Effect of Stress on Magnetic Performance of GMR Head Used for Hard-Disk Drive*

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The effect of stress on the magnetic performance of a giant magneto-resistive (GMR) head was investigated. The stress in the GMR head consists of residual stress caused by thin-film processing and thermal stress due to heat dissipation in the GMR element. When the difference between the in-plane stresses in the GMR element is large, the output voltage of the head changes; thus, the read characteristic of the hard-disk drive is deteriorated. The stress in the GMR head was analyzed by a three-step finite-element analysis, called zooming FEA, and the magnetic performance of the head under the effect of the stress was calculated. Accordingly, it was found that to reduce the effect of the stress on magnetic performance, the intrinsic stress in the protective layer on the head must be optimized and the temperature rise of the GMR element must be decreased during operation.

Key Words: Residual Stress, Thermal Stress, Finite Element Method, Laminated Construction, Giant Magneto-Resistive Head, Hard Disk Drive, Magnetic Performance

1. Introduction

In hard-disk drives, whose recording density has been rapidly increasing in recent years, it is necessary that a giant magneto-resistive (GMR) head is used to read and write a magnetic signal onto a disk. In the GMR head, a read error may be caused by noise such as distortion of the signal wave form or Barkhausen noise. Such noise is caused not only by poor domain control, defective shape of the thin film or defects in the thin film (such as lattice defects or dislocations) but also by stress in the head. In regards to an inductive head⁽²⁾, which reads and writes by induced

voltage and magnetic force produced by a coil, or in a magneto-resistive (MR) head⁽¹⁾, which has been used before the GMR head, the effect of the stress in the head on the magnetic performance has previously been studied. In the current study, the effect of the stress on the magnetic performance of the GMR head was evaluated. The detailed three-dimensional stress distribution in the GMR head was analyzed by a three-step finite-element analysis (called zooming FEA hereafter). The first step of this analysis involves analyzing the macroscopic deformation of the whole GMR head. In the second and third steps, the local stresses are analyzed by using local models. The results of the former-step in the deformation analysis are then used as a boundary condition for the second or third-step local model. The stress produced by thin-film processing was analyzed, and the thermal stress due to the Joule heat in the GMR element, which had not been analyzed in the previous work^{(1),(2)}, was also analyzed. And the effect of these stresses on the magnetic performance of the head was investigated.

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Fig. 1 Cross-sectional structure of a GMR head

Fig. 2 Detailed structure of GMR element

2. Outline of GMR Head and the Effect of Stress on Its Magnetic Performance

Figure 1 shows the cross-sectional structure of a GMR head, which consists of an inductive coil for writing a magnetic signal on a disk and a GMR element for reading the signal. In the GMR head, various thin films with complex shapes of different materials with thicknesses in the range from 10 nm to 30 μm are laminated by processes such as sputtering on a ceramic substrate (with a thickness of 1 mm).

Figure 2 shows the detailed structure of the GMR element from the viewpoint of the face that is perpendicular to the y -axis and includes point O in Fig. 1 (i.e., the opposite face to the disk). When an electric current is passed through the free layer, and the pin layer, and the external magnetic field, H , from the disk changes, the direction of the magnetization, M_F , in the free layer changes (but the direction of the magnetization, M_P , in the pin layer does not change). As a result, the resistance of the GMR element changes. The GMR head then reads this change in resistance as the signal on the disk, i.e., it utilizes the GMR effect.

Here, it is assumed that the free layer is on the $x-y$ plane and an easy-axis of magnetization in the free layer is along the x -axis. And it is also assumed that principal stresses σ_1 , σ_2 , and σ_3 exist in the free layer and the directions of the stresses, i.e., σ_1 , σ_2 and

σ_3 , are at angles with the z -axis and this x -axis of (ξ_1, ξ_2) , (ζ_2, ξ_2) and (ζ_3, ξ_3) respectively. Under these assumptions, when M_F rotates by angle ϕ from the initial direction, i.e., the direction of the x -axis and current, a change of an internal magnetic energy, i.e., magnetic anisotropic energy, in the free layer can be expressed as follows.

$$E_a = K_u \sin^2 \phi + \frac{3}{2} \lambda [\sigma_1 \sin^2 \xi_1 \sin^2(\phi - \xi_1) + \sigma_2 \sin^2 \xi_2 \sin^2(\phi - \xi_2) + \sigma_3 \sin^2 \xi_3 \sin^2(\phi - \xi_3)] \quad (1)$$

