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MAGNETORESISTIVE EFFECT ELEMENT, MAGNETIC FIELD DETECTION DEVICE, AND MAGNETIC SENSOR SYSTEM

Abstract

A magnetoresistive effect element includes a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction. An outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority from Japanese Patent Application No. 2024-023438 filed on Feb. 20, 2024, the entire contents of which are hereby incorporated by reference.

BACKGROUND

[0002] The disclosure relates to a magnetoresistive effect element, and to a magnetic field detection device and a magnetic sensor system that each include the magnetoresistive effect element.

[0003] A magnetic sensor including a magnetoresistive effect element has been used in various applications. The magnetoresistive effect element includes, for example, a magnetization pinned layer having a magnetization pinned in a certain direction, a magnetization free layer having a magnetization whose direction is changeable in accordance with a direction of an applied magnetic field, and a nonmagnetic layer disposed between the magnetization pinned layer and the magnetization free layer.

[0004] Further, for example, Japanese Unexamined Patent Application Publication (JP-A) No. 2023-055294 proposes a magnetoresistive effect element including a first magnetic layer, a nonmagnetic layer, and a second magnetic layer arranged in order. The first magnetic layer has a magnetic shape anisotropy set in a first reference direction and has a magnetization whose direction changes in accordance with an external magnetic field. The second magnetic layer has a magnetic shape anisotropy set in a second reference direction intersecting the first reference direction and has a magnetization whose direction changes in accordance with the external magnetic field. JP-A No. 2023-055294 further discloses a magnetic sensor that detects an intensity and a direction of the external magnetic field, based on a change in resistance value of the magnetoresistive effect element in response to a change in the external magnetic field.

[0005] International Publication No. WO 2020/250489 proposes a magnetic sensor including a magnetic field intensity sensor and a magnetic field angle sensor.

SUMMARY

[0006] A magnetoresistive effect element according to one embodiment of the disclosure includes a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction. An outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.

[0007] A magnetic field detection device according to one embodiment of the disclosure includes one or more magnetoresistive effect elements. The one or more magnetoresistive effect elements each include a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction. An outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.

[0008] A magnetic field detection device according to one embodiment of the disclosure includes a bridge circuit including first to fourth magnetoresistive effect elements. The first to fourth magnetoresistive effect elements each include a stacked structure including a magnetization pinned layer, a second nonmagnetic layer, a second magnetization free layer, a first nonmagnetic layer, and a first magnetization free layer that are stacked in order in a stacking direction. The first magnetization free layer has an easy axis of magnetization along the stacking direction. The second magnetization free layer has a hard axis of magnetization along the stacking direction.

[0009] A magnetic sensor system according to one embodiment of the disclosure includes a magnetic field detection device, and a magnetic field generator generating a magnetic field. The magnetic sensor system is configured to change a direction of the magnetic field applied to the magnetic field detection device, by causing the magnetic field detection device and the magnetic field generator to rotate relative to each other around a first axis as a center of rotation, and configured to change an intensity of the magnetic field applied to the magnetic field detection device, by changing relative positions of the magnetic field detection device and the magnetic field generator along the first axis. The magnetic field detection device includes one or more magnetoresistive effect elements. The one or more magnetoresistive effect elements each include a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction. An outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The accompanying drawings are included to provide a further understanding of the disclosure, and are incorporated in and constitute a part of this specification. The drawings illustrate embodiments and, together with the specification, serve to explain the principles of the disclosure.

[0011] FIG. **1**A is a perspective diagram illustrating an outer appearance of a magnetoresistive effect element according to one example embodiment of the disclosure.

[0012] FIG. **1**B is a cross-sectional diagram illustrating a cross-sectional configuration of the magnetoresistive effect element illustrated in FIG. **1**A.

[0013] FIG. **2** is a characteristic diagram illustrating a relationship between a magnetic flux density of an external magnetic field applied to the magnetoresistive effect element illustrated in FIG. **1**A and a resistance value of the magnetoresistive effect element.

[0014] FIGS. **3**A to **3**F are explanatory diagrams that schematically describe a relationship between a magnitude of the magnetic flux density of the external magnetic field applied to the magnetoresistive effect element illustrated in FIG. **1**A and directions of magnetizations.

[0015] FIG. **4** is a cross-sectional diagram illustrating a cross-sectional configuration of a magnetoresistive effect element according to a first modification example of the example embodiment illustrated in FIG. **1**A.

[0016] FIG. **5** is a characteristic diagram illustrating a relationship between the magnetic flux density of an external magnetic field applied to the magnetoresistive effect element illustrated in FIG. **4** and the resistance value of the magnetoresistive effect element.

[0017] FIGS. **6**A to **6**F are explanatory diagrams that schematically describe a relationship between the magnitude of the magnetic flux density of the external magnetic field applied to the magnetoresistive effect element illustrated in FIG. **4** and the directions of the magnetizations.

[0018] FIG. **7** is a cross-sectional diagram illustrating a cross-sectional configuration of a magnetoresistive effect element according to a second modification example of the example embodiment illustrated in FIG. **1**A.

[0019] FIG. **8** is a perspective diagram illustrating an outer appearance of a magnetoresistive effect element according to a third modification example of the example embodiment illustrated in FIG. **1**A.

[0020] FIG. **9** is a characteristic diagram illustrating a relationship between the magnetic flux density of an external magnetic field applied to the magnetoresistive effect element illustrated in FIG. **8** and the resistance value of the magnetoresistive effect element.

[0021] FIGS. **10**A to **10**E are explanatory diagrams that schematically describe a relationship between the magnitude of the magnetic flux density of the external magnetic field applied to the magnetoresistive effect element illustrated in FIG. **8** and the direction of a magnetization.

[0022] FIG. **11** is a cross-sectional diagram illustrating a cross-sectional configuration of a magnetoresistive effect element according to a fourth modification example of the example embodiment illustrated in FIG. **1**A.

[0023] FIG. **12** is a characteristic diagram illustrating a relationship between the magnetic flux density of an external magnetic field applied to the magnetoresistive effect element illustrated in

FIG. **11** and the resistance value of the magnetoresistive effect element.

[0024] FIGS. **13**A to **13**E are explanatory diagrams that schematically describe a relationship between the magnitude of the magnetic flux density of the external magnetic field applied to the magnetoresistive effect element illustrated in FIG. **11** and the directions of the magnetizations.

[0025] FIG. **14** is a circuit diagram schematically illustrating a circuit configuration of a magnetic field detection device according to one example embodiment of the disclosure.

[0026] FIG. **15** is a characteristic diagram schematically illustrating a relationship between a differential output outputted from a bridge circuit of the magnetic field detection device illustrated in FIG. **14** and an intensity of the external magnetic field.

[0027] FIG. **16** is a circuit diagram schematically illustrating a circuit configuration of a magnetic field detection device according to one example embodiment of the disclosure.

[0028] FIG. **17** is a circuit diagram schematically illustrating a circuit configuration of a magnetic field detection device according to one example embodiment of the disclosure.

[0029] FIG. **18** is a perspective diagram schematically illustrating a magnetic sensor system according to one example embodiment of the disclosure.

DETAILED DESCRIPTION

[0030] It is desired that a magnetic field detection device including a magnetoresistive effect element be more simple in configuration from a viewpoint of manufacturability or cost savings.

[0031] It is desirable to provide a magnetic field detection device and a magnetic sensor system that are each simple in configuration and yet make it possible to isotropically detect an intensity of an external magnetic field without dependence on a direction of the external magnetic field, and to provide a magnetoresistive effect element for use in such a magnetic field detection device or magnetic sensor system.

[0032] In the following, some example embodiments of the disclosure are described in detail with reference to the accompanying drawings. Note that the following description is directed to illustrative examples of the disclosure and not to be construed as limiting to the disclosure. Factors including, without limitation, numerical values, shapes, materials, components, positions of the components, and how the components are coupled to each other are illustrative only and not to be construed as limiting to the disclosure. Further, elements in the following example embodiments which are not recited in a most-generic independent claim of the disclosure are optional and may be provided on an as-needed basis. The drawings are schematic and are not intended to be drawn to scale. Throughout the present specification and the drawings, elements having substantially the same function and configuration are denoted with the same reference numerals to avoid any redundant description. In addition, elements that are not directly related to any embodiment of the disclosure are unillustrated in the drawings. Note that the description is given in the following order. [0033] 0. Background [0034] 1. First Example Embodiment and Modification Examples thereof [0035] Examples of a magnetoresistive effect element including two magnetization free layers. [0036] 2. Second Example Embodiment [0037] An example of a first magnetic field detection device with a circuit including a magnetoresistive effect element. [0038] 3. Third Example Embodiment [0039] An example of a second magnetic field detection device with a circuit including a magnetoresistive effect element. [0040] 3. Fourth Example Embodiment [0041] An example of a third magnetic field detection device with a circuit including a magnetoresistive effect element. [0042] 4. Fifth Example Embodiment [0043] An example of an application including the magnetic field detection device.

