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(54) **LAMINATED MAGNETIC INDUCTOR STACK WITH HIGH FREQUENCY PEAK QUALITY FACTOR**

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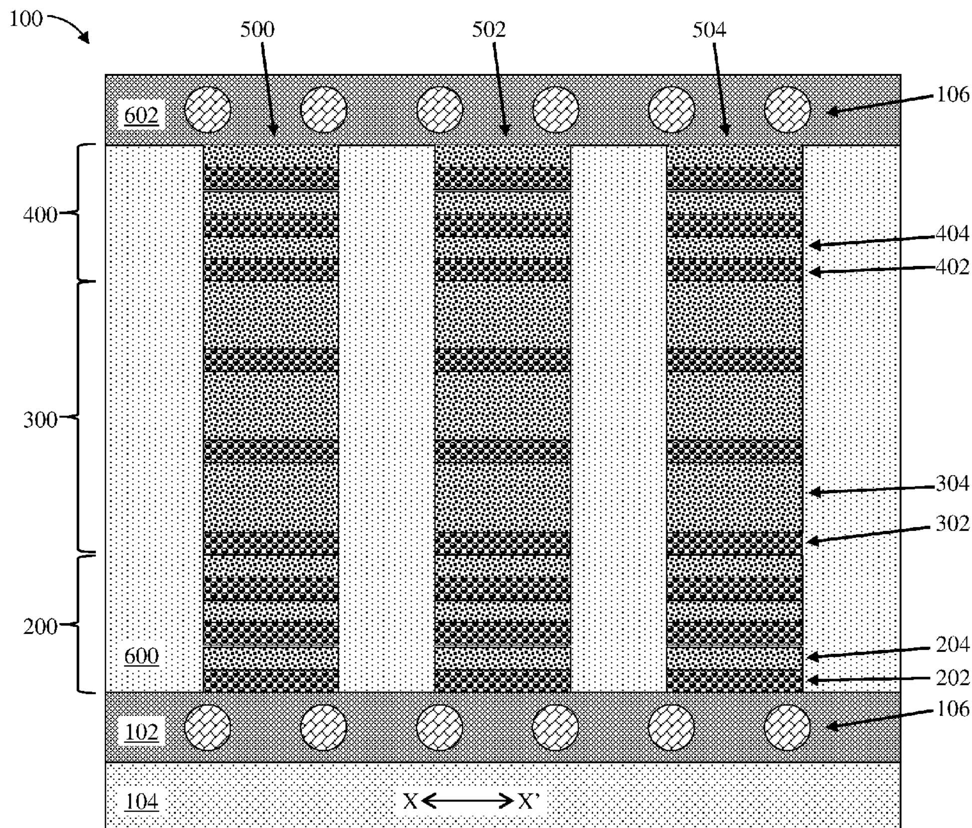
(57) **ABSTRACT**

Embodiments are directed to a method of forming a magnetic stack arrangement of a laminated magnetic inductor having a high frequency peak quality factor (Q). A first magnetic stack is formed having one or more magnetic layers alternating with one or more insulating layers in a first inner region of a laminated magnetic inductor. A second magnetic stack is formed opposite a surface of the first magnetic stack in an outer region of the laminated magnetic inductor. A third magnetic stack is formed opposite a surface of the second magnetic stack in a second inner region of the laminated magnetic inductor. The insulating layers are formed such that a thickness of an insulating layer in the second magnetic stack is greater than a thickness of an insulating layer in the first magnetic stack.