Here, K_u is a coefficient of magnetic anisotropy and λ is a coefficient of magnetostriction in the free layer^{(1),(3)}. And E_a changes the read characteristics of the GMR head. In the case that the directions of σ_1 , σ_2 , and σ_3 are along either the x , y , or z -axis, E_a can be expressed as

$$E_a = \left[\left(K_u + \frac{3}{2} \lambda (\sigma_x - \sigma_y) \right) \sin^2(\phi - \beta) + \text{Const.} \right] \quad (2)$$

where β is zero or $\pi/2$. Accordingly, the difference between in-plane stresses in the free layer, i.e., $(\sigma_x - \sigma_y)$, affects the read characteristic of the GMR head.

3. Model for Analysis of the Stress in a GMR Head

3.1 Outline of analysis

When the thin films in the GMR head are processed, the temperature of each material of the films is different. The films therefore have residual stress due to the mismatch of the thermal-expansion coefficients. In addition, when a thin film is formed, it has an initial stress, i.e., an intrinsic stress^{(4),(5)}. These stresses caused by thin-film processing are referred to as process stress hereafter. Furthermore, the temperature across the working head is distributed according to the Joule heat caused by the current in the GMR element, so the thermal stress is produced locally in the head.

Figure 3 shows the flow chart for the analysis of the GMR head. The process stress and the thermal stress are analyzed respectively, and the sum of these stresses is used in the evaluation as the stress in the working head. Before the thermal stress was analyzed, the distribution of the temperature due to the Joule heat in the head was analyzed by static-heat-conduction FEA. Then the temperature distribution was used as the thermal load to analyze the thermal stress. To analyze the stress and temperature, zooming FEA was applied. In the analysis of the stress, the local second or third-step model used the result of the node displacements in the former step as the boundary condition. And in the analysis of the temperature, the local models after the second-step used the result of

Fig. 3 Flow chart of zooming FEA analysis

Fig. 4 Schematic illustration of model for FEA

the node temperature in the former step as the boundary condition. If conventional FEA with one model is applied to analyze the whole head, the number of elements in a FEA model must be huge. That is because the size of the GMR element is about a million times smaller than the size of the whole GMR head; i.e., the minimum thickness of the thin film is a few nanometers and the length of the head is 1 mm. On the other hand, if zooming FEA is applied, the number of elements in each step model and the whole time for analyses are less than those in the case without the zooming. Furthermore, it was confirmed that the difference between the calculated stress by conventional FEA with one model and the two-step

zooming FEA is a few percent. Accordingly, it was assumed that the deterioration of the analysis accuracy by three-step zooming is less than 10%. Note that in these FEAs of stress and temperature, the SIMUS program⁽⁶⁾ was used.

3.2 Analysis of process stress

In the analysis of process stress in the head, the finite elements of each thin film with the intrinsic stress were added on the finite elements of the substrate at each ambient temperature in order. In the final process, that is, the head is cut from the wafer, the finite elements of the cut part were deleted⁽⁶⁾ from the FEA model. But the cutting process in which the opposite face to the disk becomes a free face was only

Table 1 Mechanical properties of materials

Material	Young's modulus (GPa)	Poisson's ratio	TEC ($\times 10^{-6} \text{K}^{-1}$)	Intrinsic stress (MPa)
Substrate	390	0.22	8	0
Base	410	0.25	7	-50
Lower shield	200	0.3	13	200
Insulator (for GMR)	410	0.25	7	-100
Permanent magnet	200	0.3	13	-200
Lead	190	0.3	6	90
Upper shield	200	0.3	13	200
GMR	Free layer	200	0.3	600
	Pin layer	210	0.3	900
	Antiferromagnetic layer	80	0.3	60
	Insulator (for coil)	3	0.35	20
Upper shield	150	0.3	9	200
Protective layer	410	0.25	7	-80

analyzed because other cutting faces are far from the GMR element and the cutting hardly affects the stress distribution of the GMR element.