0. Background

[0044] A magnetic field angle sensor to detect a direction of an external magnetic field has been widely used. Such a magnetic field angle sensor includes, for example, a magnetoresistive effect element in which a magnetization free layer and a magnetization pinned layer are stacked with a nonmagnetic layer interposed therebetween. The magnetization free layer has a magnetization whose direction rotates in accordance with the direction of the external magnetic field. The magnetization pinned layer has a magnetization whose direction remains unchanged irrespective of the external magnetic field. The magnetic field angle sensor acquires angle data on the external magnetic field, based on a change in resistance value of the magnetoresistive effect element that depends on a relative angle between respective magnetization directions of the magnetization free layer and the magnetization pinned layer.

[0045] However, intensity data on the external magnetic field is difficult to acquire with the magnetic field angle sensor. To detect the intensity of the external magnetic field, it is thus necessary to separately provide a magnetic field intensity sensor including a magnetoresistive effect element or any other suitable element. In a case of the magnetoresistive effect element including the magnetization pinned layer, it is necessary that the relative angle between the respective magnetization directions of the magnetization free layer and the magnetization pinned layer be caused to change in accordance with the intensity of the external magnetic field in an in-plane direction in a stack plane orthogonal to a stacking direction; however, an effective magnetic field component, on the magnetization free layer, contributing to the above-described relative angle varies depending on the direction of the external magnetic field. It is therefore difficult to acquire intensity data for all of the in-plane directions in the stack plane.

[0046] To address this, JP-A No. 2023-055294 proposes a magnetoresistive effect element without any magnetization pinned layer. However, the magnetoresistive effect element disclosed in JP-A No. 2023-055294 includes two magnetization free layers having their respective magnetic shape anisotropies in different directions from each other. Accordingly, there is room for improvement in that, in JP-A No. 2023-055294, the two magnetization free layers are to be formed separately.

[0047] In view of the above-described circumstances, the Applicant provides a magnetoresistive effect element, a magnetic field sensor, and a magnetic sensor system that each have a simple configuration superior in manufacturability and yet help to isotropically detect the intensity of the external magnetic field without dependence on the direction of the external magnetic field.

1. First Example Embodiment

[Configuration of Magnetoresistive Effect Element **10**]

[0048] A description will be given first of a configuration of a magnetoresistive effect element **10** according to a first example embodiment of the disclosure with reference to FIGS. **1**A and **1**B. FIG. **1**A is a perspective diagram illustrating a visual configuration example of the magnetoresistive effect element **10**. FIG. **1**B is a cross-sectional diagram illustrating a cross-sectional configuration example of the magnetoresistive effect element **10**. The magnetoresistive effect element **10** may correspond to a specific but non-limiting example of a “magnetoresistive effect element” in one embodiment of the disclosure.

[0049] As illustrated in FIG. **1**A, the magnetoresistive effect element **10** includes a stacked structure S**10**. The stacked structure S**10** may have an external appearance of a substantially circular columnar shape with a central axis CA. A direction of a height of the magnetoresistive effect element **10** along the central axis CA is defined herein as a z direction. A direction of a radius, of the magnetoresistive effect element **10** having the substantially circular columnar shape, orthogonal to the z direction is defined herein as an r direction. FIG. **1**B thus illustrates the cross-sectional configuration example along the z direction. Note that the r direction refers to any of in-plane directions orthogonal to the z direction, and does not refer to a specific one of such directions.

[0050] The magnetoresistive effect element **10** includes the stacked structure S**10** including, for example, a first magnetization free layer **11**, a nonmagnetic layer **13**, and a second magnetization free layer **12** that are stacked in order along the z direction as a stacking direction. An outer edge of the stacked structure S**10** along a stack plane, i.e., a plane orthogonal to the z direction, has an isotropic shape. For example, the outer edge of the stacked structure S**10** along the stack plane orthogonal to the z direction may have a circular shape. As used herein, the term “circular shape” is not limited to a geometrically exact circular shape, that is, a perfect circular shape, and conceptually encompasses a circular shape with an error that is difficult to avoid, such as a manufacturing error or a measurement error. For example, a portion of a circumference of the circular shape may include a slight imperfection such as a slight chip, depression, or protrusion. Further, the "circular shape" herein may be slightly elongated, in which case, for example, a ratio of a minimum diameter to a maximum diameter may be higher than or equal to 0.9 and less than or equal to 1.0. Moreover, as used herein, the term "isotropic shape" is not limited to a circular shape, and conceptually encompasses a regular polygonal shape. Non-limiting examples of the regular polygonal shape may include a regular hexagonal shape and a regular octagonal shape. The "regular polygonal shape" herein is not limited to a geometrically exact regular polygonal shape, and conceptually encompasses a regular polygonal shape with an error that is difficult to avoid, such as a manufacturing error or a measurement error. For example, a portion of an outer edge of the regular polygonal shape may include a slight imperfection such as a slight chip, depression, or protrusion. Further, sides constituting the regular polygonal shape may differ in length from each other by about 10%.

[0051] The first magnetization free layer **11** may have a magnetization M**11** that changes direction in accordance with an external magnetic field. The first magnetization free layer **11** may have an easy axis of magnetization along the z direction, for example. In other words, a magnetization stabilizing direction of the first magnetization free layer **11** may be parallel to the z direction. Accordingly, in an initial state where no external magnetic field is applied, the magnetization M**11** may be oriented in a direction closer to the z direction than to the r direction.

[0052] The second magnetization free layer **12** may have a magnetization M**12** that changes direction in accordance with the external magnetic field. The second magnetization free layer **12** may have a hard axis of magnetization along the z direction, for example. In other words, a magnetization stabilizing direction of the second magnetization free layer **12** may be any of the in-plane directions in the stack plane orthogonal to the z direction. Accordingly, in an initial state where no external magnetic field is applied, the magnetization M**12** may be oriented in a direction closer to the r direction than to the z direction.

[0053] The first magnetization free layer **11** and the second magnetization free layer **12** may each be a soft ferromagnetic layer, and may include a material such as CoFe, NiFe, or CoFeB. The material included in the first magnetization free layer **11** and the material included in the second magnetization free layer **12** may be the same or different from each other in kind. Further, an anisotropic magnetic field intensity of the first magnetization free layer **11** and an anisotropic magnetic field intensity of the second magnetization free layer **12** may be different from each other.

[0054] When the stacked structure S**10** has a magnetic tunnel junction (MTJ) structure, the nonmagnetic layer **13** may be a nonmagnetic tunnel barrier layer including, for example, a metal oxide such as magnesium oxide (MgO). When the nonmagnetic layer **13** is the tunnel barrier layer, the nonmagnetic layer **13** may be thin to the extent that a tunnel current based on quantum mechanics is allowed to pass through. In some embodiments, the nonmagnetic layer **13** may be a nonmagnetic electrically-conductive layer including a nonmagnetic metal such as a platinum group element or copper (Cu). Non-limiting examples of the platinum group element may include ruthenium (Ru) and gold (Au). In such a case, the stacked structure S**10** may be a giant magnetoresistive effect (GMR) film.

[0055] The magnetoresistive effect element **10** may be of a current-perpendicular-to-plane (CPP) type that allows a current for signal detection to flow in a direction substantially perpendicular to the stack plane in which the first magnetization free layer **11**, the nonmagnetic layer **13**, and the second magnetization free layer **12** each extend. When the current flows in the z direction through the magnetoresistive effect element **10** in a state where an external magnetic field is applied thereto, the magnetoresistive effect element **10** exhibits a resistance value corresponding to the external magnetic field. When the external magnetic field applied to the magnetoresistive effect element **10** changes, the resistance value of the magnetoresistive effect element **10** also changes.

[0056] A first coupling terminal T**1** may be coupled to the first magnetization free layer **11** via a wiring W**1**. A second coupling terminal T**2** may be coupled to the second magnetization free layer **12** via a wiring W**2**. Applying a voltage between the first coupling terminal T**1** and the second coupling terminal T**2** causes a current to flow through the magnetoresistive effect element **10** in the z direction.

[Behavior of Magnetoresistive Effect Element **10**]

[0057] Reference is now made to FIG. **2** and FIGS. **3**A to **3**F to describe a behavior of the magnetoresistive effect element **10**. FIG. **2** is a characteristic diagram illustrating a relationship between a magnetic flux density B of an external magnetic field applied to the magnetoresistive effect element **10** and a resistance value R of the magnetoresistive effect element **10** when a current is fed through the magnetoresistive effect element **10** in the z direction. In FIG. **2**, the horizontal axis represents the magnetic flux density B, and the vertical axis represents the resistance value R FIGS. **3**A to **3**F are explanatory diagrams schematically illustrating the behavior of the magnetoresistive effect element **10** when the external magnetic field is applied, in other words, how the magnetizations M**11** and M**12** change in accordance with a magnitude of the magnetic flux density B of the external magnetic field applied to the magnetoresistive effect element **10**.