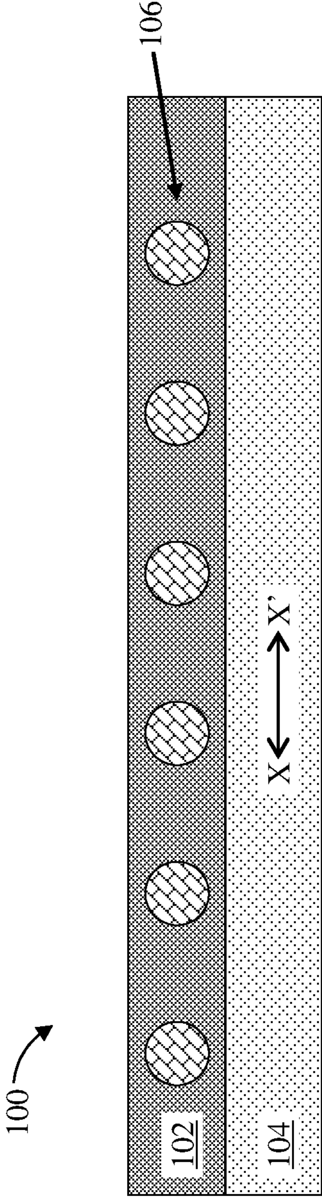


Fig. 1

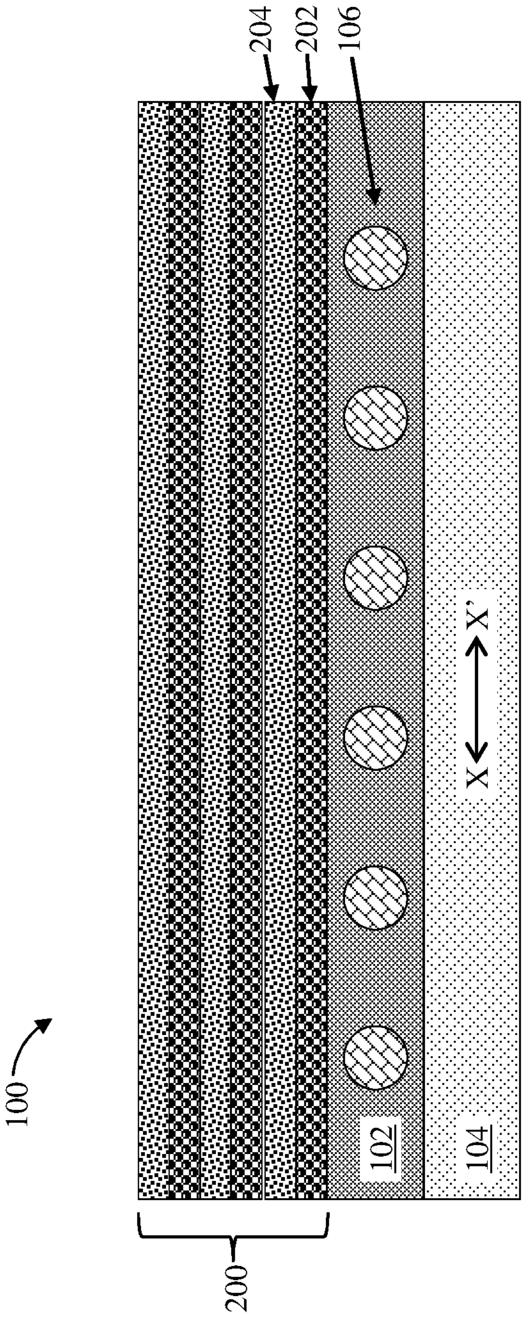


Fig. 2

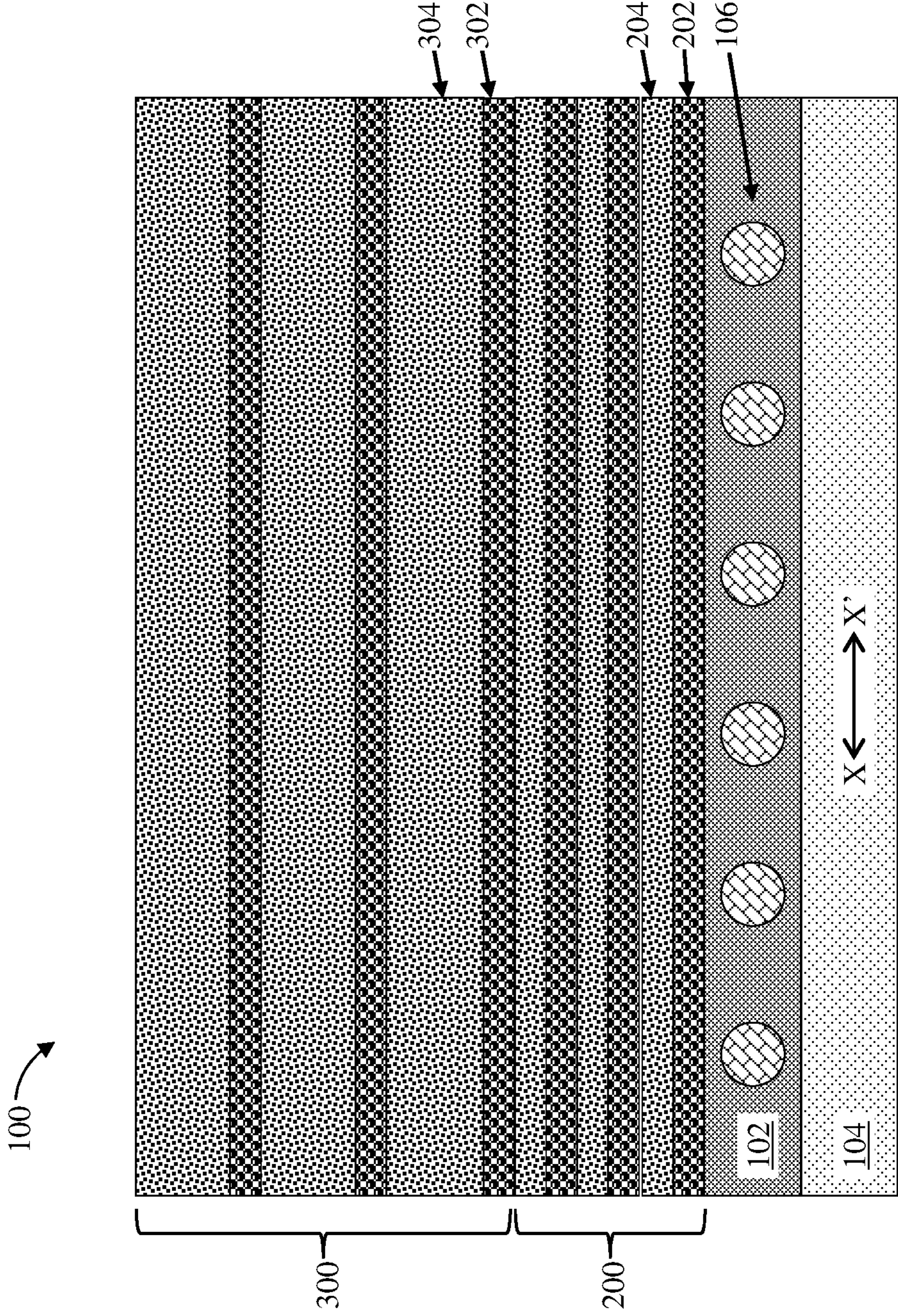


Fig. 3

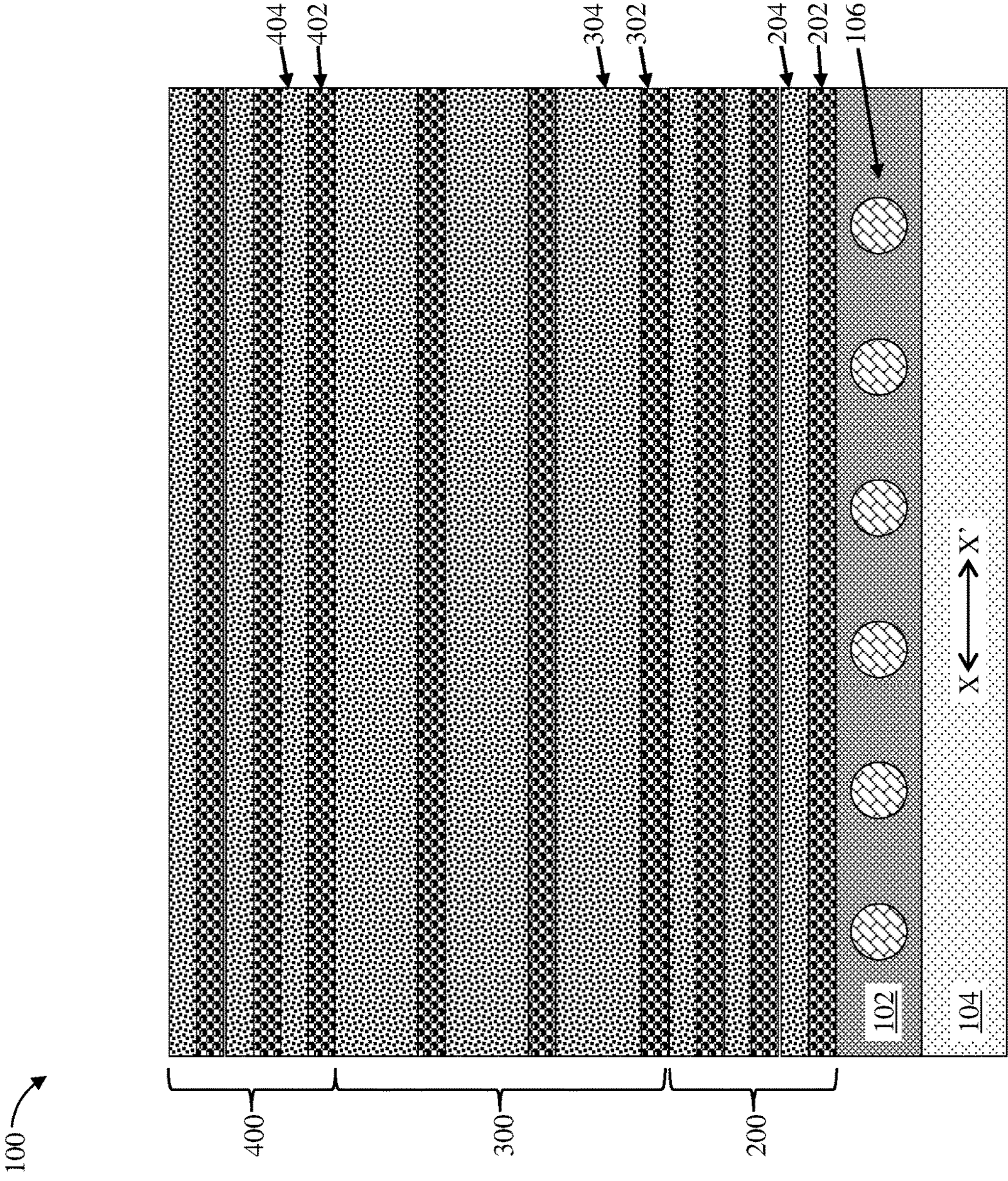


Fig. 4

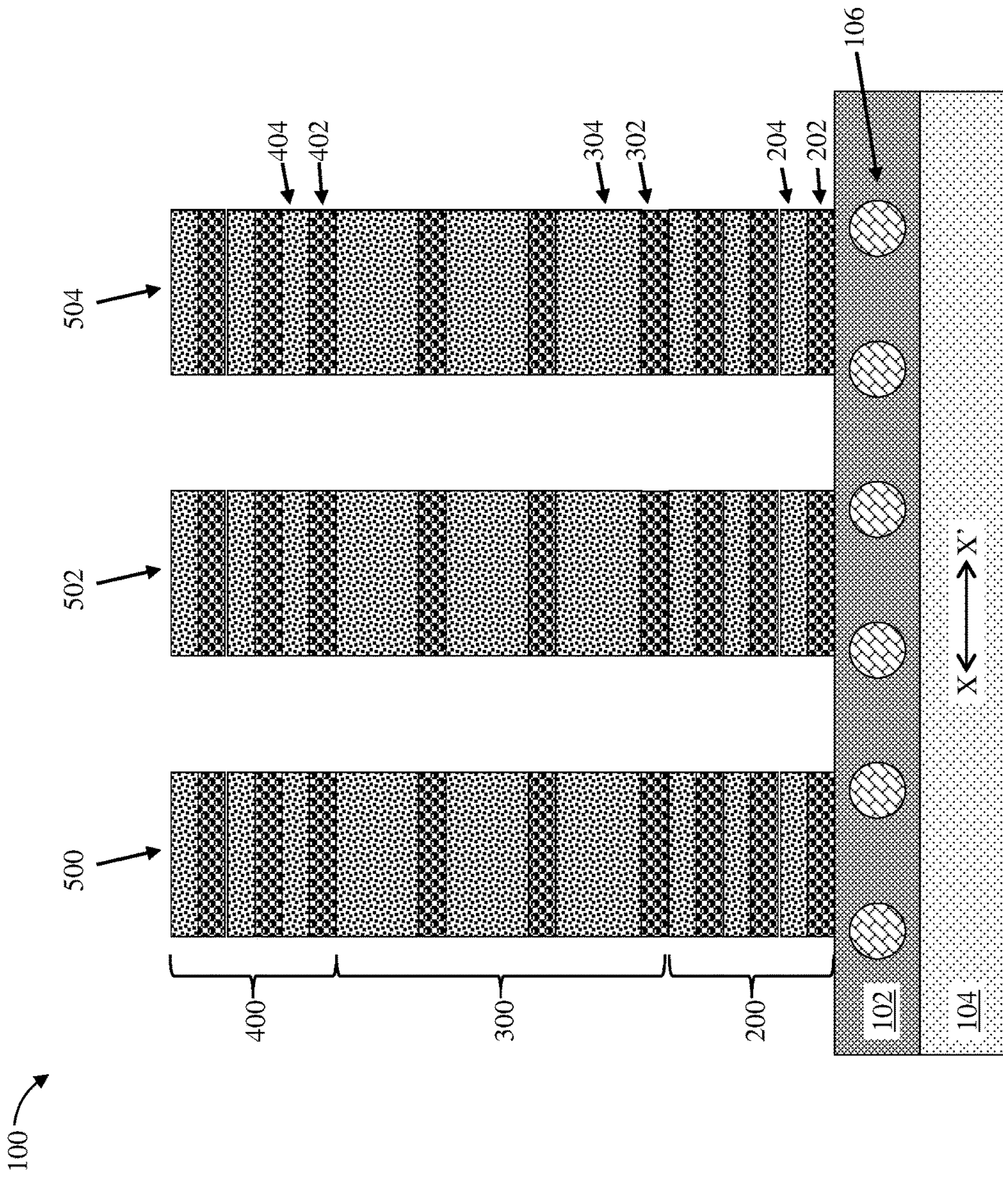


Fig. 5

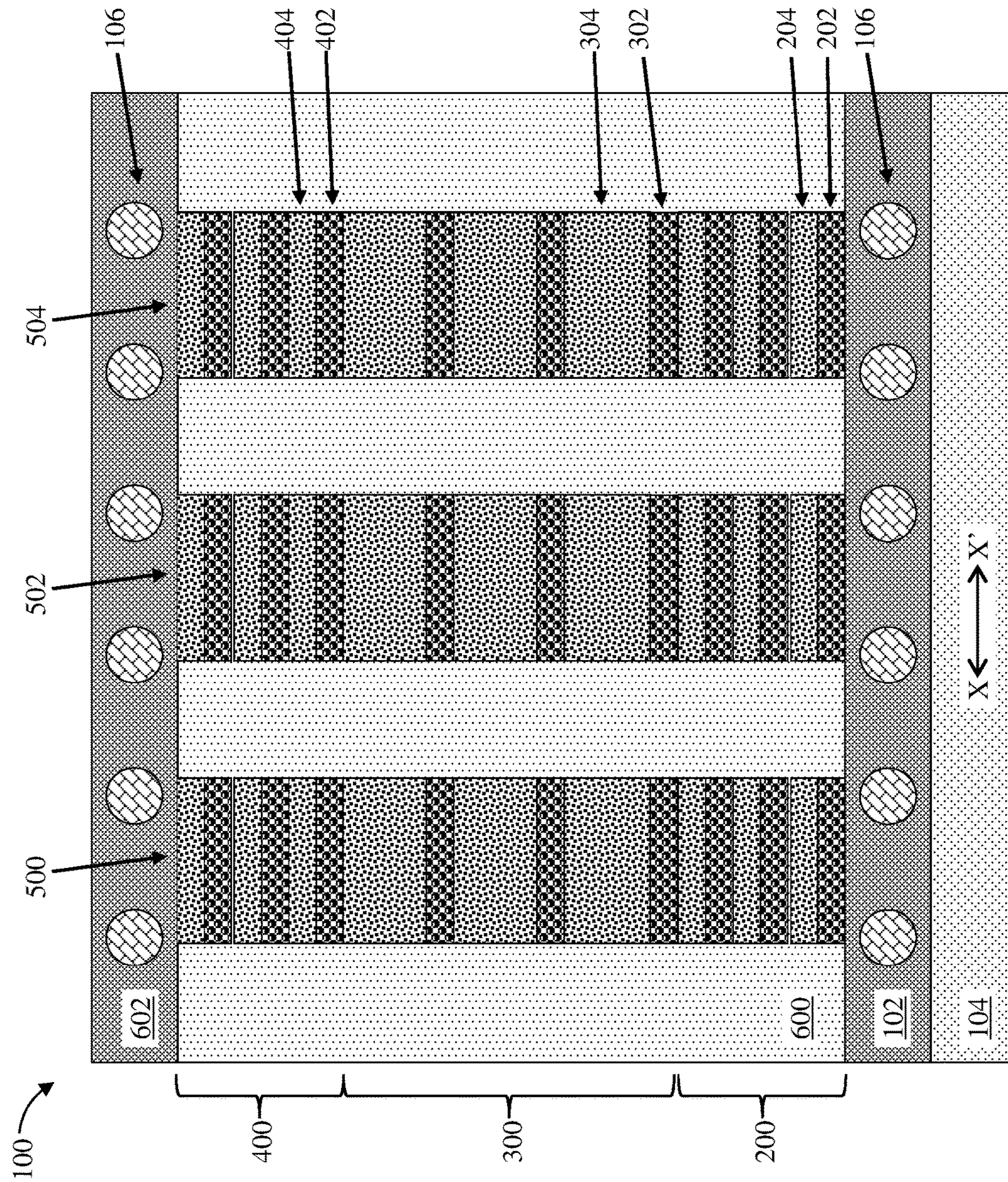


Fig. 6

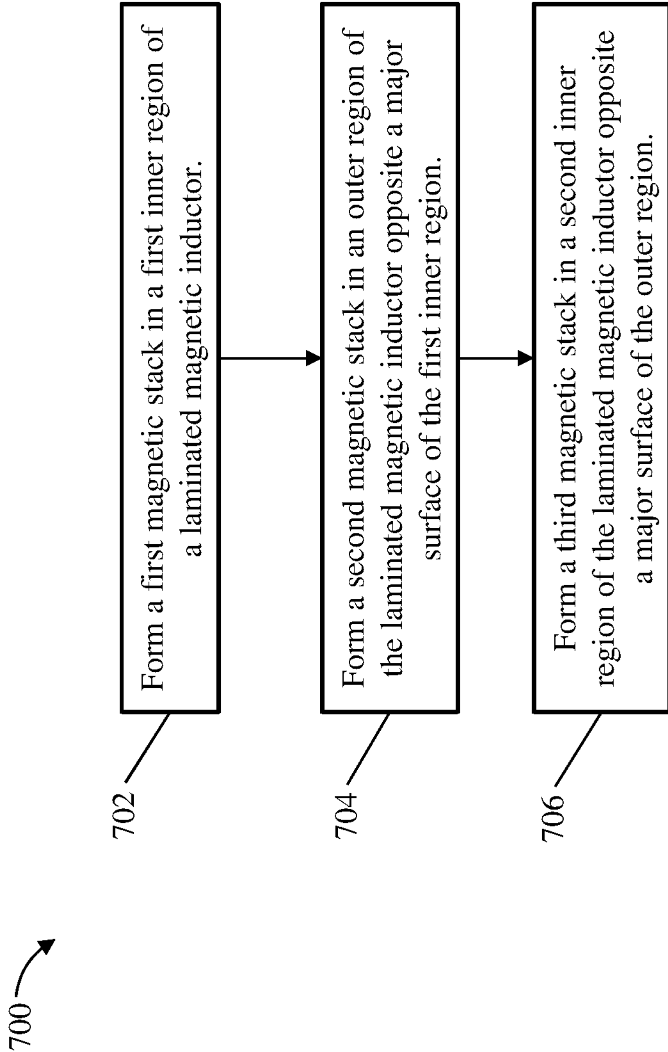


Fig. 7

LAMINATED MAGNETIC INDUCTOR STACK WITH HIGH FREQUENCY PEAK QUALITY FACTOR

BACKGROUND

[0001] The present invention generally relates to fabrication methods and resulting structures for on-chip magnetic devices. More specifically, the present invention relates to on-chip magnetic structures, e.g., a laminated magnetic inductor stack, having a high frequency peak quality factor.

[0002] Inductors, resistors, and capacitors are the main passive elements constituting an electronic circuit. Inductors are used in circuits for a variety of purposes, such as in noise reduction, inductor-capacitor (LC) resonance calculators, and power supply circuitry. Inductors can be classified as one of various types, such as a winding-type inductor or a laminated film-type inductor. Winding-type inductors are manufactured by winding a coil around, or printing a coil on, a ferrite core. Laminated film-type inductors are manufactured by stacking alternating magnetic or dielectric materials to form laminated stacks.

[0003] Among the various types of inductors the laminated film-type inductor is widely used in power supply circuits requiring miniaturization and high current due to the reduced size and improved inductance per coil turn of these inductors relative to other inductor types. A known laminated inductor configuration includes one or more magnetic or dielectric layers laminated with conductive patterns. The conductive patterns are sequentially connected by a conductive via formed in each of the layers and overlapped in a laminated direction to form a spiral-structured coil. Typically, both ends of the coil are drawn out to an outer surface of a laminated body for connection to external terminals.

SUMMARY

[0004] Embodiments of the present invention are directed to a method for fabricating a magnetic stack arrangement of a laminated magnetic inductor. A non-limiting example of the method includes forming a first magnetic stack having one or more magnetic layers alternating with one or more insulating layers in a first region of a laminated magnetic inductor. A second magnetic stack is formed having one or more magnetic layers alternating with one or more insulating layers opposite a surface of the first magnetic stack in an outer region of the laminated magnetic inductor. A third magnetic stack is formed having one or more magnetic layers alternating with one or more insulating layers opposite a surface of the second magnetic stack in a second inner region of the laminated magnetic inductor. The insulating layers are formed such that a thickness of an insulating layer in the second magnetic stack is greater than a thickness of an insulating layer in the first magnetic stack.

