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MAGNETIC SENSOR AND MAGNETIC SENSOR SYSTEM

Abstract

At a reference position within a first plane, a magnetic field to be detected has a first direction that changes within the first plane. A magnetic sensor includes an MR element. The MR element includes a magnetic layer having first magnetization that can change in direction within a second plane. The first plane and the second plane intersect at a dihedral angle α other than 90°. The magnetic field to be detected can be divided into an in-plane component parallel to the second plane and a perpendicular component perpendicular to the second plane. The in-plane component has a second direction that changes with a change in the first direction. The direction of the first magnetization changes with a change in the second direction. A detection value depends on the direction of the first magnetization.

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATION [0001] This application is a continuation of U.S. application Ser. No. 18/223,135, filed Jul. 18, 2023, which is a continuation of U.S. application Ser. No. 17/836,016, filed Jun. 9, 2022, which is a continuation of U.S. application Ser. No. 16/878,008, filed May 19, 2020, the contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION
1. Field of the Invention
[0002] The present invention relates to a magnetic sensor, and a magnetic sensor system including the magnetic sensor.
2. Description of the Related Art
[0003] Magnetic sensors have been used for a variety of applications. Examples of known magnetic sensors include one that uses a spin-valve magnetoresistive element provided on a substrate. The spin-valve magnetoresistive element includes a magnetization pinned layer having a magnetization whose direction is fixed, a free layer having a magnetization whose direction is variable depending on the direction of an applied magnetic field, and a gap layer located between the magnetization pinned layer and the free layer. In many cases, the spin-valve magnetoresistive element provided on a substrate is configured to have sensitivity to a magnetic field in a direction parallel to the surface of the substrate. Such a magnetoresistive element is thus suitable to detect a magnetic field that changes in direction within a plane parallel to the substrate surface.
[0004] On the other hand, a system including a magnetic sensor may be intended to detect a magnetic field containing a component in a direction perpendicular to the surface of a substrate by using a magnetoresistive element provided on the substrate. An example of such a system is described in US 2015/0192432 A1, JP H09-219546 A, US 2008/0169807 A1, and US 2018/0275218 A1.
[0005] US 2015/0192432 A1 describes a magnetic sensor for detecting the position of a magnet. This magnetic sensor includes a substrate, two magnetic sensor elements located on the substrate, a magnet located above the substrate, and a soft magnetic body. The soft magnetic body is located between the magnet and the two magnetic sensor elements. The soft magnetic body converts a magnetic field on an XZ plane, generated by the magnet, into a magnetic field on an XY plane to which the two magnetic sensor elements have sensitivity. The XY plane is parallel to the substrate surface. The XZ plane is perpendicular to the substrate surface.
[0006] JP H09-219546 A describes an apparatus in which a magnetoresistive element including magnetic stripes is located on a slope formed on a substrate, and a rotating body including a magnet is located above the substrate. In this apparatus, as the rotating body rotates, the direction of a magnetic field generated by the rotating body changes within a plane of variation perpendicular to

the slope. The magnetoresistive element detects the magnetic field generated by the rotating body.

[0007] US 2008/0169807 A1 and US 2018/0275218 A1 describe an apparatus including three sensors for detecting an X-direction component, a Y-direction component, and a Z-direction component of an external magnetic field. In this apparatus, the sensor for detecting the Z-direction component includes a magnetoresistive element located on a slope formed on a substrate.

[0008] The magnetic sensor described in US 2015/0192432 A1 has a problem that the detection accuracy can drop due to an unnecessary magnetic field occurring from the soft magnetic body and the magnetic hysteresis characteristics of the soft magnetic body.

[0009] Next, a problem with the apparatuses described in JP H09-219546 A, US 2008/0169807 A1, and US 2018/0275218 A1 will be described. The sensor for detecting the Z-direction component in US 2008/0169807 A1 and US 2018/0275218 A1 will hereinafter be referred to as a Z-direction sensor. The magnetic field applied to the magnetoresistive element in JP H09-219546 A and the magnetic field applied to the Z-direction sensor in US 2008/0169807 A1 and US 2018/0275218 A1 will each be referred to as an applied magnetic field. The component of the applied magnetic field to which the magnetoresistive element according to JP H09-219546 A has sensitivity and the component of the applied magnetic field to which the Z-direction sensor according to US 2008/0169807 A1 and US 2018/0275218 A1 has sensitivity will each be referred to as a sensitivity component.

[0010] The strength of the applied magnetic field can vary due to reasons such as variations in the arrangement of the constituent parts of the apparatus. The apparatuses described in JP H09-219546 A, US 2008/0169807 A1, and US 2018/0275218 A1 have a problem that the detection accuracy drops greatly relative to variations in the strength of the applied magnetic field. A detailed description thereof is given below.

[0011] The lower the strength of the sensitivity component, the greater the degree of drop in the detection accuracy relative to variations in the strength of the applied magnetic field. In the apparatus described in JP H09-219546 A, the direction of the applied magnetic field changes within the plane of variation of the magnetic field perpendicular to the slope. In the apparatus, the direction of the applied magnetic field can thus be perpendicular to the slope, i.e., direction to which the magnetoresistive element has no sensitivity. In such an apparatus, the strength of the sensitivity component can be zero.

[0012] In the apparatuses described in US 2008/0169807 A1 and US 2018/0275218 A1, the direction of the applied magnetic field can be perpendicular to the slope, i.e., direction to which the Z-direction sensor has no sensitivity. In such an apparatus, the strength of the sensitivity component can be zero.

[0013] In the apparatuses described in JP H09-219546 A, US 2008/0169807 A1, and US 2018/0275218 A1, the detection accuracy can drop greatly relative to variations in the strength of the applied magnetic field if the direction of the applied magnetic field is such that the strength of the sensitivity component has a value of zero or near zero in particular.

SUMMARY OF THE INVENTION

[0014] An object of the present invention is to provide a magnetic sensor that can generate a detection value corresponding to the direction of a magnetic field to be detected that changes in direction within a variable range including a direction outside a predetermined plane by using a magnetoresistive element suitable to detect a magnetic field that changes in direction within the predetermined plane while suppressing a drop in detection accuracy, and a magnetic sensor system including the magnetic sensor.

[0015] A magnetic sensor according to the present invention detects a magnetic field to be detected and generates a detection value. The magnetic field to be detected has a first direction at a reference position within a first plane, and the first direction changes within a predetermined variable range in the first plane. The magnetic sensor according to the present invention includes at least one magnetoresistive element. The at least one magnetoresistive element each includes a first magnetic

layer having first magnetization that can change in direction within a corresponding second plane. The first plane and the second plane intersect at a dihedral angle other than 90°.

[0016] The magnetic field to be detected received by each of the at least one magnetoresistive element can be divided into an in-plane component parallel to the second plane and a perpendicular component perpendicular to the second plane. The in-plane component has a second direction that changes with a change in the first direction. The direction of the first magnetization changes with a change in the second direction. The detection value depends on the direction of the first magnetization.

[0017] In the magnetic sensor according to the present invention, the first magnetic layer may have a characteristic that the first magnetization is saturated by the magnetic field to be detected if the first direction is in at least part of the variable range.

[0018] In the magnetic sensor according to the present invention, the at least one magnetoresistive element may each further include a second magnetic layer having second magnetization in a direction parallel to the second plane, and a gap layer located between the first magnetic layer and the second magnetic layer.

[0019] In the magnetic sensor according to the present invention, the dihedral angle may be in a range of 30° to 84°.

[0020] The magnetic sensor according to the present invention may include a first magnetoresistive element and a second magnetoresistive element as the at least one magnetoresistive element. In this case, the magnetic sensor may further include a signal output node. The first and second magnetoresistive elements may be connected in series via the signal output node. The detection value may depend on a potential of the signal output node.

[0021] The magnetic sensor according to the present invention may further include a substrate that supports the at least one magnetoresistive element. The substrate may include a main surface perpendicular to the first plane and at least one slope oblique to the main surface. The at least one magnetoresistive element may be located on the at least one slope. The second plane corresponding to each of the at least one magnetoresistive element may be parallel to the slope on which each of the at least one magnetoresistive element is located. It will be understood that the slope here is a flat surface (plane). In the present invention, that two planes are parallel, like the second plane and the slope are parallel, covers a situation where the two planes overlap.

[0022] If the magnetic sensor according to the present invention includes the substrate, the magnetic sensor may include a first magnetoresistive element and a second magnetoresistive element as the at least one magnetoresistive element. The substrate may include, as the at least one slope, a first slope on which the first magnetoresistive element is located and a second slope on which the second magnetoresistive element is located. The second plane corresponding to the first magnetoresistive element may be parallel to the first slope. The second plane corresponding to the second magnetoresistive element may be parallel to the second slope.

[0023] If the magnetic sensor according to the present invention includes the substrate and the first and second magnetoresistive elements, the magnetic sensor may further include a signal output node. The first and second magnetoresistive elements may be connected in series via the signal output node. The detection value may depend on a potential of the signal output node.

[0024] If the magnetic sensor according to the present invention includes the substrate and the first and second magnetoresistive elements, the first and second magnetoresistive elements may be connected in series. The detection value may depend on a combined resistance of the first and second magnetoresistive elements.

[0025] The magnetic sensor according to the present invention may further include a first magnetic detection unit that includes the at least one magnetoresistive element and generates a first detection signal dependent on the direction of the first magnetization, a second magnetic detection unit that detects the magnetic field to be detected and generates a second detection signal dependent on the first direction, and a detection value generation unit that generates the detection value on the basis

of the first detection signal and the second detection signal. The variable range may include a first region and a second region that are different from each other. In this case, two candidates for the first direction corresponding to a specific same value of the first detection signal may fall within the respective first and second regions. Two values of the second detection signal corresponding to the two candidates may be different from each other.

[0026] A magnetic sensor system according to the present invention includes the magnetic sensor according to the present invention and a magnetic field generator that generates the magnetic field to be detected. The magnetic sensor and the magnetic field generator may be configured such that the first direction changes as a relative position of the magnetic field generator with respect to the magnetic sensor changes. In this case, the relative position of the magnetic field generator with respect to the magnetic sensor may be rotatable about the magnetic sensor.

[0027] In the magnetic sensor and the magnetic sensor system according to the present invention, the first plane and the second plane intersect at a dihedral angle other than 90°. This prevents the strength of the in-plane component from becoming zero regardless of the first direction within the variable range as long as there is a magnetic field to be detected. For this reason, according to the present invention, the detection value corresponding to the direction of the magnetic field to be detected that changes in direction within a variable range including a direction outside a predetermined plane can be generated by using a magnetoresistive element or elements suitable to detect a magnetic field that changes in direction within the predetermined plane while suppressing a drop in detection accuracy.

[0028] Other and further objects, features and advantages of the present invention will appear more fully from the following description.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIG. **1** is a perspective view showing a schematic configuration of a magnetic sensor system according to a first embodiment of the invention.

[0030] FIG. **2** is a front view showing a schematic configuration of a magnetic sensor system according to the first embodiment of the invention.

[0031] FIG. **3** is an explanatory diagram for describing a magnetic field to be detected of the first embodiment of the invention.

[0032] FIG. **4** is an explanatory diagram showing an in-plane component and a perpendicular component of the magnetic field to be detected of the first embodiment of the invention.

[0033] FIG. **5** is a perspective view showing a magnetic sensor according to the first embodiment of the invention.

[0034] FIG. **6** is a circuit diagram showing a configuration of the magnetic sensor according to the first embodiment of the invention.

[0035] FIG. **7** is a perspective view showing a part of a magnetoresistive element of the first embodiment of the invention.

[0036] FIG. **8** is an explanatory diagram showing a definition of a first angle of the first embodiment of the invention.

[0037] FIG. **9** is an explanatory diagram showing a definition of a second angle of the first embodiment of the invention.

[0038] FIG. **10** is a waveform chart showing a change in a component of each of first and second vectors with respect to a change in the first angle of the first embodiment of the invention.

[0039] FIG. **11** is an explanatory diagram showing a configuration of a throttle to which the magnetic sensor system according to the first embodiment of the invention can be applied.

[0040] FIG. **12** is an explanatory diagram showing a schematic configuration of a magnetic sensor

system according to a second embodiment of the invention.

[0041] FIG. **13** is a perspective view showing a magnetic sensor according to the second embodiment of the invention.

[0042] FIG. **14** is a circuit diagram showing a configuration of the magnetic sensor according to the second embodiment of the invention.

[0043] FIG. **15** is a waveform chart showing a relationship between a second angle and a first detection signal in the second embodiment of the invention.

