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Magnetostriction Measurement of Giant Magnetoresistance Films on the Practical Substrates by using Inverse-magnetostriction Effect

K. Okita[1]

[1]Industrial Instrumentation Division, Tohoku Steel Co., Ltd., Miyagi, 989-1393 Japan

Abstract. After forming electric devices, a magnetostriction effect sometimes deteriorates the sensitivity of sensors such as read heads of hard disk devices, or the bit stability of memories such as magnetic random access memories through the inverse-magnetostriction phenomenon. We should, therefore, know the magnetostriction constant of magnetic films on the practical substrates. In this paper, I present a new method by detecting the changes in coercive force, Hc, with mechanically bending the substrates. This method uses the inverse-magnetostriction effect and I show the magnetostriction constant can be calculated from the gradient of the applied stress vs. Hc curves. With this method, I have successfully measured the magnetostriction constant of the GMR films fabricated on the practical substrates with a high sensitivity over 10^{-7}. This method will be useful for the magnetic thin films with a large anisotropy field.

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 λ_S by cantilevered samples under an applied field [1]. The trend of storage technology makes harder to measure λ_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 λ_S. In our previous paper, a new method for measuring λ_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 [3,4]. The effectiveness of this proposed method was validated by the measurement using the developed equipment. It was confirmed that the resolution of the measurement of λ_S was very high.

In those days, magnetic thin films with a lager anisotropy field used for in-plane type random access memories or perpendicular oriented type ones have been developed. For those films, it became to be hard to measure the anisotropy field H_k, because of necessary to apply larger magnetic field more than a few kOe. We need a new method for measuring the magnetostriction constant of the magnetic thin films instead of measuring H_k.

2 Principal of Measurement

2.1 Calculation λ_s from H_c

The magnetostatic energy E is given by the following equation [5].

$$E = -K_u \cos^2\theta + I_s H \cos\theta - \frac{3}{2}\lambda_s \sigma \cos^2\theta \qquad (1)$$

Here, K_u is anisotropy constant, I_s the saturation magnetization, H the applied magnetic field along the easy axis, λ_s the saturation magnetostriction constant, σ the applied stress(tensile) along the easy axis and θ the angle of I_s to H in figure 1.

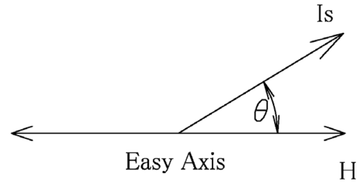


Fig. 1. The relationship between a saturation magnetization I_s and an applied magnetic field H. H is applied parallel to the easy axis of the magnetic thin film.

The magnetization vector will be in equilibrium with respect to the applied field and the anisotropy energy when the following condition is satisfied.

$$\frac{\partial E}{\partial \theta} = 0 \tag{2}$$

This means that the following equation can be derived from eq. (1).

$$2K_u \cos\theta \sin\theta - I_s H \sin\theta + 3\lambda_s \sigma \cos\theta \sin\theta = 0 \tag{3}$$

$$\sin\theta(2K_u \cos\theta - I_s H + 3\lambda_s \sigma \cos\theta) = 0 \tag{4}$$

There are 3 solutions to the above equation. Two solutions are θ = 0° and θ = 180°, and another one is the following condition.

$$(2K_u + 3\lambda_s \sigma)\cos\theta - I_s H = 0 \tag{5}$$

$$\cos\theta = \frac{I_s H}{2K_u + 3\lambda_s \sigma} \tag{6}$$

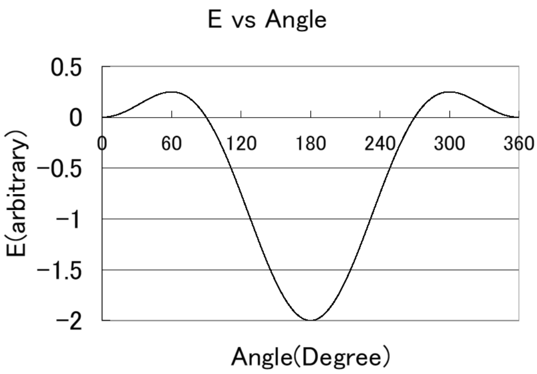


Fig. 2. E vs. θ curve under the condition of $I_s H/(2K_u + 3\lambda_s \sigma) = 1/2$. This curve contains 2 bottoms and 1 peak.