[0005] Embodiments of the present invention are directed to a method for fabricating a magnetic stack arrangement of a laminated magnetic inductor. A non-limiting example of the method includes forming a first insulating layer proximate to a conductive coil of the laminated magnetic inductor. A second insulating layer is formed proximate to the conductive coil opposite a surface of the first insulating layer. A third insulating layer is formed between the first and second insulating layers such that the third insulating layer is further from the conductive coil than either the first insulating layer or the second insulating layer. The insulating layers are formed such that a thickness of the third insulating layer is greater than a thickness of either the first or second insulating layers.

[0006] Embodiments of the present invention are directed to a laminated magnetic inductor. A non-limiting example of the laminated magnetic inductor includes a first inner region having one or more magnetic layers alternating with one or more insulating layers. An outer region having one or more magnetic layers alternating with one or more insulating layers is formed opposite a surface of the first inner region. A second inner region having one or more magnetic layers alternating with one or more insulating layers is formed opposite a surface of the outer region. The insulating layers are formed such that a thickness of an insulating layer in the outer region is greater than a thickness of an insulating layer in either the first or second inner regions.

[0007] Additional technical features and benefits are realized through the techniques of the present invention. Embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed subject matter. For a better understanding, refer to the detailed description and to the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The specifics of the exclusive rights described herein are particularly pointed out and distinctly claimed in the claims at the conclusion of the specification.

[0009] The foregoing and other features and advantages of the embodiments of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

[0010] FIG. **1** depicts a laminated magnetic inductor after a fabrication operation according to embodiments of the invention;

