inductors 150A-F may be embedded between the different layers of the package 100. For example, one or more of the inductors 150A-F may be embedded between the PCB 102 and the package substrate 108, between the package substrate 108 and the interposer 110, and/or between the interposer 110 and the die 112.

[0074] For example, as shown by FIG. 1A, an inductor 150F is embedded between the die 112 and the interposer 110 of the package 100. The inductor 150F is formed between two of the solder features 120. In this embodiment, a metal layer 128 of the interposer 110 electrically couples the solder features 120 supporting the inductor 150F. While the interposer 110 may include additional metallization (as noted above), only the portion of the metal layer 128 forming the inductor 150F has been depicted in FIG. 1A for ease of illustration. In an embodiment, the portion of the metal layer 128 is copper, gold, or another conductive metal. In an embodiment, the portion of the metal layer 128 forming the inductor 150F is from the top or upper metal layer of the interposer 110. In an embodiment, the portion of the metal layer 128 creates an inductor pattern (e.g., a partial loop, rectangle, etc., when viewed from above).

[0075] While the inductors 150A-F have non-magnetic cores that do not contain magnetic materials, the embodiments disclosed herein are directed to injecting magnetic material within the non-magnetic cores of the inductors 150A-F. By injecting magnetic material into the non-magnetic cores of the inductors 150A-F, the permeability of the non-magnetic core of the inductors 150A-F increases, thereby increasing the inductance of the inductors 150A-F.

[0076] In an embodiment, a blind hole is drilled into a substrate (e.g., PCB 102, package substrate 108, and/or interposer 110) of the package 100 having an inductor 150A-F. A blind hole is a hole that is drilled to a specified depth without breaking through to the other side of the substrate.

[0077] In an embodiment, a method of forming a package 100 includes obtaining a package substrate 108 with an embedded inductor 150A or creating a package substrate 108 with an embedded inductor 150A. After obtaining or creating the package substrate 108 with an embedded inductor 150A, the method of forming the package 100 further includes drilling a blind hole through the package substrate 108 and through a non-magnetic core of the inductor 150A without drilling all the way through the non-magnetic core. In one embodiment, the

blind hole is drilled until the drill reaches a bottom end of the inductor 150A. In another embodiment, the blind hole is drilled through a center of the non-magnetic core. The blind hole extends from a surface of the package substrate 108, through the core of the inductor 150A, and to the bottom end of the inductor 150A.

[0078] Thereafter, magnetic material 126 is deposited or otherwise inserted into the blind hole within the core of the inductor 150A. In an embodiment, the magnetic material 126 is continuously deposited into the blind hole until the magnetic material 126 fills up to anywhere between the top end of the inductor 150A and the surface of the package substrate 108.

[0079] In an embodiment, the magnetic material 126 may be magnetic powder, discrete magnetic particles, magnetic paste, or any other form of ferromagnetic material. In an embodiment, the magnetic material 126 is soft magnetic material, in which the magnetic field or the polarity of the magnetic material can be easily reversed. Soft magnetic materials have a high magnetic permeability (also referred to herein as simply “permeability”). Magnetic permeability refers to the measure of the ability of a material to support the formation of a magnetic field within itself. In other words, magnetic permeability is a degree of magnetization that a material obtains in response to an applied magnetic field.

[0080] The magnetic material 126 may be any material able to provide or generate a magnetic field and fit within the core of the inductors 150A-F. The magnetic material 126 may include a variety of different materials, alloys, or compounds. By way of example, the magnetic material 126 may be a nickel iron (NiFe) alloy.

[0081] In an embodiment, the magnetic material 126 comprises iron having a body-centered cubic (BCC) structure or iron having a face-centered cubic (FCC) structure. In an embodiment, the magnetic material 126 comprises nickel having the BCC structure nickel having the hexagonal closed packed (HCP) structure, or cobalt having the HCP structure. In an embodiment, the magnetic material 126 comprises gadolinium having the HCP structure. In an

embodiment, the magnetic material 126 comprises a manganese bismuthide (MnBi) having a hexagonal structure.

[0082] In an embodiment, the magnetic material 126 comprises an 81 nickel (Ni) - 19 iron (Fe) having the FCC structure, a 50Ni - 50Fe having the FCC structure, or a 3Ni - 97Fe having the BCC structure. In an embodiment, the magnetic material 126 comprises a nickel-iron-aluminum alloy. In an embodiment, the magnetic material 126 comprises an 80Ni - 17Fe - 3 cobalt (Co) having the FCC structure, a 57Ni - 13Fe - 30Co having the FCC structure, a 48.6Ni - 2.8Fe - 48.6Co having the FCC structure, or a 45Ni - 30Fe - 25Co having the FCC structure.

[0083] In an embodiment, the magnetic material 126 comprises a nickel-iron-chromium having the FCC structure or a nickel-iron-copper. In an embodiment, the magnetic material 126 comprises nickel-iron-molybdenum having the FCC structure. In an embodiment, the magnetic material 126 comprises nickel-iron-phosphorus. In an embodiment, the magnetic material 126 comprises iron-aluminum with about 22% to about 25% aluminum having the BCC structure. In an embodiment, the magnetic material 126 comprises 50Fe-50Co having the BCC structure. In an embodiment, the magnetic material 126 comprises 5Fe-95Co.

[0084] In an embodiment, the magnetic material 126 comprises nickel-copper having the FCC structure. In an embodiment, the magnetic material 126 comprises nickel-palladium having the FCC structure. In an embodiment, the magnetic material 126 comprises nickel alloy. In an embodiment, the magnetic material 126 comprises cobalt-copper, cobalt-nickel, or cobalt-phosphorous. In an embodiment, the magnetic material 126 comprises cobalt-nickel-phosphorous or cobalt-nickel-phosphorous with a mixture of the HCP structure and the FCC structure. In an embodiment, the magnetic material 126 comprises a ferrite (NiFe_2O_4) film having a cubic structure. In an embodiment, the magnetic material 126 comprises a garnet film ($\text{Y}_3\text{Fe}_5\text{O}_{12}$) having a cubic structure.

[0085] In an embodiment, the magnetic material 126 comprises a NiFe with a ratio of about 45%/55% and a permeability up to about 1300. In an embodiment, the magnetic material 126 comprises Ni₈₁Fe₁₇Cu_{1.5}Mo_{0.5} spherical particles having a particle diameter in a range of 2 micrometers (μm) to about 20 μm in a polymer matrix. In an embodiment, the magnetic material 126 comprises a polycrystalline or monocrystal-line layer of a ferromagnetic metal, alloy, or magnetic oxide about 0.01 μm to about 10 μm thick.

[0086] In an embodiment, the inductors 150A-F and the capacitor 122 collectively form a filter configured for a predetermined frequency of a DC voltage output by the IVR 114. In an embodiment, the predetermined frequency corresponds to a switching speed of the IVR 114 and is in a range of about one hundred mega Hertz (MHz) to about one hundred and fifty MHz. In an embodiment, the inductors and the capacitors are selected based on ripple current and ripple voltage as well as on loop stability considerations.

[0087] In an embodiment, the inductors 150A-F are each configured to store energy for use by, for example, circuits, components, or devices of the package 100. In an embodiment, the inductors 150A-F are each configured to mitigate or prevent a ripple effect, which is the residual periodic variation of the DC voltage, produced by the IVR 114. In an embodiment, the inductors 150A-F are each configured to receive a voltage of about 0.8 V and output a voltage of about 0.8 V. However, the inductors 150A-F are able to input and output different voltages in other embodiments.

[0088] The inductance produced by the inductors 150A-F depends on, for example, the type of the magnetic material 126 deposited into the non-magnetic core of the inductors 150A-F, the size of the blind hole drilled into the core of the inductors 150A-F, the particular voltage supplied to the inductor 150A-F, and so on.

[0089] Still referring to FIG. 1A, an electrical path 132 extending from the DC voltage source 106 to the IVR 114 or electrical components 124 is illustrated. The electrical path 132

illustrates, in general, how the DC voltage from the DC voltage source 106 is provided to the IVR 114 or electrical components 124 on the die 112. It should be appreciated that the electrical path 132 may take a variety of different routes through the package 100 in practical applications due to the varying pattern of metallization within the package 100. Indeed, the electrical path 132 of FIG. 1A is simply provided as an example of the general route taken.

[0090] As shown in FIG. 1A, the DC voltage source 106 outputs a DC voltage at DC_{out} . The DC voltage is transported through the solder feature 104, the package substrate 108, the solder feature 118, the interposer 110, and the solder feature 120 along the electrical path 132. Once the DC voltage has arrived at the die 112, the DC voltage is input at IVR_{in} into the IVR 114 as shown by the electrical path 132. As noted above, the IVR 114 regulates the voltage to, for example, reduce the DC voltage from 1.8 V to 0.8 volts.

