

DESCRIPTION

ULTRA HIGH-SENSITIVITY MICRO MAGNETIC SENSOR

Field

[0001] The present invention relates to a technology of
5 improving sensitivity characteristics of a GSR sensor by
adopting rising pulse detection.

Here, the GSR sensor is an ultra high-sensitivity
micro magnetic sensor based on the GHz spin rotation effect.

Background

10 [0002] The high-sensitivity micro magnetic sensor
includes a horizontal FG sensor, a vertical FG sensor, a
hole sensor, a GMR sensor, a TMR sensor, a MI sensor, a GSR
sensor, a high frequency carrier sensor, and the like.
These sensors are currently used widely in smartphones,
15 vehicles, medical treatment, robots, and the like. Among
the above-described sensors, the GSR sensor is excellent in
sensitivity and size, and draws the most attention.

[0003] To achieve remote control of an in-vivo motion
device, an investigation is currently advanced for finding
20 a position and a direction by providing a three-dimensional
magnetic sensor utilizing a GSR sensor.

The sensor is preferably smaller to provide it in a
motion device. However, the detection sensitivity is
deteriorated inversely proportional thereto. Furthermore,

with the restriction of a supply power source, the reduction of power consumption during measurement has been demanded.

Citation List

5 Patent Literature

[0004] Patent Literature 1: Japanese Patent No. 5839527

Summary

Technical Problem

[0005] As the detection method by the GSR sensor, there
10 exist two methods of rising pulse detection and falling pulse detection. In rising pulse detection, the magnetic field sensitivity is about 2.5 times as high as that of falling pulse detection, which shortens pulse time and reduces power consumption. However, the linearity is about
15 1 to 2% and is inferior to that of falling pulse detection of 0.5% or lower.

The invention aims at making the most use of advantages of rising pulse detection while making its linearity 0.5% or lower.

20 [0006] A coil output voltage (hereinafter, referred to as a coil voltage) of the GSR sensor includes two kinds of voltages of an induced voltage dependent on a pulse current (referred to as an "a voltage") and a voltage dependent on an external magnetic field (referred to as a "b voltage").
25 In comparison between rising pulse detection and falling pulse detection, two voltage peaks are more adjacent to

each other in the case of falling pulse detection, and the influence by a pulse current is larger. Moreover, the MI effect changes the impedance of magnetic wires by a magnetic field. As a result, the "a voltage" dependent on
5 a pulse current is also influenced by the magnetic field, and may not be canceled easily. That is, if the "a voltage" is not influenced by a magnetic field, the "a voltage" may be measured with $H = 0G$, and a net b voltage may be thus detected by cancelling the "a voltage".

10 [0007] The investigation for removing an induced voltage dependent on a pulse current from a coil voltage found by rising pulse detection has been performed for 20 years. However, it remains an unsolved difficult problem.

Solution to Problem

15 [0008] The inventors found that if two magnetic wires are arranged in one coil and a pulse current is applied in opposite directions, a coil induced voltage of rising pulse detection becomes 0 when $H = 0 G$ (Fig. 7). It is recognized that if an electric current is applied in
20 opposite directions in the case where a magnetic field H exists, the coil voltage is not changed and only the "b voltage" is detected (Fig. 8). That is, the "a voltage" is apparently disappeared.

Furthermore, in the measurement of the "b voltage"
25 while changing a magnetic field, they found that the voltage is

linearly output symmetrically relative to the positive/negative of the magnetic field with the linearity of 0.3% or lower, which is excellent.

Even when the magnetic field H is changed from zero, the "a voltage" is disappeared. This is apparently because the impedance of two wires is changed symmetrically relative to the magnetic field H , regardless of a direction of an electric current, and thus the impedance thereof is constantly same and a pulse current flowing in the two wires is same, which cancels the influence on their coils even when a magnetic field is changed (Fig. 9).

[0009] In the case of rising pulse detection, the detection is performed with rising, which allows pulse time of 1 ns (1 nanosecond) or shorter. Meanwhile, in the case of falling pulse detection, the detection needs to be performed after the rising coil voltage is attenuated completely. Thus, the pulse time needs to be maintained for about 10 ns. Therefore, if the rising pulse detection is adopted, the pulse current consumption may be 1/10 or smaller.