[0044] FIG. **16** is a waveform chart showing a relationship between a first angle and a second detection signal in the second embodiment of the invention.

[0045] FIG. **17** is a perspective view showing a magnetic sensor according to a third embodiment of the invention.

[0046] FIG. **18** is a perspective view showing at least part of a magnetic sensor according to a fourth embodiment of the invention.

[0047] FIG. **19** is a circuit diagram showing a configuration of a first magnetic detection unit of the magnetic sensor according to the fourth embodiment of the invention.

[0048] FIG. **20** is a perspective view showing a magnetic sensor according to a fifth embodiment of the invention.

[0049] FIG. **21** is a sectional view showing a cross section of the magnetic sensor according to the fifth embodiment of the invention.

[0050] FIG. **22** is a circuit diagram showing a configuration of a first magnetic detection unit of a magnetic sensor according to a sixth embodiment of the invention.

[0051] FIG. **23** is a perspective view showing a magnetic sensor according to a seventh embodiment of the invention.

[0052] FIG. **24** is a sectional view showing a cross section of the magnetic sensor according to the seventh embodiment of the invention.

[0053] FIG. **25** is a sectional view showing another cross section of the magnetic sensor according to the seventh embodiment of the invention.

[0054] FIG. **26** is a block diagram showing a configuration of the magnetic sensor according to the seventh embodiment of the invention.

[0055] FIG. **27** is a circuit diagram showing a configuration of a first magnetic detection unit of the magnetic sensor according to the seventh embodiment of the invention.

[0056] FIG. **28** is a circuit diagram showing a configuration of a second magnetic detection unit of the magnetic sensor according to the seventh embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

First Embodiment

[0057] Preferred embodiments of the present invention will now be described in detail with reference to the drawings. Initially, a magnetic sensor system according to a first embodiment of the invention will be outlined with reference to FIGS. **1** and **2**. A magnetic sensor system **1** according to the present embodiment includes a magnetic sensor **2** according to the present embodiment and a magnetic field generator **5** that generates a magnetic field to be detected.

[0058] The magnetic field generator **5** has a ring shape with a rotation axis C at the center, and is rotatable about the rotation axis C. Considering the magnetic field generator **5** as a ring, the magnetic sensor **2** is located in a portion corresponding to the hole of the ring. The magnetic sensor **2** is located on the rotation axis C. In FIG. **1**, the magnetic sensor **2** and the magnetic field generator **5** are shown to be separated from each other along the rotation axis C. The magnetic sensor **2** detects the magnetic field to be detected generated by the magnetic field generator **5**, and generates a detection value θs. The detection value θs corresponds to a relative position, or rotational position in particular, of the magnetic field generator **5** with respect to the magnetic sensor **2**.

[0059] The magnetic field generator **5** includes two magnets **6**A and **6**B and two yokes **7**A and **7**B.

The magnets **6**A and **6**B are arranged at symmetrical positions with a virtual plane including the rotation axis C at the center. The magnets **6**A and **6**B each have an N pole and an S pole at respective ends in the direction of rotation of the magnetic field generator **5**. The yoke **7**A connects the N pole of the magnet **6**A and the N pole of the magnet **6**B. The yoke **7**B connects the S pole of the magnet **6**A and the S pole of the magnet **6**B.

[0060] Now, we define X, Y, and Z directions as shown in FIGS. **1** and **2**. The X, Y, and Z directions are orthogonal to one another. In the present embodiment, a direction parallel to the rotation axis C (in FIG. **1**, rightward direction) will be referred to as the X direction. In FIG. **2**, the Y direction is shown as a leftward direction. In FIGS. **1** and **2**, the Z direction is shown as an upward direction. The opposite directions to the X, Y, and Z directions will be referred to as −X, −Y, and −Z directions, respectively.

[0061] Next, the magnetic field to be detected generated by the magnetic field generator **5** will be described with reference to FIGS. **1** to **4**. FIG. **3** is an explanatory diagram for describing the magnetic field to be detected. FIG. **4** is an explanatory diagram showing an in-plane component and a perpendicular component of the magnetic field to be detected.

[0062] In the present embodiment, both a magnetic flux occurring from the N pole of the magnet **6**A and a magnetic flux occurring from the N pole of the magnet **6**B flow out of the yoke **7**A into the yoke **7**B. This generates a magnetic field to be detected MF directed from the yoke **7**A to the yoke **7**B.

[0063] In FIGS. **3** and **4**, a plane denoted by the symbol PL**1** represents a YZ plane intersecting the magnetic sensor **2** and the magnetic field generator **5**. This plane will hereinafter be referred to as a first plane PL**1**. The magnetic field to be detected MF has a first direction D**1** at a reference position P**0** within the first plane PL**1**. The reference position P**0** is located inside or at the surface of the magnetic sensor **2**. The first direction D**1** changes within a predetermined variable range in the first plane PL**1**. In FIG. **3**, the arrow denoted by the symbol D**1** represents the first direction D**1** and the strength of the magnetic field to be detected MF at the reference position P**0**. The end of the arrow denoted by the symbol D**1** moves along a circle denoted by the symbol C**1**. In the present embodiment, the variable range of the first direction D**1** is 180° or less in size.

[0064] The magnetic sensor **2** and the magnetic field generator **5** are configured such that the first direction D**1** changes as the relative position of the magnetic field generator **5** with respect to the magnetic sensor **2** changes. More specifically, as the magnetic field generator **5** rotates about the rotation axis C, the relative position of the magnetic field generator **5** with respect to the magnetic sensor **2** rotates about the magnetic sensor **2**. The first direction D**1** thus rotates about the reference position P**0**.

[0065] In FIGS. **3** and **4**, a plane denoted by the symbol PL**3** represents an XY plane passing the reference position P**0**. This plane will hereinafter be referred to as a reference plane PL**3**.

[0066] In the present embodiment, a second plane related to the magnetic sensor **2** is defined. The second plane is oblique to both the first plane PL**1** and the reference plane PL**3**. The first plane PL**1** and the second plane intersect at a dihedral angle α other than 90°. The dihedral angle α is greater than 0° and smaller than 90°. The second plane of the present embodiment is a plane obtained by rotating the XY plane about an axis in the Y direction by an angle of 90°−α. A plane PL**2** shown in FIGS. **3** and **4** is an example of the second plane. The plane PL**2** shown in FIGS. **3** and **4** passes the reference position P**0**. However, the second plane does not necessarily pass the reference position P**0**.

[0067] A direction rotated from the Z direction toward the −X direction by a will be referred to as a U direction. The direction opposite to the U direction will be referred to as a −U direction. The plane PL**2** is a plane parallel to the U direction and the Y direction, i.e., a UY plane.

[0068] As shown in FIG. **4**, the magnetic field to be detected MF at the reference position P**0** can be divided into an in-plane component MFa parallel to the plane PL**2** and a perpendicular component MFb perpendicular to the plane PL**2**. FIG. **4** shows a state where the first direction D**1**

that is the direction of the magnetic field to be detected MF at the reference position P0 coincides with the Z direction. The in-plane component MFa has a second direction D2 that changes with a change in the first direction D1. In FIG. 3, the arrow denoted by the symbol D2 represents the second direction D2 and the strength of the in-plane component MFa. The end of the arrow denoted by the symbol D2 moves along an ellipse denoted by the symbol C2.

[0069] FIG. 3 shows a virtual line L1, a virtual line L2, and intersections P1, P2, P3, and P4. The virtual line L1 passes the reference position P0 and is parallel to the Z direction. The virtual line L2 passes the reference position P0 and is parallel to the U direction. The intersections P1 and P2 are those of the virtual line L1 and the circle C1. The intersections P3 and P4 are those of the virtual line L2 and the ellipse C2. The virtual line L2, the ellipse C2, the intersections P3 and P4, and the second direction D2 are orthogonal projections of the virtual line L1, the circle C1, the intersections P1 and P2, and the first direction D1 upon the plane PL2, respectively.

[0070] The magnetic sensor 2 includes at least one magnetoresistive element (hereinafter, referred to as an MR element). In the present embodiment, a second plane is defined for each of the at least one MR element. In the present embodiment, each second plane intersects its corresponding MR element.

[0071] The at least one MR element each includes a first magnetic layer having first magnetization that can change in direction within the corresponding second plane. Like the magnetic field to be detected MF at the reference position P0, the magnetic field to be detected MF received by each of the at least one MR element can be divided into an in-plane component parallel to the second plane and a perpendicular component perpendicular to the second plane. Like the in-plane component MFa shown in FIG. 4, the in-plane component has a second direction that changes with a change in the first direction D1. The direction of the first magnetization in each of the at least one MR element changes with a change in the second direction. The detection value θs depends on the direction of the first magnetization.

[0072] Since the second direction changes with a change in the first direction D1, the direction of the first magnetization changes with a change in the first direction D1. The detection value θs thus corresponds to the first direction D1.

[0073] If the magnetic sensor 2 includes a plurality of MR elements, the plurality of MR elements are located within an area where no substantial difference occurs in the direction of the magnetic field to be detected MF depending on the positions where the plurality of MR elements receive the magnetic field to be detected MF. The directions of the magnetic field to be detected MF received by the plurality of MR elements are thus substantially the same.

[0074] Next, a configuration of the magnetic sensor 2 will be described with reference to FIGS. 5 and 6. FIG. 5 is a perspective view showing the magnetic sensor 2. FIG. 6 is a circuit diagram showing the configuration of the magnetic sensor 2. As shown in FIG. 6, in the present embodiment, the magnetic sensor 2 includes a first magnetic detection unit 10 that includes at least one MR element and generates a first detection signal S1 dependent on the direction of first magnetization. In the present embodiment, the first magnetic detection unit 10 includes an MR element 11.

[0075] As shown in FIG. 5, the magnetic sensor 2 further includes a substrate 3 that supports the MR element 11. The substrate 3 includes a main surface 3a perpendicular to the first plane PL1 (YZ plane) shown in FIGS. 3 and 4. In particular, in the present embodiment, the main surface 3a is parallel to the reference plane PL3 (XY plane) shown in FIGS. 3 and 4.

[0076] The substrate 3 further includes a groove portion 3c open in the main surface 3a. The groove portion 3c includes a slope 3b oblique to the main surface 3a. The slope 3b is a flat surface. The MR element 11 is located on the slope 3b. The second plane corresponding to the MR element 11 is parallel to the slope 3b.

[0077] In the present embodiment, the position where the MR element 11 is located is the reference position P0. The plane PL2 shown in FIGS. 3 and 4 is the second plane corresponding to the MR

element **11**. For the sake of convenience, in the present embodiment, the second plane corresponding to the MR element **11** will be referred to as a second plane PL**2**. Like the second plane PL**2**, the slope **3***b* is tilted to form the dihedral angle α with respect to the first plane PL**1** and is parallel to the UY plane.

[0078] In the present embodiment, the in-plane component MFa shown in FIG. **4** is the in-plane component of the magnetic field to be detected MF received by the MR element **11**. The second direction D**2** shown in FIG. **3** is the second direction of the in-plane component of the magnetic field to be detected MF received by the MR element **11**. For the sake of convenience, in the present embodiment, the in-plane component of the magnetic field to be detected MF received by the MR element **11** will be referred to as an in-plane component MF**2***a*. The second direction of the in-plane component of the magnetic field to be detected MF received by the MR element **11** will be referred to as a second direction D**2**.

[0079] As shown in FIG. **6**, the first magnetic detection unit **10** further includes a resistor **12**, a signal output node E**1**, a power supply node V**1**, and a ground node G**1**. Since the first magnetic detection unit **10** is part of the magnetic sensor **2**, the magnetic sensor **2** can be said to include the resistor **12**, the signal output node E**1**, the power supply node V**1**, and the ground node G**1**. The MR element **11** and the resistor **12** are connected in series via the signal output node E**1**. The resistor **12** is arranged between the power supply node V**1** and the signal output node E**1**. The MR element **11** is arranged between the signal output node E**1** and the ground node G**1**. A predetermined magnitude of power supply voltage is applied to the power supply node V**1**. The ground node G**1** is grounded.