[0091] After the DC voltage has been suitably regulated by the IVR 114, the DC voltage is output from the IVR 114 at IVR_{out} and transported through the solder feature 120, the interposer 110, the solder feature 118, and input at L_{in} into the inductor 150A, as shown by the electrical path 132. The desired or predetermined inductance is generated at the inductor 150A based on the input at L_{in} . The DC voltage is output at L_{out} from the inductor 150A and transported through the solder feature 118, the interposer 110, the solder feature 120, and input at Cap_{in} to the optional capacitor 122 as shown by the electrical path 132.

[0092] Thereafter, the DC voltage is output at Cap_{out} from the capacitor 122 and input at $Comp_{in}$ into the electrical components 124 as shown by the electrical path 132. The electrical components 124 are then able to utilize the DC voltage to effectuate the function of the circuit on the die 112.

[0093] In an embodiment, two or more inductors 150A-F may be used within the package 100 to generate a greater amount of inductance or to create a multi-phase design. In such an embodiment, the inductors 150A-F may be coupled in series or in parallel, respectively. When

in series, the input L_{in} of the first inductor 150A-F in the series would receive the DC voltage from the IVR 114. The output L_{out} of the first inductor 150A-F would then be coupled to the input L_{in} of the second or next inductor 150A-F in the series. The output L_{out} of the last inductor 150A-F in the series would then be fed into the capacitor 122 or the electrical components 124. When in parallel, the input L_{in} of the inductors 150A-F in the parallel would receive the DC voltage from the IVR 114. The output L_{out} of the inductors 150A-F in parallel would then be fed into the capacitor 122 or the electrical components 124.

[0094] The inductors 150A-F provide numerous benefits to the package 100 relative to conventional packages containing an ACI without the magnetic material 126. For example, an ACI typically occupies a large footprint within the package while providing a low inductance. However, by injecting the ACI with magnetic material 126 to create the inductors 150A-F described herein, the inductance of the inductors greatly increased. Therefore, the embodiments disclosed herein increases the inductance of existing ACIs without having to remove or restructure any aspect of the ACI. In addition, the embodiments disclosed herein enable the production of smaller inductors 150A-F that provide substantially the same inductance as a larger sized ACI. Therefore, the inductor 150A-F may be smaller than the ACI and, therefore, take up less real estate within the package 100.

[0095] FIG. 1B is a diagram of an embodiment of another package 150, which again, may also be referred to as a semiconductor package, integrated circuit package, and so on, according to various embodiments of the disclosure. The package 150 of FIG. 1B is similar to the package 150 of FIG. 1A, except that the interposer 110 is disposed between the PCB 102 and the package substrate 108 (instead of being disposed between the die 112 and the package substrate 108 as shown in FIG. 1A). In this embodiment, the interposer 110 is electrically coupled to the package substrate 108 using the one or more solder features 118. In this

embodiment, the interposer 110 is electrically coupled to the PCB 102 using the one or more solder features 104.

[0096] Unlike the interposer 110 of FIG. 1A, the interposer 110 of FIG. 1B is formed from an organic material or a ceramic material. Otherwise, the interposer 110 of FIG. 1B is similar to the interposer 110 of FIG. 1A. For example, the interposer 110 of FIG. 1B also includes metallization such as traces, vias, and/or contact pads. The interposer 110 of FIG. 1B is a passive wafer, meaning that the interposer 110 contains only passive components.

[0097] As shown in FIG. 1B, inductors 150A-C are included in the interposer layer 110 and inductors 150D-E are included in the package substrate 109. Similarly, inductor 150F is disposed between the package substrate 108 and the die 112 and is positioned in between two of the solder features 120.

[0098] The inductors 150A-F of FIG. 1B are otherwise similar to the inductors 150A-F of FIG. 1A, in that the inductors 150A-F of FIG. 1B have non-magnetic cores and are injected with magnetic material 126. The inductance produced by the inductors 150A-F depends on, for example, the type of the magnetic material 126 deposited into the non-magnetic core of the inductors 150A-F, the size of the blind hole drilled into the core of the inductors 150A-F, the particular voltage supplied to the inductor 150A-F, and so on.

[0099] The electrical path 132 of FIG. 1B is similar to the electrical path 132 of FIG. 1A. the DC voltage source 106 outputs a DC voltage at DC_{out} . The DC voltage is transported through the solder feature 104, the interposer 110, the solder feature 118, the package substrate 108, and the solder feature 120 along the electrical path 132. Once the DC voltage has arrived at the die 112, the DC voltage is input at IVR_{in} into the IVR 114 as shown by the electrical path 132.

[00100] After the DC voltage has been suitably regulated by the IVR 114, the DC voltage is output from the IVR 114 at IVR_{out} and transported through the solder feature 120, the package

substrate 109, the solder feature 118, and input at L_{in} into the inductor 150A embedded within the interposer 110, as shown by the electrical path 132. The desired or predetermined inductance is generated at the inductor 150A based on the input at L_{in} . The DC voltage is output at L_{out} from the inductor 150A and transported through the solder feature 118, the package substrate 108, the solder feature 120, and input at Cap_{in} to the optional capacitor 122 as shown by the electrical path 132.

[00101] Thereafter, the DC voltage is output at Cap_{out} from the capacitor 122 and input at $Comp_{in}$ into the electrical components 124 as shown by the electrical path 132. The electrical components 124 are then able to utilize the DC voltage to effectuate the function of the circuit on the die 112.

[00102] In an embodiment, two or more inductors 150A-F may be used within the package 150 to generate a greater amount of inductance or to create a multi-phase design, as described above with reference to FIG. 1A. In such an embodiment, the inductors 150A-F may be coupled in series or in parallel, respectively.

[00103] FIG. 2 is a diagram of an embodiment of another package 200 according to various embodiments of the disclosure. The package 200 of FIG. 2 is similar to the package 100 of FIG. 1A or the package 150 of FIG. 1B. For example, the package 200 may be mounted to a PCB 202 by way of solder features 204 and supplied with DC voltage by way of DC voltage source 206. The PCB 202, the solder features 204, and the DC voltage source 206 are similar to the PCB 102, the solder features 104, and the DC voltage source 106 of FIGS. 1A-B.

[00104] As shown in FIG. 2, the package 200 includes a package substrate 208, an interposer 210, at least one die 212, an IVR 214, an inductor 150A, and solder features 218, 220. The package substrate 208, the interposer 210, the die 212, the IVR 214, and the solder features 204, 218, and 220 are similar to the package substrate 108, the interposer 110, the die 112, the IVR 114, and the solder features 104, 118, and 120 of FIGS. 1A-B. The interposer

210 is disposed between the package substrate 208 and the die 212 (similar to the package 100 shown in FIG. 1A). However, in another embodiment, the interposer 210 may be disposed between the PCB 202 and the package substrate 208 (similar to the package 150 shown in FIG. 1B).

[00105] Unlike the IVR 114 of FIGS. 1A-B, the IVR 214 of FIG. 2 is embedded within the interposer 210 instead of the die 212. Therefore, the electrical path 232 takes a slightly different route through the package 200 compared to the electric path 132 of FIGS. 1A-B. In FIG. 2, the DC voltage source 206 outputs the DC voltage at DC_{out} . The DC voltage is transported through the solder feature 204, the package substrate 208, the solder feature 218, and the interposer 210 along the electrical path 232. Once the DC voltage has arrived at the interposer 210, the DC voltage is input at IVR_{in} into the IVR 214 as shown by the electrical path 232. As noted above, the IVR 214 regulates the voltage to, for example, reduce the DC voltage from 1.8 V to 0.8 volts.

[00106] After the DC voltage has been suitably regulated by the IVR 214, the DC voltage is output from the IVR 214 at IVR_{out} as shown by the electrical path 232, transported through the solder feature 218, and input at L_{in} into the inductor 150A where the desired or predetermined inductance is generated. The DC voltage is output at L_{out} from the inductor 150A, transported back up through the solder feature 218, and input at Cap_{in} to the optional capacitor 222 as shown by the electrical path 232.

[00107] Thereafter, the DC voltage is output at Cap_{out} from the capacitor 222 and input at $Comp_{in}$ into the electrical components 224 as shown by the electrical path 232. The electrical components 224 are then able to utilize the DC voltage to effectuate the function of the circuit on the interposer 210.

[00108] While not shown in FIG. 2, the package 200 may include additional inductors that may be coupled in parallel or in series, as described above with reference to FIG. 1A. In

addition, the inductor 150A includes magnetic material 126, which may be in the form of magnetic powder or particles. In an embodiment, the magnetic material 126 is injected and compressed into a blind hole drilled into the package substrate 208 and through the non-magnetic core of the inductor 150A.