Figure 2 shows the E vs. θ curve of eq. (1) under the condition of $I_s H/(2K_u + 3\lambda_s \sigma) = 1/2$. This curve has 2 bottoms and 1 peak between 0° and 180° and shows that θ = 0° and θ = 180° are the stable points. From eq. (6), θ = 60° is the peak point in the figure 2. Increasing the value of $I_s H/(2K_u + 3\lambda_s \sigma)$ or H, the peak point moves to 0°. If $\cos\theta \geq 1$, then the E vs. θ curve has 1 bottom point and 1 peak one. As $\cos\theta > 1$ is unrealizable, $\cos\theta = 1$ is a significant value and θ = 0° becomes unstable point. When $\cos\theta = 1$ is satisfied by increasing H, the magnetization should rotate from 0° to 180°. This field can be called the coercive force. Therefore, the coercive force H_c of R-H curve for a giant magnetoresistance (GMR) film can be defined as the following equation.

$$H_c = (2K_u + 3\lambda_s \sigma)/I_s \tag{7}$$

The H_c is a function of σ and can be differentiated by σ. The gradient of H_c-σ curve is shown as follows.

$$\frac{\partial H_c}{\partial \sigma} = \frac{3\lambda_s}{I_s} \tag{8}$$

Therefore, λ_s can be expressed as the following equation.

$$\lambda_s = \frac{I_s}{3} \cdot \frac{\partial H_c}{\partial \sigma} \tag{9}$$

If we can know the slope of H_c-σ curve, then the magnetostriction constant can be calculated even if we do not know other terms in eq. (7). H_c is usually expressed as the function of some complicated terms. After the differentiating H_c equation like eq. (7), however, we could ignore all terms except the one related to $\lambda_s \sigma$.

2.2 Calculation of stress on the thin film

It is possible to assume that the effective elastic constant of a magnetic thin film sample deposited on a substrate because the thickness of the film is much thinner than that of the substrate.

Based on this assumption, the strain ε in the substrate can be expressed by the following Hooke's equation

$$\varepsilon = \frac{\sigma_s}{E_{sub}} \tag{10}$$

Here, E_{sub} is Young's modulus of the substrate and σ_s the stress applied to the substrate. The internal stress σ_m in the magnetic film caused by ε is shown by the following equation.

$$\sigma_m = E_{film} \cdot \varepsilon \tag{11}$$

Here, E_{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.

$$\sigma_s = \frac{M}{Z} \tag{12}$$

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 3(a).

In this figure, W and t are the width and the thickness of the substrate, respectively. Typically the thickness of substrate is 0.3 to 2 mm and the one of magnetic thin film is less than 0.1μm.

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

$$Z = \frac{W \cdot t^2}{6} \tag{13}$$

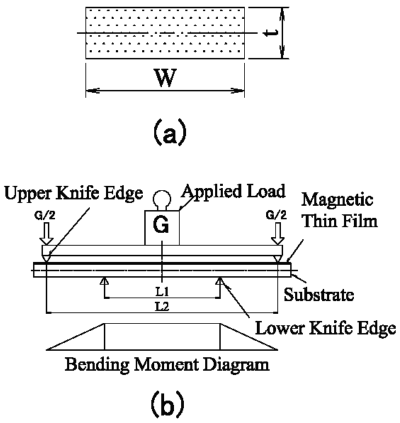


Fig. 3. (a) Cross-section of substrate. W is the width of substrate and t is its thickness. (b) Load G is applied to the wafer surface by the upper knife edges. The wafer is supported by the lower knife edges. The bending moment diagram is shown for the stress by 4 knife edges, known as the 4-point bending method.

