Magnetostriction Measurement of GMR Films on Practical Substrates

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Abstract. The magnetostriction constant $\lambda_S$ of a magnetic film is usually measured by detecting the mechanical distortion of the film deposited on a thin glass substrate under an applied field using a laser beam. This method, however, cannot be applied to a film deposited on a rigid substrate such as Si and AlTiC used widely in real-world application. This is because that the distortion of the sample is too small to be detected. In addition, $\lambda_S$ of the film deposited on the glass substrate sometimes differ from those of the film deposited on the Si or AlTiC substrate. Thus, it is very important to evaluate $\lambda_S$ of a film deposited on an actual substrate. In this paper, a new method for measuring $\lambda_S$ of a film deposited on a substrate used in actual products is proposed by detecting the change of the anisotropic field $H_k$ of the film under bending load. $\lambda_S$ can be calculated from the gradient of the applied mechanical stress dependence of the $H_k$. Utilizing this method, we have successfully measured $\lambda_S$ of GMR films fabricated on the practical substrate by a very high resolution of $2\times10^{-8}$.

1. Introduction

In a data storage technology, high-sensitive reading head has been achieved by reducing the thickness of film. For such a film, someone has tried to monitor the saturation magnetostriction constant $\lambda_S$ by cantilevered samples under an applied field [1]. This trend of storage technology makes harder to measure $\lambda_S$ because of not enough energy from a magnetic film to bend a substrate under an applied field. And it is very important to consider the lattice elastic strain induced by the magnetostriction effect for fabricating the reading heads [2]. Such a development needs high-resolution, high-repeatable and easy-to-use equipment to measure $\lambda_S$.

In this paper, a new method for measuring $\lambda_S$ of wafer-shaped sample fabricated on the practical substrate was proposed by applying mechanical loading and multi-point measurement of local deformation of a sample. The effectiveness of this proposed method was validated by the measurement using the developed equipment. It was confirmed that both the resolution of the measurement of $\lambda_S$ and repeatability of this new method were very high.

2. Principle of measurement system

When a mechanical stress is applied to a magnetic film, the direction of its magnetization is changed by the strain energy $\lambda_S\sigma$, where $\lambda_S$ is the saturation magnetostriction constant of the film and $\sigma$ is the...
applied stress. This phenomenon is called the inverse magnetostriction effect. It is possible to assume that the anisotropy energy is equal to above energy as following equation.

\[ \lambda_s \cdot \sigma = -\frac{\Delta H_k \cdot M_s}{3} \]  

(1)

Here, \( \Delta H_k \) is a deviation of anisotropy field induced by \( \sigma \), \( M_s \) the saturation magnetization. It is possible to assume that the effective elastic constant of a sample which consists of a substrate on which a magnetic film is deposited is the same as that of the substrate. This is because the thickness of the film is much thinner than that of the substrate. Based on this assumption, the strain \( \varepsilon \) in the substrate can be expressed by the following Huck’s equation.

\[ \varepsilon = \frac{\sigma}{E_{\text{sub}}} \]  

(2)

Here, \( E_{\text{sub}} \) is Young’s modulus of the substrate.

The internal stress \( \sigma_m \) in the magnetic film caused by \( \varepsilon \) is shown by the following equation

\[ \sigma_m = E_{\text{film}} \cdot \varepsilon \]  

(3)

Here, \( E_{\text{film}} \) is the Young's modulus of the magnetic film. When the stress is applied to the sample by bending load, the stress on the surface of the substrate is described by the following equation.

\[ \sigma = \frac{M}{Z} \]  

(4)

Here, \( M \) is bending moment of a sample and \( Z \) is its cross-section coefficient. A schematic of the cross-section of the substrate is shown in Figure 1(a). In this figure, \( W \) and \( t \) are the width and the thickness of the substrate, respectively. Typically the thickness is 0.3 to 2 mm and the thickness of magnetic film is less than 0.1 \( \mu m \).

![Image of substrate cross-section](image)

(a)

Figure 1 (a) Cross-section of substrate. \( W \) is the width of substrate and \( t \) is its thickness. (b) Load \( G \) is applied to the wafer surface by the upper knife edges. The wafer is supported by the lower knife edges.

Using these structural parameters, the cross-section coefficient can be expressed as follows.

\[ Z = \frac{W \cdot t^2}{6} \]  

(5)

The schematic diagram of our new mechanical loading system is depicted in Figure 1(b). In this figure \( G \) is the applied load, \( L_1 \) and \( L_2 \) are the distances of upper knife edge and lower knife edge, respectively. In this apparatus, the bending moment \( M \) is given by

\[ M = \frac{G \cdot (L_2 - L_1)}{2} \]  

(6)

From (5) and (6), \( \sigma \) is calculated as follows.

\[ \sigma = -\frac{3 \cdot (L_2 - L_1) \cdot G}{2 \cdot W \cdot t^2} \]  

(7)

By substituting this equation into (2), the strain \( \varepsilon \) can be obtained by the following equation.
Using (1) and (3), $\lambda_S$ can be expressed by the following equation.

$$\lambda_s = -\frac{\Delta H_k \cdot M_s / 3}{\epsilon \cdot E_{film}}$$

Finally, $\lambda_S$ can be determined as follows.

$$\lambda_s = \kappa \cdot \frac{\Delta H_k}{G}$$

Here, $\kappa = (2M_S \cdot W \cdot t^2 \cdot E_{sub})/(9(L^2-L1) \cdot E_{film})$. Therefore, $\lambda_S$ can be calculated by the gradient of the linear relationship between $G$ and $H_k$ when the magnetic film shows elastic deformation.

