Spin-Valve Film for Sensitive Giant Magnetoresistive Sensor Using AC Bias Magnetic Field

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A giant magnetoresistive material for a new sensitive magnetic sensor element was developed by a NiO spin-valve film. The magnetic sensor is composed of a multilayered structure that includes the spin-valve element and a bias current line. High sensitivity is obtained by using only the (rising or falling) edge of the magnetoresistive (MR) loop. An AC bias magnetic field induced by a square-wave bias current (plus or minus) is applied to the spin-valve element. The bias magnetic field is set to be slightly smaller than the rising field. The resistance of the spin-valve element is constant, if an external magnetic field is not applied. The output signal synchronizes with the input bias current, if the bias field is made to cross the rising edge of the MR loop by applying an external magnetic field. The spin-valve film: [NiO/NiFeCo/Cu/NiFeCo] exhibits the appropriate properties for the sensor element, such as an MR ratio of 5.1%, a sensing field of 0.2 kA/m, a driving field of 1.4 kA/m, an element destroying field of 32 kA/m and a high corrosion resistance. Moreover, the spin-valve element, patterned to a microscopic size, exhibits a step-shaped MR loop in which a free-layer magnetization switches like a single domain. The magnetic sensor using this spin-valve film detects an external field change of 0.04 kA/m, and operates at 30 ns.

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I. Introduction

Magnetic sensors are utilized for the reading head of a magnetic recording disk, a control part of a precision instrument, and a non-destructive inspection sensor of metallic building materials⁽¹⁾. Recently, micro-sized magnetic sensors, having high sensitivity and quick response, have been required in order to improve the performance of these applications⁽²⁾. A flux gate (FG) sensor⁽³⁾, a magneto-impedance (MI) sensor⁽⁴⁾⁽⁵⁾, and a magnetoresistive (MR) sensor⁽⁶⁾⁽⁷⁾ are known as general sensitive magnetic sensors. The FG sensor has a high resolution of $10^{-3} \sim 10^{-4}$ A/m, but micro-size fabrication is very difficult because of the complicated element structure. The MI effect is an electromagnetic phenomenon of an impedance change of a ferromagnetic wire element, with an AC current, against an external magnetic field. The MI sensor has a similar sensitivity to the FG sensor⁽⁸⁾, and has been studied as a new high sensitive micro magnetic sensor. On the other hand, the MR sensor is used for the reading head of a high density magnetic recording disk, because of its relatively high sensitivity and simple element structure. Moreover, the higher magnetoresistance of the giant MR (GMR) effect⁽⁹⁾ offers potential improvement for the reading head. GMR material having high sensitivity has been proposed in spin-valve film⁽¹⁰⁾, but the sensitivity is smaller than the FG and the MI sensors.

We recently proposed a new sensitive magnetic sensor using the GMR effect of spin-valve film⁽¹¹⁾. The spin-valve element, patterned to a micro size, exhibits the step-

shaped MR loop, and the high sensitivity is attained utilizing only the edge (rising or falling) part of the MR loop. In this paper we have developed the spin-valve material using an antiferromagnetic NiO pinning layer suitable for this sensor. Since NiO material has the property of high corrosion resistance, a highly stable sensor device is, therefore, likely to be realized.

II. Operating Principle

Our sensor element, as illustrated in **Fig. 1**, was constructed of a multilayered structure including spin-valve film, an insulator layer, a bias current line, and a sense line. The bias current line was separated from the spin-valve film by the insulator layer, and the resistance change of the spin-valve film was probed by the sense line. Thus, this sensor element structure is similar to the previously reported random access memory cell using spin-valve film⁽¹²⁾⁻⁽¹⁴⁾. The spin-valve sensor element consists of a multilayered structure including an antiferromagnetic layer and two ferromagnetic layers separated by a nonmagnetic metallic layer. The magnetic polarization of one of the ferromagnetic layers is fixed in one direction by antiferromagnetic exchange coupling. The magnetization of the other ferromagnetic layer is free to change the direction in response to an applied magnetic field. As shown in **Fig. 2**, the spin-valve film exhibits a hysteresis MR loop by means of the magnetization switching of the free layer parallel and antiparallel to the fixed layer magnetization direction. Here H_r and $-H_f$ are the rising and the falling magnetic fields of the MR loop, re-

Fig. 1 Schematic structure of the GMR sensor consisting of a spin-valve element and a bias current line.

