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Measurement of Anisotropy Dispersion in Soft Magnetic Films with Quantitative Estimation

K. Ishiyama, A. Toyoda, and K. I. Arai
Research Institute of Electrical Communication, Tohoku University 2–1–1 Katahira, Aoba–Ku, Sendai 980–77, Japan

K. Okita
Tohoku Steel Co., Ltd. 23 Nishigaoka, O–aza Murata, Murata–cho, Shibata–gun, Miyagi 989–13, Japan

Abstract--A new method of measuring magnetic anisotropy dispersion using a biaxial VSM was presented. This method made it possible to measure the magnitude and angular dispersion of magnetic anisotropy independently and quantitatively by measuring a reversal of magnetization perpendicular to a magnetic field. Adopting the measured anisotropy dispersion, frequency dependence of permeability for soft magnetic thin film has been calculated.

I. INTRODUCTION

It is known that the existence of anisotropy dispersion affects on magnetic characteristics. Various methods of measuring the anisotropy dispersion have been presented[1]–[3], but mostly those methods are not sufficient for discussing the relationship between the anisotropy dispersion and the magnetic characteristics quantitatively.

We propose a new method of measuring the magnetic anisotropy dispersion using a biaxial VSM, which made it possible to measure the magnitude and angular dispersion of magnetic anisotropy independently and quantitatively. This paper presents the method of the measuring anisotropy dispersion and the calculation of frequency dependence of permeability for thin magnetic film that have anisotropy dispersion.

II. METHOD OF MEASUREMENT

Fig. 1 shows details of detector of the biaxial VSM. Two pairs of pick–up coils make it possible to measure the components of magnetization parallel and perpendicular to the applying magnetic field. In this method the anisotropy dispersion is measured using pick–up coils perpendicular to the applied magnetic field.

A magnetic thin film that has anisotropy dispersion is assumed to consist of many small regions having different Hk and direction of easy axis. By measuring the Hk and the direction of easy axis of each region, the anisotropy dispersion of film can be measured.

We discuss the measuring method using a polar diagram model as shown in Fig. 2. The angle θ means the direction of residual magnetization and the radius means the magnitude of Hk of each region. The directions of the residual magnetizations distribute because the residual magnetizations align to their own local easy axes. In addition, if the directions of local easy axes are the same in some regions, there is a distribution of Hk. We explain the measuring method under assuming the distribution of the easy axis and Hk as shown in dark area in Fig. 2.

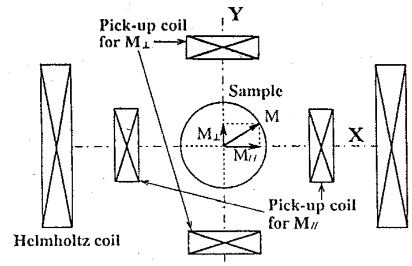

Fig. 1 Details of detector for biaxial VSM

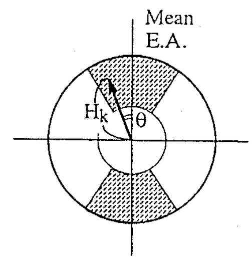

Fig. 2 Magnetization distribution model

A magnetic film is set as the angle between its mean easy axis and Y axis to be θj. The applied magnetic field is along X axis, and the pick–up coils along the Y axis. By applying and removing a large magnetic field to –X axis, every residual magnetization vector has –X components as shown in Fig.3(a). Next, the film is rotated a small angle $\Delta\theta$. In the regions with residual magnetization vectors having –Y components in this state, the direction of easy axis is in $\theta j<\theta<\theta j+\Delta\theta$ as shown in Fig.3(b) because the residual magnetization aligns to the local easy axis. The dispersion of Hk in this region will be measured as follows. When the magnetic field of H_1 was applied to –X direction and removed, the magnetization having smaller Hk than H_1 will switch from –Y to +Y direction, because the switching field is equal to the Hk if the field is perpendicular to the easy axis[5]. This operation makes it possible to measure the magnetization having easy axis in the region ($\theta j<\theta<\theta j+\Delta\theta$) and the anisotropy field magnitude of ($0<Hk<H_1$). Therefore the magnitude dispersion of magnetic anisotropy can be determined by measuring the magnetization reversal as a function of the applied magnetic field. Furthermore, by changing θj, the angular dispersion of the magnetic anisotropy of the film can be measured.