[0010] The coil voltage of the element including two magnetic wires of the invention is twice the coil voltage of the element including one magnetic wire. Moreover, the coil voltage in rising pulse detection is 2.5 times the coil voltage in falling pulse detection (Fig. 10). As compared

with the GSR sensor described in Patent Literature 1, the coil voltage is five times with the element of the same size.

[0011] It is confirmed that the relation between the coil voltage and the external magnetic field is same as the equation in the GSR sensor described in Patent Literature 1.

That is,

$$V_s = V_o \cdot 2L \cdot \pi D \cdot p \cdot N_c \cdot f \cdot \sin(\pi H / 2H_m) \dots\dots (1)$$

[0012] Here, V_s is a coil voltage, and V_o is a constant of proportionality determined by wire magnetic permeability, magnetic characteristics of wire materials with saturation magnetic flux density, and a pulse current. As a control factor constant, L is a wire length, D is a wire diameter, p is a skin depth of a pulse current, N_c is the number of winding of a coil, f is a pulse frequency, H is an external magnetic field, H_m is an external magnetic strength to obtain the maximum coil output voltage.

[0013] By applying arcsine transformation to both sides of the equation (1) and letting the resulted value to be a conversion voltage V' , the following equations (2) and (3) are obtained:

$$V' = \arcsin(V_s / V_o \cdot 2L \cdot \pi D \cdot p \cdot N_c \cdot f) = (\pi \cdot 1 / 2H_m) \cdot H \dots\dots (2)$$

$$H = 2H_m / \pi \times V' \dots\dots (3)$$

H is found on the basis of the expression (3).

V' is changed linearly from $-H_m$ to $+H_m$ relative to the

magnetic field H . The measurement range is H_m , and is about four times that in the case without arcsine transformation. Note that when $V_x = a(1-\Delta)H_x$, the linearity P is defined as $P = 100 \times \Delta$ (%).

That is, the linearity is defined on the basis of a deviation amount Δ from the equation $V_x = aH_x$ when $\Delta = 0$.

[0014] Furthermore, it is confirmed that the linearity is 0.2%, which is more preferable than 0.5% that is a deviation amount of a falling pulse of the GSR sensor (Fig. 12).

The GSR sensor strengthens electromagnetic coupling between the magnetic wire and the coil with the interval between the magnetic wire and the coil inner diameter of 3 μm or smaller. Also in the invention, the same relation remains except for the interval between the two magnetic wires.

[0015] The same electronic circuit as in Patent Literature 1 is adopted. The pulse frequency of a pulse current applied to the magnetic wire is 0.2 GHz to 4 GHz. The pulse current has the strength required to generate on the surface of a magnetic wire over a 1.5 times larger circumferential magnetic field than the magnetic anisotropy field.

The coil voltage occurring at the time of pulse energization is fed to a sample hold circuit through a pulse compliant buffer circuit. With the small number of winding of the coil, the coil voltage may be fed directly to the

sample hold circuit.

[0016] The rising pulse is detected using an electronic switch at the peak timing of a coil output waveform. The "a voltage" does not exist, and thus the temporal timing of the peak voltage is constant without being dependent on the magnetic field H. However, if the "a voltage" exists, the peak timing is changed depending on the magnetic field H. Thus, strictly speaking, it is not possible to adjust the detection at the peak timing of a coil output waveform. This causes nonlinearity.

The capacitor capacitance of the sample hold circuit is 4 pF to 100 pF. it is preferable that the intervals between on and off of the electronic switch is shortened as much as possible to also reduce the capacitor capacitance to 4 pF to 8pF. In this manner, the voltage at the peak timing is held by the capacitor as an instantaneous voltage value. The held capacitor voltage is output through a programming amplifier.

Advantageous Effects of Invention

[0017] The rising pulse detection type GSR sensor achieves, with the same element size, five times magnetic field detection sensitivity and 1/10 or less power consumption, enabling considerable downsizing of the magnetic sensor with an in-vivo motion device.