In this measurement, the accuracy is determined by the dynamic range of $G$. The main features of this measurement are as follows. 1) Practical substrates such as glass, ceramics (AlTiC, Si etc.) are available. 2) Substrate size: 5", 6" in diameter. 3) Resolution of $\lambda_S$ measurement: $10^{-8}$. The procedure of the determination of the amplitude of the applied stress is as follows. Let’s assume that the substrate material is AlTiC, the size of the substrate is $\phi 6" \times 2\text{mm}^3$, and the Young's modulus of the magnetic film is 390 GPa. When the estimated deviation of $H_k$ is 2 Oe, the amplitude of the loading stress should be more than 160 Kg (1,570 N). Under this stress, $\epsilon$ is $-4.014 \times 10^{-3}$.

3. **Experiment**

3.1. Experimental procedure

![Diagram](image)

Figure 2 (a) This can apply stress on the wafer(B) up to 200Kg by a cylinder(D) and a 2.5 multiplying booster(C) controlled by a controller(E). Orthogonal field coil (A) can apply AC field to measure R-H curve with DC transverse field. (b) $H_k$ is defined by the deviation with the field at $\Delta R/2$ and one at the intersection of the tangent line and the line of $R_{min}$. (c) Induced anisotropy direction is parallel to the tensile stress direction for the positive sign of $\lambda_S$ and right angle for the negative one.

A schematic diagram of the developed equipment is shown in Figure 2(a). The sequence of the measurement is as follows: 1) A DC field was applied to a film along its hard-axis direction. This field can stop the domain wall movement. 2) A load $G$ was applied to the wafer. 3) An AC field was applied to the film. This filed was high enough to saturate the film. 4) After acquiring R-H loop, $H_k$ was calculated. A measured value was plotted on a graph; $G$ vs. $H_k$. 5) $G$ was increased step by step, and, the procedure from 2) to 5) was repeated frequently. Finally, the relationship between $G$ and $H_k$ was measured quantitatively. $\lambda_S$ of the film was calculated by (10).

3.2. Definition of $H_k$ and the sign of $\lambda_S$

$H_k$ is defined by the field corresponding to the energy which can rotate spins in the free layer of GMR as shown in Figure 2(b). AC field is applied along up and down direction as shown in Figure 2(c). Tensile stress is applied along the same direction. With increasing stress, $H_k$ is increasing for negative sign of $\lambda_S$ and decreasing for positive one.
4. Experimental result
Some measured results are shown in Figure 3. In these measurements, the size of the substrate is \( \phi 6'' \times 1.0 \text{mm} \) and it was made of AlTiC. The maximum of applied stress \( \sigma \) was up to about 180 MPa. The thickness of the GMR film was 0.025\( \mu \)m. There were 15 measurement points and the increment of \( \sigma \) was constant. A good linear relationship between \( \sigma \) and \( H_k \) was obtained as was expected. In Figure 3(c), very small \( \lambda_S \) was obtained quantitatively though there was scattering in the measured points. The repeatability of the \( \lambda_S \) measurement is shown in Figure 4. This was repeated for 25 cycles without taking the sample out. The average fluctuation was \(-9.23 \times 10^{-7}\). The maximum deviation was \(2.09 \times 10^{-8}\) and it was the resolution of this measurement. These values of \( \lambda_S \) were rough match to others [3]. But it was difficult to compare with them precisely because of different substrate materials and sizes. This fluctuation value is good enough for practical use.

![Figure 3](image)

Figure 3 The measuring results of \( \sigma-H_k \) curve. (a) Negative sign of \( \lambda_S \) and \(-1.0275 \times 10^{-6}\). (b) Positive sign of \( \lambda_S \) and \(1.0716 \times 10^{-6}\). (c) \( \lambda_S \) is very small and \(-7.165 \times 10^{-8}\).

![Figure 4](image)

Figure 4 Repeatability with 25 cycles test is very stable and within \(2.09 \times 10^{-8}\) deviation.

5. Conclusion
A new measurement method of the magnetostriction of a thin GMR film deposited on the practical wafer has been developed by applying mechanical bending test. High resolution of \(10^{-8}\) was achieved by measuring the relationship between \( \sigma \) and \( H_k \). Thus, this method can be applied to practical use.

References
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