[00109] The inductor 150A provides numerous benefits to the package 200 relative to conventional packages containing an ACI without the magnetic material 126. For example, an ACI typically occupies a large footprint within the package while providing a low inductance. However, by injecting the ACI with magnetic material 126 to create the inductor 150A described herein, the inductance of the inductors greatly increased. Therefore, the embodiments disclosed herein increases the inductance of existing ACIs without having to remove or restructure any aspect of the ACI. In addition, the embodiments disclosed herein enable the production of smaller inductor 150A that provides substantially the same inductance as the ACI. Therefore, the inductor 150A may be smaller than the ACI and, therefore, take up less real estate within the package 200.

[00110] FIG. 3 is a diagram illustrating an embodiment of an inductor 350. The inductor 350 may be similar to inductors 150A-150F of FIGS. 1-2, which are embedded within a substrate or disposed between substrates according to various embodiments of the disclosure. In the example shown in FIG. 3, the inductor 350 is embedded within a substrate 300. In the embodiment, the substrate 300 may be the PCB 102 or 202, the package substrate 108 or 208, or the interposer 110 or 210. In an embodiment, the substrate 300 may be formed as part of the package 100, 150, or 200.

[00111] As shown by FIG. 3, a substrate 300 includes multiple layers 301-310. Each of the layers 301-310 may be any type of layer that is included in the package 100, 150, or 200, such as a conductor layer and/or a dielectric layer. In this way, each layer 301-310 may include conductive material, dielectric material, contact pads, vias, etc.

[00112] The substrate 300 may be formed with an inductor 350 embedded within the substrate 300. For example, the substrate 300 is formed by first depositing layer 301 and then depositing layer 302. After depositing layer 302, the inductor 350 is formed on the layer 302. After the inductor 350 has been formed on layer 302, layers 303-310 are sequentially formed onto and around the inductor 350. As shown by FIG. 3, layers 303-307 are formed or deposited around the inductor 350, and layers 308-310 are deposited on top of the inductor 350.

[00113] As shown by FIG. 3, the inductor 350 initially includes a non-magnetic core 313 and a coil 316 wrapped around the non-magnetic core 313. For example, assuming that the inductor 350 is an ACI, the non-magnetic core 313 may be organic, plastic, ceramic, or another non-magnetic material. The non-magnetic core 313 includes a width 320, which is less than the width of the entire inductor 350. The coil 316 wrapped around the non-magnetic core 313 may include several turns, and each turn corresponds to each layer of the substrate 300. For example, a first turn of the coil 316 is positioned within layer 303, a second turn of the coil 316 is positioned within layer 304, a third turn of the coil 316 is positioned within layer 305, a fourth turn of the coil 316 is positioned within layer 306, and a fifth turn of the coil 316 is positioned within layer 307.

[00114] According to various embodiments, after the substrate 300 has been formed with an embedded inductor 350 and before the substrate 300 becomes part of a package 100, 150, or 200, magnetic material 126 is deposited into a non-magnetic core 313 of the inductor 350 to increase the inductance of the inductor 350. In an embodiment, the inductor 350 may be transformed into a magnetic core inductor 350 by depositing magnetic material 126 into the core 316 of the inductor 350.

[00115] First, a blind hole 323 is drilled into the substrate 300. A blind hole 323 is a hole that is drilled to a specified depth 336 without breaking through to the other side of the

substrate 300 . The blind hole 323 may be drilled into the substrate 300 and the inductor 350 using any form of drilling, such as mechanical drilling or laser drilling.

[00116] In an embodiment, the blind hole 323 is drilled from the first surface 326 of the substrate 300 to anywhere within the non-magnetic core 313 of the inductor 350 to allow a sufficient amount of magnetic material 126 to be deposited within the blind hole 323. In FIG. 3, the blind hole 323 is drilled from the first surface 326 of the substrate 300 to a bottom end 329 of the non-magnetic core 313. In FIG. 3, the bottom of the blind hole 323 lines up with the bottom end 329 of the non-magnetic core 313. However, the blind hole 323 does not necessarily need to be drilled down to the bottom end 329 of the non-magnetic core 313, but may instead be drilled to a depth 336 anywhere within the non-magnetic core 313 of the inductor 350.

[00117] In an embodiment, a width 331 of the blind hole 323 is sufficiently wide to secure a predefined amount magnetic material 126 within the blind hole 323. The width 331 of the blind hole 323 is less than or equal to the width 320 of the non-magnetic core 313.

[00118] After the blind hole 323 has been drilled into the substrate 300 and the non-magnetic core 313, the magnetic material 126 is deposited into the blind hole 323. In an embodiment, the magnetic material 126 is continuously injected or deposited into the blind hole 323 until a predetermined amount of the magnetic material 126 fills at least a portion of the blind hole 323 within the non-magnetic core 313.

[00119] The predetermined amount of the magnetic material 126 is based on a type of the magnetic material 126 used to fill the blind hole 323, examples of which are described above with reference to FIG. 1A. For example, a greater amount of magnetic materials 126 with a relatively low permeability should be deposited into the blind hole 323 to achieve the same inductance as magnetic materials 126 with a relatively high permeability. For example, magnetic materials 126 with a high permeability may require a lesser amount of the magnetic

material 126 to be deposited into the blind hole 323 for the inductor 350 to achieve a specified inductance. In the same way, magnetic materials 126 with a low permeability may require a greater amount of the magnetic material 126 to be deposited into the blind hole 323 for the inductor 350 to achieve a specified inductance.

[00120] In FIG. 3, the magnetic material 126 fills up the entire non-magnetic core 313 of the inductor 350. However, in various embodiments, the magnetic material 126 may not have to fill up the entire non-magnetic core 313, and may instead only fill up a portion of the non-magnetic core 313. For example, the magnetic material 126 may be deposited into the non-magnetic core 313 from layers 303-305 instead of all the way up to layer 307.

[00121] In an embodiment, blind hole 323 may be filled with magnetic material 126 not only within the non-magnetic core 313, but also above the non-magnetic core 313. For example, magnetic material 126 may be deposited within the blind hole 323 into the entire non-magnetic core 313 and then above the core and into layers 308, 309, and 310. In this embodiment, the blind hole 323 includes the magnetic material 126 from the bottom of the blind hole 323 to anywhere within the substrate 300.

[00122] Once the blind hole 323 is deposited with the magnetic material 126, a width of the magnetic material 126 is equal to the width 331 of the blind hole 323. A depth 333 of the magnetic material 126 may be less than or equal to the depth 336 of the blind hole 323. The depth 333 of the magnetic material 126 may be less than or equal of the depth of the non-magnetic core 313 and the inductor 350 as well.

[00123] FIGS. 4A-C collectively illustrate an embodiment of a process flow 400 used to form an inductor 350 according to various embodiments of the disclosure. As shown in FIG. 4A, the process flow 400 begins with a substrate 300 of package 100, 150, or 200. As described above, the substrate 300 may be a PCB 102 or 202, a package substrate 108 or 208, or an interposer 110 or 210.

[00124] For the example shown in FIGS. 4A-C, the inductor 350 is embedded within the substrate 300. However, the inductor 350 may also be between different substrates 300 of the package 100, 150, or 200.

[00125] As described above, the inductor 350 comprises non-magnetic core 313 made of a non-magnetic material, such as organic, plastic or ceramic. For example, the inductor 350 is an ACI. As shown by FIG. 4A, a coil 316 is wrapped around the non-magnetic core 313. In FIG. 4A, the coil 316 is spirally-wound around the non-magnetic core 313.

[00126] Moving to FIG. 4B, a blind hole 323 is drilled into the center of the non-magnetic core 313 of the inductor 350. The blind hole 323 may be drilled into the non-magnetic core 313 of the inductor 350 using a drill 404 suitable for drilling small size holes into the substrate 300. For example, holes smaller than 150 micrometers (μm) can be drilled using a laser drill, and holes bigger than 150 μm can be drilled by either laser drill or mechanical drill.

[00127] In an embodiment, the width 331 of the blind hole 323 is substantially equal to a width 406 of the drill 404. However, the width 331 of the blind hole 323 may be increased or reamed after drilling using, for example, a reamer or a laser. In an embodiment, the greater the width 331 of the blind hole 323, the more magnetic material 126 (not pictured) may be injected into the non-magnetic core 313 of the inductor 350. The greater the amount of magnetic material 126 injected into the non-magnetic core 313 of the inductor 350, the higher the permeability of the non-magnetic core 313, and thus, the higher the inductance of the inductor 350. In this way, the inductance of the inductor 350 is based on the width 331 of the blind hole 323. As described above, the inductance of the inductor 350 is also based on the type of magnetic material 126 injected into the blind hole 323. Various examples of the magnetic material 126 are described above with reference to FIG. 1A. For example, magnetic materials 126 with a higher permeability produce a larger inductance than magnetic materials 126 with a

lower permeability. For example, maximum relative permeability of 99% pure Nickel can be around 600 with annealed treatment.