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K. Ishiyama, e-mail ishiyama@riec.tohoku.ac.jp, Fax&Phone +81–22–217–5489; K. I. Arai, e-mail arai@riec.tohoku.ac.jp, Fax +81–22–217–5490, Phone +81–22–217–5487.

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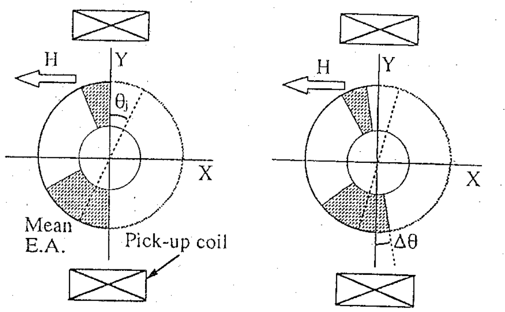

(a) residual magnetized state (b) measurement of dispersion
Fig. 3 Magnetization distribution model

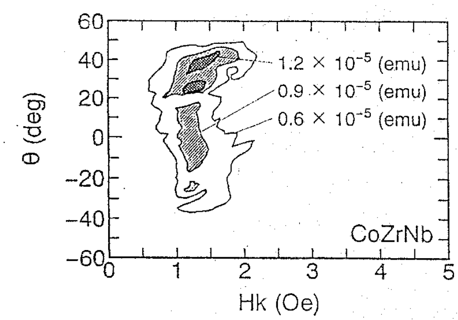

Fig. 5 Anisotropy dispersion of a CoZrNb annealed with rotating magnetic field.

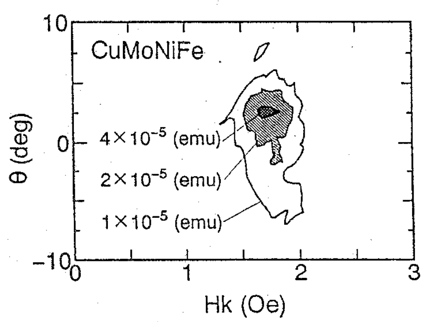

Fig. 4 Anisotropy dispersion of a CuMoNiFe annealed without magnetic field.

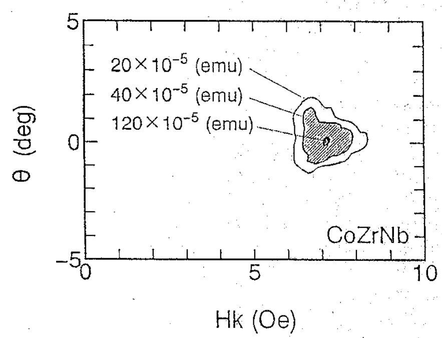

Fig. 6 Anisotropy dispersion of a CoZrNb annealed with static magnetic field.

III. Results

This section presents the results of measurements of the anisotropy dispersion of three films, a CuMoNiFe film and two CoZrNb films, using biaxial VSM. The three films were 0.1 μm in thickness, 10 mm in diameter and were rf sputter deposited on a glass substrate. The CuMoNiFe film was annealed for 1 hour at 400°C without magnetic field. One CoZrNb film was annealed for 2 hours at 400°C in a 60 rpm rotating magnetic field of 500 Oe, and the other was annealed for 1 hour at 400°C in a magnetic field of 500 Oe. $\Delta\theta$ of 1° was used in the measurement of the three films. Applied magnetic field was changed in 0.1 Oe steps in the measurement of CuMoNiFe film, and 0.2 Oe steps in the measurement of rotational field annealed CoZrNb film, and 0.5 Oe steps in the CoZrNb film annealed in the static magnetic field according to their width of dispersion.

Fig. 4 shows an anisotropy dispersion of the CuMoNiFe film by this method. The magnetization having the anisotropy condition of $2° < \theta < 3°$ and 1.6 Oe<Hk<1.7 Oe was 5.6 x 10^{-5} emu. The magnitude dispersion was distributed from about 1.3 Oe to 2.2 Oe, and the angular dispersion was distributed from about −7° to 8°. Fig. 5 shows an anisotropy dispersion of the rotational field annealed CoZrNb film. The magnitude dispersion was distributed from about 0.5 Oe to 2.2 Oe, and the angular dispersion was distributed from about −40° to 50°. Fig. 6 shows an anisotropy dispersion of the static field annealed CoZrNb film. The magnetization was 9.34 x 10^{-4} emu at the point of $0° < \theta < 1°$ and 6.0 Oe<Hk<6.5 Oe. The magnitude dispersion was distributed from about 6 Oe to 8.5 Oe, and the angular dispersion was distributed from about −1.5° to 2°. These results indicate that the anisotropy dispersion of soft magnetic thin films can be measured quantitatively by using the biaxial VSM.