Fig. 2 Operation principle of the present GMR sensor. High sensitivity is presented by using only the edge part of the MR loop.

spectively.

In the sensing operation, the AC bias magnetic field induced by the square-wave bias current: [plus or minus] is applied to the spin-valve element. The plus and the minus values of the bias field are set to be $H_f - \Delta h$ and $-H_f - \Delta H$ respectively. In this case, the resistance of the sense line is constant: [reference], because the plus value of the bias field is set to be smaller than the rising field of the MR loop (solid line). An external magnetic field H_{ex} is applied to the GMR sensor, where $\Delta h < H_{ex} < \Delta H$. The output signal synchronized with the input bias current is observed [$H_{ex}: on$], since the bias field goes across the rise of the MR loop (dotted line) by applying the external magnetic field. The magnetic sensitivity is determined by the set value of the bias current, when the GMR element has a step-shaped MR loop. Therefore, a sensitive magnetic sensor can be presented, if the magnetic field induced by the bias current is set to be slightly smaller than

the rising field.

The high-performance magnetic sensor can be developed by means of arranging the bias current⁽¹⁵⁾⁽¹⁶⁾. A highly sensitive reading head is developed, for example, by using the bias current synchronized with the clock signal of the magnetic recording drive. In addition, the direction and value of the slight change of the external field can be measured with high resolution by monitoring the switching value of a ramp-shaped bias current, in which the strength changes continually.

III. Experimental

Spin-valve films were fabricated by a four-source rf magnetron sputtering system with a rotating glass substrate. Uniaxial magnetic anisotropy was induced by a static magnetic field of about 4 kA/m at the substrate center, during the sputtering. The sputtering gas pressure of argon was mostly 0.20 Pa. The spin-valve films were constructed of two multilayered structures of [NiO/Co/Cu/Co] and [NiO/Ni₃₅Fe₂₀Co₄₅/Cu/Ni₃₅Fe₂₀Co₄₅], where the antiferromagnetic layer using the NiO film was first deposited onto the substrate. The NiO film is an insulator that has the property of high corrosion resistance⁽¹⁷⁾. In the simple cell structure shown in Fig. 1, the spin-valve structure with a bottom NiO layer is considered better for obtaining a large output.

The sensor cells were fabricated by using optical lithography and a liftoff technique in acetone liquid. The active area was patterned into a rectangular shape of 50 $\mu\text{m} \times 30 \mu\text{m}$. A 90-nm-thick Cu layer, deposited by the sputtering method, was patterned into a sense line. The Cu word line was 60 μm wide and 410 nm thick and was separated from the spin-valve film by a 325-nm-thick SiO₂ insulator layer.

The magnetoresistive measurement of the spin-valve films was performed by a four-point probe method at room temperature in which magnetic field was applied in a direction perpendicular to the sense current and in a direction parallel to the easy axis of the film. X-ray reflection measurements were performed by JEOL JDX-8030 with Cu-K α ($\lambda = 0.15405 \text{ nm}$) radiation emitted from a Cu target (30 kV, 20 mA). The incident beam was stepped at $2\theta = 0.01$ degree.

IV. Results and Discussion

1. Evaluating parameters for sensor element

Figure 3 shows the typical MR loops of a spin-valve film: [NiO/Co/Cu/Co], where magnetic field was applied between $\pm 12 \text{ kA/m}$ at the minor loop shown in Fig. 3(b). Exchange coupling between the ferromagnetic and antiferromagnetic layers produces a unidirectional anisotropy field and increases the coercivity of the ferromagnetic layer. The major loop shows that GMR behavior arises from the difference in coercivity between the two Co layers and from the unidirectional biasing field. Between 9 and 19 kA/m, magnetizations of the two lay-

Fig. 3 Typical MR loops of a spin-valve film, and evaluation parameters: the MR ratio MR, sensing field H_{sense} , driving field H_{drive} , loop shift H_{shift} and destroying field H_{destroy} for the sensor element.

ers are arranged to be antiparallel, so the resistance is high. At -8 kA/m , two magnetizations are switched at the same time, and a little bump appears. The minor loop, as shown in Fig. 3(b), shifts by a ferromagnetic coupling between two Co layers because the ferromagnetic coupling tends to convert the free layer magnetization into the magnetic direction of the fixed layer. The spin-valve film exhibited a relatively large MR ratio of about 7.3%.