[0080] The MR element **11** may be a spin valve MR element or an anisotropic MR element. In particular, in the present embodiment, the MR element **11** is a spin valve MR element. In this case, the MR element **11** includes a second magnetic layer and a gap layer aside from the foregoing first magnetic layer. The second magnetic layer has second magnetization in a direction parallel to the second plane PL**2**. The gap layer is located between the first and second magnetic layers. The direction of the second magnetization does not change with a change in the second direction D**2** of the in-plane component MFa. The spin-valve MR element may be a tunneling magnetoresistive (TMR) element or a giant magnetoresistive (GMR) element. In the TMR element, the gap layer is a tunnel barrier layer. In the GMR element, the gap layer is a nonmagnetic conductive layer. The resistance of the MR element **11** changes with an angle that the direction of the first magnetization of the first magnetic layer forms with the direction of the second magnetization of the second magnetic layer. The resistance is minimized if the angle is 0°. The resistance is maximized if the angle is 180°. In FIGS. **5** and **6**, the thick arrow indicates the direction of the second magnetization. In the present embodiment, the direction of the second magnetization is the −U direction.

[0081] As described above, the direction of the first magnetization changes with a change in the second direction D**2** of the in-plane component MFa. The second direction D**2** changes with a change in the first direction D**1** of the magnetic field to be detected MF. The resistance of the MR element **11** thus changes with a change in the first direction D**1**, and as a result, the signal output node E**1** changes in potential. The first magnetic detection unit **10** generates a signal corresponding to the potential of the signal output node E**1** as the first detection signal S**1**. The first detection signal S**1** changes with a change in the first direction D**1**.

[0082] From the viewpoint of the manufacturing accuracy of the MR element **11**, the direction of the second magnetization may be slightly different from the foregoing direction.

[0083] An example of the configuration of the MR element **11** will now be described with reference to FIG. **7**. FIG. **7** is a perspective view showing a part of the MR element **11**. In this example, the MR element **11** includes a plurality of lower electrodes **41**, a plurality of MR films **50**, and a plurality of upper electrodes **42**. The plurality of lower electrodes **41** are located on the slope **3***b* of the substrate **3**. Each of the lower electrodes **41** has a long slender shape. Every two lower electrodes **41** adjacent to each other in the longitudinal direction of the lower electrodes **41** have a

gap therebetween. As shown in FIG. **7**, MR films **50** are provided on the top surfaces of the lower electrodes **41**, near opposite ends in the longitudinal direction. Each of the MR films **50** includes a first magnetic layer **51**, a gap layer **52**, a second magnetic layer **53**, and an antiferromagnetic layer **54** which are stacked in this order, the first magnetic layer **51** being closest to the lower electrode **41**. The first magnetic layer **51** is electrically connected to the lower electrode **41**. The antiferromagnetic layer **54** is formed of an antiferromagnetic material. The antiferromagnetic layer **54** is in exchange coupling with the second magnetic layer **53** so as to pin the magnetization direction of the second magnetic layer **53**. The plurality of upper electrodes **42** are arranged over the plurality of MR films **50**. Each of the upper electrodes **42** has a long slender shape, and establishes electrical connection between the respective antiferromagnetic layers **54** of two adjacent MR films **50** that are arranged on two lower electrodes **41** adjacent in the longitudinal direction of the lower electrodes **41**. With such a configuration, the plurality of MR films **50** in the MR element **11** shown in FIG. **7** are connected in series by the plurality of lower electrodes **41** and the plurality of upper electrodes **42**. It should be appreciated that the layers **51** to **54** of the MR films **50** may be stacked in an order reverse to that shown in FIG. **7**.

[0084] As shown in FIG. **6**, the magnetic sensor **2** further includes a detection value generation unit **30** that generates the detection value θs on the basis of the first detection signal S**1**. The detection value θs depends on the first detection signal S**1**. Since the first detection signal S**1** changes with a change in the first direction D**1**, the detection value θs corresponds to the first direction D**1**. The detection value generation unit **30** includes an application specific integrated circuit (ASIC) or a microcomputer, for example.

[0085] Next, a method for generating the detection value θs will be described. Here, the angle that the first direction D**1** of the magnetic field to be detected MF forms with respect to a predetermined reference direction will be referred to as a first angle and denoted by the symbol θ1. The angle that the second direction D**2** of the in-plane component MFa forms with respect to a predetermined reference direction will be referred to as a second angle and denoted by the symbol θ2. The second angle θ2 has a correlation with the first angle θ1.

[0086] FIG. **8** is an explanatory diagram showing the definition of the first angle θ1. FIG. **8** shows the first plane PL**1**, the reference position P**0**, the first direction D**1**, and the circle C**1** shown in FIG. **3**. In the first plane PL**1**, the first direction D**1** rotates about the reference position P**0**. In the present embodiment, the Z direction serves as the reference direction for representing the first angle θ1. The first angle θ1 is expressed in positive values when seen clockwise from the Z direction in FIG. **8**. The first angle θ1 is expressed in negative values when seen counterclockwise from the Z direction in FIG. **8**.

[0087] As described above, in the present embodiment, the variable range of the first direction D**1** is 180° or less in size. In the following description, the first angle θ1 shall change within the range of 0° or more and not more than 180°.

[0088] FIG. **9** is an explanatory diagram showing the definition of the second angle θ2. FIG. **9** shows the plane PL**2**, i.e., the second plane PL**2**, the reference position P**0**, the second direction D**2**, and the ellipse C**2** shown in FIG. **3**. In the second plane PL**2**, the second direction D**2** rotates about the position where the MR element **11** is located, i.e., the reference position P**0**. In the present embodiment, the U direction serves as the reference direction for representing the second angle θ2. The second angle θ2 is expressed in positive values when seen clockwise from the U direction in FIG. **9**. The second angle θ2 is expressed in negative values when seen counterclockwise from the U direction in FIG. **9**. In the present embodiment, the second angle θ2 changes within the range of 0° or more and not more than 180°.

[0089] The detection value generation unit **30** generates a value having a correlation with the first angle θ1 as the detection value θs. In the present embodiment, the detection value generation unit **30** generates a value representing the first angle θ1 itself as the detection value θs. Instead of the value representing the first angle θ1 itself, the detection value generation unit **30** may generate a

value having a correlation with an angle representing the relative position of the magnetic field generator **5** with respect to the magnetic sensor **2** as the detection value θs. The angle representing the relative position of the magnetic field generator **5** with respect to the magnetic sensor **2** has a correlation with the first angle θ1.

[0090] A method for generating the detection value θs will be specifically described below. Initially, the method for generating the detection value θs will be outlined. The arrow indicating the first direction D**1** shown in FIG. **8** can be said to represent a vector representing the direction and strength of the magnetic field to be detected MF received by the MR element **11** in the YZ coordinate system with the reference position P**0** as the origin. This vector will hereinafter be referred to as a first vector. The Y component and the Z component of the first vector will be denoted by Y**1** and Z**1**, respectively.

[0091] The arrow indicating the second direction D**2** shown in FIG. **9** can be said to represent a vector representing the direction and strength of the in-plane component MFa received by the MR element **11** in the YU coordinate system with the reference position P**0** as the origin. This vector will hereinafter be referred to as a second vector. The second vector is an orthogonal projection of the first vector on the second plane PL**2**. The Y component of the second vector has the same value as that of the Y component of the first vector, i.e., Y**1**. The Y and U components of the second vector will hereinafter be denoted by Y**1** and U**1**, respectively.

[0092] The U component U**1** of the second vector has a correlation with the Z component Z**1** of the first vector. FIG. **10** is a waveform chart showing changes in Z**1** and U**1** with respect to a change in the first angle θ1. In FIG. **10**, the horizontal axis indicates the first angle θ1, and the vertical axis indicates Z**1** and U**1**. In FIG. **10**, a curve denoted by a reference numeral **81** represents Z**1**, and a curve denoted by a reference numeral **82** represents U**1**. In FIG. **10**, Z**1** is normalized so that Z**1** has a maximum value of 1 and a minimum value of −1. FIG. **10** shows U**1** for a case where the dihedral angle α is 60°.

[0093] Z**1** can be expressed by using U**1** and the dihedral angle x. The ratio Y**1**/Z**1** can thus be expressed by using the ratio Y**1**/U**1** and the dihedral angle α. An equation representing a relationship between the first angle θ1 and the second angle θ2 can be obtained by using a relationship between the ratio Y**1**/Z**1** and the first angle θ1, a relationship between the ratio Y**1**/U**1** and the second angle θ2, and a relationship between the ratio Y**1**/Z**1** and the ratio Y**1**/U**1**.

[0094] A value θ2s representing the second angle θ2 can be determined by using the first detection signal S**1**. In the present embodiment, the detection value generation unit **30** generates the detection value θs by determining θ2s and substituting θ2s into the equation representing the relationship between the first angle θ1 and the second angle θ2.

[0095] Next, a specific method for calculating the detection value θs will be described. The ratio Y**1**/Z**1** and the ratio Y**1**/U**1** are represented by the following Eqs. (1) and (2), respectively:

[00001] $Y1\,/\,Z1 = \tan\theta1,\, \text{and} \quad (1) \quad Y1\,/\,Z1 = \tan\theta2\,. \quad (2)$

[0096] Z**1** is represented by the following Eq. (3):

[00002] $Z1 = U1\,/\cos \quad . \quad (3)$

[0097] Transforming Eq. (1) and substituting Eqs. (2) and (3) into the transformed equation yields the following Eq. (4):

[00003]
$$
\begin{aligned}
\theta1 &= \mathrm{atan}(Y1\,/\,Z1)\\
&= \mathrm{atan}(Y1\,/\,(U1\,/\cos\ ))\\
&= \mathrm{atan}(\cos\ \ .\mathrm{Math.}\ Y1\,/\,U1)\\
&= \mathrm{atan}(\cos\ \ .\mathrm{Math.}\ \tan\theta2)\,.
\end{aligned} \quad (4)
$$

[0098] Eq. (4) represents the relationship between the first angle θ1 and the second angle θ2. The symbol "atan" represents the arctangent.

[0099] The first detection signal S**1** can be normalized so that the first detection signal S**1** has a

value of 1 if the second angle θ2 is 0°, a value of −1 if the second angle θ2 is 180°, and a value of 0 if the second angle θ2 is 90° or 270°. In this case, the first detection signal S1 can be represented by the following Eq. (5):

[00004] $S1 = \cos\theta2$.　(5)

[0100] FIG. 6 shows an example of the configuration of the detection value generation unit 30. In this example, the detection value generation unit 30 includes a first arithmetic unit 31 and a second arithmetic unit 32. The first arithmetic unit 31 calculates the value θ2s representing the second angle θ2 on the basis of the first detection signal S1. The second arithmetic unit 32 calculates the detection value θs on the basis of the value θ2s calculated by the first arithmetic unit 31. The first and second arithmetic units 31 and 32 may be functional blocks or physically separate circuits.

[0101] The first arithmetic unit 31 calculates the value θ2s by the following Eq. (6):

[00005]　$2s = \mathrm{acos}S1$.　(6)

[0102] The range of the value θ2s is 0° or more and not more than 180°. Eq. (6) is obtained by replacing θ2 in Eq. (5) with θ2s and transforming the resultant. The symbol "acos" represents the arccosine.

[0103] The second arithmetic unit 32 calculates the detection value θs by the following Eq. (7) excluding the exceptions to be described later:

[00006]　$s = \mathrm{atan}(\cos\quad.\mathrm{Math.}\tan\quad 2s)$.　(7)

[0104] The range of the detection value θs is 0° or more and not more than 180°. Eq. (7) is obtained by replacing θ1 and θ2 in Eq. (4) with θs and θ2s respectively and transforming the resultant.

[0105] The foregoing exceptions refer to situations where the value θ2s is 0° or 180°. If the value θ2s is 0° or 180°, θs in Eq. (7) has two solutions, 0° and 180°. The second arithmetic unit 32 then simply uses the value θ2s itself as the detection value θs if the value θ2s is 0° or 180°. Such exception handling uses the fact that if the first angle θ1 is 0°, the second angle θ2 is also 0°, and if the first angle θ1 is 180°, the second angle θ2 is also 180°.

[0106] The configuration and function of the detection value generation unit 30 are not limited to the foregoing example. For example, the detection value generation unit 30 may retain a table indicating the correspondence between the first detection signal S1 and the detection value θs, and generate the detection value θs from the first detection signal S1 by referring to the table. The correspondence between the first detection signal S1 and the detection value θs in the foregoing table may be theoretically determined as described above, or determined by experiment.

[0107] Next, the operation and effect of the magnetic sensor system 1 and the magnetic sensor 2 according to the present embodiment will be described. The first magnetic detection unit 10 of the magnetic sensor 2 according to the present embodiment includes the MR element 11. The MR element 11 includes the first magnetic layer having the first magnetization that can change in direction within a predetermined plane, namely, the second plane PL2. The MR element 11 is thus suitable to detect the magnetic field that changes in direction within the predetermined plane, i.e., the second plane PL2.