[00128] In an embodiment, a shape of the blind hole 323 is based on the drill 404. For example, when a laser drill 404 is used to drill the blind hole 323, the laser drill 404 may drill the blind hole 323 as any shape with a hollow section or cavity that can be used to receive and secure the magnetic material 126, as will be further described below with reference to FIG. 4C. When a mechanical drill 404 is used to drill the blind hole 323, the shape of the blind hole 323 corresponds to the shape of the mechanical drill 404. In FIG. 4B, the blind hole 323 is shaped as cylindrical section in which the base 409 of the blind hole 323 is placed on or near a bottom end 329 of the non-magnetic core 313. However, the blind hole 323 may otherwise have any other shape with a hollow section or vacuum within the non-magnetic core 313.

[00129] During operation of the drill 404, the drill 404 drills through the first surface 326 of the substrate 300, through several layers of the substrate 300, and into the center of the non-magnetic core 313. Upon entering the non-magnetic core 313, the drill 404 continues to drill through the non-magnetic core 313 until the drill 404 reaches the base 409. The point at which the drill 404 terminates drilling is referred to as the base 409 of the blind hole 323. In this way, the drill 404 drills through substrate 300 and the inductor 350 for a depth 336 until the drill reaches the base 409. In FIG. 4B, the base 409 is positioned at the bottom end 329 of the non-magnetic core 313. However, the base 409 may otherwise be positioned anywhere within the non-magnetic core 313 or even between the bottom end 329 of the non-magnetic core 313 and the bottom end of the substrate 300.

[00130] After drilling, the drill 404 is removed from the inductor 350. At this point, the blind hole 323 is an empty hole or vacuum present within the non-magnetic core 313 of the inductor 350.

[00131] Moving on the FIG. 4C, shown is a cross-section of the substrate 300 with the inductor 350 embedded within the substrate 300. In FIG. 4C, magnetic material 126 is deposited into the blind hole 323 after the blind hole 323 has been drilled. Various examples of the magnetic material 126 are described above with reference to FIG. 1A. In general, the magnetic material 126 comprises a soft magnetic material with high permeability. As described above, permeability refers to the measure of the ability of a material to support the formation of a magnetic field within itself. In an embodiment, magnetic permeability is a degree of magnetization that a material obtains in response to an applied magnetic field.

[00132] An inductance of the inductor 350 is proportional to the permeability of the non-magnetic core 313. Inductance is defined by equation (1):

$$L = \frac{\mu N^2 A}{l} \quad (1)$$

[00133] In equation (1), L is the inductance measured in Henries (H), μ is the permeability of the non-magnetic core 313, N is the number of turns in the coil 316, A is the area encircled by the coil 316, and l is the length of the coil 316. Therefore, inductance depends on a variety of factors, and increasing the permeability of the non-magnetic core 313 will increase the overall inductance of the inductor 350.

[00134] In various embodiments, the magnetic material 126 may continue to be deposited into the blind hole 323 anywhere from the base 409 of the blind hole 323 to the first surface 326 of the substrate 300. In an embodiment, the magnetic material 126 is deposited into the blind hole 323 until a consolidation of the magnetic material 126 within the non-magnetic core 313 reaches a pre-defined density, which may correspond to a pre-defined permeability. In an embodiment, the magnetic material 126 is deposited from the base 409 of the blind hole 323 to a top end 415 of the non-magnetic core 313. The top end 415 of the core may or may not align with a top end of the inductor 350. In an embodiment, the magnetic material 126 is deposited from the base 409 of the blind hole 323 to the first surface 326 of the substrate 300.

[00135] In FIG. 4C, the magnetic material 126 has been deposited from the base 409 of the blind hole 323 to about halfway up the blind hole 323. In this example, the magnetic material 126 may continue to be deposited until the magnetic material 126 reaches the top end 415 of the non-magnetic core 313.

[00136] In some embodiments, upon depositing the magnetic material 126 into the blind hole 323, the magnetic material 126 may be magnetically aligned to ensure that the coupling and interaction-mechanisms (exchange interaction, crystal anisotropy, magnetostriction, etc.) of the magnetic material 126 as a whole is accurate. Magnetically aligning or annealing refers to applying a heat treatment to the magnetic material to alter the physical and chemical properties of the magnetic material 126. In some cases, magnetically aligning or annealing the magnetic material 126 involves heating and cooling the magnetic material 126 intermittently over a period of time. In an embodiment, the magnetic material 126 may be magnetically aligned using various different methods of field annealing or magnetic annealing, the methods of which are not restricted herein. Magnetic annealing is applied to remove internal stresses and enforce recrystallization processes. One of the most important effects of magnetic thermal annealing is the reorientation of the easy axis in a ferromagnetic material, or the axis of spontaneous magnetization vector. In any ferromagnetic material, the easy axis is primarily determined by the lattice structure or in some cases, by the shape or the internal strain of a solid. If a deformed ferromagnetic lattice is annealed at a high temperature, the spins of each individual atom will align with the externally applied field. When maintained at a high temperature, this spin-field interaction will begin to reorganize the lattice. When the temperature is reduced, the lattice becomes locked and the magnet attains a new magnetization direction. The magnetic thermal annealing not only can reorient the easy axis and remove lattice defects, it can also change the shape of the object. This annealing increases permeability, reduces coercivity and defines a magnetically reliable state.

[00137] In an embodiment, the magnetic material 126 may be compressed under high pressure within the blind hole 323. For example, a high pressure tool that fits within the blind hole 323 may be used to exert pressure upon the magnetic material 126, of which the method of exerting pressure is not limited herein. In an embodiment, the magnetic material 126 is intermittently compressed during the process of depositing the magnetic material 126 to maximize the amount of magnetic material 126 deposited into the blind hole 323. As described above, the greater the amount of magnetic material 126 injected into the non-magnetic core 313 of the inductor 350, the higher the permeability of the non-magnetic core 313, and thus, the higher the inductance of the inductor 350.

[00138] In an embodiment, the magnetic material 126 may be mixed with a binder or coating. For example, the magnetic material 126 may be mixed with an epoxy and/or phenolic binder or coating.

[00139] In the embodiment shown in FIG. 4C, after the magnetic material 126 has been deposited into the blind hole 323, there is an area 417 of the blind hole 323 positioned between the top end 415 of the inductor 350 and the first surface 326 of the substrate 300. In one embodiment, materials similar to the materials within the substrate 300 may be deposited into the area 417 to close the area 417 within the substrate 300 and secure the magnetic material 126 within the blind hole 323.

[00140] In an embodiment, the area 417 may be filled with a via formed from a conductive material such as, for example, copper, gold, or other conductive metal to conduct an electrical signal through the area 417. In this embodiment, another contact pad or metallization may be positioned at the opening of the blind hole 323 at the first surface 326. The placement of the via within area 417 also closes the area 417 and secures the magnetic material 126 within the blind hole 323.

[00141] FIG. 5 is an embodiment of a method 500 of forming a package according to various embodiments of the disclosure. The method 500 may be performed during fabrication of the package 100, 150, or 200 of FIGS. 1-2. In addition, the method 500 may be performed to provide the package 100, 150, or 200 with a desired or sufficient inductance.

[00142] In block 502, a blind hole 323 is drilled into a non-magnetic core 313 of an inductor 150A-F or inductor 350. For example, a drill 404, such as a mechanical drill or a laser drill, may be used to drill the blind hole 323 into the non-magnetic core 313 of the inductor 150A-F or 350. In an embodiment, the inductor 150A-F or 350 is embedded within a substrate 300 of the package 100, 150, or 200.

[00143] In block 504, magnetic material 126 is deposited into the blind hole 323, which is positioned within the non-magnetic core 313 of the inductor 150A-F or 350. Various examples of the magnetic material 126 are described above with reference to FIG. 1A.

[00144] In block 506, the magnetic material 126 is magnetically aligned within the blind hole 323. In an embodiment, the magnetic material 126 is magnetically aligned by adjusting a temperature of the magnetic material 126 within the blind hole 323 over a period of time. The temperature of the magnetic material 126 may be adjusted by applying heat to the magnetic material 126 and then letting the magnetic material 126 cool intermittently over a period of time.

[00145] The inductors 150A-F and 350 disclosed herein provide numerous benefits to the packages 100, 150, or 200 relative to conventional packages containing the ACI. For example, ACIs and other forms of non-magnetic core inductors are typically large in size, and thus, consume a large amount of real estate within a package. In addition, the ACIs and other non-magnetic core inductors do not provide a high inductance because of the low relative permeability of the non-magnetic core within the ACIs and non-magnetic core inductors. The inductors 150A-F and 350 disclosed herein increase the permeability of the non-magnetic cores

313 by drilling a hole into the non-magnetic cores 313 and depositing soft magnetic materials 126 into the non-magnetic cores 313. By increasing the permeability of these inductors 150A-F and 350, the overall inductance of the inductors 150A-F and 350 are increased without having to increase the size of the inductors 150A-F and 350 or the packages 100, 150, or 200. In addition, even small inductors 150A-F and 350 may be constructed that provide the same inductance as an ACI that is much larger in size than the inductors 150A-F and 350.

