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MAGNETORESISTANCE ELEMENT INCLUDING A MULTI-LAYERED FREE LAYER STACK TO TUNE HYSTERESIS AND OUTPUT AMPLITUDE

Abstract

According to one aspect of the present disclosure, a magnetic field sensor includes a magnetoresistance (MR) element. In some embodiments, the MR element includes a reference layer, a free layer, and a barrier layer. In some embodiments the free layer includes two or more cobalt iron boron (CoFeB) layers, wherein a first one of the CoFeB layers is in contact with the barrier layer, and two or more spacer layers. In some embodiments, the CoFeB layers and the spacer layers alternate to form a multilayered free layer structure. In some embodiments, the magnetic field sensor comprises an angle sensor or a current sensor. In some embodiments, the contact between the first one of the CoFeB layers and the barrier layer is configured to reduce hysteresis in the MR element. In some embodiments, the alternating CoFeB layers and spacer layers are configured to increase output amplitude of the MR element.

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Background/Summary

BACKGROUND

[0001] A magnetic field sensing element describes a variety of electronic elements that can sense a magnetic field. One such magnetic field sensing element is a magnetoresistance (MR) element. An MR element has a resistance that changes in relation to changes in a magnetic field experienced by the MR element. One such example of a MR element is a tunnel magnetoresistance (TMR) element. Another example is a giant magnetoresistance (GMR) element. Magnetic-field sensors may include bridges (e.g., a Wheatstone bridge). The bridges typically include four or more MR elements. MR elements in a bridge may include TMR elements. Each TMR element may include a plurality of pillars. Some MR elements may have a linear response range such that changes in resistance of the MR element is linear to changes in an applied magnetic field.

[0002] MR elements are used in magnetic field sensors. Magnetic field sensors are used in a variety of applications, including, but not limited to, an angle sensor that senses an angle of a direction of a magnetic field; a current sensor that senses a magnetic field generated by a current carried by a current-carrying conductor; a magnetic switch that senses the proximity of a ferromagnetic object; a rotation detector that senses passing ferromagnetic articles, for example, magnetic domains of a ring magnet or a ferromagnetic target (e.g., gear teeth) where the magnetic field sensor is used in combination with a back-biased or other magnet; a magnetic field sensor that senses a magnetic field density of a magnetic field, a linear sensor that senses a position of a ferromagnetic target; and so forth. For angle sensors, one consideration is angular accuracy. Accordingly, a desire for angle sensors is to obtain magnetic sensors with improved angular accuracy.

[0003] There are multiple contributions to the total angle error (e.g., orthogonality, amplitude mismatch, hysteresis etc.). A potential impediment on the movement of the free layer is hysteresis, which is a magnetic phenomenon that impairs this ideal tracking of the free layer with the external field to be sensed. Hysteresis is the relative difference between a forward and a reverse angular (or field) sweep at a given field (or angle). A larger difference results in low accuracy and/or high error. For TMR and GMR based current sensors the ideal response is one which is non-hysteretic, whereby the response to an external field for both forward and reverse directions is perfectly linear. Hysteresis in the response curve for current sensors contributes to sensing inaccuracies. Hysteresis is a contributor to angle error specifically at low fields within the operating region.

SUMMARY

[0004] According to one aspect of the present disclosure, a magnetic field sensor includes a magnetoresistance (MR) element. In some embodiments, the MR element includes a reference layer, a free layer, and a barrier layer. In some embodiments, the free layer includes two or more cobalt iron boron (CoFeB) layers, wherein a first one of the CoFeB layers is in contact with the barrier layer, and two or more spacer layers. In some embodiments, the CoFeB layers and the spacer layers alternate to form a multilayered free layer structure. In some embodiments, the magnetic field sensor comprises an angle sensor or a current sensor. In some embodiments, the contact between the first one of the CoFeB layers and the barrier layer is configured to reduce hysteresis in the MR element. In some embodiments, the alternating CoFeB layers and spacer layers are configured to increase output amplitude of the MR element.