The schematic diagram of my new mechanical loading system is depicted in figure. 3(b). In this figure G is the applied load, L1 and L2 are the distances of upper knife edges and lower knife edges, respectively, and the bending moment diagram for this apparatus is shown. In this apparatus, the bending moment M is given by

$$M = -\frac{G}{2} \cdot \frac{L2 - L1}{2} \tag{14}$$

From eqs. (13) and (14), σ_s is calculated as follows.

$$\sigma_s = -\frac{3 \cdot (L2 - L1) \cdot G}{2 \cdot W \cdot t^2} \tag{15}$$

Using eqs. (10), (11) and (15), σ_m can be expressed by the following equation.

$$\sigma_m = -\frac{3 \cdot (L2 - L1) \cdot G}{2 \cdot W \cdot t^2} \cdot \frac{Efilm}{Esub} \tag{16}$$

From eq. (9), λ_S can be calculated by the gradient of the linear relationship between σ_m and H_c when the magnetic thin film shows elastic deformation.

3 Experiment

3.1 Experimental tool

A schematic diagram of the developed equipment is shown in figure 4.

The sequence of the measurement is as follows: 1) A load G was applied to the wafer. 2) An AC field was applied to the film along its easy-axis direction. This filed was high enough to saturate the film. 3) After acquiring R-H curve, H_c was calculated. A measured value was plotted on a graph; H_c vs. σ. 4) G was increased step by step, and the procedure from 1) to 3) was repeated frequently. Finally, the relationship between σ and H_c was measured quantitatively. λ_s of the film was calculated by eq. (9).

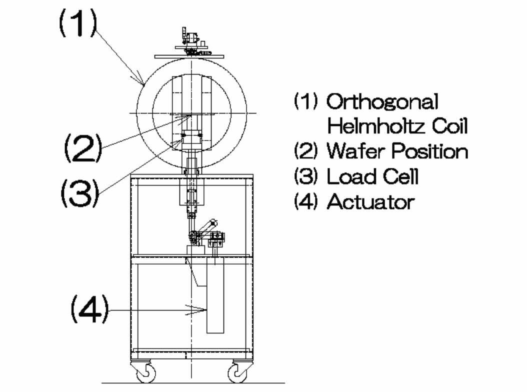


Fig. 4. The experimental tool. This can apply stress on the wafer up to 150Kg by a powerful actuator with measuring by the load cell. Horizontal magnetic field can be applied by the orthogonal Helmholtz coil to measure R-H curve by alternating field

3.2 Definition of H_c

H_c of the GMR film is defined by the field corresponding to the intersection points of the ΔR/2 line and the R-H curve like figure 5.

Where, ΔR is the deviation of the maximum of R (Rmax) and the minimum of R (Rmin).

In these measurements, the size of the substrate is φ6"×1.0mm^t and it was made of AlTiC. The maximum of applied stress σ was up to approx. 130MPa. There were 15 measurement points with increasing σ. GMR films consisted of 4 layers which were a free layer, a interlayer (spacer), a pinned layer and a anti-ferromagnet layer and the free layer was made of Ni-Fe.

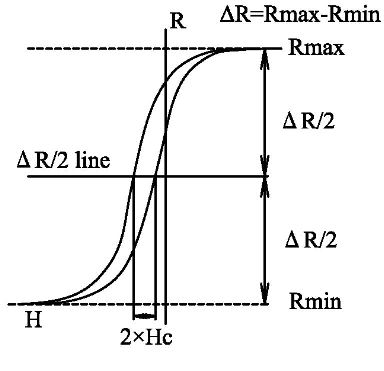


Fig. 5. A typical actual R-H curve. H_c is defined by the intersection points of the ΔR/2 line and the R-H curve.

4 Experimental results

4.1 Typical R-H curve

A typical ΔR-H curve measured by this tool is shown in figure 6. This sample was not a type of coherent rotation. It seemed that some of wall movement contained in this magnetization process. I mentioned in section 2.1 that only one term related to $\lambda_s \sigma$ remains after differentiating H_c equation, even if that equation is expressed as complicated terms. By this reason, those samples can be used for this experiment.