[0058] FIG. **3**A illustrates directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to −B**3** in the characteristic diagram of FIG. **2**. FIG. **3**B illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to −B**2** in the characteristic diagram of FIG. **2**. FIG. **3**C illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to −B**1** in the characteristic diagram of FIG. **2**. FIG. **3**D illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to B**1** in the characteristic diagram of FIG. **2**. FIG. **3**E illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to B**2** in the characteristic diagram of FIG. **2**. FIG. **3**F illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to B**3** in the characteristic diagram of FIG. **2**. Note that B**1** and −B**1** are equal in absolute value, B**2** and −B**2** are equal in absolute value, and B**3** and −B**3** are equal in absolute value. A length and a direction of a hollow arrow illustrated in each of FIGS. **3**A to **3**F represent an intensity and a direction, respectively, of the external magnetic field applied to the magnetoresistive effect element **10**. For example, the hollow arrow having a greater length indicates that the external magnetic field has a greater intensity. Further, FIGS. **3**A to **3**C indicate that the external magnetic field is applied to the magnetoresistive effect element **10** in a leftward direction in the sheet plane, and FIGS. **3**D to **3**F indicate that the external magnetic field is applied to the magnetoresistive effect element **10** in a rightward direction in the sheet plane. Note that the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is zero (0) in the characteristic diagram of FIG. **2** are as illustrated in FIG. **1**B.

[0059] As indicated in FIGS. **2** and **3**A to **3**F, the direction of the magnetization M**11** of the first magnetization free layer **11** changes in accordance with the magnitude of the magnetic flux density B. In contrast, the second magnetization free layer **12** easily becomes magnetically saturated by application of the external magnetic field, and the direction of the magnetization M**12** of the second magnetization free layer **12** approaches the direction in which the external magnetic field is applied, irrespective of the magnitude of the magnetic flux density B. Further, the resistance value R of the magnetoresistive effect element **10** reaches a maximum resistance value Rmax when the magnetic flux density B is zero. One reason for this is that when the magnetic flux density B is zero, the direction of the magnetization M**11** of the first magnetization free layer **11** is in a state of being substantially parallel to the z direction, which causes an angle between the direction of the magnetization M**11** and the direction of the magnetization M**12** that is stable in a +r direction or a −r direction orthogonal to the z direction to become maximum, i.e., 90°.

[0060] As the absolute value of the magnetic flux density B increases from zero, the resistance value R of the magnetoresistive effect element **10** gradually decreases and approaches a constant value (R=R**3**). For example, a resistance value R**1** lower than the maximum resistance value Rmax, a resistance value R**2** lower than the resistance value R**1**, and the resistance value R**3** lower than the resistance value R**2** will result. One reason for this is that as the magnetic flux density B increases, the direction of the magnetization M**11** of the first magnetization free layer **11** gradually tilts from the state of being substantially parallel to the z direction and approaches being parallel to the +r direction or the −r direction.

Example Effects of Magnetoresistive Effect Element **10**

[0061] In this way, the magnetoresistive effect element **10** exhibits a change in resistance value corresponding to the intensity (i.e., the magnetic flux density) of the external magnetic field applied to the magnetoresistive effect element **10**. Therefore, understanding a correlation between the intensity (i.e., the magnetic flux density) of the external magnetic field and the resistance value of the magnetoresistive effect element **10** in advance helps to calculate the intensity of the external magnetic field through detection of the change in the resistance value. In the magnetoresistive effect element **10**, the outer edge of the stacked structure S**10** along the stack plane orthogonal to the z direction may have a circular shape. This helps to isotropically detect the intensity of the external magnetic field without dependence on the direction of the external magnetic field.

Modification Examples of First Example Embodiment

First Modification Example

[0062] FIG. **4** is a cross-sectional diagram illustrating a cross-sectional configuration example of a magnetoresistive effect element **10**A according to a first modification example (hereinafter, “Modification Example 1-1”) of the first example embodiment of the disclosure. FIG. **4** corresponds to FIG. **1**B illustrating the magnetoresistive effect element **10** according to the foregoing first example embodiment. In the stacked structure S**10** of the magnetoresistive effect element **10** according to the foregoing first example embodiment, the direction of the magnetization M**11** of the first magnetization free layer **11** in the initial state may be substantially parallel to the z direction, and the direction of the magnetization M**12** of the second magnetization free layer **12** in the initial state may be substantially parallel to the r direction. In contrast, in a stacked structure S**10**A of the magnetoresistive effect element **10**A according to Modification Example 1-1, the direction of the magnetization M**12** of the second magnetization free layer **12** in the initial state may be substantially parallel to the z direction. In the stacked structure S**10**A of the magnetoresistive effect element **10**A, both the first magnetization free layer **11** and the second magnetization free layer **12** may thus have the easy axis of magnetization along the z direction. However, the direction of the magnetization M**11** in the initial state may be substantially parallel to a +z direction, and the direction of the magnetization M**12** in the initial state may be substantially parallel to a −z direction. In other words, in the magnetoresistive effect element **10**A, the direction of the magnetization M**11** and the direction of the magnetization M**12** may be nearly antiparallel to each other in the initial state. The magnetoresistive effect element **10**A may be otherwise substantially the same in configuration as the magnetoresistive effect element **10**.

[0063] FIG. **5** is a characteristic diagram illustrating a relationship between the magnetic flux density B of an external magnetic field applied to the magnetoresistive effect element **10**A and a resistance value RA of the magnetoresistive effect element **10**A when a current is fed through the magnetoresistive effect element **10**A in the z direction. In FIG. **5**, the horizontal axis represents the magnetic flux density B, and the vertical axis represents the resistance value RA. FIGS. **6**A to **6**F are explanatory diagrams schematically illustrating the behavior of the magnetoresistive effect element **10**A when the external magnetic field is applied, in other words, how the magnetizations M**11** and M**12** change in accordance with the magnitude of the magnetic flux density B of the external magnetic field applied to the magnetoresistive effect element **10**A. FIG. **5** corresponds to FIG. **2** illustrating the characteristic diagram of the magnetoresistive effect element **10** of the foregoing first example embodiment. FIGS. **6**A to **6**F correspond to FIGS. **3**A to **3**F illustrating the explanatory diagrams of the magnetoresistive effect element **10** of the foregoing first example embodiment.

[0064] As illustrated in FIGS. **5** and **6**A to **6**F, the magnetoresistive effect element **10**A exhibits a behavior similar to that of the magnetoresistive effect element **10** of the foregoing first example embodiment in response to the external magnetic field applied to the magnetoresistive effect element **10**A. For example, the resistance value RA of the magnetoresistive effect element **10**A reaches a maximum resistance value RAmax when the magnetic flux density B is zero. Note that the maximum resistance value RAmax of the magnetoresistive effect element **10**A is larger than the maximum resistance value Rmax of the magnetoresistive effect element **10**. One reason for this is that when the magnetic flux density B is zero, the direction of the magnetization M**11** of the first magnetization free layer **11** is in a state of being substantially parallel to the +z direction and the direction of the magnetization M**12** of the second magnetization free layer **11** is in a state of being substantially parallel to the −z direction, which causes the angle between the direction of the magnetization M**11** and the direction of the magnetization M**12** to be substantially 180°.

[0065] As the absolute value of the magnetic flux density B increases from zero, the resistance value RA of the magnetoresistive effect element **10**A gradually decreases and approaches a constant value (RA=RA**3**). For example, a resistance value RA**1** lower than the maximum resistance value RAmax, a resistance value RA**2** lower than the resistance value RA**1**, and the resistance value RA**3** lower than the resistance value RA**2** will result. One reason for this is that as the magnetic flux density B increases, the direction of the magnetization M**11** of the first magnetization free layer **11** gradually tilts from the state of being substantially parallel to the z direction and approaches being parallel to the +r direction or the −r direction.

[0066] In this way, the magnetoresistive effect element **10**A also exhibits a change in resistance value corresponding to the intensity (i.e., the magnetic flux density) of the external magnetic field applied to the magnetoresistive effect element **10**A. Therefore, understanding a correlation between the intensity (i.e., the magnetic flux density) of the external magnetic field and the resistance value of the magnetoresistive effect element **10**A in advance helps to calculate the intensity of the external magnetic field through detection of the change in the resistance value.

Second Modification Example

[0067] FIG. **7** is a cross-sectional diagram illustrating a cross-sectional configuration example of a magnetoresistive effect element **10**B according to a second modification example (hereinafter, “Modification Example 1-2”) of the first example embodiment of the disclosure. FIG. **7** corresponds to FIG. **1**B illustrating the magnetoresistive effect element **10** according to the foregoing first example embodiment. The magnetoresistive effect element **10**B according to Modification Example 1-2 may include a stacked structure S**10**B instead of the stacked structure S**10**. The magnetoresistive effect element **10**B may be otherwise substantially the same in configuration as the magnetoresistive effect element **10** according to the foregoing first example embodiment. The stacked structure S**10**B may include, in addition to the components of the stacked structure S**10**, a nonmagnetic layer **15** and a magnetization pinned layer **14** stacked in order on a side, of the second magnetization free layer **12**, opposite to the nonmagnetic layer **13**.