[0005] According to one aspect of the present disclosure, a method includes manufacturing a magnetic field sensor. In some embodiments, the manufacturing includes forming a magnetoresistance (MR) element. In some embodiments, forming the MR element includes

forming a reference layer, forming a barrier layer, and forming a free layer. In some embodiments, forming the free layer includes depositing two or more cobalt iron boron (CoFeB) layers, wherein a first one of the CoFeB layers is in contact with the barrier layer, and depositing two or more spacer layers. In some embodiments, the CoFeB layers and the spacer layers alternate to form a multilayered free layer structure. In some embodiments, manufacturing the magnetic field sensor includes manufacturing the magnetic field sensor as an angle sensor or a current sensor. In some embodiments, the contact between the first one of the CoFeB layers and the barrier layer is configured to reduce hysteresis in the MR element. In some embodiments, the alternating CoFeB layers and spacer layers are configured to increase output amplitude of the MR element.

Description

DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0006] The manner and process of making and using the disclosed embodiments may be appreciated by reference to the figures of the accompanying drawings. It should be appreciated that the components and structures illustrated in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principals of the concepts described herein. Like reference numerals designate corresponding parts throughout the different views. Furthermore, embodiments are illustrated by way of example and not limitation in the figures, in which:

[0007] FIG. **1** is an example stack up for a magnetoresistance (MR) element that includes two or more cobalt iron boron (CoFeB) layers and two or more spacer layers that alternate to form a multilayered free layer structure;

[0008] FIG. **2** is an example stack up for a MR element configured as an angle sensor that includes two CoFeB layers and two spacer layers that alternative to form a multilayered free layer structure;

[0009] FIG. **3** is an example stack up for a MR element configured as a current sensor that includes two CoFeB layers and two spacer layers that alternative to form a multilayered free layer structure;

[0010] FIG. **4** is a graph disclosing a field (mT) vs. an output amplitude (h);

[0011] FIG. **5** is a flowchart showing an example of a process for forming an MR element, such as the MR element in FIG. **1**; and

[0012] FIG. **6** is a block diagram of a MR element configured as a magnetic field sensor placed above a magnetic target for rotational speed measurement.

DETAILED DESCRIPTION

[0013] FIG. **1** shows an example of a magnetoresistance (MR) element **100** configured to detect changes in a magnetic field intensity of an external magnetic field. The MR element **100** changes resistance in response to a change in an applied magnetic field. The MR element **100** may be configured as a single pillar as shown in FIG. **1** or as multiple pillars. The MR element **100** includes a free layer **150** configured to remain free or not fixed or pinned. Accordingly, the free layer **150** is able to track or follow changes in directions or amplitude of external field. The more precisely the free layer **150** can track the external field the more accurately the sensor performs.

[0014] The MR element **100** includes: a seed layer **110**; a reference layer **120** on the seed layer **110**; a barrier layer **140** on the reference layer **120**; a free layer **150** on the barrier layer **140**; and a cap layer **160** on the free layer **150**. In the illustrated example embodiment, the free layer **150** comprises two or more cobalt iron boron (CoFeB) layers **170**, **172**, **174**, **176**, and two or more spacer layers **180**, **182**, **184**, **186**. The CoFeB layers and the spacer layers alternate to form the free layer structure, with a first one of the CoFeB layers **170** in contact with a barrier layer **140**. The barrier layer **140** on the reference layer **120** may comprise magnesium oxide (MgO) having a thickness of about 2 nm+/−0.25 nm thick.

[0015] In one particular embodiment, the free layer **150** includes: a first one of the spacer layers **180** on the first one of the CoFeB layers **170**; a second one of the CoFeB layers **172** on the first one of the spacer layers **180**; a second one of the spacer layer **182** on the second one of the CoFeB layers **172**; a third one of the CoFeB layers **174** on the second one of the spacer layers **182**; a third one of the spacer layers **184** on the third one of the CoFeB layers **174**; a fourth one of the CoFeB layers **176** on the third one of the spacer layers **184**; and a fourth one of the spacer layers **186** on the fourth one of the CoFeB layers **176**.

[0016] The contact between the first one of the CoFeB layers **170** and the barrier layer **140** is configured to reduce hysteresis in the MR element by reducing the thickness of the CoFeB layers. In example embodiments, the CoFeB layers have a thickness ranging from 0.5 nm+/−0.25 nm to about 1 nm+/−0.25 nm. The reduction of hysteresis is achieved, in part, by selecting the thickness of the first one of the CoFeB layers **170**. In embodiments, reducing the CoFeB thickness in comparison to conventional CoFeB layer thickness lowers the hysteresis contribution to the angle error. In an example embodiment, the first one of the CoFeB layers **170** has a thickness of about 0.5 nm (+/−0.25 nm) to about 1 nm (+/−0.25 nm).