The performance of the spin-valve film for the sensor element can be evaluated using the following parameters shown in Fig. 3: an MR ratio, a sensing field (H_{sense}), a driving field (H_{drive}) and a destroying field (H_{destroy}). It is desirable that the GMR material for the sensor element possesses a large MR ratio. The driving field should be small in order to restrain the electric power consumption and the temperature rising, because the magnetic field induced by the bias current is utilized in the sensing operation. The sensitivity is described by the rising slope of the MR loop, thus the sensing field should be small. The minus value of bias field is set small in order to restrain the electric power consumption and the temperature rising. The initialization by applying a large negative magnetic field is necessary if the magnetic field above the destroying field is applied to the sensor element. Thus, it is desirable to have a large value of H_{destroy} . Moreover, the magnetic coupling between ferromagnetic layers is estimated by an MR loop shift (H_{shift}), which is a center field of half MR ratio. This parameter is important for evaluat-

ing the spin-valve film characteristics. It is expected that the H_{shift} increases with increasing ferromagnetic coupling, if a vacancy in the intermediate Cu layer increases in quantity with deteriorating film quality.

These parameters should be, of course, evaluated for the accomplished sensor cell. The spin-valve films have different MR properties by the shape effect and the thermal deterioration in before and after the micro-sized fabrication. The as-sputtered spin-valve film before the micro fabrication exhibits the fundamental properties, and the patterned element can be estimated from this properties. Therefore, in this research, the above MR parameters were mainly evaluated for the as-sputtered films.

2. Magnetoresistive properties of NiO spin-valve film

The GMR properties of multilayered materials are known to depend on the fabricating conditions⁽¹⁸⁾. The MR ratio of the spin-valve material using a NiO antiferromagnetic layer is also very sensitive to the sputtering gas pressure, when the NiO film is first deposited on the substrate. Figure 4 shows that a relatively large MR ratio is obtained at low Ar pressure, and it was more than 7% at 0.20 Pa. The spin-valve structure is $[\text{NiO}(50.0)/\text{Co}(3.7)/\text{Cu}(2.0)/\text{Co}(3.7)]$, where the value in parentheses indicates the layer thickness in nm. An extraordinary precision of 0.05 Pa is necessary for a large MR ratio. In the following discussions, the spin-valve films were fabricated at 0.20 Pa. We consider that the sputtering pressure dependence of the magnetoresistive properties is influenced by the difference in the condition of the NiO surface and the Co/Cu interface. Figures 5(a) and 5(b) show the low angle X-ray reflectivity curves of the spin-valve films: $[\text{NiO}/\text{NiFeCo}/\text{Cu}/\text{NiFeCo}/\text{Cu}]$ fabricated at 0.20 Pa and 0.30 Pa, respectively. The reflectivity oscillation is due to a multiple reflection and interference in the multilayered structure. Therefore, it is inferred from these results that a high quality multilayered structure is obtained at low Ar pressure, because the reflectivity oscillation of the film is observed in the high angle region. However, a model calculation is necessary

Fig. 4 Sputtering gas pressure dependence of the MR ratio on the spin-valve films: $[\text{glass}/\text{NiO}/\text{Co}/\text{Cu}/\text{Co}]$.

Fig. 5 X-ray reflectivity of the spin-valve films: [glass/NiO/NiFeCo/Cu/NiFeCo/Cu] deposited at (a) a low argon pressure of 0.20 Pa and (b) a high argon pressure of 0.30 Pa.

for quantitative analysis⁽¹⁹⁾. Soeya *et al.* have reported about exchange anisotropy in a bilayered $\text{Ni}_{81}\text{Fe}_{19}/\text{NiO}$ film, where a better exchange coupling property has been obtained at a low sputtering pressure⁽²⁰⁾. It has been concluded from their cross-sectional transmission electron microscopy observations that one of the better exchange coupling properties is the smoothing of the NiO film surface. This is consistent with the results of our X-ray reflection measurements.