[00146] In an embodiment, disclosed herein is a method of forming a package, comprising a means for drilling a blind hole into a non-magnetic core of an inductor, a means for depositing magnetic material into the blind hole, and a means for magnetically aligning the magnetic material within the blind hole.

[00147] While several embodiments have been provided in the present disclosure, it should be understood that the disclosed systems and methods might be embodied in many other specific forms without departing from the spirit or scope of the present disclosure. The present examples are to be considered as illustrative and not restrictive, and the intention is not to be limited to the details given herein. For example, the various elements or components may be combined or integrated in another system or certain features may be omitted, or not implemented.

[00148] A method of forming an inductor means in a package means including depositing, using a depositing means, a first layer of non-magnetic adhesive means over a package substrate means or an interposer means; depositing, using a depositing means, a magnetic material means over the first layer of non-magnetic adhesive means; depositing, using a depositing means, a second layer of non-magnetic adhesive means over the magnetic material means; etching, using an etching means, through the first layer of non-magnetic adhesive means, the magnetic material means, and the second layer of non-magnetic adhesive means to expose first and second portions of a metal layer means of the package substrate means or the

interposer means; and mounting, using a mounting means, solder means onto the first and the second portions of the metal layer means on opposing sides of the magnetic material means after the etching.

[00149] In addition, techniques, systems, subsystems, and methods described and illustrated in the various embodiments as discrete or separate may be combined or integrated with other systems, modules, techniques, or methods without departing from the scope of the present disclosure. Other items shown or discussed as coupled or directly coupled or communicating with each other may be indirectly coupled or communicating through some interface, device, or intermediate component whether electrically, mechanically, or otherwise. Other examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and could be made without departing from the spirit and scope disclosed herein.

CLAIMS

What is claimed is:

1. A method of forming a package, comprising:
drilling a blind hole into a non-magnetic core of an inductor;
depositing magnetic material into the blind hole; and
magnetically aligning the magnetic material within the blind hole.
2. The method according to claim 1, wherein the blind hole is drilled to a bottom end of the non-magnetic core, and wherein the inductor is embedded within a substrate of the package.
3. The method according to any one of claims 1 to 2, wherein a width of the blind hole is less than a width of the non-magnetic core of the inductor.
4. The method according to any one of claims 1 to 3, wherein the drilling is performed using a laser drill.
5. The method according to any one of claims 1 to 4, wherein the magnetic material is deposited into the blind hole until a consolidation of the magnetic material within the non-magnetic core reaches a pre-defined permeability.
6. The method according to any one of claims 1 to 5, further comprising compressing the magnetic material into the blind hole after injecting the magnetic material into the blind hole.

7. The method according to any one of claims 1 to 6, further comprising applying heat to the magnetic material within the blind hole after depositing the magnetic material into the blind hole.
8. The method according to any one of claims 1 to 7, further comprising adjusting a width of the blind hole to adjust an amount of the magnetic material within the blind hole of the inductor.
9. The method according to any one of claims 1 to 8, wherein magnetically aligning the magnetic material within the blind hole comprises adjusting the temperature of the magnetic material within the blind hole of the inductor over a period of time.
10. A package, comprising:
a package substrate;
an interposer electrically coupled to the package substrate;
a die including an integrated voltage regulator and electrically coupled to the interposer;
and
an inductor embedded within at least one of the package substrate or the interposer, the inductor comprising a non-magnetic core filled with magnetic material.
11. The package according to claim 12, wherein the magnetic material comprises discrete magnetic particles, and wherein the magnetic material comprises soft magnetic material.
12. The package according to any of claims 10 to 11, wherein the magnetic material comprises a nickel iron (NiFe) alloy.

13. The package according to any of claims 10 to 12, wherein the magnetic material comprises iron having a body-centered cubic (BCC) structure or iron having a face-centered cubic (FCC) structure.

14. The package according to any of claims 10 to 13, wherein the magnetic material comprises nickel having the BCC structure, nickel having the hexagonal closed packed (HCP) structure, or cobalt having the HCP structure.

15. The package according to any of claims 10 to 14, wherein the magnetic material comprises gadolinium having the HCP structure.

16. The package according to any of claims 10 to 15, wherein the magnetic material comprises gadolinium having the HCP structure.

17. The package according to any of claims 10 to 16, wherein the magnetic material comprises a manganese bismuthide (MnBi) having a hexagonal structure.

18. The package according to any of claims 10 to 17, wherein the magnetic material comprises an 81 nickel (Ni) - 19 iron (Fe) having the FCC structure, a 50Ni - 50Fe having the FCC structure, or a 3Ni - 97Fe having the BCC structure.

19. The package according to any of claims 10 to 18, wherein the magnetic material comprises a nickel-iron-aluminum alloy.

20. The package according to any of claims 10 to 19, wherein the magnetic material comprises an 80Ni - 17Fe - 3 cobalt (Co) having the FCC structure, a 57Ni - 13Fe - 30Co having the FCC structure, a 48.6Ni - 2.8Fe - 48.6Co having the FCC structure, or a 45Ni - 30Fe - 25Co having the FCC structure.
21. The package according to any of claims 10 to 20, wherein the magnetic material comprises a nickel-iron-chromium having the FCC structure or a nickel-iron-copper.
22. The package according to any of claims 10 to 21, wherein the magnetic material comprises nickel-iron-molybdenum having the FCC structure.
23. The package according to any of claims 10 to 22, wherein the magnetic material comprises nickel-iron-phosphorus.
24. The package according to any of claims 10 to 23, wherein the magnetic material comprises iron-aluminum with about 22% to about 25% aluminum having the BCC structure.
25. The package according to any of claims 10 to 24, wherein the magnetic material comprises 50Fe-50Co having the BCC structure.
26. The package according to any of claims 10 to 25, wherein the magnetic material comprises 5Fe-95Co.
27. The package according to any of claims 10 to 26, wherein the magnetic material comprises nickel-copper having the FCC structure.

28. The package according to any of claims 10 to 27, wherein the magnetic material comprises nickel-palladium having the FCC structure.
29. The package according to any of claims 10 to 28, wherein the magnetic material comprises a nickel alloy.
30. The package according to any of claims 10 to 29, wherein the magnetic material comprises cobalt-copper, cobalt-nickel, or cobalt-phosphorous.
31. The package according to any of claims 10 to 30, wherein the magnetic material comprises cobalt-nickel-phosphorous or cobalt-nickel-phosphorous with a mixture of the HCP structure and the FCC structure.
32. The package according to any of claims 10 to 31, wherein the magnetic material comprises a ferrite (NiFe_2O_4) film having a cubic structure.
33. The package according to any of claims 10 to 32, wherein the magnetic material comprises a garnet film ($\text{Y}_3\text{Fe}_5\text{O}_{12}$) having a cubic structure.
34. The package according to any of claims 10 to 33, wherein the magnetic material comprises a NiFe with a ratio of about 45%/55% and a permeability up to about 1300.
35. The package according to any of claims 10 to 34, wherein the magnetic material comprises $\text{Ni}_{81}\text{Fe}_{17}\text{Cu}_{1.5}\text{Mo}_{0.5}$ spherical particles having a particle diameter in a range of 2 micrometers (μm) to about 20 μm in a polymer matrix.

36. The package according to any of claims 10 to 35, wherein the magnetic material comprises a polycrystalline or monocrystal-line layer of a ferromagnetic metal, alloy, or magnetic oxide about 0.01 μm to about 10 μm thick.

37. A method of forming a package, comprising:

drilling a blind hole into a non-magnetic core of an inductor; and

depositing magnetic material into the blind hole positioned within the non-magnetic core, the inductor being embedded within a substrate of the package, and the magnetic material comprising discrete magnetic particles.

38. A package, comprising:

a die including an integrated voltage regulator;

a package substrate electrically coupled to the die; and

an interposer electrically coupled to the package substrate and a printed circuit board,

an inductor embedded within at least one of the package substrate or the interposer, the inductor comprising a non-magnetic core filled with magnetic material.