[0011] FIG. **2** depicts a laminated magnetic inductor after a fabrication operation according to embodiments of the invention;

[0012] FIG. **3** depicts a laminated magnetic inductor after a fabrication operation according to embodiments of the invention;

[0013] FIG. **4** depicts a laminated magnetic inductor after a fabrication operation according to embodiments of the invention;

[0014] FIG. **5** depicts a laminated magnetic inductor after a fabrication operation according to embodiments of the invention;

[0015] FIG. **6** depicts a laminated magnetic inductor after a fabrication operation according to embodiments of the invention; and

[0016] FIG. **7** depicts a flow diagram illustrating a method according to one or more embodiments of the invention.

[0017] The diagrams depicted herein are illustrative. There can be many variations to the diagram or the operations described therein without departing from the spirit of the invention. For instance, the actions can be performed in a differing order or actions can be added, deleted or modified.

[0018] In the accompanying figures and following detailed description of the disclosed embodiments, the various elements illustrated in the figures are provided with two or three digit reference numbers. With minor exceptions, the leftmost digit(s) of each reference number correspond to the figure in which its element is first illustrated.

DETAILED DESCRIPTION

[0019] For the sake of brevity, conventional techniques related to semiconductor device and integrated circuit (IC) fabrication may or may not be described in detail herein. Moreover, the various tasks and process steps described herein can be incorporated into a more comprehensive procedure or process having additional steps or functionality not described in detail herein. In particular, various steps in the manufacture of laminated inductor devices are well known and so, in the interest of brevity, many conventional steps will only be mentioned briefly herein or will be omitted entirely without providing the well-known process details.

[0020] Turning now to an overview of technologies that are more specifically relevant to aspects of the invention, as previously noted herein, laminated film-type inductors offer reduced size and improved inductance per coil turn relative to other inductor types. For this reason, laminated film-type inductors are widely used in applications requiring miniaturization and high current, such as power supply circuitry. The integration of inductive power converters onto silicon is one path to reducing the cost, weight, and size of electronic devices.