[0017] The alternating CoFeB layers and spacer layers are configured to increase output amplitude of the MR element **100**. The positioning of the spacer layers within the CoFeB as well as the number of repetitions of the CoFeB layer and spacer layers tunes the response of the MR element **100**. The signal amplitude of the MR element **100** can be increased by increasing the number of repetitions of the CoFeB layer and spacer layers. The spacer layers are alternating in-between the CoFeB layers such that the total effective thickness of the free layer **150** is sufficient to generate the desired output amplitude, while the first one of the CoFeB layers **170** is thin enough to obtain the lower hysteretic contribution. The spacer layers are placed a sufficient distance from the barrier layer **140** such that the interface between the first one of the CoFeB layers **170** and the barrier layer **140** is preserved. This allows for sufficient coherent tunneling of **3***d* electrons and thereby generates the desired output amplitude.

[0018] The spacer layers comprise a non-magnetic material, such as tantalum having a thickness of about 0.1 nm (+/−0.1 nm) to about 0.2 nm (+/−0.1 nm). In an embodiment, such as MR element **100**, the first one of the spacer layers **180**, the second one of the spacer layers **182**, and the third one of the spacer layers **184** are 0.1 nm thick, while the fourth one of the spacer layers **186** is 0.2 nm thick. The first one of the CoFeB layers **170** may have a thickness that is less than a second one of the CoFeB layers **172**. In an embodiment, such as MR element **100**, the first one of the CoFeB layers **170** is 1 nm thick, while the second one of the CoFeB layers **172**, the third one of the CoFeB layers **174**, and the fourth one of the CoFeB layers **176** are 0.5 nm thick. In an embodiment, such as the MR element **100**, the MR element has four CoFeB layers and four spacer layers. The MR element may have other numbers of CoFeB layers and spacer layers. For example, the MR element may have two CoFeB layers and two spacer layers.

[0019] In addition to the thickness, the ratio of cobalt, iron, and boron that comprise the CoFeB layers may be changed. The ratio changes adjust the amount of spin polarization, resulting in different MR outputs for a given thickness. Further, the saturation magnetization also changes which affects the anisotropy of the CoFeB by changing the ratio the magnetic field at which the material saturates also changes. The higher the saturation, the higher the field. In an embodiment, the CoFeB layers comprise a ratio of 40% cobalt, 40% iron, and 20% boron. In an embodiment, the CoFeB layers comprise a ratio of 20% cobalt, 60% iron, and 20% boron. In another embodiment, the CoFeB layers comprise a ratio of 60% cobalt, 20% iron, and 20% boron.

[0020] In embodiments, the free layer **150** further comprises a NiFe layer **190** on the fourth one of the spacer layers **186**. The NiFe layer **190** comprises nickel iron (NiFe) having a thickness of about 6 nm (+/−1 nm) to about 80 nm (+/−1 nm).

[0021] The seed layer **110** may be disposed or otherwise provided upon a substrate (e.g., a silicon substrate). In one example, the seed layer **110** is a non-magnetic material (e.g., copper nitride (CuN)).

[0022] In one example, the reference layer **120** on the seed layer **110** includes: a antiferromagnetic layer **122** on the seed layer **110**; a ferromagnetic layer **124** on the antiferromagnetic layer **122**; a spacer layer **126** on the ferromagnetic layer **124**; and a ferromagnetic layer **128** on the spacer layer **126**. For a TMR or GMR element used in an angle sensor or current sensor, the reference layer remains fixed and is pinned along a particular direction. The antiferromagnetic layer **122** is called a pinning layer and includes magnetization directions (not shown) that are antiparallel to each other. In one example, the antiferromagnetic layer **122** is platinum manganese, iridium manganese, and so forth having a thickness between about 7 nm (+/−1 nm) to about 18 nm (+/−1 nm).

[0023] In one example, the ferromagnetic layer **124** includes cobalt and has a magnetization direction **130**. The ferromagnetic layer **124** is called a pinned layer as the magnetization direction **130** is pinned by the antiferromagnetic layer **122**. The ferromagnetic layer **124** is cobalt iron having a thickness of about 2.3 nm (+/−0.25 nm).

