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MAGNETIC CORE WITH HARD FERROMAGNETIC BIASING LAYERS AND STRUCTURES CONTAINING SAME

Abstract

A planar magnetic core includes multiple ferromagnetic layers including multiple hard ferromagnetic bias layers and multiple soft ferromagnetic layers. Each ferromagnetic layer comprises a soft ferromagnetic layer or a hard ferromagnetic bias layer. Each hard ferromagnetic bias layer is a neighboring ferromagnetic layer of at least one soft ferromagnetic layer. The planar magnetic core also includes a plurality of insulating layers, each insulating layer disposed between adjacent ferromagnetic layers. Each ferromagnetic layer has an easy axis of magnetization parallel to a principal plane of the planar magnetic core, where the easy axes of magnetization are aligned. Each hard ferromagnetic bias layer is magnetized to create an in-plane bias magnetic flux through the hard ferromagnetic bias layer in a first direction that is parallel to the easy axis of magnetization and forms a closed path through a neighboring soft ferromagnetic layer in a second direction parallel to the first direction.

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Background/Summary

RELATED APPLICATIONS [0001] This application is a divisional of U.S. application Ser. No. 17/108,096 titled “Magnetic Core with Hard Ferromagnetic Biasing Layers and Structures Containing Same”, filed Dec. 1, 2020, which is hereby incorporated by reference.

TECHNICAL FIELD

[0002] This application relates generally to magnetic cores and devices that include magnetic cores such as inductors.

BACKGROUND

[0003] Inductors for microelectronics include an alternating arrangement of soft ferromagnetic layers and insulating layers. An example of a typical horizontally-laminated magnetic core **10** is illustrated in FIG. **1A**. The core includes soft ferromagnetic layers **100** with an insulator layer **110** disposed between neighboring soft ferromagnetic layers **100**. The coil is configured to generate a magnetic flux through the soft ferromagnetic layers **100**, which results in alternating magnetization states **120**, as indicated by the arrows.

[0004] One problem with this configuration is that some of the magnetic flux forms a closed path within a given layer in addition to forming a closed path in a neighboring layer. Forming a closed path within a given layer results in multiple magnetic domains **130** with antiparallel magnetization states **135** that minimize the energy for the intra-layer closed path(s), for example as illustrated in FIG. **1B** which illustrates a top view of the top soft ferromagnetic layer **100** in core **10**. The top insulator **110** is not illustrated in FIG. **1B** for clarity. Magnetic domain walls **140** form between the magnetic domains **130** in which some of the magnetic moments **145** are not aligned with either magnetic domain **130**. The applied field from the inductor coil causes these magnetic moments **145** to reorient, which creates both hysteresis and eddy current power loss.

[0005] It would be desirable to overcome these and/or other deficiencies in the art.

SUMMARY

[0006] Example embodiments described herein have innovative features, no single one of which is indispensable or solely responsible for their desirable attributes. The following description and drawings set forth certain illustrative implementations of the disclosure in detail, which are indicative of several exemplary ways in which the various principles of the disclosure may be carried out. The illustrative examples, however, are not exhaustive of the many possible embodiments of the disclosure. Without limiting the scope of the claims, some of the advantageous features will now be summarized. Other objects, advantages and novel features of the disclosure will be set forth in the following detailed description of the disclosure when considered in conjunction with the drawings, which are intended to illustrate, not limit, the invention.

[0007] An aspect of the invention is directed to a horizontally-laminated planar magnetic core comprising: a plurality of ferromagnetic layers that includes a plurality of hard ferromagnetic layers and a plurality of soft ferromagnetic layers, wherein: each ferromagnetic layer comprises one of the soft ferromagnetic layers or one of the hard ferromagnetic layers, and each hard ferromagnetic layer is a neighboring ferromagnetic layer of at least one soft ferromagnetic layer.

The horizontally-laminated planar magnetic core further comprises a plurality of insulating layers, each insulating layer disposed between adjacent ferromagnetic layers, wherein each ferromagnetic layer has an easy axis of magnetization parallel to a principal plane of the planar magnetic core, and the easy axes of magnetization are aligned.

[0008] In one or more embodiments, the ferromagnetic layers are stacked along a height of the planar magnetic core. In one or more embodiments, the plurality of hard ferromagnetic layers includes a top hard ferromagnetic layer disposed as a top ferromagnetic layer. In one or more embodiments, the plurality of hard ferromagnetic layers includes a bottom hard ferromagnetic layer disposed as a bottom ferromagnetic layer. In one or more embodiments, the plurality of soft ferromagnetic layers are disposed between the top and bottom hard ferromagnetic layers. In one or more embodiments, the plurality of soft ferromagnetic layers comprises N soft ferromagnetic layers, where N is an odd integer greater than or equal to 3.

[0009] In one or more embodiments, a soft ferromagnetic thickness of each soft ferromagnetic layer is the same, a hard ferromagnetic thickness of each hard ferromagnetic layer is the same, and the hard ferromagnetic thickness is related to the soft ferromagnetic thickness. In one or more embodiments, a ratio of the hard ferromagnetic thickness to the soft ferromagnetic thickness is

$$[00001] \frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1$$

where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic layer.

[0010] In one or more embodiments, the top and bottom hard ferromagnetic layers are each magnetized to produce a respective bias magnetic flux through the top and bottom hard ferromagnetic layers, respectively, in a first direction that is parallel to the easy axes of magnetization in the top and bottom hard ferromagnetic layers. In one or more embodiments, the respective bias magnetic flux through the top hard ferromagnetic layer forms a closed loop through a first neighboring soft ferromagnetic layer, the respective bias magnetic flux through the bottom hard ferromagnetic layer forms a closed loop through a second neighboring soft ferromagnetic layer, and the respective bias magnetic flux passes through the first and second neighboring soft ferromagnetic layers in a second direction that is opposite to the first direction. In one or more embodiments, the respective bias magnetic flux through the first and second neighboring soft ferromagnetic layers induces a magnetic flux through the first and second neighboring soft ferromagnetic layers in the second direction, the induced magnetic flux through the first neighboring soft ferromagnetic layer forms a closed loop through a third neighboring soft ferromagnetic layer in the first direction, the induced magnetic flux through the second neighboring soft ferromagnetic layer forms a closed loop through a fourth neighboring soft ferromagnetic layer in the first direction, the top hard ferromagnetic layer and the third neighboring soft ferromagnetic layer are the neighboring ferromagnetic layers of the first neighboring soft ferromagnetic layer, and the bottom hard ferromagnetic layer and the fourth neighboring soft ferromagnetic layer are the neighboring ferromagnetic layers of the second neighboring soft ferromagnetic layer.

[0011] In one or more embodiments, the hard and soft ferromagnetic layers comprise cobalt, iron, and/or nickel. In one or more embodiments, the insulating layers comprise: (a) aluminum, cobalt, chromium, silicon, tantalum, titanium, and/or zirconium, or (b) a compound of (1) aluminum, cobalt, chromium, silicon, tantalum, titanium, and/or zirconium and (2) oxygen and/or nitrogen. In one or more embodiments, each hard ferromagnetic layer has a coercivity above 50 Oe, and each soft ferromagnetic layer has a coercivity below 1 Oe. In one or more embodiments, a thickness of each ferromagnetic layer is in a range of about 10 nm to about 1,000 nm, the thickness measured with respect to an axis that is orthogonal to the principal plane of the planar magnetic core. In one or more embodiments, a thickness of each insulating layer is in a range of about 1 nm to about 50 nm, the thickness of each insulating layer measured with respect to the axis. In one or more embodiments, a total thickness of the core is less than or equal to 100,000 nm, the total thickness measured with respect to the axis.