Figure 4 shows a schematic illustration of the model for each step analysis. The hatched parts in the figure show which elements were deleted in the cutting process. In the first step, half of one side of the head was analyzed because the structure of the head is symmetric. On the plane of symmetry in the first-step model, the perpendicular node displacements to the plane were then fixed. In the case that the thin films in the head are much thinner than the substrate, the stress in the thin films (including the effect of out-of-plane deformation of the substrate) can be approximately analyzed by the model shown in Fig. 4(a)⁽⁶⁾. On the side face of the model in Fig. 4(a), the node displacements perpendicular to the face are constrained by the displacement of the substrate in multi-point. And in the model, the substrate part consists of two layers, i.e., a layer with the same material property as the substrate and a thickness of 10 μm and an equivalent-stiffness layer with a Young's modulus of 47 000 GPa and a thickness of 2 μm . In the first and second steps, several films in the GMR element and a permanent magnet were omitted, and only the films with maximum thickness in each layer, i.e., an antiferromagnetic layer and a lead layer, were included. It was assumed that the omission of the films in the first- and second-step models hardly affects the displacement as the boundary condition of the next-step model. Table 1 lists mechanical properties of the materials used in the FEA.

3.3 Analysis of thermal stress

In the analysis of the temperature distribution in a working head, four-step zooming FEA was applied. It was difficult to set the boundary conditions in the model with the same size as the first-step model in Fig. 4(a), the first step thus analyzed the whole head by using the model in Fig. 5. The boundary conditions of the first-step model for analyzing the temperature are shown in Fig. 5. A half of one side of the head was only analyzed because the structure of the head is

Fig. 5 Model for analysis of temperature

symmetric. In the second to fourth steps, the sizes of the models were the same as first- to third-step models for the analysis of the process stress (except the cutting parts, i.e., the models without the hatched parts in Fig. 4). It was assumed that the heat transfer from the opposite face to the disk is by conduction from the head to the disk because the distance between the head and the disk is very small, i.e., less than 100 nm. Accordingly, the coefficient of heat transfer⁽⁷⁾, h , of the opposite face was set to $1 \times 10^5 \text{ W/m}^2\text{K}$ according to

$$h = \frac{\alpha}{2} \left(\frac{\gamma + 1}{\gamma - 1} \right) \sqrt{\frac{R}{2\pi T}} \cdot \frac{p}{J} \quad (3)$$

where α (accommodation coefficient) was set to 0.9, γ (ratio of specific heat) to 1.4, R (gas constant) to 287 $\text{m}^2/\text{s}^2\text{K}$, T (room temperature) to 300 K, p (pressure) to 10^5 Pa , and J (mechanical equivalent of heat) to 1.0 $\text{N}\cdot\text{m}\cdot\text{K}/\text{J}$. The coefficient of heat transfer⁽⁸⁾ of the back side of the head adhered to a stainless-steel suspension was set to $6.2 \times 10^3 \text{ W/m}^2\text{K}$ according to the heat conduction from the back side to the suspension given by

$$h = \frac{\lambda_1 \lambda_2}{(\lambda_2 t_1 + \lambda_1 t_2)} \quad (4)$$

where λ_1 (coefficient of heat conduction of an adhesive) was set to 0.13 W/mK , λ_2 (coefficient of heat conduction of the suspension) to 16 W/mK , t_1 (thickness of the adhesive) to 20 μm , and t_2 (thickness of the suspension) to 25 μm . The condition of the plane of symmetry was assumed to be one of heat insulation. On the other face, the coefficients of heat transfer were assumed to take the value for heat transfer by natural convection in static air, i.e., 5.8 $\text{W/m}^2\text{K}$. However, the coefficients of heat transfer of the faces (except the opposite face) hardly affect the tempera-

Table 2 Thermal properties of materials

Material	Thermal conductivity (W/m·K)
Upper Pole, Upper shield, Lower shield	35
Protective layer, Insulator (for read), base, Substrate	1.0
Insulator (for write)	0.5

Fig. 6 Principal stress vector in GMR free layer

ture distribution in the head. This is because the heat in the head is mainly transferred from the opposite face (the coefficient of heat transfer of the opposite face is much larger than the coefficients of the other face). The Joule heat in the GMR elements and the lead were respectively estimated as 6.1×10^{-4} W and 1.6×10^{-4} W from each current and resistance. The ambient temperature was assumed to be 20°C. Table 2 lists the thermal properties of the materials used in the FEA.

The thermal stress was analyzed by using the FEA-determined temperature distribution as the thermal load. By using the models with sizes the same as the models for the analysis of the temperature in the second to fourth steps, three-step zooming FEA was applied to analyze the thermal stress. It was assumed that the opposite face of these models is free. The other boundary conditions were the same as those for the models for the analysis of the process stress in Fig. 4. The mechanical properties of the materials in Table 1 (without intrinsic stresses) were used to analyze the thermal stress.