IV. Permeability of Magnetic Thin Films Which Have Anisotropy Dispersion

The frequency dependence of permeability was calculated for magnetic thin films which have anisotropy dispersion. The calculation was adopted for the rotational field annealed CoZrNb film whose anisotropy dispersion was determined by this method.

The frequency dependence of the permeability including ferromagnetic resonance and macroscopic eddy current loss calculated by solving the Landau–Lifshitz equation is given as[5][6]:

$$\mu(H_k,\theta) = \frac{4\pi M_s\omega_0^2\{(\omega_0^2-\omega^2) - j4\pi\lambda\omega\}}{H_k\{(\omega_0^2-\omega^2)^2 + (4\pi\lambda\omega)^2\}}(\cos^2\theta) \cdot \frac{\sinh\psi + \sin\psi + j(\sinh\psi - \sin\psi)}{\psi(\cosh\psi + \cos\psi)} \qquad (1)$$

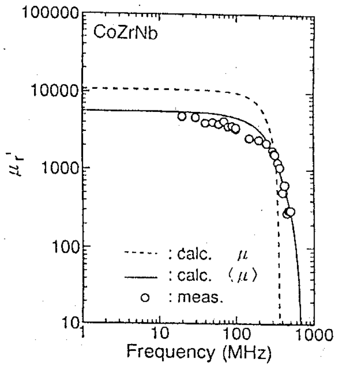

Fig. 7 Frequency dependence of the real part of the permeability for CoZrNb annealed with rotating magnetic field.

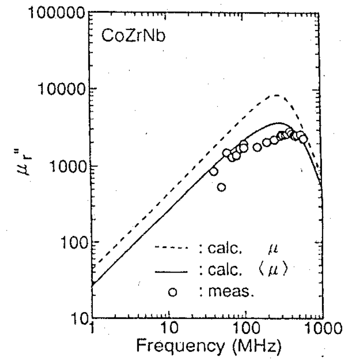

Fig. 8 Frequency dependence of the imaginary part of the permeability for CoZrNb annealed with rotating magnetic field.

where $\omega_0 = (4\pi\,|\gamma|^2\,Ms\,Hk)^{1/2}$ is the ferromagnetic resonance frequency, γ is the gyromagnetic constant, $\lambda = \alpha\,|\gamma|\,Ms$ is the damping constant, α is the Gilbert damping constant, θ is the angle between the mean easy axis and the local easy axis. s is the skin depth as $s = d/\psi = (2\rho/\omega\mu)^{1/2}$ where d is the film thickness, and ρ is the resistivity. In this paper we use values of $\gamma=2.26\times10^5(\mathrm{m\,A^{-1}\,s^{-1}})$[6], $\alpha=0.14$[7], $\rho=1.2\times10^{-6}(\Omega\mathrm{m})$[7].

The frequency dependence of permeability including the anisotropy dispersion is calculated as a sum of the permeabilities of small anisotropic regions having different Hk and direction of easy axes.

$$\langle\mu\rangle = \sum_{i,j} \mu(Hki,\theta j)\,\{M(Hki,\theta j)/Ms\} \tag{2}$$

where $M(Hki,\theta j)$ is the function of the magnetization with anisotropy field Hki and θj.Fig. 7 and Fig. 8 show the frequency dependence of real and imaginary part of the permeability respectively. The broken line shows the values of each calculated to include ferromagnetic resonance and macroscopic eddy current loss. The solid line is the values of each calculated to also include anisotropy dispersion. The circles denote the experimental values of permeability measured by a permeance meter using a microstrip pickup coil[8]. This result indicates that these experimental values agree well with the calculated values when anisotropy dispersion is included.

V. Conclusion

This work demonstrates that the magnetic anisotropy dispersion of soft magnetic thin films can be measured quantitatively using the biaxial VSM. The frequency dependence of the permeability for a CoZrNb thin film was calculated using the measured magnetic anisotropy dispersion. The calculated values agree well with the measured values.

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