[0068] The nonmagnetic layer **15** may be a tunnel barrier layer or a nonmagnetic electrically-conductive layer, as with the nonmagnetic layer **13**, for example. The nonmagnetic layer **15** may thus include a material the same as the material included in the nonmagnetic layer **13**.

[0069] The nonmagnetic layer **15** may correspond to a specific but non-limiting example of a “second nonmagnetic layer” in one embodiment of the disclosure.

[0070] The magnetization pinned layer **14** may be a ferromagnetic layer having a magnetization that is pinned in a specific direction and does not change direction in accordance with an external magnetic field. In the example embodiment illustrated in FIG. **7**, the magnetization pinned layer **14** may have a magnetization M**14** pinned in the leftward direction in the sheet plane; however, the direction of the magnetization M**14** is not limited to that illustrated in FIG. **7**. The magnetization pinned layer **14** may include a ferromagnetic material such as cobalt (Co), cobalt-iron alloy (CoFe), or cobalt-iron-boron alloy (CoFeB). In the stacked structure S**10**B, an antiferromagnetic layer may be provided to be adjacent to the magnetization pinned layer **14** on an opposite side from the nonmagnetic layer **15**. The antiferromagnetic layer includes an antiferromagnetic material. Non-limiting examples of the antiferromagnetic material may include platinum-manganese alloy (PtMn) and iridium-manganese alloy (IrMn).

[0071] The stacked structure S**10**B may correspond to a structure in which a magnetic field intensity data detector and a magnetic field angle data detector are stacked in the z direction. Accordingly, feeding a current through the stacked structure S**10**B in the z direction by applying a voltage between the coupling terminals T**1** and T**2** allows a change in resistance value corresponding to the intensity of the external magnetic field and a change in resistance value corresponding to the direction of the external magnetic field to be detected from the stacked structure S**10**B. For example, a stack part S**10**B**1** including a stack of the first magnetization free layer **11**, the nonmagnetic layer **13**, and the second magnetization free layer **12** may serve as the magnetic field intensity data detector exhibiting a resistance value that changes in accordance with the intensity of the external magnetic field. A stack part S**10**B**2** including a stack of the second magnetization free layer **12**, the nonmagnetic layer **15**, and the magnetization pinned layer **14** may serve as the magnetic field angle data detector exhibiting a resistance value that changes in accordance with the angle of the external magnetic field. When the direction of the external magnetic field rotates in any of the in-plane directions in the stack plane orthogonal to the z direction, the direction of the magnetization M**12** of the second magnetization free layer **12** rotates to coincide with the direction of the external magnetic field. Accordingly, when the direction of the external magnetic field changes, an angle between the direction of the magnetization M**12** and the direction of the magnetization M**14** changes. The stack part S**10**B**2** thus exhibits a resistance value corresponding to the direction of the external magnetic field.

[0072] In this way, in the magnetoresistive effect element **10**B, the integrated stacked structure S**10**B helps to detect both intensity data and angle data on the external magnetic field.

Third Modification Example

[0073] FIG. **8** is a perspective diagram illustrating an outer appearance of a magnetoresistive effect element **10**C according to a third modification example (hereinafter, “Modification Example 1-3”) of the first example embodiment of the disclosure. FIG. **8** corresponds to FIG. **1**A illustrating the magnetoresistive effect element **10** according to the foregoing first example embodiment. The magnetoresistive effect element **10**C according to Modification Example 1-3 may include a stacked structure S**10**C instead of the stacked structure S**10**. The magnetoresistive effect element **10**C may be otherwise substantially the same in configuration as the magnetoresistive effect element **10** according to the foregoing first example embodiment. The stacked structure S**10**C may include a first magnetization free layer **16** instead of the first magnetization free layer **11**. The first magnetization free layer **16** may have what is called a spin-vortex structure. The first magnetization free layer **16** may include a magnetization M**16** that spirals around a vortex core VC and along the stack plane orthogonal to the z direction.

[0074] FIG. **9** is a characteristic diagram illustrating a relationship between the magnetic flux density B of an external magnetic field applied to the magnetoresistive effect element **10**C and a resistance value RC of the magnetoresistive effect element **10**C when a current is fed through the magnetoresistive effect element **10**C in the z direction. In FIG. **9**, the horizontal axis represents the magnetic flux density B, and the vertical axis represents the resistance value RC. FIG. **9** corresponds to FIG. **2** illustrating the characteristic diagram of the magnetoresistive effect element **10** of the foregoing first example embodiment.

[0075] FIGS. **10**A to **10**E are explanatory diagrams schematically illustrating a behavior of the first magnetization free layer **16** of the magnetoresistive effect element **10**C when the external magnetic field is applied, in other words, how the magnetization M**16** changes in accordance with the magnitude of the magnetic flux density B of the external magnetic field applied to the magnetoresistive effect element **10**C. FIG. **10**A illustrates a direction of the magnetization M**16** when the magnetic flux density B is equal to −B**2** in the characteristic diagram of FIG. **9**. FIG. **10**B illustrates the direction of the magnetization M**16** when the magnetic flux density B is equal to −B**1** in the characteristic diagram of FIG. **9**. FIG. **10**C illustrates the direction of the magnetization M**16** when the magnetic flux density B is zero (0) in the characteristic diagram of FIG. **9**. FIG. **10**D illustrates the direction of the magnetization M**16** when the magnetic flux density B is equal to B**1** in the characteristic diagram of FIG. **9**. FIG. **10**E illustrates the direction of the magnetization M**16** when the magnetic flux density B is equal to B**2** in the characteristic diagram of FIG. **9**. Note that B**1** and −B**1** are equal in absolute value, and B**2** and −B**2** are equal in absolute value. The length and the direction of the hollow arrow illustrated in each of FIGS. **10**A, **10**B, **10**D, and **10**E represent the intensity and the direction, respectively, of the external magnetic field applied to the magnetoresistive effect element **10**C. For example, the hollow arrow having a greater length indicates that the external magnetic field has a greater intensity. Further, FIGS. **10**A and **10**B indicate that the external magnetic field is applied to the magnetoresistive effect element **10**C in the leftward direction in the sheet plane, and FIGS. **10**D and **10**E indicate that the external magnetic field is applied to the magnetoresistive effect element **10**C in the rightward direction in the sheet plane.

[0076] As illustrated in FIG. **9**, the magnetoresistive effect element **10**C exhibits a behavior similar to that of the magnetoresistive effect element **10** of the foregoing first example embodiment in response to the external magnetic field applied to the magnetoresistive effect element **10**C. For example, the resistance value RC of the magnetoresistive effect element **10**C reaches a maximum resistance value RCmax when the magnetic flux density B is zero. FIGS. **8** and **10**C schematically illustrate a state of the magnetoresistive effect element **10**C when the magnetic flux density B is zero. As indicated in FIGS. **8** and **10**C, when the magnetic flux density B of the external magnetic field is zero, the vortex core VC is present at a center of the stack plane, and the magnetization M**16** spirals around the vortex core VC. Accordingly, while the magnetization M**16** in the same direction as the magnetization M**12** of the second magnetization free layer **12** is present in the first magnetization free layer **16**, the magnetization M**16** in a direction orthogonal to the direction of the magnetization M**12** of the second magnetization free layer **12** and the magnetization M**16** in a direction antiparallel to the direction of the magnetization M**12** are also present in the first magnetization free layer **16**. This causes the resistance value RC of the magnetoresistive effect element **10**C to be relatively high. However, as illustrated in FIGS. **10**(A), **10**(B), **10**(D), and **10**(E), when subjected to the external magnetic field, the first magnetization free layer **16** having the spin-vortex structure will increase in magnetic moment in the same direction as the direction of the external magnetic field. In other words, most part of the first magnetization free layer **16** will have the magnetization M**16** in the same direction as the direction of the external magnetic field. The direction of the magnetization M**12** of the second magnetization free layer **12** also coincides with the direction of the external magnetic field. Accordingly, the magnetoresistive effect element **10**C decreases in resistance value with increasing intensity of the external magnetic field applied to the magnetoresistive effect element **10**C with a current fed therethrough in the z direction.

[0077] In this way, the magnetoresistive effect element **10**C according to Modification Example 1-3 also exhibits a change in resistance value corresponding to the intensity (i.e., the magnetic flux density) of the external magnetic field applied to the magnetoresistive effect element **10**C. Therefore, understanding a correlation between the intensity (i.e., the magnetic flux density) of the external magnetic field and the resistance value of the magnetoresistive effect element **10**C in advance helps to calculate the intensity of the external magnetic field through detection of the change in the resistance value.