[0024] The spacer layer **126** includes a nonmagnetic material such a metal, for example, ruthenium. Ruthenium allows for antiferromagnetic or ferromagnetic coupling (also called Ruderman Kittel Kasuya Yoshida (RKKY) coupling) between surrounding layers, according to the thickness of the ruthenium. RKKY coupling decreases and switches between a maximum antiferromagnetic coupling and a maximum ferromagnetic coupling as the thickness of the spacer layer **126** is increased. Accordingly, the ruthenium material permits coupling through the ruthenium material. In one particular example, the spacer layer **126** is ruthenium having a thickness of about 0.8 nm (+/−0.02 nm).

[0025] In one example, the ferromagnetic layer **128** includes CoFeB having a thickness of about 1 nm+/−0.25 nm. The ferromagnetic layer **128** has a magnetization direction **132** and is the reference direction of the MR element **100**. The reference direction is the direction the MR element **100** has the most changes in resistivity with changes in a detected magnetic field. In one particular example, the antiferromagnetic layer **122** is cobalt iron boron having a thickness of about 1.0 nm+/−0.25 nm. The magnetization direction **132** may be parallel or antiparallel to the magnetization direction **130** depending on the thickness of the spacer layer **126**. The cap layer **160** on the free layer **150** may be made from a nonmagnetic or diamagnetic material (e.g., Ta, Cu or Ru) and may be about 10 nm (+/−0.5 nm) thick.

[0026] FIG. **2** shows an example MR element **200** configured for an angle sensor with two CoFeB layers and two spacer layers that alternate to form a multilayered free layer structure. FIG. **3** shows an example of MR element **300** configured for a current sensor with two CoFeB layers and two spacer layers that alternative to form a multilayered free layer structure. Each MR element **200**, **300** includes a free layer **250**, **350** including a NiFe layer **290**, **390**. The thickness of the NiFe layer **290**, **390** may be selected to provide a magnetic field sensor configured as an angle sensor or a current sensor.

[0027] For angle-based sensors, the MR element **200** angular hysteresis is reduced by the multilayered free layer structure allowing for a more accurate angular response. In the illustrated embodiment, the MR element **200** includes: a seed layer **210**; a reference layer **220** on the seed layer **210**; a barrier layer **240** on the reference layer **220**; a free layer **250** on the barrier layer **240**; and a cap layer **260** on the free layer **250**. The seed layer **210**, reference layer **220**, barrier layer **240**, and cap layer **260** maybe similar to or the same as the seed layer **110**, reference layer **120**, barrier layer **140**, and cap layer **160** disclosed in FIG. **1**.

[0028] The reference layer **220** includes: a antiferromagnetic layer **222** on the seed layer **210**; a ferromagnetic layer **224** on the antiferromagnetic layer **222**; a spacer layer **226** on the ferromagnetic layer **224**; and a ferromagnetic layer **228** on the spacer layer **226**. The ferromagnetic layer **224** may be referred to as a pinned layer as the magnetization direction **230** is pinned by the antiferromagnetic layer **222**. The ferromagnetic layer **228** has a magnetization direction **232** that provides a reference direction of the MR element **200**, which is not shown.

[0029] The free layer **250** includes two or more cobalt iron boron (CoFeB) layers **270**, **272**, two or more spacer layers **280**, **282**, and a NiFe layer **290**. The NiFe layer **290** may be made from nickel iron (NiFe) having a thickness of about 6 nm (+/−1 nm). The CoFeB layers and the spacer layers alternative to form the free layer structure, with a first one of the CoFeB layers **270** is in contact with the barrier layer **240**.

[0030] The free layer **250** includes: a first one of the spacer layers **280** on the first one of the CoFeB layers **270**; a second one of the CoFeB layers **272** on the first one of the spacer layers **280**; and a second one of the spacer layers **282** on the second one of the CoFeB layers **272**. The CoFeB layers have a thickness of about 0.5 nm+/−0.25 nm to about 1 nm (+/−0.25 nm) thick. The spacer layers comprise a non-magnetic material, such as tantalum having a thickness of about 0.1 nm (+/−0.1 nm) to about 0.2 nm (+/−0.1 nm).