39. The package of claim 38, wherein the magnetic materials are magnetically aligned.

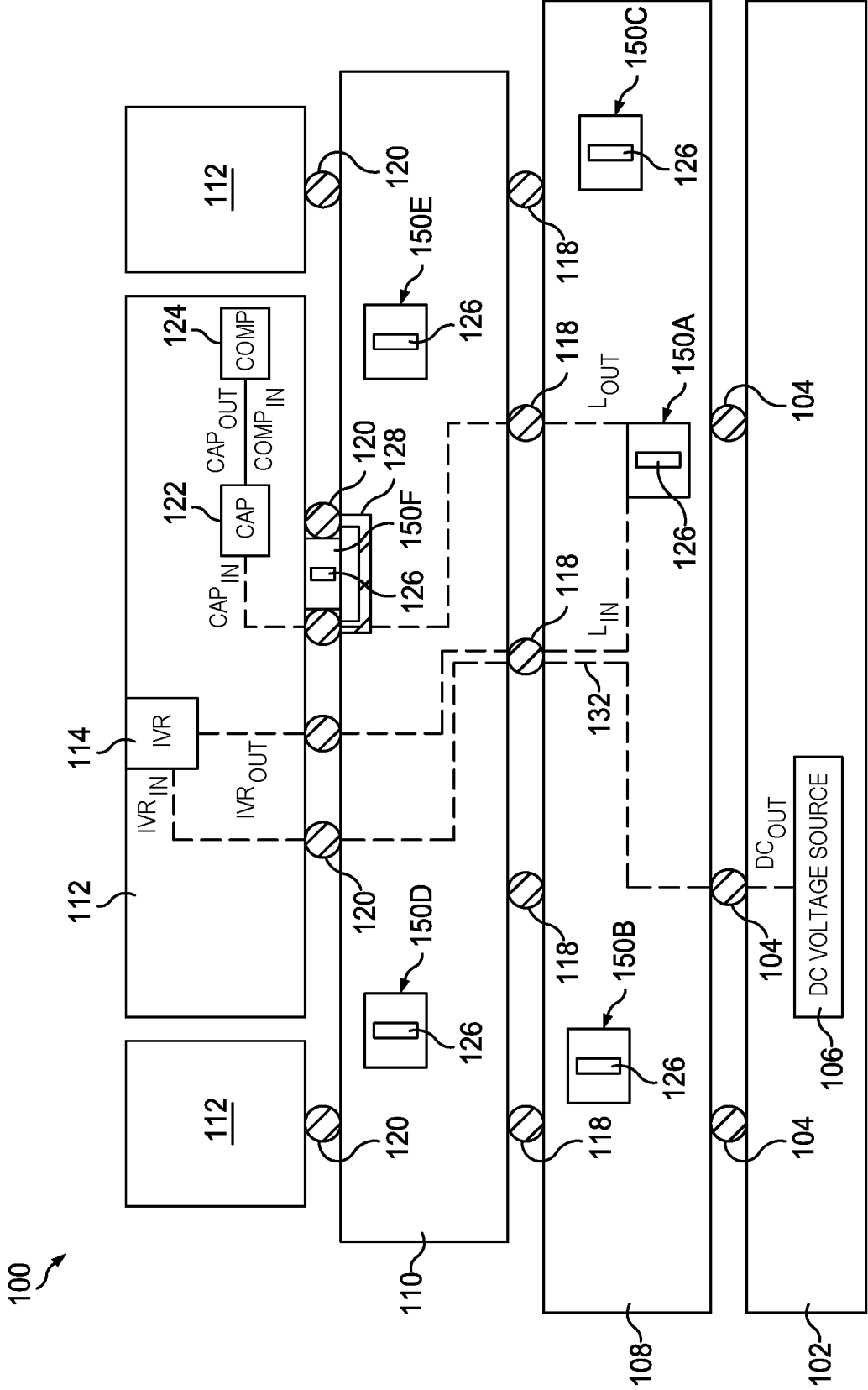


FIG. 1A