[0078] Further, as compared with the magnetoresistive effect element **10** of the foregoing first example embodiment, the magnetoresistive effect element **10**C exhibits low variations in resistance value in response to a z-direction component of the external magnetic field. This helps to achieve higher reliability.

Fourth Modification Example

[0079] FIG. **11** is a cross-sectional diagram illustrating a cross-sectional configuration example of a magnetoresistive effect element **10**D according to a fourth modification example (hereinafter, “Modification Example 1-4”) of the first example embodiment of the disclosure. FIG. **11** corresponds to FIG. **1**B illustrating the magnetoresistive effect element **10** according to the foregoing first example embodiment. The magnetoresistive effect element **10**D according to Modification Example 1-4 may include a stacked structure S**10**D instead of the stacked structure S**10**. The magnetoresistive effect element **10**D may be otherwise substantially the same in configuration as the magnetoresistive effect element **10** according to the foregoing first example embodiment. In the stacked structure S**10**D, the magnetization M**11** of the first magnetization free layer **11** and the magnetization M**12** of the second magnetization free layer **12** may be antiferromagnetically coupled to each other. When the nonmagnetic layer **13** is the tunnel barrier layer, the magnetization M**11** and the magnetization M**12** are magnetostatically coupled to each other and are antiparallel to each other. When the nonmagnetic layer **13** is the nonmagnetic electrically-conductive layer, the magnetization M**11** and the magnetization M**12** are coupled to each other by Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction and are antiparallel to each other.

[0080] FIG. **12** is a characteristic diagram illustrating a relationship between the magnetic flux density B of an external magnetic field applied to the magnetoresistive effect element **10**D and a resistance value RD of the magnetoresistive effect element **10**D when a current is fed through the magnetoresistive effect element **10**D in the z direction. In FIG. **12**, the horizontal axis represents the magnetic flux density B, and the vertical axis represents the resistance value RD. FIG. **12** corresponds to FIG. **2** illustrating the characteristic diagram of the magnetoresistive effect element **10** of the foregoing first example embodiment.

[0081] FIGS. **13**A to **13**E are planar diagrams schematically illustrating a behavior of each of the first magnetization free layer **11** and the second magnetization free layer **12** of the magnetoresistive effect element **10**D when the external magnetic field is applied, in other words, how the magnetizations M**11** and M**12** each change in accordance with the magnitude of the magnetic flux density B of the external magnetic field applied to the magnetoresistive effect element **10**D. FIG. **13**A illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to −B**2** in the characteristic diagram of FIG. **12**. FIG. **13**B illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to −B**1** in the characteristic diagram of FIG. **12**. FIG. **13**C illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is zero (0) in the characteristic diagram of FIG. **12**. FIG. **13**D illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to B**1** in the characteristic diagram of FIG. **12**. FIG. **13**E illustrates the directions of the magnetizations M**11** and M**12** when the magnetic flux density B is equal to B**2** in the characteristic diagram of FIG. **12**. Note that B**1** and −B**1** are equal in absolute value, and B**2** and −B**2** are equal in absolute value. The length and the direction of the hollow arrow illustrated in each of FIGS. **13**A, **13**B, **13**D, and **13**E represent the intensity and the direction, respectively, of the external magnetic field applied to the magnetoresistive effect element **10**D. For example, the hollow arrow having a greater length indicates that the external magnetic field has a greater intensity. Further, FIGS. **13**A and **13**B indicate that the external magnetic field is applied to the magnetoresistive effect element **10**D in the leftward direction in the sheet plane, and FIGS. **13**D and **13**E indicate that the external magnetic field is applied to the magnetoresistive effect element **10**D in the rightward direction in the sheet plane.

[0082] As illustrated in FIG. **12**, the magnetoresistive effect element **10**D exhibits a behavior similar to that of the magnetoresistive effect element **10** of the foregoing first example embodiment in response to the external magnetic field applied to the magnetoresistive effect element **10**D. For example, the resistance value RD of the magnetoresistive effect element **10**D reaches a maximum resistance value RDmax when the magnetic flux density B is zero. FIGS. **11** and **13**C schematically illustrate a state of the magnetoresistive effect element **10**D when the magnetic flux density B is zero. As indicated in FIGS. **11** and **13**C, when the magnetic flux density B of the external magnetic field is zero, the respective directions of the magnetizations M**11** and M**12** are antiparallel to each other. This causes the resistance value RD of the magnetoresistive effect element **10**D to be relatively high. However, as illustrated in FIGS. **13**(A), **13**(B), **13**(D), and **13**(E), when subjected to the external magnetic field, the respective directions of the magnetizations M**11** and M**12** rotate to approach the direction of the external magnetic field. Here, as the intensity, i.e., the absolute value of the magnetic flux density B, of the external magnetic field increases, the directions of the magnetizations M**11** and M**12** approach being parallel to each other. Accordingly, the magnetoresistive effect element **10**D decreases in resistance value with increasing intensity of the external magnetic field applied to the magnetoresistive effect element **10**D with a current fed therethrough in the z direction.

[0083] In this way, the magnetoresistive effect element **10**D according to Modification Example 1-4 also exhibits a change in resistance value corresponding to the intensity (i.e., the magnetic flux density) of the external magnetic field applied to the magnetoresistive effect element **10**D. Therefore, understanding a correlation between the intensity (i.e., the magnetic flux density) of the external magnetic field and the resistance value of the magnetoresistive effect element **10**D in advance helps to calculate the intensity of the external magnetic field through detection of the change in the resistance value.

2. Second Example Embodiment

[Configuration of Magnetic Field Detection Device **1**]

[0084] Reference is now made to FIG. **14** to describe a configuration of a magnetic field detection device **1** according to a second example embodiment of the disclosure. FIG. **14** is a circuit diagram schematically illustrating a circuit configuration of the magnetic field detection device **1** according to the second example embodiment of the disclosure. As illustrated in FIG. **14**, the magnetic field detection device **1** may include a bridge circuit **7**, a difference detector **8**, and an arithmetic circuit **9**. The magnetic field detection device **1** may be configured to detect a change in intensity of an external magnetic field applied to the magnetic field detection device **1**, based on a change in output from the bridge circuit **7**.

[0085] The bridge circuit **7** may include four resistors **21** to **24**. The bridge circuit **7** may have a configuration in which a pair of resistors **21** and **22** and a pair of resistors **23** and **24** are coupled in parallel to each other. The resistor **21** and the resistor **22** may be coupled in series to each other. The resistor **23** and the resistor **24** may be coupled in series to each other. For example, in the bridge circuit **7**, a first end of the resistor **21** and a first end of the resistor **22** may be coupled to each other at a node P**1**, a first end of the resistor **23** and a first end of the resistor **24** may be coupled to each other at a node P**2**, a second end of the resistor **21** and a second end of the resistor **24** may be coupled to each other at a node P**3**, and a second end of the resistor **22** and a second end of the resistor **23** may be coupled to each other at a node P**4**. The node P**3** may be set to a first potential, and the node P**4** may be set to a second potential. In the example embodiment illustrated in FIG. **14**, the node P**3** may be coupled to a power supply Vcc, and the node P**4** may be coupled to a ground terminal GND. The node P**1** and the node P**2** may be coupled to respective input-side terminals of the difference detector **8**, for example.

[0086] In the bridge circuit **7**, the magnetoresistive effect element **10** described in relation to the foregoing first example embodiment may be employed as each of the resistors **21** and **23**. For example, the resistors **21** and **23** may each be configured to detect the intensity of the external magnetic field as a target of detection. In some embodiments, any of the magnetoresistive effect elements **10**A to **10**D according to Modification Examples 1-1 to 1-4 described above may be employed as each of the resistors **21** and **23**. In the bridge circuit **7**, in contrast, the resistors **22** and

24 may each be a fixed resistor, for example. Note that the resistors **22** and **24** are each not limited to the fixed resistor. In some embodiments where each of the resistors **22** and **24** is a magnetoresistive effect element, a magnetization direction of the magnetization pinned layer of the magnetoresistive effect element serving as the resistor **22** and a magnetization direction of the magnetization pinned layer of the magnetoresistive effect element serving as the resistor **24** may be opposite to each other. One reason for this is that in such a case, a resistance variation of the resistor **22** exhibited in accordance with the angle of the external magnetic field and a resistance variation of the resistor **24** exhibited in accordance with the angle of the external magnetic field are allowed to be in opposite directions to each other, that is, to be of opposite signs, which helps to allow the respective resistance variations to cancel each other out by taking a differential potential between a resistance of the resistor **22** and a resistance of the resistor **24**, which in turn helps to offer expectations for relatively easy detection of the intensity of the external magnetic field.