[0031] In an embodiment, the first one of the CoFeB layers **270** has a thickness that is less than a second one of the CoFeB layers **272**. In such an embodiment, such as MR element **200**, the first one of the CoFeB layers **270** is 1 nm thick, while the second one of the CoFeB layers **272** is 0.5 nm thick. The first one of the spacer layers **280** is 0.1 nm thick, while the second one of the spacer layers **282** is 0.2 nm thick.

[0032] For current-based sensors, such as the MR element **300**, the field sweep based hysteresis is reduced by the multilayered free layer structure providing for a more accurate linear response. The MR element **300** includes: a seed layer **310**; a reference layer **320** on the seed layer **310**; a barrier layer **340** on the reference layer **320**; a free layer **350** on the barrier layer **340**; and a cap layer **360** on the free layer **250**. The seed layer **310**, reference layer **320**, barrier layer **340**, and cap layer **360** maybe similar to or the same as the seed layer **110**, reference layer **120**, barrier layer **140**, and cap layer **160** in FIG. **1**.

[0033] The reference layer **320** includes: a antiferromagnetic layer **322** on the seed layer **310**; a ferromagnetic layer **324** on the antiferromagnetic layer **322**; a spacer layer **326** on the ferromagnetic layer **324**; and a ferromagnetic layer **328** on the spacer layer **326**. The ferromagnetic layer **324** is called a pinned layer as the magnetization direction **330** is pinned by the antiferromagnetic layer **322**. The ferromagnetic layer **328** has a magnetization direction **332** and is the reference direction of the MR element **300**, which is not shown.

[0034] The free layer **350** includes: two or more cobalt iron boron (CoFeB) layers **370**, **372**, two or more spacer layers **380**, **382**, and a vortex layer **390**. The vortex layer **390** may be made from nickel iron (NiFe) having a thickness of about 80 nm (+/−1 nm). According to an aspect of the disclosure, the thickness of the NiFe layer induces a vortex in the vortex layer **390**. Illustrative vortexes that may be used within MR element **300** are described, for example, in co-pending U.S. patent application Ser. No. 17/806,336, having Publication No. US2023/0400537 and entitled “Magnetic Field Current Sensor to Reduce Stray Magnetic Fields” which is hereby incorporated by reference in its entirety. The CoFeB layers and the spacer layers alternate to form the free layer structure, with a first one of the CoFeB layers **370** is in contact with the barrier layer **340**.

[0035] The free layer structure includes a first one of the spacer layers **380** on the first one of the CoFeB layers **370**; a second one of the CoFeB layers **372** on the first one of the spacer layers **380**; and a second one of the spacer layers **382** on the second one of the CoFeB layers **372**. The CoFeB layers have a thickness of about 0.5 nm (+/−0.25 nm) to about 1 nm (+/−0.25 nm). The spacer layers comprise a non-magnetic material, such as tantalum having a thickness of about 0.1 nm (+/−0.1 nm) to 0.2 nm (+/−0.1 nm).

[0036] In an embodiment, the first one of the CoFeB layers **370** has a thickness that is less than a second one of the CoFeB layers **372**. In such an embodiment, such as MR element **300**, the first one of the CoFeB layers **370** is 1 nm thick, while the second one of the CoFeB layers **372** is 0.5 nm thick. The first one of the spacer layers **380** is 0.1 nm thick, while the second one of the spacer layers **382** is 0.2 nm thick.

[0037] FIG. **4** is a graph **400** of field (mT) **410** vs. an output amplitude (h) **420** for a first MR element **430** with a multilayered free layer structure having two repetitions of CoFeB layers and spacer layers, which alternate to form the free layer structure and a second MR element **440** with a multilayered free layer structure having five repetitions of CoFeB layers and spacer layers, which alternate to form the free layer structure. The CoFeB layers and spacer layers that make up the structures of the MR elements **430**, **440** have the same size and the CoFeB layers have the same composition. The CoFeB layers have a thickness of 0.5 nm and the spacer layers have a thickness of 0.1 nm. The CoFeB layers comprise a ratio of 60% cobalt, 20% iron, and 20% boron. As demonstrated by graph **400**, increasing the number of repetitions of CoFeB layers and spacer layers increases the total output amplitude of the MR element.