[0021] Laminated film-type inductor performance can be improved by adding layers of magnetic film. There are two basic laminated film-type magnetic inductor configurations: the closed yoke type laminated inductor and the solenoid type laminated inductor. The closed yoke type laminated inductor includes a metal core (typically a copper wire) and magnetic material wrapped around the core. Conversely, the solenoid type laminated inductor includes a magnetic material core and a conductive wire (e.g., copper wire) wrapped around the magnetic material. Both the closed yoke type laminated inductor and the solenoid type laminated inductor benefit by having very thick magnetic stacks or yokes (e.g., magnetic layers having a thickness of greater than about 50 nm). Thick magnetic layers offer faster throughput and are significantly more efficient to deposit. There are challenges, however, in providing laminated film-type inductor architectures having thick magnetic layers.

[0022] One such challenge is addressing the increased loss in energy due to the powerful eddy currents associated with inductors having multiple dielectric layer thicknesses. Eddy currents (also known as Foucault currents) are loops of electrical current induced by a changing magnetic field in a conductor. Eddy currents flow in closed loops within conductors in a plane perpendicular to the magnetic field. Eddy currents are created when the time varying magnetic fields in the magnetic layers create an electric field that drives a circular current flow. These losses can be substantial and increase with the thickness of the magnetic layers.

[0023] The magnetic loss caused by eddy currents in a thick film inductor is largest in the region of the inductor where the coil is in close proximity to the magnetic material. Specifically, magnetic layers closer to the coil (that is, the "inner layers") have larger losses than magnetic layers further from the coil (the "outer layers"). Moreover, magnetic flux densities in the space occupied by inner layers are generally higher than those characterizing the outer layers due to the magnetic reluctance of the insulating layers (also called spacer layers) interposed between the winding and the outer layers. Due to these relatively large magnetic flux densities in the space occupied by the inner layers, the inner layers tend to magnetically saturate at lower drive currents and have greater losses than the outer layers. Accordingly, the inner layer region is a critical region—the losses in this critical region dominate the overall losses of the inductor.

[0024] As magnetic film thicknesses increase, the eddy currents become severe enough to degrade the quality factor (also known as "Q") of the inductor. The quality factor of an inductor is the ratio of its inductive reactance to its resistance at a given frequency, and is a measure of its efficiency. The maximum attainable quality factor for a given inductor across all frequencies is known as peak Q (or maximum Q). Some applications can require the peak Q to be at a low frequency and other applications can require the peak Q to be at a high frequency.

[0025] Turning now to an overview of the aspects of the invention, one or more embodiments of the invention address the above-described shortcomings by providing methods of fabricating a laminated magnetic inductor having a high frequency peak Q. The frequency at which peak Q occurs for a given inductor is, in general, inversely proportional to permeability. Permeability (μ) is the degree of magnetization that a material obtains in response to an applied magnetic field. Incorporating materials with high permeability in an inductor increases losses and shifts the frequency of peak Q to a higher frequency.

[0026] By patterning specific regions of the inductor into laminations having thin or thick dielectric layers the frequency of peak Q can be adjusted. In particular, inner regions of the inductor (i.e., those critical regions proximate to the conductive coil) are patterned with laminations having thin dielectric layers to increase the effective permeability of the inner layers and to shift the frequency of peak Q to a higher frequency. In this manner, eddy current losses in the critical regions of the inductor are leveraged to modulate the frequency of peak Q. The outer regions of the inductor (i.e., those regions positioned farther away from the conductive coil than the inner regions) are patterned with laminations having thick dielectric layers. Patterning the outer layers with thick dielectric layers decreases the effective permeability of these layers and reduces losses.

[0027] Turning now to a more detailed description of aspects of the present invention, FIG. **1** depicts a cross-sectional view of a structure **100** along a direction X-X' having a dielectric layer **102** (also referred to as a bottom dielectric layer) formed opposite a surface of a substrate **104** during an intermediate operation of a method of fabricating a semiconductor device according to embodiments of the invention. The dielectric layer **102** can be any suitable material, such as, for example, a low-k dielectric, silicon nitride (SiN), silicon dioxide (SiO_2), silicon oxynitride (SiON), and silicon oxycarbonitride (SiOCN). Any known manner of forming the dielectric layer **102** can be utilized. In some embodiments, the dielectric layer **102** is SiO_2 conformally formed on exposed surfaces of the substrate **104** using a conformal deposition process such as PVD, CVD, plasma-enhanced CVD (PECVD), or a combination thereof. In some embodiments, the dielectric layer **102** is conformally formed to a thickness of about 50 nm to about 400 nm, although other thicknesses are within the contemplated scope of embodiments of the invention.

[0028] The substrate **104** can be a wafer and can have undergone known semiconductor front end of line processing (FEOL), middle of the line processing (MOL), and back end of the line processing (BEOL). FEOL processes can include, for example, wafer preparation, isolation, well formation, gate patterning, spacer, extension and source/

drain implantation, and silicide formation. The MOL can include, for example, gate contact formation, which can be an increasingly challenging part of the whole fabrication flow, particularly for lithography patterning. In the BEOL, interconnects can be fabricated with, for example, a dual damascene process using PECVD deposited interlayer dielectric (ILDs), PVD metal barriers, and electrochemically plated conductive wire materials. The substrate **104** can include a bulk silicon substrate or a silicon on insulator (SOI) wafer. The substrate **104** can be made of any suitable material, such as, for example, Ge, SiGe, GaAs, InP, AlGaAs, or InGaAs.

[0029] A conductive coil **106** is formed in the dielectric layer **102** and a dielectric layer **600** (depicted in FIG. **6**) and helically around portions of the structure **100**. The conductive coil **106** can be formed by, for example, depositing copper lines in the dielectric layer **102**, forming vias on top of the copper lines, and then depositing coper lines on top of the vias in the dielectric layer **600**. For ease of discussion reference is made to operations performed on and to a conductive coil **106** having six turns or windings formed in the dielectric layer **102** (e.g., the conductive coil **106** wraps through the dielectric layer **102** a total of six times). It is understood, however, that the dielectric layer **102** can include any number of windings. For example, the dielectric layer **102** can include a single winding, 2 windings, 5 windings, 10 windings, or 20 windings, although other winding counts are within the contemplated scope of embodiments of the invention. The conductive coil **106** can be made of any suitable conducting material, such as, for example, metal (e.g., tungsten, titanium, tantalum, ruthenium, zirconium, cobalt, copper, aluminum, lead, platinum, tin, silver, gold), conducting metallic compound material (e.g., tantalum nitride, titanium nitride, tantalum carbide, titanium carbide, titanium aluminum carbide, tungsten silicide, tungsten nitride, ruthenium oxide, cobalt silicide, nickel silicide), carbon nanotube, conductive carbon, graphene, or any suitable combination of these materials.

[0030] FIG. **2** depicts a cross-sectional view of the structure **100** along the direction X-X' after forming a first inner layer region **200** opposite a surface of the dielectric layer **102** during an intermediate operation of a method of fabricating a semiconductor device according to embodiments of the invention. The first inner layer region **200** (also referred to as a magnetic stack) includes one or more inner magnetic layers (e.g., inner magnetic layer **202**) alternating with one or more insulating layers (e.g., insulating layer **204**). The first inner layer region **200** is formed by depositing alternating magnetic and insulating layers. For ease of discussion the first inner layer region **200** is depicted as having three inner magnetic layers alternating with three insulating layers. It is understood, however, that the first inner layer region **200** can include any number of inner magnetic layers alternating with a corresponding number of insulating layers. For example, the first inner layer region **200** can include a single inner magnetic layer, two inner magnetic layers, five inner magnetic layers, eight inner magnetic layers, or any number of inner magnetic layers, along with a corresponding number of insulating layers (i.e., as appropriate to form an inner layer region having a topmost insulating layer on a topmost inner magnetic layer and an insulating layer between each pair of adjacent inner magnetic layers).