[0012] Another aspect of the invention is directed to a horizontally-laminated planar magnetic core comprising: a plurality of soft-hard ferromagnetic layer pairs, each soft-hard ferromagnetic layer pair including a soft ferromagnetic layer and a hard ferromagnetic layer; an intra-pair spacer layer disposed between the soft ferromagnetic layer and the hard ferromagnetic layer in each soft-hard ferromagnetic layer pair; an inter-pair spacer layer disposed between neighboring soft-hard ferromagnetic layer pairs, wherein an inter-pair spacer thickness of each inter-pair spacer layer is greater than an intra-pair spacer thickness of each intra-pair spacer layer, and the inter-pair spacer thickness and the intra-pair spacer thickness are measured with respect to an axis that is orthogonal to a major plane of the core.

[0013] In one or more embodiments, for each soft-hard ferromagnetic pair, a relative position of the soft ferromagnetic layer with respect to the hard ferromagnetic layer is the same. In one or more embodiments, for each soft-hard ferromagnetic pair, the soft ferromagnetic layer is disposed below the hard ferromagnetic layer.

[0014] In one or more embodiments, the horizontally-laminated planar magnetic core further comprises a first inter-pair spacer layer disposed between a first soft-hard ferromagnetic layer pair and a second soft-hard ferromagnetic layer pair; and a second inter-pair spacer layer disposed between the second soft-hard ferromagnetic layer pair and a third soft-hard ferromagnetic layer pair, the second soft-hard ferromagnetic layer pair disposed between the first and third soft-hard ferromagnetic layer pairs.

[0015] In one or more embodiments, a soft ferromagnetic thickness of each soft ferromagnetic layer is the same, a hard ferromagnetic thickness of each hard ferromagnetic layer is the same, the soft and hard ferromagnetic thicknesses are measured with respect to the axis, and the hard ferromagnetic thickness is related to the soft ferromagnetic thickness. In one or more embodiments, in each soft-hard ferromagnetic layer pair: the hard ferromagnetic layer is magnetized to produce a bias magnetic flux through the hard ferromagnetic layer in a first direction that is parallel to an easy axis of magnetization in the hard ferromagnetic layer, the easy axis of magnetization disposed within a major plane of the hard ferromagnetic layer, and the bias magnetic flux forms a closed loop only through the soft ferromagnetic layer in a second direction that is parallel to an easy axis of magnetization in the soft ferromagnetic layer, the easy axis of magnetization disposed within a major plane of the soft ferromagnetic layer. In one or more embodiments, in each soft-hard ferromagnetic layer pair: the bias magnetic flux through the soft ferromagnetic layer induces a magnetic flux through the soft ferromagnetic layer in the second direction, and the induced magnetic flux forms a closed loop only through the hard ferromagnetic layer in the first direction.

[0016] In one or more embodiments, a ratio of the hard ferromagnetic thickness to the soft ferromagnetic thickness is

$$[00002] \frac{M_{S_soft}}{M_{S_hard}} : 1$$

where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic layer. In one or more embodiments, the inter-pair spacer thickness of the first and second inter-pair spacer layers is the same, the intra-pair spacer thickness of each intra-pair spacer layer is the same, and the inter-pair spacer thickness is in a range of 2 to 10 times the intra-layer spacer thickness. In one or more embodiments, the intra-pair spacer layers and the inter-pair spacer layers comprise an insulator material.

[0017] Yet another aspect of the invention is directed to an inductor comprising: a horizontally-laminated planar magnetic core comprising: a plurality of ferromagnetic layers that includes a plurality of hard ferromagnetic layers and a plurality of soft ferromagnetic layers, wherein each ferromagnetic layer comprises one of the soft ferromagnetic layers or one of the hard ferromagnetic layers, and each hard ferromagnetic layer is a neighboring ferromagnetic layer of at least one neighboring soft ferromagnetic layer. The inductor further comprises a plurality of insulating layers, each insulating layer disposed between adjacent ferromagnetic layers. Each ferromagnetic

layer has an easy axis of magnetization parallel to a principal plane of the planar magnetic core, and the easy axes of magnetization are aligned. The inductor further comprises a conductive winding that turns around in a generally spiral manner on the outside of said planar laminated magnetic core.

[0018] In one or more embodiments, each ferromagnetic layer has a hard axis of magnetization that is orthogonal to the easy axis of magnetization within a major plane of the respective ferromagnetic layer, and the hard axes of magnetization are aligned, and the conductive winding is configured to produce an inductor coil magnetic flux through the horizontally-laminated planar magnetic core in a direction parallel to the hard axis of magnetization in each ferromagnetic layer. In one or more embodiments, the plurality of hard ferromagnetic layers includes a top hard ferromagnetic layer disposed as a top ferromagnetic layer and a bottom hard ferromagnetic layer disposed as a bottom ferromagnetic layer, the plurality of soft ferromagnetic layers are disposed between the top and bottom hard ferromagnetic layers, each of the top and bottom hard ferromagnetic layers is magnetized to produce a respective bias magnetic flux through the top and bottom hard ferromagnetic layers, respectively, in a first direction that is parallel to the easy axes of magnetization in the top and bottom hard ferromagnetic layers, the bias magnetic flux through the top hard ferromagnetic layer forms a closed loop through a first neighboring soft ferromagnetic layer, the bias magnetic flux through the bottom hard ferromagnetic layer forms a closed loop through a second neighboring soft ferromagnetic layer, and the bias magnetic flux passes through the first and second neighboring soft ferromagnetic layers in a second direction that is opposite to the first direction. In one or more embodiments, the bias magnetic flux through the first and second neighboring soft ferromagnetic layers induces a magnetic flux through the first and second neighboring soft ferromagnetic layers in the second direction, the induced magnetic flux through the first neighboring soft ferromagnetic layer forms a closed loop through a third neighboring soft ferromagnetic layer in the first direction, the induced magnetic flux through the second neighboring soft ferromagnetic layer forms a closed loop through a fourth neighboring soft ferromagnetic layer in the first direction, the top hard ferromagnetic layer and the third neighboring soft ferromagnetic layer are the neighboring ferromagnetic layers of the first neighboring soft ferromagnetic layer, and the bottom hard ferromagnetic layer and the fourth neighboring soft ferromagnetic layer are the neighboring ferromagnetic layers of the second neighboring soft ferromagnetic layer.

[0019] Another aspect of the invention is directed to a structure comprising a semiconductor integrated circuit comprising a multilevel wiring network formed on a substrate, wherein the inductor is integrated into the multilevel wiring network.

[0020] Yet another aspect of the invention is directed to a method of manufacturing comprising: depositing, over a semiconductor substrate, a plurality of ferromagnetic layers that includes a plurality of hard ferromagnetic layers and a plurality of soft ferromagnetic layers, wherein: each ferromagnetic layer comprises one of the soft ferromagnetic layers or one of the hard ferromagnetic layers, and each hard ferromagnetic layer is a neighboring ferromagnetic layer of at least one neighboring soft ferromagnetic layer. The method further comprises depositing an insulating layer between adjacent ferromagnetic layers; inducing an easy axis of magnetization in each ferromagnetic layer, the easy axes of magnetization aligned and parallel to a top planar surface of the semiconductor substrate; magnetizing each hard ferromagnetic layer so as to produce a bias magnetic flux through the respective hard ferromagnetic layer in a first direction, the bias magnetic flux parallel to the easy axis of magnetization in the respective hard ferromagnetic layer; and defining a horizontally-laminated planar magnetic core that comprises the plurality of ferromagnetic layers and the insulating layers.