4. Evaluation of Effect of Stress on Magnetic Performance of a GMR Head

Figure 6 shows the analysis result of the principal stress vector in the GMR free layer. In the GMR element, since the directions of the principal stresses, i.e., σ_1 , σ_2 , and σ_3 , are along the x -, y -, and z -axes respectively, the difference between in-plane stresses,

Fig. 7 Position for stress evaluation in GMR free layer

Fig. 8 Distribution of stress in GMR free layer ($x=0$)

Fig. 9 Distribution of stress in GMR free layer

i.e., $(\sigma_x - \sigma_y)$, affects the read characteristic of the GMR head according to Eq. (2). Figure 8 shows the distribution of $(\sigma_x - \sigma_y)$ (along the line o - A in Fig. 7) in the GMR free layer. As shown in Fig. 9, the distributions of $(\sigma_x - \sigma_y)$ along any parallel lines to the y -axis in the GMR free layer (except near the lead) are similar to the distribution in Fig. 8.

In regards to the process stress in the GMR free layer, there is a large difference between in-plane stresses, i.e., $(\sigma_x - \sigma_y)$, near the opposite face to the disk (on the y -axis up to 0.3 mm). The maximum $(\sigma_x - \sigma_y)$ was about -200 MPa. And $(\sigma_x - \sigma_y)$ at near the opposite face is mainly caused by the intrinsic stress of the uppermost alumina protective layer, which is shown in Fig. 1, because the thickness of the protective layer is the highest of the several films of the head. The protective layer has a compressive intrinsic

Fig. 10 Temperature increase in GMR element by Joule heating

sic stress, i.e., -80 MPa, as shown in Table 1. As a result, after the head was cut from the wafer and the opposite face of the head became free, the protective layer caused a deformation that compresses the GMR element in a perpendicular direction to the element plane (the parallel direction to the z -axis). The perpendicular compressive stress in the GMR element plane due to the deformation causes an in-plane expansion of the GMR element. However, the lead layer resists an expansion along the x -axis, so the stress along the x -axis in the GMR free layer differs from the stress along the y -axis, as shown in Fig. 8.

Figure 10 shows the temperature distribution in the working head. The figure shows that the temperature rises only in a local region around the GMR element, and the maximum temperature rise is about 30°C . The maximum temperature rise is approximately equal to the experimentally measured temperature rise in the GMR element (which was estimated from the resistance change due to the temperature change). A difference between in-plane thermal stresses, i.e., $(\sigma_x - \sigma_y)$, in the GMR free layer due to the temperature distribution in the head is compared with the process stress in Fig. 8. And $(\sigma_x - \sigma_y)$ due to temperature distribution is tens of megapascals in the whole area of the GMR free layer.

The effect of the stress on the magnetic performance of the GMR head was investigated next. The following Landau-Lifshitz-Gilbert (LLG) equation^{(9),(10)} was used to calculate the quantities and directions of magnetization in the GMR element.

$$(1 + \alpha^2) \dot{M} = -\gamma \left\{ M \times \left[H + \frac{\alpha}{|M|} (M + H) \right] \right\} \quad (5)$$

where M is the vector of magnetization, H is the effective magnetic field, α is the damping coefficient, and γ is the gyromagnetic ratio. To calculate the magnetization in the GMR free layer, the layer was divided into shell elements. Under a given H , the quantity and the direction of the magnetization in

Table 3 Averaged stresses in GMR free layer

	$\sigma_x - \sigma_y$ (MPa)
Process stress	-57
Thermal stress	-19
Process and thermal stress	-75

Fig. 11 Effect of stress on magnetic performance

each shell element in the GMR free layer were calculated by using Eq. (5) as the equilibrium state of the magnetization, i.e., the state that the magnetic energy was minimum, in whole free layer. And H includes the external magnetic field from the disk and the field due to the magnetic anisotropic energy, which was calculated by Eq. (1). This means that H includes the effect of the stress. The output voltage of the GMR head was then calculated from the resistance of the GMR element, which was estimated from the magnetization in the GMR free layer calculated by Eq. (5).