[Operation of Magnetic Field Detection Device **1**]

[0087] In the magnetic field detection device **1**, signals taken out from the nodes P**1** and P**2** of the bridge circuit **7** may flow into the difference detector **8**. The difference detector **8** may detect a potential difference between the nodes P**1** and P**2** occurring when a voltage is applied between the nodes P**3** and P**4**, that is, a differential output dV that is a difference between a voltage drop occurring in the resistor **21** and a voltage drop occurring in the resistor **24**, and may output the detected differential output dV as a difference signal SL to the arithmetic circuit **9**. In the magnetic field detection device **1**, when the resistors **22** and **24** are each configured to have a resistance value equal to the resistance value of each of the resistors **22** and **24** at a zero magnetic field, the differential output dV is zero (0) in an initial state where no external magnetic field is applied. In a state where an external magnetic field is applied to the bridge circuit **7**, the magnetoresistive effect elements **10** serving as the resistors **21** and **23** each exhibit a change in resistance value corresponding to the intensity of the applied external magnetic field. This results in the differential output dV corresponding to the intensity of the external magnetic field.

[0088] FIG. **15** is a characteristic diagram schematically illustrating a relationship between the magnetic flux density B (on the horizontal axis) and the differential output dV (on the vertical axis). The magnetic flux density B indicates the intensity of the external magnetic field. As indicated in FIG. **15**, the magnetic field detection device **1** allows the magnetic flux density B and the differential output dV to have a proportional relationship within a range of the magnetic flux density B not greater than a certain magnitude. In accordance with a correlation illustrated in FIG. **15**, the arithmetic circuit **9** may calculate the intensity of the external magnetic field applied to the bridge circuit **7**, based on the difference signal SL from the difference detector **8**.

[0089] In this way, the magnetic field detection device **1** helps to determine the intensity of the applied external magnetic field.

3. Third Example Embodiment

[Configuration of Magnetic Field Detection Device **2**]

[0090] Reference is now made to FIG. **16** to describe a configuration of a magnetic field detection device **2** according to a third example embodiment of the disclosure. FIG. **16** is a circuit diagram schematically illustrating a circuit configuration of the magnetic field detection device **2** according to the third example embodiment of the disclosure. As illustrated in FIG. **16**, the magnetic field detection device **2** may include resistors **35** and **36**, a bridge circuit **17**, and analog-to-digital converter circuits (ADCs) **18**A and **18**B. The magnetic field detection device **2** may be configured to detect a change in intensity of an external magnetic field applied to the magnetic field detection device **2**, based on changes in outputs from the resistors **35** and **36** and the bridge circuit **17**.

[0091] The bridge circuit **17** may include resistors **31** to **34**. The bridge circuit **17** may have a configuration in which a pair of resistors **31** and **32** and a pair of resistors **33** and **34** are coupled in parallel to each other. The resistor **31** and the resistor **32** may be coupled in series to each other. The resistor **33** and the resistor **34** may be coupled in series to each other. For example, in the bridge circuit **17**, a first end of the resistor **31** and a first end of the resistor **32** may be coupled to each other at the node P**1**, a first end of the resistor **33** and a first end of the resistor **34** may be coupled to each other at the node P**2**, a second end of the resistor **31** and a second end of the resistor **34** may be coupled to each other at the node P**3**, and a second end of the resistor **32** and a second end of the resistor **33** may be coupled to each other at the node P**4**. In the example embodiment illustrated in FIG. **16**, the node P**3** may be coupled to the power supply Vcc via the resistor **35**, and the node P**4** may be coupled to the ground terminal GND via the resistor **36**. The node P**1** may be coupled to an input terminal of the ADC **18**A, and the node P**2** may be coupled to an input terminal of the ADC **18**B. The resistors **31** to **34** of the bridge circuit **17** may each be a GMR element having a spin-valve structure, for example. For example, the resistors **31** to **34** may each include a stacked structure including a magnetization free layer, a nonmagnetic layer, and a magnetization pinned layer, and may exhibit a resistance value that changes in accordance with the direction of the external magnetic field. The magnetization free layer has a magnetization that changes direction in accordance with the direction of the external magnetic field. The magnetization pinned layer has a magnetization that is pinned in a specific direction irrespective of the external magnetic field.

[0092] The bridge circuit **17** may correspond to a specific but non-limiting example of a "bridge circuit" in one embodiment of the disclosure. The node P**3** may correspond to a specific but non-limiting example of a "first terminal" in one embodiment of the disclosure. The node P**4** may correspond to a specific but non-limiting example of a "second terminal" in one embodiment of the disclosure. A "first potential" in one embodiment of the disclosure may correspond to a power supply potential set by the power supply Vcc. A "second potential" in one embodiment of the disclosure may correspond to a ground potential. The resistor **31** may correspond to a specific but non-limiting example of a "first magnetoresistive effect element" in one embodiment of the disclosure. The resistor **32** may correspond to a specific but non-limiting example of a "second magnetoresistive effect element" in one embodiment of the disclosure.

[0093] In the magnetic field detection device **2**, the magnetoresistive effect element **10** described in relation to the foregoing first example embodiment may be employed as each of the resistors **35** and **36**. For example, the resistors **35** and **36** may each be configured to detect the intensity of the external magnetic field as a target of detection. In some embodiments, any of the magnetoresistive effect elements **10**A, **10**C, and **10**D according to Modification Examples 1-1, 1-3, and 1-4 described above may be employed as each of the resistors **35** and **36**.

[0094] In the magnetic field detection device **2**, the bridge circuit **17** may serve as the magnetic field angle data detector to detect the direction of the external magnetic field, and the resistors **35** and **36** may serve as the magnetic field intensity data detector to detect the intensity of the external magnetic field. Note that a signal component including magnetic field angle data and a signal component including magnetic field intensity data may be outputted as paired digital signals corresponding to analog signals that are taken out from the respective nodes P**1** and P**2** and converted at the respective ADCs **18**A and **18**B.

[0095] FIG. **16** schematically illustrates a magnetization direction Fr of the magnetization free layer and a magnetization direction Pin of the magnetization pinned layer when each of the resistors **31** to **34** is a magnetoresistive effect element. In FIG. **16**, the magnetization direction Fr is indicated in a dashed arrow, and the magnetization direction Pin is indicated in a solid arrow. Note that in FIG. **16**, an X-axis direction and a Y-axis direction are assumed to be parallel to a plane orthogonal to the z direction, and an external magnetic field Hex is assumed to be applied in a direction at an angle Θ with respect to a +X direction. In an example of the bridge circuit **17** illustrated in FIG. **16**, the magnetization direction Pin of the magnetization pinned layer of the resistor **31** may be pinned in the +X direction, the magnetization direction Pin of the magnetization pinned layer of the resistor **32** may be pinned in a −X direction, the magnetization direction Pin of the magnetization pinned layer of the resistor **33** may be pinned in a −Y direction, and the magnetization direction Pin of the magnetization pinned layer of the resistor **34** may be pinned in a +Y direction. In this case, where an output from the ADC **18**A is represented by V cos and an output from the ADC **18**B is represented by V sin, an intensity Vamp of the external magnetic field Hex is calculated by Equation (1) below, and the angle Θ of the external magnetic field Hex is calculated by Equation (2) below. Note that in Equations (1) and (2), Vs0 represents the output V sin when the angle Θ is 0°, and Vc0 represents the output V cos when the angle Θ is 90°.

[00001] $$V_{amp} = ((V_{\sin} - V_{s0})^2 + (V_{cos} - V_{c0})^2)^{\frac{1}{2}} \quad (1) \qquad = \mathrm{atan}\left(\frac{V_{\sin} - V_{s0}}{V_{cos} - V_{c0}}\right) \quad (2)$$

[0096] In this way, in the magnetic field detection device **2**, the bridge circuit **17** serving as the magnetic field angle data detector to detect the direction of the external magnetic field and the resistors **35** and **36** serving as the magnetic field intensity data detector to detect the intensity of the external magnetic field may be integrated into a single circuit. This helps to achieve simplification and size reduction of an overall configuration.

4. Fourth Example Embodiment

[Configuration of Magnetic Field Detection Device **3**]

[0097] Reference is now made to FIG. **17** to describe a configuration of a magnetic field detection device **3** according to a fourth example embodiment of the disclosure. FIG. **17** is a circuit diagram schematically illustrating a circuit configuration of the magnetic field detection device **3** according to the fourth example embodiment of the disclosure. As illustrated in FIG. **17**, the magnetic field detection device **3** may include neither of the resistors **35** and **36**, and may include a bridge circuit **19** instead of the bridge circuit **17**. The magnetic field detection device **3** may be otherwise substantially the same in configuration as the magnetic field detection device **2**. The magnetic field detection device **3** may be configured to detect a change in intensity of an external magnetic field applied to the magnetic field detection device **3**, based on a change in output from the bridge circuit **19**.