The magnetoresistive properties of the spin-valve film: [NiO/Co/Cu/Co] sensitively depend on the thickness of the NiO pinning layer, too. **Figure 6** shows the dependence of the above evaluation parameters on the NiO thickness. It is found from the MR ratio variation that the optimum NiO thickness is approximately 15 to 60 nm. The decrease in the MR ratio at the NiO layer of less than 15 nm in thickness can be explained in terms of the reduction of the exchange coupling between the NiO layer and the adjoining Co layer. In practice, a margin is necessary in device fabrication because the MR ratio suddenly decreases if NiO thickness is less than approximately 15 nm. On the other hand, the MR ratio decreased at the NiO layer of more than 60 nm in thickness, and the H_{drive} and H_{shift} increased with increasing NiO layer thickness. The optimum NiO thickness is 25 to 60 nm for the H_{destroy} , similar to the MR ratio, and the H_{sense} is roughly

Fig. 6 NiO layer thickness dependence of the evaluation parameters: MR, H_{sense} , H_{drive} , H_{shift} and H_{destroy} on spin-valve films: [glass/NiO/Co/Cu/Co].

Fig. 7 Cu layer thickness dependence of the evaluation parameters: MR, H_{sense} , H_{drive} , H_{shift} and H_{destroy} on spin-valve films: [glass/NiO/Co/Cu/Co].

constant. It is considered that these magnetoresistive property changes are due to the influence of the NiO under layer, and detailed investigation is necessary. It is concluded from the MR ratio and H_{drive} that the appropriate NiO layer thickness is relatively thin, of approximately 20 to 30 nm.

Next, **Fig. 7** shows the dependence of the evaluation parameters on the thickness of the intermediate Cu layer. The spin-valve film: [NiO/Co/Cu/Co] shown in Fig. 3 is difficult to apply to the sensor element due to the large H_{drive} of about 10 kA/m, and the magnetoresistive property exhibits an asymmetric minor loop. It is expected that the H_{shift} representing the strength of the ferromagnetic coupling depends on the Cu layer thickness. The H_{shift} , as shown in Fig. 7, decreases with increasing Cu layer thickness, as a result the H_{drive} decreases about 20%. However, this is not an effective method, because the MR ratio reduces with increasing amount of conduction electrons passing through the Cu layer. Thus, the optimum thickness of the Cu layer was approximately 2 nm for a large MR ratio.

The ferromagnetic Co layers were changed to a soft magnetic material ($\text{Ni}_{35}\text{Fe}_{20}\text{Co}_{45}$) in order to decrease the

Fig. 8 Dependence of the evaluation parameters: MR, H_{sense} , H_{drive} and H_{shift} on thicknesses of (a) the ferromagnetic pinned layer and of (b) the free ferromagnetic layer for the spin-valve films: [glass/NiO/NiFeCo/Cu/NiFeCo].

Fig. 9 Dependence of the destroying magnetic field H_{destroy} on thicknesses of the pinned and free ferromagnetic layers for the spin-valve films: [glass/NiO/NiFeCo/Cu/NiFeCo].

driving field, and the layer thickness effect on the magnetoresistivities has been investigated. **Figures 8(a)** and **8(b)** show the dependence of the evaluation parameters on the thickness of the NiFeCo layer (the pinned layer) neighboring the NiO layer and of the NiFeCo layer (the free layer) distant from the NiO layer, respectively. In this case, the thicknesses of the NiO and Cu layers were fixed at 25.0 and 2.0 nm, respectively. The MR ratio, as shown in Fig. 8(a), was more than 6%, when the pinned

Fig. 10 MR loops of the spin-valve film: [glass/NiO/NiFeCo/Cu/NiFeCo] suitable for the sensor element.

layer is between 2 and 5 nm in thickness. The H_{shift} and the H_{drive} decreased with decreasing pinned layer thickness, but the optimum thickness was about 2 nm for the MR ratio. The H_{destroy} sensitively, as shown in **Fig. 9**, depends on the pinned layer thickness and exhibits a large value at a relatively thin of 2 nm. Both the H_{shift} and the H_{drive} , as shown in Fig. 8(b), were reduced by increasing the free layer thickness where the pinned layer was fixed at 2.2 nm. When the free layer is 11.0 nm thick, the H_{drive} and the H_{sense} were 14 kA/m and 2 kA/m respectively. **Figure 10** shows the MR curves of this spin-valve film: [NiO(25.0)/NiFeCo(2.2)/Cu(2.0)/NiFeCo(11.0)]. The minor MR loop has the steeply change and the squareness ratio of almost unity in the range of ± 3 kA/m, thus this spin-valve film has superior MR properties for the sensor element.