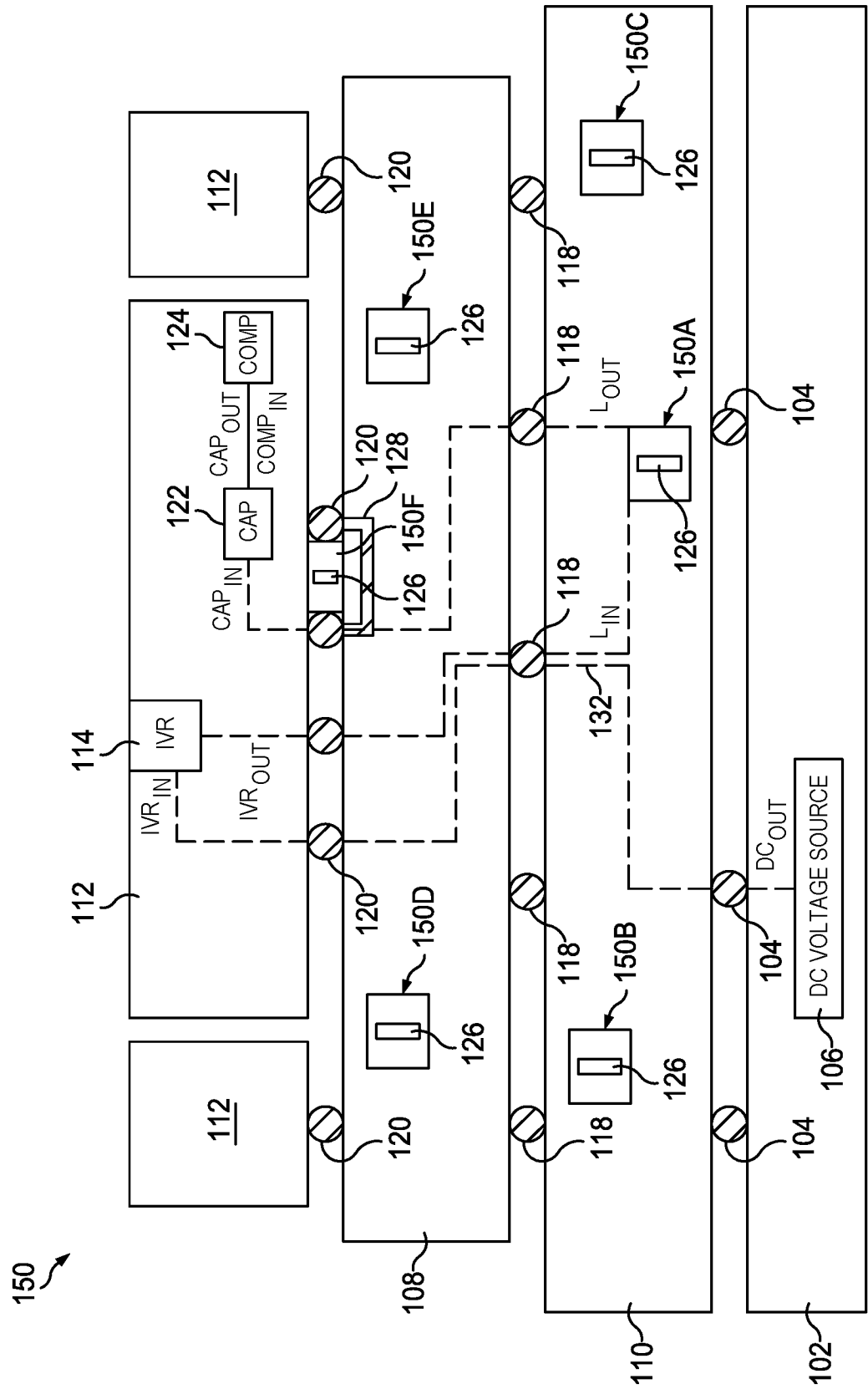


FIG. 1B

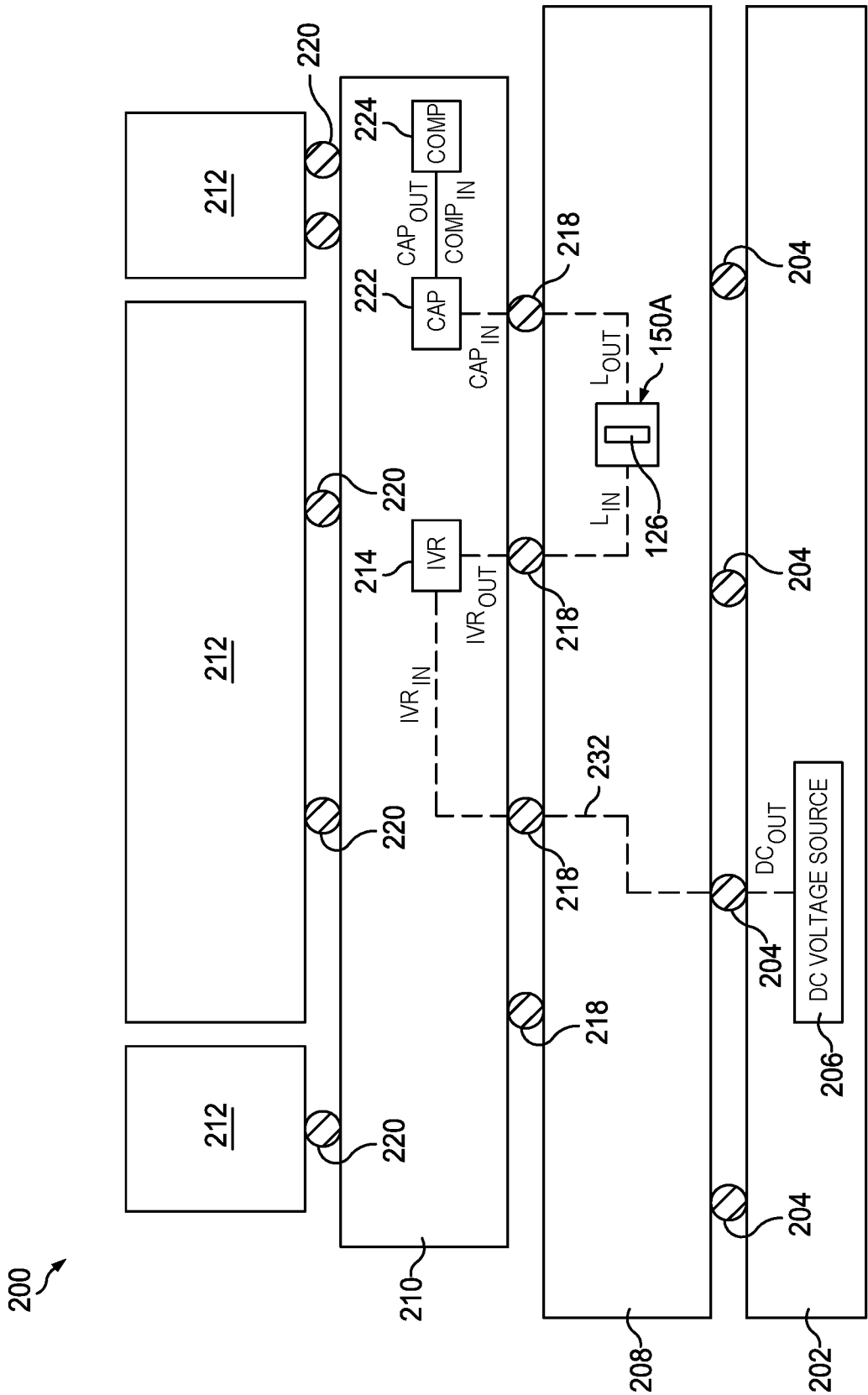
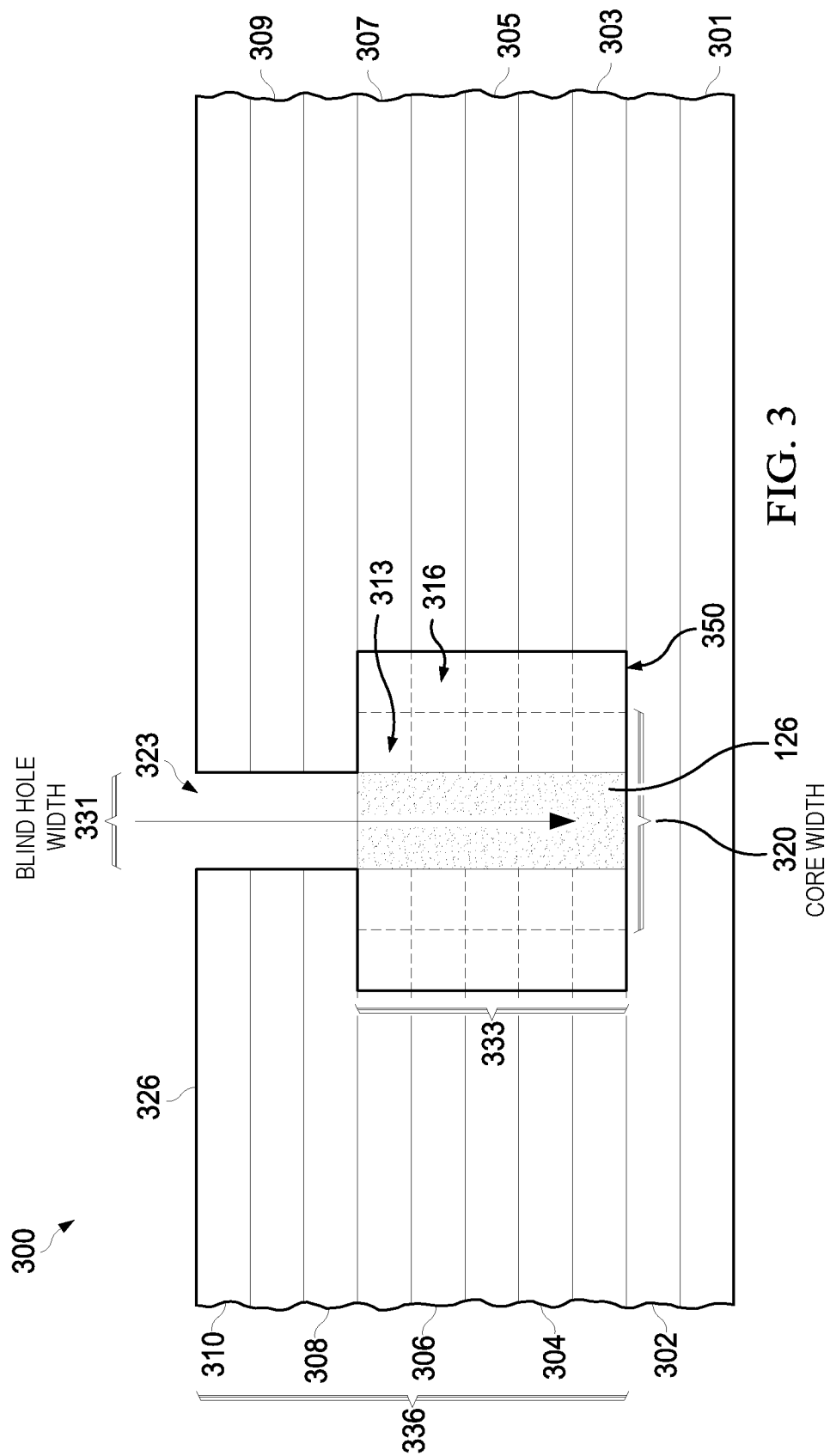