[0031] The inner magnetic layer **202** can be made of any suitable magnetic material known in the art, such as, for example, a ferromagnetic material, soft magnetic material, iron alloy, nickel alloy, cobalt alloy, ferrites, plated materials such as permalloy, or any suitable combination of these materials. In some embodiments, the inner magnetic layer **202** includes a Co containing magnetic material, FeTaN, FeNi, FeAlO, or combinations thereof. Any known manner of forming the inner magnetic layer **202** can be utilized. The inner magnetic layer **202** can be deposited through vacuum deposition technologies (i.e., sputtering) or electrodepositing through an aqueous solution. In some embodiments, the inner magnetic layer **202** is conformally formed on exposed surfaces of the dielectric layer **102** using a conformal deposition process such as PVD, CVD, PECVD, or a combination thereof. In some embodiments, the inner magnetic layer **202** is conformally formed to a thickness of about 50 nm to about 500 nm, although other thicknesses are within the contemplated scope of embodiments of the invention.

[0032] The insulating layer **204** serves to isolate the adjacent magnetic material layers from each other in the stack and can be made of any suitable non-magnetic insulating material known in the art, such as, for example, aluminum oxides (e.g., alumina), silicon oxides (e.g., SiO_2), silicon nitrides, silicon oxynitrides (SiO_xN_y), polymers, magnesium oxide (MgO), or any suitable combination of these materials. Any known manner of forming the insulating layer **204** can be utilized. In some embodiments, the insulating layer **204** is conformally formed on exposed surfaces of the inner magnetic layer **202** using a conformal deposition process such as PVD, CVD, PECVD, or a combination thereof.

[0033] As discussed previously herein, the target thickness of the insulating layers in the first inner layer region **200** (e.g., insulating layer **204**) is adjusted to increase the effective permeability of the inner layers and to shift the frequency of peak Q to a higher frequency. The insulating layer **204** is conformally formed to a relatively thin thickness (i.e., a thickness of about 0.5 nm to about 20 nm, although other thicknesses are within the contemplated scope of embodiments of the invention) to increase losses and to shift the frequency of peak Q to a higher frequency. In some embodiments, the thickness of the insulating layer **204** can be 0.5 nm, 1 nm, 2 nm, 3 nm, 4 nm, 5 nm, 10 nm, 15 nm, and 20 nm.

[0034] FIG. **3** depicts a cross-sectional view of the structure **100** along the direction X-X' after forming an outer layer region **300** opposite a surface of the first inner layer region **200** during an intermediate operation of a method of fabricating a semiconductor device according to embodiments of the invention. The outer layer region **300** includes one or more outer magnetic layers (e.g., outer magnetic layer **302**) alternating with one or more insulating layers (e.g., insulating layer **304**). The outer layer region **300** is formed in a similar manner as the first inner layer region **200**—by depositing alternating magnetic and insulating layers. For ease of discussion the outer layer region **300** is depicted as having three outer magnetic layers alternating with three insulating layers. It is understood, however, that the outer layer region **300** can include any number of outer magnetic layers alternating with a corresponding number of insulating layers. For example, the outer layer region **300** can include a single outer magnetic layer, two outer magnetic layers, five outer magnetic layers, eight outer magnetic layers, or any number of outer magnetic layers, along with a corresponding number of insulating layers (i.e., as appropriate to form

an outer layer region having a topmost insulating layer on a topmost outer magnetic layer and an insulating layer between each pair of adjacent outer magnetic layers). It is further understood that the outer layer region **300** can include a different number of magnetic layers than the first inner layer region **200**.

[0035] The outer magnetic layer **302** can be made of any suitable magnetic material and can be formed using any suitable process in a similar manner as the inner magnetic layer **202**. In some embodiments, the outer magnetic layer **302** is conformally formed to a thickness of about 50 nm to about 500 nm, although other thicknesses are within the contemplated scope of embodiments of the invention. The outer magnetic layer **302** can have a same thickness, a larger thickness, or a smaller thickness as the inner magnetic layer **202** in the first inner layer region **200**.

[0036] The insulating layer **304** can be made of any suitable non-magnetic insulating material and can be formed using any suitable process in a similar manner as the insulating layer **204**. As discussed previously herein, the insulating layer **304** in the outer layer region **300** is formed to a relatively large thickness (i.e., a thickness of at least 50 nm) to decrease the effective permeability of these layers and to reduce losses. In some embodiments, the insulating layer **204** is conformally formed to a thickness of about 100 nm to about 1 μm. The thickness of the insulating layer **304** in the outer layer region **300** is greater than the thickness of the insulating layer **204** in the first inner layer region **200**. In some embodiments, the thickness of the insulating layer **304** is two times, three times, four times, five times, ten times, twenty times, or fifty times the thickness of the insulating layer **204**, although other thicknesses are within the contemplated scope of embodiments of the invention.

[0037] FIG. **4** depicts a cross-sectional view of the structure **100** along the direction X-X' after forming a second inner layer region **400** opposite a surface of the outer layer region **300** during an intermediate operation of a method of fabricating a semiconductor device according to embodiments of the invention. The second inner layer region **400** includes one or more outer magnetic layers (e.g., second inner magnetic layer **402**) alternating with one or more insulating layers (e.g., insulating layer **404**). The second inner layer region **400** is formed in a similar manner as the first inner layer region **200**—by depositing alternating magnetic and insulating layers. For ease of discussion the second inner layer region **400** is depicted as having three outer magnetic layers alternating with three insulating layers. It is understood, however, that the second inner layer region **400** can include any number of outer magnetic layers alternating with a corresponding number of insulating layers. For example, the second inner layer region **400** can include a single outer magnetic layer, two outer magnetic layers, five outer magnetic layers, eight outer magnetic layers, or any number of outer magnetic layers, along with a corresponding number of insulating layers (i.e., as appropriate to form an inner layer region having a topmost insulating layer on a topmost outer magnetic layer and an insulating layer between each pair of adjacent outer magnetic layers). It is further understood that the second inner layer region **400** can include a different number of magnetic layers than the first inner layer region **200**.

[0038] The second inner magnetic layer **402** can be made of any suitable magnetic material and can be formed using any suitable process in a similar manner as the inner magnetic layer **202**. In some embodiments, the second inner magnetic layer **402** is conformally formed to a thickness of about 50 nm to about 500 nm, although other thicknesses are within the contemplated scope of embodiments of the invention. The second inner magnetic layer **402** can have a same thickness, a larger thickness, or a smaller thickness as the inner magnetic layer **202** in the first inner layer region **200**.

[0039] The insulating layer **404** can be made of any suitable non-magnetic insulating material and can be formed using any suitable process in a similar manner as the insulating layer **204**. As discussed previously herein, the target thickness of the insulating layers in the second inner layer region **400** (e.g., insulating layer **404**) is adjusted to increase the effective permeability of the inner layers and to shift the frequency of peak Q to a higher frequency. In some embodiments, the insulating layer **404** is conformally formed to a relatively thin thickness (i.e., a thickness of about 0.5 nm to about 20 nm, although other thicknesses are within the contemplated scope of embodiments of the invention) to increase losses and to shift the frequency of peak Q to a higher frequency. The insulating layer **404** can have a same thickness, a larger thickness, or a smaller thickness as the insulating layer **204** in the first inner layer region **200**.

[0040] FIG. **5** depicts a cross-sectional view of the structure **100** along the direction X-X' after patterning the first inner layer region **200**, the outer layer region **300**, and the second inner layer region **400** to form laminated stacks **500**, **502**, and **504** during an intermediate operation of a method of fabricating a semiconductor device according to embodiments of the invention. Any known method for patterning laminated stacks can be used, such as, for example, a wet etch, a dry etch, or a combination of sequential wet and/or dry etches. In some embodiments, the laminated stacks **500**, **502**, and **504** are formed by removing portions of the first inner layer region **200**, the outer layer region **300**, and the second inner layer region **400** selective to the dielectric layer **102**. For ease of discussion the structure **100** is depicted as having three laminated stacks (e.g., the laminated stacks **500**, **502**, and **504**). It is understood, however, that the structure **100** can include any number of laminated stacks. For example, the structure **100** can include a single laminated stack, two laminated stacks, five laminated stacks, eight laminated stacks, or any number of laminated stacks.