[0021] In one or more embodiments, the method further comprises defining a hard axis of magnetization in each ferromagnetic layer, the hard axis of magnetization orthogonal to the easy axis of magnetization within a major plane of each ferromagnetic layer; and forming a conductive winding around the horizontally-laminated planar magnetic core, the conductive winding

configured to form an inductor coil magnetic field that passes through the horizontally-laminated planar magnetic core in a direction parallel to the hard axis of magnetization in each ferromagnetic layer.

[0022] In one or more embodiments, the method further comprises depositing a top hard ferromagnetic layer as a top ferromagnetic layer; depositing a bottom hard ferromagnetic layer as a bottom ferromagnetic layer; and depositing the plurality of soft ferromagnetic layers between the bottom and top hard ferromagnetic layers.

[0023] In one or more embodiments, a ratio of a hard ferromagnetic thickness of each hard ferromagnetic layer to a soft ferromagnetic thickness of each soft ferromagnetic layer is

$$[00003] \frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1$$

where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic layer, and the soft and hard ferromagnetic thicknesses are measured with respect to an axis that is orthogonal to the top planar surface of the semiconductor substrate.

[0024] In one or more embodiments, the method further comprises depositing a plurality of soft-hard ferromagnetic layer pairs, each soft-hard ferromagnetic layer pair including one of the soft ferromagnetic layers and one of the hard ferromagnetic layers; depositing an intra-pair spacer layer between the soft ferromagnetic layer and the hard ferromagnetic layer in each soft-hard ferromagnetic layer pair; and depositing an inter-pair spacer layer between neighboring soft-hard ferromagnetic layer pairs, wherein each insulator layer comprises one of the intra-pair spacer layers or one of the inter-pair spacer layers, an inter-pair spacer layer thickness of each inter-pair spacer layer is greater than an intra-pair spacer layer thickness of each intra-pair spacer layer, and the inter-pair spacer layer thickness and the intra-pair spacer layer thickness are measured with respect to an axis that is orthogonal to the top planar surface of the semiconductor substrate. In one or more embodiments, a ratio of a hard ferromagnetic thickness of each hard ferromagnetic layer to a soft ferromagnetic thickness of each soft ferromagnetic layer is

$$[00004] \frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1$$

where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic layer, and the soft and hard ferromagnetic thicknesses are measured with respect to the axis.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] For a fuller understanding of the nature and advantages of the present concepts, reference is made to the detailed description of preferred embodiments and the accompanying drawings.

[0026] FIG. 1A is a cross-sectional view of an existing horizontally-laminated magnetic core.

[0027] FIG. 1B is a top view of the horizontally-laminated magnetic core illustrated in FIG. 1A.

[0028] FIG. 2 is a cross-sectional view of a planar magnetic core according to an embodiment.

[0029] FIG. 3 is an exploded perspective view of the planar magnetic core illustrated in FIG. 2.

[0030] FIG. 4 is a cross-sectional view of a planar magnetic core according to another embodiment.

[0031] FIG. 5 is a cross-sectional view of a planar magnetic core according to another embodiment.

[0032] FIG. 6 is an exploded perspective view of the planar magnetic core illustrated in FIG. 5.

[0033] FIG. 7 is a flow chart of a method of manufacturing a semiconductor device according to an embodiment.

[0034] FIG. 8 is a representative cross section of a magnetic core inductor integrated into a semiconductor device on a substrate according to an embodiment.

DETAILED DESCRIPTION

[0035] A horizontally-laminated planar magnetic core includes a plurality of ferromagnetic layers,

which includes multiple hard ferromagnetic bias layers and multiple soft ferromagnetic layers. At least one soft ferromagnetic layer is the neighboring ferromagnetic layer of each hard ferromagnetic bias layer. Each hard ferromagnetic bias layer is magnetized so it creates an in-plane bias magnetic flux through the respective hard ferromagnetic bias layer in a first direction. The bias magnetic flux forms a closed path by passing through the neighboring soft ferromagnetic layer in a second direction that is opposite to the first direction (e.g., the first and second directions are antiparallel). The ferromagnetic layers are anisotropic such that their easy axes of magnetization are parallel to one another and to the first and second directions. The hard axes of magnetization of the ferromagnetic layers are orthogonal to the easy axes of magnetization within the major plane of the respective ferromagnetic layers.

[0036] The bias magnetic flux through the neighboring soft ferromagnetic layer sets the preferential direction for the magnetization of the soft ferromagnetic layer magnetic moments, such that an inter-layer closed path for magnetic flux is formed between the hard ferromagnetic bias layer and the soft ferromagnetic layer(s). This reduces the number of domain walls that are formed in the soft ferromagnetic layer since the magnetic flux now closes in the adjacent hard ferromagnetic bias layer, rather than closing back through the soft ferromagnetic layer which would form new magnetic domains that are magnetized in both the first and second directions. The elimination of magnetic domains, and their associated domain walls, caused by the bias magnetic flux of the hard ferromagnetic bias layer, reduces hysteresis and eddy current power losses in an inductor compared to using an inductor core that does not include hard ferromagnetic bias layers.

[0037] An inductor can be formed using the horizontally-laminated planar magnetic core. The coil of the inductor can be configured to produce an inductor coil magnetic flux through the ferromagnetic layers in a direction parallel to the hard axes of magnetization.

[0038] FIG. 2 is a cross-sectional view of a horizontally-laminated planar magnetic core **20** according to an embodiment. The planar magnetic core **20** can be fabricated on a substrate **250** and/or integrated into a multilevel wiring structure on substrate **250** to form an inductor.

[0039] The magnetic core **20** includes a plurality of ferromagnetic layers **200** and insulator layers **210**. Each ferromagnetic layer **200** is either a soft ferromagnetic layer **202** or a hard ferromagnetic bias layer **204**. The ferromagnetic layers **200** include a plurality of soft ferromagnetic layers **202** and a plurality of hard ferromagnetic bias layers **204**, which are arranged in an alternating sequence of (a) a soft ferromagnetic layer **202** and (b) a hard ferromagnetic bias layer **204**. The ferromagnetic layers **204** are stacked along the height of the core **20** (e.g., along the “z” axis).

[0040] Each hard ferromagnetic bias layer **204** is a neighboring ferromagnetic layer **200** of at least one soft ferromagnetic layer **202**. For example, in FIG. 2 the top ferromagnetic layer **200A** in the stack of ferromagnetic layers **200** is a top hard ferromagnetic bias layer **204**. The neighboring ferromagnetic layer of layer **200A** is ferromagnetic layer **200B**, which is a soft ferromagnetic layer **202**. In another example, the neighboring ferromagnetic layers of the hard ferromagnetic bias layer **200C** are soft ferromagnetic layers **200B** and **200D**.

[0041] Each ferromagnetic layer **200** is anisotropic such that its easy axis of magnetization **220** is parallel to the “x” axis and its hard axis of magnetization **222** is parallel to the “y” axis. For example, the hard axis of magnetization **222** is orthogonal to the easy axis of magnetization **220** within the major plane of the ferromagnetic layer **200**. The major plane of the ferromagnetic layer **200** corresponds to the x-y plane (e.g., the length (x) and width (y) of the ferromagnetic layer **200** while the thickness (z) of the ferromagnetic layer is orthogonal to the x-y plane). In some embodiments, the anisotropy of the ferromagnetic layers **200** is induced during manufacturing to permanently or semi-permanently set the hard and easy axes of magnetization. For example, the easy axis of magnetization **220** can be set by applying a bias magnetic field during or after deposition of each ferromagnetic layer **200** that is parallel to the desired easy axis of magnetization **220**, and then annealing the respective ferromagnetic layer **200**.