Figure 11 shows the amplitude of the output voltage, i.e., dV , of the GMR head in the case that a pulse magnetic signal was input into the head as the external magnetic field. It shows dV as a function of the coefficient of magnetostriction, i.e., λ , in the free layer for two cases: (i) including the effect of only the process stress and (ii) including the effects of process stress and thermal stress. According to Eq. (2), if the difference between in-plane stresses, i.e., $(\sigma_x - \sigma_y)$, in the free layer is zero, the magnetic anisotropic energy does not change, and dV also does not change when λ changes. This means that the larger the gradient of the function of dV and λ is, the larger the effect of the stress on the magnetic performance of the head. Though $(\sigma_x - \sigma_y)$ including only thermal stress in the working head is small, i.e., several tens of megapascals, the gradient of the function of dV and λ including the effect of both process stress and thermal stress is 30% larger than that including the effect of only process stress.

Table 3 lists the average of $(\sigma_x - \sigma_y)$ in the free layer, i.e., the value that the integral $(\sigma_x - \sigma_y)$ in Fig. 8 along the y -axis was divided by the length of the

Fig. 12 Dependence of process stress in GMR free layer on intrinsic stress in protective layer

GMR element along the y -axis (the length of the line o - A in Fig. 7). The average of $(\sigma_x - \sigma_y)$ including both process stress and thermal stress is up to 30% higher than that of the process stress only. The difference between the average of $(\sigma_x - \sigma_y)$ including thermal stress and that not including it is the same as the difference between the gradient of $dV - \lambda$ function including the effect of thermal stress and that not including it. Accordingly, it can be assumed that the average of $(\sigma_x - \sigma_y)$ in the GMR free layer is in proportion to the effect on the magnetic performance of the GMR head. It can be therefore assumed that the thermal stress in the working head affects the magnetic performance largely because the thermal $(\sigma_x - \sigma_y)$ is distributed uniformly in the free layer.

The analysis of the stress and the magnetization in the GMR head shows that the effect of the stress on the magnetic performance of the head can be decreased by optimizing the intrinsic stress in the protective layer. Figure 12 shows the dependence of the distribution of $(\sigma_x - \sigma_y)$ along the line o - A in Fig. 7 in the GMR free layer on the intrinsic stress in the protective layer. When the intrinsic stress in the protective layer changes from current value, i.e., -80 MPa, to a positive side, the distribution of $(\sigma_x - \sigma_y)$ also shifts to the positive side in parallel. According to Eq. (2), the effect of $(\sigma_x - \sigma_y)$ on the magnetic performance of the head is equivalent to the effect of λ . Therefore, dV is in proportion to not only λ , as shown in Fig. 11, but also $(\sigma_x - \sigma_y)$. Accordingly, when it is assumed that the average of $(\sigma_x - \sigma_y)$ in the GMR free layer is in proportion to the effect on the magnetic performance of the GMR head, dV should depend on the intrinsic stress in the protective layer (as shown in Fig. 13). When the intrinsic stress in the protective layer changes to the positive side, the effect of the stress on the magnetic performance of the head can be decreased. It can also increase the read sensitivity of the GMR head, i.e., dV , by changing the intrinsic stress in the protective layer to the negative

Fig. 13 Dependence of magnetic performance on intrinsic stress in protective layer

side if the read error does not occur. By changing the processing conditions for the protective layer or changing the material of the protective layer, the intrinsic stress in the protective layer can be changed, and the magnetic performance of the GMR head can be controlled.

Since the effect of the thermal stress in the working head on the magnetic performance is also large, the effect can be also reduced by decreasing the temperature rise. The temperature rise, i.e., the thermal stress, can be decreased, for example, by using a material with a high coefficient of heat conduction.

5. Summary

The effect of stress on the magnetic performance of a giant magneto-resistive (GMR) head was investigated. The detailed three-dimensional stress distribution in the head was analyzed by a three-step finite element analysis, i.e., zooming FEA, and the magnetic performance of the head under the effect of the stress was calculated. Accordingly, it was found that not only the residual stress due to thin-film processing, i.e., the process stress, but also the thermal stress due to the Joule heat in the head cause the difference between the in-plane stresses in the GMR element and affect the magnetic performance of the head. Furthermore, it was found that the difference between the in-plane stresses in the GMR element due to the process stress is mainly caused by the intrinsic stress in the protective layer in the head. It is thus concluded that to reduce the effect of the stress on magnetic performance, the intrinsic stress in the protective layer must be optimized and the temperature rise in the GMR element must be decreased during operation.

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performance of a head by the Landau-Lifshitz-Gilbert (LLG) equation^{(9),(10)}.

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