[0041] FIG. **6** depicts a cross-sectional view of the structure **100** along the direction X-X' after forming a dielectric layer **600** opposite a surface of the dielectric layer **102** during an intermediate operation of a method of fabricating a semiconductor device according to embodiments of the invention. The dielectric layer **600** can be any suitable insulating material, such as, for example, a low-k dielectric, SiO_2, SiON, and SiOCN. Any known manner of forming the dielectric layer **600** can be utilized. In some embodiments, the dielectric layer **600** is SiO_2 conformally formed opposite a surface of the dielectric layer **102** using a conformal deposition process such as PVD, CVD, PECVD, or a combination thereof. In some embodiments, the dielectric layer **600** is conformally formed to a thickness sufficient to cover a surface of the laminated stacks **500**, **502**, and **504**. In some embodiments, a CMP selective to the laminated stacks **500**, **502**, and **504** planarizes the dielectric layer **600** to a surface of the laminated stacks **500**, **502**, and **504**.

[0042] A dielectric layer **602** (also referred to as a top dielectric layer) is formed opposite a surface of the dielectric layer **600** during an intermediate operation of a method of

fabricating a semiconductor device according to embodiments of the invention. The dielectric layer **602** can be any suitable material, such as, for example, a low-k dielectric, SIN, SiO_2, SiON, and SiOCN. Any known manner of forming the dielectric layer **602** can be utilized. In some embodiments, the dielectric layer **602** is SiO_2 conformally formed on exposed surfaces of the dielectric layer **600** using a conformal deposition process such as PVD, CVD, PECVD, or a combination thereof. In some embodiments, the dielectric layer **602** is conformally formed to a thickness of about 50 nm to about 400 nm, although other thicknesses are within the contemplated scope of embodiments of the invention.

[0043] As discussed previously herein, the conductive coil **106** is formed in the dielectric layer **602** and helically wraps around portions of the structure **100**. For ease of discussion reference is made to operations performed on and to a conductive coil **106** having six turns or windings formed in the dielectric layer **602**. It is understood, however, that the dielectric layer **602** can include any number of windings. For example, the dielectric layer **602** can include a single winding, 2 windings, 5 windings, 10 windings, or 20 windings, although other winding counts are within the contemplated scope of embodiments of the invention.

[0044] FIG. **7** depicts a flow diagram illustrating a method for forming a laminated magnetic inductor according to one or more embodiments of the invention. As shown at block **702**, a first magnetic stack having one or more magnetic layers alternating with one or more insulating layers is formed in a first inner region of a laminated magnetic inductor. The magnetic layers of the first magnetic stack can be formed in a similar manner as the inner magnetic layer **202** (as depicted in FIG. **2**) according to one or more embodiments. The insulating layers of the first magnetic stack can be formed in a similar manner as the insulating layer **204** (as depicted in FIG. **2**) according to one or more embodiments.

[0045] As shown at block **704**, a second magnetic stack having one or more magnetic layers alternating with one or more insulating layers is formed in an outer region of the laminated magnetic inductor opposite a surface of the first inner region. The magnetic layers of the second magnetic stack can be formed in a similar manner as the outer magnetic layer **302** (as depicted in FIG. **3**) according to one or more embodiments. The insulating layers of the first magnetic stack can be formed in a similar manner as the insulating layer **304** (as depicted in FIG. **3**) according to one or more embodiments.

[0046] As shown at block **706**, a third magnetic stack having one or more magnetic layers alternating with one or more insulating layers is formed in a second inner region of the laminated magnetic inductor opposite a surface of the outer region. The magnetic layers of the third magnetic stack can be formed in a similar manner as the second inner magnetic layer **402** (as depicted in FIG. **4**) according to one or more embodiments. The insulating layers of the third magnetic stack can be formed in a similar manner as the insulating layer **404** (as depicted in FIG. **4**) according to one or more embodiments.

[0047] As discussed previously herein, the first, second, and third magnetic stacks are structured such that a thickness of the insulating layers in the outer layer region **300** is greater than a thickness of the insulating layers in the first inner layer region **200** or the second inner layer region **400**. In this manner, eddy current losses can be leveraged in the critical regions (i.e., the first and second inner regions **200** and **400**) to modulate the frequency of peak Q while still mitigating losses in the noncritical regions (i.e., the outer region **300**).

[0048] Various embodiments of the present invention are described herein with reference to the related drawings. Alternative embodiments can be devised without departing from the scope of this invention. Although various connections and positional relationships (e.g., over, below, adjacent, etc.) are set forth between elements in the following description and in the drawings, persons skilled in the art will recognize that many of the positional relationships described herein are orientation-independent when the described functionality is maintained even though the orientation is changed. These connections and/or positional relationships, unless specified otherwise, can be direct or indirect, and the present invention is not intended to be limiting in this respect. Similarly, the term "coupled" and variations thereof describes having a communications path between two elements and does not imply a direct connection between the elements with no intervening elements/connections between them. All of these variations are considered a part of the specification. Accordingly, a coupling of entities can refer to either a direct or an indirect coupling, and a positional relationship between entities can be a direct or indirect positional relationship. As an example of an indirect positional relationship, references in the present description to forming layer "A" over layer "B" include situations in which one or more intermediate layers (e.g., layer "C") is between layer "A" and layer "B" as long as the relevant characteristics and functionalities of layer "A" and layer "B" are not substantially changed by the intermediate layer(s).

[0049] The following definitions and abbreviations are to be used for the interpretation of the claims and the specification. As used herein, the terms "comprises," "comprising," "includes," "including," "has," "having," "contains" or "containing," or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a composition, a mixture, process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but can include other elements not expressly listed or inherent to such composition, mixture, process, method, article, or apparatus.

[0050] Additionally, the term "exemplary" is used herein to mean "serving as an example, instance or illustration." Any embodiment or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or designs. The terms "at least one" and "one or more" are understood to include any integer number greater than or equal to one, i.e. one, two, three, four, etc. The terms "a plurality" are understood to include any integer number greater than or equal to two, i.e. two, three, four, five, etc. The term "connection" can include an indirect "connection" and a direct "connection."

[0051] References in the specification to "one embodiment," "an embodiment," "an example embodiment," etc., indicate that the embodiment described can include a particular feature, structure, or characteristic, but every embodiment may or may not include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described

in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

[0052] For purposes of the description hereinafter, the terms "upper," "lower," "right," "left," "vertical," "horizontal," "top," "bottom," and derivatives thereof shall relate to the described structures and methods, as oriented in the drawing figures. The terms "overlying," "atop," "on top," "positioned on" or "positioned atop" mean that a first element, such as a first structure, is present on a second element, such as a second structure, wherein intervening elements such as an interface structure can be present between the first element and the second element. The term "direct contact" means that a first element, such as a first structure, and a second element, such as a second structure, are connected without any intermediary conducting, insulating or semiconductor layers at the interface of the two elements.

[0053] The terms "about," "substantially," "approximately," and variations thereof, are intended to include the degree of error associated with measurement of the particular quantity based upon the equipment available at the time of filing the application. For example, "about" can include a range of ±8% or 5%, or 2% of a given value.

[0054] The phrase "selective to," such as, for example, "a first element selective to a second element," means that the first element can be etched and the second element can act as an etch stop.