[0108] Meanwhile, the magnetic field to be detected MF at the reference position P0 has the first direction D1 that changes within a predetermined variable range in the first plane PL1 (YZ plane). In other words, the first direction D1 of the magnetic field to be detected MF changes within a variable range including a direction outside the foregoing predetermined plane. According to the present embodiment, the detection value θs corresponding to the first direction D1 of the magnetic field to be detected MF that changes in direction within the variable range including a direction outside the predetermined plane, namely, the second plane PL2 can be generated by using the MR element 11 suitable to detect a magnetic field that changes in direction within the predetermined plane in the following manner.

[0109] In the present embodiment, the MR element 11 is located on the slope 3b of the substrate 3, and the second plane PL2 corresponding to the MR element 11 is tilted to form a dihedral angle α

with respect to the first plane PL**1**. The MR element **11** can thus detect the in-plane component MFa that is a component of the magnetic field to be detected MF. The second direction D**2** that is the direction of the in-plane component MFa changes with a change in the first direction D**1** that is the direction of the magnetic field to be detected MF at the reference position P**0**. In the MR element **11**, the direction of the first magnetization changes with a change in the second direction D**2**. The detection value θs depends on the direction of the first magnetization. The detection value θs therefore corresponds to the first direction D**1**. According to the present embodiment, the detection value θs corresponding to the first direction D**1** can thus be generated by using the MR element **11**.

[0110] Now, if the second plane PL**2** is a plane perpendicular to the first plane PL**1**, the strength of the in-plane component MFa may have a value of 0 or near 0 depending on the first direction D**1**. An example of the case where the second plane PL**2** is perpendicular to the first plane PL**1** is where the second plane PL**2** is a plane obtained by rotating the XY plane about an axis in the X direction by an angle greater than 0° and smaller than 90°. In this case, the strength of the in-plane component MFa has a value of 0 if the first direction D**1** is perpendicular to the second plane PL**2**, and a value near 0 if the first direction D**1** is almost perpendicular to the second plane PL**2**. Thus, if the strength of the in-plane component MFa has a value of 0 or near 0, the detection accuracy of the magnetic sensor **2** drops greatly with respect to variations in the strength of the magnetic field to be detected MF.

[0111] In the present embodiment, the first plane PL**1** and the second plane PL**2** intersect at a dihedral angle α other than 90°. This prevents the strength of the in-plane component MFa from becoming zero regardless of the first direction D**1** within the variable range as long as there is a magnetic field to be detected MF. According to the present embodiment, the detection value θs corresponding to the first direction D**1** of the magnetic field to be detected MF can thus be generated by using the MR element **11** while suppressing a drop in the detection accuracy.

[0112] In the present embodiment, the first plane PL**1** is perpendicular to the main surface **3**a of the substrate **3**. According to the present embodiment, the positional relationship between the magnetic sensor **2** and the magnetic field generator **5** can therefore be easily defined.

[0113] A favorable range of the dihedral angle α will now be described. Assuming that the magnetic field to be detected MF has a strength of H**1**, the minimum value of the strength of the in-plane component MFa is H**1**.Math.cos α. The minimum value of the strength of the in-plane component MFa is preferably 10% or more of H**1**, more preferably 30% or more. The dihedral angle α is thus preferably 84° or less, more preferably 73° or less. Too small a dihedral angle α can make it difficult to form the MR element **11** on the slope **3**b of the substrate **3**. The dihedral angle α is therefore preferably 30° or greater, more preferably 45° or greater. In summary, the dihedral angle α is preferably in the range of 30° to 84°, more preferably in the range of 45° to 73°.

[0114] The direction of the first magnetization in the first magnetic layer of the MR element **11** preferably follows a change in the second direction D**2** of the in-plane component MFa with high accuracy. For that purpose, the first magnetic layer preferably has a characteristic that the first magnetization is saturated by the magnetic field to be detected MF if the first direction D**1** of the magnetic field to be detected MF is in at least a part of the variable range. The first magnetic layer more preferably has a characteristic that the first magnetization is saturated by the magnetic field to be detected MF regardless of what direction within the variable range the first direction D**1** is.

[0115] If the MR element **11** is a spin valve MR element, the first magnetic layer preferably has a small uniaxial magnetic anisotropy in order for the direction of the first magnetization of the first magnetic layer to follow a change in the second direction D**2** with high accuracy.

[0116] The first magnetic layer of the MR element **11** may have a characteristic that the first magnetization is saturated by the magnetic field to be detected MF regardless of what direction within the variable range the first direction D**1** is. In this case, the direction of the first magnetization of the first magnetic layer does not vary depending on variations in the strength of

the magnetic field to be detected MF. This can reduce variations in the detection value θs due to variations in the strength of the magnetic field to be detected MF. The strength of the magnetic field to be detected MF can vary, for example, due to a change in the ambient temperature and variations in the positional relationship between the magnetic sensor **2** and the magnetic field generator **5**.

[0117] In the present embodiment, the variable range of the first direction D**1** is 180° or less in size. In particular, in the present embodiment, as the magnetic field generator **5** rotates about the rotation axis C, the relative rotational position of the magnetic field generator **5** with respect to the magnetic sensor **2** changes, and as a result, the first direction D**1** changes. The variable range of the relative rotational position of the magnetic field generator **5** with respect to the magnetic sensor **2** is also 180° or less. The magnetic sensor system **1** according to the present embodiment can thus be used as a device for detecting the rotational position of a rotatable moving part in an apparatus that includes the moving part and where the variable range of the moving part is 180° or less. An example of such an apparatus is a throttle.

[0118] FIG. **11** is an explanatory diagram showing a configuration of a throttle to which the magnetic sensor system **1** according to the present embodiment can be applied. A throttle **200** shown in FIG. **11** includes a throttle valve **201** that is a moving part and a main body **202** that rotatably supports the throttle value **201** about a predetermined rotation axis. If the magnetic sensor system **1** is applied to the throttle **200**, for example, the magnetic sensor system **1** may be configured so that the magnetic field generator **5** rotates along with the throttle valve **201** without the magnetic sensor **2** rotating along with the throttle valve **201**.

[0119] The variable range of the throttle valve **201** is 90° or less in size. If the magnetic sensor system **1** is applied to the throttle **200**, the magnetic sensor system **1** can be configured such that θ1 and θ2 shown in FIGS. **8** and **9** become 90° when the rotational position of the throttle valve **201** comes to the center position of the variable range. This configuration can improve the linearity of change of the first detection signal S**1** with respect to a change in the rotational position of the throttle valve **201**.

[0120] Another example of the apparatus to which the magnetic sensor system **1** according to the present embodiment can be applied is a gearshift. The gearshift includes a lever and a support unit that swingably supports the lever. If the magnetic sensor system **1** is applied to the gearshift, the magnetic sensor system **1** can be configured such that the magnetic field generator **5** rotates along with the lever without the magnetic sensor **2** rotating along with the lever.

Second Embodiment

[0121] A second embodiment of the invention will now be described. Initially, differences of a magnetic sensor system **1** according to the present embodiment from that according to the first embodiment will be described with reference to FIG. **12**. FIG. **12** is an explanatory diagram showing a schematic configuration of the magnetic sensor system **1**.

[0122] The magnetic sensor system **1** according to the present embodiment includes a magnetic field generator **105** that generates a magnetic field to be detected MF instead of the magnetic field generator **5** of the first embodiment. The magnetic field generator **105** is rotatable about a rotation axis C. The magnetic field generator **105** includes a pair of magnets **106**A and **106**B. The magnets **106**A and **106**B are located at positions symmetrical about a virtual plane including the rotation axis C.

[0123] The magnets **106**A and **106**B each include an N pole and an S pole. The magnets **106**A and **106**B are situated so that the N pole of the magnet **106**A is opposed to the S pole of the magnet **106**B. In the present embodiment, the magnetic field generator **105** generates a magnetic field to be detected MF directed from the N pole of the magnet **106**A to the S pole of the magnet **106**B.

[0124] The magnetic sensor **2** is configured such that the first direction D**1** (see FIGS. **3** and **8**) of the magnetic field to be detected MF changes as the relative position of the magnetic field generator **105** with respect to the magnetic sensor **2** changes. More specifically, as the magnetic

field generator **105** rotates about the rotation axis C, the relative position of the magnetic field generator **105** with respect to the magnetic sensor **2** rotates about the magnetic sensor **2**. The first direction D**1** of the magnetic field to be detected MF thus rotates about the reference position P**0**.

[0125] In the present embodiment, the variable range of the first direction D**1** and the variable ranges of the magnets **106**A and **106**B are all within 360°. The magnetic sensor system **1** according to the present embodiment can thus be used as a device for detecting the rotational position of a rotatable moving part in an apparatus that includes the moving part and the variable range of the moving part is within 360°. Examples of such an apparatus include a joint of an industrial robot. FIG. **12** shows an example where the magnetic sensor system **1** is applied to an industrial robot **300**.

[0126] The industrial robot **300** shown in FIG. **12** includes a moving part **301** and a support unit **302** that rotatably supports the moving part **301**. The moving part **301** and the support unit **302** are connected at a joint. The moving part **301** rotates about a rotation axis C. The variable range of the moving part **301** is within 360°. For example, if the magnetic sensor system **1** according to the present embodiment is applied to the joint of the industrial robot **300**, the magnetic sensor **2** may be fixed to the support unit **302**, and the magnets **106**A and **106**B may be fixed to the moving part **301**.

[0127] Next, differences of the magnetic sensor **2** according to the present embodiment from that according to the first embodiment will be described with reference to FIGS. **13** and **14**. FIG. **13** is a perspective view showing the magnetic sensor **2**. FIG. **14** is a circuit diagram showing a configuration of the magnetic sensor **2**. As shown in FIG. **14**, the magnetic sensor **2** according to the present embodiment includes a second magnetic detection unit **20** aside from the first magnetic detection unit **10** and the detection value generation unit **30**. The second magnetic detection unit **20** detects the magnetic field to be detected MF and generates a second detection signal S**2** dependent on the first direction D**1**. In the present embodiment, the detection value generation unit **30** generates the detection value θs on the basis of the first detection signal S**1** and the second detection signal S**2**. The detection value θs corresponds to a relative position, or rotational position in particular, of the magnetic field generator **105** with respect to the magnetic sensor **2**.

[0128] The second magnetic detection unit **20** includes an MR element **21** shown in FIGS. **13** and **14**. The MR element **21** is located on the main surface **3**a of the substrate **3**. The second magnetic detection unit **20** further includes a resistor **22**, a signal output node E**2**, a power supply node V**2**, and a ground node G**2**. The MR element **21** and the resistor **22** are connected in series via the signal output node E**2**. The resistor **22** is arranged between the power supply node V**2** and the signal output node E**2**. The MR element **21** is arranged between the signal output node E**2** and the ground node G**2**. A predetermined magnitude of power supply voltage is applied to the power supply node V**2**. The ground node G**2** is grounded.

[0129] The MR element **11** of the first magnetic detection unit **10** and the MR element **21** of the second magnetic detection unit **20** are located within an area where no substantial difference occurs in the direction of the magnetic field to be detected MF depending on the positions where the MR elements **11** and **21** receive the magnetic field to be detected MF. The directions of the magnetic field to be detected MF received by the MR elements **11** and **21** are thus substantially the same.

[0130] In the present embodiment, the MR element **21** is a spin valve MR element like the MR element **11**. The MR element **21** includes a third magnetic layer, a fourth magnetic layer, and a gap layer. The third magnetic layer has third magnetization that can change in direction within a virtual plane parallel to the reference plane PL**3** (XY plane). The fourth magnetic layer has fourth magnetization in a direction parallel to the foregoing virtual plane. The gap layer is located between the third and fourth magnetic layers. The resistance of the MR element **21** changes with an angle that the direction of the third magnetization of the third magnetic layer forms with respect to the direction of the fourth magnetization of the fourth magnetic layer. The resistance is minimized if the angle is 0°. The resistance is maximized if the angle is 180°. In FIGS. **13** and **14**, the thick

arrow in the MR element **21** indicates the direction of the fourth magnetization of the fourth magnetic layer. In the present embodiment, the direction of the fourth magnetization of the fourth magnetic layer is the −Y direction.

[0131] From the viewpoint of the manufacturing accuracy of the MR element **21**, the direction of the fourth magnetization may be slightly different from the foregoing direction.