FIG. 2



5/8

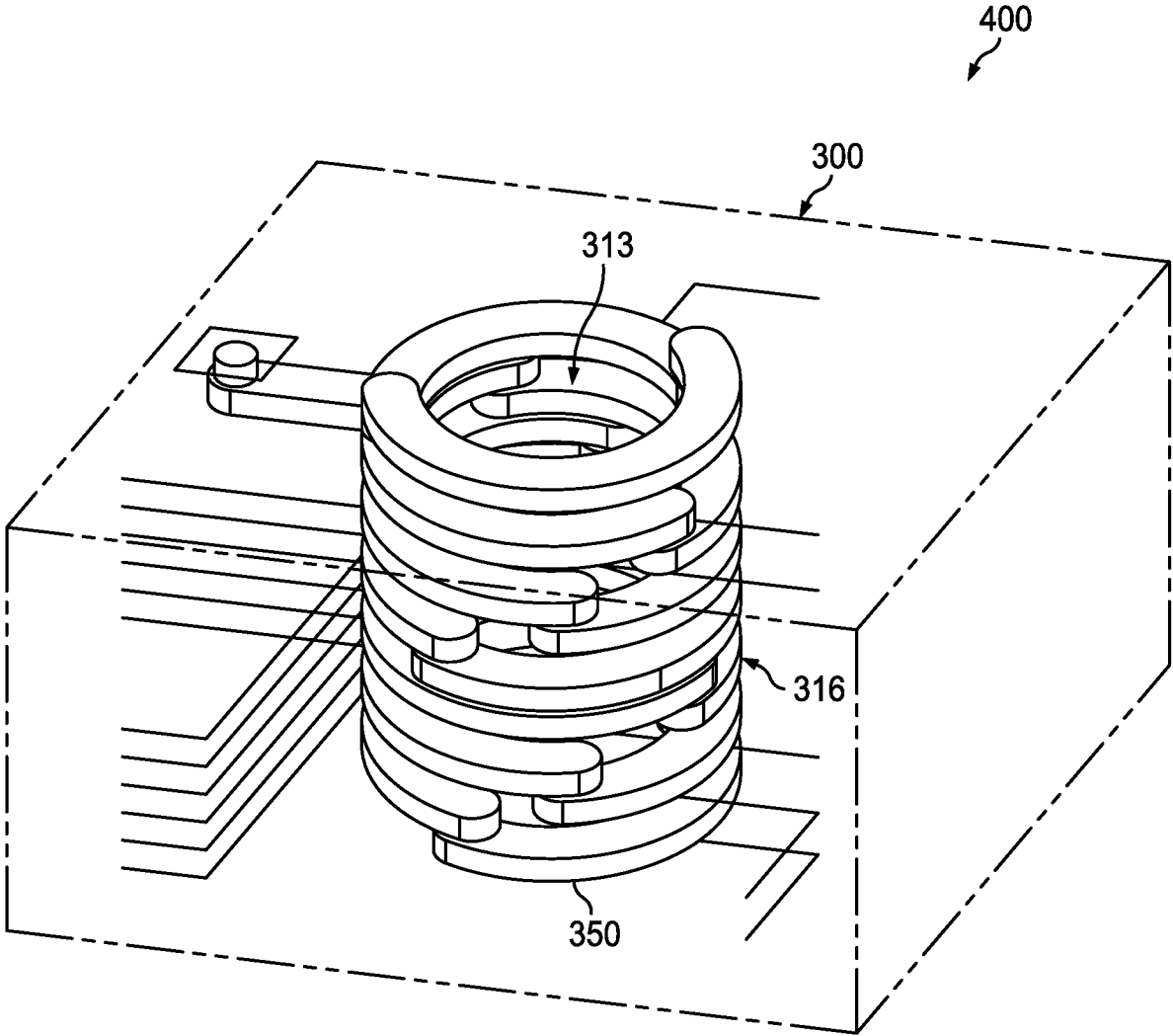


FIG. 4A

6/8

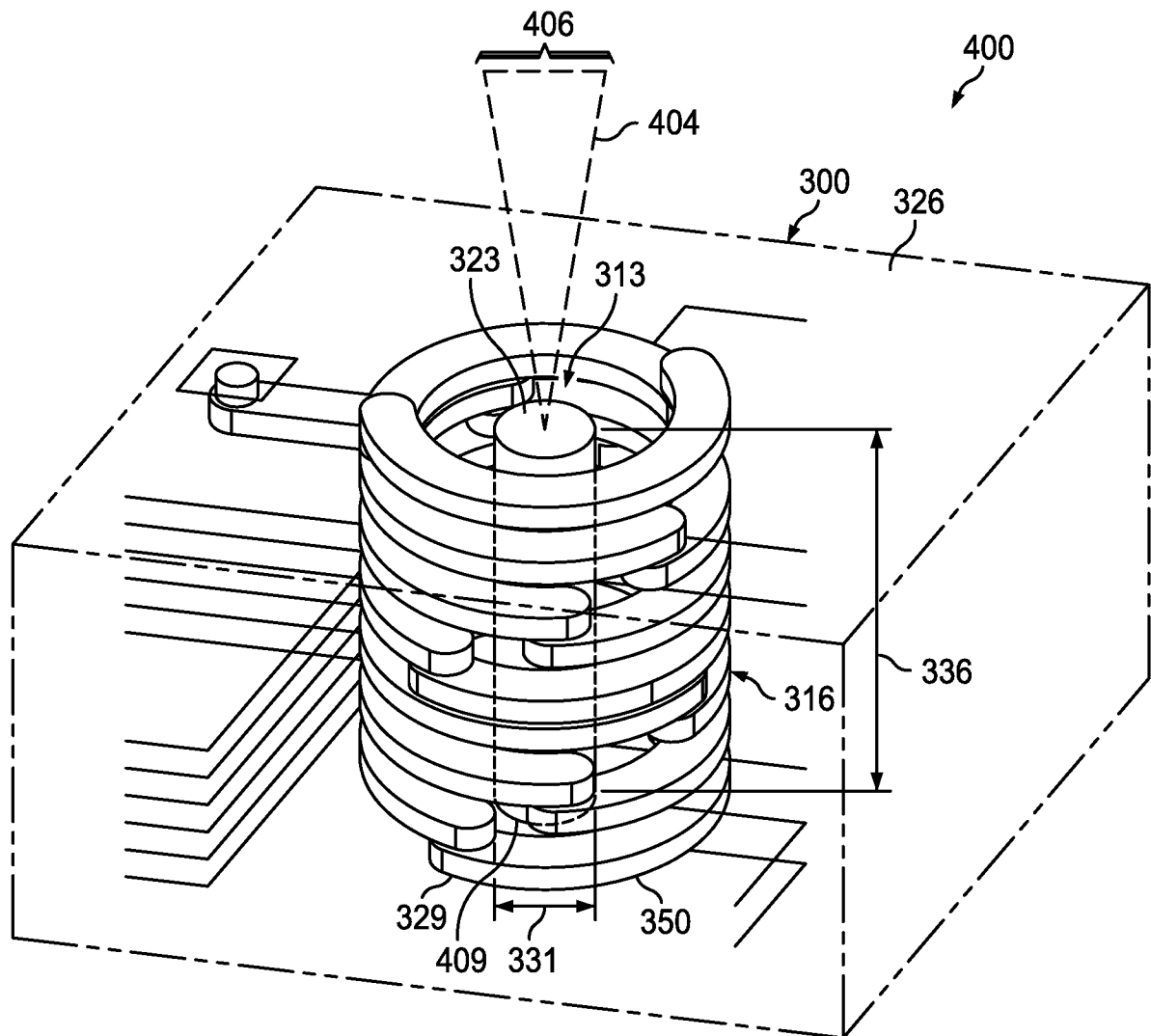


FIG. 4B

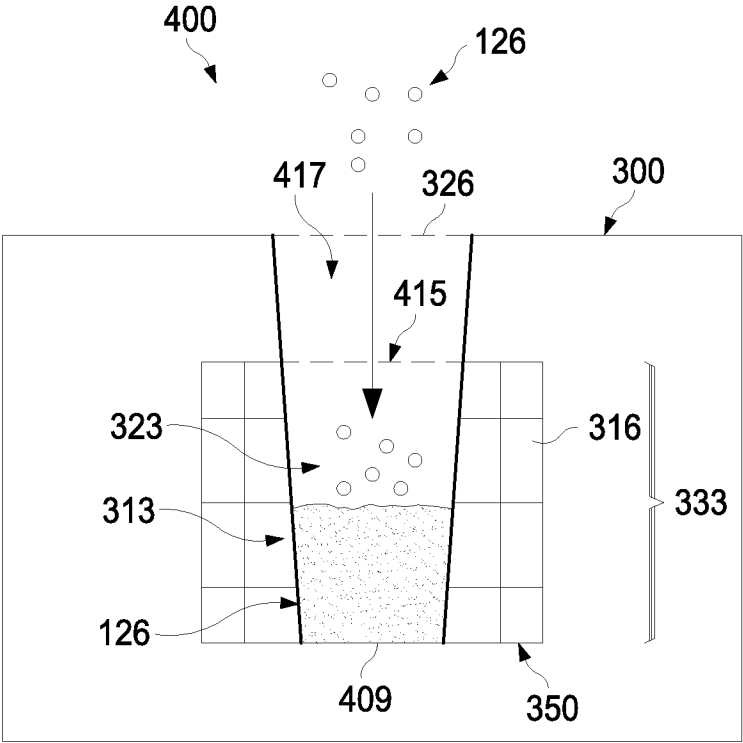


FIG. 4C

8/8

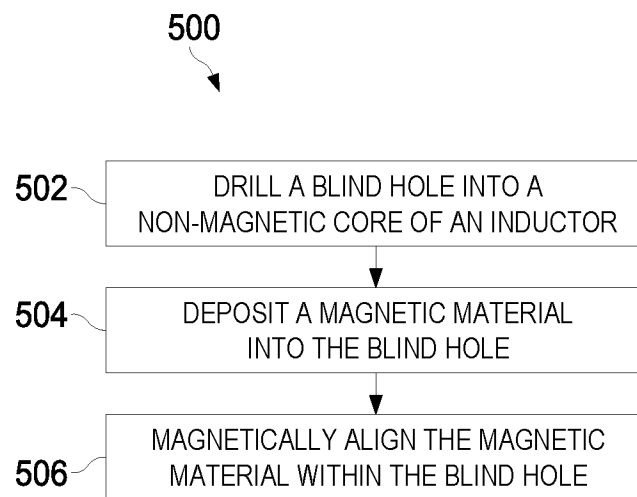


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2019/031334

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01L21/48 H01L23/498
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01L H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2019/066868 A1 (INTEL CORP [US]) 4 April 2019 (2019-04-04) figure 10	10-36, 38,39
A	----- Anonymous: "Magnetic core - Wikipedia", Wikipedia, 5 June 2017 (2017-06-05), pages 1-8, XP055514410, Retrieved from the Internet: URL:https://en.wikipedia.org/w/index.php?t itle=Magnetic_core&oldid=783992097#Sendust , KoolMU [retrieved on 2018-10-11] page 1 - page 4	11-36
A	----- US 2006/044101 A1 (FRUTSCHY KRISTOPHER J [US] ET AL) 2 March 2006 (2006-03-02) figures 1-9 -----	1-39



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

22 January 2020

Date of mailing of the international search report

18/02/2020

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Kästner, Martin

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2019/031334

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2019066868	A1	04-04-2019	NONE

US 2006044101	A1	02-03-2006	NONE