Brief Description of Drawings

[0018] Fig. 1 is a plane view of a GSR sensor element according to an embodiment and an example,

Fig. 2 is a section view of the GSR sensor element along line A1-A2 of Fig. 1,

Fig. 3 is an electronic circuit diagram according to the embodiment and the example,

Fig. 4 is a relational diagram between the pulse time and the pulse current application according to the embodiment and the example,

Fig. 5 is a waveform chart of a coil voltage when a pulse current is applied according to the embodiment and the example,

Fig. 6 is an output waveform chart according to the embodiment and the example,

Fig. 7 is a diagram of an output V when two magnetic wires are subjected to a pulse current in opposite directions (+ direction and - direction) when the external magnetic field $H = 0$,

Fig. 8 is a diagram of an output V when the external magnetic field $H = -2G$ to $+2G$,

Fig. 9 is a relational diagram between the external magnetic field H and impedance Z ,

Fig. 10 is an output diagram of the coil voltage in rising pulse detection and falling pulse detection with one

magnetic wire and two magnetic wires,

Fig. 11 is an explanatory diagram of the linearity P in relation between the change of the external magnetic field and the output, and

5 Fig. 12 is a relational diagram between the magnetic field Hx and a deviation amount in the rising pulse of the GSR sensor.

Description of Embodiments

[0019] An embodiment of the invention is described as
10 follows.

Note that one, or two or more configurations arbitrarily selected from the specification may be added to the configuration of the invention. The most preferable embodiment varies depending on a subject and required
15 characteristics.

[0020] A GSR sensor that is an ultra high-sensitivity micro magnetic sensor according to the invention includes
a magnetic field detection element including two
conductive magnetic wires for magnetic field detection
20 arranged adjacent to each other on a substrate, a round coil wound around the two magnetic wires, two electrodes for wire energization, and two electrodes for coil voltage detection, a means for applying a pulse current to the magnetic wires, a circuit for detecting a coil voltage
25 occurred when the pulse current is applied to the magnetic wires in opposite directions, and a means for converting

the coil voltage into an external magnetic field H,

in which the magnetic wire has a magnetic anisotropy field of 20 G or less, with a two-phase magnetic domain structure of a surface magnetic domain with circumferential spin alignment and a center core magnetic domain with longitudinal spin alignment, and

the pulse current applied to the magnetic wire has a pulse frequency of 0.2 GHz to 4 GHz and a strength required to generate over a 1.5 times larger circumferential magnetic field than the anisotropy field on a surface of the wire, and

the coil has a coil pitch of 10 μm or less. The average inner diameter of the coil is preferably 35 μm or smaller.

In the case where a plurality of pairs of wires are arranged, the interval between the coil and the magnetic wire is preferably 1 μm to 5 μm .

[0021] Moreover, in the GSR sensor that is the ultra high-sensitivity micro magnetic sensor according to the invention,

the pulse current is applied to the magnetic wire, and the circumferential spin inclined in an axial direction is subjected to super high speed rotation by a wire axial magnetic field in the surface magnetic domain, to take out only a magnetization change in the wire axial direction due to a super high speed rotation phenomena occurred at the

rotation and perform conversion into a field H using an equation (1):

$$V_s = V_o \cdot 2L \cdot \pi D \cdot p \cdot N_c \cdot f \cdot \sin(\pi H / 2H_m) \dots\dots (1)$$

where V_s is a coil output voltage and V_o is a constant of proportionality, and as a control factor constant, L is a wire length, D is a wire diameter, p is a skin depth of a pulse current, N_c is the number of winding of a coil, f is a pulse frequency, H_m is an external magnetic strength to obtain a maximum coil output voltage.

10 [0022] Furthermore, the GSR sensor that is the ultra high-sensitivity micro magnetic sensor according to the invention further includes an electronic circuit including a pulse generating circuit for generating the pulse current, an input circuit for inputting a coil voltage, a pulse
15 compliant buffer circuit, a sample hold circuit with an electronic switch for detecting a peak voltage of an output waveform of the coil voltage and a capacitor with a capacitance of 4 to 100 pF for holding the peak voltage, and an programming amplifier for amplification before AD
20 (analog-digital) conversion.

[0023] The embodiment of the invention will be described in detail with reference to Fig. 1 to Fig. 6.