[0042] Each ferromagnetic layer **200** can include cobalt, iron, and/or nickel, or a compound or

alloy comprising cobalt, iron, and/or nickel. In one example, the soft ferromagnetic layers **202** comprise $\text{Co}_{0.915}\text{Zr}_{0.04}\text{Ta}_{0.045}$ (CZT) with x and y being approximately 0.915 and 0.04, respectively. In another example, the soft ferromagnetic layers **202** can comprise CoZrTa-B (or CoZrTaB), CoNiFe , NiFe , CoFe , and/or CoFeB , or alloys that include any of the foregoing compounds. The hard ferromagnetic bias layers **204** can comprise AlNiCo , NdFeB , SmCo , ferrite alloys of Fe_xO_y that include one or more metals such as Co , Sr , and/or Ba , or alloys that include any of the foregoing compounds.

[0043] The insulator layer **210** can comprise (a) aluminum, cobalt, chromium, silicon, tantalum, titanium, and/or zirconium, or (b) a compound of (1) aluminum, cobalt, chromium, silicon, tantalum, titanium, and/or zirconium and (2) oxygen and/or nitrogen. For example, the insulator layer **210** can comprise silicon dioxide (SiO_2), aluminum oxide (Al_xO_y), chromium oxide (Cr_xO_y), cobalt oxide (Co_xO_y), tantalum oxide (Ta_xO_y), titanium oxide (Ti_xO_y), silicon nitride (Si_xN_y), aluminum nitride (Al_xN_y), tantalum nitride (Ta_xN_y), or a combination of two or more of the foregoing. In some embodiments, the insulator layer **210** can function as a spacer layer between neighboring ferromagnetic layers **200**. The thickness of each spacer layer is related to the energy state for forming a closed magnetic field loop in neighboring soft and hard ferromagnetic layers **202**, **204**. In some embodiments, the thickness of the spacer layers can be adjusted to promote closed magnetic field loops in pairs of soft and hard ferromagnetic layers **202**, **204**, for example as discussed below with respect to FIG. 4.

[0044] On the top of the core **20**, the insulator layer **210** can function as a capping layer **212**. On the bottom of the core **20**, the insulator layer **210** can function as an adhesion layer **214**. Of course, the magnetic core **20** can be turned or rotated such that the terms “top” and “bottom” do not apply, but the layers would maintain the same relative positions with respect to each other.

[0045] The hard ferromagnetic bias layers **204** are magnetized to produce a respective bias magnetic field. The in-plane bias magnetic field flux **230**, from the bias magnetic field, through the hard ferromagnetic bias layers **204** is in a first direction (e.g., from right to left as indicated by the arrows in FIG. 2) parallel to the easy axis of magnetization **220**. The bias magnetic flux **230** through each hard ferromagnetic bias layer **204** forms a closed bias magnetic field loop by passing through the neighboring soft ferromagnetic layer(s) **202**, as indicated by the curved arrows **235**. The bias magnetic flux **230** through each soft ferromagnetic layer **202** is in a second direction (e.g., from left to right) that is opposite (e.g., antiparallel) to the first direction. The second direction is parallel to the easy axis of magnetization **220**.

[0046] It is lower energy for the bias magnetic flux **230** to form a closed loop by passing through the neighboring hard ferromagnetic bias layer(s) **204** (as indicated by the curved arrows **235**) than to form a closed loop by passing back through the same soft ferromagnetic layer **202** (e.g., to form domain walls within the respective soft ferromagnetic layer **202**). For example, the hard ferromagnetic layers **204** have a higher permeability than the soft ferromagnetic layers **202**.

[0047] The bias magnetic flux **230** through the soft ferromagnetic layers **202** produces magnetic moments and an induced magnetic flux **240** through the soft ferromagnetic layers **202** in the second direction. As with the bias magnetic flux **230**, it is lower energy for the induced magnetic flux **240** to form a closed loop by passing through the neighboring hard ferromagnetic bias layer(s) **204** (as indicated by the curved arrows **235**) than to form a closed loop by passing back through the same soft ferromagnetic layer **202** (e.g., to form domain walls within the respective soft ferromagnetic layer **202**).

[0048] Domain wall reduction in the soft ferromagnetic layers **202** can improve the efficiency of the core **20** (e.g., by lowering the coercivity of the stacked core **20** compared to when the core **20** does not include hard ferromagnetic bias layers **204**), such as when the core **20** is integrated into an inductor that operates at a high frequency (e.g., at least 1 MHz). For example, the core **20** can have lower hysteresis and eddy current power losses compared to when the core **20** does not include

hard ferromagnetic bias layers **204**.

[0049] Each hard ferromagnetic bias layer **204** can have a coercivity greater than 50 Oe, such as a range of about 50 Oe to about 1,000 Oe, including about 250 Oe, about 500 Oe, about 750 Oe, and any range or value between any two of the foregoing coercivities. Each soft ferromagnetic layer **204** can have a coercivity less than 1 Oe, such as a range of about 0.01 Oe to 1 Oe, including about 0.1 Oe, about 0.25 Oe, about 0.5 Oe, about 0.75 Oe, and any range or value between any two of the foregoing coercivities.

[0050] The thickness of each ferromagnetic layer **200** can be about 10 nm to about 1,000 nm. The thickness of each insulating layer **210** can be about 1 nm to about 50 nm. The total thickness of the core **20** can be less than or equal to about 100,000 nm (i.e., 100 microns). The thickness of the ferromagnetic layers **200**, insulating layers **210**, and core **20** is measured with respect to the “z” axis which is orthogonal to the principal plane of the core **20**.

[0051] When core **20** is integrated into a multilevel wiring structure to form an inductor, the inductor coil is preferably configured and oriented so that the inductor coil magnetic flux passes through the ferromagnetic layers **200** in a direction parallel to the hard axis of magnetization **222**.

[0052] FIG. **3** is an exploded perspective view of the planar magnetic core **20** illustrated in FIG. **2**. The capping layer **212** is not illustrated in FIG. **3** for clarity. FIG. **3** further illustrates the magnetic flux lines **230**, **240** as they pass in a first direction (i.e., from in FIG. **3**) through the hard ferromagnetic bias layers **204**, in a second direction (i.e., from left-to-right right-to-left in FIG. **3**) through the soft ferromagnetic layers **202**, and as they extend between the soft and hard ferromagnetic layers **202**, **204**. Accordingly, the magnetic flux has a closed path through the soft and hard ferromagnetic layers **202**, **204**. The magnetic flux lines **230**, **240** through the soft and hard ferromagnetic layers **202**, **204** are parallel or substantially parallel to (e.g., within 10 degrees of) the easy axis of magnetization **220**. In addition, the magnetic flux lines **230**, **240** through the soft and hard ferromagnetic layers **202**, **204** are orthogonal to or substantially orthogonal to (i.e., within 10 degrees of) the hard axis of magnetization **222** within the respective major planes of the soft and hard ferromagnetic layers **202**, **204**.

[0053] FIG. **4** is a cross-sectional view of a planar magnetic core **40** according to another embodiment. Core **40** is the same as core **20** except as described below. In FIG. **4**, the soft and hard ferromagnetic layers **202**, **204** are labeled as **202A**, **202B**, . . . **202N** and as **204A**, **204B**, . . . **204N**, respectively, for discussion purposes. The thicknesses of the soft and hard ferromagnetic layers **202**, **204** in core **40** are related (e.g., co-optimized) such that the magnetic flux through a pair of neighboring soft and hard ferromagnetic layers **202**, **204** is equal. In other words,

$$[00005] \phi_{HL} = \phi_{SL} \quad (1)$$

where $\phi_{\text{sub.HL}}$ is the magnetic flux through the hard ferromagnetic bias layer **204** and $\phi_{\text{sub.SL}}$ is the magnetic flux through the soft ferromagnetic layer **202**. Equation (1) can be rewritten as:

$$[00006] \mu_0 M_{S_{\text{soft}}} \tau_{\text{soft}} = \mu_0 M_{S_{\text{hard}}} \tau_{\text{hard}} \quad (2)$$

where $\mu_{\text{sub.0}}$ is the permeability of free space, $M_{\text{sub.S}_{\text{soft}}}$ is the saturation magnetization of the soft ferromagnetic layer **202**, $M_{\text{sub.S}_{\text{hard}}}$ is the saturation magnetization of the hard ferromagnetic bias layer **204**, $\tau_{\text{sub.soft}}$ is the thickness of the soft ferromagnetic layer **202**, and $\tau_{\text{sub.hard}}$ is the thickness of the hard ferromagnetic bias layer **204**.