[0132] The third magnetic layer may have uniaxial magnetic anisotropy in a direction parallel to the X direction. The uniaxial magnetic anisotropy may be shape magnetic anisotropy. In this case, the direction of the third magnetization of the third magnetic layer changes with a change in the strength of a component of the magnetic field to be detected MF in a direction parallel to the Y direction. The component of the magnetic field to be detected MF in the direction parallel to the Y direction will hereinafter be referred to as a Y-direction component. The strength of the Y-direction component is expressed in positive values if the direction of the Y-direction component is the Y direction. The strength of the Y-direction component is expressed in negative values if the direction of the Y-direction component is the −Y direction. The strength of the Y-direction component depends on the first angle θ1 (see FIG. **8**) that the first direction D**1** forms with respect to the Z direction. More specifically, assuming the strength of the magnetic field to be detected MF is H**1**, the strength of the Y-direction component is given by H**1**.Math.sin θ1. The direction of the third magnetization of the third magnetic layer thus depends on H**1**.Math.sin θ1.

[0133] The potential of the signal output node E**2** of the second magnetic detection unit **20** depends on the resistance of the MR element **21**. The resistance of the MR element **21** depends on H**1**.Math.sin θ1. The second magnetic detection unit **20** generates a signal corresponding to the potential of the signal output node E**2** as the second detection signal S**2**. In particular, in the present embodiment, the second detection signal S**2** is normalized to sin θ1.

[0134] Like the first embodiment, the first detection signal S**1** generated by the first magnetic detection unit **10** is normalized as represented by Eq. (5).

[0135] FIG. **15** is a waveform chart showing a relationship between the second angle θ2 and the first detection signal S**1**. FIG. **16** is a waveform chart showing a relationship between the first angle θ1 and the second detection signal S**2**. If the first angle θ1 is 0°, the second angle θ2 is also 0°. If the first angle θ1 is 90°, the second angle θ2 is also 90°. If the first angle θ1 is 180°, the second angle θ2 is also 180°. If the first angle θ1 is 270°, the second angle θ2 is also 270°. In terms of both angles θ1 and θ2, 360° is equivalent to 0°. In the following description, items applicable to both 0° and 360° in terms of the angles θ1 and θ2 will therefore be only described for 0°.

[0136] Next, a method for generating the detection value θs of the present embodiment will be described. In the present embodiment, the variable range of the first direction D**1** includes a first region R**1** and a second region R**2** that are different from each other. As described above, the variable range of the first direction D**1** is within 360°. The first angle θ1 will hereinafter be assumed to change within the variable range of 0° or greater and not greater than 360°. Here, a range of the first direction D**1** where the first angle θ1 is greater than 0° and smaller than 180° will be referred to as the first region R**1**. A range of the first direction D**1** where the first angle θ1 is greater than 180° and smaller than 360° will be referred to as the second region R**2**. If the first direction D**1** is in the first region R**1**, both the first and second angles θ1 and θ2 fall within the range of greater than 0° and smaller than 180°. If the first direction D**1** is in the second region R**2**, both the first and second angles θ1 and θ2 fall within the range of greater than 180° and smaller than 360°.

[0137] As shown in FIG. **15**, the first detection signal S**1** changes with a change in the second angle θ2. Like the first angle θ1, the second angle θ2 changes within the variable range of 0° or greater and not greater than 360°. There are two values of the second angle θ2 at which the first detection signal S**1** has a specific same value, within the variable range of the second angle θ2 except 0° and 180°. Similarly, there are two values of the first angle θ1 at which the first detection signal S**1** has the specific same value, within the variable range of the first angle θ1 except 0° and 180°. In other

words, there are two candidates for the first direction D**1** corresponding to a specific same value of the first detection signal S**1**, within the variable range of the first angle θ1 except 0° and 180°. One of the two candidates is in the first region R**1**, and the other thereof is in the second region R**2**. If the first angle θ1 changes within the variable range of 0° or greater and not greater than 360° and the first angle θ1 is other than 0° or 180°, the first direction D**1** is unable to be identified by using only the first detection signal S**1**.

[0138] In the present embodiment, the detection value θs corresponding to the first direction D**1** on a one-to-one basis can be generated on the basis of the first and second detection signals S**1** and S**2**. In other words, according to the present embodiment, the first direction D**1** can be identified on the basis of the first and second detection signals S**1** and S**2**. A detailed description thereof is given below.

[0139] As shown in FIG. **16**, the second detection signal S**2** has a positive value if the first direction D**1** is in the first region R**1**, i.e., the first angle θ1 is greater than 0° and smaller than 180°. The second detection signal S**2** has a negative value if the first direction D**1** is in the second region R**2**, i.e., the first angle θ1 is greater than 180° and smaller than 360°. The second detection signal S**2** thus has two different values corresponding to the two candidates for the first direction D**1** corresponding to a specific same value of the first detection signal S**1**. Which of the two candidates for the first direction D**1** is the true first direction D**1** can therefore be found out by using the second detection signal S**2**. Specifically, if the second detection signal S**2** has a positive value, the candidate for the first direction D**1** in the first region R**1** is the true first direction D**1**. If the second detection signal S**2** has a negative value, the candidate for the first direction D**1** in the second region R**2** is the true first direction D**1**. In such a manner, according to the present embodiment, the first direction D**1** can be identified on the basis of the first and second detection signals S**1** and S**2**.

[0140] In the present embodiment, the detection value generation unit **30** generates the detection value θs corresponding to the first direction D**1** on a one-to-one basis by using the foregoing characteristic. Now, first and second examples of the configuration and processing content of the detection value generation unit **30** will be described. In the first and second examples, as shown in FIG. **14**, the detection value generation unit **30** includes a comparator **33** and an angle calculation unit **34**. The comparator **33** determines whether the value of the second detection signal S**2** is greater than or equal to 0, and outputs the determination result.

[0141] In the first example, the angle calculation unit **34** initially calculates the value θ2s representing the second angle θ2 on the basis of the first detection signal S**1** by using Eq. (6) in the first embodiment. In the first example, the range of the value θ2s is 0° or greater and not greater than 180°. The angle calculation unit **34** then calculates the detection value θs by using Eq. (7) in the first embodiment, excluding the exceptions to be described later. In the present embodiment, the range of the detection value θs is 0° or greater and smaller than 360°. Like the first embodiment, the foregoing exceptions refer to situations where the value θ2s is 0° or 180°. If the value θ2s is 0° or 180°, the angle calculation unit **34** simply uses the value θ2s as the detection value θs.

[0142] In the first example, θs in Eq. (7) has two solutions except the exceptions. One of the two solutions is in the range of greater than 0° and smaller than 180°. The other is in the range of greater than 180° and smaller than 360°. The angle calculation unit **34** then determines which of the two solutions of θs in Eq. (7) is the true value of θs by using the determination result of the comparator **33**. Specifically, if the second detection signal S**2** has a value of 0 or more, the angle calculation unit **34** selects the solution in the range of greater than 0° and smaller than 180° as θs. If the second detection signal S**2** has a negative value, the angle calculation unit **34** selects the solution in the range of greater than 180° and smaller than 360° as θs.

[0143] In the second example, the angle calculation unit **34** initially calculates the value θ2s on the basis of the first detection signal S**1** by using Eq. (6) in the first embodiment. In the second example, the range of the value θ2s is 0° or greater and smaller than 360°. θ2s in Eq. (6) has two

solutions except the exceptions when the value θ2s is other than 0° and 180°. One of the two solutions is in the range of greater than 0° and smaller than 180°. The other is in the range of greater than 180° and smaller than 360°. The angle calculation unit **34** determines which of the two solutions of θ2s in Eq. (6) is the true value of 02s by using the determination result of the comparator **33**. Specifically, if the second detection signal S**2** has a value of 0 or more, the angle calculation unit **34** selects the solution in the range of greater than 0° and smaller than 180° as θ2s. If the second detection signal S**2** has a negative value, the angle calculation unit **34** selects the solution in the range of greater than 180° and smaller than 360° as θ2s. If the value θ2s is 0° or 180°, the angle calculation unit **34** simply uses the value θ2s as the detection value θs.

[0144] Next, the angle calculation unit **34** calculates the detection value θs by using Eq. (7) in the first embodiment. The range of the detection value θs is 0° or greater and smaller than 360°. θs in Eq. (7) has two solutions. One of the two solutions is in the range of greater than 0° and smaller than 180°. The other is in the range of greater than 180° and smaller than 360°. The angle calculation unit **34** selects the closer of the two solutions to the value of θ2s as θs.

[0145] The configuration, operation and effects of the present embodiment are otherwise the same as those of the first embodiment.

Third Embodiment

[0146] A third embodiment of the invention will now be described. Initially, differences of a magnetic sensor **2** according to the present embodiment from that according to the second embodiment will be described with reference to FIG. **17**. FIG. **17** is a perspective view showing the magnetic sensor **2**. As shown in FIG. **17**, in the present embodiment, the MR element **21** of the second magnetic detection unit **20** of the magnetic sensor **2** is located on the slope **3**b of the substrate **3** like the MR element **11** of the first magnetic detection unit **10** of the magnetic sensor **2**.

[0147] Like the second embodiment, the MR elements **11** and **21** are located within an area where no substantial difference occurs in the direction of the magnetic field to be detected MF depending on the positions where the MR elements **11** and **21** receive the magnetic field to be detected MF. The directions of the magnetic field to be detected MF received by the MR elements **11** and **21** are thus substantially the same.

[0148] In the present embodiment, the third magnetization of the third magnetic layer of the MR element **21** can change in direction within the same plane as the second plane PL**2** (see FIGS. **3** and **4**) corresponding to the MR element **11** or within a plane parallel to the second plane PL**2**. The direction of the third magnetization changes with a change in the second direction D**2** (see FIGS. **3** and **9**) of the in-plane component MFa of the magnetic field to be detected MF received by the MR element **11**. The direction of the third magnetization preferably follows the change in the second direction D**2** with high accuracy. For that purpose, the third magnetic layer preferably has a characteristic that the third magnetization is saturated by the magnetic field to be detected MF if the first direction D**1** of the magnetic field to be detected MF is in at least part of the variable range. The third magnetic layer more preferably has a characteristic that the third magnetization is saturated by the magnetic field to be detected MF regardless of what direction within the variable range the first direction D**1** is.

[0149] As described in the second embodiment, the MR element **11** is a spin valve MR element. The third magnetic layer preferably has a small uniaxial magnetic anisotropy so that the direction of the third magnetization of the third magnetic layer follows a change in the second direction D**2** with high accuracy.

[0150] As described in the first embodiment, the second direction D**2** changes with a change in the first direction D**1** (see FIGS. **3** and **8**) of the magnetic field to be detected MF. The resistance of the MR element **21** thus changes with a change in the first direction D**1**, and as a result, the signal output node E**2** (see FIG. **13**) of the second magnetic detection unit **20** changes in potential. The second magnetic detection unit **20** generates a signal corresponding to the potential of the signal output node E**2** as the second detection signal S**2**. The second detection signal S**2** changes with a

change in the first direction D**1**.

[0151] As described in the second embodiment, the direction of the fourth magnetization in the fourth magnetic layer of the MR element **21** is the −Y direction. The direction of the fourth magnetization does not change with a change in the second direction D**2** of the in-plane component MFa. The second detection signal S**2** can be normalized so that the second detection signal S**2** has a value of 0 if the second angle θ2 (see FIG. **9**) that the second direction D**2** forms with respect to the U direction is 0° or 180°, a value of 1 if the second angle θ2 is 90°, and a value of −1 if the second angle θ2 is 270°. In this case, the second detection signal S**2** is represented by the following Eq. (8):

[00007] $S2 = \sin\theta2 .$ (8)

[0152] Next, a method for generating the detection value θs of the present embodiment will be described. As described in the second embodiment, there are two candidates for the first direction D**1** corresponding to a specific same value of the first detection signal S**1** within the variable range of the first angle θ1 except 0° and 180°. One of the two candidates is in the first region R**1**, and the other is in the second region R**2**.

[0153] From Eq. (8), the second detection signal S**2** has a positive value if the first direction D**1** is in the first region R**1**, i.e., the second angle θ2 is greater than 0° and smaller than 180°. The second detection signal S**2** has a negative value if the first direction D**1** is in the second region R**2**, i.e., the second angle θ2 is greater than 180° and smaller than 360°. The second detection signal S**2** thus has two different values corresponding to the two candidates for the first direction D**1** corresponding to a specific same value of the first detection signal S**1**. Which of the two candidates for the first direction D**1** is the true first direction D**1** can therefore be found out by using the second detection signal S**2**. Specifically, if the second detection signal S**2** has a positive value, the candidate for the first direction D**1** in the first region R**1** is the true first direction D**1**. If the second detection signal S**2** has a negative value, the candidate for the first direction D**1** in the second region R**2** is the true first direction D**1**. In this manner, according to the present embodiment, the first direction D**1** can be identified on the basis of the first and second detection signals S**1** and S**2**.