The GSR sensor element (hereinafter, referred to as an

element) 1 includes, on a substrate 10, two magnetic wires (21 and 22), one coil 3 wound around the two magnetic wires, two electrodes (24 and 25) for wire energization, two electrodes (34 and 35) for coil voltage detection, a connection part between the magnetic wires and the wire energization electrodes, and a connection part between the coil and the coil voltage detection electrodes. Moreover, the element 1 includes a means 23 for applying a pulse current to the two magnetic wires (21 and 22) in opposite directions. Then, the element 1 further includes a circuit for detecting a coil voltage occurred when a pulse current is applied and a means for converting a coil voltage into an external magnetic field. The external magnetic field H and the coil voltage V_s are expressed by the mathematical relation of the above-described expression (1).

[0024] < Structure of element >

The structure of the element 1 is as illustrated in Fig. 1 and Fig. 2.

The size of the element 1 is 0.07 mm to 0.4 mm in width and 0.25 mm to 1 mm in length, which is the size of the substrate 1. In the center part of the element 1, the substrate 10 has a groove of 20 to 60 μm in width and 2 to 20 μm in depth so that the two magnetic wires (21 and 22) are aligned and disposed in parallel to each other. The two

magnetic wires (21 and 22) are adjacent to each other with the interval of 1 to 5 μm . It is preferable that the magnetic wires (21 and 22) are isolated from each other by an insulating material, such as an insulating separation wall, for example.

[0025] < Magnetic wire >

The magnetic wire 2 is formed of a CoFeSiB amorphous alloy with a diameter of 5 to 20 μm . The periphery of the magnetic wire 2 is preferably coated with an insulating material, such as insulating glass, for example. The length is 0.07 to 1.0 mm.

The magnetic wire 2 has a magnetic anisotropy field of 20 G or less, with a two-phase magnetic domain structure of a surface magnetic domain with circumferential spin alignment and a center part core magnetic domain with axial spin alignment.

[0026] < Coil >

In the coil 3, it is preferable that the number of winding of the coil is 6 to 180 times and the coil pitch is 5 μm . The interval between the coil 3 and the magnetic wire 2 is preferably 3 μm or smaller. The average inner diameter of the coil is preferably 10 to 35 μm .

[0027] < Manufacturing method of element >

The manufacturing method of the element is described

with reference to Fig. 2.

Electrode wiring is performed on a lower coil 31 and the substrate surface along the groove 11 formed on the substrate 10. Then, an insulating separation wall 41 is formed in the center part of the groove 11 to have a two-groove form, and each of the two magnetic wires 21 and 22 coated with glass is arranged therein. Next, an insulating resist is applied to the entire surface of the substrate. Thus, the magnetic wires 21 and 22 are fixed in the groove 11. The insulating resist is applied thinly onto the upper part of the magnetic wires 21 and 22. At that part, an upper coil 32 is formed by a photolithographic technology.

In the case where the magnetic wires 2 not coated with glass are used, an insulating material 4 needs to be preliminarily applied to prevent electrical contact between the lower coil 31 and the magnetic wires 21 and 22.

[0028] In the manufacturing of the coil, the recessed lower coil 31 is formed along the groove surface and the both sides of the groove 11 formed on the substrate 11. The projecting upper coil 32 is electrically jointed to the lower coil through a joint part 33 to form the spiral coil 3.

[0029] At the ends of the two magnetic wires 21 and 22, glass as an insulating film is removed to allow electrical connection by metal vapor deposition.

[0030] < Magnetic wire and coil wiring structure >

In the wiring structure of the magnetic wire 2, the wire input electrode (+) 24 is connected to the upper part of the magnetic wire 21, and the lower part of the magnetic wire 21 is connected to the lower part of the magnetic wire 22 through the wire connection part 23, as illustrated in Fig. 1. The upper part of the magnetic wire 22 is connected to the wire output electrode (-) 25. This wire connection part 23 enables a downward flow of a pulse current from the upper part to the lower part in the magnetic wire 21, and an upward flow of a pulse current from the lower part to the upper part (in the opposite direction from the direction in the magnetic wire 21) in the magnetic wire 22.

[0031] In the wiring structure of the coil 3, the coil output electrode (+) 34 is connected to the lower end part of the coil 3, and the upper end part of the coil 3 is connected to a coil ground electrode (-) 35, as illustrated in Fig. 1.