[0054] In order for the magnetic flux through a pair of neighboring soft and hard ferromagnetic layers **202**, **204** to be equal, according to equations (1) and (2), the ratio of the thickness of the hard ferromagnetic bias layer **204** to the thickness of the soft ferromagnetic layer **202** is

$$[00007] \frac{M_{S_{\text{soft}}}}{M_{S_{\text{hard}}}} : 1,$$

which co-optimizes the soft and hard ferromagnetic layer thicknesses for layer-to-layer magnetic flux closure. In FIG. **4**, this thickness ratio is illustrated with each soft ferromagnetic layer **202** having a unit thickness (UT) and each hard ferromagnetic bias layer **204** having a thickness of

$$[00008]UT \times \frac{M_{S_soft}}{M_{S_hard}}.$$

[0055] The thickness of the insulator layers **210** can be adjusted to promote closed magnetic field loops in pairs of soft and hard ferromagnetic layers **202**, **204**. In general, the core **40** has N soft-hard ferromagnetic pairs **440**, with each soft-hard ferromagnetic pair **440** comprising one soft ferromagnetic layer **202** and one hard ferromagnetic bias layer **204**. The N soft-hard ferromagnetic pairs **440** are repeating units in the core **40** where the relative positions of the soft and hard ferromagnetic layers **202**, **204** are the same across each soft-hard ferromagnetic pair **440**. For example, if the soft ferromagnetic layer **202** is disposed above the hard ferromagnetic bias layer **204** in a soft-hard ferromagnetic pair **440**, the soft ferromagnetic layer **202** is disposed above the hard ferromagnetic bias layer **204** in all N soft-hard ferromagnetic pairs **440**. Likewise, if the soft ferromagnetic layer **202** is disposed below the hard ferromagnetic bias layer **204** in a soft-hard ferromagnetic pair **440**, the soft ferromagnetic layer **202** is disposed below the hard ferromagnetic bias layer **204** in all N soft-hard ferromagnetic pairs **440**.

[0056] When a soft ferromagnetic layer **202** has two neighboring hard ferromagnetic bias layers **204**, the thickness of a first insulator **210** that is disposed between the soft ferromagnetic layer **202** and a first neighboring hard ferromagnetic bias layer **204** (e.g., a hard ferromagnetic bias layer **204** in a neighboring soft-hard ferromagnetic pair **440**) can be greater than the thickness of a second insulator **210** that is disposed between the soft ferromagnetic layer **202** and a second neighboring hard ferromagnetic bias layer **204** (e.g., a hard ferromagnetic bias layer **204** in the soft-hard ferromagnetic pair **440** as the soft ferromagnetic layer **202**). Using soft ferromagnetic layer **202A** as an example, the thickness of insulator layer **210B** is greater than the thickness of insulator layer **210A**. The thicker insulator layer (e.g., insulator layer **210B**) can be referred to as an inter-pair spacer layer **400**. The thinner insulator layer (e.g., insulator layer **210A**) can be referred to as an intra-pair spacer layer **410**.

[0057] The inter-pair spacer layer **400** can be about 2 to about 10 times the thickness of the intra-pair spacer layer **410**. The thickness of the intra-pair spacer layer **410** can be about 1 nm to about 50 nm, including about 10 nm, about 20 nm, about 30 nm, about 40 nm, and any value or range between any two of the foregoing thicknesses. Thus, the thickness of the inter-pair spacer layer **400** is greater than the thickness of the intra-pair spacer layer **410**. The thickness of each layer (e.g., ferromagnetic layers **200** and insulator layers **210**) is measured with respect to the “z” axis which is orthogonal to the top and bottom planar surfaces of substrate **250** and to the major plane of core **40**.

[0058] As a result of this difference in insulator layer thickness, it is lower energy for the bias and induced magnetic flux **230**, **240** through soft ferromagnetic layer **202A** to form a return path through hard ferromagnetic bias layer **204A** than to form a return path through hard ferromagnetic bias layer **204B**. Therefore, all or substantially all of the magnetic flux (e.g., bias and induced magnetic flux **230**, **240**) through soft ferromagnetic layer **202A** forms a closed loop through hard ferromagnetic bias layer **204A**, as indicated by curved arrows **435**. In addition, all or substantially all of the magnetic flux (e.g., bias and induced magnetic flux **230**, **240**) through hard ferromagnetic bias layer **204A** forms a closed loop through soft ferromagnetic layer **202A**, as indicated by curved arrows **437**.

[0059] In general, for each soft ferromagnetic layer **202** that has two neighboring hard ferromagnetic bias layers **204**, an inter-pair spacer layer **400** is disposed on (e.g., in direct physical contact with) a first side **420** of each soft ferromagnetic layer **202** and an intra-pair spacer layer **410** is disposed on (e.g., in direct physical contact with) a second side **425** of the respective soft ferromagnetic layer **202**. The first and second sides **420**, **425** are on opposing sides of the soft ferromagnetic layer **202**. In FIG. 4, the first side **420** is on the bottom of each soft ferromagnetic layer **202**, where the bottom is closer to the substrate **250** than the top. Soft ferromagnetic layer **202N**, located on the bottom of core **40**, only has one neighboring hard ferromagnetic bias layer, **204N**, and thus does not need a thicker inter-pair spacer layer **400** below the bottom surface of soft ferromagnetic layer **202N** to set the magnetization. Instead, a thinner adhesion layer **214** is formed

below soft ferromagnetic layer **202N**. The thickness of the adhesion layer **214** and capping layer **212** can be the same as the thickness of the intra-pair spacer layer **410**.

[0060] In an alternative embodiment, for each soft ferromagnetic layer **202** that has two neighboring hard ferromagnetic bias layers **204**, the inter-pair spacer layer **400** is disposed above (e.g., in direct physical contact with) the second side **425** of each soft ferromagnetic layer **202** and the intra-pair spacer layer **410** is disposed below (e.g., in direct physical contact with) the first side **425** of the respective soft ferromagnetic layer **202** the top surface of each soft ferromagnetic layer **202**. This would be the equivalent to rotating FIG. **4** by 180 degrees, such that hard ferromagnetic bias layer **204A** is now on the “bottom” of core **40**.

[0061] An advantage to pairing the soft and hard ferromagnetic layers **202**, **204** is to direct all or substantially all of the bias magnetic flux **230** through one hard ferromagnetic bias layer **204** to pass through a corresponding soft ferromagnetic layer **202** in a soft-hard ferromagnetic pair **440**, which maximizes the reduction in domain wall formation in each soft ferromagnetic layer **202**.

[0062] It is noted that even when layer-to-layer flux closure occurs, it is still common to have some magnetic domain walls present within the soft ferromagnetic layers **202**. However, the number of domain walls is reduced relative to the case where magnetic flux is primarily closed within an individual magnetic layer, such as when the hard ferromagnetic bias layers **204** are removed from core **40**. This is advantageous because (1) domain walls can move when the core is exposed to an alternating magnetic field which causes power loss and (2) domain patterns that form when magnetic flux is closed within individual magnetic layers can reduce the total volume of magnetic material that respond to alternating magnetic fields, consequently reducing the maximum achievable inductance.