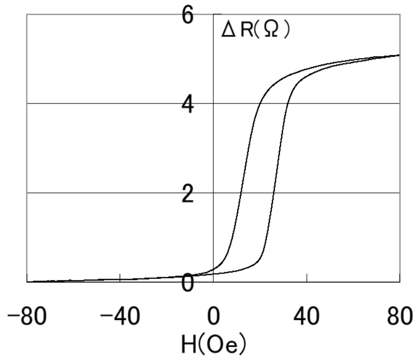
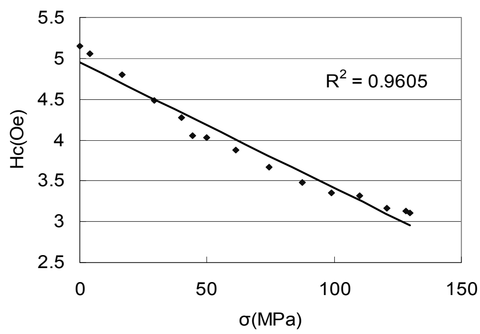
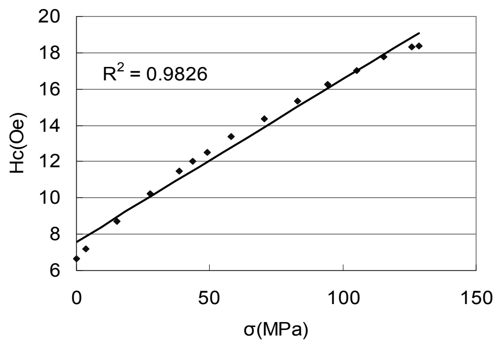


Fig. 6. A typical R-H curve without stress.

4.2 H_c- σ curves



(a)



(b)

Fig. 7. The measuring results of Hc-σ curve. (a) Negative sign and λ_s =-6.11×10^{-7}. (b) Positive sign and λ_s = 3.57×10^{-6}.

Some results of H_c-σ curves are shown in figure 7. These two films have λ_s =-6.11×10^{-7} and λ_s = 3.57×10^{-6} , respectively. A good linear relationship between H_c and σ was obtained as was expected. These values of λ_s were rough match to the ones measured from H_k by another method which we presented before [3].

By this another method, I have obtained the results of λ_s = -6.47×10^{-7} and λ_s = 1.91×10^{-6} , respectively.

5 Discussion and conclusion

A new measurement method of the magnetostriction of a thin GMR film deposited on the practical wafer has been developed by measuring H_c and applying mechanical bending. This method is especially useful when we measure the magnetic thin film having higher anisotropy field such as magnetic random access memory (MRAM) films with an in-plane or a perpendicular anisotropy. I showed asteroid curves under the tensile stress of the GMR film along the easy axis in figure 8.

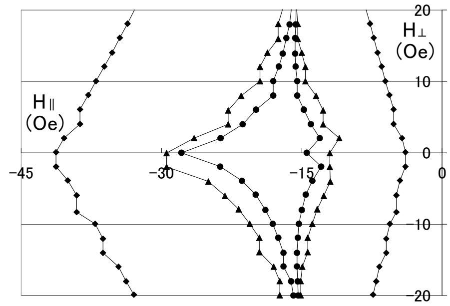


Fig. 8. Asteroid curves under the tensile stress.
● was measured for 0 tensile, ▲ for 15(MPa), ◆ for 120(MPa).

In this figure, H ∥ is the switching field parallel to the easy axis and H⊥ the switching field parallel to the hard axis. Increasing the tensile stress, H ⊥ is increasing rapider than H ∥ . It makes hard to measure the magnetostriction constant by the anisotropy field H_k, because this method needs to apply a larger magnetic field for saturating the magnetic thin films to pin the wall movement.

In this paper, I assumed the Stoner-Wolhfarth model. But some practical wafers usually follow other magnetization process and Hc for these processes is expressed as more complicated equation than eq. (7). However, the term related to the $\lambda_s \sigma$ in the above equation is usually only one and differentiating H_c by σ can derive the simple equation like eq. (8). Other terms which are not the function of σ can be ignored and this new method can be applied to measure the magnetostriction constant of magnetic thin films of which magnetization rotation models are different.

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