[0038] FIG. **5** shows a flowchart of example of a process **500** for forming an MR element, such as the MR element **100** in FIG. **1**. Process **500** forms a reference layer in block **510**. Process **500** forms a barrier layer in block **512**. Process **500** forms a free layer in block **514**. Process **500** deposits two or more cobalt iron boron (CoFeB) layers, with a first CoFeB layer is in direct contact with the barrier layer in block **516**. Process **500** deposits two or more spacer layers in block **518**. The CoFeB layers and the spacer layers alternate to form a multilayered free layer structure.

[0039] Referring now to FIG. **6**, a magnetic field sensor **600** can include one or more magnetoresistance elements. Here, four magnetoresistance elements, which can be of a type described above in conjunction with FIG. **1**, are arranged over a common substrate. The four magnetoresistance elements can be arranged in a bridge. Other electronic components (not shown), for example, amplifiers and processors, i.e., an electronic circuit, can also be integrated upon the common substrate. In some embodiments, the electronic circuit can generate an output signal indicative of a movement, e.g., a rotation, of an object, e.g., **602**.

[0040] A surrounding package (not shown) e.g., a plastic package, can surround or otherwise be included with the magnetic field sensor **600**. Also, a leadframe (not shown) can be coupled to or otherwise be included with the magnetic field sensor **600**.

[0041] The magnetic field sensor **600** can be disposed proximate to a moving magnetic object, for example, a ring magnet **602** having alternating north and south magnetic poles. The ring magnet **602** is subject to rotation.

[0042] The magnetic field sensor **600** can be configured to generate an output signal indicative of at least a speed of rotation of the ring magnet. In some arrangements, the ring magnet **602** is coupled to a target object, for example, a cam shaft in an engine, and the sensed speed of rotation of the ring magnet **602** is indicative of a speed of rotation of the target object. While the magnetic field sensor **600** is used as a rotation detector, it should be understood that other similar magnetic field sensors, for example, current sensors, having one or more the magnetoresistance elements of FIG. **1** can also be realized.

[0043] Depending on the device type and other application requirements, the magnetic field sensing element may be a device made of a type IV semiconductor material such as Silicon (Si) or Germanium (Ge), or a type Ill-V semiconductor material like Gallium-Arsenide (GaAs) or an Indium compound, e.g., Indium-Antimonide (InSb).

[0044] Although reference is made herein to particular materials, it is appreciated that other materials having similar functional and/or structural properties may be substituted where appropriate, and that a person having ordinary skill in the art would understand how to select such materials and incorporate them into embodiments of the concepts, techniques, and structures set forth herein without deviating from the scope of those teachings.

[0045] Various embodiments of the concepts, systems, devices, structures and techniques sought to be protected are described herein with reference to the related drawings. Alternative embodiments can be devised without departing from the scope of the concepts, systems, devices, structures and techniques described herein. It is noted that various connections and positional relationships (e.g., over, below, adjacent, etc.) are set forth between elements in the following description and in the drawings. These connections and/or positional relationships, unless specified otherwise, can be direct or indirect, and the described concepts, systems, devices, structures and techniques are not intended to be limiting in this respect. 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.

[0046] 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). 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.

[0047] 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 “one or more” is 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.”

[0048] 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 can 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.

[0049] 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, where 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 elements.

[0050] Use of ordinal terms such as “first,” “second,” “third,” etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

[0051] The terms “approximately” and “about” may be used to mean within ±20% of a target value in some embodiments, within ±10% of a target value in some embodiments, within ±5% of a target value in some embodiments, and yet within ±2% of a target value in some embodiments. The terms “approximately” and “about” may include the target value. The term “substantially equal” may be used to refer to values that are within ±20% of one another in some embodiments, within ±10% of one another in some embodiments, within ±5% of one another in some embodiments, and yet within ±2% of one another in some embodiments.

[0052] The term “substantially” may be used to refer to values that are within ±20% of a comparative measure in some embodiments, within ±10% in some embodiments, within ±5% in some embodiments, and yet within ±2% in some embodiments. For example, a first direction that is "substantially" perpendicular to a second direction may refer to a first direction that is within ±20% of making a 90° angle with the second direction in some embodiments, within ±10% of making a 90° angle with the second direction in some embodiments, within ±5% of making a 90° angle with the second direction in some embodiments, and yet within ±2% of making a 90° angle with the second direction in some embodiments.