[0063] When core **40** is integrated into a multilevel wiring structure to form an inductor, the inductor coil is preferably configured and oriented so that the inductor coil magnetic flux passes through the soft and hard ferromagnetic layers **202**, **204** in a direction parallel to the hard axis of magnetization **222**.

[0064] FIG. **5** is a cross-sectional view of a planar magnetic core **50** according to another embodiment. The planar magnetic core **50** can be fabricated on a substrate **550** and/or integrated into a multilevel wiring structure on substrate **550** to form an inductor.

[0065] The core **50** includes a plurality of ferromagnetic layers **500A-G** (in general, ferromagnetic layers **500**) and insulator layers **510**. The core **50** also includes a capping layer **212** and an adhesion layer **214**. Each ferromagnetic layer **500** is either a soft ferromagnetic layer **502** or a hard ferromagnetic bias layer **504**. Each ferromagnetic layer **500** is anisotropic such that its easy axis of magnetization **520** is parallel to the “x” axis and its hard axis of magnetization **522** is parallel to the “y” axis. Thus, the hard axis of magnetization is orthogonal to the easy axis of magnetization **520** within the major plane of the ferromagnetic layer **500**. The soft and hard ferromagnetic layers **502**, **504** can be the same as the soft and hard ferromagnetic layers **202**, **204**, respectively. The insulator layers **510** can be the same as insulator layers **210** and/or intra-pair spacer layer **410**.

[0066] The top and bottom (or first and last, respectively) ferromagnetic layers **500** (e.g., layers **500A**, **500G**) are hard ferromagnetic bias layers **504** (e.g., top and bottom hard ferromagnetic bias layers). The hard ferromagnetic bias layers **504** are configured to produce a bias magnetic field **540** in a first direction (e.g., from right to left) that is parallel to the easy axis of magnetization **520**. All ferromagnetic layers **500** between the top and bottom hard ferromagnetic bias layers **504** are soft ferromagnetic layers **502**. Core **50** is configured so that half of the magnetic flux through each soft ferromagnetic layer **502** forms a closed path through each neighboring ferromagnetic layer **500**.

[0067] At the top of the core **50**, the bias magnetic flux **530** passes through the hard ferromagnetic bias layer **500A** in a first direction (e.g., from right to left) that is parallel to the easy axis of magnetization **520**. The bias magnetic flux **530** has a return path through the soft ferromagnetic layer **500B**, in a second direction (e.g., from left to right) that is parallel to the easy axis of magnetization **520**, to form a closed loop. It is a lower energy state for the bias magnetic flux **530**

through the soft ferromagnetic layer **500B** to form a closed path through the hard ferromagnetic bias layer **500A** than to form a closed loop by passing back through the same soft ferromagnetic layer **500B** (e.g., to form domain walls).

[0068] The bias magnetic flux **530** through the soft ferromagnetic layer **500B** produces magnetic moments and an induced magnetic flux **540** through the soft ferromagnetic layer **500B** in the second direction. The magnitude of the induced magnetic flux **540** is equal to or approximately equal to the magnitude of the bias magnetic flux **530**. The induced magnetic flux **540** through the soft ferromagnetic layer **500B** (e.g., in the second direction) forms a closed loop through the soft ferromagnetic layer **500C** (e.g., in the first direction) where the induced magnetic flux **540** functions as a bias magnetic flux **530'**. It is a lower energy state for the induced magnetic flux **540** through soft ferromagnetic layer **500B** to form a closed loop through soft ferromagnetic layer **500C** (e.g., as bias magnetic flux **530'**) than to form a closed loop by passing back through soft ferromagnetic layer **500B** (e.g., to form domain walls). Thus, half of the magnetic flux (e.g., the bias magnetic flux **530**) through the soft ferromagnetic layer **500B** forms a closed loop through the hard ferromagnetic bias layer **500A** and the other half of the magnetic flux (e.g., the induced magnetic flux **540**) through the soft ferromagnetic layer **500B** forms a closed loop through the soft ferromagnetic layer **500C** (e.g., as bias magnetic flux **530'**).

[0069] This repeats for all soft ferromagnetic layers **502** (e.g., soft ferromagnetic layers **500C-F**). For example, the bias magnetic flux **530'** through the soft ferromagnetic layer **500C** produces additional magnetic moments and induced magnetic flux **540** through the soft ferromagnetic layer **500C**. The magnitude of the induced magnetic flux **540** is approximately equal to the magnitude of the bias magnetic flux **530'**. The induced magnetic flux **540** through the soft ferromagnetic layer **500C** (e.g., in the first direction) forms a closed loop through the soft ferromagnetic layer **500D** (e.g., in the second direction) where the induced magnetic flux **540** functions as a bias magnetic flux **530'**. It is a lower energy state for the induced magnetic flux **540** through soft ferromagnetic layer **500C** to form a closed loop through soft ferromagnetic layer **500D** (e.g., as bias magnetic flux **530'**) than to form a closed loop by passing back through soft ferromagnetic layer **500C** (e.g., to form domain walls). Thus, half of the magnetic flux (e.g., the bias magnetic flux **530'**) through the soft ferromagnetic layer **500C** forms a closed loop through the soft ferromagnetic layer **500B** (e.g., as induced magnetic flux **540**) and the other half of the magnetic flux (e.g., the induced magnetic flux **540**) through the soft ferromagnetic layer **500C** forms a closed loop through the soft ferromagnetic layer **500D** (e.g., as bias magnetic flux **530'**).

[0070] At the bottom of the core **50**, the bias magnetic flux **530** passes through the hard ferromagnetic bias layer **500G** in a first direction (e.g., from right to left) that is parallel to the easy axis of magnetization **520**. The bias magnetic flux **530** has a return path through the soft ferromagnetic layer **500F**, in a second direction (e.g., from left to right) that is parallel to the easy axis of magnetization **520**, to form a closed loop. It is a lower energy state for the induced magnetic flux **540** through the soft ferromagnetic layer **500F** to form a closed path through the hard ferromagnetic bias layer **500G** than to form a closed loop by passing back through the same soft ferromagnetic layer **500F** (e.g., to form domain walls).

[0071] The bias magnetic flux **530** through the soft ferromagnetic layer **500F** produces magnetic moments and an induced magnetic flux **540** through the soft ferromagnetic layer **500F** in the second direction. The magnitude of the induced magnetic flux **540** through soft ferromagnetic layer **500F** is equal to or approximately equal to the magnitude of the bias magnetic flux **530** through soft ferromagnetic layer **500F**.

[0072] The induced magnetic flux **540** through the soft ferromagnetic layer **500F** (e.g., in the second direction) forms a closed loop through the soft ferromagnetic layer **500E** (e.g., in the first direction) where the induced magnetic flux **540** functions as a bias magnetic flux **530'**. It is a lower energy state for the induced magnetic flux **540** through soft ferromagnetic layer **500F** to form a closed loop through soft ferromagnetic layer **500E** (e.g., as bias magnetic flux **530'**) than to form a

closed loop by passing back through soft ferromagnetic layer 500F (e.g., to form domain walls). Thus, half of the magnetic flux (e.g., the bias magnetic flux 530) through the soft ferromagnetic layer 500F forms a closed loop through the hard ferromagnetic bias layer 500G and the other half of the magnetic flux (e.g., the induced magnetic flux 540) through the soft ferromagnetic layer 500F forms a closed loop through the soft ferromagnetic layer 500E (e.g., as bias magnetic flux 530').