[0032] < Electronic circuit >

An electronic circuit 5 includes a pulse generating circuit 51 for generating a pulse current, an input circuit 53 for inputting a coil voltage, a pulse compliant buffer circuit 54, the sample hold circuit with an electronic switch 56 for detecting a peak voltage of an output waveform of a coil voltage and a capacitor with a capacitance of 4 to 100

pF for holding a peak voltage, and an amplifier 58. The amplifier 58 includes a programming amplifier for amplification before AD conversion.

Moreover, the GSR sensor element is connected to output a coil voltage of the electronic circuit 5.

[0033] At a pulse frequency of a pulse current of 0.2 to 4 GHz, the pulse current strength is 50 to 200 mA and the pulse time is 0 to 2 nsec. Fig. 4 illustrates the relation between the elapse of energizing time and the application of a pulse current when the pulse current is applied to the GSR sensor element. In the example of Fig. 4, the pulse current rises in 0.5 nsec from the start of energization, and this applied state is kept for given pulse time of 0.5 nsec. Once such energization is cut off, the pulse current falls in 0.5 nsec.

[0034] < Waveform of coil voltage >

Fig. 5 illustrates a waveform chart of a coil voltage when the above-described pulse current is applied.

In the invention, the timing of a peak voltage is detected. The electronic switch is turned on and off repeatedly with the opening-closing time of 0.1 to 1.5 nsec.

[0035] The capacitor capacitance of the sample hold circuit is 4 to 100 pF, and the AD conversion of the electronic circuit is 14 to 16 bits. Note that to shorten the interval of the on and off of the electronical switch,

the capacitor capacitance is preferably 4 to 8 pF.

In the coil output, the sensitivity is 50 mV/G to 3 V/G in the measurement range of 3 to 100G with a sin wave output, as illustrated in Fig. 6. The linearity is 0.3% or
5 lower.

[0036] < Example >

Fig. 1 illustrates a plane view of the GSR sensor element according to the example. Fig. 2 illustrates a section view thereof. Fig. 5 illustrates an electronic
10 circuit. The GSR sensor of the invention includes the GSR sensor element 1 having the two magnetic wires (21 and 22), the one coil 3 wound around the two magnetic wires, the two electrodes (24 and 25) for wire energization, and the electrodes (34 and 35) for coil voltage detection, the
15 means for applying a pulse current to the magnetic wire 2, the circuit for detecting a coil voltage occurred when the pulse current is applied, and the means for converting a coil voltage into an external magnetic field H. The external magnetic field H and the coil voltage are
20 expressed in the mathematical relation shown in the expression (1).

[0037] The size of the element 1 is 0.12 mm in length and 0.20 mm in width. The groove 11 on the substrate 10 is 40 μm in width and 8 μm in depth. The wire interval is 3
25 μm .

[0038] The magnetic wire (21 and 22) is formed of a CoFeSiB amorphous alloy coated with glass of 10 μm in

diameter and 1 μm or smaller in thickness.

The magnetic anisotropy field is 15G.

[0039] In the coil 3, the number of winding is 14 times with a coil pitch of 5 μm . The average inner diameter of the coil 3 is 30 μm , and the interval between the coil 3 and the magnetic wire 2 is 2 μm .

[0040] In the structure of the element, the half in diameter of the magnetic wires (21 and 22) coated with glass is embedded in the groove 11 formed on the substrate 10. The lower coil 31 is arranged on the inner surface of the groove 11, and the upper coil 32 is arranged above the magnetic wires. The lower coil 31 and the upper coil 32 are fixed with insulating resin and jointed by the joint part 33 on the substrate surface.

Between each of both end parts of the coil 3 and each of the coil electrodes, electrical connection part is provided using a conductive metal vapor deposition film.

In the magnetic wires 2 and the electrodes, after removing the glass coating material on the upper surface part at the end part of the magnetic wires, an electrical joint part is provided using a conductive metal vapor deposition film between the wire surface with the coating removed and the electrode.

Moreover, the connection part 23 between the two

magnetic wires 21 and 22 is also subjected to electrical connection by the same processing.

[0041] The GSR sensor element 1 is provided in the electronic circuit 5 and is energized by the pulse generation circuit 51 with a pulse width of 0.8 nnsec at a pulse frequency of 1 GHz and a pulse current strength of 120 mA. The interval of the on and off of the electronic switch is 0.2 nsec. The capacitor capacitance of the sample hold circuit is 6pF.