[0098] The bridge circuit **19** may include resistors **41** to **44**. The bridge circuit **19** may have a configuration in which a pair of resistors **41** and **42** and a pair of resistors **43** and **44** are coupled in parallel to each other. The resistor **41** and the resistor **42** may be coupled in series to each other. The resistor **43** and the resistor **44** may be coupled in series to each other. For example, in the bridge circuit **19**, a first end of the resistor **41** and a first end of the resistor **42** may be coupled to each other at the node P**1**, a first end of the resistor **43** and a first end of the resistor **44** may be coupled to each other at the node P**2**, a second end of the resistor **41** and a second end of the resistor **44** may be coupled to each other at the node P**3**, and a second end of the resistor **42** and a second end of the resistor **43** may be coupled to each other at the node P**4**. In the example embodiment illustrated in FIG. **17**, the node P**3** may be coupled to the power supply Vcc, and the node P**4** may be coupled to the ground terminal GND. The node P**1** may be coupled to the input terminal of the ADC **18**A, and the node P**2** may be coupled to the input terminal of the ADC **18**B. The resistors **41** to **44** of the bridge circuit **19** may be the magnetoresistive effect element **10**B according to Modification Example 1-2 described above, for example.

[0099] The bridge circuit **19** may correspond to a specific but non-limiting example of the “bridge circuit” in one embodiment of the disclosure. The node P**3** may correspond to a specific but non-limiting example of the “first terminal” in one embodiment of the disclosure. The node P**4** may correspond to a specific but non-limiting example of the “second terminal” in one embodiment of the disclosure. The “first potential” in one embodiment of the disclosure may correspond to the power supply potential set by the power supply Vcc. The “second potential” in one embodiment of the disclosure may correspond to the ground potential. The resistor **41** may correspond to a specific but non-limiting example of the “first magnetoresistive effect element” in one embodiment of the disclosure. The resistor **42** may correspond to a specific but non-limiting example of the “second magnetoresistive effect element” in one embodiment of the disclosure.

[0100] In the magnetic field detection device **3**, the bridge circuit **19** may serve as the magnetic field angle data detector to detect the direction of the external magnetic field and also as the magnetic field intensity data detector to detect the intensity of the external magnetic field. In the magnetic field detection device **3**, the intensity Vamp of the external magnetic field Hex is calculated by Equation (1), and the angle Θ of the external magnetic field Hex is calculated by Equation (2), as in the magnetic field detection device **2** according to the foregoing third example embodiment.

[0101] In this way, the magnetic field detection device **3** may include the bridge circuit **19** serving as both the magnetic field angle data detector to detect the direction of the external magnetic field and the magnetic field intensity data detector to detect the intensity of the external magnetic field. This helps to achieve simplification and size reduction of the overall configuration.

5. Fifth Example Embodiment

[0102] Reference is now made to FIG. **18** to describe a magnetic sensor system **200** according to a fifth example embodiment of the disclosure. FIG. **18** is a perspective diagram illustrating an overall configuration example of the magnetic sensor system **200** according to the fifth example embodiment. The magnetic sensor system **200** may correspond to a specific but non-limiting example of a "magnetic sensor system" in one embodiment of the disclosure.

[0103] The magnetic sensor system **200** may include a component **201**, and a body **202** accommodating all or a part of the component **201**. The component **201** may incorporate a magnetic field generator generating a magnetic field, such as a permanent magnet or an electromagnet, and may be configured to perform an action of rotating in a direction D**1** around a reference axis C as a first axis and an action of moving in a direction D**2** parallel to the reference axis C. The component **201** may be a component to be caused to operate by human operation, such as a knob. Non-limiting examples of the magnetic sensor system **200** including such a component **201** may include an operation device for a car air-conditioner, a car navigation system, or any of other in-vehicle devices, an operation device for a digital camera, a radio, or any of other portable electronic devices, and a crown of a smartwatch or any of other electronic watches serving as wearable electronic devices. In some embodiments, the component **201** may operate in synchronization with any driving device. In some embodiments, the body **202** may incorporate a magnetic field detection device. Any of the magnetic field detection devices **1** to **3** described in relation to the foregoing second to fourth example embodiments, respectively, may be used as the magnetic field detection device incorporated in the body **202**.

[0104] For example, the magnetic sensor system **200** is configured to change the direction of the magnetic field applied to the magnetic field detection device, by causing the magnetic field detection device and the magnetic field generator to rotate relative to each other around the reference axis C as a center of rotation, and configured to change the intensity of the magnetic field applied to the magnetic field detection device, by changing relative positions of the magnetic field detection device and the magnetic field generator along the reference axis C.

[0105] In this way, the magnetic sensor system **200** helps to detect both the angle and the intensity of the magnetic field applied to the magnetic field detection device, while being simple in configuration.

[0106] The example embodiments and modification examples described above are to facilitate understanding of the disclosure, and are not intended to limit the disclosure. Each element disclosed in the example embodiments and modification examples described above shall thus be construed to include all design modifications and equivalents that fall within the technical scope of the disclosure. In other words, the disclosure is not limited to the example embodiments and modification examples described above, and may be modified in a variety of ways.

[0107] The disclosure encompasses any possible combination of some or all of the various embodiments and the modification examples described herein and incorporated herein. It is possible to achieve at least the following configurations from the foregoing example embodiments and modification examples of the disclosure.

(1)
[0108] A magnetoresistive effect element including [0109] a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction, in which [0110] an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.
(2)
[0111] The magnetoresistive effect element according to (1), in which [0112] the first magnetization free layer has an easy axis of magnetization along the stacking direction, and [0113] the second magnetization free layer has a hard axis of magnetization along the stacking direction.
(3)
[0114] The magnetoresistive effect element according to (1), in which the first magnetization free layer and the second magnetization free layer each have an easy axis of magnetization along the stacking direction.
(4)
[0115] The magnetoresistive effect element according to (1), in which the stacked structure further includes a second nonmagnetic layer and a magnetization pinned layer that are stacked in order on a side, of the second magnetization free layer, opposite to the first nonmagnetic layer.
(5)
[0116] The magnetoresistive effect element according to (1), in which [0117] the first magnetization free layer has a spin-vortex structure including a magnetization that spirals along the plane, and [0118] the second magnetization free layer has a hard axis of magnetization along the stacking direction.
(6)
[0119] The magnetoresistive effect element according to (1), in which the first magnetization free layer and the second magnetization free layer are antiferromagnetically coupled to each other.
(7)
[0120] The magnetoresistive effect element according to (6), in which an angle between a magnetization direction of the first magnetization free layer and a magnetization direction of the second magnetization free layer in a state where no external magnetic field is applied is greater than 90 degrees and less than or equal to 180 degrees.
(8)
[0121] The magnetoresistive effect element according to (1), in which the outer edge of the stacked structure has a circular shape.
(9)
[0122] The magnetoresistive effect element according to (1), in which an anisotropic magnetic field intensity of the first magnetization free layer and an anisotropic magnetic field intensity of the second magnetization free layer are different from each other.
(10)
[0123] A magnetic field detection device including [0124] one or more magnetoresistive effect elements, in which [0125] the one or more magnetoresistive effect elements each include a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction, and [0126] an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.
(11)
[0127] The magnetic field detection device according to (10), further including an angle sensor coupled in series to the one or more magnetoresistive effect elements.
(12)
[0128] The magnetic field detection device according to (10), further including: [0129] a first terminal to be set to a first potential; [0130] a second terminal to be set to a second potential different from the first potential; and [0131] a bridge circuit disposed between the first terminal and

the second terminal, in which [0132] the one or more magnetoresistive effect elements include a first magnetoresistive effect element and a second magnetoresistive effect element, and [0133] the bridge circuit includes the first magnetoresistive effect element and the second magnetoresistive effect element.

(13)

[0134] The magnetic field detection device according to (12), in which the bridge circuit includes a first fixed resistor and a second fixed resistor in addition to the first magnetoresistive effect element and the second magnetoresistive effect element.

(14)

[0135] The magnetic field detection device according to (12), in which [0136] the bridge circuit includes a third magnetoresistive effect element and a fourth magnetoresistive effect element in addition to the first magnetoresistive effect element and the second magnetoresistive effect element, [0137] the third magnetoresistive effect element and the fourth magnetoresistive effect element each include a magnetization pinned layer, and [0138] a magnetization direction of the magnetization pinned layer of the third magnetoresistive effect element and a magnetization direction of the magnetization pinned layer of the fourth magnetoresistive effect element are opposite to each other.

(15)

[0139] The magnetic field detection device according to (10), further including: [0140] a first terminal to be set to a first potential; [0141] a second terminal to be set to a second potential different from the first potential; and [0142] a bridge circuit disposed between the first terminal and the second terminal, in which [0143] the one or more magnetoresistive effect elements are [0144] disposed between the first terminal and the bridge circuit, or between the second terminal and the bridge circuit, or [0145] disposed between the first terminal and the bridge circuit, and between the second terminal and the bridge circuit.

(16)

[0146] The magnetic field detection device according to (15), in which the bridge circuit is configured to detect both an intensity of an external magnetic field applied to the bridge circuit and an angle of the external magnetic field.

(17)

[0147] The magnetic field detection device according to (10), in which the outer edge of the stacked structure has a circular shape.