[0073] The thicknesses of the soft and hard ferromagnetic layers 502, 504 are co-optimized for layer-to-layer magnetic flux closure. As can be seen, the magnitude of the magnetic flux through the hard ferromagnetic bias layers 504 is equal to or approximately equal to half of the magnitude of the magnetic flux through the soft ferromagnetic layers 502. Therefore, the flux balancing equation (1) can be rewritten as:

$$[00009] \frac{1}{2} \mu_0 M_{S_soft} \tau_{soft} = \mu_0 M_{S_hard} \tau_{hard} \quad (3)$$

[0074] In order for the magnetic flux through neighboring soft and hard ferromagnetic layers 502, 504 to be equal, the ratio of the thickness of the hard ferromagnetic bias layer 504 to the thickness of the soft ferromagnetic layer 502 is

$$[00010] \frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1,$$

which co-optimizes the soft and hard ferromagnetic layer thicknesses for layer-to-layer magnetic flux closure. In FIG. 5, this thickness ratio is illustrated with each soft ferromagnetic layer 502 having a unit thickness (UT) and each hard ferromagnetic bias layer 504 having a thickness of

$$[00011] \frac{1}{2} \text{UT} \times \frac{M_{S_soft}}{M_{S_hard}}.$$

The thickness of each layer (e.g., ferromagnetic layers 500 and insulator layers 510) is measured with respect to the “z” axis which is orthogonal to the top and bottom planar surfaces of substrate 550 and to the major plane of core 50. It is noted that the “demagnetizing” field is very strong in whatever the shortest direction of the structure is. In this case, the thickness (“z” dimension) is typically >100× smaller than the “y” and “x” dimensions of the ferromagnetic layers 500 so this field is very strong and prevents the “z” axis from being set as the easy axis in most cases.

[0075] When core 50 is integrated into a multilevel wiring structure to form an inductor, the inductor coil is preferably configured and oriented so that the inductor coil magnetic flux passes through the ferromagnetic layers 500 in a direction parallel to the hard axis of magnetization 522.

[0076] In general, the core 50 includes N ferromagnetic layers 500 where N is an odd integer that is greater than or equal to 3. In other words, the core 50 includes top and bottom hard ferromagnetic bias layers 504 and an odd integer of soft ferromagnetic layers 502 between the top and bottom hard ferromagnetic bias layers 504. An odd integer of soft ferromagnetic layers 502 prevents accumulation of induced magnetic flux 540 in the core 50.

[0077] FIG. 6 is an exploded perspective view of the planar magnetic core 50 illustrated in FIG. 5. The capping layer 212 is not illustrated in FIG. 6 for clarity. FIG. 6 further illustrates the magnetic flux lines 530, 530', 540 in the ferromagnetic layers 500. The magnetic flux lines 530, 530', 540 through the soft and hard ferromagnetic layers 502, 504 are parallel or substantially parallel to (i.e., within 10 degrees of) the easy axis of magnetization 520. In addition, the magnetic flux lines 530 and/or 540 through the soft and hard ferromagnetic layers 502, 504 are orthogonal to or substantially orthogonal to (i.e., within 10 degrees of) the hard axis of magnetization 522.

[0078] FIG. 7 is a flow chart 70 of a method of manufacturing a semiconductor device according to an embodiment. In step 700, an alternating sequence of ferromagnetic layers and insulating layers is deposited. The ferromagnetic layers include a plurality of hard ferromagnetic layers and a plurality of soft ferromagnetic layers, and each ferromagnetic layer comprises a soft ferromagnetic layer or a hard ferromagnetic layer. In addition, each hard ferromagnetic layer is a neighboring ferromagnetic layer of at least one (i.e., 1 or 2) neighboring soft ferromagnetic layers. For example, each hard ferromagnetic layer can be the top or bottom ferromagnetic layer in horizontally-laminated magnetic core. In this case, each hard ferromagnetic layer is a neighboring ferromagnetic

layer of only one soft ferromagnetic layer (e.g., the hard ferromagnetic layer on top of the core has a neighboring soft ferromagnetic layer below the top hard ferromagnetic layer, and the hard ferromagnetic layer on the bottom of the core has a neighboring soft ferromagnetic layer above the bottom hard ferromagnetic bias layer). In another example, the hard ferromagnetic layer is disposed between the top and bottom ferromagnetic layers, in which case the hard ferromagnetic layer has two neighboring soft ferromagnetic layers (one above and one below the hard ferromagnetic bias layer). In some embodiments, the ferromagnetic layers can be deposited in soft-hard ferromagnetic layer pairs.

[0079] In step **710**, an easy axis of magnetization is induced in each ferromagnetic layer. The easy axis of magnetization is parallel to a top planar surface of the semiconductor substrate over or on which the semiconductor device is formed and is within the major plane of the respective ferromagnetic layer. The easy axis is also within the major plane of the respective ferromagnetic layer. The easy axis of magnetization can be induced during or after ferromagnetic layer deposition (step **700**). For example, during ferromagnetic layer deposition (e.g., electrodeposition and/or sputter deposition) a bias magnetic field can be applied. The bias magnetic field is configured to pass through the ferromagnetic layer, as it is deposited, in a direction parallel to the top planar surface of the semiconductor substrate to form the easy axis of magnetization. Additionally or alternatively, the bias magnetic field can be applied during a post-deposition anneal.

[0080] Inducing an easy axis of magnetization in each ferromagnetic layer induces a hard axis of magnetization in the respective ferromagnetic layer. The hard axis of magnetization is orthogonal to the easy axis of magnetization within the major plane of the respective ferromagnetic layer. For example, the easy axis of magnetization can be parallel to the “x” axis, the hard axis of magnetization can be parallel to the “y” axis, and the ferromagnetic layers can be deposited along the “z” axis.

[0081] In step **720**, each hard ferromagnetic layer is magnetized to form a respective hard ferromagnetic bias layer. Each hard ferromagnetic bias layer creates an in-plane bias magnetic flux through the respective hard ferromagnetic bias layer in a first direction that is parallel to the easy axis of magnetization (e.g., induced in step **710**) in each ferromagnetic layer. The bias magnetic flux has a magnetization state oriented in a first direction. The bias magnetic flux forms a closed path by passing through the neighboring soft ferromagnetic layer in a second direction that is opposite to the first direction. Each hard ferromagnetic layer can be magnetized during deposition of the hard ferromagnetic layer, during a post-deposition anneal (e.g., in the presence of an in-plane magnetic field of sufficient strength), and/or during the inducement of the easy axis of magnetization in the hard ferromagnetic layer (e.g., in step **710**). In some embodiments, steps **710** and **720** occur simultaneously.

[0082] In step **730**, a horizontally-laminated planar magnetic core that includes the ferromagnetic layers and the insulating layers is defined, such as through photolithography and etching.

[0083] In some embodiments, the method can include forming a conductive winding around the horizontally-laminated planar magnetic core, such as to form an inductor. The conductive winding can be configured to form an inductor coil magnetic field that passes through the at least one neighboring soft ferromagnetic layer in a direction parallel to the hard axis of magnetization of the at least one neighboring soft ferromagnetic layer, for example to avoid domain wall motion and associated energy losses.

[0084] In one embodiment, the top ferromagnetic layer in the plurality of ferromagnetic layers is a hard ferromagnetic bias layer (e.g., a top hard ferromagnetic bias layer). Additionally or alternatively, the bottom ferromagnetic layer in the plurality of ferromagnetic layers is a hard ferromagnetic bias layer (e.g., a bottom hard ferromagnetic bias layer). When the top and bottom ferromagnetic layers are hard ferromagnetic bias layers, respectively, the other ferromagnetic layers can be only soft ferromagnetic layers (e.g., an odd integer of soft ferromagnetic layers). In this embodiment, the ratio of the hard ferromagnetic thickness of each hard ferromagnetic bias layer to

the soft ferromagnetic thickness of each soft ferromagnetic layer can be

$$[00012] \frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1$$

where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic bias layer, as discussed above.