3. Magnetoresistive properties of patterned film

Figure 11 shows the MR loop of the spin-valve film patterned to micro size. The spin-valve structure was [NiO/NiFeCo/Cu/NiFeCo/Cu], where the surface Cu layer, in order to inhibit corrosion, was 2.0 nm in thickness and the thicknesses of other layers were the same as shown in Fig. 10. The evaluation parameters of the driving field and the squareness ratio were not affected, but the MR ratio decreased to approximately half due to microscopic processing and the shunt effect of the surface Cu layer.

Fig. 11 MR minor loop of the patterned spin-valve film. The patterned spin-valve film shows a symmetrical and step-shaped MR loop.

The Cu shunt effect is estimated by considering the thicknesses and resistivities of each of the spin-valve layers, and the reduction ratio is approximately 73%. It is considered that the remaining reduction is caused by thermal deterioration in microscopic fabrication, and detailed investigation is necessary. In this measurement, the magnetic field was applied along the 50 μm long side, which is in the same direction as the uniaxial magnetic anisotropy. The magnetization of the free layer switches like a single domain, since the shape anisotropy effect is increased. As a result, the patterned element exhibits a symmetrical and a step-shaped MR loop. Therefore, a sensitive magnetic sensor can be developed by using only the edge part of this MR loop.

4. Sensing operation

Figure 12 shows a top view of the fabricated GMR sensor cell. The spin-valve film is similar to the structure shown in Fig. 11. The uniaxial anisotropic axis is parallel to the 30 μm short side, and the resistance of this patterned spin-valve element also switches like a single domain from a low to a high value. The sensor cell can easily approach the sensing matter because of the edge shape.

Figure 13 demonstrates the response of this GMR sensor against the external magnetic field change. The external field change was sensed by monitoring the output voltage of the sense line, when a square-wave current of $\pm 130\text{ mA}$ was applied to the bias current line. The square-wave output signal synchronizing with the input bias current, as shown in Fig. 13(b), was observed by applying a magnetic field of 0.04 kA/m. In this experiment, the sensing speed is slow since the frequency of the bias current is 20 Hz. However, Tang *et al.* have reported that the spin-valve memory cell, which is in the single domain state, was able to switch state in less than 2 ns⁽¹²⁾. We think that our GMR sensor can work in short time of the GHz level, because the operation principle is similar to this spin-valve memory. We confirmed the fabricated sensor operation up to a bias current pulse of a 30 ns

Fig. 12 Top view of the GMR sensor fabricated by the lift-off technique. The active sensor element is the rectangular shape of dimension 50 $\mu\text{m} \times 30\text{ }\mu\text{m}$.

Fig. 13 Response of the sensor element against the square-wave AC bias magnetic field generated from the bias current line. (a) Reference: $H_{\text{ex}} = \text{off}$ and (b) in an external magnetic field: $H_{\text{ex}} = 0.04\text{ kA/m}$.

width⁽²¹⁾.

The sensitivity of this GMR sensor is determined by fluctuating the rising field of the MR loop, in which a thermal fluctuation is anticipated. The bias current should be set low also for the operation speed of the electric driving circuit. The size dependence of bias current is estimated by a model calculation of magnetic field in-

duced from the bias current, in which the spin-valve element and the bias current line are divided to a matrix. It is expected that the sensor is operated by a bias current of 20 mA by patterning to a micro size of 1 μm .

V. Conclusion

We developed a spin-valve film for a new sensitive GMR sensor consisting a bias current line and a spin-valve element. The spin-valve film: [NiO/NiFeCo/Cu/NiFeCo] has highly efficient properties suitable for the sensor element, such as an MR ratio of 5.1%, a sensing field of 0.2 kA/m, a driving field of 1.4 kA/m, and a destroying field of 32 kA/m. The spin-valve element patterned into a rectangular shape of 50 $\mu\text{m} \times 30 \mu\text{m}$ exhibited a step-shaped MR loop. The high sensitivity was attained using only the edge part of this MR loop. A plus value of the bias magnetic field, induced from the bias current line, was set to be slightly smaller than the rising field, and the sensor detected an external field change of 0.04 kA/m. We confirmed the sensor operation up to a pulse width of 30 ns in the demonstration using a bias current pulse.

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