[0154] In the present embodiment, the detection value generation unit **30** generates the detection value θs corresponding to the first direction D**1** on a one-to-one basis by using the foregoing characteristic. First and second examples of the configuration and processing content of the detection value generation unit **30** in the present embodiment will now be described. In the first and second examples, like the second embodiment, the detection value generation unit **30** includes the comparator **33** and the angle calculation unit **34** shown in FIG. **14**. However, in the present embodiment, the angle calculation unit **34** calculates the value θ2s on the basis of the first and second detection signals S**1** and S**2** by using the following Eq. (9) instead of Eq. (6) in the second embodiment:

[00008] $2s = \mathrm{atan}(S2 / S1) .$ (9)

In other respects, the first and second examples in the present embodiment are the same as those in the second embodiment.

[0155] The configuration, operation and effects of the present embodiment are otherwise the same as those of the second embodiment.

Fourth Embodiment

[0156] A fourth embodiment of the invention will now be described. A magnetic sensor **2** according to the present embodiment has the same configuration as that according to any one of the first to third embodiments except that the configuration of the first magnetic detection unit **10** is different.

[0157] FIG. **18** is a perspective view showing at least a part of the magnetic sensor **2**. FIG. **19** is a circuit diagram showing a configuration of the first magnetic detection unit **10** of the magnetic sensor **2**. As shown in FIG. **19**, in the present embodiment, the first magnetic detection unit **10** of the magnetic sensor **2** includes a first MR element **13** and a second MR element **14** instead of the

MR element **11** and the resistor **12** of the first embodiment. Since the first magnetic detection unit **10** is a part of the magnetic sensor **2**, the magnetic sensor **2** can be said to include the first and second MR elements **13** and **14**.

[0158] All the MR elements included in the magnetic sensor **2** are located within an area where no substantial difference occurs in the direction of the magnetic field to be detected MF depending on the positions where all the MR elements receive the magnetic field to be detected MF. The directions of the magnetic field to be detected MF received by all the MR elements are thus substantially the same.

[0159] In the present embodiment, the substrate **3** of the magnetic sensor **2** supports the first and second MR elements **13** and **14**. As shown in FIG. **18**, the first and second MR elements **13** and **14** are located on the slope **3***b* of the substrate **3**. In the present embodiment, the reference position P**0** (see FIGS. **3** and **4**) may be the position where the first MR element **13** or the second MR element **14** is located, or an intermediate position between the first and second MR elements **13** and **14**.

[0160] As shown in FIG. **19**, the first and second MR elements **13** and **14** are connected in series via the signal output node E**1**. The first MR element **13** is arranged between the power supply node V**1** and the signal output node E**1**. The second MR element **14** is arranged between the signal output node E**1** and the ground node G**1**.

[0161] In the present embodiment, a common second plane PL**2** is defined for the first and second MR elements **13** and **14**. In the present embodiment, one second plane PL**2** therefore serves both as a second plane corresponding to the first MR element **13** and as a second plane corresponding to the second MR element **14**. The second plane PL**2** of the present embodiment is the same as that corresponding to the MR element **11** of the first embodiment (see FIGS. **3** and **4**).

[0162] In the present embodiment, the second direction of the in-plane component of the magnetic field to be detected MF received by the first MR element **13** and the second direction of the in-plane component of the magnetic field to be detected MF received by the second element **14** are the same as the second direction D**2** of the first embodiment, shown in FIG. **3**.

[0163] The first and second MR elements **13** and **14** each have the same configuration as that of the MR element **11** of the first embodiment. More specifically, the first and second MR elements **13** and **14** each include a first magnetic layer, a second magnetic layer, and a gap layer. The first magnetic layer has first magnetization that can change in direction within the second plane PL**2**. The second magnetic layer has second magnetization in a direction parallel to the second plane PL**2**. The gap layer is located between the first and second magnetic layers. In FIGS. **18** and **19**, the thick arrows indicate the directions of the second magnetization in the respective second magnetic layers. In the present embodiment, the direction of the second magnetization in the second magnetic layer of the first MR element **13** is the U direction. The direction of the second magnetization in the second magnetic layer of the second MR element **14** is the −U direction.

[0164] In each of the first and second MR elements **13** and **14**, the direction of the first magnetization of the first magnetic layer changes with a change in the second direction D**2** (see FIGS. **3** and **9**) of the in-plane component MFa of the magnetic field to be detected MF. The second direction D**2** changes with a change in the first direction D**1** (see FIGS. **3** and **8**) of the magnetic field to be detected MF. The resistances of the respective first and second MR elements **13** and **14** thus change with a change in the first direction D**1**. In the present embodiment, as the first direction D**1** changes, either one of the resistances of the first and second MR elements **13** and **14** increases and the other decreases. This changes the potential of the signal output node E**1**. Like the first embodiment, the first magnetic detection unit **10** generates a signal corresponding to the potential of the signal output node E**1** as the first detection signal S**1**. In the present embodiment, the detection value θs depends on the potential of the signal output node E**1**.

[0165] From the viewpoint of the manufacturing accuracy of the MR elements **13** and **14**, the direction of the second magnetization may be slightly different from the foregoing direction.

[0166] The remainder of configuration, function and effects of the present embodiment are similar

to those of any of the first to third embodiments.

Fifth Embodiment

[0167] A fifth embodiment of the invention will now be described. Initially, differences of a magnetic sensor **2** according to the present embodiment from that according to the fourth embodiment will be described with reference to FIGS. **20** and **21**. FIG. **20** is a perspective view showing the magnetic sensor **2**. FIG. **21** is a sectional view showing a cross section of the magnetic sensor **2**. In the present embodiment, the groove portion **3***c* in the substrate **3** of the magnetic sensor **2** includes a first slope **3***d* and a second slope **3***e* both oblique to the main surface **3***a*, instead of the slope **3***b* of the first embodiment. Both the first and second slopes **3***d* and **3***e* are flat surfaces. The first and second slopes **3***d* and **3***e* are symmetrical about the YZ plane therebetween.

[0168] Like the fourth embodiment, all the MR elements included in the magnetic sensor **2** are located within an area where no substantial difference occurs in the direction of the magnetic field to be detected MF depending on the positions where all the MR elements receive the magnetic field to be detected MF. The directions of the magnetic field to be detected MF received by all the MR elements are thus substantially the same.

[0169] The first MR element **13** of the first magnetic detection unit **10** of the magnetic sensor **2** is located on the first slope **3***d*. The second MR element **14** of the first magnetic detection unit **10** of the magnetic sensor **2** is located on the second slope **3***e*. FIG. **21** shows a cross section of the magnetic sensor **2** parallel to the XZ plane, where the first and second MR elements **13** and **14** intersect.

[0170] As shown in FIG. **21**, in the present embodiment, different second planes PL**21** and PL**22** are defined for the first and second MR elements **13** and **14**, respectively. The second plane PL**21** corresponding to the first MR element **13** is the same as the second plane PL**2** (see FIGS. **3** and **4**) corresponding to the MR element **11** according to the first embodiment. The second plane PL**21** is thus a UY plane that intersects the first plane PL**1** at a dihedral angle α.

[0171] The second plane PL**22** corresponding to the second MR element **14** is symmetrical with the second plane PL**21** about the YZ plane. As shown in FIG. **21**, a direction rotated from the Z direction toward the X direction by a will be referred to as a V direction. The direction opposite to the V direction will be referred to as a −V direction. The second plane PL**22** is a plane that intersects the first plane PL**1** at a dihedral angle α and that is parallel to the V direction and the Y direction, i.e., a VY plane.

[0172] The first slope **3***d* is tilted to form a dihedral angle α with respect to the first plane PL**1** and is parallel to the UY plane. The second plane PL**21** is thus parallel to the first slope **3***d*.

[0173] The second slope **3***e* is tilted to form a dihedral angle α with respect to the first plane PL**1** and is parallel to the VY plane. The second plane PL**22** is thus parallel to the second slope **3***e*.

[0174] In the present embodiment, the first magnetic layer of the first MR element **13** has first magnetization that can change in direction within the second plane PL**21** corresponding to the first MR element **13**. The magnetic field to be detected MF received by the first MR element **13** can be divided into an in-plane component (hereinafter, referred to as a first in-plane component) parallel to the second plane PL**21** and a perpendicular component perpendicular to the second plane PL**21**. The first in-plane component has a second direction that changes with a change in the first direction D**1** of the magnetic field to be detected MF. The first magnetization of the first magnetic layer of the first MR element **13** changes in direction with a change in the second direction of the first in-plane component. In the present embodiment, the angle that the second direction of the first in-plane component forms with respect to the U direction will be referred to as a second angle θ2. The positive and negative signs of the angle that the second direction of the first in-plane component forms with respect to the U direction are defined the same as those of the second angle θ2 described in the first embodiment.

[0175] In the present embodiment, the first magnetic layer of the second MR element **14** has first magnetization that can change in direction within the second plane PL**22** corresponding to the

second MR element **14**. The magnetic field to be detected MF received by the second MR element **14** can be divided into an in-plane component (hereinafter, referred to as a second in-plane component) parallel to the second plane PL**22** and a perpendicular component perpendicular to the second plane PL**22**. The second in-plane component has a second direction that changes with a change in the first direction D**1** of the magnetic field to be detected MF. The first magnetization of the first magnetic layer of the second MR element **14** changes in direction with a change in the second direction of the second in-plane component.

[0176] The angle that the second direction of the second in-plane component forms with respect to the V direction will be referred to as a third angle. Within the second plane PL**22** corresponding to the second MR element **14**, the second direction of the second in-plane component rotates about the position where the second MR element **14** is located. The third angle is expressed in positive values when seen in a direction of rotation from the V direction to the Y direction, and expressed in negative values when seen in a direction of rotation from the V direction to the −Y direction. The third angle is equal to the second angle θ2.

[0177] In FIGS. **20** and **21**, the thick arrows indicate the directions of the second magnetization in the respective second magnetic layers of the first and second MR elements **13** and **14**. The direction of the second magnetization in the second magnetic layer of the first MR element **13** is the U direction. The direction of the second magnetization in the second magnetic layer of the second MR element **14** is the −V direction. In the present embodiment, as the first direction D**1** changes, either one of the resistances of the first and second MR elements **13** and **14** increases and the other decreases. This changes the potential of the signal output node E**1** (see FIG. **19**). The first magnetic detection unit **10** generates a signal corresponding to the potential of the signal output node E**1** as the first detection signal S**1**. In the present embodiment, the detection value θs depends on the potential of the signal output node E**1**.

[0178] From the viewpoint of the manufacturing accuracy of the MR elements **13** and **14**, the direction of the second magnetization may be slightly different from the foregoing direction.

[0179] The configuration, operation and effects of the present embodiment are otherwise the same as those of the fourth embodiment.

Sixth Embodiment

[0180] A sixth embodiment of the invention will now be described. Initially, differences of a magnetic sensor **2** according to the present embodiment from that according to the fifth embodiment will be described with reference to FIG. **22**. FIG. **22** is a circuit diagram showing a configuration of a first magnetic detection unit **10** of the magnetic sensor **2**. As shown in FIG. **22**, in the present embodiment, the first magnetic detection unit **10** of the magnetic sensor **2** includes a resistor **15** aside from the first MR element **13**, the second MR element **14**, the signal output node E**1**, the power supply node V**1**, and the ground node G**1**. The resistor **15**, the first MR element **13**, and the second MR element **14** are connected in series in this order from the power supply node V**1** side. The resistor **15** is arranged between the power supply node V**1** and the signal output node E**1**. The first and second MR elements **13** and **14** are arranged between the signal output node E**1** and the ground node G**1**.

[0181] Like the fifth embodiment, all the MR elements included in the magnetic sensor **2** are located within an area where no substantial difference occurs in the direction of the magnetic field to be detected MF depending on the positions where all the MR elements receive the magnetic field to be detected MF. The directions of the magnetic field to be detected MF received by all the MR elements are thus substantially the same.

[0182] In FIG. **22**, the thick arrows indicate the directions of the second magnetization in the respective second magnetic layers of the first and second MR elements **13** and **14**. In the present embodiment, the direction of the second magnetization in the second magnetic layer of the first MR element **13** is the −U direction (see FIG. **21**). The direction of the second magnetization in the second magnetic layer of the second MR element **14** is the −V direction (see FIG. **21**).