[0085] In another embodiment, the ferromagnetic layers are deposited as soft-hard ferromagnetic layer pairs where each soft-hard ferromagnetic layer pair includes one soft ferromagnetic layer and one hard ferromagnetic bias layer. An intra-pair spacer layer is deposited between the soft ferromagnetic layer and the hard ferromagnetic bias layer in each soft-hard ferromagnetic layer pair, and an inter-pair spacer layer is deposited between neighboring soft-hard ferromagnetic layer pairs. The inter-layer spacers and the intra-layer spacers are insulating layers, where the inter-pair spacer layer thickness of each inter-pair spacer layer is greater than the intra-layer spacer thickness of each intra-layer spacer. In this embodiment, a ratio of a hard ferromagnetic thickness of each hard ferromagnetic bias layer to a soft ferromagnetic thickness of each soft ferromagnetic layer is

$$[00013] \frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1$$

where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic bias layer.

[0086] FIG. 8 is a representative cross section **80** of a magnetic core inductor **800** integrated into a semiconductor device on a substrate **810** according to an embodiment. The inductor **800** includes a horizontally-laminated magnetic core **820** and a conductive winding **830**.

[0087] The conductive winding **830** is integrated into a multilevel wiring network **835** that provides electrical connections between PMOS and NMOS transistor gates **862**, **864**, the inductor **800**, and integrated circuit (IC) chip contact structures **832**. The PMOS and NMOS transistor gates **862**, **864** are fabricated on a semiconductor substrate **810** (e.g., silicon, silicon-on-insulator, or another semiconductor substrate). The IC chip contact structures **832** can comprise C4 contacts, solder bumps, or copper pillars, but any other contacts for the semiconductor device's external communication are acceptable without limitation.

[0088] The multilevel wiring network **835** is arranged into wiring planes **820**. Each wiring plane **820** contains wire segments **850**. Electrical connections between wiring segments **850** of differing wiring planes **837** are provided by conductive VIAs **840**. The spaces in the multilevel wiring network **835** are filled with a dielectric insulating material **860** such as SiO₂.

[0089] The inductor **800** is integrated on top of the multilevel wiring network **835**. The conductive winding **830** is piecewise constructed of wire segments **850'** and of VIAs **840'** that are disposed in at least two integration planes **839** on top of the multilevel wiring network **835**. The VIAs **840'** that form parts of the winding **830** are vertical or orthogonal to the principal plane **875** and electrically interconnect the wire segments **850'** in the two integration planes **839**. In other embodiments, the inductor **800** can be integrated into the multilevel wiring network **835** instead of in the integration planes **830** on top of the multilevel wiring network **835**.

[0090] The magnetic core **820** can comprise any of the magnetic cores described herein. For example, magnetic core **820** can be the same as or can comprise core **20**, core **40**, or core **50**. The conductive winding **830** is configured and/or arranged to generate an inductor coil magnetic field that produces an inductor coil magnetic flux through the soft ferromagnetic layers in the core **820**. The inductor coil magnetic flux is parallel to the hard axis of magnetization in the respective soft ferromagnetic layer. The inductor coil magnetic flux through the soft ferromagnetic layers and the easy axis of magnetization in the soft ferromagnetic layers are parallel and/or substantially parallel to the principal plane **875** of the planar magnetic core **820**, which is also parallel and/or substantially parallel to the wiring planes **837** and the top surface **812** of the semiconductor substrate **810**.

[0091] The inductor **800** can be a component of a power converter, such as a switched inductor

DC-DC power converter. In some embodiments, the power converter can include multiple inductors, with each inductor being the same as or similar to inductor **800**. The inductors can be arranged in parallel electrically with one another, in series electrically with one another, or a combination thereof. The plurality of inductors can be integrated on the same integration or wiring planes or in different integration or wiring planes.

[0092] The invention should not be considered limited to the particular embodiments described above, but rather should be understood to cover all aspects of the invention as fairly set out in the attached claims. Various modifications, equivalent processes, as well as numerous structures to which the invention may be applicable, will be apparent to those skilled in the art to which the invention is directed upon review of this disclosure. The claims are intended to cover such modifications and equivalents.

Claims

1. A method of manufacturing comprising: depositing, over a semiconductor substrate, a plurality of ferromagnetic layers that includes a plurality of hard ferromagnetic layers and a plurality of soft ferromagnetic layers, wherein: each ferromagnetic layer comprises one of the soft ferromagnetic layers or one of the hard ferromagnetic layers, and each hard ferromagnetic layer is a neighboring ferromagnetic layer of at least one neighboring soft ferromagnetic layer, and depositing an insulating layer between adjacent ferromagnetic layers; inducing an easy axis of magnetization in each ferromagnetic layer, the easy axes of magnetization aligned and parallel to a top planar surface of the semiconductor substrate; magnetizing each hard ferromagnetic layer so as to produce a bias magnetic flux through the respective hard ferromagnetic layer in a first direction, the bias magnetic flux parallel to the easy axis of magnetization in the respective hard ferromagnetic layer; and defining a horizontally-laminated planar magnetic core that comprises the plurality of ferromagnetic layers and the insulating layers.
2. The method of claim 1, further comprising: defining a hard axis of magnetization in each ferromagnetic layer, the hard axis of magnetization orthogonal to the easy axis of magnetization within a major plane of each ferromagnetic layer; and forming a conductive winding around the horizontally-laminated planar magnetic core, the conductive winding configured to form an inductor coil magnetic field that passes through the horizontally-laminated planar magnetic core in a direction parallel to the hard axis of magnetization in each ferromagnetic layer.
3. The method of claim 1, further comprising: depositing a top hard ferromagnetic layer as a top ferromagnetic layer; depositing a bottom hard ferromagnetic layer as a bottom ferromagnetic layer; and depositing the plurality of soft ferromagnetic layers between the bottom and top hard ferromagnetic layers.
4. The method of claim 3, wherein: a ratio of a hard ferromagnetic thickness of each hard ferromagnetic layer to a soft ferromagnetic thickness of each soft ferromagnetic layer is $\frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1$ where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic layer, and the soft and hard ferromagnetic thicknesses are measured with respect to an axis that is orthogonal to the top planar surface of the semiconductor substrate.
5. The method of claim 1, further comprising: depositing a plurality of soft-hard ferromagnetic layer pairs, each soft-hard ferromagnetic layer pair including one of the soft ferromagnetic layers and one of the hard ferromagnetic layers; depositing an intra-pair spacer layer between the soft ferromagnetic layer and the hard ferromagnetic layer in each soft-hard ferromagnetic layer pair; and depositing an inter-pair spacer layer between neighboring soft-hard ferromagnetic layer pairs, wherein: each insulator layer comprises one of the intra-pair spacer layers or one of the inter-pair spacer layers, an inter-pair spacer layer thickness of each inter-pair spacer layer is greater than an

intra-pair spacer layer thickness of each intra-pair spacer layer, and the inter-pair spacer layer thickness and the intra-pair spacer layer thickness are measured with respect to an axis that is orthogonal to the top planar surface of the semiconductor substrate.

6. The method of claim 5, wherein: a ratio of a hard ferromagnetic thickness of each hard ferromagnetic layer to a soft ferromagnetic thickness of each soft ferromagnetic layer is $\frac{1}{2} \times \frac{M_{S_soft}}{M_{S_hard}} : 1$ where M_{S_soft} is the saturation magnetization of each soft ferromagnetic layer and M_{S_hard} is the saturation magnetization of each hard ferromagnetic layer, and the soft and hard ferromagnetic thicknesses are measured with respect to the axis.