[0055] The term "conformal" (e.g., a conformal layer) means that the thickness of the layer is substantially the same on all surfaces, or that the thickness variation is less than 15% of the nominal thickness of the layer.

[0056] As previously noted herein, for the sake of brevity, conventional techniques related to semiconductor device and integrated circuit (IC) fabrication may or may not be described in detail herein. By way of background, however, a more general description of the semiconductor device fabrication processes that can be utilized in implementing one or more embodiments of the present invention will now be provided. Although specific fabrication operations used in implementing one or more embodiments of the present invention can be individually known, the described combination of operations and/or resulting structures of the present invention are unique. Thus, the unique combination of the operations described in connection with the fabrication of a semiconductor device according to the present invention utilize a variety of individually known physical and chemical processes performed on a semiconductor (e.g., silicon) substrate, some of which are described in the immediately following paragraphs.

[0057] In general, the various processes used to form a micro-chip that will be packaged into an IC fall into four general categories, namely, film deposition, removal/etching, semiconductor doping and patterning/lithography. Deposition is any process that grows, coats, or otherwise transfers a material onto the wafer. Available technologies include physical vapor deposition (PVD), chemical vapor deposition (CVD), electrochemical deposition (ECD), molecular beam epitaxy (MBE) and more recently, atomic layer deposition (ALD) among others. Removal/etching is any process that removes material from the wafer. Examples include etch processes (either wet or dry), chemical-mechanical planarization (CMP), and the like. Reactive ion etching (RIE), for example, is a type of dry etching that uses chemically reactive plasma to remove a material, such as a masked pattern of semiconductor material, by exposing the material to a bombardment of ions that dislodge portions of the material from the exposed surface. The plasma is typically generated under low pressure (vacuum) by an electromagnetic field. Semiconductor doping is the modification of electrical properties by doping, for example, transistor sources and drains, generally by diffusion and/or by ion implantation. These doping processes are followed by furnace annealing or by rapid thermal annealing (RTA). Annealing serves to activate the implanted dopants. Films of both conductors (e.g., poly-silicon, aluminum, copper, etc.) and insulators (e.g., various forms of silicon dioxide, silicon nitride, etc.) are used to connect and isolate transistors and their components. Selective doping of various regions of the semiconductor substrate allows the conductivity of the substrate to be changed with the application of voltage. By creating structures of these various components, millions of transistors can be built and wired together to form the complex circuitry of a modern microelectronic device. Semiconductor lithography is the formation of three-dimensional relief images or patterns on the semiconductor substrate for subsequent transfer of the pattern to the substrate. In semiconductor lithography, the patterns are formed by a light sensitive polymer called a photo-resist. To build the complex structures that make up a transistor and the many wires that connect the millions of transistors of a circuit, lithography and etch pattern transfer steps are repeated multiple times. Each pattern being printed on the wafer is aligned to the previously formed patterns and slowly the conductors, insulators and selectively doped regions are built up to form the final device.

[0058] The flowchart and block diagrams in the Figures illustrate possible implementations of fabrication and/or operation methods according to various embodiments of the present invention. Various functions/operations of the method are represented in the flow diagram by blocks. In some alternative implementations, the functions noted in the blocks can occur out of the order noted in the Figures. For example, two blocks shown in succession can, in fact, be executed substantially concurrently, or the blocks can sometimes be executed in the reverse order, depending upon the functionality involved.

[0059] The descriptions of the various embodiments of the present invention have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments described herein.

What is claimed is:

1. A method of fabricating a magnetic stack arrangement of a laminated magnetic inductor, the method comprising:

forming a first magnetic stack comprising one or more magnetic layers alternating with one or more insulating layers in a first inner region of the laminated magnetic inductor;

forming a second magnetic stack comprising one or more magnetic layers alternating with one or more insulating layers opposite a surface of the first magnetic stack in an outer region of the laminated magnetic inductor; and

forming a third magnetic stack comprising one or more magnetic layers alternating with one or more insulating layers opposite a surface of the second magnetic stack in a second inner region of the laminated magnetic inductor;

wherein a thickness of an insulating layer in the second magnetic stack is greater than a thickness of an insulating layer in the first magnetic stack.

2. The method of claim **1** further comprising forming a first dielectric layer opposite a surface of the first magnetic stack.

3. The method of claim **2** further comprising forming a second dielectric layer opposite a surface of the third magnetic stack.

4. The method of claim **3** further comprising forming a conductive coil helically wrapping through the first and second dielectric layers.

5. The method of claim **4**, wherein the first and third magnetic stacks are positioned proximate to the conductive coil.

6. The method of claim **5**, wherein the second magnetic stack is positioned between the first and third magnetic stacks such that the second magnetic stack is further from the conductive coil than either the first magnetic stack or the second magnetic stack.

7. The method of claim **1**, wherein the one or more magnetic layers in the first magnetic stack comprise cobalt (Co), FeTaN, FeNi, FeAlO, or a combination thereof.

8. The method of claim **1**, wherein the one or more magnetic layers in the first magnetic stack comprises a thickness of about 50 nm to about 500 nm.

9. The method of claim **1**, wherein the one or more insulating layers in the first magnetic stack comprise alumina (Al_2O_3), silicon dioxide (SiO_2), a silicon nitride, a silicon oxynitride (SiO_xN_y), magnesium oxide (MgO), or a combination thereof.

10. The method of claim **1**, wherein the one or more insulating layers in the first magnetic stack comprises a thickness of about 0.5 nm to about 20 nm.

11. The method of claim **10**, wherein the one or more insulating layers in the first magnetic stack comprises a thickness of about 1 nm to about 5 nm.

12. The method of claim **1**, wherein the thickness of an insulating layer in the second magnetic stack is at least ten times greater than a thickness of an insulating layer in the first magnetic stack.

13. The method of claim **1**, wherein the thickness of an insulating layer in the second magnetic stack is at least twenty times greater than a thickness of an insulating layer in the first magnetic stack.

14. A method of fabricating a magnetic stack arrangement of a laminated magnetic inductor, the method comprising:

forming a first insulating layer proximate to a conductive coil of the laminated magnetic inductor;

forming a second insulating layer proximate to the conductive coil opposite a surface of the first insulating layer; and

forming a third insulating layer between the first and second insulating layers such that the third insulating layer is further from the conductive coil than either the first insulating layer or the second insulating layer;

wherein a thickness of the third insulating layer is greater than a thickness of either the first or second insulating layers.

15. The method of claim **14**, wherein the first insulating layer comprises a thickness of about 0.5 nm to about 20 nm.

16. The method of claim **14**, wherein a thickness of the third insulating layer is at least twenty times greater than a thickness of either the first or second insulating layers.

17. A laminated magnetic inductor comprising:

a first inner region comprising one or more magnetic layers alternating with one or more insulating layers;

an outer region comprising one or more magnetic layers alternating with one or more insulating layers, the outer region formed opposite a surface of the first inner region; and

a second inner region comprising one or more magnetic layers alternating with one or more insulating layers, the second inner region formed opposite a surface of the outer region;

wherein a thickness of an insulating layer in the outer region is greater than a thickness of an insulating layer in either the first or second inner regions.

18. The laminated magnetic inductor of claim **17**, further comprising:

a substrate;

a first dielectric layer positioned between the substrate and the first inner region;

a second dielectric layer formed opposite a surface of the second inner region; and

a conductive coil helically wrapping through portions of the first and second dielectric layers.

19. The laminated magnetic inductor of claim **17**, wherein the one or more insulating layers in the first inner region each comprise a thickness of about 0.5 nm to about 20 nm.

20. The laminated magnetic inductor of claim **19**, wherein a thickness of an insulating layer in the outer region is at least ten times greater than a thickness of an insulating layer in either of the first or second inner regions.

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