[0183] In the present embodiment, the resistances of the respective first and second MR elements **13** and **14** change similarly with a change in the first direction D**1** of the magnetic field to be detected MF. As the first direction D**1** changes, the combined resistance of the first and second MR elements **13** and **14** therefore changes. This changes the potential of the signal output node E**1**. The first magnetic detection unit **10** generates a signal dependent on the potential of the signal output node E**1** as the first detection signal S**1**. In the present embodiment, the detection value θs depends on the combined resistance of the first and second MR elements **13** and **14**.

[0184] From the viewpoint of the manufacturing accuracy of the MR elements **13** and **14**, the direction of the second magnetization may be slightly different from the foregoing direction.

[0185] Next, characteristic operation and effect of the magnetic sensor **2** according to the present embodiment will be described. The main surface **3***a* of the substrate **3** is ideally parallel to the reference plane PL**3** (XY plane) of the first embodiment, shown in FIGS. **3** and **4**. However, the magnetic sensor **2** can be tilted because of installation accuracy of the magnetic sensor **2**, and as a result, the main surface **3***a* of the substrate **3** can be tilted with respect to the reference plane PL**3**. In this case, the dihedral angle (hereinafter, referred to as a first dihedral angle) that the second plane PL**21** (see FIG. **21**) corresponding to the first MR element **13** forms with respect to the first plane PL**1** (YZ plane) and the dihedral angle (hereinafter, referred to as a second dihedral angle) that the second plane PL**22** (see FIG. **21**) corresponding to the second MR element **14** forms with respect to the first plane PL**1** deviate from their design values.

[0186] If the first dihedral angle deviates from its design value, the second direction of the first in-plane component of the magnetic field to be detected MF received by the first MR element **13** deviates from a desired direction. The direction of the first magnetization in the first magnetic layer of the first MR element **13** then deviates from a desired direction, and as a result, the resistance of the first MR element **13** deviates from a desired value.

[0187] Similarly, if the second dihedral angle deviates from its design value, the second direction of the second in-plane component of the magnetic field to be detected MF received by the second MR element **14** deviates from a desired direction. The direction of the first magnetization in the first magnetic layer of the second MR element **14** then deviates from a desired direction, and as a result, the resistance of the second MR element **14** deviates from a desired value.

[0188] In the present embodiment, when either one of the first and second dihedral angles becomes greater than its design value due to the tilt of the magnetic sensor **2**, the other becomes smaller than its design value. Consequently, when either one of the resistances of the first and second MR elements **13** and **14** becomes greater than a desired value due to the tilt of the magnetic sensor **2**, the other becomes smaller than a desired value. According to the present embodiment, the combined resistance of the first and second MR elements **13** and **14** does not vary much because of the tilt of the magnetic sensor **2**. According to the present embodiment, the detection accuracy can thus be prevented from dropping due to the tilt of the magnetic sensor **2**.

[0189] The configuration, operation and effects of the present embodiment are otherwise the same as those of the fifth embodiment.

Seventh Embodiment

[0190] A seventh embodiment of the invention will now be described. A magnetic sensor system **1** according to the present embodiment differs from that of the second embodiment in the following respects. The magnetic sensor system **1** according to the present embodiment includes a magnetic sensor **102** according to the present embodiment instead of the magnetic sensor **2** according to the second embodiment. A positional relationship between the magnetic sensor **102** and the magnetic field generator **105** is the same as that between the magnetic sensor **2** and the magnetic field generator **105** in the second embodiment, shown in FIG. **12**. The magnetic sensor **102** detects the magnetic field to be detected MF generated by the magnetic field generator **105** and generates a detection value θs.

[0191] A configuration of the magnetic sensor **102** will be described below with reference to FIGS.

23 to **28**. FIG. **23** is a perspective view showing the magnetic sensor **102**. FIG. **24** is a sectional view showing a cross section of the magnetic sensor **102**. FIG. **25** is a sectional view showing another cross section of the magnetic sensor **102**. FIG. **26** is a block diagram showing the configuration of the magnetic sensor **102**. FIG. **27** is a circuit diagram showing a configuration of a first magnetic detection unit of the present embodiment. FIG. **28** is a circuit diagram showing a configuration of a second magnetic detection unit of the present embodiment.

[0192] As shown in FIG. **26**, the magnetic sensor **102** includes a first magnetic detection unit **110**, a second magnetic detection unit **120**, and a detection value generation unit **130**. The first magnetic detection unit **110** generates a first detection signal S**11**. The second magnetic detection unit **120** generates a second detection signal S**12**. The detection value generation unit **130** generates the detection value θs on the basis of the first detection signal S**11** and the second detection signal S**12**. The detection value generation unit **130** includes an ASIC or a microcomputer.

[0193] As will be described in detail later, the first magnetic detection unit **110** includes eight MR elements. The second magnetic detection unit **120** includes four MR elements. The MR elements are located within an area where no substantial difference occurs in the direction of the magnetic field to be detected MF depending on the positions where the plurality of MR elements receive the magnetic field to be detected MF. The directions of the magnetic field to be detected MF received by the MR elements are therefore substantially the same.

[0194] As shown in FIGS. **23** to **25**, the magnetic sensor **102** further includes a substrate **103**. The substrate **103** includes a main surface **103***a* perpendicular to the first plane PL**1** (YZ plane) of the first embodiment, shown in FIGS. **3** and **4**. The substrate **103** also has two groove portions **103***f* and **103***g* open in the main surface **103***a*. The groove portions **103***f* and **103***g* are arranged in this order along the X direction. The groove portion **103***f* includes a first slope **103***b* and a second slope **103***c* each oblique to the main surface **103***a*. The groove portion **103***g* includes a first slope **103***d* and a second slope **103***e* each oblique to the main surface **103***a*. The first and second slopes **103***b* and **103***c* are symmetrical about a YZ plane therebetween. Similarly, the first and second slopes **103***d* and **103***e* are symmetrical about a YZ plane therebetween.

[0195] As shown in FIG. **27**, the first magnetic detection unit **110** includes eight MR elements **111**, **112**, **113**, **114**, **115**, **116**, **117**, and **118**. The substrate **103** supports the MR elements **111** to **118**. In the example shown in FIG. **23**, the MR elements **111** to **114** are arranged in a row in this order along the X direction. In the example shown in FIG. **23**, the MR elements **115** to **118** are arranged in a row in this order along the X direction, at positions on the −Y direction side of the MR elements **111** to **114**. As shown in FIG. **23**, the MR elements **111** and **115** are located on the first slope **103***b*. The MR elements **112** and **116** are located on the second slope **103***c*. The MR elements **113** and **117** are located on the first slope **103***d*. The MR elements **114** and **118** are located on the second slope **103***e*. FIG. **24** shows a cross section of the magnetic sensor **102** parallel to the XZ plane, intersecting the MR elements **111** to **114**. FIG. **25** shows a cross section of the magnetic sensor **102** parallel to the XZ plane, intersecting the MR elements **115** to **118**. In the present embodiment, the reference position P**0** (see FIGS. **3** and **4**) is located inside or at the surface of the magnetic sensor **102**.

[0196] As shown in FIG. **27**, the first magnetic detection unit **110** further includes two signal output nodes E**11** and E**12**, a power supply node V**11**, a ground node G**11**, and a differential detector **119**. The MR elements **111**, **112**, **113**, and **114** are connected in series in this order from the power supply node V**11** side. The MR elements **111** and **112** are arranged between the power supply node V**11** and the signal output node E**11**. The MR elements **113** and **114** are arranged between the signal output node E**11** and the ground node G**11**. The MR elements **112** and **113** are connected in series via the signal output node E**11**.

[0197] The MR elements **115**, **116**, **117**, and **118** are connected in series in this order from the power supply node V**11** side. The MR elements **115** and **116** are arranged between the power supply node V**11** and the signal output node E**12**. The MR elements **117** and **118** are arranged

between the signal output node E**12** and the ground node G**12**. The MR elements **116** and **117** are connected in series via the signal output node E**12**.

[0198] A predetermined magnitude of power supply voltage is applied to the power supply node V**11**. The ground node G**11** is grounded. The differential detector **119** outputs a signal corresponding to a potential difference between the signal output nodes E**11** and E**12** as the first detection signal S**11**.

[0199] As shown in FIGS. **24** and **25**, in the present embodiment, a second plane PL**211** common to the MR elements **111** and **115**, a second plane PL**212** common to the MR elements **112** and **116**, a second plane PL**213** common to the MR elements **113** and **117**, and a second plane PL**214** common to the MR elements **114** and **118** are defined. The second plane PL**211** is the same as the second plane PL**2** (see FIGS. **3** and **4**) corresponding to the MR element **11** of the first embodiment. The second plane PL**211** is thus a UY plane intersecting the first plane PL**1** at a dihedral angle α.

[0200] As in the fifth embodiment, a direction rotated from the Z direction toward the X direction by a will be referred to as a V direction. The direction opposite to the V direction will be referred to as a −V direction. The second plane PL**212** is symmetrical with the second plane PL**211** about the YZ plane. The second plane PL**212** is a plane that intersects the first plane PL**1** at a dihedral angle α and that is parallel to the V direction and Y direction, i.e., a VY plane.

[0201] The second plane PL**213** is a UV plane parallel to the second plane PL**211**. The second plane PL**214** is a VY plane parallel to the second plane PL**212**.

[0202] The first slope **103***b* is tilted to form a dihedral angle α with respect to the first plane PL**1** and is parallel to the UY plane. The second plane PL**211** is thus parallel to the first slope **103***b*.

[0203] The second slope **103***c* is tilted to form a dihedral angle α with respect to the first plane PL**1** and is parallel to the VY plane. The second plane PL**212** is thus parallel to the second slope **103***c*.

[0204] The first slope **103***d* is tilted to form a dihedral angle α with respect to the first plane PL**1** and is parallel to the UY plane. The second plane PL**213** is thus parallel to the first slope **103***d*.

[0205] The second slope **103***e* is tilted to form a dihedral angle α with respect to the first plane PL**1** and is parallel to the VY plane. The second plane PL**214** is thus parallel to the second slope **103***e*.

[0206] The MR elements **111** to **118** each have the same configuration as that of the MR element **11** of the first embodiment. More specifically, the MR elements **111** to **118** each include a first magnetic layer, a second magnetic layer, and a gap layer.

[0207] The magnetic field to be detected MF received by each of the MR elements **111** and **115** can be divided into an in-plane component (hereinafter, referred to as a first in-plane component) parallel to the second plane PL**211** and a perpendicular component perpendicular to the second plane PL**211**. The first in-plane component has a second direction that changes with a change in the first direction D**1** of the magnetic field to be detected MF. The first magnetization of the first magnetic layer of each of the MR elements **111** and **115** changes in direction with a change in the second direction of the first in-plane component. In the present embodiment, the angle that the second direction of the first in-plane component forms with respect to the U direction will be referred to as a second angle θ2. The positive and negative signs of the angle that the second direction of the first in-plane component forms with respect to the U direction are defined the same as those of the second angle θ2 described in the first embodiment.

[0208] The magnetic field to be detected MF received by each of the MR elements **112** and **116** can be divided into an in-plane component (hereinafter, referred to as a second in-plane component) parallel to the second plane PL**212** and a perpendicular component perpendicular to the second plane PL**212**. The second in-plane component has a second direction that changes with a change in the first direction D**1** of the magnetic field to be detected MF. The first magnetization of the first magnetic layer of each of the MR elements **112** and **116** changes in direction with a change in the second direction of the second in-plane component.

[0209] The angle that the second direction of the second in-plane component forms with respect to the V direction will be referred to as a third angle. Within the second plane PL**212**, the second

direction of the second in-plane component rotates about the position where each of the MR elements **112** and **116** is located. The third angle is expressed in positive values when seen in a direction of rotation from the V direction to the Y direction, and expressed in negative values when seen in a direction of rotation from the V direction to the −Y direction. The third angle is equal to the second angle θ2.

[0210] The magnetic field to be detected MF received by each of the MR elements **113** and **117** can be divided into an in-plane component (hereinafter, referred to as a third in-plane component) parallel to the second plane PL**213** and a perpendicular component perpendicular to the second plane PL**213**. The third in-plane component has a second direction that changes with a change in the first direction D**1** of the magnetic field to be detected MF. The first magnetization of the first magnetic layer of each of the MR elements **113** and **117** changes in direction with a change in the second direction of the third in-plane component.