(18)

[0148] A magnetic field detection device including [0149] a bridge circuit including first to fourth magnetoresistive effect elements, in which [0150] the first to fourth magnetoresistive effect elements each include a stacked structure including a magnetization pinned layer, a second nonmagnetic layer, a second magnetization free layer, a first nonmagnetic layer, and a first magnetization free layer that are stacked in order in a stacking direction, [0151] the first magnetization free layer has an easy axis of magnetization along the stacking direction, and [0152] the second magnetization free layer has a hard axis of magnetization along the stacking direction.

(19)

[0153] The magnetic field detection device according to (18), in which an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.

(20)

[0154] The magnetic field detection device according to (18) or (19), in which the bridge circuit is configured to detect both an intensity of an external magnetic field applied to the bridge circuit and an angle of the external magnetic field.

(21)

[0155] A magnetic sensor system including: [0156] a magnetic field detection device; and [0157] a magnetic field generator generating a magnetic field, [0158] the magnetic sensor system being

configured to change a direction of the magnetic field applied to the magnetic field detection device, by causing the magnetic field detection device and the magnetic field generator to rotate relative to each other around a first axis as a center of rotation, and configured to change an intensity of the magnetic field applied to the magnetic field detection device, by changing relative positions of the magnetic field detection device and the magnetic field generator along the first axis, in which [0159] the magnetic field detection device includes one or more magnetoresistive effect elements, [0160] the one or more magnetoresistive effect elements each include a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction, and [0161] an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.
[0162] A magnetoresistive effect element according to at least one embodiment of the disclosure exhibits a resistance value corresponding to an intensity of an in-plane component, of an external magnetic field, along a plane orthogonal to a stacking direction. The resistance value of the magnetoresistive effect element changes in response to a change in intensity of the in-plane component of the external magnetic field, and does not depend on a direction of the in-plane component of the external magnetic field. In other words, the resistance value of the magnetoresistive effect element isotropically changes in response to the change in intensity of the in-plane component of the external magnetic field, irrespective of the direction of the in-plane component of the external magnetic field.
[0163] A magnetic field detection device and a magnetic sensor system according to at least one embodiment of the disclosure, and the magnetoresistive effect element according to at least one embodiment of the disclosure for use in the magnetic field detection device or the magnetic sensor system are each simple in configuration and yet make it possible to isotropically detect the intensity of an external magnetic field without dependence on the direction of the external magnetic field.
[0164] It is to be noted that the effects of the disclosure should not be limited thereto, and may be any of the effects described herein.
[0165] Although the disclosure has been described hereinabove in terms of the example embodiment and modification examples, the disclosure is not limited thereto. It should be appreciated that variations may be made in the described example embodiment and modification examples by those skilled in the art without departing from the scope of the disclosure as defined by the following claims.
[0166] The limitations in the claims are to be interpreted broadly based on the language employed in the claims and not limited to examples described in this specification or during the prosecution of the application, and the examples are to be construed as non-exclusive.
[0167] As used in this specification and the appended claims, the singular forms “a,” “an,” and “the” include, especially in the context of the claims, are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context.
[0168] Throughout this specification and the appended claims, unless the context requires otherwise, the terms “comprise”, “include”, “have”, and their variations are to be construed to cover the inclusion of a stated element, integer or step but not the exclusion of any other non-stated element, integer or step.
[0169] The use of the terms first, second, etc. do not denote any order or importance, but rather the terms first, second, etc. are used to distinguish one element from another.
[0170] The term “substantially”, “approximately”, “about”, and its variants having the similar meaning thereto are defined as being largely but not necessarily wholly what is specified as understood by one of ordinary skill in the art.
[0171] The term “disposed on/provided on/formed on” and its variants having the similar meaning thereto as used herein refer to elements disposed directly in contact with each other or indirectly by having intervening structures therebetween.

Claims

1. A magnetoresistive effect element comprising a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction, wherein an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.
2. The magnetoresistive effect element according to claim 1, wherein the first magnetization free layer has an easy axis of magnetization along the stacking direction, and the second magnetization free layer has a hard axis of magnetization along the stacking direction.
3. The magnetoresistive effect element according to claim 1, wherein the first magnetization free layer and the second magnetization free layer each have an easy axis of magnetization along the stacking direction.
4. The magnetoresistive effect element according to claim 1, wherein the stacked structure further includes a second nonmagnetic layer and a magnetization pinned layer that are stacked in order on a side, of the second magnetization free layer, opposite to the first nonmagnetic layer.
5. The magnetoresistive effect element according to claim 1, wherein the first magnetization free layer has a spin-vortex structure including a magnetization that spirals along the plane, and the second magnetization free layer has a hard axis of magnetization along the stacking direction.
6. The magnetoresistive effect element according to claim 1, wherein the first magnetization free layer and the second magnetization free layer are antiferromagnetically coupled to each other.
7. The magnetoresistive effect element according to claim 6, wherein an angle between a magnetization direction of the first magnetization free layer and a magnetization direction of the second magnetization free layer in a state where no external magnetic field is applied is greater than 90 degrees and less than or equal to 180 degrees.
8. The magnetoresistive effect element according to claim 1, wherein the outer edge of the stacked structure has a circular shape.
9. The magnetoresistive effect element according to claim 1, wherein an anisotropic magnetic field intensity of the first magnetization free layer and an anisotropic magnetic field intensity of the second magnetization free layer are different from each other.
10. A magnetic field detection device comprising one or more magnetoresistive effect elements, wherein the one or more magnetoresistive effect elements each include a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction, and an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.
11. The magnetic field detection device according to claim 10, further comprising an angle sensor coupled in series to the one or more magnetoresistive effect elements.
12. The magnetic field detection device according to claim 10, further comprising: a first terminal to be set to a first potential; a second terminal to be set to a second potential different from the first potential; and a bridge circuit disposed between the first terminal and the second terminal, wherein the one or more magnetoresistive effect elements include a first magnetoresistive effect element and a second magnetoresistive effect element, and the bridge circuit includes the first magnetoresistive effect element and the second magnetoresistive effect element.
13. The magnetic field detection device according to claim 12, wherein the bridge circuit includes a first fixed resistor and a second fixed resistor in addition to the first magnetoresistive effect element and the second magnetoresistive effect element.
14. The magnetic field detection device according to claim 12, wherein the bridge circuit includes a third magnetoresistive effect element and a fourth magnetoresistive effect element in addition to the first magnetoresistive effect element and the second magnetoresistive effect element, the third magnetoresistive effect element and the fourth magnetoresistive effect element each include a

magnetization pinned layer, and a magnetization direction of the magnetization pinned layer of the third magnetoresistive effect element and a magnetization direction of the magnetization pinned layer of the fourth magnetoresistive effect element are opposite to each other.

15. The magnetic field detection device according to claim 10, further comprising: a first terminal to be set to a first potential; a second terminal to be set to a second potential different from the first potential; and a bridge circuit disposed between the first terminal and the second terminal, wherein the one or more magnetoresistive effect elements are disposed between the first terminal and the bridge circuit, or between the second terminal and the bridge circuit, or disposed between the first terminal and the bridge circuit, and between the second terminal and the bridge circuit.

16. The magnetic field detection device according to claim 15, wherein the bridge circuit is configured to detect both an intensity of an external magnetic field applied to the bridge circuit and an angle of the external magnetic field.

17. The magnetic field detection device according to claim 10, wherein the outer edge of the stacked structure has a circular shape.

18. A magnetic field detection device comprising a bridge circuit including first to fourth magnetoresistive effect elements, wherein the first to fourth magnetoresistive effect elements each include a stacked structure including a magnetization pinned layer, a second nonmagnetic layer, a second magnetization free layer, a first nonmagnetic layer, and a first magnetization free layer that are stacked in order in a stacking direction, the first magnetization free layer has an easy axis of magnetization along the stacking direction, and the second magnetization free layer has a hard axis of magnetization along the stacking direction.

19. The magnetic field detection device according to claim 18, wherein an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.

20. The magnetic field detection device according to claim 18, wherein the bridge circuit is configured to detect both an intensity of an external magnetic field applied to the bridge circuit and an angle of the external magnetic field.

21. A magnetic sensor system comprising: a magnetic field detection device; and a magnetic field generator generating a magnetic field, the magnetic sensor system being configured to change a direction of the magnetic field applied to the magnetic field detection device, by causing the magnetic field detection device and the magnetic field generator to rotate relative to each other around a first axis as a center of rotation, and configured to change an intensity of the magnetic field applied to the magnetic field detection device, by changing relative positions of the magnetic field detection device and the magnetic field generator along the first axis, wherein the magnetic field detection device includes one or more magnetoresistive effect elements, the one or more magnetoresistive effect elements each include a stacked structure including a first magnetization free layer, a first nonmagnetic layer, and a second magnetization free layer that are stacked in order in a stacking direction, and an outer edge of the stacked structure along a plane orthogonal to the stacking direction has an isotropic shape.