[0042] 16 bits are obtained by AD conversion. Moreover, with the sine wave output, the sensitivity is 200 mV in the measurement range of 90G. At the time, the power consumption is 0.3 mW, and the linearity is 0.2%.

Industrial Applicability

[0043] The invention achieves higher sensitivity and lower power consumption of the GSR sensor. The invention is expected to be used when ultra small size and high performance are required such as in the in-vivo motion device.

Reference Signs List

[0044] 1 GSR sensor element
10 substrate
11 groove
2 magnetic wire
21 one of two magnetic wires

22 the other of two magnetic wires
23 wire connection part
24 wire input electrode (+)
25 wire output electrode (-)
3 coil
31 lower coil
32 upper coil
33 joint part
34 coil output electrode (+)
35 coil ground electrode (-)
4 insulating resin
41 insulating separation wall
5 electronic circuit
51 pulse generation circuit
52 GSR sensor element
53 input circuit
54 buffer circuit
55 sample hold circuit
56 electronic switch
57 capacitor
58 amplifier

CLAIMS

1. An ultra high-sensitivity micro magnetic sensor, comprising:

5 a magnetic field detection element including two conductive magnetic wires for magnetic field detection arranged adjacent to each other on a substrate, a round coil wound around the two magnetic wires, two electrodes for wire energization, and two electrodes for coil voltage
10 detection;

a means for applying a pulse current to the magnetic wires;

a circuit for detecting a coil voltage occurred when the pulse current is applied to the two magnetic wires in
15 opposite directions; and

a means for converting the coil voltage into an external magnetic field H , wherein

the two magnetic wires for magnetic field detection include a first magnetic wire and a second magnetic wire,
20 the first magnetic wire and the second magnetic wire being arranged parallel to each other,

the first magnetic wire has a first end and a second end in order according to a direction of the pulse current,

the second magnetic wire has a first end and a second
25 end in order according to the direction of the pulse current,

the first end of the first magnetic wire and the second end of the second magnetic wire are respectively connected to the two electrodes for wire energization,

30 the second end of the first magnetic wire and the first end of the second magnetic wire are respectively

connected to each other,

the first magnetic wire and the second magnetic wire are separated by an insulating wall interposed therebetween in the round coil,

5 the magnetic wire has a magnetic anisotropy field of 20 G or less, with a two-phase magnetic domain structure of a surface magnetic domain with circumferential spin alignment and a center core magnetic domain with longitudinal spin alignment, and

10 the pulse current applied to the magnetic wire has a pulse frequency of 0.2 GHz to 4.0 GHz and a strength required to generate over a 1.5 times larger circumferential magnetic field than the anisotropy field on a surface of the wire, and

15 the coil has a coil pitch of 10 μm or less.

2. The ultra high-sensitivity micro magnetic sensor according to claim 1, wherein the pulse current is applied to the magnetic wire, and the circumferential spin inclined
20 in an axial direction is subjected to super high speed rotation by a wire axial magnetic field in the surface magnetic domain, to take out as a coil output only a magnetization change in the wire axial direction due to a super high speed rotation phenomena occurred at the
25 rotation and perform conversion into a field H using an equation (1):

$$V_s = V_o \cdot 2L \cdot \pi D \cdot p \cdot N_c \cdot f \cdot \sin(\pi H / 2H_m) \dots\dots (1)$$

where V_s is a coil output voltage and V_o is a constant of proportionality, and as a control factor constant, L is a
30 wire length, D is a wire diameter, p is a skin depth of a pulse current, N_c is number of winding of a coil, f is a

pulse frequency, H_m is an external magnetic strength to obtain a maximum coil output voltage.

3. The ultra high-sensitivity micro magnetic sensor
5 according to claim 1, further including an electronic
circuit including a pulse generating circuit for generating
the pulse current, an input circuit, a pulse compliant
buffer circuit for inputting the coil voltage, a sample
hold circuit with an electronic switch for detecting a peak
10 voltage of an output waveform of the coil voltage and a
capacitor with a capacitance of 4 to 100 pF for holding the
peak voltage, and an programming amplifier for
amplification before AD conversion.