[0211] The angle that the second direction of the third in-plane component forms with respect to the U direction will be referred to as a fourth angle. Within the second plane PL**213**, the second direction of the third in-plane component rotates about the position where each of the MR elements **113** and **117** is located. The fourth angle is expressed in positive values when seen in a direction of rotation from the U direction to the Y direction, and expressed in negative values when seen in a direction of rotation from the U direction to the −Y direction. The fourth angle is equal to the second angle θ2.

[0212] The magnetic field to be detected MF received by each of the MR elements **114** and **118** can be divided into an in-plane component (hereinafter, referred to as a fourth in-plane component) parallel to the second plane PL**214** and a perpendicular component perpendicular to the second plane PL**214**. The fourth in-plane component has a second direction that changes with a change in the first direction D**1** of the magnetic field to be detected MF. The first magnetization of the first magnetic layer of each of the MR elements **114** and **118** changes in direction with a change in the second direction of the fourth in-plane component.

[0213] The angle that the second direction of the fourth in-plane component forms with respect to the V direction will be referred to as a fifth angle. Within the second plane PL**214**, the second direction of the fourth in-plane component rotates about the position where each of the MR elements **114** and **118** is located. The fifth angle is expressed in positive values when seen in a direction of rotation from the V direction to the Y direction, and expressed in negative values when seen in a direction of rotation from the V direction to the −Y direction. The fifth angle is equal to the second angle θ2.

[0214] The MR elements **111** to **118** each further include a second magnetic layer having second magnetization in a direction parallel to the respective corresponding second plane, and a gap layer located between the first magnetic layer and the second magnetic layer. In FIGS. **24**, **25**, and **27**, the thick arrows indicate the directions of the second magnetization in the second magnetic layers. In the present embodiment, the direction of the second magnetization in the second magnetic layer of each of the MR elements **111** and **117** is the U direction. The direction of the second magnetization in the second magnetic layer of each of the MR elements **112** and **118** is the V direction. The direction of the second magnetization in the second magnetic layer of each of the MR elements **113** and **115** is the −U direction. The direction of the second magnetization in the second magnetic layer of each of the MR elements **114** and **116** is the −V direction.

[0215] In each of the MR elements **111** to **118**, the direction of the first magnetization of the first magnetic layer changes with a change in the first direction D**1** of the magnetic field to be detected MF. The resistance of each of the MR elements **111** to **118** therefore changes with a change in the first direction D**1**. As a result, the first detection signal S**11** changes with a change in the first direction D**1**.

[0216] From the viewpoint of the manufacturing accuracy of the MR elements **111** to **118**, the direction of the second magnetization may be slightly different from the foregoing direction.

[0217] As described above, the third to fifth angles are all equal to the second angle θ2. The first detection signal S**11** can be normalized so that the first detection signal S**11** has a value of 1 if the second angle θ2 is 0°, a value of −1 if the second angle θ2 is 180°, and a value of 0 if the second angle θ2 is 90° or 270°. In this case, the first detection signal S**11** is represented by the following Eq. (10):

[00009] $S11 = \cos\theta2.$ (10)

[0218] As shown in FIG. **28**, the second magnetic detection unit **120** includes four MR elements **121**, **122**, **123**, and **124**. As shown in FIG. **23**, the MR elements **121** to **124** are located on the main surface **103***a*. In the example shown in FIG. **23**, the MR elements **121** and **122** are arranged in this order along the X direction, at positions on the −X direction side of the MR element **111**. In the example shown in FIG. **23**, the MR elements **123** and **124** are arranged in this order along the X direction, at positions on the −Y direction side of the MR elements **121** and **122** and on the −X direction side of the MR element **115**.

[0219] As shown in FIG. **28**, the second magnetic detection unit **120** further includes two signal output nodes E**21** and E**22**, a power supply node V**12**, a ground node G**12**, and a differential detector **125**. The MR element **121** is arranged between the power supply node V**12** and the signal output node E**21**. The MR element **122** is arranged between the signal output node E**21** and the ground node G**12**. The MR elements **121** and **122** are connected in series via the signal output node E**21**.

[0220] The MR element **123** is arranged between the power supply node V**12** and the signal output node E**22**. The MR element **124** is arranged between the signal output node E**22** and the ground node G**12**. The MR elements **123** and **124** are connected in series via the signal output node E**22**. A predetermined magnitude of power supply voltage is applied to the power supply node V**12**. The ground node G**12** is grounded. The differential detector **125** outputs a signal corresponding to a potential difference between the signal output nodes E**21** and E**22** as the second detection signal S**12**.

[0221] The MR elements **121** to **124** each have the same configuration as that of the MR element **21** of the second embodiment. More specifically, the MR elements **121** to **124** each include a third magnetic layer, a fourth magnetic layer, and a gap layer. The third magnetic layer has third magnetization that can change in direction within a virtual plane parallel to the reference plane PL**3** (XY plane). The fourth magnetic layer has fourth magnetization in a direction parallel to the virtual plane. The gap layer is located between the third and fourth magnetic layers. The symbols near the MR elements **121** to **124** in FIGS. **24** and **25** and the thick arrows in FIG. **28** indicate the directions of the fourth magnetization in the respective fourth magnetic layers. In the present embodiment, the directions of the fourth magnetization in the fourth magnetic layers of the MR elements **121** and **124** are the Y direction. The directions of the fourth magnetization in the fourth magnetic layers of the MR elements **122** and **123** are the −Y direction.

[0222] From the viewpoint of the manufacturing accuracy of the MR elements **121** to **124**, the direction of the fourth magnetization may be slightly different from the foregoing direction.

[0223] Like the MR element **21** of the second embodiment, the third magnetic layers of the MR elements **121** to **124** may have uniaxial magnetic anisotropy in a direction parallel to the X direction. In this case, the directions of the third magnetization of the third magnetic layers change with the strength of the Y-direction component of the magnetic field to be detected MF, i.e., H**1**.Math.sin θ1. The resistances of the respective MR elements **121** to **124** thus change with a change in H**1**.Math.sin θ1. As a result, the second detection signal S**12** changes with a change in H**1**.Math.sin θ1. In particular, in the present embodiment, the second detection signal S**12** is normalized to sin θ1.

[0224] A method for generating the detection value θs of the present embodiment is the same as that of the second embodiment except that the first and second detection signals S**1** and S**2** are

replaced with the first and second detection signal S**11** and S**12**. The configuration and function of the detection value generation unit **130** are the same as those of the detection value generation unit **30** of the second embodiment except that the first and second detection signals S**1** and S**2** of the second embodiment are replaced with the first and second detection signals S**11** and S**12**.

[0225] Next, characteristic operation and effect of the magnetic sensor **102** according to the present embodiment will be described. The main surface **103***a* of the substrate **103** is ideally parallel to the reference plane PL**3** (XY plane) of the first embodiment, shown in FIGS. **3** and **4**. However, the magnetic sensor **102** can be tilted because of installation accuracy of the magnetic sensor **102**, and as a result, the main surface **103***a* of the substrate **103** can be tilted with respect to the reference plane PL**3**. In this case, the dihedral angle α that each of the second planes PL**211**, PL**212**, PL**213**, and PL**214** forms with respect to the first plane PL**1** (YZ plane) deviates from its design values.

[0226] In the present embodiment, like the MR elements **13** and **14** of the sixth embodiment, when either one of the resistances of the MR elements **111** and **112** becomes greater than a desired value due to the tilt of the magnetic sensor **102**, the other becomes smaller than a desired value. According to the present embodiment, the combined resistance of the MR elements **111** and **112** does not vary much because of the tilt of the magnetic sensor **102**.

[0227] The foregoing description of the pair of MR elements **111** and **112** also applies to the pair of MR elements **113** and **114**, the pair of MR elements **115** and **116**, and the pair of MR elements **117** and **118**. According to the present embodiment, the detection accuracy of the first magnetic detection unit **110** can be prevented from dropping due to the tilt of the magnetic sensor **102**.

[0228] The other configuration, function and effects of the present embodiment are the same as those of the second or sixth embodiment.

[0229] The present invention is not limited to the foregoing embodiments, and various modifications may be made thereto. For example, the magnetic sensor **102** according to the seventh embodiment may include the second magnetic detection unit **20** of the second or third embodiment instead of the second magnetic detection unit **120**.

[0230] Obviously, many modifications and variations of the present invention are possible in the light of the above teachings. Thus, it is to be understood that, within the scope of the appended claims and equivalents thereof, the invention may be practiced in other embodiments than the foregoing most preferable embodiments.

Claims

1. A magnetic sensor system comprising: a magnetic field generator configured to generate a magnetic field to be detected having a first direction at a reference position within a first plane; and a magnetic sensor configured to detect the magnetic field to be detected and generate a detection value, wherein: the magnetic sensor includes: a substrate including a main surface and at least one slope, the at least one slope being formed in parallel with a second plane oblique to each of the main surface and the first plane; and at least one magnetoresistive element disposed on the at least one slope, the at least one magnetoresistive element each including a first magnetic layer having first magnetization, a direction of the first magnetization being changeable within a plane, the plane being the second plane corresponding to each of the at least one magnetoresistive element; the first direction changes according to rotation of the magnetic field generator within a variable range of not greater than 360° in the first plane; the magnetic field to be detected received by each of the at least one magnetoresistive element includes an in-plane component parallel to the second plane, the in-plane component having a second direction that changes with a change in the first direction; the first magnetic layer is configured such that the direction of the first magnetization changes with a change in the second direction; and the detection value depends on the direction of the first magnetization.

2. The magnetic sensor system according to claim 1, wherein the first magnetic layer has a

characteristic that the first magnetization is saturated by the magnetic field to be detected when the first direction is in at least a part of the variable range of the first direction.

3. The magnetic sensor system according to claim 1, wherein each of the at least one magnetoresistive element further includes a second magnetic layer having second magnetization in a direction parallel to the second plane, and a gap layer disposed between the first magnetic layer and the second magnetic layer.

4. The magnetic sensor system according to claim 1, wherein a dihedral angle formed by the first plane and the second plane is in a range of 30° to 84°.

5. The magnetic sensor system according to claim 1, wherein the second plane corresponding to each of the at least one magnetoresistive element is parallel to the at least one slope on which each of the at least one magnetoresistive element is disposed.

6. The magnetic sensor system according to claim 1, further comprising another magnetoresistive element including a third magnetic layer having third magnetization, a direction of the third magnetization being changeable in a plane intersecting each of the first plane and the second plane, wherein: the third magnetic layer is configured such that the direction of the third magnetization changes with the first direction of the magnetic field to be detected.

7. The magnetic sensor system according to claim 6, wherein the third magnetic layer is configured such that the direction of the third magnetization changes with an angle that the first direction of the magnetic field to be detected forms with respect to a reference direction.

8. The magnetic sensor system according to claim 6, wherein the other magnetoresistive element is disposed on the main surface.

9. The magnetic sensor system according to claim 6, wherein the other magnetoresistive element is disposed on the at least one slope.

10. The magnetic sensor system according to claim 1, wherein: the at least one magnetoresistive element includes a first magnetoresistive element and a second magnetoresistive element; and the at least one slope includes one slope on which the first and second magnetoresistive elements are disposed.

11. The magnetic sensor system according to claim 1, wherein: the at least one magnetoresistive element includes a first magnetoresistive element and a second magnetoresistive element; and the at least one slope includes a first slope on which the first magnetoresistive element is disposed and a second slope on which the second magnetoresistive element is disposed.

12. The magnetic sensor system according to claim 1, wherein the magnetic sensor further comprises: a first magnetic detection unit that includes the at least one magnetoresistive element and configured to generate a first detection signal dependent on the direction of the first magnetization; a second magnetic detection unit configured to detect the magnetic field to be detected and generate a second detection signal dependent on the first direction; and a detection value generation unit configured to generate the detection value on a basis of the first detection signal and the second detection signal, wherein: the variable range of the first direction includes a first region and a second region that are different from each other; two candidates for the first direction corresponding to a specific same value of the first detection signal fall within the respective first and second regions; and two values of the second detection signal corresponding to the two candidates are different from each other.

13. A magnetic sensor configured to detect a magnetic field to be detected and generate a detection value, wherein: the magnetic field to be detected has a first direction at a reference position within a first plane, the first direction being changeable in the first plane; the magnetic sensor includes: a substrate including a main surface and at least one slope; and at least one magnetoresistive element disposed on the at least one slope; the magnetic field to be detected received by each of the at least one magnetoresistive element includes an in-plane component parallel to the second plane oblique to each of the main surface and the first plane, the in-plane component having a second direction that changes with a change in the first direction; the at least one magnetoresistive element is each

configured such that a resistance of the at least one magnetoresistive element changes with a change of the in-plane component; and the detection value depends on the resistance.