[0053] It is to be understood that the disclosed subject matter is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The disclosed subject matter is capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting. As such, those skilled in the art will appreciate that the conception, upon which this disclosure is based, may readily be utilized as a basis for the designing of other structures, methods, and systems for carrying out the several purposes of the disclosed subject matter. Therefore, the claims should be regarded as including such equivalent constructions insofar as they do not depart from the spirit and scope of the disclosed subject matter.

[0054] Although the disclosed subject matter has been described and illustrated in the foregoing exemplary embodiments, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the details of implementation of the disclosed subject matter may be made without departing from the spirit and scope of the disclosed subject matter.

Claims

1. A magnetic field sensor, comprising: a magnetoresistance (MR) element including: a reference layer, a free layer, and a barrier layer; wherein the free layer comprises: two or more cobalt iron boron (CoFeB) layers, wherein a first one of the CoFeB layers is in contact with the barrier layer; and two or more spacer layers, wherein the CoFeB layers and the spacer layers alternate to form a multilayered free layer structure.

2. The sensor of claim 1, wherein the magnetic field sensor comprises an angle sensor or a current sensor.

3. The sensor of claim 1, wherein the contact between the first one of the CoFeB layers and the barrier layer is configured to reduce hysteresis in the MR element.

4. The sensor of claim 1, wherein the first one of the CoFeB layers has a thickness that is less than a second one of the CoFeB layers.

5. The sensor of claim 1, wherein the first one of the CoFeB layers in direct contact with the barrier layer has a thickness of about 0.5 nanometers to about 1 nanometers.

6. The sensor of claim 1, wherein the alternating CoFeB layers and spacer layers are configured to increase output amplitude of the MR element.

7. The sensor of claim 1, wherein the MR element has four CoFeB layers and four spacer layers.

8. The sensor of claim 1, wherein the MR element has two CoFeB layers and two spacer layers.

9. The sensor of claim 1, wherein the spacer layers have a thickness of about 0.1 nanometers to about 0.2 nanometers.

10. The sensor of claim 1, wherein the CoFeB layers have a thickness of about 0.5 nanometers to about 1 nanometers.

11. The sensor of claim 1, wherein the MR element further comprises: a cap layer; and a seed layer, wherein the reference layer is located between the seed layer and the barrier layer, and wherein the free layer is located between the barrier layer and the cap layer.

12. A method, comprising: manufacturing a magnetic field sensor, the manufacturing comprising: forming a magnetoresistance (MR) element, wherein forming the MR element comprises: forming a reference layer; forming a barrier layer; and forming a free layer, wherein forming the free layer comprises: depositing two or more cobalt iron boron (CoFeB) layers, wherein a first one of the CoFeB layers is in contact with the barrier layer; and depositing two or more spacer layers, wherein the CoFeB layers and the spacer layers alternate to form a multilayered free layer structure.

13. The method of claim 12, wherein manufacturing the magnetic field sensor comprises manufacturing the magnetic field sensor as an angle sensor or a current sensor.

14. The method of claim 12, wherein the contact between the first one of the CoFeB layers and the barrier layer is configured to reduce hysteresis in the MR element.

15. The method of claim 12, wherein the first one of the CoFeB layers has a thickness that is less than a second one of the CoFeB layers.

16. The method of claim 12, wherein the first one of the CoFeB layers in direct contact with the barrier layer has a thickness of about 0.5 nanometers to about 1 nanometers.

17. The method of claim 12, wherein the alternating CoFeB layers and spacer layers are configured to increase output amplitude of the MR element.

18. The method of claim 12, wherein the depositing of two or more CoFeB layers comprises depositing four CoFeB layers and the depositing of two or more spacer layers comprises depositing four spacer layers.

19. The method of claim 12, wherein the depositing of two or more CoFeB layers comprises depositing two CoFeB layers and the depositing of two or more spacer layers comprises depositing two spacer layers.

20. The method of claim 12, wherein the spacer layers have a thickness of about 0.1 nanometers to about 0.2 nanometers.

21. The method of claim 12, wherein the CoFeB layers have a thickness of about 0.5 nanometers to about 1 nanometers.

22. The method of claim 12, further comprising: forming a cap layer; and forming a seed layer, wherein the reference layer is formed between the seed layer and the barrier layer, and wherein forming the free layer comprises forming the free layer between the barrier layer and the cap layer.